UNIVERSITY OF THE AEGEAN
School of the Environment
Department of Marine Sciences

Influence of Meteorological Factors and Conditions on Sea Surface Chlorophyll Concentrations

by

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ΠΑΝΕΠΙΣΤΗΜΙΟ ΑΙΓΑΙΟΥ
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της

Διονυσίας Κόττα

Διδακτορική Διατριβή

Μυτιλήνη, 2019

In memory of
my mother Marianthi Kotta
and my uncle Athanasios Papalexis
for being the salt of the earth

and

to
my friends (term definitely including my sister)
of high emotional intelligence and no university degree

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- **Dr. Michael Karydis** – Professor Emeritus– University of the Aegean, School of the Environmernt, Department of Marine Sciences
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Preliminary Note

The publications in peer-reviewed international journals, based on the work of the present Ph.D Thesis, formed the main parts of this dissertation.

No funding was received.

All was done during ‘leisure’ time, and in no case had a negative impact on work performance at Hellenic National Meteorological Service which always was the priority.

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Dionysia

1. Introduction

1.1. Objectives and Innovation

The 'Influence of Meteorological Factors and Conditions on Sea Surface Chlorophyll Concentrations' is an interesting research topic. Sea surface chlorophyll concentrations are indicative of phytoplankton's abundance which is important to life on Earth. Phytoplankton is affected by various meteorological factors and environmental conditions and their impact needs to be assessed at different spatio-temporal scales. The Mediterranean Sea and in particular, the main body of the Eastern Mediterranean Sea and the Hellenic Seas, is an interesting study area regarding this topic, since they represent an oligotrophic marine environment affected by a variety of weather conditions. In addition, nowadays the ocean colour satellite measured property provides numerous datasets for sea surface chlorophyll concentration which give the opportunity to examine its changes.

In order to add to the research carried out so far, the objectives of this thesis were defined and aimed to the study of:
a) The contribution of desert dust on sea surface chlorophyll concentrations, focusing on dust episodes connected mainly with the Hellenic Seas.
b) The influence of extreme weather events on sea surface chlorophyll values, especially over the open sea;
c) The relations between sea surface chlorophyll concentrations and meteorological parameters at broad spatial and temporal scales.

The innovation of the present research relies mainly on:
a) The exploration of the 'dust fertilization effect' through specific dust events that affected extended areas of the Eastern Mediterranean Sea, focusing on the Hellenic Seas, which have been minimally and only locally examined. The prevailing weather conditions before, during and after the events are also taken into account regarding their possible influence on chlorophyll concentrations.
b) The medicanes' impact on sea surface chlorophyll. These Mediterranean cyclones are examined for the first time in respect to their impact on chlorophyll concentrations. The influence of extreme weather events on the open sea's chlorophyll has not been studied so far in the Mediterranean and medicanes undoubtedly induce extreme weather conditions that affect extended open sea areas.
c) The correlation of chlorophyll concentrations with meteorological parameters, such as wind speed, wave height, precipitation and mean sea level pressure; some of them have not been assessed so far. The correlations are discriminated among seasons and the calculations are based on consistent chlorophyll and meteorological data sets of the longest time period (1998-2016) studied up to now.

1.2. Thesis Outline

This Thesis has been organized into six chapters.

Chapter 1 provides an extended abstract of the thesis, including the objectives and the innovation of the conducted research. The extended abstract is also provided in Greek.

Chapter 2 presents the basic theoretical background.
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Chapter 3 refers to the possible impact of desert dust on sea surface chlorophyll.

Chapter 4 presents the research related to the influence of extreme weather events on sea surface chlorophyll concentrations.

Chapter 5 presents the assessment of the relations between sea surface chlorophyll concentrations and meteorological factors.

Chapter 6 summarizes the main findings and makes some suggestions for future work.

1.3. Extended Abstract

Phytoplankton plays a critical role in Earth's system. It is at the base of the marine food web and it accounts for half of the planet's primary production; climate variability highly influences phytoplankton abundance but at the same time phytoplankton affects climate, by providing a sink for the atmospheric CO_2 through photosynthesis. During the last decades, the satellite measured ocean colour, which is regarded as an essential climate variable by the Global Climate Observing System, provides information for the sea surface concentration of chlorophyll α, a pigment that is indicative for phytoplankton abundance. The availability of these data has led to ongoing related research that includes the possible relations between atmospheric variables and chlorophyll α. The present thesis is a contribution to the study of the influence of meteorological factors and conditions on sea surface chlorophyll concentrations, focusing on the Eastern Mediterranean and the Hellenic Seas.

The Eastern Mediterranean Sea is an oligotrophic marine environment due to the limited nutrient availability for phytoplankton growth. The broader area is often impacted by extreme weather events, it is affected by dust episodes and it is regarded as a 'hot-spot' for climate change. Several environmental variables have been examined regarding their possible influence on the Mediterranean waters' chlorophyll concentrations: the sea surface temperature and the wind speed, to a much lesser extent the mean sea level pressure and the precipitation, which has been mainly studied for coastal areas. Some extreme weather events have also been related to phytoplankton growth in some near shore regions. The possible nutrient enrichment desert dust effect on phytoplankton has been more extensively studied with contradictory results. Consequently, there are fields for further work.

The study of the research carried out so far resulted into the goals of the present thesis that were aiming at adding new aspects to the existing knowledge. The objectives were delineated as follows: a) to explore further any possible impact of desert dust on chlorophyll focusing on specific events and mainly for the Hellenic Seas; b) to study the influence of extreme weather events on sea surface chlorophyll concentrations, especially over the open sea; c) to explore the relations between sea surface chlorophyll concentrations and selected meteorological parameters on a monthly basis at broader spatial scale and for a large time period.

A wide range of data was used for assessing the aims of the present thesis. The Copernicus Marine Environment Monitoring Service was the major data source for the satellite derived data and especially for chlorophyll α products that are computed via regional (Mediterranean) ocean colour algorithms. The European Centre for Medium-Range Weather Forecasts was the other important data source, since the provided numerical model products and in most cases the ones of its reanalysis projects were mainly used for the meteorological parameters.

Desert dust, being rich in the limiting nutrients, has been proposed to stimulate phytoplankton growth in many parts of the world ocean. For the Mediterranean Sea, which is subject to dust transport, experimental, observational and statistical studies on this topic have provided contradictory results particularly for the eastern part of the Basin. The present work further explored this controversial matter by examining several dust episodes, mainly focusing on the Hellenic Seas that are poorly studied

and, taking into account the prevailing weather conditions before-during and after the events. The results showed that no safe conclusion could be drawn since both increases and decreases in surface chlorophyll concentrations were observed after the episodes. However, the absolute chlorophyll differences exceeding 50% indicated a possible favourable dust effect mainly during the low productive period. They also highlighted the difficulty in discriminating between dust and other meteorological factors in favouring phytoplankton growth.

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Some extreme weather events for the Hellenic Seas were studied, as a preliminary research, in respect to their influence on sea surface chlorophyll and their favouring effect was observed. Since relevant studies have been conducted locally and referred to coastal or near shore areas, the present research focused towards examining the impact of such events on chlorphyll concentrations in the open sea. For this purpose, a couple of tropical-like Mediterranean cyclones (medicanes) that affected a wide open sea area were examined. It was noted that the tropical cyclones have been identified for their positive influence on phytoplankton growth. The results showed that medicanes trigger surface chlorophyll increases; after the cyclones' passage, chlorophyll concentrations were higher compared both with those before and with the climatological monthly values over a large part of the affected areas. The increase in chlorophyll was comparable, though on smaller scale, to the one caused by hurricanes in oligotrophic environments. The main mechanisms that have been proposed to explain the increased chlorophyll concentrations following tropical cyclones seem to be valid for medicanes as well.

Another part of the thesis presented here explored the possible relations between surface marine chlorophyll concentration and selected meteorological parameters at broader temporal and spatial scales. The chlorophyll variations of two dissimilar – regarding their primary production – regions, the Rhodes Gyre and the Cyclades Plateau, were examined for a 10-year period during March, which is a month characterized by enhanced chlorophyll concentrations. Higher wind speeds, considerable precipitation amounts, lower mean sea level pressure and relatively low sea surface temperatures compared to climatological values, seemed to be the possible prerequisites for higher chlorophyll α concentrations. The research proceeded to the calculation of the correlations between sea surface chlorophyll α and environmental factors' monthly anomalies for the whole Eastern Mediterranean Sea. The study was conducted in a 1°×1° grid for the period 1998–2016. The statistically significant results showed that chlorophyll was negatively related with sea surface temperature and positively with wind speed and wave height. Its correlations with precipitation were positive and low, while those with mean sea level pressure were negative and local. The correlations were strongly dependent on the season and higher, in most cases, for the open southern part of the study area.

The novelty of the present thesis relies mainly on: a) the research carried out on the possible effects of dust episodes on chlorophyll concentrations for extended areas of the Hellenic Seas; b) the examination of the medicanes' influence on sea surface chlorophyll, especially over the open sea; c) the assessment of the correlations between sea surface chlorophyll concentrations and meteorological parameters based on the longest time series of robust data sets (1998-2016) used so far, discriminating between seasons and including the less or non studied parameters of wave height, mean sea level pressure and precipitation.

1.4. Περίληψη

Ο ρόλος του φυτοπλαγκτού στο σύστημα της γης είναι σημαντικός. Αποτελεί τη βάση της θαλάσσιας τροφικής αλυσίδας και συνεισφέρει το ήμισυ της πρωτογενούς παραγωγής του πλανήτη˙ επίσης, επηρεάζει το κλίμα δεσμεύοντας CO_2 από την ατμόσφαιρα μέσω της φωτοσύνθεσης αλλά και η μεταβολές του κλίματος επηρεάζουν τον πληθυσμό του. Τις τελευταίες δεκαετίες, το δορυφορικά μετρούμενο «χρώμα του ωκεανού», το οποίο θεωρείται βασική κλιματική μεταβλητή από το Παγκόσμιο Σύστημα Παρακολούθησης του Κλίματος, παρέχει πληροφορίες για τη συγκέντρωση της χλωροφύλλης-*α* στην επιφάνεια της θάλασσας, μιας φωτοσυνθετικής χρωστικής ουσίας που είναι ενδεικτική της αφθονίας του φυτοπλαγκτού. Η διαθεσιμότητα αυτών των δεδομένων οδήγησε σε διαρκή έρευνα που περιλαμβάνει και τις πιθανές σχέσεις της χλωροφύλλης-*α* με ατμοσφαιρικές παραμέτρους. Η παρούσα διδακτορική διατριβή συμβάλλει στη μελέτη της κατανόησης της επίδρασης μετεωρολογικών παραγόντων και συνθηκών στις συγκεντρώσεις χλωροφύλλης του επιφανειακού θαλάσσιου στρώματος, εστιάζοντας στην Ανατολική Μεσόγειο και τις Ελληνικές Θάλασσες.

Η Ανατολική Μεσόγειος χαρακτηρίζεται ως ένα ολιγοτροφικό θαλάσσιο περιβάλλον λόγω της περιορισμένης διαθεσιμότητας θρεπτικών συστατικών και της περιορισμένης ανάπτυξης του φυτοπλαγκτού. Η ευρύτερη περιοχή επηρεάζεται συχνά από ακραία καιρικά φαινόμενα και από επεισόδια μεταφοράς σκόνης ενώ θεωρείται ως «καυτό σημείο» για την κλιματική αλλαγή. Αρκετές περιβαλλοντικές μεταβλητές έχουν εξετασθεί σχετικά με την πιθανή επίδρασή τους στις συγκεντρώσεις χλωροφύλλης στα νερά της Μεσογείου: η θερμοκρασία της επιφάνειας της θάλασσας και η ταχύτητα του ανέμου, σε πολύ μικρότερο βαθμό η πίεση στη μέση στάθμη θάλασσας και ο υετός (συνήθως βροχόπτωση) που έχει μελετηθεί κυρίως σε παράκτιες περιοχές. Ακραία καιρικά φαινόμενα έχουν επίσης συσχετιστεί με την ανάπτυξη του φυτοπλαγκτού σε μερικές περιοχές κοντά στην ξηρά. Η πιθανή επίδραση της σκόνης από την έρημο στο φυτοπλαγκτόν έχει μελετηθεί εκτενέστερα με αντιφατικά αποτελέσματα. Κατά συνέπεια, υπάρχουν πεδία για περαιτέρω έρευνα.

Η μελέτη της μέχρι σήμερα διεθνούς βιβλιογραφίας είχε ως αποτέλεσμα τον προσδιορισμό των στόχων της παρούσας διδακτορικής διατριβής, με σκοπό να προστεθούν νέα στοιχεία στην υπάρχουσα γνώση. Οι στόχοι της διατριβής είναι οι εξής: α) η περαιτέρω διερεύνηση της πιθανής επίδρασης της σκόνης από την έρημο στη χλωροφύλλη μέσω της μελέτης επεισοδίων σκόνης και εστιάζοντας κυρίως στις Ελληνικές Θάλασσες· β) η μελέτη της επίδρασης ακραίων καιρικών φαινομένων στη χλωροφύλλη με έμφαση στην ανοικτή θάλασσα· γ) η εξέταση της σχέσης μεταξύ της συγκέντρωσης της χλωροφύλλης του επιφανειακού θαλάσσιου στρώματος και επιλεγμένων μετεωρολογικών παραμέτρων σε μηνιαία βάση και σε μεγάλη χρονική περίοδο και χωρική κλίμακα.

Ένα ευρύ φάσμα δεδομένων χρησιμοποιήθηκε για την επίτευξη των παραπάνω στόχων. Η υπηρεσία Copernicus Marine Environment Monitoring Service ήταν η κύρια πηγή για τα δορυφορικά δεδομένα που αφορούν στη θάλασσα και κυρίως για τα προϊόντα χλωροφύλλης-*α* που υπολογίζονται μέσω προσαρμοσμένων στη Μεσόγειο αλγορίθμων. Το European Centre for Medium-Range Weather Forecasts ήταν η δεύτερη σημαντική πηγή δεδομένων, αφού τα προϊόντα των αριθμητικών

μοντέλων του και, στις περισσότερες περιπτώσεις αυτά της επανανάλυσης, κυρίως χρησιμοποιήθηκαν για τις μετεωρολογικές παραμέτρους.

Η σκόνη που προέρχεται από την έρημο, όντας πλούσια στα απαραίτητα θρεπτικά συστατικά, έχει προταθεί ως ευνοϊκός παράγοντας για την ανάπτυξη του φυτοπλαγκτού σε αρκετές περιοχές των ανά τον κόσμο ωκεανών. Για τη Μεσόγειο Θάλασσα, η οποία υπόκειται σε μεταφορά σκόνης από ερήμους, οι σχετικές πειραματικές και στατιστικές μελέτες έχουν καταλήξει σε αντιφατικά αποτελέσματα, ιδιαίτερα για το ανατολικό της τμήμα. Η παρούσα διδακτορική διατριβή διερεύνησε περαιτέρω αυτό το αμφιλεγόμενο θέμα εξετάζοντας διάφορα επεισόδια σκόνης. Εστίασε κυρίως στις Ελληνικές Θάλασσες που δεν έχουν μελετηθεί επαρκώς και έλαβε υπόψη τις καιρικές συνθήκες που επικρατούσαν κατά τη διάρκεια των επεισοδίων αλλά και πριν και μετά από αυτά. Τα αποτελέσματα δεν οδήγησαν σε ασφαλή συμπεράσματα, καθώς παρατηρήθηκαν αυξήσεις αλλά και μειώσεις στη συγκέντρωση της χλωροφύλλης μετά τα επεισόδια. Όμως, οι μεταβολές στη χλωροφύλλη που υπερέβαιναν το 50% υπέδειξαν πιθανή ευνοϊκή επίδραση της σκόνης κυρίως για την περίοδο χαμηλής παραγωγικότητας. Η μελέτη κατέδειξε επίσης τη δυσκολία διάκρισης μεταξύ σκόνης και άλλων μετεωρολογικών παραγόντων ως προς την επίδραση τους στην ανάπτυξη του φυτοπλαγκτού.

Ορισμένα ισχυρά καιρικά φαινόμενα μελετήθηκαν όσον αφορά στην επίδρασή τους στη χλωροφύλλη για τις Ελληνικές Θάλασσες στο πλαίσιο προκαταρκτικής έρευνας και παρατηρήθηκε πως ευνοούν την αύξησή της. Δεδομένου ότι οι έως τώρα σχετικές μελέτες έχουν διεξαχθεί σε πολύ τοπικό επίπεδο και αναφέρονται σε παράκτιες περιοχές, η παρούσα έρευνα προσανατολίστηκε προς την εξέταση της επίδρασης τέτοιων γεγονότων στη χλωροφύλλη του επιφανειακού στρώματος της ανοιχτής θάλασσας. Για το σκοπό αυτό, εξετάστηκαν περιπτώσεις μεσογειακών κυκλώνων που επηρέασαν μια ευρεία περιοχή ανοιχτής θάλασσας. Σημειώνεται ότι οι τροπικοί κυκλώνες (ή τυφώνες) έχουν αναγνωριστεί για τη θετική τους επίδραση στην ανάπτυξη του φυτοπλαγκτού. Τα αποτελέσματα έδειξαν ότι, μετά τη διέλευση των κυκλώνων, οι συγκεντρώσεις της επιφανειακής χλωροφύλλης ήταν υψηλότερες συγκρινόμενες με εκείνες πριν αλλά και με τις κλιματολογικές μηνιαίες τιμές σε μεγάλο μέρος των περιοχών που επηρεάστηκαν. Η αύξηση της χλωροφύλλης ήταν συγκρίσιμη, αν και σε μικρότερη κλίμακα, με εκείνη που προκαλούν οι τυφώνες σε ολιγοτροφικά θαλάσσια περιβάλλοντα. Οι κύριοι μηχανισμοί που έχουν προταθεί για να εξηγήσουν τις αυξημένες συγκεντρώσεις χλωροφύλλης μετά από τροπικούς κυκλώνες φαίνεται να ισχύουν και για τους μεσογειακούς κυκλώνες.

Η παρούσα διδακτορική διατριβή διερεύνησε επίσης τις πιθανές σχέσεις μεταξύ των συγκεντρώσεων της χλωροφύλλης του θαλάσσιου επιφανειακού στρώματος και επιλεγμένων μετεωρολογικών παραμέτρων σε ευρύτερη χρονική και χωρική κλίμακα. Οι διακυμάνσεις στη χλωροφύλλη δύο διαφορετικών – όσον αφορά στην πρωτογενή παραγωγή τους – περιοχών, του κυκλώνα της Ρόδου και της περιοχής των Κυκλάδων, εξετάστηκαν για μια περίοδο 10 ετών και για το μήνα Μάρτιο που χαρακτηρίζεται από αυξημένες συγκεντρώσεις χλωροφύλλης. Μεγαλύτερες ταχύτητες ανέμου, αρκετή βροχόπτωση, χαμηλότερη πίεση στη μέση στάθμη της θάλασσας και σχετικά χαμηλή θερμοκρασία επιφάνειας θάλασσας, σε σύγκριση με τις κλιματολογικές τιμές, αναγνωρίστηκαν ως πιθανοί παράγοντες για υψηλότερες τιμές χλωροφύλλης. Η έρευνα προχώρησε στον υπολογισμό των συντελεστών συσχέτισης μεταξύ των μηνιαίων ανωμαλιών της χλωροφύλλης του επιφανειακού θαλάσσιου στρώματος και περιβαλλοντικών παραγόντων για ολόκληρη την Ανατολική Μεσόγειο. Η μελέτη έγινε σε πλέγμα 1°×1° για την περίοδο 1998-2016. Τα στατιστικά σημαντικά αποτελέσματα έδειξαν αρνητικές συσχετίσεις της χλωροφύλλης με την επιφανειακή θερμοκρασία της θάλασσας, γενικά θετικές με την ταχύτητα του ανέμου και το ύψος κύματος, ασθενέστερη και θετική συσχέτιση με τον υετό και αρνητική, αλλά περιορισμένη τοπικά και εποχιακά, με την πίεση στη μέση στάθμη θάλασσας. Οι συσχετίσεις αυτές βρέθηκαν ισχυρότερες στο ανοικτό νότιο τμήμα της περιοχής μελέτης και έντονα εξαρτώμενες από την εποχή του χρόνου.

Η καινοτομία της παρούσας έρευνας συνίσταται κυρίως: α) στην κάλυψη του κενού στη διεθνή βιβλιογραφία σχετικά με τις πιθανές επιπτώσεις των επεισοδίων σκόνης στη συγκέντρωση χλωροφύλλης για τις Ελληνικές Θάλασσες· β) στην εξέταση της επίδρασης των μεσογειακών κυκλώνων στη συγκέντρωση χλωροφύλλης, με έμφαση στην ανοιχτή θάλασσα· γ) στον υπολογισμό συντελεστών συσχέτισης μεταξύ της συγκέντρωσης χλωροφύλλης του επιφανειακού θαλάσσιου στρώματος και μετεωρολογικών παραμέτρων χρησιμοποιώντας τη μεγαλύτερη χρονοσειρά δεδομένων υψηλής ακρίβειας που έχει χρησιμοποιηθεί μέχρι τώρα (1998-2016), διακρίνοντας τις συσχετίσεις μεταξύ των εποχών και, συμπεριλαμβάνοντας τις λιγότερο ή καθόλου μελετημένες παραμέτρους του ύψους κύματος, της πίεσης στη μέση στάθμη θάλασσας και της βροχόπτωσης.

2. Basic Theoritical Background

2.1. Sea Surface Chlorophyll and Phytoplankton

2.1.1. Phytoplankton and Chlorophyll *α*

The term phytoplankton refers to the microscopic photosynthetic organisms that live in the surface waters of the oceans and lakes. They form the base of the marine food chain [Vargas et al., 2006]; through photosynthesis, carbon dioxide (CO_2) is converted into organic compounds that are available to higher trophic levels. The process of carbon fixation, transforming CO_2 into organic biomass, is called primary production.

Phytoplankton has limited or zero mobility, is short-lived but can grow very quickly; it needs light and nutrients for its growth and to carry out photosynthesis. The aerobic destruction of particulate and aggregated dissolved organic matter, produced in photosynthesis, is performed by bacteria and other microorganisms via respiration processes through all depths; these are defined as remineralization or nutrient regeneration and comprise the complete decomposition of organic matter to nitrogen, phosphorus and carbon soluble forms. The products of remineralization in the euphotic layer can be reused for photosynthesis that accounts for the regenerated production. A fraction of primary production, the export production, ends to the deep sea where the remineralization partly results in sequestering carbon from the atmosphere. Due to remineralization, nutrients increase with depth reaching their maximum concentrations between 500 and 1000 m [Lévy, 2008 and references therein]. An upward flux of nutrients to the euphotic layer plus nutriens imported from external sources result in the new production. All this procedure is referred as the biological pump and it is shown in Fig. 1 in a simplified way.

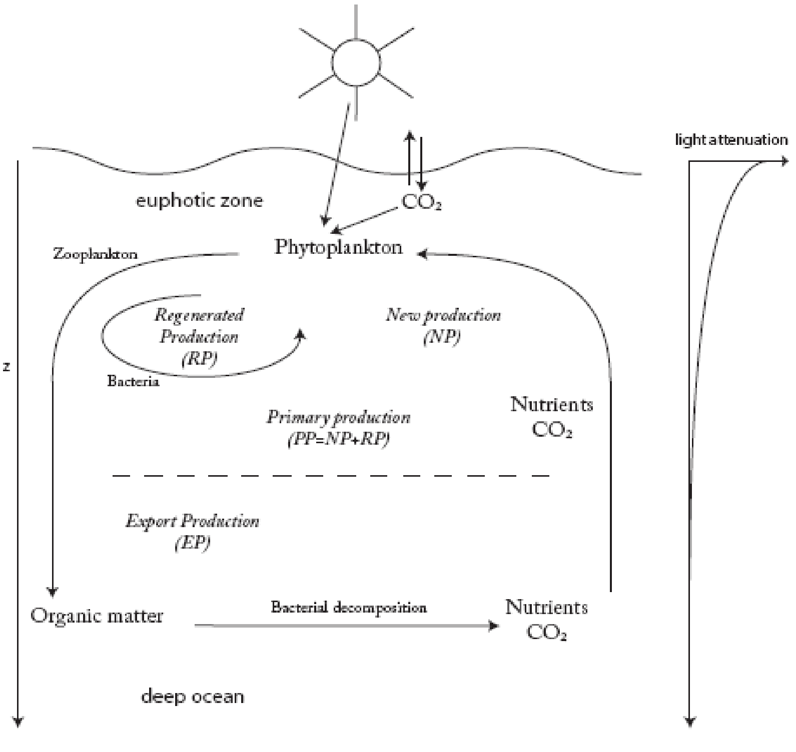


Fig.1. Schematic representation of the biological pump in the ocean (adopted from Lévy, 2008).

Phytoplankton's photosynthesis is comparable with that of the terrestrial plants [Behrenfeld et al., 2001] and they are accounting for half of the planet's primary production [Field et al., 1998; Gregg et al., 2003]. By fixing 40 GT of carbon per year into organic material [Falkowski et al., 1998, Behrenfeld et al., 2006] and providing a sink for atmospheric CO_2, they play a key role in the global carbon cycle affecting climate in this way [Gregg et al., 2003; Hays et al., 2005].

Waters characterized by low nutrient concentrations and low biological productivity are characterised as oligotrophic, by medium values as mesotrophic and by high values as eutrophic; bloom refers to the rapid phytoplankton growth under favourable conditions. However, the term 'eutrophication', describing the natural process of nutrient enrichment which results in increased levels of primary production, is used for coastal waters and, usually, with a negative sense. Thus, its various definitions mainly refer to enhanced nutrient availability due to human activities that produce undesirable disturbance to water quality and living organisms. In its worst phase can lead to oxygen depletion, fish mortality and harmful algal blooms of toxic species [Kitsiou and Karydis, 2011].

Chlorophyll α is the principal and more abundant photosynthetic pigment not only for phytoplankton but also for almost all photosynthetic organisms. Since it is also relatively easy to quantify, it is widely used in phytoplankton biomass estimations. In addition, it is also used separately as a proxy for phytoplankton abundance.

2.1.2. Light, Nutrients and the Role of the Mixed Layer Depth

Phytoplankton growth and photosynthesis are influenced by temperature and the availability of light and nutrients, the latter fueling the upper ocean layers mainly driven by mixing and upwelling processes of deeper, colder and nutrient rich water [Doney, 2006].

Phytoplankton uses the visible spectrum (400-700 nm) of the solar radiation, the photosynthetically active radiation *(*PAR), for the photosynthetic reactions. Light attenuates exponentially with depth by scattering and absorption, with the blue wavelengths reaching deeper oceanic layers due to their smaller attenuation coefficient. Thus, photosynthesis occurs in the euphotic zone that is the upper sunlit layer of the ocean and it is typically defined down to the depth where light is the 1% of that at the surface (up to 200 m for clear oceanic waters).

The growth of phytoplankton is mainly controlled by the availability of nutrients (macronutrients) mainly nitrogen (N) and phosphorous (P), in inorganic forms; they are used for the biosynthesis of proteins, nucleic acids and other biomolecules. Phytoplankton also requires several trace metals also known as micronutrients because they are needed in very small amounts; a significant element is iron (Fe) which takes part in biochemical processes [Raven et al., 1999]. Other nutrients, which are used by certain phytoplankton types for constructing their cells –such as silicon (Si) for diatoms– are also needed. Human activities can add nutrients to the ocean, N mainly from fertilizers, animal manure and the utilization of fossil fuels and P mainly from detergents and sewage. The key process in importing nutrients to the euphotic layer is the intrusion from deeper oceanic layers (plus river and land discharges for near coast areas); however, atmospheric inputs are an alternative source of nutrients especially during the stratification summer period [Bethoux, 1989; Migon et al., 2002].

Nutrients and light are the inverse of one another: nutrients increase with depth and light decreases. Physical processes, such as ocean circulation, upwelling, mixed-layer dynamics and the solar cycle, determine these two limiting factors for phytoplankton growth [Behrenfeld et al., 2006]. In conclusion, the ocean to become productive needs nutrients and light to co-occur.

Mixed layer is the upper thin ocean layer characterized by constant temperature and salinity that are different from the ones below it. Although this difference is quantified quite arbitrary, its bottom temperature must be up to 0.1 ^{o}C lower than at the surface [Stewart, 2008]. Mixed layer depth (MLD) and the layer's temperature vary from season to season and even from day to day due to heat fluxes and turbulence. Heat fluxes between the ocean surface and the atmosphere change the temperature (and consequently the density) of the surface waters. The lower the contrast among the surface and the deeper layers, the easier their mixing. The turbulence, caused by wind speed and waves, mixes heat downward. In mid-latitude oceans, MLD is shallower in late summer, when the surface layer is warmer. It begins to deepen in fall, it is deeper in late winter due to the season's heat loss and turbulence (often derived from storms) and, in spring as sunlight increases it begins to shallow [Stewart, 2008]. The mean MLD in tropical and mid-latitude regions lies between 10-200 m depending on the season.

Among the physical factors controlling phytoplankton dynamics, the MLD is considered to have the strongest influence, controlling both nutrient and light availability [Lavigne et al., 2013]. A deep MLD results in the replenishment of the upper ocean layers (that may or may not coincide with parts or the entire euphotic zone) with nutrients from below. Two regimes characterize, in general, the phytoplankton response to MLD dynamics: the sup-polar or temperate regime and the subtropical one. According to the first, MLD presents strong variations with season and chlorophyll concentrations are characterized by a drastic increase in spring; the latter refers to co varying inverse seasonal cycles for MLD and chlorophyll, with deeper MLD coinciding with maximum chlorophyll concentration [Wilson and Coles, 2005; Henson et al., 2009]. In sub-polar regions, the winter mixing is strong and MLD becomes deeper than the euphotic zone. In consequence, phytoplankton –drifted throughout the MLD– spends time in the dark and cannot exploit all the available nutrients; in addition, the reduced illumination during the winter season also limits its growth. In spring, the MLD becomes shallower due to heat input, phytoplankton and nutrients are held in the well sunlit zone, more light is available and a bloom occurs. This bloom is more intense when the heat input that favors restratification is greater. A relatively smaller bloom occurs in fall when the MLD begins to deepen. In the regions following the sub-tropical regime, the winter mixing is less intense and the MLD does not become deeper than the well-lit zone while light is never a limiting factor for phytoplankton growth. Consequently, the deepening of the MLD results in more nutrients in the upper layers and coincides with primary production increases. The greater the mixing and the surface heat lost, the more pronounced the phytoplankton growth [Follows and Dutkiewicz, 2002; Lévy et al., 2005]. It is noted, that phytoplankton may continue to grow below the MLD in cases when the euphotic zone exceeds this depth.

2.1.3. Ocean Colour

Chlorophyll *α*, which is indicative for phytoplankton concentration, is characterized by an absorption spectrum for visible wavelengths with a primary peak in the blue (~440 nm) and a secondary one in the red (~ 675 nm) while between 500 and 600 nm the absorption is low [Bricaud et al., 1995]. In general, the lower the chlorophyll concentration, the bluer the waters will appear.

During the last decades, satellites provide information on the oceanographic properties of the sea surface such as chlorophyll *α* concentrations [Maritorena and Siegel, 2005], filling up the gap of the *in situ* measurements' limited spatiotemporal extent and making data available over extended areas and time series.

Satellites measure the Remote Sensing Reflectance (Rrs or Normalised Water Leaving Radiance) of the ocean, which is defined as the ratio of the Radiance (light leaving the surface vertically upwards) to the Irradiance (the incoming solar radiation), at different wavelenghts in the visible part of the electromagnetic spectrum. The spectral variability of Rrs defines the so-called ocean colour that is regarded as one of the essential climate variables by the Global Climate Observing System (https://gcos.wmo.int/en/essential-climate-variables/ecv-factsheets for ocean colour, assessed on 10/7/2019). Since chlorophyll's absorption spectrum peaks at blue wavelengths (~440 nm), the higher the water's reflectance in blue, the lower its chlorophyll concentration (Fig.2). The blue-to-green reflectance ratio is sensitive to the amount of chlorophyll in the oceans due to its strong absorption in the blue and the week absorption in the green: higher ratios indicate lower chlorophyll values. Specific algorithms (the bio-optical algorithms) are applied to the blue-to-green reflectance ratio for deriving the sea surface chlorophyll concentrations [O'Reilly et al., 1998; Morel and Maritorena, 2001].

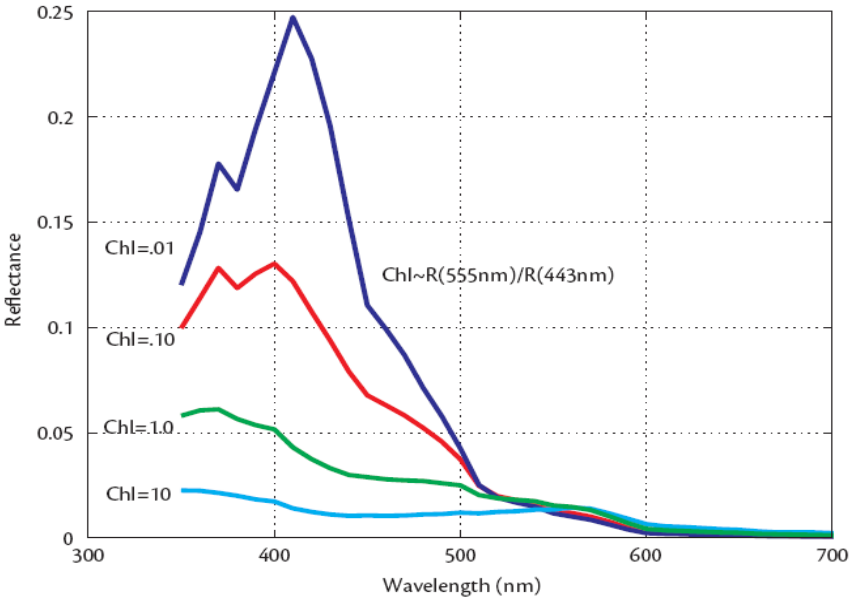


Fig.2. Idealized reflectance spectra for different chlorophyll *α* concentrations (adopted from Yoder and Kennelly, 2006).

The satellite-derived chl-a concentrations have been demonstrated as good indicators for phytoplankton [Joint and Groom, 2000; Maritorena and Siegel, 2005]; they are widely used, considering that differences in chlorophyll concentration reflect differences in phytoplankton abundance.

The ocean colour observations give a synoptic view of the world oceans' zonation in terms of primary production (as in Fig.3). They provide information for the seasonal phytoplankton variability on a global scale, for the role of the oceans in the global carbon cycle, the variations of coastal upwelling systems and even the ENSO impact on chlorophyll distributions [Yoder and Kennelly, 2006]. These data are also valuable in identifying regional chlorophyll patterns, determining trends, monitoring the coastal water quality, as a guide for marine resources management etc. The ocean colour data can be used together with other environmental variables' data for identifying possible forcing mechanisms on chlorophyll concentrations.

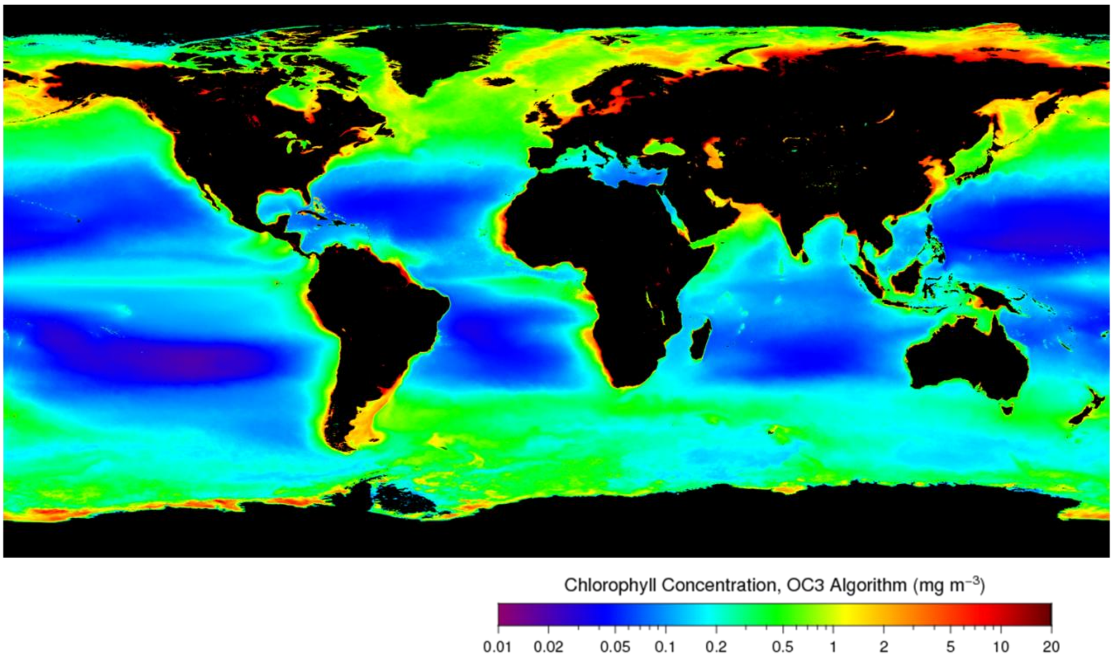


Fig.3. *C*hlorophyll composite (mean values) from the MODIS-Aqua mission (4 July 2002 up to 31 July 2019) as derived through https://oceancolor.gsfc.nasa.gov/l3/.

2.1.4. Satellite Chlorophyll Data and the Copernicus Marine Environment Monitoring Service (CMEMS) as a major Data Source

The wide scale ocean colour observations practically started in 1997 with the launch of SeaWiFS (Seaviewing Wide Field-of-view Sensor) from NASA (1997- 2010). It was followed by MODIS/Aqua (Moderate Resolution Imaging Spectroradiometer) from NASA (2002, ongoing), MERIS (MEdium Resolution Imaging Spectrometer) from ESA (2002-2012), VIIRS (Visible Infrared Imager Radiometer Suite) from NOAA (2012, ongoing) and recently the Copernicus Sentinel 3A OLCI (Ocean and Land Colour Instrument) (2016, ongoing), all sensors on polar-orbiting satellites.

Operational global bio-optical algorithms have been developed in order to convert the satellite measured reflectance into chlorophyll concentration. They exploit the blue-to-green ratio reflectance ratio and they are based on regressions between *in situ* measurements of both chlorophyll and water leaving radiances. The first algorithms made computations using a single band blue-to-green ratio, i.e. a single wavelength in blue and one in green. They evolved into log-transformed maximum band ratio (MBR) algorithms with a use of various ratios between several blue wavelengths and one in green and making estimations based on the maximum ratio. This approach gave the potential advantage of the highest signal to noise ratio [O'Reilly et al., 1998]. Their functional form is: $log_{10}(Chl) = \sum_0^i a_i MRB^i$ where α_i is an empirically determined coefficient and usually $i = 4$.

The global (standard) algorithms fulfilled the required by the space agencies level of uncertainties; on a global scale, the chlorophyll uncertainties were < 35% for the SeaWiFS derived concentrations [e.g. Gregg and Casey, 2004]. However, for several marine areas such as the Mediterranean Sea, their performance was worse than expected [Bricaud et al., 2002; Claustre et al., 2002; D'Ortenzio et al., 2002]. Basin focused –regional– algorithms were formed in order to reflect more accurately than the global ones the bio-optical properties of different ocean regions [e.g. Szeto et al., 2011; Pitarch et al., 2016]. Two regional algorithms were soon developed for the Mediterranean [Bricaud et al., 2002; D'Ortenzio et al., 2002] plus the one introduced by Volpe et al. (2007), the MedOC4 algorithm. With the use of an *in situ* chlorophyll dataset, they were validated for SeaWiFS and they were also compared to the global NASA algorithm OC4v4; the results showed that the regional algorithms performed better than the global one and pointed out the MedOC4 as the best algorithm for the Mediterranean [Volpe at al., 2007]. The employment of MedOC4, compared to the use of the global algorithm, reduced the absolute percentage error between satellite estimated and *in situ* measurements from 117% to 40% over the whole range of chlorophyll and from 134% to 35% for oligotrophic waters. The pronounced difference between the global and the MedOC4 algorithms were mainly attributed to colour peculiarities of the Mediterranean; its oligotrophic waters are less blue (30%) and greener (15%) than the global ocean's ones, resulting in significant chlorophyll overestimations by the standard algorithm [Volpe at al., 2007]. The spectral signature of phytoplankton groups populating the Mediterranean could be the reason for the Sea's colour discrepancy. The MedOC4 algorithm was also applied to reflectance's data of other sensors [Volpe et al., 2012], providing chlorophyll concentrations for the Mediterranean that were made available through CMEMS (former myOcean project).

It is not yet possible for a unique algorithm to describe the chlorophyll regime across different marine environments, even on a basin scale. That is because the optical properties of a water body can be mainly dependent on phytoplankton or not. There are waters, usually in the open ocean, whose optical properties are controlled by phytoplankton, their associated materials and the related colored dissolved organic matter (CDOM), the Case 1 waters; in such waters chlorophyll is determined by phytoplankton abundance. On the other hand, there are Case 2 waters, especially in coastal regions, whose colour is significantly influenced by other constituents such as CDOM or mineral particles not related to phytoplankton [e.g. Morel and Prieur, 1977; Morel and Maritorena, 2001]. Thus specific algorithms have been also developed for Case 2 waters [e.g. D'Alimonte and Zibordi, 2003]; however Case 1 and 2 classes are not easy to be sharply discriminated.

The existence of several ocean colour satellite sensors, measuring ocean reflectance in different wavelengths, led to the development of multi-sensor merging, a technique to unify all the available data using band-shifting methods over the SeaWiFS native bands. This technique is estimated to cause minor reflectance uncertainties (below 5%) [e.g. Lee et al., 2002; Mélin and Sclep 2015], while the multi-sensor spectra is in better agreement with the *in situ* data [Volpe et al., 2019].

Within CMEMS, it is the Ocean Colour Thematic Assembly Centre (OCTAC) that provides global and regional ocean colour products. The OCTAC produces daily L3 products plus L4 time-averaged monthly and weekly products or daily interpolated ones, in near real time (NRT) and reprocessed (REP) modes [Volpe et al., 2019 and references therein]. Until recently, the multi-sensor approach included for L3 products the MODIS Aqua and VIIRS sensors and for L4 ones the SeaWiFS, MODIS Aqua, MERIS and VIIRS sensors; the OLCI sensor is currently being incorporated.

During the last years, an updated configuration of the MedOC4 algorithm is applied for deriving the Mediterranean CMEMS chlorophyll products. This updated version has been derived using a wider basin-representative Mediterranean bio-optical dataset (the MedBiOp) which included much more *in situ* data points than the previous one acquired with the use of advanced measurements procedures [Volpe et al., 2019 and references therein]. The validations of the updated MedOC4 algorithm and a newer version of the global one OC4v6 against the *in situ* Mediterranean observations are shown in Fig.4. The CMEMS Mediterranean chlorophyll products include the identification of the water type (Case 1 or Case 2) according their spectrum through a comparison with *in situ* measurements [D'Alimonte et al., 2003]. The updated MedOC4 algorithm is used for Case 1 and another regional algorithm, the ADOC4 [D'Alimonte and Zibordi, 2003] for Case 2 waters.

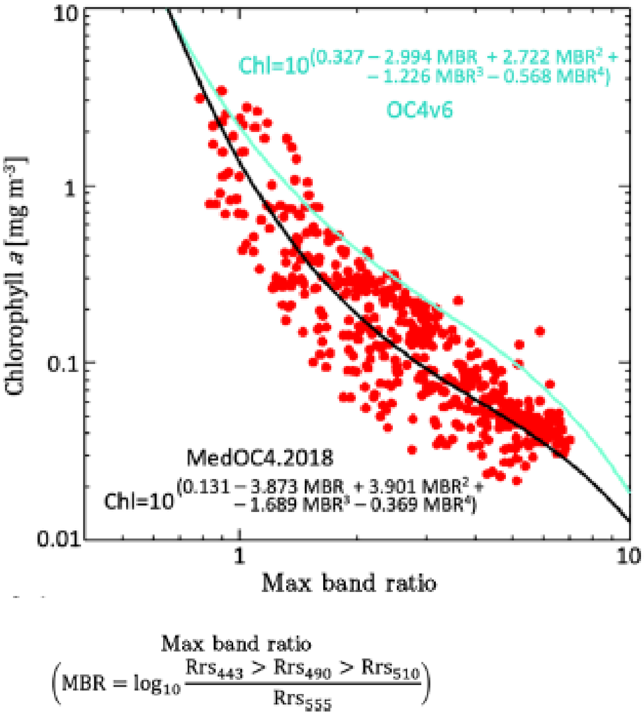


Fig. 4. Validation of algorithms for chlorophyll retrievals over the Mediterranean Sea. The line and functional form in black refers to the updated CMEMS operational algorithm MedOC4 for the Mediterranean, while the turquoise ones refer to the global OC4v6 algorithm. The red dots are *in situ* Mediterranean bio-optical data (MedBiOp dataset) that was also used to compute the regional algorithm. The wavelengths involved in the computation of MRB are also shown (adopted from Volpe et al., 2019).

Climate studies and long-term analyses should be based on consistent and homogenous ocean colour datasets [Sathyendranath et al., 2017]. In order to produce such data, the OCTAC performs a reprocessing procedure of the whole time series once a year, which results to the REP data. These data are characterized by stable accuracy; they evolve from a single software configuration, while all recent findings – such as the updated algorithms– are applied to them [Volpe et al., 2019].

Although extensive efforts have been made on extracting chlorophyll α concentrations in surface waters from the satellite observed reflectance, the related errors are still greater than the required measurement uncertainty of 30% according to the Global Climate Observing System. The present practice in developing global algorithms is to take into account the type of water present each time; however, the regional algorithms are still expected to perform better than the global ones. It is noted that the CMEMS chlorophyll dataset used here, created through updated Mediterranean algorithms, presents an absolute percentage error between satellite derived data and *in situ* measurements of 47%, while the MBR reflectance explains 74% of the observed phytoplankton variability [Volpe 2019].

2.2. The Eastern Mediterranean Sea

2.2.1. General Description

The Mediterranean region is located between mid (Southern Europe) and sub-tropical (Northern Africa) latitudes. In addition, it presents a complicated land and sea morphology (Fig.5) that results to a variety of atmospheric and oceanic features [Lionello et al., 2006a]. The Mediterranean (Med) Sea, presenting most of the global oceans' circulation patterns and physical processes on smaller temporal and spatial scales, is considered as a complex marine environment and has been characterized as a miniature ocean [Lacombe et al., 1981; Williams, 1998]. Its two parts are relatively isolated from each other, communicating through the Sicily Straits (150 km width and maximum depth of about 400 m). The Straits of Dardanelles (7 km max width and 55 m average depth) connect the Eastern Med with the Black Sea, while the narrower (200 m width), shallow (18 m mean depth) and elongated (190 km length) Suez Canal forms its connection to the Red Sea. The Aegean and the Adriatic Seas can be considered as semi-enclosed extensions of the Eastern Basin. The greatest depth (5,267 m) of the entire Med and a large shallow part (<200m) are encounter in the Eastern Med, southwest of Peloponnese (Greece) and in the Northern Adriatic Sea, respectively.

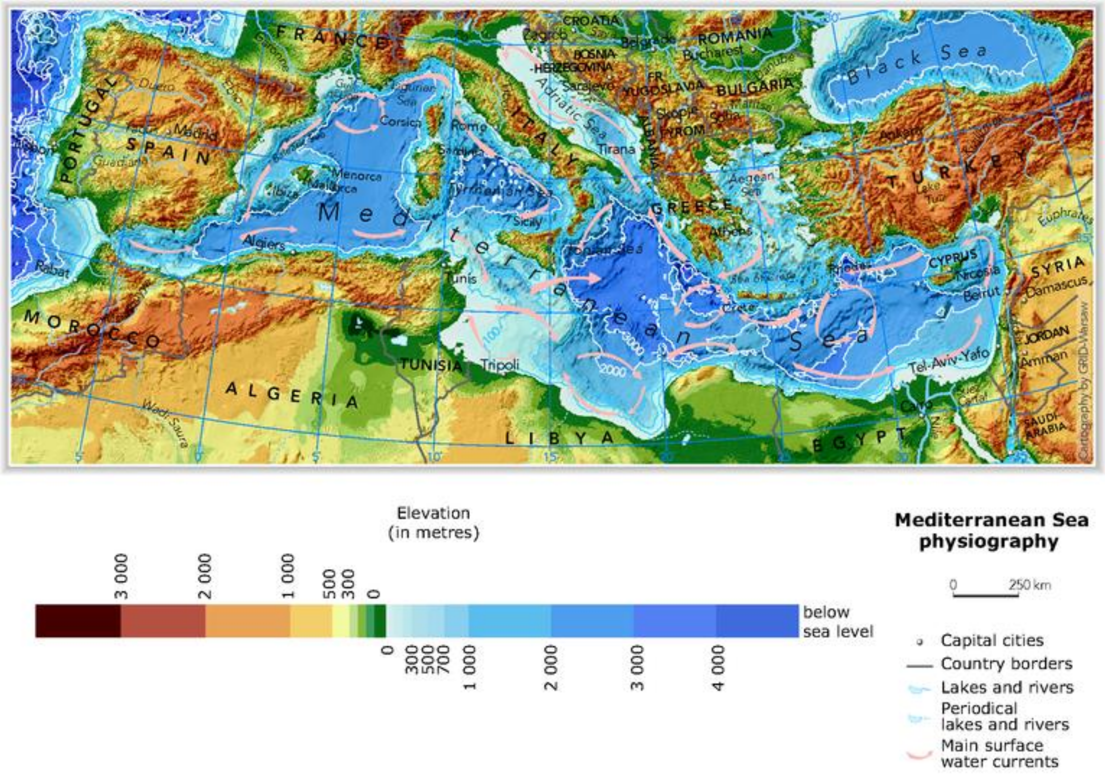


Fig.5. The Mediterranean Sea physiography (adapted from European Environment Agency, https://www.eea.europa.eu/data-and-maps/figures/mediterranean-sea-physiography/figure-01-1pia.eps, assessed on 2/7/2019).

The 'Mediterranean' climate of the region is characterized by winters that are mild and wet and, by warm to hot, dry summers; the transitional seasons of spring and autumn present uncertain characteristics [Lionello et al., 2006]. Although this is the broad picture, there are significant variations: a decreasing north to south temperature and precipitation gradient and a western-eastern gradient of the atmospheric circulation that is mainly influenced by Atlantic-Asian patterns. During the cold season, the area is influenced by the atmospheric circulation systems of the Azores High and the Siberian High as well as by low pressure systems (depressions) that form or gain strength and moisture in the warm Med Sea [Maheras et al., 1999, 2001]. The Sea has also been recognized as one of the main regions for cyclogenesis in the world [e.g. Hoskins and Hodges 2002; Wernli and Schwierz, 2006] while there are rare cases of cyclones resembling the tropical ones [Emanuel, 2005]. In the warm period, the area is mainly characterized by anticyclonic activity and a high index circulation. The Asian thermal low and the extension of the North Atlantic Ocean anticyclone towards the region are the main synoptic patterns of this period; their combination results in the Etesians, the characteristic summer winds mainly over the Aegean [Kallos et al., 2007 and references therein]. The Sea is characterized by an October to March rainy period presenting a maximum in November and December [Mehta and Yang, 2008]. The area is subject to desert dust transport and deposition [Engelstaedter et al., 2006], which are characterized by a northward decreasing gradient, during 20-37% of the annual days [Pey et al., 2013]. As far as future climate projections are concerned, the Med area has been identified as a 'hot spot' for climate change [Giorgi, 2006]. Both global and regional climate models suggest a forthcoming warming along with a decrease in precipitation especially in the warm season [Giorgi and Lionello, 2008]. In addition, an increase in SST is projected [Shaltout and Omstedt, 2014]. A sea level pressure increase is projected for the Basin, except during the warm season when a decrease is expected [Giorgi and Lionello, 2008; Makris et al., 2016]. By the end of the 21st century and over the eastern Med, the wind speed is expected to decrease, with the exception of the Aegean Sea where an increase in projected [Bloom et al., 2008; Makris et al., 2016]; the same pattern is also valid for the wave height [Makris et al., 2016]. In addition, a decrease in extreme rainfall events is also forecasted, except in autumn when an increase is expected [Oikonomou et al., 2008].

The Med is a concentration basin, with evaporation exceeding by far the freshwater inputs; this excess of evaporation presents an increasing eastward gradient and induces such a gradient for salinity as well. The above results in anti-estuarine circulation [Siokou-Frangou et al., 2010 and references therein]. In the surface layer, Atlantic water enters the Basin through the Gibraltar Straits, travels eastwards and reaches the Levantine basin, being modified by becoming saltier and decreasing its nutrient content [Bethoux et al., 1992]. In the East Med, mainly in the area of the Rhodes cyclonic gyre, it is transformed into denser salty water, due to heat loss during winter; it sinks to intermediate depths and becomes the Levantine Intermediate Water (LIW) [Lascaratos, 1993]. Then, as a deeper current, it travels back exiting again to the Atlantic. This main thermohaline cell, which forms the basin-scale circulation [Lascaratos et al., 1999], completes a circle in 80-100 years [Turley, 1999; El-Geziry and Bryden, 2010] and it is restricted to the upper and intermediate layers due to the shallow depths of the Sicily and Gibraltar Straits [Manzella et al., 1988; Astraldi et al., 1999]. Thus, the deep water formation, which also takes place in the Med, is a sub-basin phenomenon and takes place on a seasonal time-scale [Lascaratos et al., 1999]. In Eastern Med, the main region where deep dense water is formed is the South Adriatic cyclonic gyre; between the end of 80' and the first half of 90' the principal source of the denser water process shifted to the Aegean. This transition, known as the Eastern Mediterranean Transient, has been attributed to atmospheric forcing through important meteorological anomalies [Lascaratos et al., 1999; Malanotte-Rizzoli, 2003]. Changes in the circulation of the North Ionian gyre have been also observed on a decadal scale [Civitarese et al., 2010 and reference therein]. It is noted that the north-eastern part of the Basin (North Aegean) is highly influenced by the inflow of mesotrophic Black Sea's waters and a front is created where these waters are met with the warmer and saltier ones originating from the Levantine [Zervakis and Georgopoulos, 2002; Androulidakis, 2012]. The general circulation of the Basin is also characterized by a distribution of eddies and gyres, mainly cyclonic in its northern parts and anticyclonic in the south [Pinardi and Masetti, 2000].

2.2.2. Chlorophyll Regime

The Med Sea is characterized, in general, by oligotrophic conditions that are enhanced eastwards and southwards [Siokou-Frangou et al., 2010 and references therin]. The eastern part of the Basin has even been mentioned as a marine desert [Azov 1991]; however, it presents high biodiversity [Coll et al., 2010]. As far as phytoplankton is concerned, during the productive winter period the Eastern Med is dominated by nano-phytoplankton followed by pico-phytoplankton. The highest micro-phytoplankton abundance is found in cyclonic gyres that are also characterized by higher chlorophyll concentration; the different is valid for anticyclonic gyres where the highest contribution by pico-phyplankton is observed [Vidussi et al., 2001]. In addition, the eastern Aegean's wind-induced upwelling area that is the main one of the eastern Basin [Bakun and Agostini, 2001], has not been identified to influence the sea surface chlorophyll concentrations [Skliris et al., 2010].

The oligotrophic character of the Med Sea is due to nutrient limitation and mainly to P scarcity; the Sea presents an unusually high N/P ratio, especially over its eastern part [e.g. Krom et al., 1991; Thingstad et al., 2005], as compared to the one of the global ocean. Due to the Sea's internal nutrient limitation, the role of the atmosphere and the coasts in importing nutrients is increased. The primary production in the Eastern Med is considered to be significantly supported by atmospheric inputs, with N inputs rather sufficient for the whole production and P ones contributing up to 40% [Kouvarakis et al., 2001; Markaki et al., 2003; Krom et al., 2004].

For the Eastern Med, sea surface chlorophyll concentrations reveal an almost uniform oligotrophic environment; mesotrophic patterns are scarce and encountered in the northern parts of Adriatic and Aegean Seas, while higher chlorophyll values are also found in the Gulf of Gabes, the Nile plume affected area and the cyclonic Rhodes Gyre in the Levantine basin [Barale et al., 2008]. However, the whole Basin presents a deep chlorophyll maximum as a semi-permanent feature that lacks in late winter [Siokou-Frangou et al., 2010 and references therin]. The SeaWiFS-derived monthly chlorophyll means revealed the seasonal cycle of sea surface chlorophyll: the minimum summer concentrations are increasing during fall, reach their higher values in winter and decrease again during spring; few areas present a late winter-early spring maximum: the Adriatic and North Aegean Seas plus the Rhodes Gyre [Barale et al., 2008]. This seasonal variability largely coincides with the MLD variations [Barale et al., 2008; Volpe et al., 2012b] as estimated from *in situ* measurements [D'Ortenzio et al., 2005; Houpert et al., 2015] and it is shown in Fig.6. Thus, the MLD –through determining nutrient availability– is proposed as the primary controller for chlorophyll variations [Barale et al., 2008; Lavigne et al., 2013] along with the continental runoff for coastal areas. Consequently, the atmospheric forcing that results in MLD variations plays an important role in the Basin's fertilization [Barale et al., 2008].

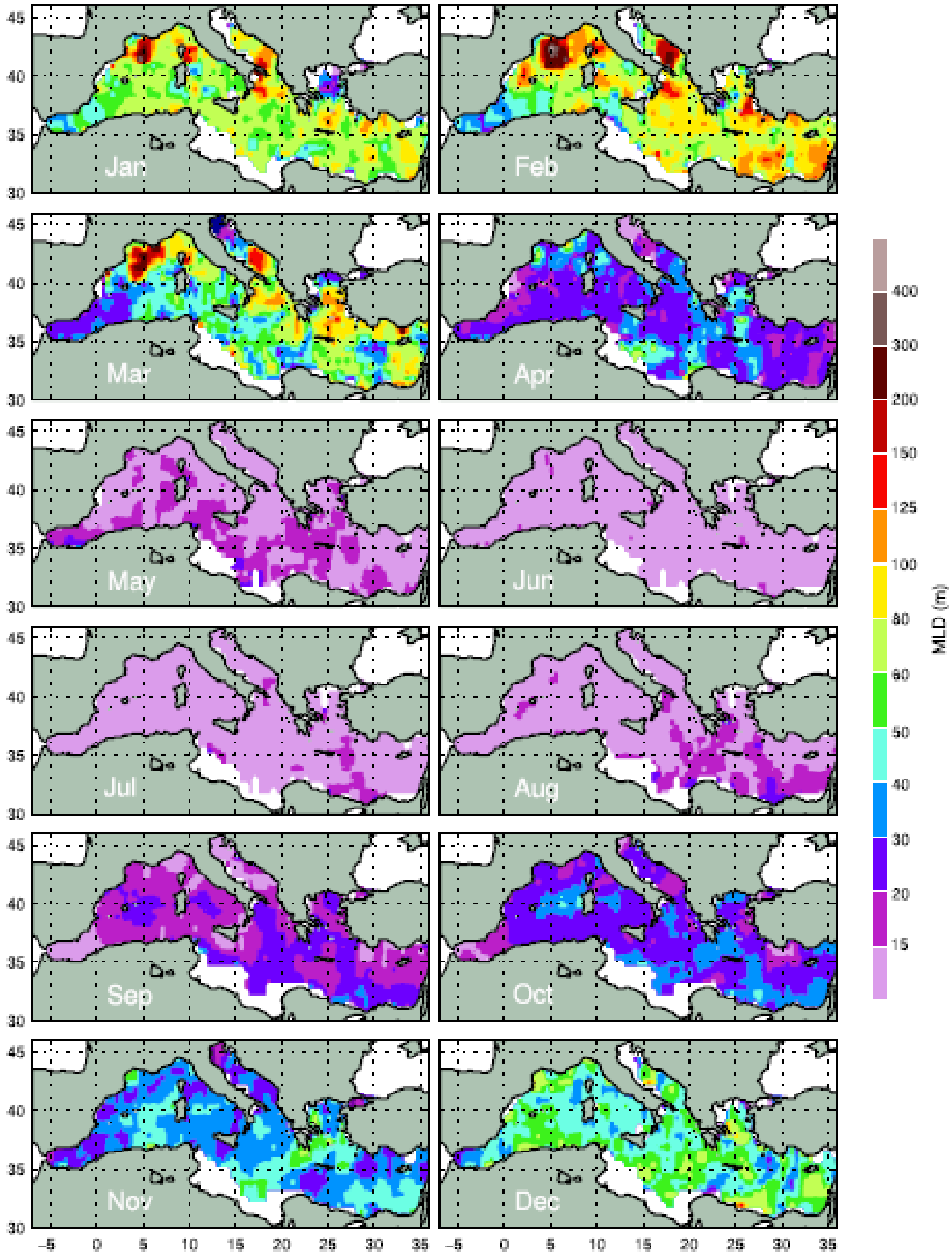


Fig.6. Mediterranean climatology of MLD, based on a temperature difference criterion of DT = 0.1 °C applied to individual profiles (adopted from Houpert et al., 2015).

A k-means cluster analysis, applied on ten years satellite derived chlorophyll concentrations, resulted in the classification of Med waters [D'Ortenzio and Ribera D'Alcalà, 2009] that is shown in Fig.7. The major part of the Basin exhibits non-blooming characteristics that is smooth chlorophyll changes between its highest winter values to the lowest summer ones. Thus, the subtropical regime for phytoplankton growth, which is nutrient and not light limited, dominates the Basin [D'Ortenzio and Ribera D'Alcalà, 2009]. Indeed, concomitant sea surface chlorophyll and MLD maxima have been found for this extended area [Lavigne et al., 2013]. In the Eastern Med, only a few areas have been found to present blooming or intermittently blooming behavior; they are characterized by spring chlorophyll peaks and follow the sup-polar (or temperate) cycle for primary production [D'Ortenzio and Ribera D'Alcalà, 2009]. For these areas, MLD first reaches its maximum depth and 30 days after the highest chlorophyll concentrations are observed [Lavigne et al., 2013]. Some areas have been aharacterized as coastal; they present very similar chlorophyll values throughout the year or a pronounced maximum in late summer-early autumn period [D'Ortenzio and Ribera D'Alcalà, 2009]. It is noted that eutrophication problems are sparse and only observed in a few coastal areas influenced by river and land discharges impacted by human activities [Karydis and Kitsiou, 2012].

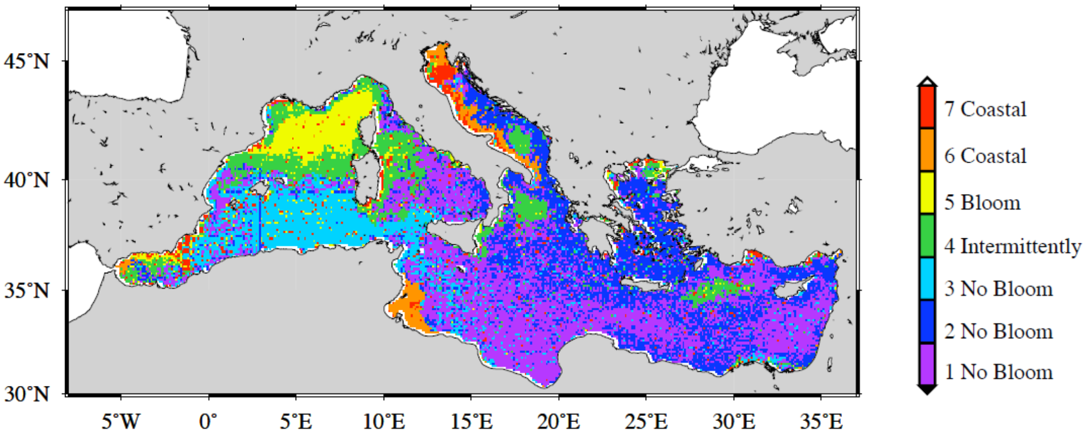


Fig.7. Mediterranean's biogeography patterns obtained from the k-means cluster analysis of ten years SeaWiFS chlorophyll concentrations (adopted from D'Ortenzio and Ribera D'Alcalà, 2009).

Atmospheric forcing seems to play a key role in the Basin's fertilization [Barale et al., 2008]; thus, the research upon the relations between meteorological factors and conditions and chlorophyll concentrations is important. In addition, the environmental variables are projected to change in the future, which makes more significant the identification of such relationships.

2.3. Meteorological Factors and Conditions

2.3.1. Sea Surface Temperature

Sea Surface Temperature (SST) is considered as an essential component of the climate system, being important for the coupling between the ocean and the atmosphere. Although it is thought as an oceanographic variable representative of the underlying ocean dynamics, it also plays an important role on the weather systems (https://gcos.wmo.int/en/essential-climate-variables/ecv-factsheets for SST, assessed on 10/7/2019). *In situ* observations provide SST measurements, at stated depth close to the sea surface, in a rather poor spatial and temporal coverage. During the last decades, this has changed with the use of satellite measurements that estimate SST down to 1 mm depth; Fig.8 provides the seasonal SST means of the period 1998-2016 for the Eastern Med based on satellite data. Since SST is included in numerical models, it can be also derived through their reanalysis data.

SST is considered as an important variable linked to primary production [e.g. Behrenfeld et al., 2006]. It can influence sea surface chlorophyll concentrations by altering the upper layers temperature stratification, which in turn is associated with the depth of the mixed layer that determines the available nutrients in the euphotic zone [Behrenfeld et al., 2006; Doney, 2006].

Several global studies have been conducted regarding the relationship between SST and chlorophyll or primary production. Correlation patterns between chlorophyll and SST were estimated based on 16-year monthly multi-satellite data in a large scale analysis referring to ocean provinces. Coastal regions and upwelling regimes plus the Med Sea were not included in this study; however; for the subtropical oceans, SST and chlorophyll were generally inversely correlated [Feng et al., 2015]. A comparison of satellite SST variations and modelled net primary production plus depth-integrated chlorophyll data for the period 1999-2004, resulted in their inverse relationship over 74% of the global oceans. Such relationship was also found for the Eastern Med, with the exception of a few areas mainly over the Levantine Basin [Behrenfeld et al., 2006]. Quite similarly, another global study, based on satellite data, revealed opposite SST and chlorophyll changes over 60% of the oceans lying between the equator and 50^o latitude. However, for the Eastern Med and the period 1999-2004, chlorophyll increases as well as decreases were observed over different areas together with decreases in SST [Martinez et al., 2009]. Co-variations of SST and sea surface chlorophyll were globally examined for the long 2002-2015 interval with the use of daily satellite observations. Both positive and negative relationships were found between the two parameters; surprisingly, in the Eastern Med the results showed warming along with chlorophyll increases [Dunstan et al., 2018]. In a basin-scale study for the Med, the two parameters were referred as negatively correlated when based on the statistically significant results [Katara et al., 2008].

SST has been quite extensively examined in relation to chlorophyll. However, this crucial parameter cannot be absent from a study exploring the influences of environmental parameters on chlorophyll concentrations. In addition, neither the long time series of ocean colour data that are available nowadays have been thoroughly exploited, nor the relationship of these two parameters has been assessed on a seasonal basis.

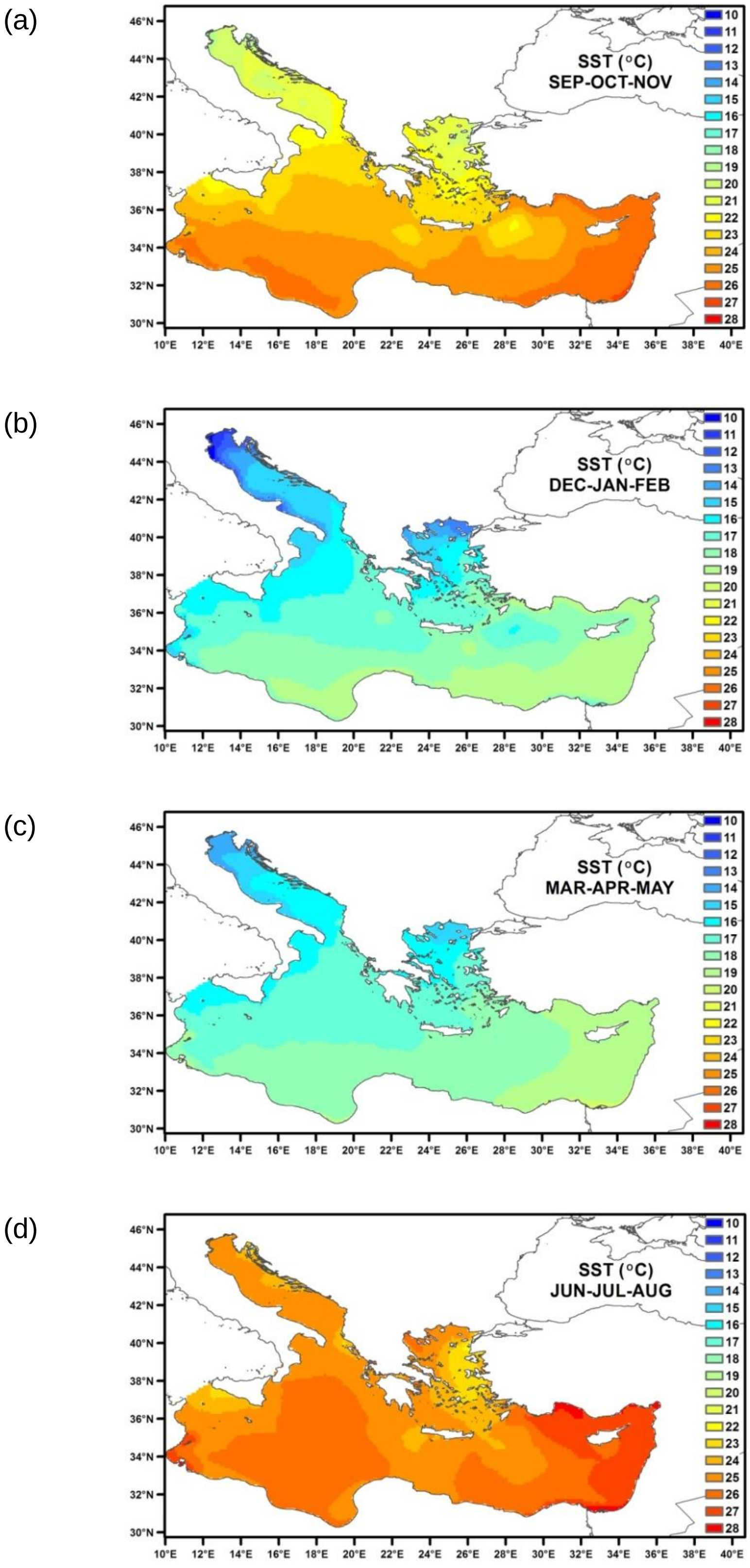


Fig.8. SST means for the period 1998–2016 as computed from the daily REP CMEMS product which is based on the Advanced Very High Resolution Radiometer (AVHRR) measurements provided by NOAA: (a) autumn, (b) winter, (c) spring, and (d) summer.

2.3.2. Surface Winds

Surface winds play a key role in forcing the ocean circulation and determine the exchange of momentum between the atmosphere and the ocean (https://gcos.wmo.int/en/essential-climate-variables/ecv-factsheets for surface wind speed and direction, assessed on 10/7/2019). *In situ* observations, scatterometer remote sensing measurements and numerical models' reanalysis projects are sources for surface wind data. The usual reference height for wind speeds is 10 m [WMO-No. 702, 1998].

Winds are considered as one of the more important physical factors influencing phytoplankton growth mainly by altering the MLD as well as determining the upwelling process, on a global [e.g. Behrenfeld et al., 2006; Kahru et al., 2010] and Mediterranean scale [e.g. D'Ortenzio and Ribera D'Alcalà, 2009; Siokou-Frangou et al., 2010]. In some locations, they can even overcome the summer stratification and sustain increased chlorophyll concentrations [Carranza and Gille, 2014].

The relation between wind speed and chlorophyll has been explored on a global scale. Satellite derived winds and chlorophyll concentrations for the long November 1996–October 2009 period were found both positively and negatively correlated. High positive correlations of the two parameters occurred in the largest part of the ocean which is characterized by comparatively shallow mixed layer. In these areas, phytoplankton growth is nutrient and not light limited; thus, increased winds can result in mixed layer deepening and in importing more nutrients from below into the euphotic zone. On the other hand, strong negative correlations between chlorophyll and winds were found in areas where the winter mixed layer is deep and the factor controlling primary production is light, which can be reduced along with stronger winds [Kahru et al., 2010]. In this study, the statistically significant correlations between winds and chlorophyll were found positive for the Eastern Med and mainly occurred over the southern open sea. Quite similar results were derived from another large scale long period study where monthly sea surface chlorophyll concentration was found positively connected with wind speed in several tropical, subtropical and equatorial ocean provinces. This positive relation of the parameters in low-latitude oceans was again attributed to the nutrient limited regime of these regions that can be relieved by the mixed layer deepening due to strong winds [Fend et al., 2015] In a study focusing on the Med, positive correlations between these two parameters were also mentioned [Katara et al., 2008].

For the Med, the relation between wind speed and sea surface chlorophyll has been examined to some extent. However, nowadays longer time series are available which can provide important information for such studies. In addition, this relationship has never been explored on a seasonal basis.

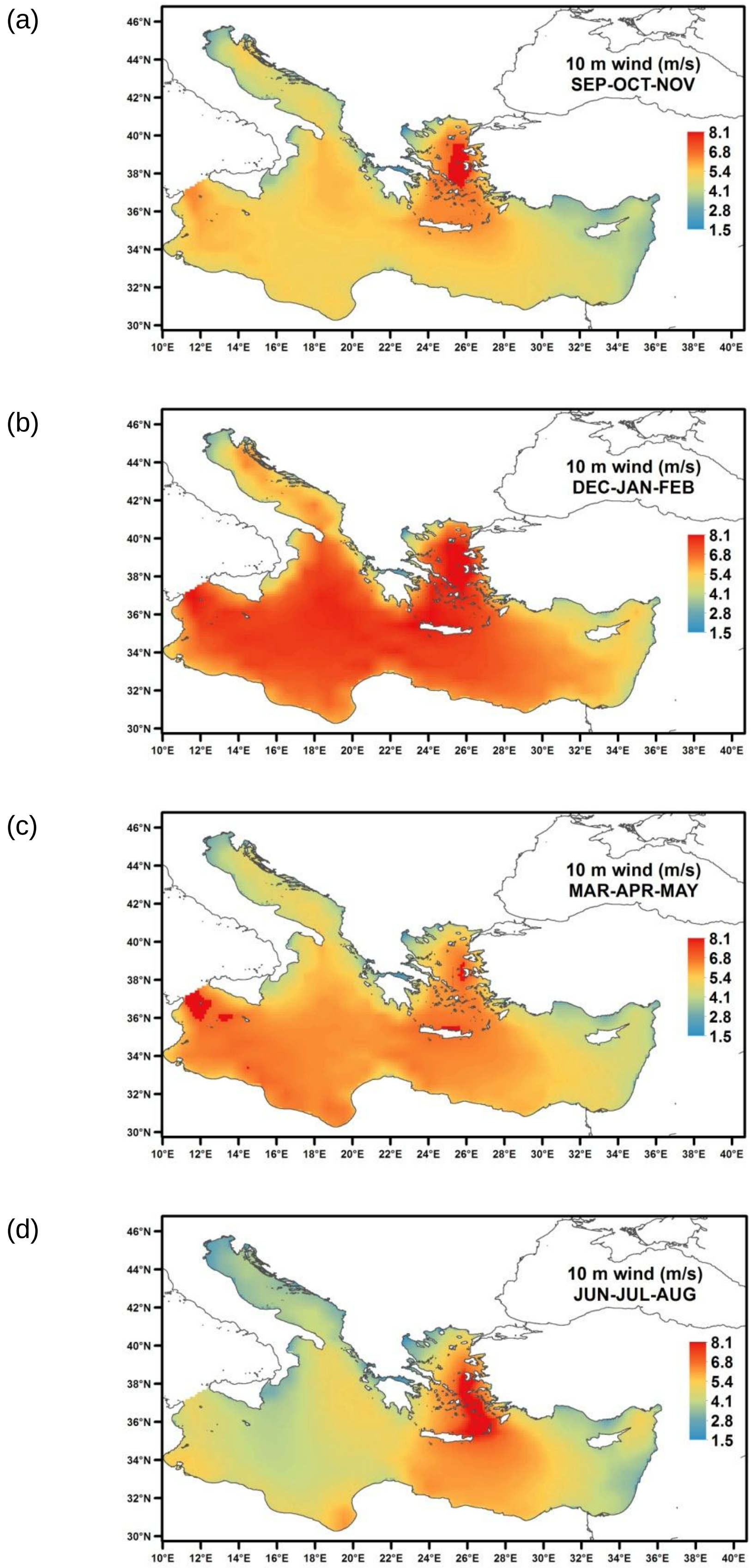


Fig.9. 10 m wind seasonal means for the period 1998–2016 as computed from the ECMWF ERA-Interim reanalyis: (a) autumn, (b) winter, (c) spring, and (d) summer.

2.3.3. Wave Height

The term Sea State refers to wave and swell and it is well known in relation to its impacts on marine safety and transport. However, it significantly modifies the air-sea exchanges and is described through waves, which can also contribute to storm surge, modify the sea ice, provoke beach erosion, change the sea surface albedo etc (https://gcos. wmo.int/en/essential-climate-variables/ecv-factsheets for Sea state, assessed on 10/7/2019).

Ocean waves are basically driven by the wind surface stress that corresponds to the horizontal force exerted by the wind on the sea surface and it also depends on properties of the atmospheric boundary layer such as stability. The wind generated waves mostly contribute to wave energy [WMO-No. 702, 1998]. They include wind waves that are under the influence of the local wind and swell which refers to waves that have traveled out of their generating area. Their size mainly depends on the wind strength, the duration that the wind blows and the fetch i.e. the distance over which the wind blows without a significant change in its direction across the open water. Under the influence of waves, the water particles are in vertical circular motion that decreases exponentially with depth and it is practically negligible when depth equals to half a wavelength [WMO-No. 702, 1998]. It is noted that typical wind wave wavelengths are 60-150 m, storms can induce wavelengths of 150–220 m and swell wavelengths exceed 260 m [Toffoli and Bitner-Gregersen, 2017 and referrences therein].

The wave height H is the surface elevation difference between the wave crest and the previous wave trough; the wave energy is proportional to H^2. The significant wave height (SWH) is the average height of the 1/3 highest waves ($H_{1/3}$) and it is roughly approximate to the visually observed wave. The usual practice, in numerical models also, is to describe the wave regime through its spectrum i.e. by the distribution of wave heights or wave energy with respect to frequency. In this case, the SWH (H_{mo}) is defined as four times the standard deviation of the surface elevation and it can be derived by the area under the spectral curve (moment of zero-order) which represents the total variance of the sea state. The $H_{1/3}$ and H_{mo} correspond to each other as closely as possible [WMO-No. 702, 1998]. Neither the *in situ* nor the remote sensing altimeters' measurements provide SWH with high spatial and temporal coverage; thus, numerical model reanalysis that assimilates the observations is the only source of continuous and dense data. Fig.10 presents the SWH seasonal means for the Eastern Med Sea.

Waves could influence chlorophyll concentrations through the same mechanism as the wind does; in addition, they are rather more representative of the stress exerted on the sea surface by the atmosphere. The wave height has never been involved as a parameter in the studies referring to the assessment of relationships between sea surface chlorophyll and environmental variables.

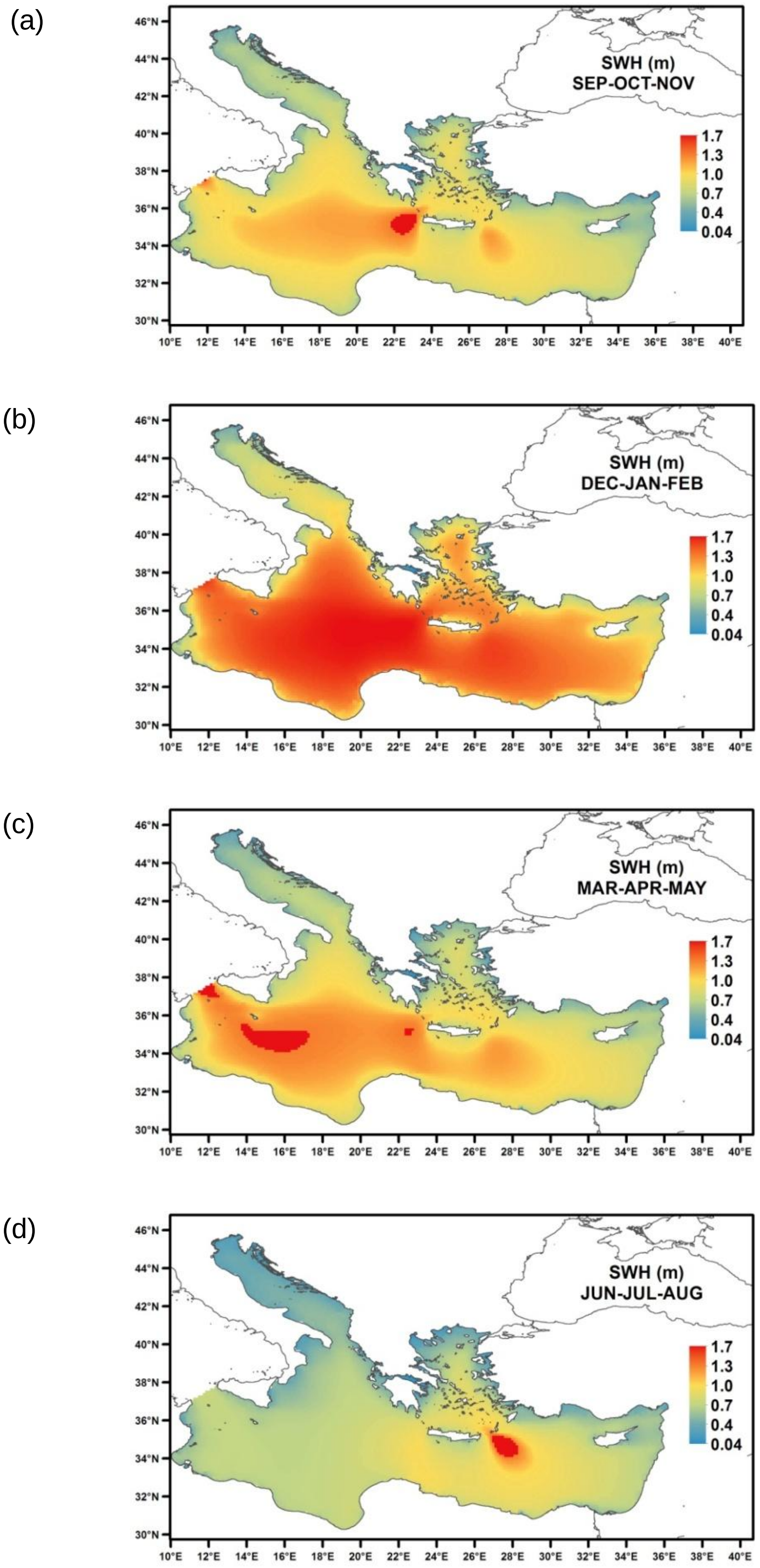


Fig.10. SWH seasonal means for the period 1998–2016 as computed from the 4 daily analysis of the ECMWF ERA-Interim reanalysis: (a) autumn, (b) winter, (c) spring, and (d) summer.

2.3.4. Precipitation

Precipitation, in either of its forms (liquid or solid), is the climate variable that affects humans in a direct way; being at the heart of the hydrological cycle, regulates the water supply and cause risks when it is intense or absent (https://gcos.wmo.int/ en/essential-climate-variables/ecv-factsheets for Precipitation). It is also closely related to ocean surface salinity and its deficit or not in respect to evaporation plays a regulative role in ocean circulation. The seasonal precipitation means for the Eastern Med and the period 1998–2016 are shown in Fig.11.

In situ precipitation data cannot provide an adequate global coverage; spatial and temporal dense data can be derived through numerical weather model reanalysis and satellite measurements. Two major satellite missions were specifically designed for obtaining precipitation data in a NASA-Japan Aerospace Exploration Agency joint effort; the Tropical Rainfall Measuring Mission (TRMM) (1998- mid 2015) and the ongoing Global Precipitation Measurement (GPM) mission. They provide precipitation estimates through multi satellite data and a combination of sensors, incorporating also *in situ* gauge data in after real time analysis products [Huffman et al., 2007; https://earthdata.nasa.gov/learn/articles/trmm-to-gpm, assessed on 1/7/ 2019).

Precipitation can be related to chlorophyll variations mainly due to the added nutrients of atmospheric or land origin. According to author’s knowledge, global scale studies that explore such a relation have not been conducted. A relevant work, referring to the eastern United States waters, discriminated different sea surface chlorophyll responses in low and high nutrient areas: for waters characterized by nutrient limitation (south of 36°N), precipitation was associated with chlorophyll increases; in nutrient rich waters, rainfall was connected to decreases in chlorophyll. Since rainfall events can be combined with strong winds that can deepen the MLD and reduce light availability, these differences chlorophyll responses were attributed to the alternative roles of nutrients or light acting as limiting factors for phytoplankton growth [Kim et al., 2014].

For the Med, and especially for its eastern part, where the atmospheric inputs have been identified as the secondary nutrient source for primary production [e.g. Christodoulaki et al., 2013], the precipitation has been only mentioned as positively correlated with surface chlorophyll [Katara et al., 2008]. Local scale studies mainly refer to coastal areas and attribute the imported nutrients that induce primary production increase to agricultural and river runoff [e.g. Arhonditsis et al., 2002; Mozetic et al., 2012]. The possible influence of precipitation has been minimally examined and the relevant studies mainly refer to coastal and near shore areas; a research focusing on the open sea is not available in literature.

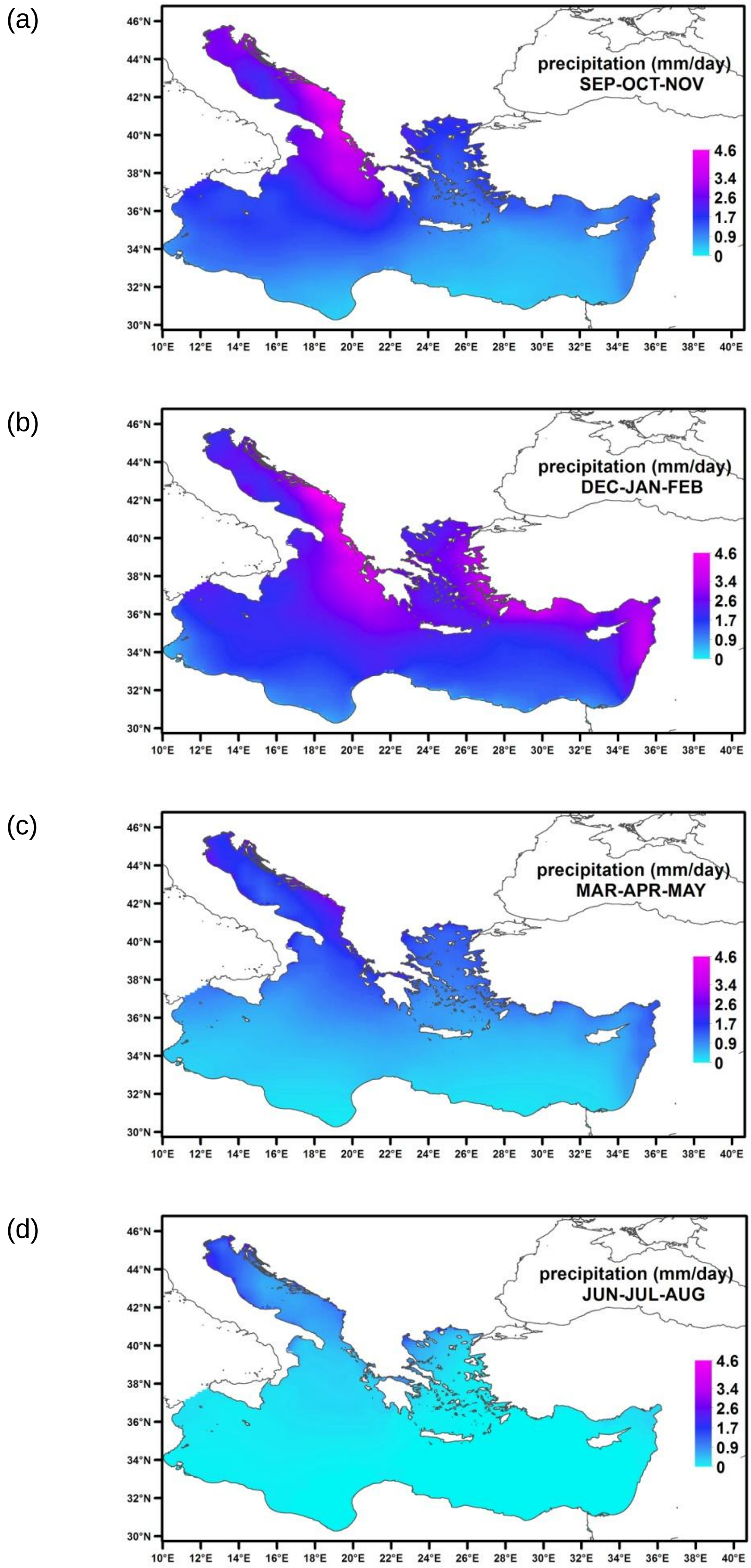


Fig.11. Precipitation means for the period 1998–2016 as computed from ECMWF ERA-Interim reanalysis: (a) autumn, (b) winter, (c) spring, and (d) summer.

2.3.5. Mean Sea Level Pressure

Surface pressure is a fundamental meteorological variable that controls weather systems and their intensity; it is also used in constructing circulation indices for describing global and regional climate variations (https://gcos.wmo.int/en/essential-climate-variables/ecv-factsheets for Surface pressure, assessed on 10/7/2019). Atmospheric pressure influences the sea level through the inverse barometer effect according to which a decrease of 1 hPa in pressure raises the water level by 1 cm. This effect, in cases combined with wind effects, is the principal cause for the storm surges due to low pressure weather systems in the Med [Krestenitis et al., 2011; Conte and Lionello, 2013].

The term Mean Sea Level (MSL) pressure refers to the pressure adjusted to mean sea level conditions in order to be comparable all over the world; it is the commonly used pressure by meteorologists to track weather systems at the surface. The main source for MSL pressure data come from numerical weather model reanalysis projects that have assimilated numerous *in situ* observations in simulating past weather and climate.

Sea level pressure has been referred to as an important climate variable related to ocean productivity [Behrenfeld et al., 2006]. Low pressure systems, associated with windy and rainy weather and, in cases of deep barometric lows even with Ekman upwelling, could affect chlorophyll concentrations. The most relevant study is the one of Sheridan et al. (2013) who examined the linkage of circulation weather patterns –derived from sea level pressure data– and ocean colour chlorophyll data for the period 1997-2010. The study, referring to south Florida shelf (edge of tropical Atlantic), showed that anticyclonic conditions were related to lower chlorophyll levels. On the other hand, the cyclonic patterns –that can be connected to precipitation, wind stress and the presence of cyclones– were associated with increased chlorophyll concentrations. These relations were more pronounced for the northern parts of their study area in winter and spring.

For the Med Sea, the seasonal MSL pressure patterns of which are shown in Fig.12, the relative bibliography is extremely limited. The only available study of this parameter in relation to chlorophyll, at least to author's knowledge, is the one of Katara et al. (2008) where the sea level pressure of the northern hemisphere was examined through teleconnection patterns in respect to the Sea's chlorophyll concentrations. In any case, sea level pressure and chlorophyll have not been examined at local scale and correlations between the two parameters have not been estimated.

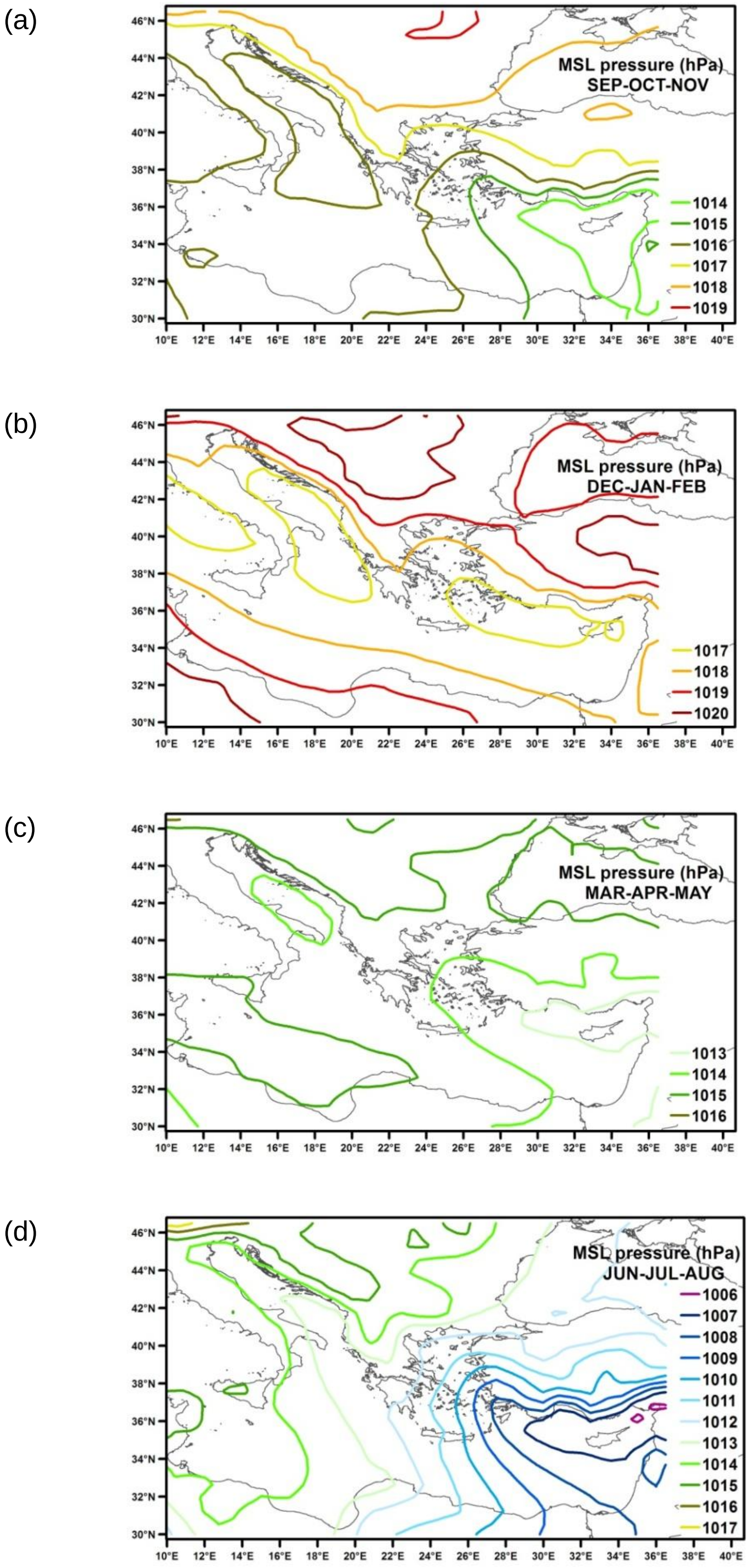


Fig.12. SST mean seasonal patterns for the period 1998–2016 as computed from ECMWF ERA-Interim reanalysis: (a) autumn, (b) winter, (c) spring, and (d) summer.

2.3.6. Extreme Weather Events – Medicanes

The World Meteorological Organization (WMO) Commission for climatology defines an extreme weather event as an event that exceeds a certain threshold and should be statistically rare; this threshold can be a fixed one or it can be a percentile-based one. The latter can be derived from statistical cumulative density functions of the past climate (a 30-year period or more) and refer to the upper 90th, 95th, and 99th percentile of a parameter's value. Extreme events are characterized by magnitude, duration, extent and severity (indicating the potential associated damages and impacts). The definition of a weather event varies from place to place and depends on the regional climate: something extreme for one location can be within the normal range for another location (http://www.wmo.int/pages/prog/ wcp/ccl/documents/ GUIDELINES ONTHEDEFINTIONANDMONITORINGOFEXTREMEWEATHERANDCLIMATEEVENTS_09032018.pdf, assessed on 15/7/2019).

Tropical cyclones are undoubtedly extreme events and they have been examined in respect to their influence on chlorophyll and primary production. Studies were conducted both for the Atlantic hurricanes [Son et al., 2007 and references therein; Shi and Wang, 2007 and references therein] and for typhoons in the Pacific Ocean [Merritt-Takeuchi and Chiao, 2013 and references therein]; oligotrophic Atlantic marine areas were also included in the relevant research [Babin et al., 2004; Merritt-Takeuchi and Chiao, 2013]. The results indicated chlorophyll and primary production increases and even phytoplankton blooms. The role of cyclone induced upwelling and wind mixing in importing nutrients from the deeper layers was highlighted, while a complementary favoring role of heavy rainfall was also proposed [e.g. Davis and Yan, 2004; Merritt-Takeuchi and Chiao, 2013].

In the Med, extreme weather events have been sporadically examined for their possible influence on primary production. The relevant studies referred to coastal areas and involved the meteorological parameters of precipitation and wind in storm events. Even during the summer period, a phytoplankton increase was observed; it was largely attributed to nutrient inputs due to continental runoff or highly influenced by anthropogenic emissions precipitation [Malej et al., 1997; Guadayol et al., 2009].

Cyclones in the Med present features similar to the tropical cyclones in rare cases: "eye", spiral cloud bands, warm core and very strong surface winds (Fig.13) and they are known as Mediterranean hurricanes or medicanes [e.g. Emanuel, 2005]. Although they are less intense than hurricanes, some of them have gained tropical strengths [Moscatello et al., 2008; Akhtar et al., 2014]. They induce hazardous weather that can cause significant damages over the sea and the coastal zones [Nastos et al., 2018] and they fulfill all preconditions describing an extreme event. Climatological studies have defined the Ionian Sea and the western Med (around the Balearic islands) as the most common regions for their formation; their frequency has been estimated to ~1.5 per year for the whole basin and they are usually met in autumn and winter [Miglietta et al., 2013; Cavicchia et al., 2014; Nastos et al., 2018]. As far as their formation mechanism is concerned, several atmospheric processes such as high low-level vorticity and surface heat fluxes, high moisture and deep convection plus upper-level potential vorticity anomalies and dry air intrusions have been identified for their significant role [Emanuel, 2005; Fita et al., 2007; Flaounas et al., 2015; Carrió et al., 2017; Raveh-Rubin and Flaounas, 2017]. There is not a strict Medicane definition;

however, the usual practice is the objective determination of their symmetry and warm core structure with the use of the phase-space Hart diagram [Hart, 2003].

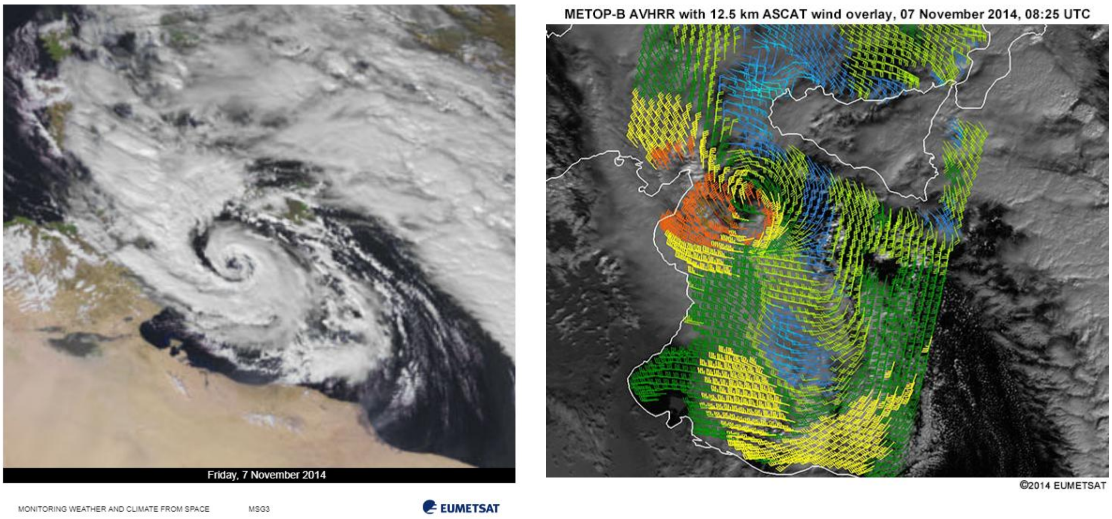


Fig.13. Medicane Qendresa on 07 November 2014 through EUMETSAT satellite images. In the right panel, satellite derived winds are superimposed with brown and red colours indicating hour mean winds > 40 knots.

Although the tropical cyclones have been studied numerous times for their influence on chlorophyll concentrations, such a research has not been so far conducted for their Mediterranean tropical-like counterparts.

2.3.7. Desert Dust

Desert dust is considered as a climate and environmental modifier that can influence the earth’s system in various ways (Fig.14). It alters the radiation budget, modifies the properties and lifetimes of the clouds affecting the precipitation processes, possibly impacts the biogeochemistry of ocean and land ecosystems by providing nutrients and can harm human health mainly by its smaller and more breathable particles [Kallos et al., 2007 and references therein; Mahowald et al., 2014 and references therein].

The terms ‘aerosols’ and particulate matter refer to tiny liquid or solid particles suspended in the atmosphere; they originate from various sources such as volcanoes, dust storms, fires, human induced pollution.

Particulate matter PM10 stands for particles with diameter less than or equal to 10 μm that includes dust. Thus, PM10 ground based measurements can be used for the detection of dust. It is noted that a limit of 50 $\mu g/m^3$ for mean daily PM10 concentration has been established by the European Union as an atmospheric quality standard. Across the Med, the dust particles strongly contribute in PM10 concentration levels [Querol et al., 2009].

The aerosol optical depth (AOD) τ, or aerosol optical thickness (AOT), is a measure of the degree to which the aerosols prevent the transmission of light by absorption or scattering. It describes the exponential attenuation of the incoming solar radiation caused by atmospheric, according to the Lambert-Beer law $I(\lambda) = I_0\,(\lambda)\ e^{-\tau(\lambda)}$, where $I_0(\lambda)$ and $I(\lambda)$ are the intensities of the incoming radiation on top of the atmosphere and on ground level at wavelength λ. Thus, AOD is defined as $AOD = \ln[Io(\lambda)/I(\lambda)]$ and it refers to the vertical column. This dimensionless variable is ideally zero when no aerosols are present while there is not a maximum value. It can obviously be used for the detection of dust in the atmosphere; in addition, it is derived through satellite measurements and it is a parameter included in numerical weather models that can also be part of their assimilation procedure. AOD at 550 nm is usually used as indicative for the presence of dust. In a study referring to the broader Med region, dust episodes characterized by AOD values 0.67-0.77 were considered as strong while the ones of AOD 1.14-2.06 as extreme [Gkikas et al., 2014].

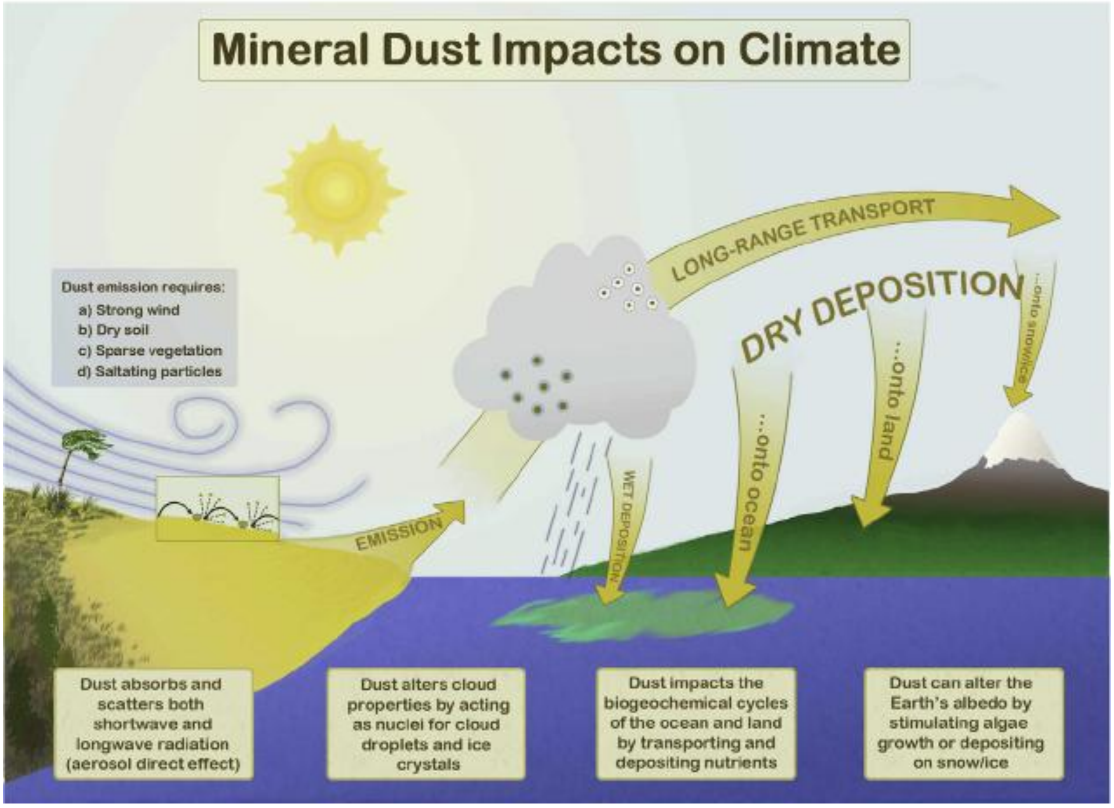


Fig.14. Schematic of interactions between dust and climate and biogeochemistry (adopted from Mahowald et al., 2014).

The recognition of dust as an important source of nutrients [Jickells et al., 2005] led to the research on its impacts on oceans productivity, which has started long ago. High-nutrient, low-chlorophyll (HNLC) marine areas, i.e. areas of low primary production in respect to their nutrient availability (mainly the northern and east Equatorial Pacific Ocean and the Southern Ocean), were fist examined. Since Fe was recognized as the limiting nutrient [Martin and Fitzwater, 1988], the relevant studies referred to the 'iron limitation hypothesis' that was also connected with possible effects on CO_2 drawdown and climate [Jickells et al., 2005]. Numerous iron addition experiments have been conducted and supported the above hypothesis [Boyd et al., 2007 and references therein]. When the research was expanded to the larger ocean part where nutrient availability as well as chlorophyll concentrations is low, namely the low-nutrient low-chlorophyll (LNLC) areas, the study subject became the ‘dust fertilization hypothesis’ and the results supported this hypothesis in most cases [Mills et al., 2004]. In these areas, Fe may have a limiting role together with other nutrients [Mills et al., 2004], while the dust impacted areas are usually not Fe-limited [e.g. Aumont et al., 2008]. The research is ongoing: dust storms in Australia resulted in ocean fertilization and a strong CO_2 drawdown [Gabric et al., 2010]; monthly chlorophyll concentration and dust storm occurrence were found correlated in many sea areas from the North to Equatorial Pacific [Tan et al., 2013]; spring dust events caused significantly increased chlorophyll concentrations in western North Pacific [Yoon et al., 2017].

The Med area is highly impacted by dust. For the broader region, the highest percentage of dust episode was found in spring –with a May maximum– and the lowest in winter [Gkikas et al., 2014]. The Med Sea is mainly affected by Saharan dust events, that present a seasonal cycle with a spring-summer maximum and a winter minimum [Moulin et al., 1998; Antoine and Nobileau, 2006]; during March to August, a shift from the eastern to the western basin is observed. These events are primarily connected with the thermal convective activity of the North Africa Sharav cyclones which favor dust uplift to higher atmospheric levels (Fig.15a) and thus, its transport over longer distances (Fig.15b). During winter, these thermal lows are absent while the transport of dust over long distances is mainly prohibited by precipitation events [Moulin et al., 1998; Kallos at al., 2007 and references therein]. However, desert-dust outflows can be observed throughout the year under favorable meteorological conditions; the ones in winter mainly occur over the Eastern Med [Engelstaedter et al., 2006] and during summer and autumn months a large part of dust outbreaks reach the East Med region [Papayannis et al., 2005]. As far as the atmospheric circulation is concerned, the results of a long period 2000–2013 study showed that the central and eastern parts of the Med region are affected by dust mainly under the combination of an anticyclone in the Eastern Med with a low-pressure system in the central Mediterranean or central Europe [Gkikas et al., 2014].

The atmospheric inputs are an alternative source of nutrients for the oligotrophic Med surface waters and become the primary source during the stratification summer period [Guerzoni et al., 1999; Ternon et al., 2010]; the dust imported nutrients can also be of particular importance and dust has been examined in respect to its influence on the Sea’s productivity. In the frame of experiments conducted over oligotrophic NW Med areas, the results were, in general, supportive to the dust fertilization hypothesis [e.g. Bonnet et al., 2005; Giovagnetti et al., 2013; Ridame et al., 2014]. In the Eastern Med Sea, the locally conducted experiments and measurements ended with contradictory results. For example: chlorophyll increased after a N-P addition and not after a P addition [Zohary et al., 2005; Psarra et al., 2005]; added dust led to proportional chlorophyll increase while after a dust storm a slight increase in chlorophyll was observed [Herut et al., 2005]; in the NE Med, intense spring dust deposition events caused slight or no phytoplankton increase while less intense summer events favoured phytoplankton growth [Eker-Develi et al., 2006]. Basin scale studies have been conducted based on ocean colour chlorophyll data. The most recent ones also used numerical model dust deposition data and resulted supportive to the dust’s favoring role. Statistically significant positive correlations were found between chlorophyll and dust for 64% of the region. These correlations mainly referred to the Central and Eastern Basins, presented a south to north decreasing gradient and their higher values in spring. [Gallisai et al, 2014]. The Basin's response to large and very large dust deposition events was investigated for the period 2000-2007; chlorophyll increases were observed after the events, but this response also presented a west to east decreasing trend [Gallisai et al., 2016].

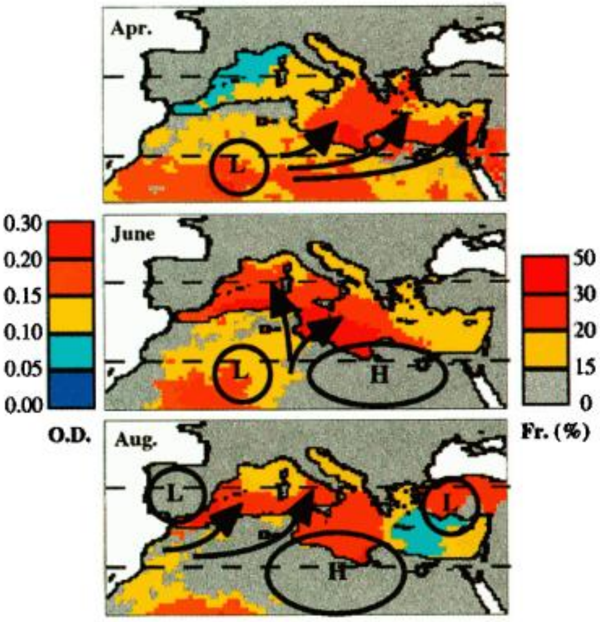
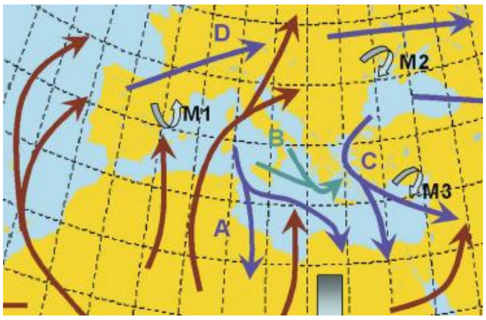


Fig. 15.

(a) The main meteorological synoptic patterns (L:low; H:high) that generate dust transport toward the Med Sea during spring and summer: the Sharav cyclones in April; the coupling between Saharan low and Libyan high in June; and the effect of the Balearic cyclogenesis in August. The left legend stands for monthly dust optical depths (O.D.) and the right one for the frequency of dust mobilization over North Africa (adapted from Moulin et al., 1998).

(b) Transport of desert dust from the Africa region in the lower 5 km of the troposphere is indicated by the red-brown arrows, while other arrows show transport paths of anthropogenic pollutants (adopted from Kallos et al., 2007 and slightly modified).



Studies upon the dust fertilization effect are considered significant. In addition, this is a controversial issue for the Med Sea. Despite the large number of relevant studies, the Hellenic Seas have been minimally and only locally examined in respect to the possible dust influence on their primary production.

2.3.8. Numerical Weather Models and the ECMWF major Data Source

A numerical weather prediction (NWP) model is a set of equations forecasting the state of the atmosphere. It solves the basic (primitive) differential equations that describe the conservation of mass, heat, motion, water and of other gaseous and aerosol materials in the atmosphere. Parameterization schemes are used in simulating non solvable, at the model grid due to their scale, procedures such as: the transfer of heat, moisture, and momentum between the surface, the planetary boundary layer and further aloft; the moist thermodynamic processes such as the water phase changes in a convectively stable or unstable atmosphere (convection, precipitation and clouds). Parameterizations are also used for the description of the surface layer (land and sea surface characteristics) and the shortwave (solar) and long wave (terrestrial) radiation [Pielke, 2002].

Data assimilation, the procedure in which the best possible atmospheric model state is determined through comparisons between short range forecasts and the available near real time observations, is a crucial matter in the NWP process. It also results to the ‘analysis’, i.e. to the updated model state that better reflects the observations.

An ensemble prediction system (EPS) is a set of multiple NWP forecasts which are valid for the same time and they are produced by changing the initial model conditions. Its concept is based on the fact that the atmosphere is “chaotic”, i.e. sensitive to initial condition differences that can lead to different forecasted weather patterns (butterfly effect). Another factor leading to EPS formulation is the necessary model approximations that can also induce errors.

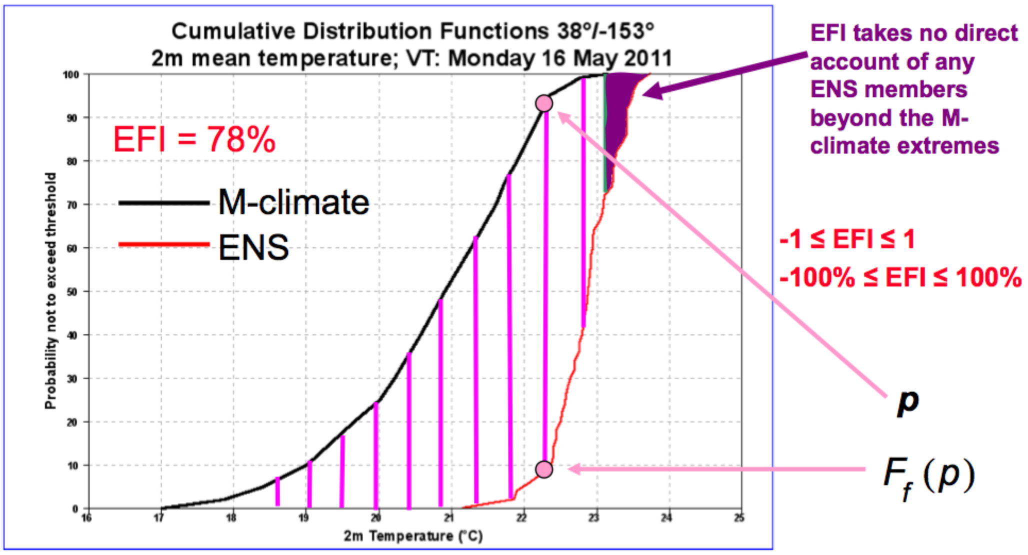
Climate reanalysis refers to the numerical description of the recent climate (usually some decades) and generates consistent time series of multiple variables on 3D grids and at sub-daily intervals combining model outputs with observations. Its products promoted climate research and relevant applications by providing homogenous data on sufficient spatial and temporal scales that cannot be acquired by *in situ* measurements [Kostopoulou et al., 2010].

The independent intergovernmental organization of ECMWF (European Centre for Medium-Range Weather Forecasts) forms a 24/7 operational service as well as a research institute (https://www.ecmwf.int/en/about, assessed on 17/7/2019). It provides NWP forecasts and reanalyses based on a self developed atmospheric numerical model and data assimilation system through one computer software system called the Integrated Forecasting System (IFS). The model uses a hydrostatic dynamical core and a spectral transform method to numerically solve its equations. The IFS products comprise high resolution (HRES) deterministic and EPS forecasts plus monthly and seasonal ones. Products are also derived through ocean wave models. All atmospheric forecast systems are coupled to an ocean model, while the reanalysis ones are coupled to wave model forecasts. The HRES atmospheric model, that is the former deterministic atmospheric model, has currently a resolution of about 9 km and 137 vertical levels up to 0.01 hPa. The atmospheric EPS or ensemble (ENS) consists of 51 members; its spatial resolution is about 18 km and has 91 vertical levels up to 0.01 hPa. The wave models and the ENS wave forecast are characterized by 11-14 km and 28 km spatial resolution, respectively.

ECMWF’s assimilation procedure uses data from numerous satellite instruments, weather stations, ships, buoys, and other components of the global observing system. It is also applied to the reanalysis projects and specific land data and ocean data assimilation systems are included. By a four dimensional (4D-Var) assimilation method, observations not only in space but also in a time domain are used.

The ERA-Interim is the global ECMWF atmospheric reanalysis from 1979 until 31 August 2019. It includes the 4D-Var assimilation method, its spatial resolution is approximately 80 km and it comprises 60 vertical levels from the surface up to 0.1 hPa [Dee et al., 2011]. ERA5 is the latest climate reanalysis (released by the end of 2018) that replaced ERA-Interim and provides hourly data of a large number of atmospheric, land and oceanic climate variables. It covers the earth on a ~31 km grid and resolves the atmosphere in 137 levels from the surface up to a height of 80 km. It uses vast amounts of historical observations, especially from satellites, that will be also provided in future and it is expected to be extended back in time to 1950. The much higher spatial and temporal resolution and the better representation of tropical cyclones are some of the ERA5 improvements in respect to ERA-Interim. ERA5 data are available via the Copernicus Climate Change Service C3S Climate Data Store (CDS). ECMWF is also implementing the Copernicus Atmosphere Monitoring Service (CAMS, http://atmosphere.copernicus.eu) delivering near-real-time analyses and forecasts plus reanalysis products of global atmospheric composition.

The ECMWF Extreme Forecast Index (EFI) is an EPS product developed many years ago for extreme weather alerts [Lalaurette, 2003]. Its concept is the comparison between the ENS forecast and the model climate (M-climate). Thus, it not only takes into account the forecast related uncertainties, but also defines an extreme event as one that departs from the regional climate. The M-climate is constructed for the last 20 years, through 9 re-forecast (15-day) runs of an 11-member ensemble that covers a 5-week period centered on the day or period of interest. Then, the cumulative distribution function (CDF) curves are built for the ENS forecast distribution and the M-climate. EFI is computed from the difference between these curves (Fig.16). Thus, EFI is zero when the ENS forecast and the M-climate distribution coincide and it is +1(-1) when all the ENS members forecast values above (below) the maximum (minimum) M-climate values. According to ECMWF, the significant absolute EFI values are those > 0.5 and signify an unusual event being 0.5-0.8 and a very unusual or extreme one when exceeding 0.8.



$$EFI = \frac{2}{\pi}\int_0^1 \frac{p-F_f(p)}{\sqrt{p(1-p)}}\mathrm{dp}$$

Fig.16. Schematic CDF diagram showing positive EFI as the area between the M-climate and ENS curves. The area is positive where the ENS curve (red line) is to the right of (i.e. values greater than) M-climate (black line). The EFI formula is also shown. Note: forecast values beyond the limits of the M-climate are not used in evaluating EFI and the additional weight towards an extreme is missed. Shift of Tails (SOT), which compares the tails of these distributions, has been developed to offset this disadvantage (adopted from ECMWF, https://confluence.ecmwf.int/display/FUG/Extreme+Forecast+Index+-+EFI, assessed on 17/7/2019).

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3. Dust Episodes and Sea Surface Chlorophyll Concentrations

3.1. Introduction

The research on the possible impact of desert dust on sea surface chlorophyll concentrations began with an ‘observation’. It was noticed that the Aegean Sea was characterized by elevated chlorophyll values in May 2013 compared to May 2012, when, respectively, a high dust load for almost 15 days and a no significant dust transport were observed. A short study was carried out, where the differences between other environmental parameters were also examined, and was presented in an international conference.

An extended study of the relevant bibliography followed. Numerous papers had addressed this subject throughout the world oceans including the Med. The latter were local experimental and observational studies plus several basin scale statistical ones. Their results were quite controversial, especially for the eastern part of the Med. Since the Hellenic Seas were also minimally examined as a whole and through specific dust events, the present thesis moved towards examining this issue.

Five dust events were studied for the Hellenic Seas, two strong events that were also extreme weather events and three events during the stratification period; one strong event which had affected the Central Mediterranean Sea was examined as well. The prevailing weather before, during and after the events was also taken into account. The results were published in a peer-reviewed journal.

3.2. Influence of desert dust on the Aegean Sea chlorophyll concentrations

Abstract

In the oligotrophic Eastern Mediterranean Sea, every factor that could increase primary production is considered significant. African desert dust deposition is thought to act as fertilizer, stimulating the phytoplankton production, since it is rich in nutrients and contains iron, a trace element necessary for photosynthesis. Greece is subject to dust transport usually during spring. In this paper, the effects of a significant dust transport event in May 2013 on chlorophyll-a concentrations of the Aegean Sea are examined, using remote sensing plus model data and GIS techniques. The dust load was high for almost 15 days and was combined with some rain episodes. Compared to May 2012 – when no significant dust load was observed – May 2013 was characterized by approximately doubled chlorophyll-a values even over the less productive areas of the Aegean Sea.

Keywords: primary production, dust transport, wet deposition, GIS, satellite data

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Introduction

The Mediterranean Sea is considered as one of the less productive seas of the world, with its eastern part being the most oligotrophic. The basin follows the subtropical model for primary production [Karydis and Kitsiou 2012] where light is not the limiting factor for phytoplankton growth; though nutrients always are. Higher chlorophyll-a (chl-a) values, indicating higher primary production, are observed during the colder, windy and wet season while during May are expected to be in a decreasing phase [Barale et al. 2008]. In such an oligotrophic environment every factor that could increase primary production is considered significant.

Atmospheric dust deposition can be an important source of nutrients, supplying phosphorus, nitrogen and iron to the surface waters. As the Mediterranean atmosphere is subject to a continuous presence of Saharan mineral dust particles, there is a continuous research on the potential contribution of atmospheric dust nutrients to marine production [Lekunberri et al. 2010].

Greece is influenced by dust transport, usually during spring; thus dust can be a source of nutrients for the primary production of the Aegean. The aim of the present study is the detection of the possible effects of the significant dust transport during May 2013 (the dust load was high for almost 15 days) on chl-a concentrations in the Aegean Sea. This mostly qualitative study is conducted in comparison to May 2012 (where no significant dust load was observed) while other factors with possible influence on primary production, such as sea surface temperature (SST), wind and precipitation, are also comparatively examined. Remote sensing chl-a data retrieved from my Ocean project (www.myocean.eu), dust model data from the BSC-DREAM8b (v2.0) model operated by the Barcelona Supercomputing Center (http://www.bsc.es/earth-sciences/mineral-dust-forecast-system), SST, wind and precipitation data from the ERA Interim Re-analysis project of the European Centre for Medium-Range Weather Forecasts (ECMWF - www.ecmwf.int) and GIS techniques were combined.

Several studies have assessed the relationship between meteorological conditions and chl-a variations. Low SST, indicating a mixed water column with nutrients from the deeper layers, corresponds to high chl-a values. Strong winds favor primary productivity, since they disturb the stratification of the water column causing nutrient import into the euphotic zone especially through upwelling. Precipitation over the Mediterranean usually presents a positive correlation with chl-a values attributed to nutrient supply into the upper layers and its role has been found to be significant for nutrient limited areas. In Eastern Mediterranean, atmospheric inputs of N and P leading to increase of primary production are an alternative to the vertical mixing source of nutrients.

Desert dust deposition is thought to enhance phytoplankton production benefiting marine food chain, especially due to iron, a trace element necessary for photosynthesis (iron fertilization). Iron can even increase the carbon dioxide removal from the atmosphere reversing the greenhouse effect according to Martin's famous 1991 quip "Give me a half a tanker of iron and I will give you another ice age". As far as the primary production is concerned, the Redfield ratio describing the relative atomic concentrations of critical nutrients in plankton biomass has expanded to "106 C: 16 N: 1 P: .001 Fe".

Results

The results of the present study, presented through Figs.1-5, imply a close relationship between increased chl-a values and high dust concentrations. They are consistent with the findings of earlier studies. Surface ocean chlorophyll and dust deposition have been found highly correlated in the Eastern Mediterranean Sea[Cropp et al. 2005, Gallisai et al. 2012].

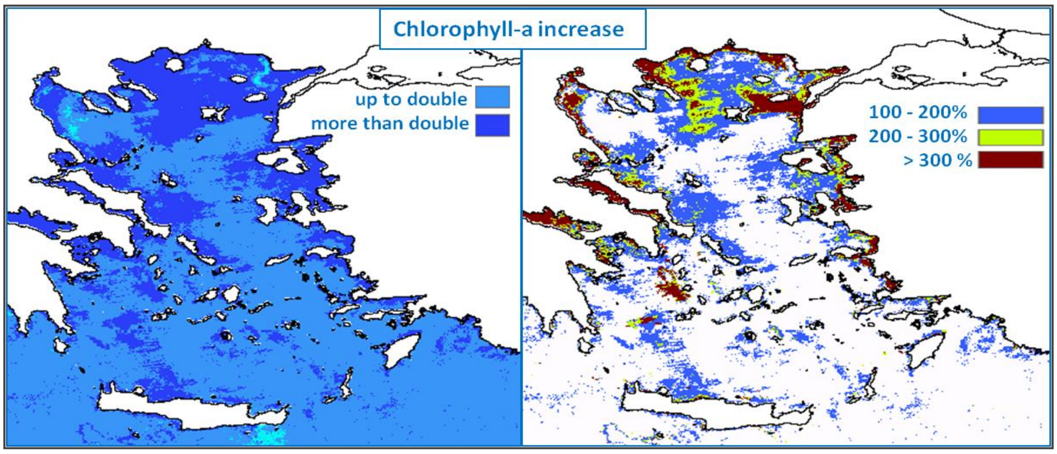

Fig.1. Chl-a increase during May 2013 compared to May 2012. An increase over almost all Aegean Sea is observed. There are areas characterized by large increases as can be seen from the relative % differences. Values more than doubled are observed even in the less productive area of the South Aegean, while near shore and in the North Aegean Sea greater differences are detected.

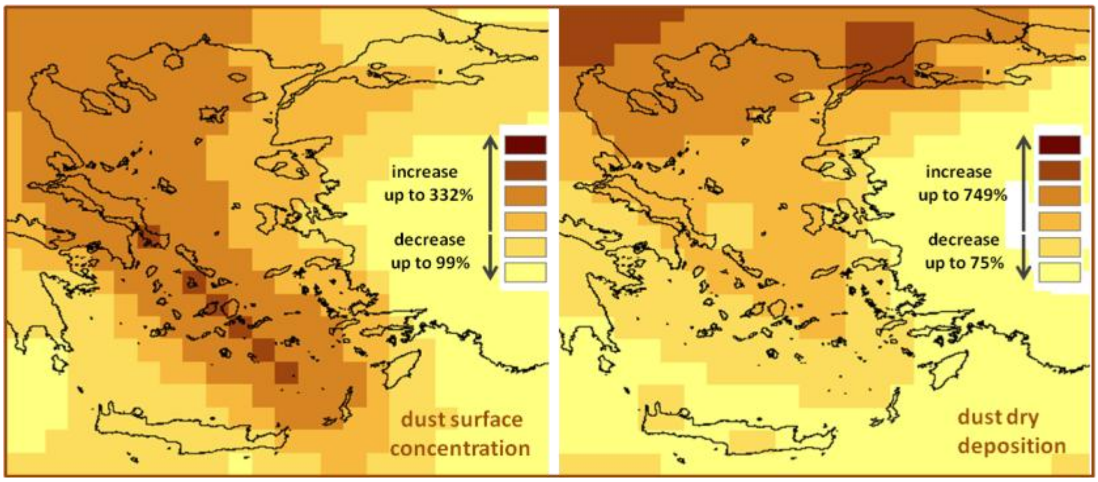

Fig.2. Relative % differences of dust parameters between May 2013 and May 2012. In almost all the Aegean Sea the large chl-a increases seem to be related with dust increases.

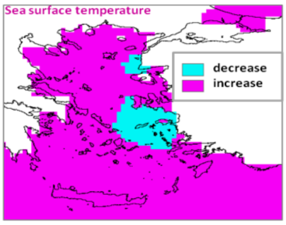

Fig.3. SST of May 2013 minus May 2012. Higher SST values could be a limiting factor for primary production increase; however, an increase in chlorophyll concentrations was observed.

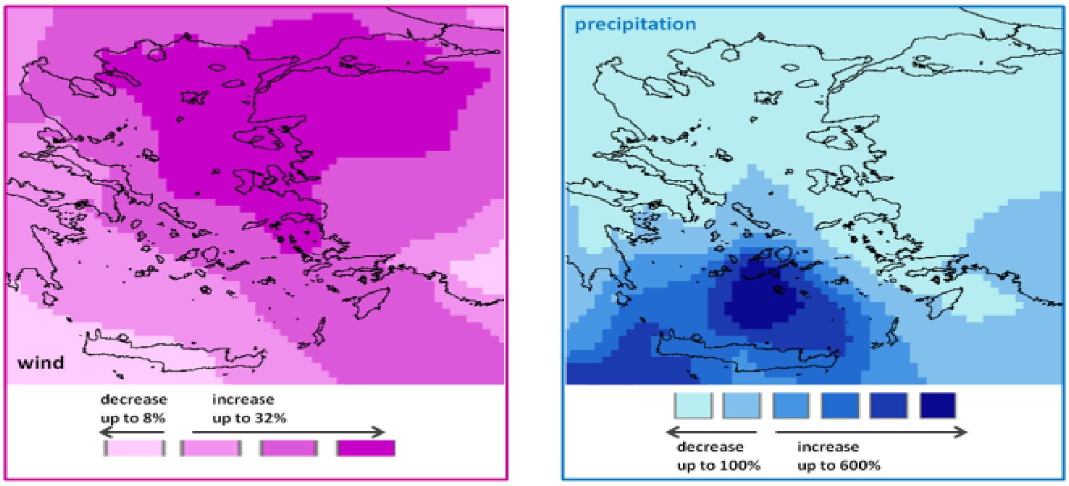

Fig.4. Relative % differences of wind speed and precipitation between May 2013 and May 2012. Increases of wind speed and precipitation could have favoured chl-a increase over the whole region and over the southern part respectively.

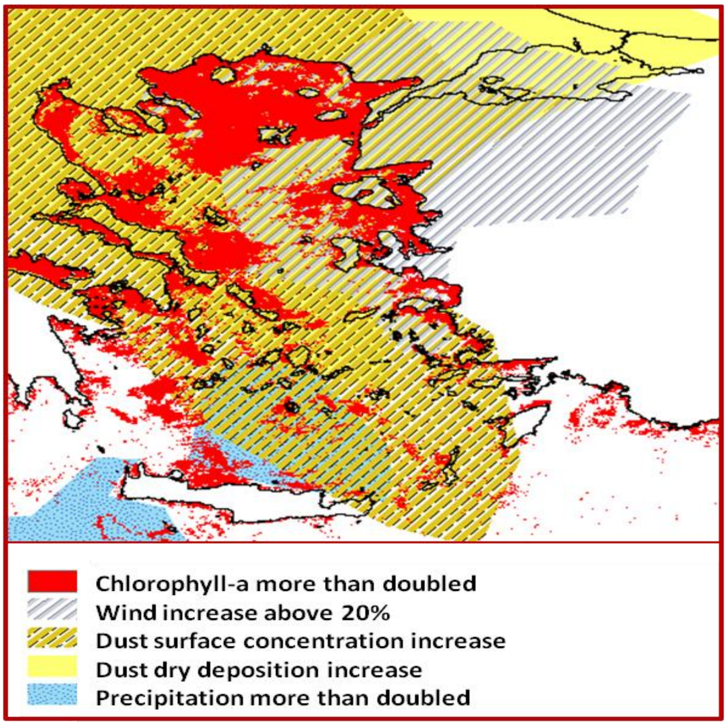

Fig.5. Areas characterized by large differences of the examined parameters.

Chl-a increases seem to have been favoured by: wind speed increase over the NE part, precipitation increase over the S-SW part and, over all the rest areas only by the increased dust concentrations.

Conclusion

The findings of the current study give further evidence for the possible impact of dust deposition on phytoplankton production even in the oligotrophic area of the Aegean Sea. The fertilizing role of dust on chlorophyll should be futher examined.

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3.3. Exploring Possible Influence of Dust Episodes on Surface Marine Chlorophyll Concentrations

Abstract: Desert dust deposition is thought to act as fertilizer for phytoplankton growth, since it is rich in the required nutrients. The Mediterranean Sea is a nutrient poor marine environment—with its eastern part being the most oligotrophic—which is subject to dust transport. The Hellenic Seas are part of this low-nutrient, low-chlorophyll environment and they are also affected by dust deposition events. Thus, the dust fertilizing effect can be particularly important, especially during the stratification period, when the nutrients needed for phytoplankton growth are not imported from deeper layers. Some individual dust events are examined here in respect of their possible influence on phytoplankton, through the observed variations of satellite derived chlorophyll concentrations. Two strong dust events that were also extreme weather events and three events in the June–September stratification period are examined for the Hellenic Seas as well as a strong dust event in the Central Mediterranean Sea. The results, only when based on absolute chlorophyll differences above 50%, show that dust events seem to favour phytoplankton abundance mainly during the low productive period; however, these differences are area-limited. The difficulty of reaching safe results through specific dust events and discriminating between other meteorological factors favouring phytoplankton growth are also discussed.

Keywords: ocean color satellite data; phytoplankton; Hellenic Seas; Aegean Sea; Ionian Sea; Central Mediterranean; Low-Nutrient Low-Chlorophyll (LNLC) Marine Areas; Geographic Information System (GIS)

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1. Introduction

Phytoplankton is the basis of the marine food chain, with its photosynthesis being comparable with that of the terrestrial plants [1]. Its growth is controlled by the availability of light and the macronutrients nitrogen (N) and phosphorous (P), plus the micronutrient iron (Fe) that is required in small amounts for cellular processes [2]. The sources and mechanisms by which these nutrients are made available to phytoplankton are subject to continuous research. For most of the oceanic regions, atmospheric deposition is the main source of nutrients [3] and especially dust deposition since it contains all the required ingredients [4,5]. The relevant research started on the high-nutrient, low-chlorophyll (HNLC) marine areas, characterized by low primary production and at the same time by high nutrient availability. For these regions, Fe was recognized as the limiting nutrient and was found to increase chlorophyll concentrations proportionally to its added amount [6]. The "iron limitation hypothesis" was formulated with possible effects even on climate, as a result of the drawdown of atmospheric carbon dioxide (CO_2) due to great phytoplankton abundance caused by Fe-dust enrichment [7]. Experiments were conducted and supported the iron limitation hypothesis, for example, [8–11], while several studies dealt with its connection to climate variability, for example, [4,12].

The research was expanded to low-nutrient low-chlorophyll (LNLC) areas, that is, to the oligotrophic 60% of the global ocean [13], where Fe can only have a co-limiting role for phytoplankton [14]. The dust impacted LNLC areas usually have enough Fe and their primary production is mainly controlled by the availability of P and N [15–17]. Since desert dust contains these nutrients, the "iron limitation hypothesis" was reformed to the "dust fertilization hypothesis" and was tested in LCLN regions, usually with supportive results [14,18–20].

The Mediterranean Sea is a LNLC environment in which higher chlorophyll-a (chl-a) concentrations—a proxy for phytoplankton abundance—are observed during late winter-early spring [21] and its central and eastern parts have in general been identified as non-blooming areas [22]. A large part of this phytoplankton variability can be explained by the winter-spring water column mixing and the differences in the mixed layer depth (MLD) [23], which is deeper in the eastern part of the basin [24]. The Sea presents a high N:P ratio suggesting that P is the limiting factor, especially for its eastern part, where this ratio is unusually high [25]. Thus, P is thought to be the main limiting nutrient for phytoplankton growth with decreasing concentrations from west to east [26] similar to the eastward enhancement of the oligotrophic conditions [27]. The low nutrient concentrations in the Mediterranean—the lowest being over the eastern part—[28] reveals the importance of the atmospheric nutrient deposition, especially during the stratification period. The presence of desert dust particles characterizes the Mediterranean atmosphere [29,30] and the Sea is subject to a high rate of desert dust deposition [31] mainly favoured in winter and spring, when dust is transferred close to the surface [32]. Increased frequency of large and very large dust deposition events has been found in autumn and winter [33]. Dust deposition over the Mediterranean presents a decreasing gradient to the north and the Central Mediterranean has been found to be the most affected by dust deposition events [34]. According to the study in Reference [33] the frequency of large deposition events is higher over the western basin, while very large events characterize its central and eastern parts. Thus, the Mediterranean Sea offers an ideal LNLC environment for testing the dust fertilization hypothesis.

Experiments and observations in the Mediterranean have shown that dust can provide seawaters with N, P or both [35–42] that are of particular importance, especially during the stratification period when nutrients cannot be transferred from deeper waters to the surface. As far as Fe is concerned, its concentrations in the Sea due to dust addition or atmospheric deposition rather exclude Fe-limitation [38,42]. However, it has been argued that although this is the case during the stratification period, in spring the increased biological activity can decrease the dissolved Fe even to limited levels for phytoplankton [43]. It has also been suggested that dust derived Fe, by absorbing P, could even be the reason for the high N:P ratio in the Eastern Mediterranean, that is unfavourable for phytoplankton growth [25].

Experiments conducted over LNLC areas of the NW Mediterranean Sea and mainly under stratification conditions were in general supportive to the dust fertilization hypothesis: two successive wet dust additions both favoured phytoplankton species [44,45] and wet deposition resulted in significant increases of chl-a concentration and primary production [46]; Saharan dust and Fe plus P inputs favoured primary production, although the environment remained oligotrophic [35]; dust amended favoured both autotrophic and heterotrophic communities and chlorophyll concentration was remarkably increased after high dust inputs [39]; high dust and P additions favoured the autotrophic community [47]. On the contrary, dust events primarily favoured heterotrophic bacteria [48]; low dust additions were found to first favour the heterotrophic community [47] and dry dust deposition caused no changes in chl-a concentration [46]. Experiments and measurements in the Eastern Mediterranean Sea have shown more contradictory results: a significant increase in chl-a concentration was observed after the addition of both N and P [49]; chl-a increased linearly to the added fresh dust and after a dust storm a slight increase in chl-a and bacterial was observed [42]; the atmospheric deposition of N and P seemed to increase primary production [40]. On the other side: no phytoplankton increase was detected after dust events [37]; after a P-addition no change in chl-a was found [50]; a P addition resulted in an increase in bacterial and a chlorophyll decline [51]; after dry and wet deposition events little or no phytoplankton response was observed [52].

Studies based on satellite derived chlorophyll data for the entire Mediterranean have also ended up showing contradictory results: negative correlations were found between chlorophyll concentration and aerosol optical depth (as proxy for the presence of dust in the atmosphere) [53]; the significant correlations between aerosol optical thickness and chlorophyll concentrations at near-zero time lag were interpreted as an artefact caused by the impact of dust on the satellite data, while the significant correlations at greater time lags were few and indicative of a rather insignificant dust role [54]. In contrary: chlorophyll increases were observed shortly after dust deposition events [55]; weekly chlorophyll concentration data and model dust deposition data were found correlated in quite large areas especially of the Eastern Mediterranean and the Central part of the Sea was characterized as “the most responsive to dust deposition” [56]; small positive statistically significant correlations were found between chlorophyll and dust deposition, mainly in spring and for the Central and Eastern basins, with the seasonally detrended chlorophyll data resulting in lower and more limited correlations [57]; significant chlorophyll peaks in respect to the week before were found after very large dust events along with a possible pattern of an eastward decrease in the Sea’s responsiveness to high deposition dust events [33].

The Hellenic Seas, part of the LNLC eastern Mediterranean, are poorly studied regarding the possible effects of dust on phytoplankton growth. A significant dust transport in May 2013 over the area when dust load was high for almost 15 days, in respect to May 2012 when no significant dust load was observed, resulted in approximately doubled monthly chl-a concentrations even over the less productive areas of South Aegean Sea [58]. In the current study, the possible influence of dust events on phytoplankton is examined as revealed by satellite derived chlorophyll concentrations. The study is focused on the Hellenic Seas, while a strong event over the Central Mediterranean Sea is also assessed. It is noted that such a research focusing on the Hellenic Seas is missing from literature. Two strong events in March characterized also by extreme weather conditions and three events during the stratification period (one in June and two in September), when dust nutrients are supposed to have the maximum influence on the marine environment, are examined for the Hellenic Seas. Care was taken in the selection of the episodes during the June-September period in order not to be accompanied by high winds and heavy rainfall; these weather conditions can also favour phytoplankton growth by introducing nutrients from deeper layers or from the atmosphere to the surface waters. Chlorophyll differences before and after the events were calculated for the dust-affected areas and separately for the subareas of wet dust deposition. The results show both increases and decreases in chlorophyll concentrations after the events; however, when based on the area-limited absolute chlorophyll differences above 50%, they indicate a possible favourable effect of dust on phytoplankton, mainly during the low productive period. The present paper contributes to the relevant research through the study of specific events that is quite rare especially for the Hellenic Seas; the difficulties in drawing a safe conclusion are highlighted as well.

2. Materials and Methods

The marine area of about 460000 km^2 lying between 41.1°N, 19.5°E, 34°N and 29.6°E, herein referred to as “the Hellenic Seas,” is the main study area for the dust episodes; it is shown in Figure 1 along with the nineteen years (1998–2016) chlorophyll mean from June to September calculated from Copernicus Marine Environment Monitoring Service (CMEMS) monthly products. The area of the Central Mediterranean that is also examined was determined by dust Aerosol Optical Depth (AOD) values >0.8. In summary, for each dust episode recognized through dust AOD values—plus particulate matter (PM10) measurements for the Hellenic area—percentage differences of weekly satellite derived chlorophyll concentrations before and after the event were computed. Such differences were also calculated for the areas impacted by rain and account for wet deposition. For the episodes over the Hellenic Seas, daily chlorophyll differences were also computed. Absolute percentage chlorophyll differences above 50% were considered “significant” and are presented separately. The major part of data analysis was implemented in a Geographic Information System (GIS) environment.

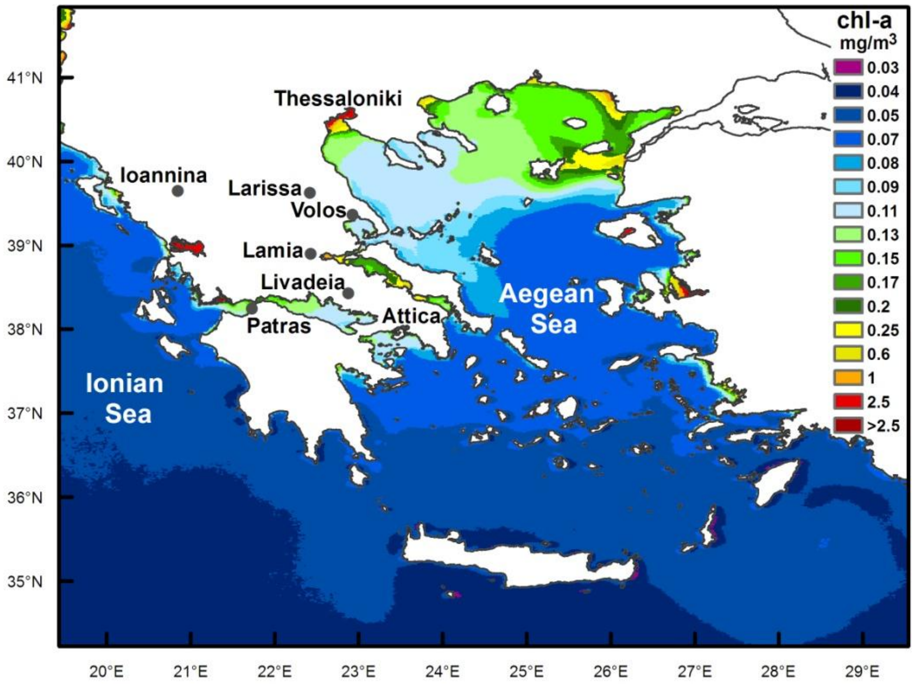

Figure 1. The main study area together with the chlorophyll concentration 1998–2016 climatological mean from June to September plus the geographical locations of PM10 stations.

2.1. Data

For the presence of dust in the atmosphere, near-real-time data of the "Dust Aerosol Optical Depth at 550nm" (dust AOD), available from the Copernicus Atmosphere Monitoring Service (CAMS) were used. It is noted that the typical dust AOD values are 0.1–1, with values <0.1 denoting there is virtually no dust at all; however, they can be >1 showing very high dust concentrations. In addition, PM10 station data (Figure 1) of the Greek Ministry of Environment and Energy through http://www.ypeka.gr were used. These measurements are conducted very close to the surface and the stations are situated in urban or suburban mainland areas. The chlorophyll data is multi satellite observations from CMEMS, L4 for the weekly data and L3 for the daily ones, computed via regional (Mediterranean) ocean colour algorithms. Data from the European Centre for Medium-Range Weather Forecasts interim reanalysis (ECMWF-ERA Interim project) plus daily accumulated precipitation of the Global Precipitation Measurement (GPM) product from giovanni.gsfc.nasa.gov were employed to define areas with precipitation. The Extreme Forecast Index (EFI) of the ECMWF ensemble prediction system was used for the identification of areas impacted by extreme precipitation or winds for the March episodes. The description of the weather conditions was also based on data from the Hellenic National Meteorological Service (HNMS) plus satellite Advanced Scatterometer (ASCAT) wind measurements.

2.2. Method

The first two dust episodes, that have taken place in March, were selected as extreme episodes that affected all the study area. Strong dust episodes, in winter and spring, are accompanied by gale winds, heavy rains or strong thunderstorms, that can also favour primary production importing nutrients to the surface layers through mixing processes from deeper layers or through precipitation from the atmosphere. Therefore, it was difficult to disentangle between the meteorological factors possibly affecting phytoplankton growth. Thus, the next three dust events studied were selected to have taken place in June-September period for two reasons: (a) because of the water column stratification during summer and early fall that highlights the role of dust imported nutrients and (b) because during this period it is quite possible to find individual dust events not accompanied by gale winds and heavy rainfall. The disadvantage is that, during this time of the year, dust transport can be above a certain level and deposition can be quite limited. It was difficult to select such dust episodes, since some strict criteria were set: the episodes were not to have been accompanied by gale winds, heavy rains or strong thunderstorms and if possible such phenomena to be also excluded before and after the events. It is noted that high winds were found together with dust events when chlorophyll increases were observed and their effects could not be disentangled [55,59]. The episode concerning the Central Mediterranean was selected for being strong and reported in the ECMWF-CAMS validation report of March–May 2017 as well captured by the dust AOD data.

A minimum dust AOD value of 0.3 was set—where needed—in defining the areas impacted by dust to ensure the presence of dust in the atmosphere over the Hellenic Seas. Evaluations of the ECMWF/MACC (Monitoring Atmospheric Composition and Climate) AOD re-analysis at visible wavelengths against measurements and observations showed that it presents an overestimation when dust load is low especially during spring, summer and autumn and an underestimation for values >0.3 [60], while a root mean square difference from observations of about 0.25 was reported for Thessaloniki AERONET (AErosol RObotic NETwork) station [61]. In addition, during the summer and autumn events of the present study, PM10 values <50 were observed when the forecasted dust AOD was <0.25. For the dust episode over the Central Mediterranean, the study was conducted for the region with dust AOD >0.8, in order to define an area with more than doubled AOD values during the event compared to the weeks before and after it, although during these weeks the values were <0.2 over the greater part of the region. Since high atmospheric dust loads revealed through AOD values do not necessarily account for deposition, the latter was confirmed with the use of PM10 station data. The use of these data is especially important for the June and September events when dust travels at higher altitudes in the atmosphere and is usually not accompanied by precipitation [62], facts that could result in low or near zero deposition.

Dust influence on chlorophyll concentration has been found to last about a week [46,47]; thus, weekly chlorophyll percentage differences for the weeks before and after the events were calculated. Since the absolute percentage differences reported between *in situ* observations and chlorophyll satellite data is approximately 50% [63], the chlorophyll differences above this level, are separately presented and hereafter mentioned as “significant.” The area indicated for precipitation during the episodes by both ECMWF and Giovanni data was considered as area of wet deposition and weekly chlorophyll differences were separately calculated. A statistical paired-t test was applied to the weekly chlorophyll values, in order to check whether their means over the dust affected areas differ significantly before and after the events. For the first two episodes, that were extreme weather events for Greece, weekly chlorophyll differences were also calculated for the area impacted by extreme rain or by extreme wind, as indicated by the precipitation EFI and the wind EFI respectively. In addition, for all cases of the Hellenic Seas, chlorophyll differences were calculated between some day before the event and the 3rd up to 6th day after the event depending on the availability of the daily chlorophyll data in a quite wide area. It is noted that chlorophyll responses to dust addition have been found after 3 to 4 days [33,35,42,45,47,49]. Taking in mind the possible disturbance in satellite derived chl-a concentrations caused by dust mimicking chlorophyll and increasing the extracted values that has been referred in the past, for example, [54,64], care was taken in order the daily satellite data used not to be affected by the presence of dust in the atmosphere. Thus, the selected days before and after the event were characterized by dust AOD <0.1 over a large region, while all chlorophyll data in areas with AOD >0.1 were excluded. It is noted that daily data was used in order to capture possible temporary chlorophyll increases that had no particular influence on the weekly concentrations. However, the relevant calculation presents two disadvantages: the smaller amount of available data and the possibility chlorophyll variations not to have taken place on these days. Last but not least, the prevailing weather before-during and after the events was taken into account in order to comment on other possible influences, except the ones of dust, on chl-a concentration.

3. Results

3.1. Heavy Rainfall and Dust: 25–28 March 2015

From 25 to 28 March 2015 an extreme weather event was recorded for Greece, with heavy rains and thunderstorms, gale southeasterlies that reached 9 Beaufort (Bf) over the Ionian and the S Aegean and 8 Bf over the N Aegean plus African dust transport over the country. The southern part of a highly meridional pattern at 500 hPa extending from north Europe down to Africa with cold air masses of −25 °C developed a cut-off low of 540 gpdm and a 1005 hPa surface depression southwest of Greece. This well-organized system moved north-eastwards affecting Greece with extreme weather and caused the dust transport. The event was mainly characterized by abnormal heavy rainfall regarding the season. Ending the episode, northerlies up to 7 Bf prevailed for one day overseas. The following week was characterized by low to moderate winds that at times reached 7 Bf only over the south parts, some local rains and a lot of shiny intervals. By the end of the week after the event, meteorological conditions were again favourable to dust transportation and southerlies reinforced to 8 Bf over the Aegean.

PM10 measurements gave maximum values of 112 $\mu g/m^3$ for Patras and 123 $\mu g/m^3$ for Attica region. It is noted that over the north-northwest part of the country, PM10 concentrations, compared to the AOD values, indicated a less strong episode. The maximum dust AOD during the episode and the chlorophyll percentage differences between the week that followed (30 March–6 April 2016) and the previous one (14–21 March 2016) are given in Figure 2, while chl-a concentrations of the week before the episode are shown in Figure S1. An increase in chlorophyll concentrations was recorded the week after the event in respect to the one before over the 59.9% of the region. The significant chl-a differences referred to the 7.7% of the data and were increases for the 94.4%, mainly over areas with low initial chl-a concentrations (as shown in Figure S1). It is noted that since precipitation was recorded over all areas, the above results account also for wet dust deposition. The mean chlorophyll concentration of the affected area was statistically significant higher after the event for both the above comparisons; over the area presenting absolute percentage chl-a differences above 50% this increase is larger.

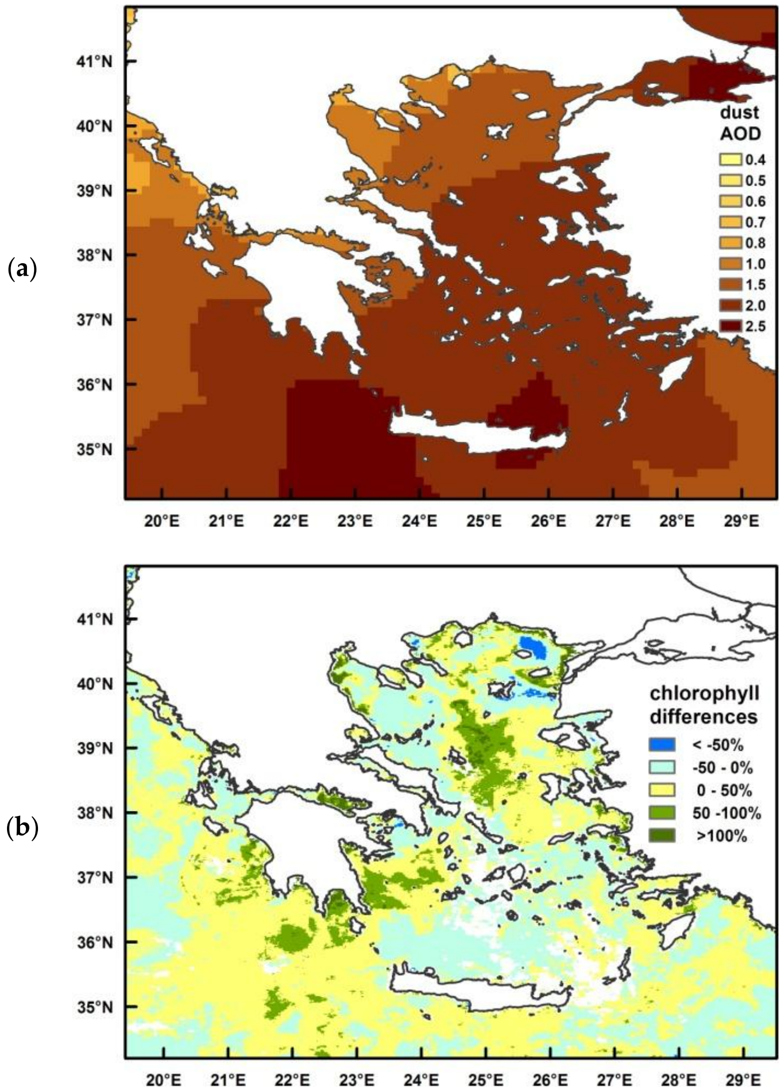

Figure 2. (**a**) Maximum dust aerosol optical depth (AOD) during the episode 25–28 March 2015; (**b**) Chl-a % differences between the weeks before (14–21 March 2015) and after (30 March–6 April 2015) the event.

The daily chlorophyll differences before and after the event were computed between 19 or 20 March—from 21 to 24 March AOD values implied the presence of some dust over the west and south parts—and 31 March or 1 April, that is, three or four days after the event. The chl-a percentage differences between 20 March and 31 March referred to the Ionian Sea (Figure S2a) and were increases for the 59.2% of the region, with the significant ones (7% of the data) being increases by 97.9%, not presenting large differences from the weekly calculations. Between 19 March and 1 April, the available data referred to the Aegean Sea and revealed an increase in chl-a over the 66.9% of the region, with the significant chlorophyll differences (15.5% of the data) being increases by 92.9% (Figure S2b). A quite larger area presenting significant chl-a increases was revealed in respect to the weekly differences, showing in addition that large temporal increases have taken place over the south-eastern part of the study area.

Over the area impacted by extreme rainfall as defined by the precipitation EFI, the weekly chlorophyll differences were increases for the 62.2% of the region, with the significant ones (9.5% of the data) being increases by 94.5% (Figures S3a,b). These results are quite similar to those for the whole area, since its greater part was affected by heavy rains. The area indicated by the wind EFI for extreme winds, presented an increase in chl-a over the 61.9%, with the significant chlorophyll differences referring to the 4.0% of the data and being increases by 98.1% (Figures S3c,d). It is noted that the latter area was also affected by extreme rainfall.

In all calculation cases more than 59.2% of the areas presented chlorophyll increases after the event and the significant chl-a differences—although limited to a maximum of 15.5% of the data—were increases at a percentage exceeding 92.9%. The above results imply that the dust episode could have had an impact on phytoplankton growth; however, it is difficult to disentangle between dust and extreme rainfall as favouring factors.

3.2. Strong Gale Winds and Large Amounts of Dust: 22–24 March 2016

A mid-level trough with SW-NE orientation, minimum height of 532 gpdm at 500 hPa and cold air masses (−25 °C) affected the study area. It developed an extended 995 hPa surface depression over NW Greece accompanied by a cold front that passed through the country, causing high impact weather. The dust transport episode initiated on 22 March together with south southeasterlies 7–8 Bf overseas and absence of rain. It continued up to 24 March with surface winds that over the Aegean reached 9 Bf with gusts up to 11 Bf and some rains and storms at places; the rainfall was of no particular intensity, except over the Ionian Sea—as far as marine areas were concerned—and the west and north mainland. Compared to the episode of March 2015, significant smaller precipitation amounts were recorded overseas and stronger southerlies prevailed especially over the Aegean Sea. The main characteristic of this event was the strong gale winds. Ending the episode north-northwesterlies (locally up to 7 Bf over the S Aegean) and unstable weather with some rains and storms prevailed. The following week was characterized by a lot shiny intervals and winds that locally reached 7 Bf over the Aegean for one day, that is, quite similar weather conditions with the ones of the corresponding week of the previous case examined.

During this dust episode, visibilities were reduced to 2 km and even lower on 23 March—according to HNMS station data—a rare phenomenon for Greece. The maximum values of PM10 concentrations recorded were: over Attica region 806 μg/m^3; over west Greece 243 μg/m^3 for Patras and 174 μg/m^3 for Ioannina; over central mainland 94 μg/m^3 for Livadeia, 79 μg/m^3 for Lamia and 66 μg/m^3 for Volos; over north Greece 132 μg/m^3 for the Thessaloniki region. The above measurements denote an extended and extreme dust episode over the country, much stronger than the one previously examined.

In Figure 3 are shown the maximum dust AOD values during the event and the percentage chl-a differences of the week after the event (29 March–5 April 2016) in respect to the week before (13–20 March 2016); the initial chlorophyll concentrations of the week before the event are given in Figure S4a. An increase in chlorophyll was observed only over the 7.6% of the area, while the very few significant chl-a differences (0.9% of the data) were increases by 56.7%. For the region with precipitation, accounted as area of wet deposition (Figure S4b), the above percentages were quite higher: increases in chlorophyll cover the 11.1% of the area, the significant chl-a differences were the 1.7% of the data and were increases by 57.7%. Area's chlorophyll means before and after the event were statistically significant different; however, they revealed a decrease when all data were considered and an increase when only the data referring to absolute chl-a differences above 50% were taken into account.

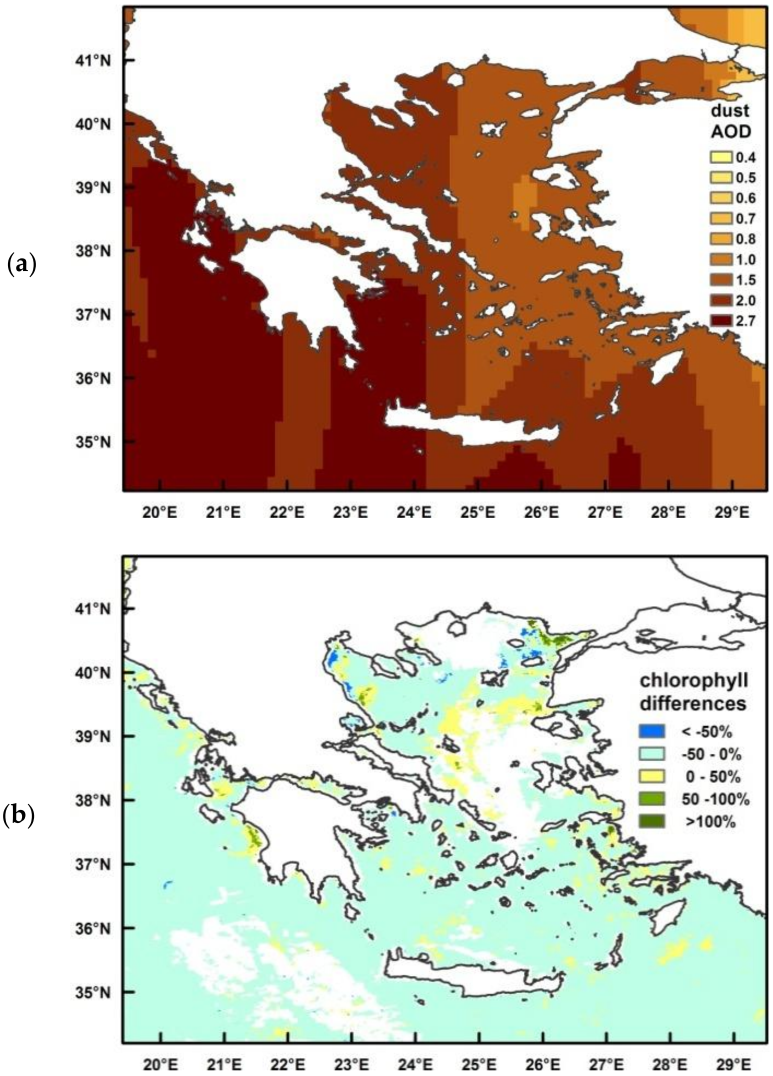

Figure 3. (**a**) Maximum dust AOD during the episode 22-24 March 2016; (**b**) Chl-a % differences between the weeks before (13–20 March 2016) and after (29 March–5 April 2016) the event.

The above results, being controversial to the ones of the previous case, led to the calculation of the chlorophyll differences between several pairs of days before and after the event, in an effort to reveal possible temporal chlorophyll increases; all calculations were made under the condition of AOD <0.1. Although chlorophyll data were not available over wide areas, their differences between 20 and 28 plus 19 and 28 March—4 days after the event—and 19 and 30 plus 20 and 30 March—6 days after the event—were calculated. The analytical results (Figure S5a–d) are included in Table 1 of the discussion section. The maximum percentages were: chlorophyll increases for the 37.8% of the area between 19 and 28 March, significant chl-a differences for the 4.6% of the data between the same days and significant increases for the 68.6% of the data between 20 and 28 March. The latter revealed a wider region with increased chl-a values over the S Aegean than the weekly data, denoting a probable temporal increase although differences are not >50%.

Extreme rainfall impacted a small area of the Ionian Islands and coastal areas. For this area, chlorophyll increases covered the 19.2% and the significant chl-a differences were the 3.4% of the data with the 73.3% of them being increases (Figure S6a,b). The percentage of the area presenting an increase in chlorophyll was higher here but this fact can also be attributed to nutrients brought to the Ionian near coast sea area by heavy rains and/or river discharges. Extreme winds impacted almost all areas and the results were comparable to the ones of the weekly calculations (Figure S6c,d): chlorophyll increases for the 7.5% of the region, significant chl-a differences for the 0.9% and 58.4%.of them increases.

This very strong dust episode did not favour chlorophyll concentrations. Compared to the previous case examined that has possibly favoured phytoplankton growth, this dust event was more intense and characterized by stronger winds and lower precipitation.

3.3. Early Summer Heat Wave and Dust: 18–21 June 2016

An extended 500 hPa ridge over Greece together with a thermal ridge at 850 hPa and a quite smooth surface pressure field causing light northerlies overseas depict the synoptic conditions of the 18–21 June 2016 dust event. A heat wave was recorded during this episode with temperatures up to 41 °C over mainland and 37 °C over islands. Before the event, the measured chlorophyll could have been positively influenced by winds from south directions that reached 6 Bf over the Ionian and 7 Bf over the Aegean plus some strong storms over the Ionian Sea. The dust episode and the heat wave ended by 21 June from the north part, with north winds reaching locally 6 Bf over the Ionian and 7 Bf over the Aegean Seas until 23 June.

The available PM10 data showed concentrations that reached 172 $\mu g/m^3$ over Attica region, 79 $\mu g/m^3$ over Thessaloniki region and 83 $\mu g/m^3$ over Patras. The maximum dust AOD during the episode and the chlorophyll percentage differences of the weeks before (9–16 June 2016) and after (25 June–2 July 2016) the event are presented in Figure 4. The chl-a values of the week before the event and the chlorophyll differences for the area accounted for wet deposition are given in Figure S7a,b. The weekly chlorophyll differences showed increases for the 33.3% of the area, while the significant chl-a differences (1.6% of the data) were by 74.8% increases. The area of wet deposition was not an extended one and was characterized by higher percentages of chlorophyll increases (44.2% of the region) as well as of significant differences (4.8% of the data) and quite the same percentage of significant increases (74.2%); these results probably show a more favourable influence of wet deposition on chlorophyll concentrations. Comparing the chlorophyll means over the affected area before and after the event, the statistically significant results revealed a small decrease when all data were considered and a larger increase when the data corresponding to absolute percentage chl-a differences above 50% were used.

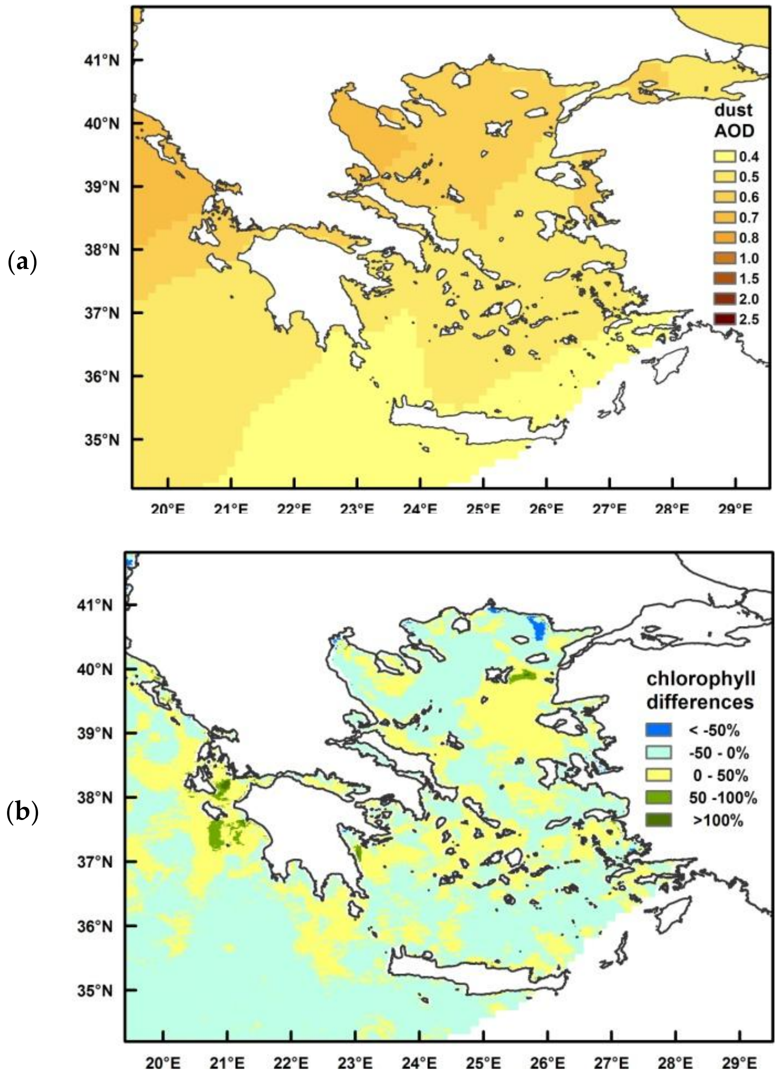

Figure 4. (**a**) Maximum dust AOD during the episode 18–21 June 2016; (**b**) Chl-a % differences between the weeks before (9–16 June 2016) and after (25 June–2 July 2016) the event.

The daily chlorophyll differences, calculated between 16 and 24 June 2016—3 days after the event—referred to the Aegean and revealed a significant chlorophyll increase over its E-NE part (Figure S8) where the initial concentrations were quite low, that was not shown by the weekly data. The daily results presented a greater area of chlorophyll increases (51.3% of the region), as well as of significant chl-a differences (9.9% of the data) and increases (96.2%) than the weekly data, denoting that chlorophyll concentrations could have temporarily been favoured by the dust episode. At this time of year, chlorophyll is in a decreasing face and the marine environment is in general oligotrophic. Thus, the temporal character of the chl-a increase could be attributed to the quick phytoplankton consumption by the upper trophic levels. It is noted that although the wind intensity after the event was comparable to the one before, the strong northerlies, that prevailed over the Aegean Sea just after it, could have caused upwelling over the area presenting the significant chl-a increases revealed by the daily data. However, during the summer period the nutricline is deep and upwelling is not capable of importing nutrients to the surface layers [65,66].

3.4. Late Summer Heat Wave and Dust: 6–8 September 2015

A 500 hPa anticyclonic pattern, an 850 hPa ridge together with warm air masses from Africa and light to moderate northerlies overseas were the synoptic conditions of the 6–8 September 2015 episode that was accompanied by a heat wave. Although dust transport was favoured at higher altitudes in the atmosphere, it was already intense at 850 hPa. In most areas winds before and after the event did not vary significantly and some heavy rains were recorded over the N Aegean parts. The important to be noticed is the reinforcement of southerlies on 9 September (just after the event) over the Ionian to 6–7 Bf and over its western parts to 8–9 Bf and the heavy rains over this area from 9 to 11 September, that could have also affected positively the observed chl-a after the event.

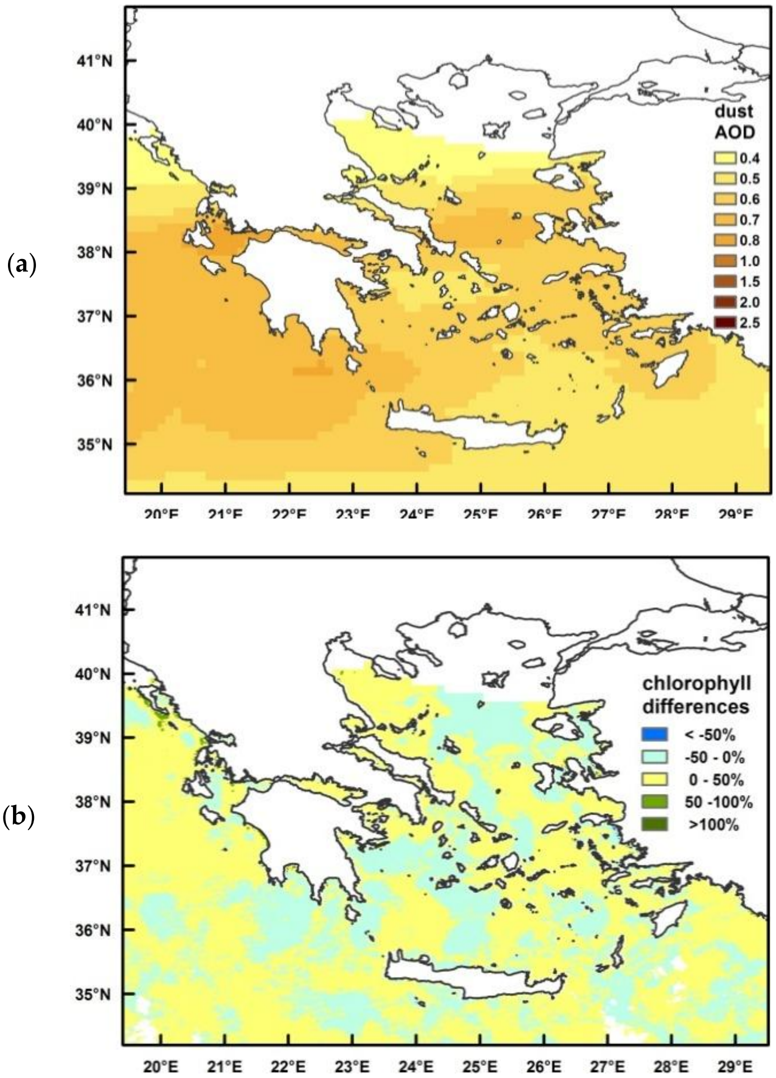

Figure 5. (**a**) Maximum dust AOD during the episode 6-8 September 2015; (**b**) Chl-a % differences between the weeks before (29 August–5 September 2015) and after (14–21 September 2015) the event.

PM10 data was very limited; however, over Attica region the concentration reached 69 μg/m^3. In Figure 5 are shown the maximum dust AOD values during the episode and the percentage chlorophyll differences between the weeks before (29 August–5 September 2015) and after (14–21 September 2015) the event. The chl-a concentrations of the week before the event are presented in Figure S9a. The weekly chlorophyll differences were increases for the 66.1% of the area, with the significant ones—extremely limited to the 0.4% of the data—showing increase for the 95.0%. All the calculated percentages were higher for the small area of wet deposition (Figure S9b): chlorophyll increases over the 69.6% of the area with the significant chl-a differences, limited to the 0.5% of the data, being all increases. A possible important role of wet deposition is again implied though based on a very small amount of data. In all comparisons, the area-averaged chlorophyll values were statistically significant higher after the event; the increase was larger when only the data referring to significant differences were taken into account.

Daily chlorophyll differences (Figure S10) calculated between 4 and 12 September 2015—4 days after the event—showed less chlorophyll increases (18.7% of the area), more significant chl-a differences (3.5% of the data) and less significant increases (73.4%). In addition, they revealed a large part of the N Ionian Sea with chlorophyll increases even >100% that was not shown by the weekly data. However, this area was affected by heavy rains after the event and south winds were also reinforced. In consequence, the possible favouring factor for these significant chlorophyll increases cannot be determined. It is noted that extreme weather events this time of the year have been found to cause an increase in chl-a and sign the start of the chlorophyll increasing phase [67].

3.5. Fair Weather and Dust: 21–23 September 2014

An anticyclonic pattern at 500 hPa as well as at 850 hPa extended over the western central and southern parts of the country, with warm air masses and a smooth surface pressure field with light winds, were the synoptic weather conditions that favoured dust transport during 21–23 September 2014. Before the episode a few quite strong rains were recorded over the Ionian and the N Aegean Seas while northerlies reached at times 7 Bf locally over the Aegean. The episode ended with northerlies that temporarily reached 7–8 Bf over the Aegean and rainy weather over the north parts of the country. The days that followed—25 to 27 September—a 500 hPa trough affected the area, resulting in heavy rainfall and thunderstorms while gale winds prevailed the following days. The rains and thunderstorms together with the gale winds just after the episode could have also positively influenced the observed chlorophyll concentrations. Thus, the chlorophyll variations calculated for this episode could be very much affected by the prevailing weather conditions just after it.

PM10 concentration during the episode reached 87 $\mu g/m^3$ over Attica region, 72 $\mu g/m^3$ over Ioannina, 96 $\mu g/m^3$ over Patras and 74 $\mu g/m^3$ over Larissa. The maximum dust AOD during the episode and the chlorophyll percentage differences of the weeks before (30 September–7 October 2014) and after (14–21 September 2014) the events are shown in Figure 6. In Figure S11 are presented the chlorophyll concentrations of the week before the event and the weekly chlorophyll differences for the area accounted for wet deposition. The week that followed the event, chlorophyll presented an increase over the 80.0% of the region, with the significant chl-a differences (2.8% of the data) being by 99.1% increases. For the region accounted for wet deposition, which was a very limited one, the percentages were higher: increases in chlorophyll for the 87.8% of the area and the significant chl-a differences (8.8% of the data) were all increases. Similar to the previous case, the area-averaged chlorophyll values were statistically significant higher after the event in all comparisons; larger chlorophyll increases resulted from the data referring to significant differences.

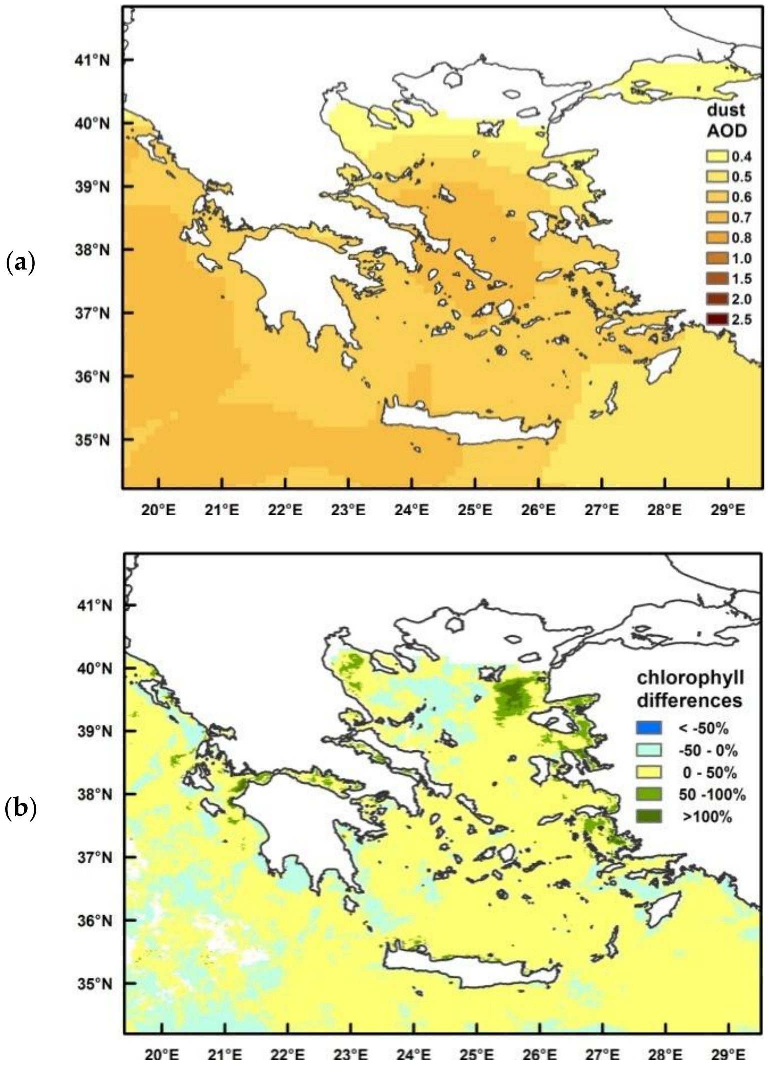

Figure 6. (**a**) Maximum dust AOD during the episode 21–23 September 2014; (**b**) Chl-a % differences between the weeks before (14–21 September 2014) and after (30 September–7 October 2014) the event.

The daily chlorophyll differences between 18 and 28 September (Figure S12) revealed significant increases over the south-eastern part of the study area, that were not shown by the weekly data. The 75.8% of the area presented an increase in chlorophyll and the significant chl-a differences (7.7% of the data) were by 98.7% increases.

The results here are quite supportive of the dust fertilizing role and especially the one of wet deposition; however, the weather conditions just after the event were also favourable for phytoplankton growth. It is noted that regardless the care taken for the selection of dust episodes not to be accompanied by strong rains and winds, it is very difficult such weather conditions not to be present before and after the dust events.

3.6. Dust over Central Mediterranean: 11–13 May 2017

The episode studied here is the one mentioned in the CAMS validation report as "Dust event over Tropical North Atlantic and Central Mediterranean: 9–12 May 2017"; it was characterized as a strong one and well captured by the model. The area studied was determined by dust AOD values >0.8 between 11 and 13 May 2017 when this strong dust episode affected the Central Mediterranean.

A strong NW flow at 500 hPa, an 850 hPa ridge with warm air masses and strong surface southerlies characterized the episode and favoured dust transport through lower and higher atmospheric levels. The week before the event, winds locally reached 7 Bf for one or two days and some rains were recorded over the Ionian Sea. During the episode southerlies 7–8 Bf prevailed over the study area and precipitation was recorded almost everywhere. The week that followed was quite rainy over the north parts and winds reached locally 7 Bf for one day. It is noted that the wind reinforcement during the event could have also affected positively chlorophyll concentrations.

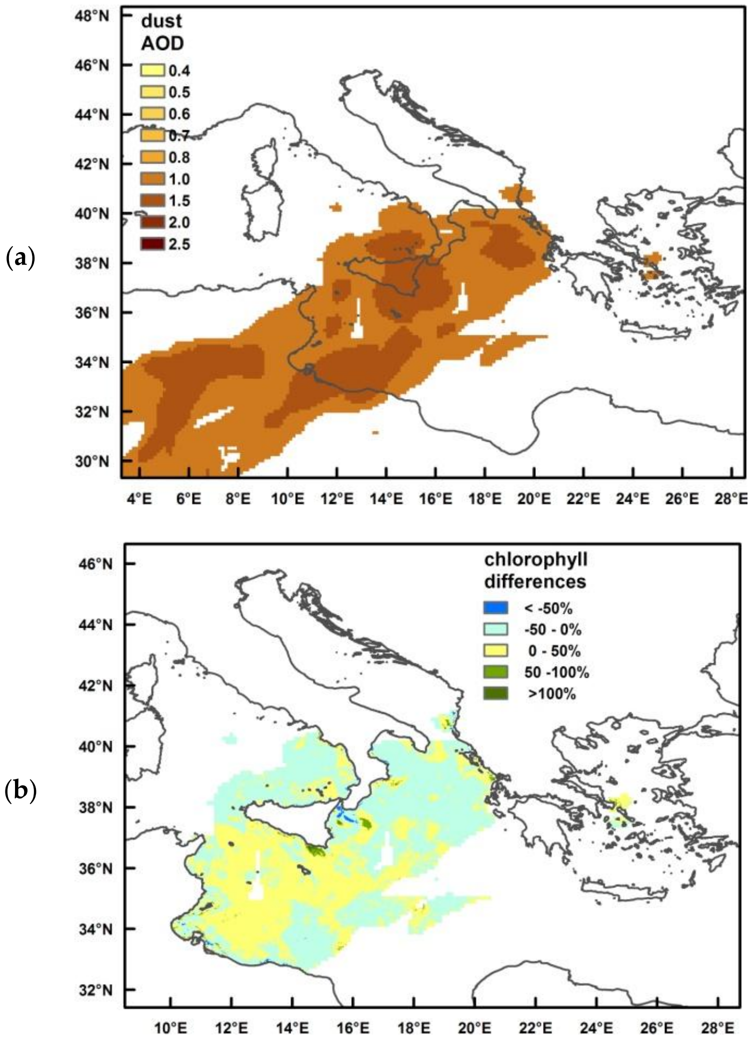

Figure 7. (**a**) Maximum dust AOD >0.8 during the episode 11–13 May 2017 that defined the study area; (**b**) Chl-a % differences between the weeks before (1–8 May 2017) and after (17–24 May 2017) the event.

The examined area of dust AOD >0.8 and the chlorophyll percentage differences between the weeks before (1–8 May 2017) and after the event (17–24 May 2017) are shown in Figure 7; the chl-a concentrations of the week before are presented in Figure S13a. The weekly chlorophyll differences were increases for the 44.4% of the area and the significant chl-a differences (limited to the 1.4% of the data) were by 74.9% increases. Wet deposition characterized the major part of the area where a chlorophyll increase was recorded over the 47.0% and the significant chl-a differences (1.8% of the data) were increases by 74.7% (Figure S13b). It is noted that the areas with lower initial chl-a concentrations mainly presented increases. The area's mean chl-a concentration was statistically significant different after the event only for the data referring to absolute chlorophyll differences above 50% and revealed an increase.

For proving that dust can positively affect phytoplankton growth, more pronounced chlorophyll increases would have been expected after such an extreme event. Only based on the significant chlorophyll differences—that were area limited—one can argue in favour of the fertilizing dust effect.

4. Discussion and Conclusions

The results of the study are summarized in Table 1.

The two March's events that were also extreme weather events gave contradictory results and made clear that no safe conclusion can be drawn when other favouring factors such as strong winds and heavy rains are involved, although all of them could have led to chlorophyll increases. The most extreme dust episode of March 2016, characterized by strong gale winds and limited heavy rainfall, did not favour chlorophyll concentrations which presented a decrease over large areas. Significant chl-a differences (a small amount of the data) presented increases over wider areas only in two cases: over the 73.3% of the area of extreme rainfall—that being a coastal one could have also been affected by river discharges—and over the 68.6% of the area as revealed through the daily calculations. Contradictory results were extracted from the March 2015 episode, characterized mainly by extreme rainfall, where the area presenting chl-a increases was larger than the one of decreases and the significant chlorophyll differences (up to 15.5% of the data) were increases at least by 92.9%. Although during these dust events, there were also other meteorological factors (winds and rainfall) that could have favoured primary production, chlorophyll did not increase after the stronger dust episode of March 2016. It is noted that for the Eastern Mediterranean Sea the lower chlorophyll responses to large dust addition events have been found [33]. In the same study [33], chlorophyll peaks were temporary even after very large dust events, while a slight chlorophyll decrease was found for two events; in addition, no pattern of larger amount of dust leading to greater chlorophyll increases was observed. For this area and this period of the year, when chlorophyll concentrations over the Hellenic Seas have elevated values, only a few positive correlations between chlorophyll concentration and dust deposition were found and concern the N Ionian Sea [57]. It is noted that the MLD is the deepest in March at least for the Aegean [24]; it is possible that under the enhanced mixing induced of the strong gale winds of the March 2016 episode, nutrients were quickly scattered through the deep mixed layer and their effects on surface waters could not be seen. It is also possible that nutrients from dust, compared to the available ones from the deeper layers, can rather cause unimportant increases at this time of the year. On the other hand, in an experimental study, dust accompanied by high winds (turbulence) was likely to stronger affect phytoplankton [39]. One, arguing in favour of the dust fertilizing effect, could propose as an explanation for the non-increased chlorophyll after the stronger event, that the environment had become Fe limited; evidences found in the study of [68] denoted that large dust deposition events may sink the surface dissolved iron. In any case, during these episodes there were also strong winds and rainfall and their effects cannot be disentangled from the ones of dust.

Table 1. The results of all calculations are summarized. The cases presenting statistically significant differences in the mean chlorophyll concentrations before and after the events, as derived by the weekly data, are marked with an "s" (s-i for increase and s-d for decrease).

Dust Episode	Chlorophyll Increase (Area %)	Significant Chlorophyll Difference (Area %)	Significant Chlorophyll Increase (Area %)
Heavy rainfall and dust 25-28 March 2015 (dust AOD 0.8-2.5)	59.9 $^{s-i}$ 59.9 $^{s-i}$ (wet deposition) 62.2 (extreme rain) 61.9 (extreme wind) 59.2 * (Ionian Sea) 66.9 * (Aegean Sea)	7.7 7.7 9.5 4.0 7.0 * 15.5 *	94.4 $^{s-i}$ 94.4 $^{s-i}$ 94.5 98.1 97.9 * 92.9 *
Strong gale winds and large amounts of dust 22-24 March 2016 (dust AOD 1.0-2.7)	7.6 $^{s-d}$ 11.1 $^{s-d}$ (wet deposition) 19.2 (extreme rain) 7.5 (extreme wind) 26.2 * (20-28 March) 37.8 * (19-28 March) 21.7 * (19-30 March) 4.9 *(20-30 March)	0.9 1.7 3.4 0.9 1.0* 4.6* 1.9* 0.6*	56.7 $^{s-i}$ 57.7 $^{s-i}$ 73.3 58.4 68.6 * 43.1 * 58.7 * 51.1 *
Early summer heat wave and dust 18-21 June 2016 (dust AOD 0.3-0.7)	33.3 $^{s-d}$ 44.2 $^{s-d}$ (wet deposition) 51.3 * (Aegean Sea)	1.6 4.8 9.9 *	74.8 $^{s-i}$ 74.2 $^{s-i}$ 96.2 *
Late summer heat wave and dust 6-8 September 2015 (dust AOD 0.3-0.8)	66.1 $^{s-i}$ 69.6 $^{s-i}$ (wet deposition) 18.7 *	0.4 0.5 3.5 *	95.0 $^{s-i}$ 100.0 $^{s-i}$ 73.4 *
Fair weather and dust 21-23 September 2014 (dust AOD 0.3-0.7)	80.0 $^{s-i}$ 87.8 $^{s-i}$ (wet deposition) 75.8 *	2.8 8.8 7.7 *	99.1 $^{s-i}$ 100.0 $^{s-i}$ 98.7*
Dust over Central Mediterranean 9-13 May 2017 (dust AOD 0.8-1.5)	44.4 47.0 (wet deposition)	1.4 1.8	74.9 $^{s-i}$ 74.7 $^{s-i}$

* Denotes daily data.

For the early summer heat wave and dust episode of June 2016, only by the significant chlorophyll differences (again a limited amount of data) being increases by more than 74.2% can be assumed a possible favourable influence of dust. It is noted that daily differences revealed a quite larger area (9.9%) of differences >50% that were by 96.2% increases, including areas not shown by the weekly data. In the ultraoligotrophic and stratified June environment with low chlorophyll concentrations in a further decreasing phase, when dust nutrients are supposed to have a dominant role, the increased primary production is expected to be quickly transferred to upper trophic levels. Thus, it is possible that temporal chlorophyll increases could not be seen neither in the weekly differences nor in the examined daily differences. It is noted that statistically significant correlations between dust deposition and chlorophyll concentration have been found for the area for the April-June period [57]. Two September dust episodes were studied here, the late summer heat wave of September 2015 and the fair weather one of September 2014; the latter's results are very much "contaminated" by the weather conditions that followed. For both, the chlorophyll differences were for most areas increases, with the significant ones being almost all increases and for the limited areas of wet deposition all increases. Since in September the quite low chlorophyll concentrations of the area are in an increasing phase and the end of the stratification period begins, it is easier for the marine environment to sustain the increased primary production. A more favouring effect of wet deposition can be implied by the increase of both the percentages of the chlorophyll's significant differences and the significant increases, as in other studies [46]. For the July-September period, a relevant statistical analysis did not result in significant correlations between chlorophyll and dust for the region [57]. It is also noted that in the oligotrophic environment of the Eastern Mediterranean, bacteria can be firstly favoured by the dust nutrients [42,69] and that the area is at times subject to air pollutants that can inhibit phytoplankton growth [69].

For the strong dust episode of May 2017 over the Central Mediterranean Sea, only the area-limited significant chlorophyll differences were by 74.9% increases, while these increases could also be attributed to the gale southerlies during the event. It is noted that the area was found to present significant positive relationships between chlorophyll concentrations and dust deposition for this time of the year [57] and in May presents quite low chlorophyll values in a decreasing phase.

Comparing the chlorophyll differences found before and after the dust events studied, no safe conclusion can be drawn, since increases as well as decreases were both present. A more favouring role of wet dust deposition was implied by the heavy rainfall March event and the June-September episodes. The significant chl-a differences for all cases were in high percentages increases (above 74.2% of the data if the very extreme dust episode of March 2016 is excluded). However, these significant differences corresponded, again for all cases, to a small amount of data (maximum 15.5% and in majority much smaller. A possible favouring effect of dust on chlorophyll could be assumed from the five out of six events and only by the significant differences; the two heat wave and dust episodes of September 2015 and June 2016 stronger support this outcome. Since there are studies suggesting that chlorophyll variations due to dust events even of moderate strength can hardly be detected from satellite observations [42,70], maybe one should trust these significant chlorophyll differences. It is also noted that for the area presenting absolute chlorophyll differences above 50%, the weekly mean chl-a concentration after the events was statistically significantly higher than the one before in all cases (Table 1). However, some of these significant increases could be also related to other factors favouring phytoplankton growth, such as strong winds and heavy rainfall. Even if the studied episodes of the June-September period were carefully selected in order other favouring meteorological conditions for phytoplankton growth to be excluded, this could not be completely achieved especially regarding the weather conditions that followed the September 2014 event. The method followed here could be applied in any region for examining the influence of dust on primary production. Since there are difficulties in discriminating between the influence of dust and of other meteorological factors, the results would be safer for regions or time periods characterized by more stable weather conditions. Statistical methods applied in long time-series of dust plus wind and precipitation data are rather more suitable for disentangling the influence of these factors on chlorophyll concentrations.

The work presented here was an effort to explore the possible influence of desert dust on marine chlorophyll concentrations through the study of specific dust events. According to authors' knowledge, it is the first time that such a study is conducted for the Hellenic Seas. The prevailing weather before-during and after the events was taken into account and emphasis was given to the meteorological factors of wind and precipitation that can also lead to chlorophyll increases. The results showed both sign—positive and negative—chlorophyll variations; nevertheless, when based on the area-limited significant chlorophyll differences, one could argue in favour of the "dust fertilization effect" mainly during the low productive period. The study revealed also the difficulty in discriminating between dust and other meteorological factors favouring phytoplankton growth and reach safe conclusions. The possible fertilizing effect of dust remains a questionable matter as discussed in the introduction section and as revealed from the present study of specific events.

Supplementary Materials: The following are available online at http://www.mdpi.com/2077-1312/7/2/50/s1, Figure S1: Chl-a concentrations of the week before the event of 25–28 March 2015, Figure S2: Daily chlorophyll % differences between: (a) 20 and 31 March 2015; (b) 19 March and 1 April 2015, Figure S3: For the episode of 25–28 March 2015: (a) maximum values of precipitation EFI during the episode; (b) weekly chlorophyll % differences over the area of extreme rainfall as defined by EFI; (c) same as (a) for wind EFI; (d) same as (b) over the area of extreme wind; Figure S4: (a) Chl-a concentrations of the week before the event of 22–24 March 2016; (b) chl-a % differences between the weeks before (13–20 March 2016) and after (29 March–5 April 2016) the event for the area of wet deposition; Figure S5: Daily chlorophyll % differences between: (a) 20 and 28 March 2016; (b) 19 and 28 March 2016; (c) 19 and 30 March 2016; (d) 20 and 30 March 2016, Figure S6: For the episode of 22–24 March 2016: a) maximum values of precipitation EFI during the episode; (b) weekly chlorophyll % differences over the area of extreme rainfall as defined by EFI; (c) same as (a) for wind EFI; (d) same as (b) over the area of extreme wind, Figure S7: (a) Chl-a concentrations of the week before the event of 18-21 June 2016; (b) chl-a % differences between the weeks before (9–16 June 2016) and after (25 June–2 July 2016) the event for the area of wet deposition, Figure S8: Daily chlorophyll % differences between 16 and 24 June 2016, Figure S9: (a) Chl-a concentrations of the week before the event of 6–8 September 2015; (b) chl-a % differences between the weeks before (29 August–5 September 2015) and after (14–21 September 2015) the event for the area of wet deposition, Figure S10: Daily chlorophyll % differences between 4 and 12 September 2015, Figure S11: (a) Chl-a concentrations of the week before the event of 21–23 September 2014; (b) chl-a % differences between the weeks before (14–21 September 2014) and after (30 September–7 October 2014) the event for the area of wet deposition, Figure S12: Daily chlorophyll % differences between 18 and 28 September 2014, Figure S13: (a) Chl-a concentrations of the week before the event of 11–13 May 2017; (b) chl-a % differences between the weeks before (1–8 May 2017) and after (17–24 May 2017) the event for the area of wet deposition.

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Supplementary Materials:

Heavy Rainfall and Dust: 25–28 March 2015

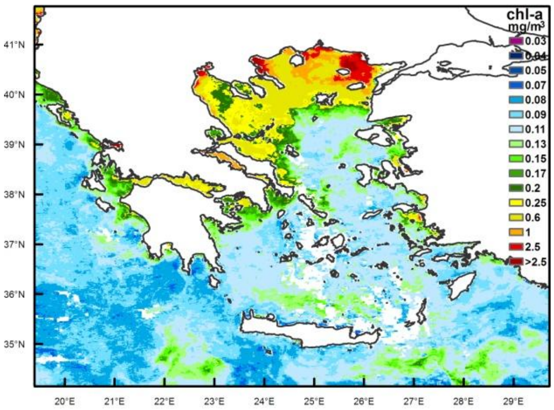
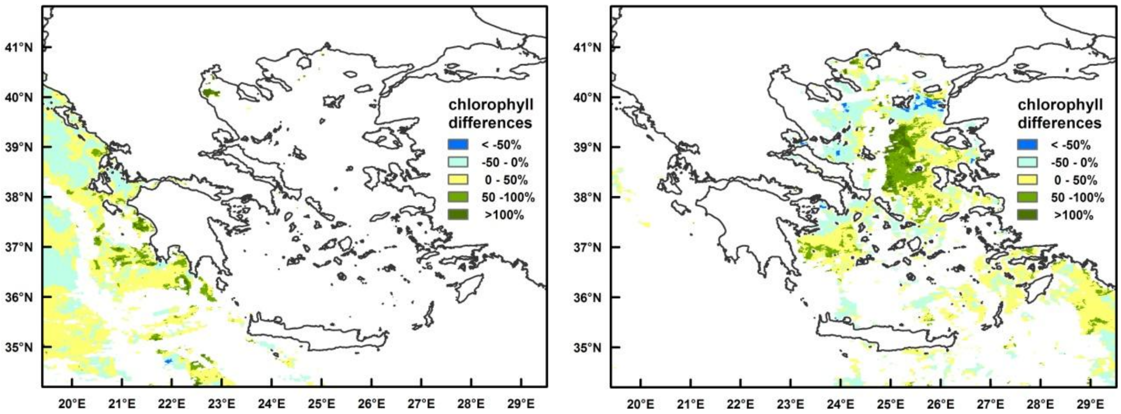
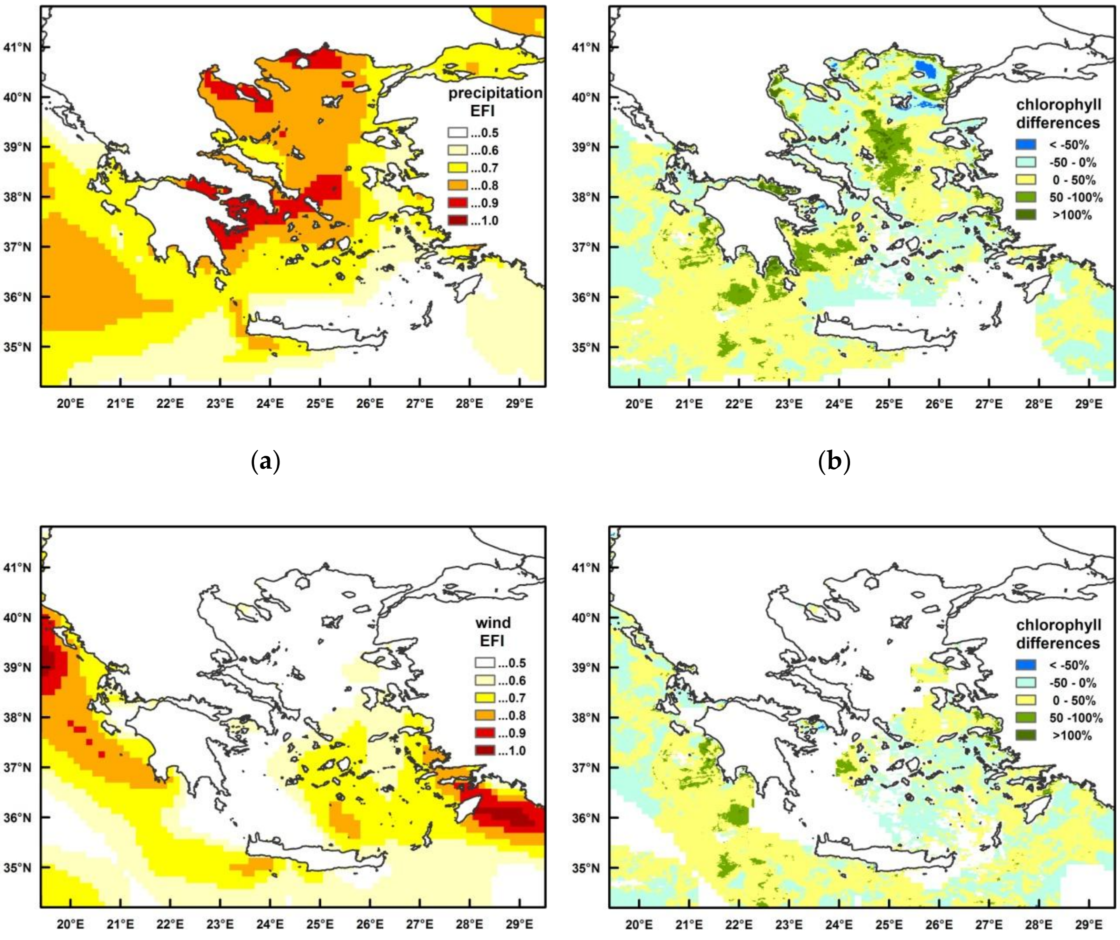


Figure S1. Chl-a concentrations of the week before the event of 25–28 March 2015.



(**a**) (**b**)

Figure S2. Daily chlorophyll % differences between: (**a**) 20 and 31 March 2015; (**b**) 19 March and 1 April 2015.

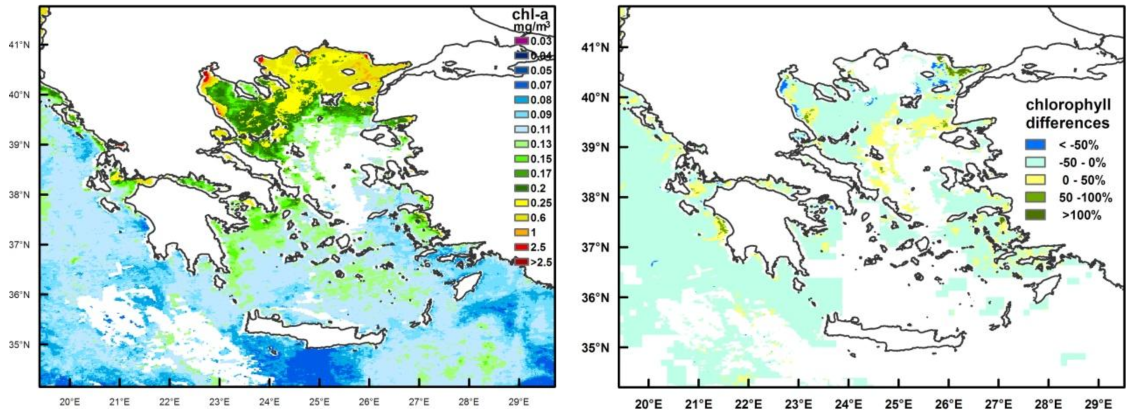


(**a**) (**b**)

(**c**) (**d**)

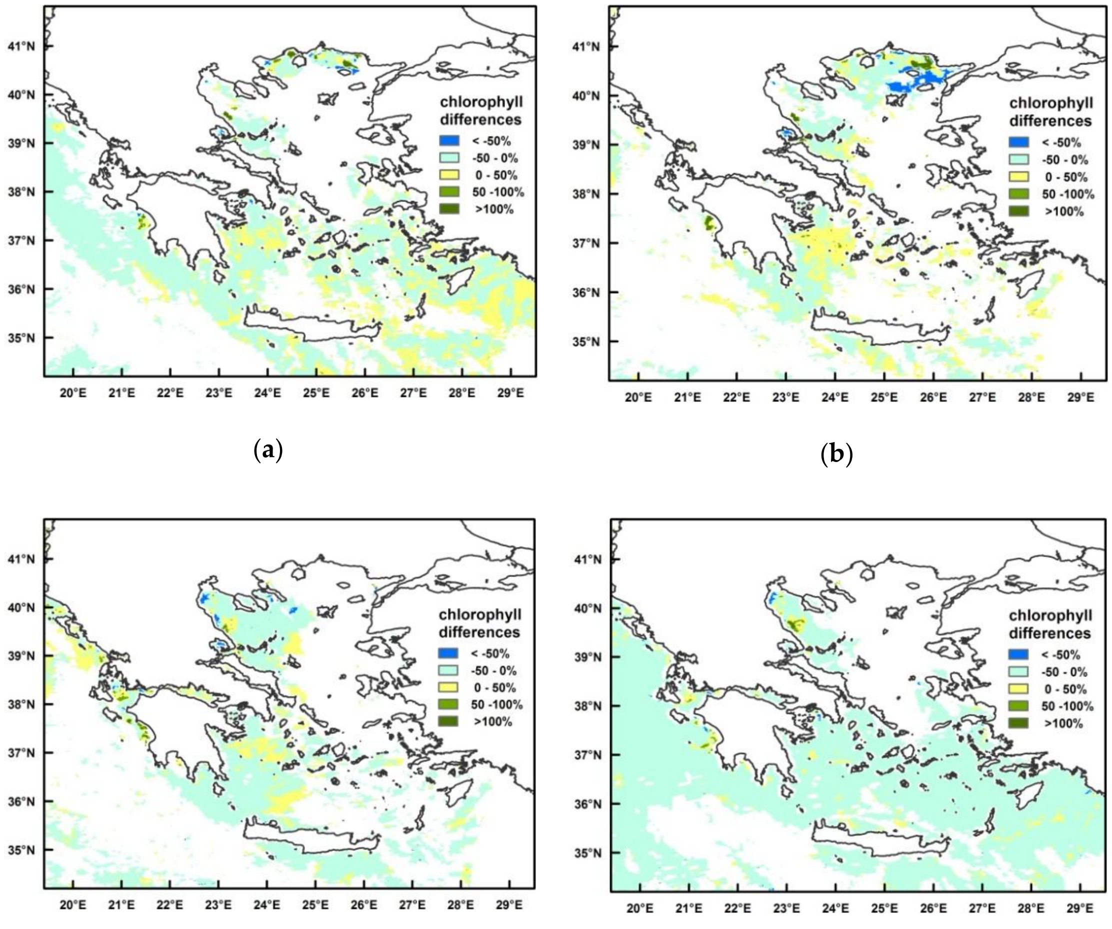
Figure S3. For the episode of 25–28 March 2015: (**a**) maximum values of precipitation EFI during the episode; (**b**) weekly chlorophyll % differences over the area of extreme rainfall as defined by EFI; (**c**) same as (a) for wind EFI; (**d**) same as (b) over the area of extreme wind.

Strong Gale Winds and Large Amounts of Dust: 22–24 March 2016



(**a**) (**b**)

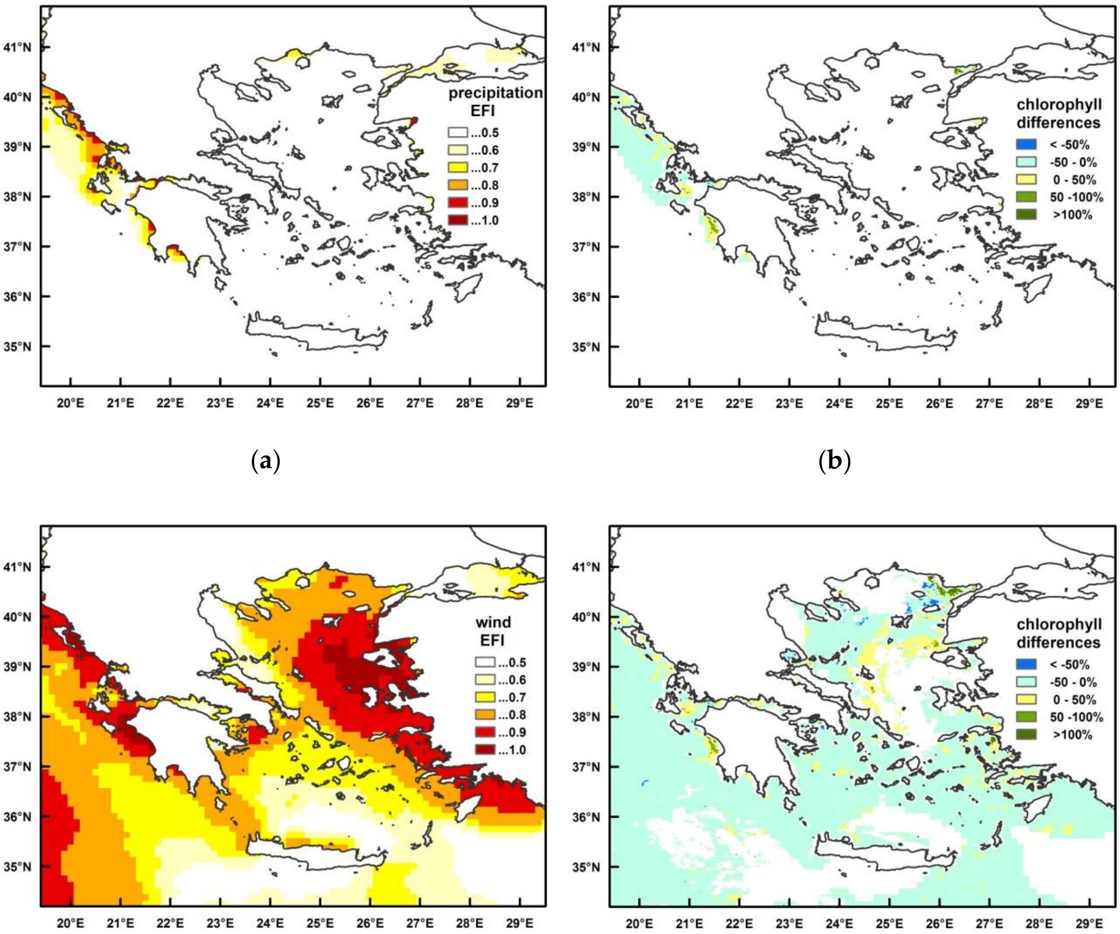
Figure S4. (**a**) Chl-a concentrations of the week before the event of 22–24 March 2016; (**b**) chl-a % differences between the weeks before (13–20 March 2016) and after (29 March–5 April 2016) the event for the area of wet deposition.



(**a**) (**b**)

(**c**) (**d**)

Figure S5. Daily chlorophyll % differences between: (**a**) 20 and 28 March 2016; (**b**) 19 and 28 March 2016; (**c**) 19 and 30 March 2016; (**d**) 20 and 30 March 2016.

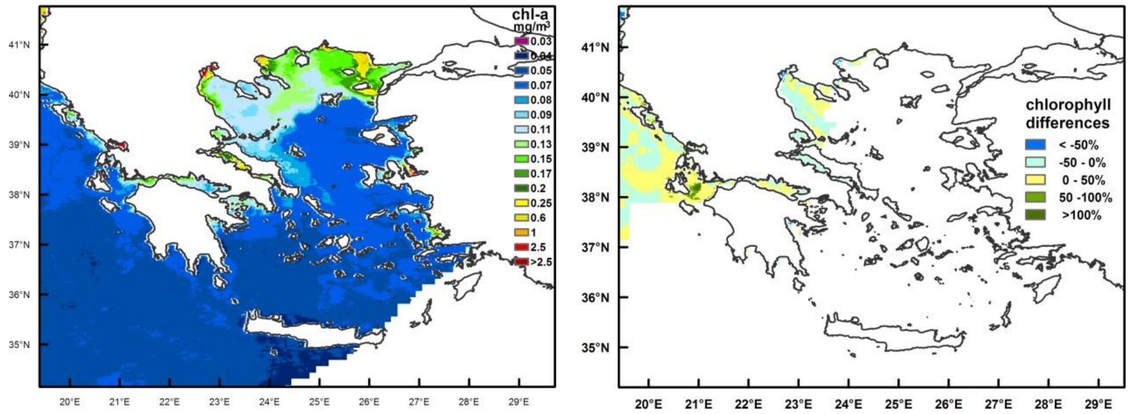


(**a**) (**b**)

(**c**) (**d**)

Figure S6. For the episode of 22–24 March 2016: (**a**) maximum values of precipitation EFI during the episode; (**b**) weekly chlorophyll % differences over the area of extreme rainfall as defined by EFI; (**c**) same as (a) for wind EFI; (**d**) same as (b) over the area of extreme wind.

Early Summer Heat Wave and Dust: 18–21 June 2016



(**a**) (**b**)

Figure S7. (**a**) Chl-a concentrations of the week before the event of 18-21 June 2016; (**b**) chl-a % differences between the weeks before (9–16 June 2016) and after (25 June–2 July 2016) the event for the area of wet deposition.

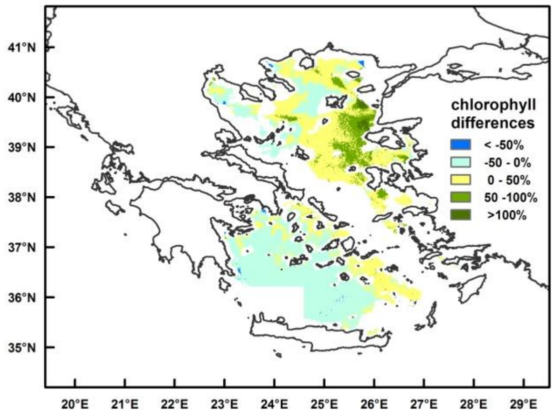
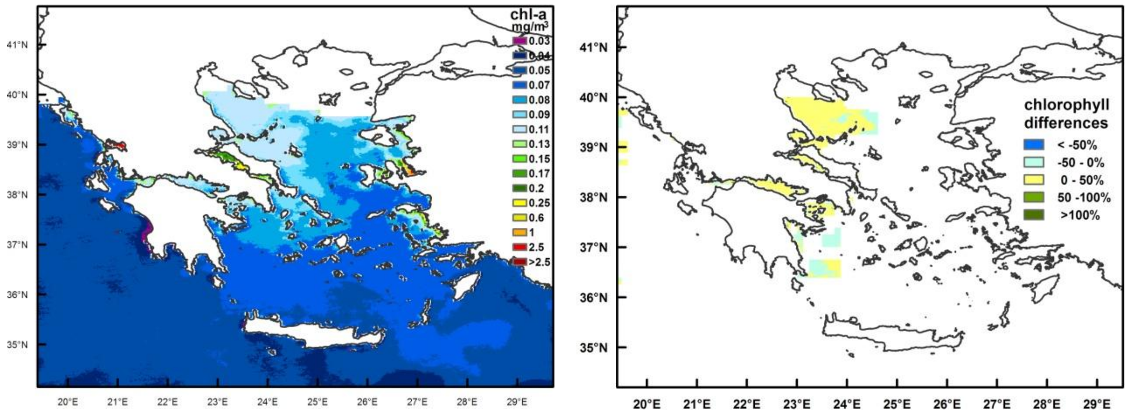


Figure S8. Daily chlorophyll % differences between 16 and 24 June 2016.

Late Summer Heat Wave and Dust: 6–8 September 2015



(**a**) (**b**)

Figure S9. (**a**) Chl-a concentrations of the week before the event of 6–8 September 2015; (**b**) chl-a % differences between the weeks before (29 August–5 September 2015) and after (14–21 September 2015) the event for the area of wet deposition.

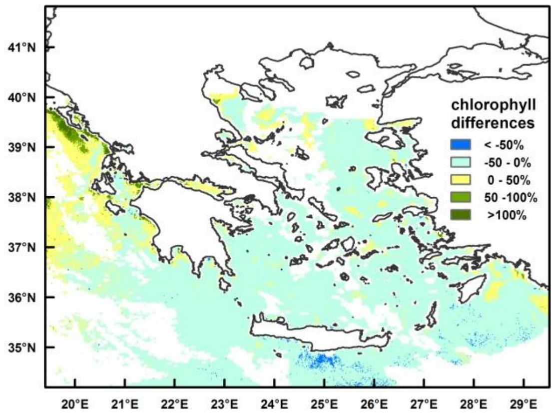
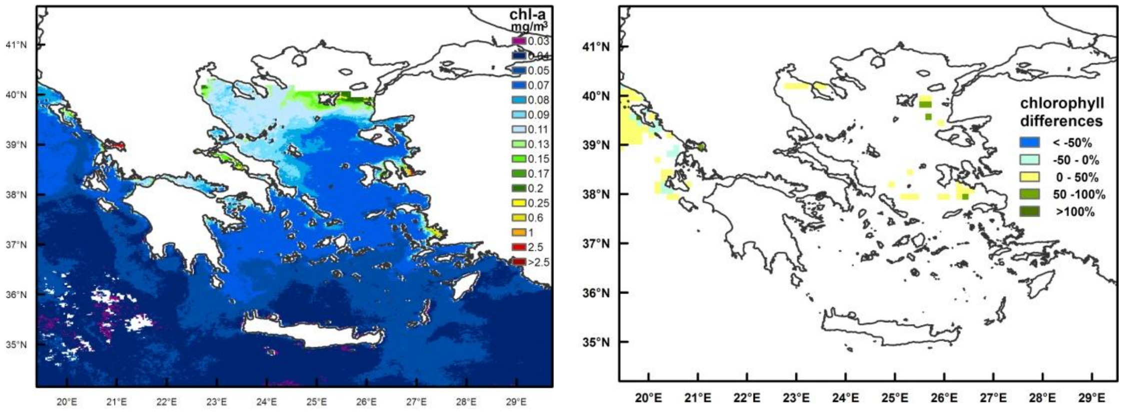


Figure S10. Daily chlorophyll % differences between 4 and 12 September 2015.

Fair Weather and Dust: 21–23 September 2014



(**a**) (**b**)

Figure S11. (**a**) Chl-a concentrations of the week before the event of 21–23 September 2014; (**b**) chl-a % differences between the weeks before (14–21 September 2014) and after (30 September–7 October 2014) the event for the area of wet deposition.

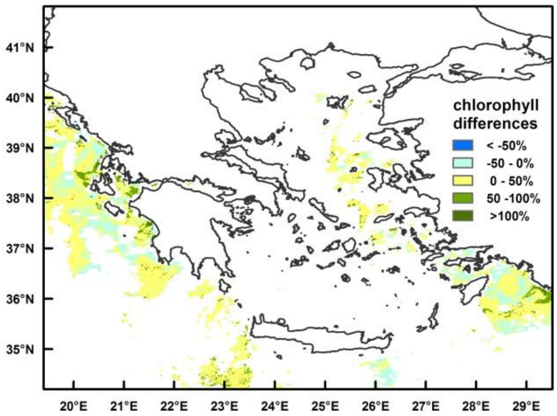
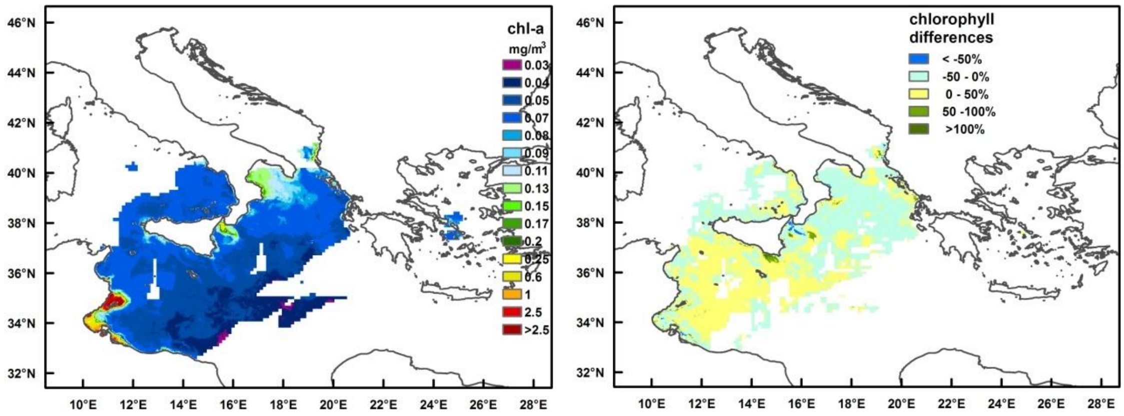


Figure S12. Daily chlorophyll % differences between 18 and 28 September 2014.

Dust over Central Mediterranean: 11–13 May 2017



(**a**) (**b**)

Figure S13. (**a**) Chl-a concentrations of the week before the event of 11–13 May 2017; (**b**) chl-a % differences between the weeks before (1–8 May 2017) and after (17–24 May 2017) the event for the area of wet deposition.

4. Extreme Weather Events and Sea Surface Chlorophyll Concentrations

4.1. Introduction

The examination of several extreme weather events that affected the Hellenic Seas in respect to their possible influence on sea surface chlorophyll concentrations forms a quite large part of the present thesis. These events were also studied for their meteorological characteristics, while the ECMWF Extreme Forecast Index (EFI) was checked for its performance. The results were published in proceedings of International Conferences.

However, some of the areas impacted by the above mentioned events were near shore ones and consequently, they could be affected by terrestrial and riverine nutrients. Since the existent studies mainly dealt with the influence of extreme events on coastal waters' primary production, the present research moved towards studying their effect on the open sea's chlorophyll concentrations.

The idea emerged from the studies that had assessed the influence of hurricanes and typhoons on the oceans' primary production. The Med is rarely impacted by tropical-like cyclones, the medicanes. These cyclones are formed and spend the largest part of their life in the open sea while they undoubtedly are extreme weather events. Thus, a couple of medicanes were examined with regard to their possible influence on sea surface chlorophyll concentrations. The relevant study was published in a peer-reviewed journal.

4.2. A 1010 hPa cyclone causing extreme rainfall and an autumn chlorophyll bloom

Abstract The Mediterranean Sea, a typically oligotrophic environment, is influenced by extreme weather events reflected in the primary production of the basin. A quasi stationary barometric low over the Ionian Sea on 14-16 October 2011, while not a deep one, caused significant rainfall that locally exceeded the monthly means, especially over the NW Peloponnese coast and the nearby shore area. In addition it seemed to have triggered phytoplankton growth over the related sea area. In this paper, the meteorological characteristics of the event are analyzed and some operational tools for its forecast a few days before are presented. The temporary bloom of phytoplankton, detected as high chlorophyll concentrations using Ocean Color satellite data, is assessed.

Kotta D., Kitsiou D., Kassomenos P. and Karydis M. (2014) A 1010 hPa cyclone causing extreme rainfall and an autumn chlorophyll bloom. 12th International Conference on Meteorology, Climatology and Atmospheric Physics, COMECAP 2014, Heraklion, Greece, e-book of contributions, Vol. 2, pp. 39-44.

1 Introduction

The Mediterranean basin, due to its special geographical configuration - a warm sea surrounded by high mountains, is an area often impacted by extreme weather events. Intense cyclones often associated with wind storms, floods, high waves and storm surges can lead to economic damages and even casualties (Davolio 2009). Therefore the accurate prediction of hazardous weather conditions is of great importance for Mediterranean Meteorological Services. Attention is usually paid to the rather rare phenomenon of explosive cyclones in specific cases when they present characteristics of a tropical storm (Pytharoulis et al. 2000, Reale and Atlas 2001). Extreme weather events can even be caused by barometric lows that are neither particularly deep nor deepen quickly. That was the case of 14-16 October 2011, when a quasi-stationary 1010 hPa low over the Ionian sea between southern Italy and Greece resulted in extreme weather conditions over the NW Peloponnese coast and the nearby off-shore sea area (Fig. 1). Extensive publicity has been given to the heavy rainfall, storms and hail, strong winds and even whirlwinds as well as flooded roads and houses, damages to crops and electricity network. The synoptic conditions and some characteristics of the cyclone that led to this event are examined along with some tools of the ensemble prediction system for forecasting the event a few days before.

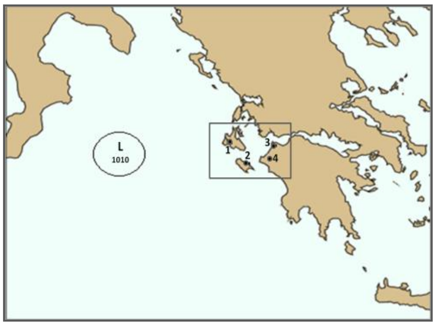


Fig. 1. In the rectangle the area of interest where precipitation above climatology was recorded over the stations 1 to 4; in the circle the average position of the surface low that mainly defined the event.

Marine scientists consider Mediterranean Sea as one of the less productive seas of the world - except of few coastal areas. The eastern part is the most oligotrophic one (Azov 1991). Many studies relate phytoplankton and primary production with meteorological factors and environmental variables (Gacic et al. 2002, Katara et al. 2008). At least during winter, phytoplankton should respond to variations in meteorological conditions (Zingone et al. 2010). After the extreme meteorological event, an increase of the chlorophyll-a values (proxy for phytoplankton abundance), was detected by Ocean Color satellite data over the mentioned above sea area. This rather temporary "autumn bloom" signaled the cold season higher production period and is assessed as a result of the meteorological extreme event.

2 Data and Methodology

The numerical weather products come from the deterministic model analysis (resolution 0,125^{o} x 0,125^{o}) and the ensemble prediction system (EPS) of the European Centre for Medium-Range Weather Forecasts (ECMWF - www.ecmwf.int). The real time data correspond to meteorological station observations and lightning activity data from the Hellenic National Meteorological Service (HNMS) network and satellite images. The satellite chlorophyll-a data were retrieved from My Ocean project (www.myocean.eu), and especially the weekly means of Mediterranean Sea - Surface Chlorophyll product, which is operationally produced using the Mediterranean regional ocean color algorithms (resolution 1.1km). In addition, the standard 8-day composite, monthly and monthly climatology products of Aqua MODIS Chlorophyll concentration (resolution 4km) were retrieved from the NASA Ocean Color Website (http://oceancolor.gsfc.nasa.gov).

The meteorological event was studied using 500hPa, 850hPa and mean sea level pressure (MSL) analysis, the vertical velocity and relative vorticity advection parameters as well as satellite images. For its potential forecast, ensemble prediction products were examined. The variations of chlorophyll-a concentrations on water masses, which indicate the presence of phytoplankton species, were at first detected through the NASA ocean color satellite data and then studied using the finer resolution of My Ocean project data.

3 Results

3.1 The meteorological event: Analysis and forecast

Between 14 and 16 October 2011 a quite shallow 1010 hPa low over the Ionian sea between south Italy and Greece caused extreme weather over the western Greek region shown in Fig.1. The phenomena were locally particularly extreme from the night of 14 October and during the 15 October. The HNMS stations of 1:Argostoli 2:Zakynthos 3:Araxos and 4:Andravida (Fig.1) recorded during 24 hours precipitation amounts of 115mm, 111mm, 141mm and 195 mm respectively which are far beyond their climatological mean values of the whole month (HNMS climatological data base). The extreme weather is illustrated in Fig.2 by the enhanced lightning activity and the station observations of HNMS network. Extreme weather events do happen over the particular region especially in November and October when a maximum of lightning activity is also recorded (Katsanos et al. 2007).

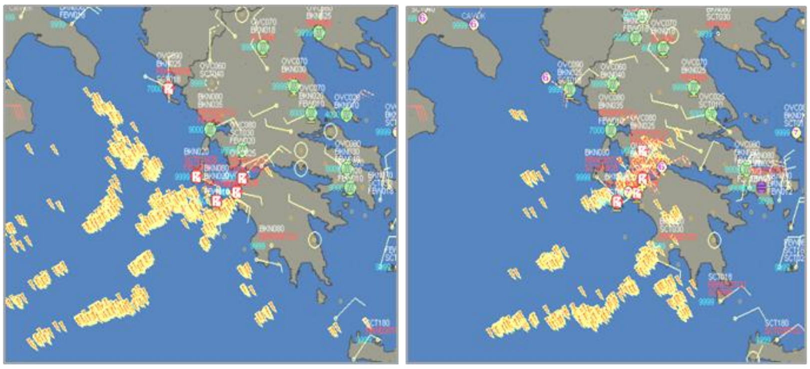


Fig. 2. Lightning activity and meteorological station observations from HNMS network for 06:00 UTC and 12:00 UTC, respectively, on 15 October 2011.

The parent low began as an Atlas lee cyclone (not shown), not a rare event, and was triggered by an upper level trough (Fig.3 left panel). The 1010 hPa low moved slowly from southern Italy - Sicily to western Greece on 15 October 2011 from 06:00UTC to 18:00UTC. The position of the surface low on 15 October 2011, 12:00UTC is shown in MSL analysis (Fig.3 right panel). Its very slow movement (during the entire day of

15 October was quasi stationary between southern Italy and Greece) might be due to the orography of the region as in a case of Reale and Atlas (2001).

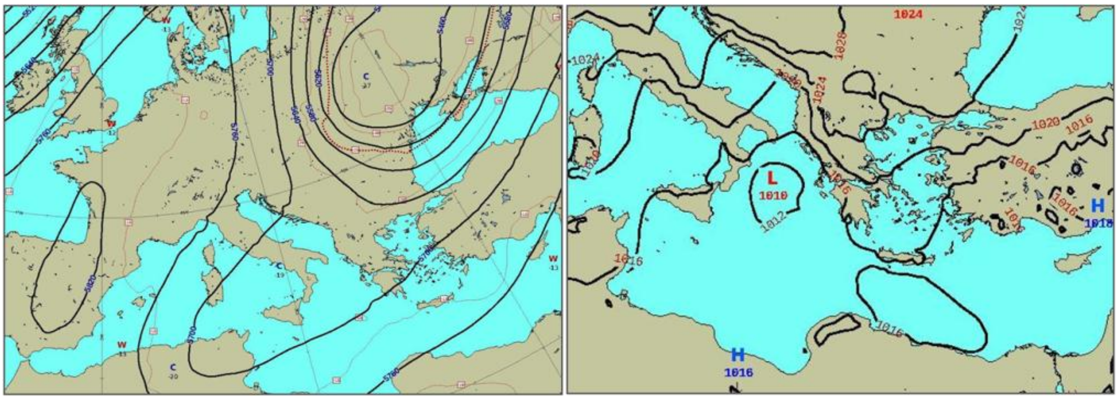


Fig. 3. ECMWF analysis of 500hPa geopotential height - temperature (left panel) and MSL (right panel) for 15 October 2011, 12:00 UTC.

According to ECMWF analysis data there was a positive relative vorticity advection between 0.0005 and 0.001 s^{-1} from 00:00UTC to 06:00UTC on 15 October 2011 over the region (Fig.4 left panel). In addition, at 06:00UTC there was an intense vertical motion over the low up to 200hPa; the vertical velocity of 1.7 Pa/s over its centre for 300hPa is shown in Fig.4 (middle panel). The intense vertical motion combined with the lightning activity could suggest that the low was sustained by latent heat release associated with strong convective activity. The 850 hPa temperature shows a maximum of 10.65 ^{o}C above the vortex (Fig.4 right panel), indicating a warm-core structure. The above mentioned could even characterize the low as a tropical-like Mediterranean cyclone (Pytharoulis et al. 2000, Davolio et al. 2009). Indeed the low at 12:00UTC almost became tropical-like as can be seen in the infrared satellite image of Fig.5 (left panel) temporarily defining an 'eye' and spirally cloud bands around it.

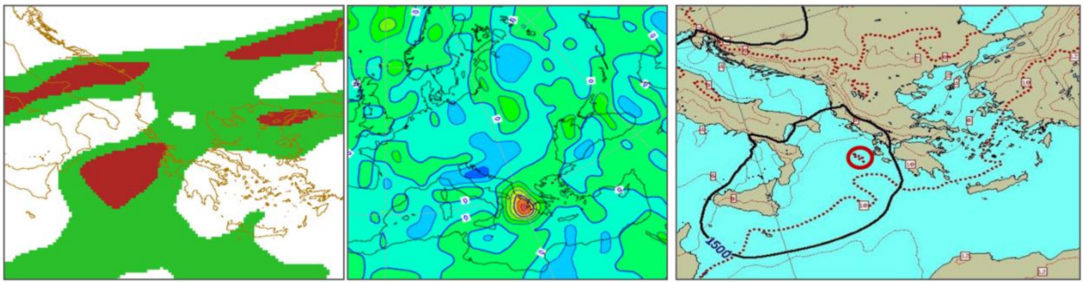


Fig. 4. The positive relative vorticity advection values, in red between 5 10^{-4} s^{-1} and 10 $10^{-4}s^{-1}$ (ECMWF data processed in a GIS environment) (left panel). Vertical velocity at 300hPa on 15 October 2011, 06:00UTC (up to 1.7Pa/s in dark red) (middle panel). 850hPa geopotential height - temperature for 12:00UTC (right panel) where the red circle indicates the warm core.

For forecasting the event a few days before, products of the ECMWF ensemble prediction system (EPS) can be used operationally, complementing the deterministic forecast with probabilistic information reflecting the uncertainty. Two of its components, the extreme forecast index (EFI) - a measure of the difference between the EPS forecast distribution and the model climate – potentially useful in alerting forecasters to the risk of severe weather some days in advance (Lalaurette 2003) and the EPSgram - a probabilistic interpretation of the EPS forecasts for a given location - can be easily used and proved helpful. Although the particular extreme event was rather area-limited, it could be properly forecasted at least three days before (Fig.5 middle and right panels).

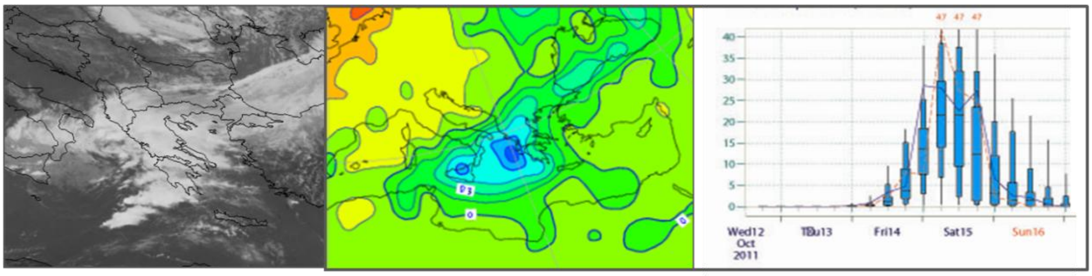


Fig. 5. Infrared satellite image on 15 October 2011, 12:00UTC (source: Eumetsat) (left panel). EFI for precipitation for 15 October 2011, in dark blue values above 0.9 (middle panel). Argostoli EPSgram for precipitation in mm/6h (right panel) based on 12 October 2011, 12:00UTC run.

3.2 Meteorological forcing on primary production

The Mediterranean Sea, which is nutrient limited (Karydis and Kitsiou 2012), follows the subtropical model for the primary production. As light is not a limiting factor for phytoplankton growth, higher chlorophyll-a values are usually observed during the colder, windy and wet season (Barale et al 2008). The area of study follows this trend, which was also confirmed from the chlorophyll-a satellite data of MODIS monthly climatology.

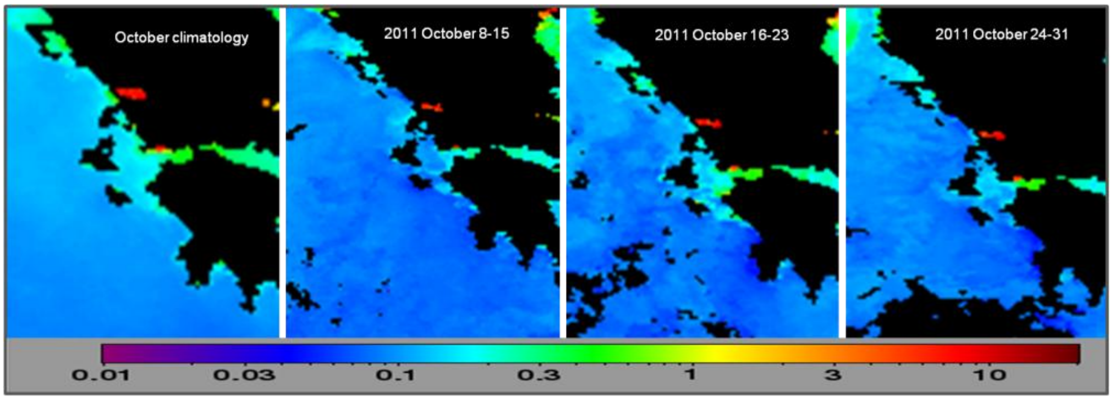


Fig. 6. Ocean Color MODIS chlorophyll-a concentrations (mg/m^3): October climatology and 8-day composites for the week before and the two weeks after the event.

An increase in chlorophyll-a concentrations was detected over the study area, the week after the meteorological event (16-23 October 2011, week0) by the MODIS Ocean Color satellite data. The values ranged between 0.04-0.08mg/m^3 reaching at certain places near shore 0.3mg/m^3 the week before the event (8-15 October 2011, week-1) and the week that followed, with fair weather, the values even doubled at places (Fig.6) reaching the monthly climatology values. One week after (24-31 October 2011, week1) there was a decrease in values, however they remained slightly higher than those before the event.

Using the finer resolution of My Ocean data (excluding values greater than 1mg/m^3, as they can only be observed near shore) an increase in chlorophyll-a concentrations was found from week-1 to week0 over 76% of the area which was mostly greater than 50% (Fig.7). The mean chlorophyll value of week0 and week1 was greater than values of week-1 over 70% of the area. Similar trend was also observed during October 2010.

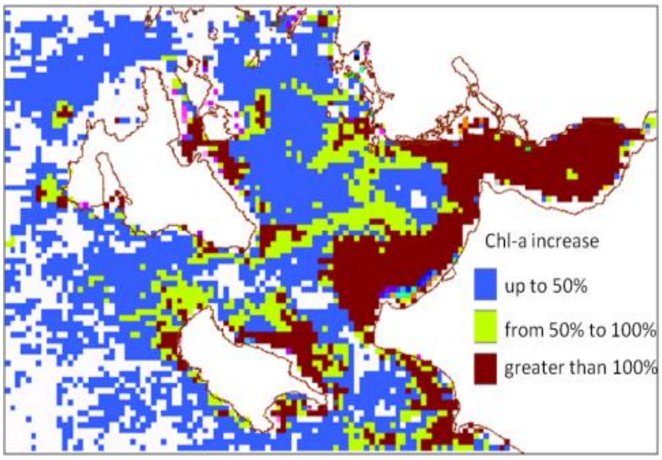


Fig. 7. Chlorophyll-a increase from week-1 to week0 (data processed in a GIS environment).

During the days after the 2-day rainfall event, moderate northerly winds prevailed that could not cause significant upwelling which is the main mechanism for nutrient input into the water column. In addition, river runoff could not be accounted as a significant contributor to the nutrient input, since the maximum of precipitation amount was over the area of interest. Therefore, the increase of chlorophyll-a should rather be attributed to the meteorological event itself. Storm events are likely to trigger higher phytoplankton biomass, even during the summer, due to the atmospheric deposition of nutrients into the sea through rainfall events (Malej et al. 1997). In addition, several short-term spring high-production episodes associated with calm weather, took place after violent mixing events such as storms over the Adriatic (Gacic et al. 2002). This could also be the case here, as the extreme event was followed by sunny weather, but an autumn event. In addition, the anticyclonic circulation during 2011 of the North Ionian Gyre (NIG) causes upwelling of the nutricline along its border (Civitarese et al. 2010), i.e. along the area of interest as well. Thus, even weak convective mixing events could be able to inject significant amounts of nutrients into the euphotic layer. Finally, Zingone et al. (2010) suggest for winter blooms a time lag of the meteorological forcing on the water column dynamics, associate the biomass increase with a decrease in surface salinity (can be caused by freshwater input) and state that such blooms are generally short-lived, quite similar to the case here.

4 Conclusions

A cyclone over the warm October Mediterranean Sea, though quite shallow, caused extreme weather conditions leading to an autumn chlorophyll bloom. EPS products proved very helpful for the operational forecast of the event. Extreme weather events seem to play a key role in meteorological forcing on the basin’s primary production and should be further examined.

Acknowledgments Authors would like to thank ECMWF, My Ocean project, NASA Ocean Color and HNMS for the data.

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4.3. First rains as extreme events influencing marine primary production

Abstract First rains of September 2014 and 2015 could be characterized as extreme events: from 1st to 3rd September 2014 heavy rains were recorded over western and northern Greece exceeding 50mm in one day and reaching at places 100mm; on the 10th of September 2015 precipitation exceeded 100mm over the northwest part of the country. After both time periods, chlorophyll-α concentrations - a proxy for phytoplankton abundance - were increased over the related sea areas and in some cases doubled, even over the oligotrophic Ionian Sea. The meteorological characteristics of these events and possible factors responsible for their high intensity are examined, along with the potential capability for being operationally forecasted a few days before. The higher marine primary production that followed and was detected through chlorophyll-α concentrations using Ocean Color satellite data, is also assessed as result of the meteorological extreme events.

Kotta D., Kitsiou D. and Kassomenos P. (2016) First Rains as Extreme Events Influencing Marine Primary Production. 13th International Conference on Meteorology, Climatology and Atmospheric Physics, COMECAP 2016, Thessaloniki, Greece. Perspectives on Atmospheric Sciences, Springer Atmospheric Sciences, Springer International Publishing Switzerland 2017, T.S. Karacostas et al. (eds.), p. 263-270, doi: 10.1007/978-3-319-35095-0_37.

1 Introduction

The Mediterranean basin, a warm sea surrounded by high mountains, is often affected by extreme weather events that can lead to economic damages and even casualties (Davolio 2009). Therefore, the accurate prediction of hazardous weather conditions is of great importance for Mediterranean Meteorological Services. Although attention is usually paid to the rather rare phenomenon of explosive cyclones, extreme weather events can be the result of barometric lows that are not particularly deep (Kotta et al. 2014). Even the rainy autumn period can begin with intense rainfall; that were the cases of the 1st to 3rd September 2014 and of the 10th of September 2015, when first rains were extreme events at places, with precipitation amounts being rare within their statistical reference distribution.

The synoptic conditions of these events are briefly described using 500hPa, 850hPa and mean sea level pressure (MSL) analysis. Potential vorticity PV (on the 300hPa isobaric surface) is examined, since it shows intrusion of dry stratospheric air that can lead to event enhancement. Although PV is usually studied in major cyclogenesis, it could highlight cases of weaker upper level forcing, giving added credence to the model forecast and be proven a useful tool for the operational forecaster (Mansfield 1996). Surface latent and sensible heat fluxes are also assessed as factors that can determine the event intensity, since they are the main mechanisms contributing to the energy enrichment of the lower tropospheric layers. The above parameters were chosen as there are scarcely used quantified in operational forecast. The performance of the Extreme Forecast Index (EFI) - a measure of the difference between the ensemble prediction system EPS forecast distribution and the model climate and potentially useful in alerting forecasters to foresee the risk of severe weather some days in advance (Lalaurette 2003) - is also checked. The numerical data used comes from the European Centre for Medium-Range Weather Forecasts (ECMWF).

The Mediterranean Sea is nutrient limited (Karydis and Kitsiou 2012) and considered as one of the less productive seas of the world, with the eastern part being the most oligotrophic. Concentration of the most abundant photosynthetic pigment (chl α) is used extensively as a proxy measure for phytoplankton biomass. In the Mediterranean Sea, since nutrient level is the limiting factor for phytoplankton growth, higher chl α values are usually observed during the colder, windy and wet season (Barale et al. 2008). Many studies relate phytoplankton and primary production with meteorological factors and environmental variables (Katara et al. 2008, Zingone et al. 2010, Kotta and Kitsiou 2014). The variations of satellite detected chl α concentrations on water masses, possibly connected to the extreme meteorological events presented here, are examined.

The differences of chl α concentrations were calculated between the week after and before the events, since a time lag of the meteorological forcing on the water column dynamics is suggested (Zingone et al. 2010) at least for winter blooms. As the current relative percentage difference between the chl α remote sensing data used and the in-situ observations is much lower than 40% (Volpe et al. 2012), it was selected to present chl α variations above 35% for safer results. The remote sensing chl α data comes from Copernicus Marine Environment Monitoring Service (http://marine.copernicus.eu) and corresponds to the weekly interpolated means of

Mediterranean Sea Surface Chlorophyll Concentration product (resolution 1km), which is operationally produced using regional ocean color algorithms.

2 Results

2.1 The event of 1 - 3 September 2014

The first rains of September 2014 recorded from the night of the 1st to the 3rd of the month over the whole country, resulting in notably precipitation amounts over west, central and north parts: Florina 84mm, Kastoria 86mm, Preveza 108mm, Kalamata 58mm, Andravida 56mm, Chrysoupolis 80mm, Zakynthos 43mm (according to Hellenic Meteorological Service HNMS stations); Kerkyra 75mm, Lefkas 128.4mm, Asprovalta 54mm (according to National Observatory of Athens NOA stations). Especially for Chrysoupolis (Kavala) the rainfall, all in one day, was far beyond the mean value of the whole month (HNMS climatological data base). On 2/9/14, the west, northwest and central parts of the country were mainly affected; on 3/9/14, the weather turned unstable over the above areas, the system influenced the northeastern part of Greece and gradually attenuated.

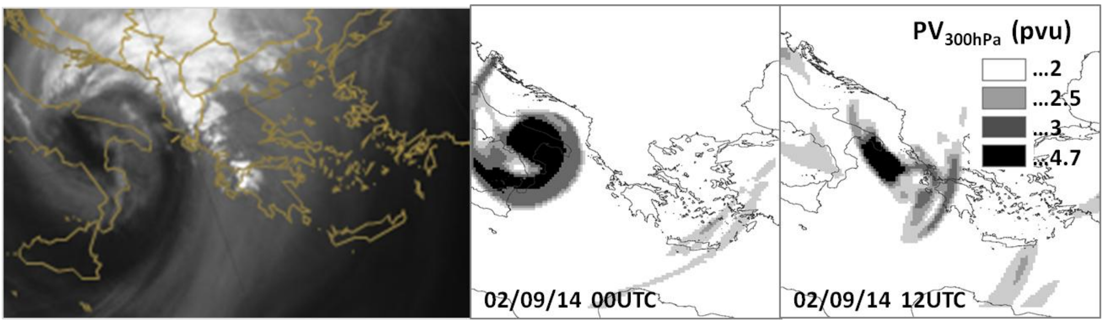

Fig. 1. For 2/9/14: WV image on 00UTC and the respective 300hPa PV values (left and middle), PV values on 12UTC (right).

A stratospheric intrusion characterized the event: by 2/9/14 00UTC, and even earlier, the water vapor (WV) satellite image revealed it as a dark area (Fig. 1, left). ECMWF analysis showed that it was a quite important stratospheric intrusion, as PV values over the 300hPa isobaric surface were up to 4.7pvu (Fig. 1, middle). On 1/9/14 12UTC, over central Italy, PV exceeded 6pvu (not shown), values usually observed during explosive cyclogenesis (Kouroutzoglou et al. 2015). Although PV values were decreasing with time (Fig. 1, right) the system could had already gained dynamics.

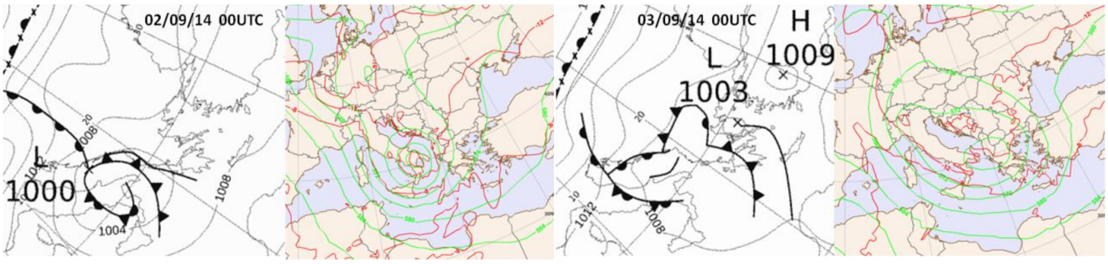

Fig. 2. MSL and frontal analysis (Met Office) and analysis of 500hPa geopotential height - temperature (ECMWF) for 2/9/14 00UTC (left panels) and 3/9/14 00UTC (right panels).

A 5600gpm vortex from Italy moved eastwards influencing Greece, where although the heights gradually increased to 5680gpm (Fig. 2), resulted in extreme weather. Afterwards, it moved northeastwards and attenuated. The related surface low, accompanied by front, was 1000hPa over the Adriatic Sea and became 1003hPa over north Ionian; then another low 1003hPa was formed over northwest Aegean where it finally filled up. Frontal activity affected all the country except southeastern parts.

The surface latent heat flux towards the atmosphere was not high during the event, as it exceeded 150 W/m^2 per hour locally over the Ionian and at places over the Aegean, reaching 250 W/m^2 only over the open Ionian Sea (not shown). Surface sensible heat fluxes were between 50 and 150 W/m^2 per hour over land, before being affected by the cold front (not shown). Although surface latent fluxes seemed to have contributed to the extreme events, there were rather the middle and upper level atmospheric processes that played the key role.

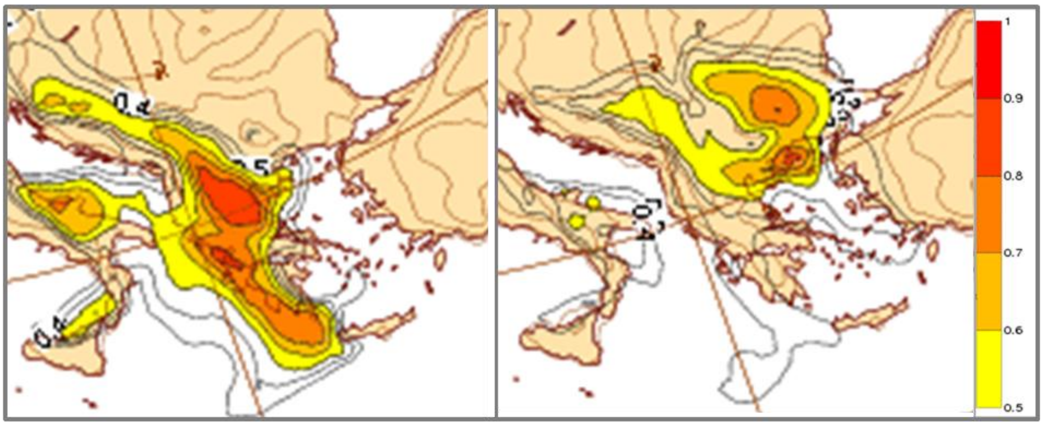

Fig. 3. Precipitation EFI for the 2nd and the 3rd of September 2014 respectively based on the 31/8/14 12UTC run.

The EFI for precipitation (Fig. 3) advocated the issue of warning for the public regarding intense rainfall and succeeded in precisely defining the regions where the extreme events occurred.

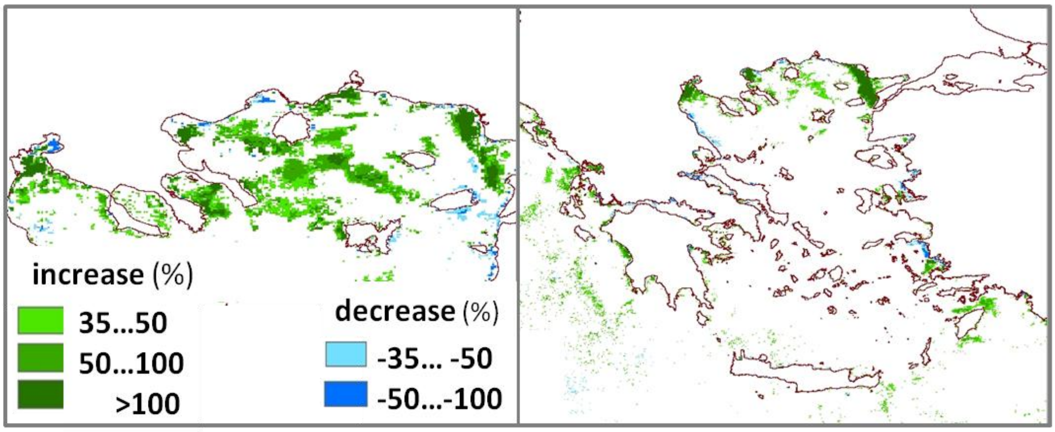

Fig. 4. Chl-α differences after-before the event over north Aegean (left) and in respect to one week ahead (right).

Chl-α concentrations presented variations between the weeks before (27/8/14 to 2/9/14) and after the event (3/09/14 to 9/9/14); the increases exceeded 50% only locally and mainly over coastal areas. No correlation was found between the detected chl-α variations and the precipitation amount as derived from ECMWF. Especially over the Ionian, chl-α increases and decreases were quite ≤ 35% over its greater part, possibly due to the limited sunshine during the following days. More notable differences were recorded over north Aegean (Fig. 4, left), where chl-α increase was recorded over the 64% of the area, being above 35% over the one quarter of the area. Although for this region, a small positive correlation was found between chl-α variations and precipitation, no safe conclusion can be drawn, since the area is influenced by Black Sea waters. The rainy weather continued over west and north parts of the country a few days more after the event described; for this reason chl-α differences were also computed between the week before the rains started and the week when they stopped (10/09/14 to 16/9/14) and they are more pronounced as sunny intervals favored primary production (Fig. 4, right).

3.2 The event of 10 September 2015

On 10 September 2015, the first autumn system resulted in excessive rainfall amounts and thunderstorms especially over the northwestern part of the country: Lefkas 144.8 mm, Paxi 128 mm, Parga 127.4 mm, Ioannina region up to 104.6mm, Igoumenitsa 70.6 mm (according to NOA stations); Kerkyra 91mm (HNMS station) exceeding the climatological mean monthly values.

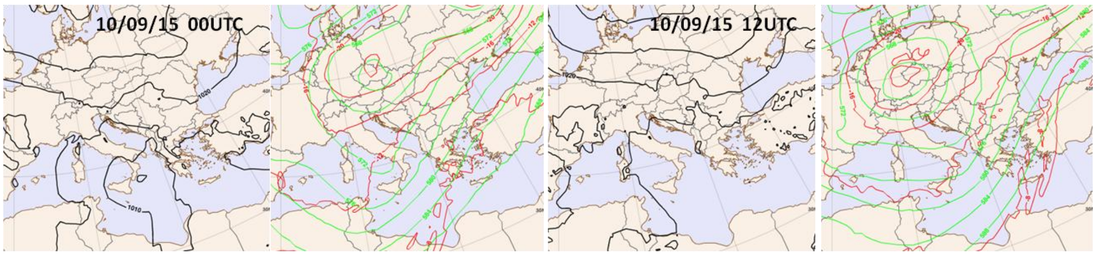

Fig. 5. MSL and 500hPa geopotential height - temperature analysis (ECMWF) for 10/9/15 on 00UTC (left panels) and 12UTC (right panels)

An elongated upper level trough west of Italy related to a low, over central Europe, moved northeastwards through west-central and north Greece (Fig. 5). A surface 1005hPa low moved from Boot to north Ionian were it filled up, with its frontal affecting mainly the west northwest part of the country and then diluted falling on mainland.

No stratospheric intrusion was observed as PV values over the 300hPa isobaric surface did not exceed 2pvu (not shown). The surface latent heat flux towards the atmosphere was especially high over the Ionian Sea, exceeding 250 W/m^2 per hour for the time interval from 00UTC to 06UTC of that day (Fig. 6, left). It should be noted that such values are similar to those of the nearby regions during explosive cyclogenesis or deep surface lows (Kouroutzoglou et al. 2015). Surface sensible heat flux was higher than 50 W/m^2 per hour during the same time interval over the northwestern part of the Ionian (Fig. 6, middle). The above could lead to the assumption that the extreme event was mainly due to low and middle atmospheric processes.

The precipitation EFI for 10/9/18 based on 9/9/15 00UTC run, the last available for forecasting the event, left out the Ionian region; even the one based on 10/9/15 00UTC run (Fig. 6, right) - although specifying quite accurately the affected regions - gave lower values than the ones expected according to the severity of the event. A question if the model can properly predict extreme events due to low and middle level atmospheric processes is raised.

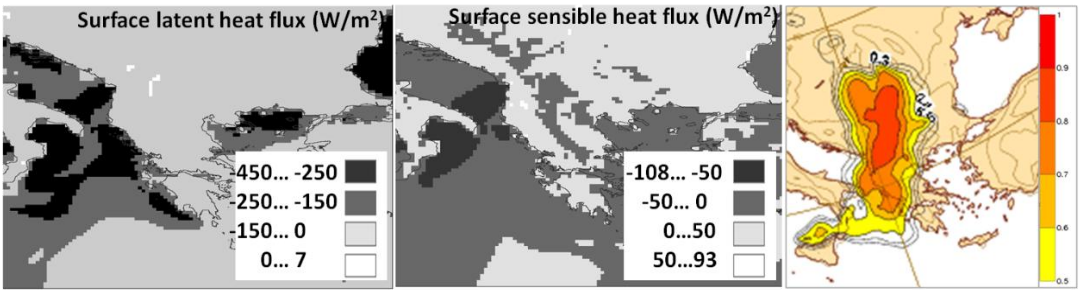

Fig. 6. For 10/9/15: hourly surface fluxes from 00UTC to 06UTC, for latent and sensible heat (left and middle). Precipitation EFI based on 10/9/15 00UTC run (right).

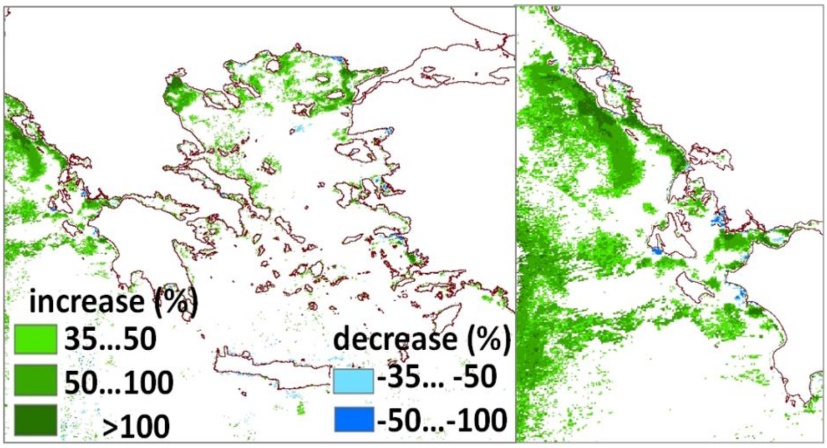

Fig. 7.
Chl-α differences of the weeks after-before the event and and focus on theIonian Sea.

Chl-α concentration presented notable increases (Fig. 7) the week after the extreme rainfall (10/9/15 to 16/9/15) in respect to the week before (3/09/15 to 9/9/15). Low positive correlations were found between chl-α differences and precipitation. Nevertheless, over the oligotrophic Ionian Sea, an increase was recorded over the 90% of the area, exceeding 35% over at least the one third; at places the concentration was more than doubled. The fair weather that followed the event favored primary production. Such increases of chl-α concentrations could be connected to extreme rainfall events (Kotta et al. 2014), mainly due to the atmospheric deposition of nutrients into the sea.

Conclusions

The quantified use of PV and surface heat fluxes during the operational forecast can give signs for the intensity of an event when presenting high values. Precipitation EFI performed better regarding the first event, which was mainly caused by middle and upper level atmospheric processes. Extreme weather events, especially when followed by fair weather, influence phytoplankton abundance and seem to play a key role in meteorological forcing on marine primary production.

Acknowledgments Authors would like to thank ECMWF, Copernicus Marine Environment Monitoring Service, Met Office, NOA and HNMS for the data, as well as Dr J. Kouroutzoglou for useful advices.

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Zingone A, Dubroca L, Iudicone D, Margiotta F, Corato F, d’Alcalà MR, Saggiomo V, Sarno D (2010) Coastal Phytoplankton Do Not Rest in Winter. Estuaries and Coasts 33: 342–361. doi:10.1007/s12237-009-9157-9.

4.4. Summer Rainfall Event: The Skill of Extreme Forecast Index and Effects on Marine Chlorophyll Concentrations

Abstract The Extreme Forecast Index (EFI) of the ECMWF ensemble prediction system can be a useful tool for operational forecasters in identifying areas at risk due to severe weather some days in advance. A heavy rainfall event of abnormal intensity and duration affected large part of Greece on 16 and 17 July 2017. Precipitation EFI for the event was analyzed for different lead times and its skill in defining the regions of the extreme rainfall was examined, relative to the amounts of rain recorded. EFI performance was quite exceptional, reinforcing its use as a tool for forecasting extreme events. Such events, over marine and coastal areas, are thought to influence marine primary production and phytoplankton abundance, a proxy of which is chlorophyll-a concentration. Differences of satellite derived chlorophyll concentrations before and after the event were calculated for the marine area affected by the extreme event, in a weekly and daily basis. A remarkable chlorophyll increase was observed, even though during summer the Hellenic Seas are characterized by extreme oligotrophic conditions.

Kotta D., Kitsiou D. and Kassomenos P. (2018) Summer Rainfall Event: The Skill of Extreme Forecast Index and Effects on Marine Chlorophyll Concentrations. 14th International Conference on Meteorology, Climatology and Atmospheric Physics, COMECAP 2018, Alexandroupolis, Greece, ebook of proceedings, pp. 547-552, ISBN 978-960-98220-4-6.

1 Introduction

On 16 and 17 July 2017, an extreme rainfall event affected Greek mainland and parts of Ionian and North Aegean Seas. It was characterized by abnormal - regarding the season -intensity and duration, enhanced lightning activity and continued during night hours. The rainfall amounts recorded exceeded at places the climatological mean monthly values and in many cases they were characterized as record values for July (Hellenic National Meteorological Service - HNMS data base). The event was caused by a well organized mainly in the middle and upper atmospheric levels disturbance (a 500hPa trough with cold masses plus stratospheric air intrusion) together with increased low-level moisture and convective instability.

The Extreme Forecast Index (EFI) of the ECMWF/IFS/EPS, as a measure of the difference between the ensemble prediction system (EPS) forecast distribution and the model climate, has been suggested and is continuously improved as a useful tool for operational forecasters in foreseeing the risk of severe weather some days in advance (Lalaurette 2003, Tsonevsky 2015). The skill of the precipitation EFI was checked regarding the extreme rainfall, from the forecasters' point of view.

The Hellenic Seas, similar to Eastern Mediterranean Sea, are in general an oligotrophic marine environment, characterized by low phytoplankton abundance, with their primary production being nutrient and not light limited (Karydis and Kitsiou 2012). Chlorophyll (chl-a) concentration, a proxy for phytoplankton, reaches the lowest values during summer (Barale et al. 2008). Several studies relate marine primary production enhancement with rainfall events (Gacic et al. 2002, Kotta et al. 2014) even during summer (Malej et al. 1997) due to the atmospheric deposition of nutrients into the sea. Variations of chl-a concentration were examined, for the marine area impacted by the extreme event.

2 Data and Methodology

Precipitation EFI data came from ECMWF/IFS/EPS and rainfall data from the National Observatory of Athens (NOA) and HNMS stations. Chl-a weekly and daily concentrations are satellite derived data from Copernicus Marine Environment Monitoring Service (http://marine.copernicus.eu).

EFI was checked for different IFS-EPS lead times for the time period 15 to 18 July (since the extreme event started the night of 15 July from North Greece and lasted - locally over the eastern parts - up to 18 July). The runs checked were from 12/7/17-12UTC up to 15/7/17-00UTC. EFI was examined in respect to its consistency in determining the areas to be affected as well as the rainfall intensity, elements that reinforce the forecaster's confidence in its use.

EFI's skill in defining the regions of the extreme rainfall was assessed against the amounts of rain recorded by NOA and HNMS stations in a GIS environment. The index from the 14/7/17-00UTC run (the last available to the forecasters before the issue of the relative warning by HNMS) and from the 15/7/17-00UTC run (the last available before the beginning of the event) were checked.

Chlorophyll percentage differences were calculated in a weekly and daily basis before and after the event for the marine area affected from 15 to 18 July which was specified using EFI values > 0.5. Differences above 50%, which is quite the accuracy of the ocean color chl-a data (Volpe et al. 2012), are hereafter mentioned as “significant”.

3 Results

3.1 The skill of EFI

For 15 July, the index, although presenting indications for extreme rainfall locally over North Greece, showed no particular consistency in defining heavy rainfalls both locally and in respect to their intensity, in the successive runs. For 16 and 17 July, the two main days of the event, EFI as early as 13/7/17-00UTC run, presenting values >0.8 over an extended area, indicated a high risk for extreme rainfall. Approaching the event, the index presented remarkable consistency in defining the areas to be affected, indicating even heavier rains (two of these runs are shown in Figs. 1 and 2).

The skill of the index for the 14/7/17-00UTC and 15/7/17-00UTC runs, as checked against rainfall amounts recorded for 16 and 17 July are shown in Figs. 1 and 2, where precipitation amounts >30mm are also separately presented along with 15/7/17-00UTC run. For both days, greater precipitation amounts corresponded to EFI values >0.7 (alertness values) or they were adjacent to them. Approaching the event, the areas affected and the rainfall intensity were defined even better. However, in respect to the precipitation amounts recorded over Peloponnese (especially over the SW parts) on 17 July, a forecaster would expect greater EFI values. It is noted that no heavy rainfall was recorded over areas not indicated by the index. The precipitation EFI succeeded in defining quite precisely the regions of extreme rainfall. The index’s skill seems to be high for extreme events mainly caused by middle and upper level atmospheric processes, as in other cases (Kotta et al. 2016).

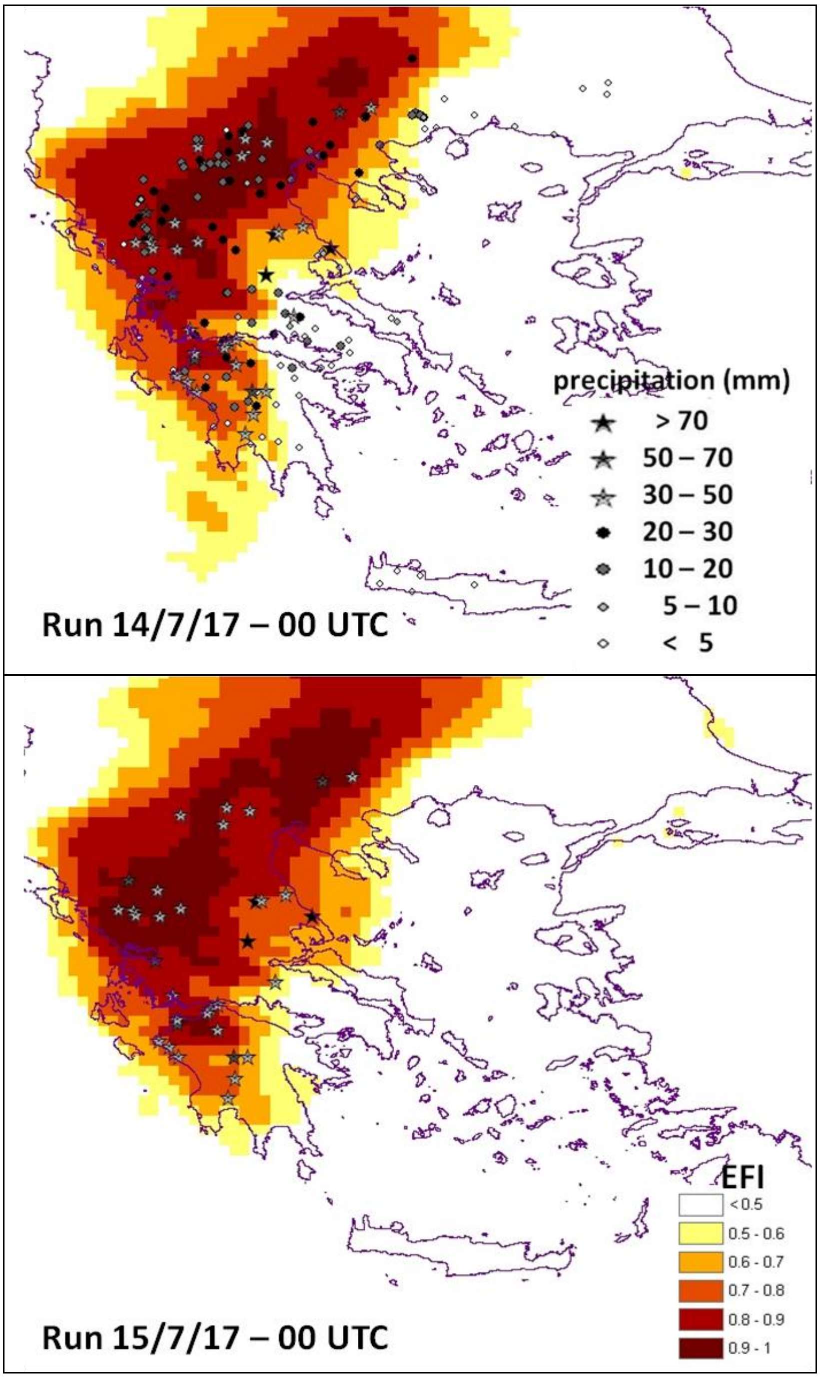

Fig. 1. Rainfall amounts recorded on 16/7/2017 by HNMS and NOA stations (upper panel: all rainfall data, lower panel: precipitation exceeding 30mm) along with ECMWF precipitation EFI for the same day according to 00 UTC runs of the two previous days.

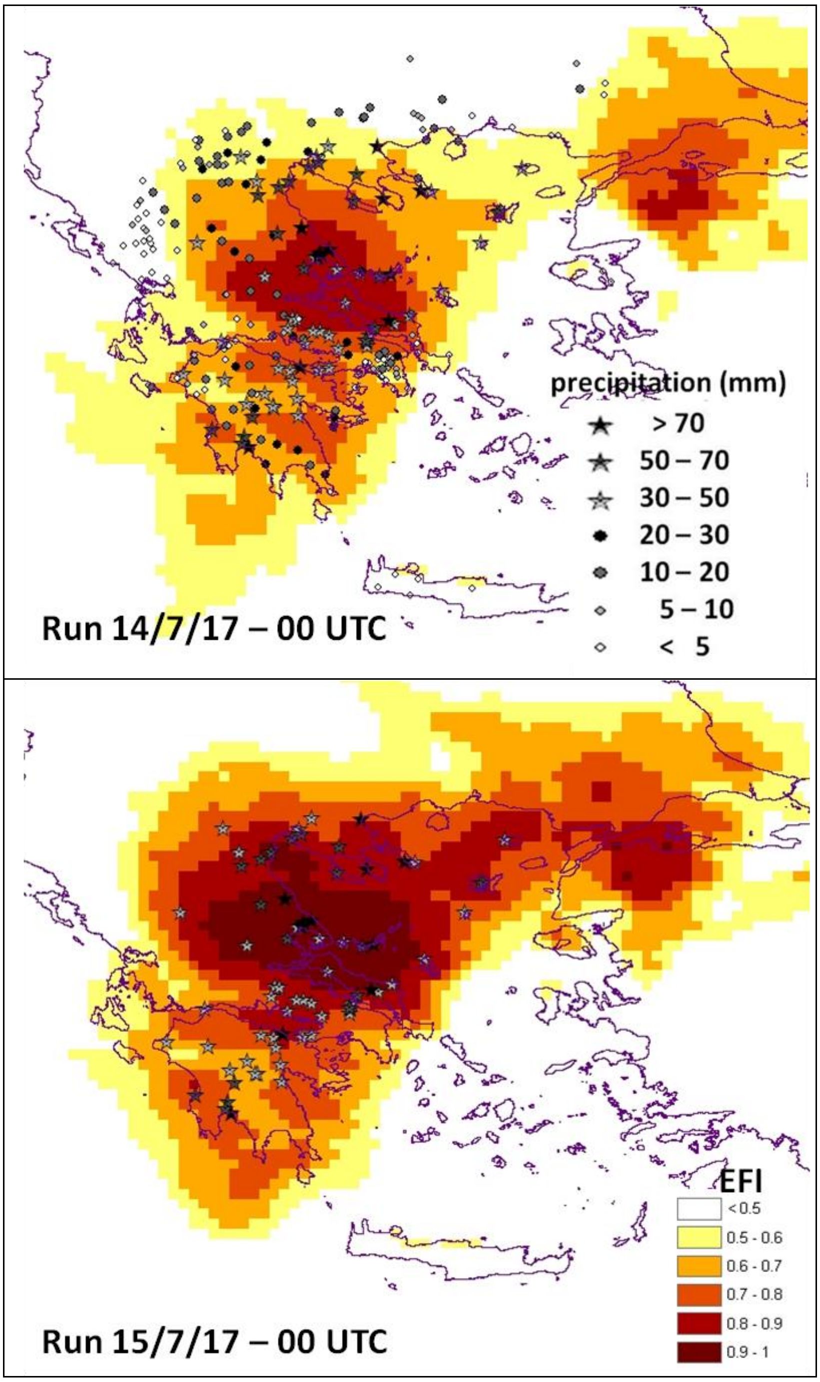

Fig. 2. Rainfall amounts recorded on 17/7/2017 by HNMS and NOA stations (upper panel: all rainfall data, lower panel: precipitation exceeding 30mm) along with ECMWF precipitation EFI for the same day according to 00 UTC runs of two previous days.

3.2 Effects on Marine Chlorophyll concentrations

Chlorophyll percentage differences before and after the event, calculated over the marine area corresponding to EFI values >0.5 from 15 to 18 July, in a weekly basis (between the weeks 4-11/7/17 and 20-27/7/17) and in a daily basis (between 13 and 21 July), are shown in Fig.3.

Weekly chl-a differences reveal increases over the 46.9% of the area, while the significant differences cover the 12.1% of the area and they are by 68.0% increases. The significant increases are by 11.9% greater than 100% and by 3.0% greater than 200%, the latter locally near river estuaries of Thermaikos Gulf and Thracian Sea - fact quite expected due to large riverine nutrient loads (Skliris et al. 2010) caused by the extreme event. The above results are not particularly supportive to the assumption that extreme rainfall led to marine primary production enhancement for the week that followed the event. It is noted that extreme rainfall events in autumn have been found to cause such chlorophyll increases (Kotta et al. 2014). Although chlorophyll concentration increases >50% are mainly observed over North Aegean, where precipitation amounts were larger, this is an area influenced by the mesotrophic Black Sea waters (Androulidakis et al. 2012) and no safe conclusion can be drawn.

Daily chl-a differences between 21 and 13 July reveal increase for the 80.1% of the area; the significant differences cover the 30.3% of the area and are by 95.5% increases. Of these significant increases, 35.3% exceed 100% and 13.5% exceed 200%, the latter near coastal parts where increased watershed discharges due to intense rainfall can lead to high nutrient loads and phytoplankton enhancement. The daily results show that the extreme rainfall could have temporarily favored marine primary production. The reason that the observed phytoplankton increase (as shown by the chl-a increase) was of temporary character could be its quick consumption by the upper trophic levels, since the marine environment during summer is ultra-oligotrophic.

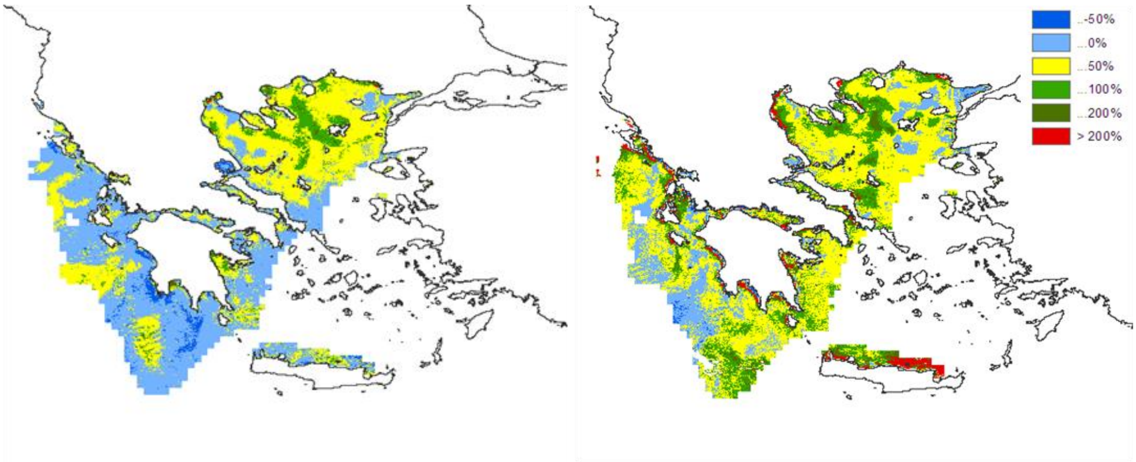

Fig. 3. Chlorophyll percentage differences before and after the event for the marine area presenting EFI values >0.5 from 15 to 18 July; weekly differences between 4-11/7/17 and 20-27/7/17 (left panel) and daily ones between 13 and 21 July 2017 (right panel).

4 Conclusions

EFI’s skill during the event can be considered at least satisfactory and reinforce its use as an effective tool for operational forecasters in identifying areas at risk due to severe weather conditions.

Extreme rainfall seems to be able to favor marine primary production during the summer period; however of temporary character.

Acknowledgments Authors would like to thank ECMWF, Copernicus Marine Environment Monitoring Service, NOA and HNMS for the data.

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4.5. Medicanes Triggering Chlorophyll Increase

Abstract: Studies have shown that hurricanes and typhoons, apart from being extreme weather phenomena, cause increases in marine chlorophyll-a concentrations and even phytoplankton blooms. Medicanes are the tropical-like Mediterranean cyclones that induce hazardous weather conditions as well. In this study, a couple of medicanes, over the central and eastern parts of the Sea, are examined for the first time in respect to their possible influence on chlorophyll concentrations. The affected area was delineated with the use of numerical model data, while the sea surface temperature and chlorophyll variations were assessed based on satellite-derived data. The results showed that medicanes trigger surface chlorophyll increases; after the cyclones' passage, the concentrations were higher compared both with those before and with the climatological monthly values over a large part of the affected area. The mechanisms proposed to explain hurricanes' favorable influence on chlorophyll concentration seem to be valid for medicanes as well. Area averaged chlorophyll concentrations presented analogous increases to the ones reported for hurricanes, though on a smaller scale. Despite the much lower intensity of medicanes compared with hurricanes, the observed increase in surface chlorophyll after their passage points to their favorable influence.

Keywords: Mediterranean; tropical-like cyclones; phytoplankton; sea surface temperature; satellite data; geographic information system (GIS)

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1. Introduction

The Mediterranean Sea is characterized by a very high rate of cyclone formation and is ranked as one of the world's main regions for cyclogenesis [1–3]. In rare cases, the Mediterranean cyclones gain features of tropical cyclones: "eye", axisymmetry with spiral cloud bands, very strong surface winds and warm core [4,5]. Due to their similarities with hurricanes, these cyclones are called **Medi**terranean hurri**canes** or medicanes [4]. The associated extreme and hazardous weather conditions can cause significant damage over the sea and the coastal zones [6]. Medicanes usually begin as upper-level baroclinic disturbances (e.g., cutoff lows, troughs) and then evolve into tropical-like structures; this transition is highly dependent on upper-level potential vorticity anomalies and dry air intrusions, high low-level vorticity and surface heat fluxes, high moisture, and deep convection [4,7–10]. The above procedures involve sea surface temperature (SST) plus the upper atmospheric layers and differentiate medicanes from tropical cyclones, where SST plays the major role [7]. Medicanes are much weaker than hurricanes; however, a few of them have reached Category 1 of the Saffir–Simpson scale [11,12]. Heavy rainfall and deep convection, caused by these extreme lows, usually precedes their tropical-like phase during which precipitation is less and scattered in rainbands [13,14]. Climatological approaches have estimated the medicanes' frequency to ~1.5 per year for the whole basin [6,15,16]; they have also indicated the most common regions for medicane formation: the western Mediterranean (around the Balearic islands) and the Ionian Sea (often extended southward to the North African coast) [6,14,16,17]. The frequency of medicane formation is higher in autumn and winter, decreases significantly in spring and tends to zero during summer [6,14–16]; this preferred period for formation is another difference from tropical cyclones, which are formed during periods of high SST. A frequency decrease along with an intensity increase is predicted for medicanes in the following years [15,18–20].

Tropical cyclones have been studied in respect to their possible influence on chlorophyll-a (chl-a) concentration, as an indicator of phytoplankton growth, mainly with the use of satellite data and in some cases with field measurements. The studies refer both to hurricanes in the Atlantic ocean [21–27] including oligotrophic marine areas [23,27] and typhoons in the Pacific ocean [27–30]; their results indicate an increase in chlorophyll concentration and primary production and even phytoplankton blooms. A decrease in SST is observed in all cases, as it has been proposed for cyclones, due to upwelling, vertical mixing, and deepening of the mixed layer depth (MLD) together with cooling due to heat fluxes towards the atmosphere [31,32]. Most studies highlight the role of cyclone induced upwelling and wind mixing process in lowering SST and providing the upper sea layers with nutrients from below, resulting in enhanced phytoplankton growth and increased chl-a concentration [22,23,25,27,29,30]; the favoring role of heavy rainfall for the observed increase in chlorophyll is also proposed [22,27]. The high chlorophyll concentration after the passage of a cyclone is not attributed as a whole to new production triggered by the increased nutrient availability; an upward displacement of mid/deep chlorophyll maxima has been proposed as another reason [22–24].

The Mediterranean Sea is affected from time to time by medicanes, that could also have an influence on the Sea's primary production. However, relative studies have not been conducted until now, and this is exactly the attempt of the present work. It is noted that algal blooms are natural processes occurring under favorable environmental conditions. Various reasons, such as extreme meteorological conditions as those studied here, could lead to an increase in phytoplankton, which in turn could provoke substantial perturbations of the entire food web structure and functioning. In addition, for the oligotrophic Mediterranean environment, every factor that could lead to an increase in primary production is considered significant. Hence, the possible impact of medicanes on the Sea's surface chlorophyll concentration is explored here. The study is focused on events that affected the central or eastern parts of the basin, that are in general oligotrophic areas characterized as "non-blooming" [33] and reach their higher chlorophyll concentrations by the end of winter—beginning of spring period [34]. Three cyclones, that have been identified as tropical-like ones in bibliography, were examined. Numerical model data were used for delineating the sea area affected by the medicanes and satellite-derived data for computing the variations in SST and chlorophyll. An increase in chlorophyll concentrations was observed after the cyclones' passage for a very high percentage of the affected area in all cases, while the involved procedures seem to be the same as for hurricanes. The chl-a concentrations after the events were also higher than the climatological monthly values for a large part of the impacted region. Area averaged chlorophyll presented an increase which is comparable, though on smaller scale, to the one caused by hurricanes when affecting oligotrophic waters. Considering the lower medicanes' intensity compared to that of hurricanes, the results of the current study are, at least, supportive regarding their positive influence on surface chlorophyll concentration.

2. Materials and Methods

The Mediterranean tropical-like cyclones that are studied here, in respect to their possible influence on marine chlorophyll concentrations, have been identified as medicanes in bibliography. They were all formed east of the Strait of Sicily, affected a quite large area of the central-eastern part of the Sea and during their lifetime they presented sea level pressure below 1,000 hPa.

The study area affected by the medicanes was delineated by the higher closed isobaric surface presenting symmetry at the time of minimum pressure—quite arbitrary although based on the axisymmetric structure of the medicanes—plus 10 m wind speed >17.5 m/s (i.e., gale force) [20,35] adjacent to the low pressures. For this procedure, the hourly data (mean sea level pressure and 10 m wind speed) from the European Centre for Medium-Range Weather Forecasts ERA5 high-resolution reanalysis project (ECMWF ERA5) were used (of 31 km native resolution and bilinearly interpolated at 0.125°). The track of the cyclone was based on the same data and was determined by the minimum pressure. The properties of tropical-like cyclones in the Mediterranean are usually studied using finer resolution numerical models; otherwise an underestimation in minimum pressure and wind intensity is possible. Therefore, the data used here for delineating the affected region, in the way described above, has possibly led to a smaller study area undoubtedly influenced by the extreme event.

The response of the marine environment was assessed by calculating SST differences. The results presented here refer to the differences between 3 days before and after the events, while for selected areas an ~11-day time period centered on the events was considered for SST variations. The data used were derived from the high resolution (0.04°) SST daily mean (L4) product of the Copernicus Marine Environment Monitoring Service (CMEMS); this dataset (SST MED SST L4 REP

OBSERVATIONS 010 021) is the nighttime Pathfinder V5.3 Advanced Very High Resolution Radiometer (AVHRR) product, provided by the National Oceanic and Atmospheric Administration (NOAA), reprocessed through an optimal interpolation algorithm for the production of daily gap-free maps. The chlorophyll data of the study also come from CMEMS: daily (OCEANCOLOUR MED CHL L3 REP OBSERVATIONS 009 073), weekly and monthly (OCEANCOLOUR MED CHL L4 NRT OBSERVATIONS 009 041) surface chlorophyll concentrations (at 1 km resolution) from multi-satellite observations. Further details for the CMEMS datasets used here can be found at http://marine.copernicus.eu. The possible influence of the meteorological phenomenon on chlorophyll concentrations was examined by calculating the percentage differences between the maximum concentrations of 5 days after the event and 5 days before it. It is noted that a time interval of 2 to 4 days for chl-a increases has been reported in cases of tropical cyclones [24,26,27]. The day just before the event was excluded, since chlorophyll increases have been found 1 day before a hurricane's passage [27]; in any case, during this day the available data were very limited. Chlorophyll percentage differences of the 5 days after the medicanes and the respective monthly climatological values of the period 1996–2016 were also calculated to highlight the significance of the influence. The above calculations were also performed on a weekly basis, using 8-day data as in other studies [23]. In all results, the absolute chlorophyll percentage differences that exceed 50%—the approximate difference reported between *in situ* observations and chl-a satellite data [36]—and could be considered more significant are mentioned separately. For the open sea oligotrophic area with distance from coast >50 km plus climatological chlorophyll concentration values <0.2 mg/m^3, the averages of the maximum chl-a values 5 days before and after the event were computed; a paired *t*-test was applied to check the statistical significance of these variations. Averaged daily values for SST and chl-a were computed for a period of ~11 days around the day of minimum pressure, for the areas along the cyclone's track (50 km width) and for areas that presented a large increase in chlorophyll concentration (P areas), in an effort to further explore the phenomenon. It is noted that even if the analysis of ERA5 did not depict the exact cyclones' track—a difficult task for numerical models—the along-track areas are at least areas very near to it; the P areas are all in the open sea and present low climatological chl-a concentration. It should be noted that the calculations of the area averaged chlorophyll concentrations are quite indicative due to lack of data at different area's locations each day. The major part of data processing was performed in the framework of a geographic information system (GIS).

The wind intensity and the total rainfall amount are commented as well. Regarding rainfall, the precipitation sum for the period one day before the event until one day after it was considered —as referred in the introduction, higher amounts of rain are expected just before the tropical-like phase of the cyclone. The precipitation data are TRMM (Tropical Rainfall Measuring Mission) daily values obtained through the Giovanni online data system.

3. Results

3.1. The Medicane of 13 to 15 December 2005

The cyclone of 13 to 15 December 2005 has been more than once recognized as a medicane [7,13,14,37]. The minimum pressure computed differs from study to study, e.g., 986 hPa [14], 980 hPa [37]. According to ERA5 reanalysis used here, the minimum pressure was 989.52 hPa and the maximum 10 m wind 25.38 m/s. The cyclone was formed over the southeast of Malta on 13 December, travelled first westwards and then moved to the east, gained its minimum pressure and continued its eastward track moving faster and increasing its central pressure. The isobaric surface used in this case for determining the medicane affected area was 1,000 hPa. The area studied (of about 510,000 km^2) and the cyclone track, together with the mean 1998–2016 chlorophyll-a concentration for December, are shown in Figure 1a. The major part of the study area has been characterized as no blooming and its southwestern part as coastal [33].

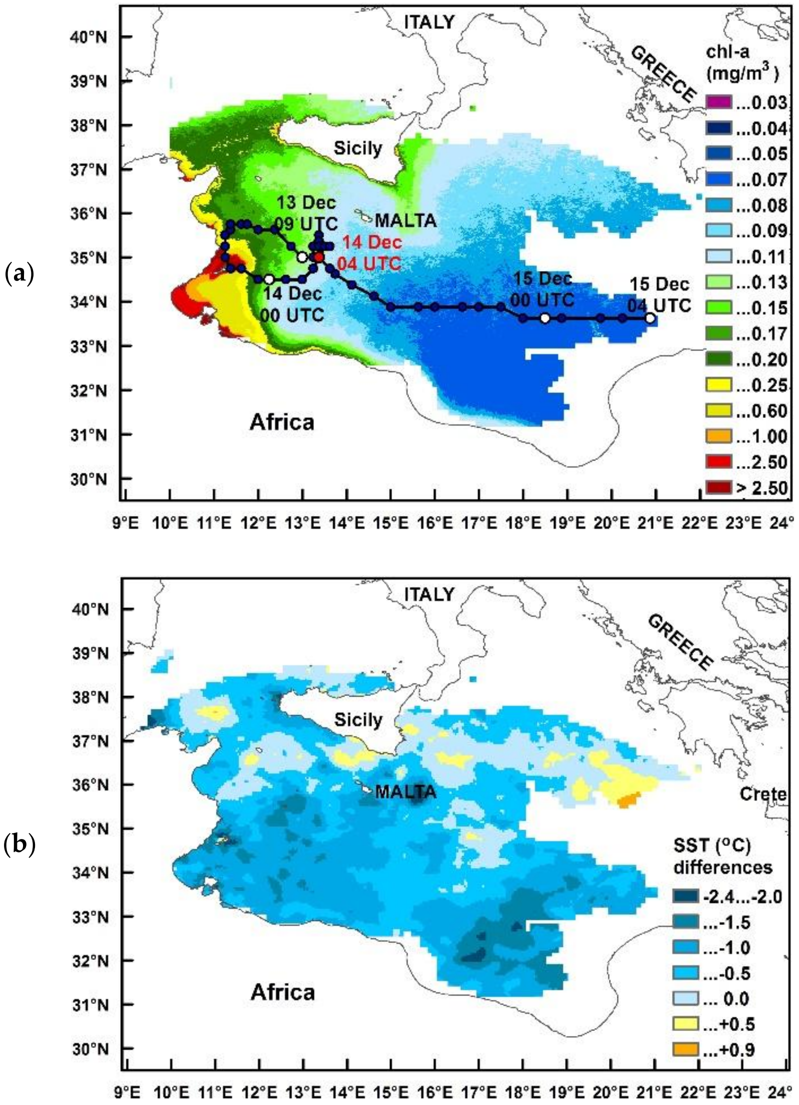


Figure 1 (a,b). (**a**) The study area together with the mean 1998–2016 chlorophyll-a concentration for December and the medicane's track. Day and hour refer to the white dots while the red dot denotes the minimum pressure; (**b**) Sea surface temperature (SST) differences between 11 and 17 December 2005.

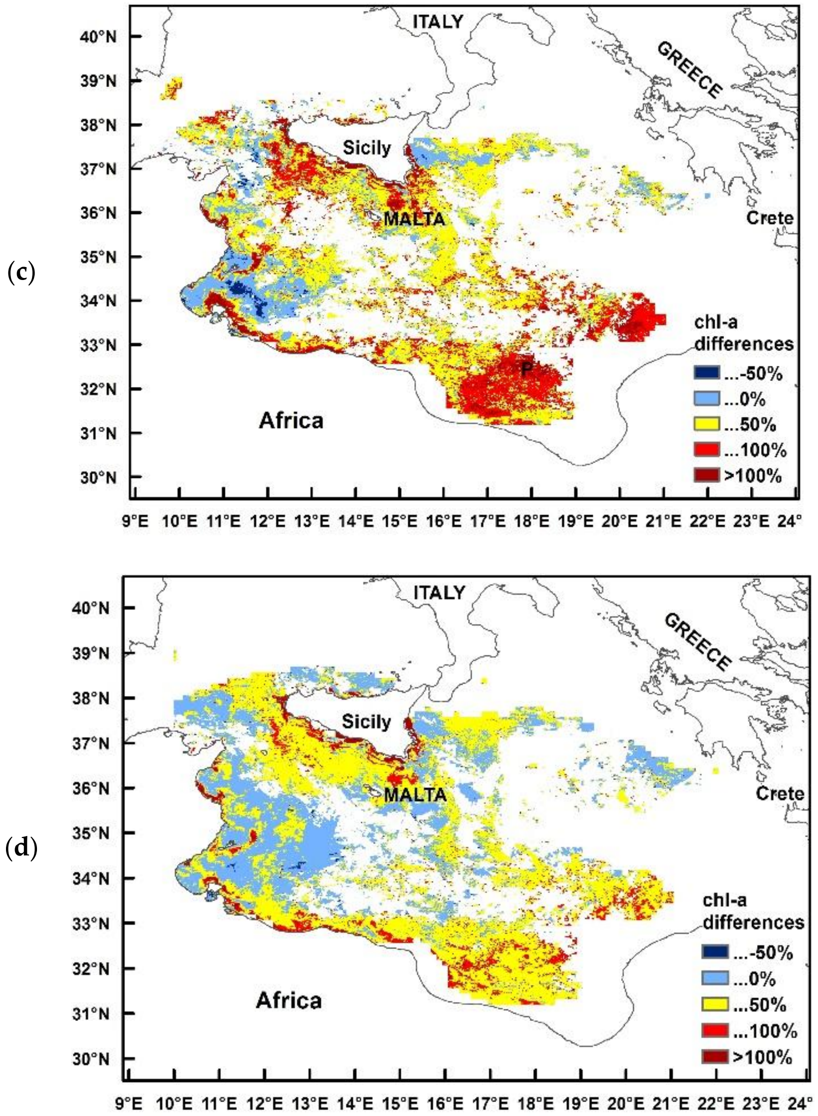


Figure 1 (c,d). (**c**) Chlorophyll percentage differences between the maximum concentrations of 5 days after the event (15–19 December 2005) and 5 days before (7–11 December 2005), P denotes the area of large chlorophyll increase referred in the text; (**d**) Same as (c) for the 5 days after the event and December 1998–2016 climatology.

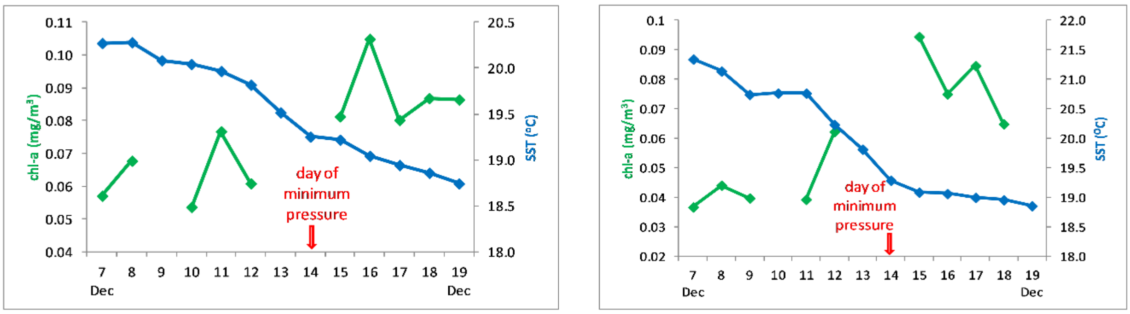
SST differences between 11 and 17 December 2005 (Figure 1b)—3 days before and after the central day of the event (14 December)—revealed a drop over 95.5% of the area and presented differences <−1 °C for 40.6% and <−1.5 °C for 9.3% of the area. The region near the medicane's track and south of it, i.e., over the right side of the track, presented the maximum SST drop.

The differences between the maximum chlorophyll concentration of 5 days after the event (15–19 December 2005) and 5 days before the event (7–11 December 2005) are given in Figure 1c; 77.5% of the study area presented an increase in chlorophyll concentration, while over 30.4% of the area chlorophyll percentage increases were >50% and over 8.6% were >100%. It is noted that a large proportion of chlorophyll increases exceeding 50% was observed over the open sea and not near the coastal areas, especially over the oligotrophic southeast part of the study area. The absolute chlorophyll differences >50% (that could be considered as significant) were found for

31.9% of the study area and were by 95.3% increases. The comparison between the chlorophyll concentrations of the 5 days that followed the event with the 19-year climatological values for December is shown in Figure 1d. Chlorophyll values after the medicane's passage were greater than the climalogical ones for 63.0% of the area; these increases were >50% for 10.1% of the area, while more than doubled concentrations were observed for 2.2%. The absolute differences >50% covered 10.5% of the area and were by 96.2% increases. It is noted that over 76% of the area that presented a drop in SST (as presented in Figure 1b), a chl-a increase was observed. The maximum 10 m wind speed during the episode and the total precipitation between 12 and 16 December 2005—maximum values were recorded during the episode—are given in Appendix A (Figure A1). The large southeastern area of more than doubled chlorophyll concentrations was mainly affected by high winds and presented a decrease of 1 to 2 °C in SST; these findings denote that upwelling and wind mixing were the mechanisms that caused the observed chl-a increase. There are regions of significant chlorophyll increases that were affected by high winds and/or extreme rainfall. The northern coastal areas were affected by large precipitation amounts plus high winds, while SST presented a smaller decrease or a slight increase; the chlorophyll increase of this area should rather be attributed both to nutrients brought by precipitation and/or river discharges and wind mixing processes. An important chl-a decrease was observed over the southwest of the study area in a region of generally high concentrations that was affected by both large precipitation amounts and very high winds. The means of the maximum chlorophyll concentrations observed before and after the event for the open oligotrophic sea area were found to differ in a statistically significant way; they were 0.070 mg/m^3 and 0.087 mg/m^3 respectively, revealing a 24.3% increase, while SST mean dropped by 1.1 °C.

Chlorophyll percentage differences between the week after the event (19–26 December 2005) and the week before the event (3–10 December 2005) showed an increase for 81.7% of the area, with increases >50% covering 20.7% and those >100%, 3.7% of the area; the absolute differences >50% referred to 21.6% of the area and were by 95.7% increases (Figure A2a). These differences revealed that the enhanced chlorophyll concentrations were sustained and further confirmed, as the daily data did, that the largest chlorophyll increases were not observed along the medicane's track but over neighboring regions. Chlorophyll concentrations during the week after the event compared to December climatology (Figure A2b) were greater for 46.3% of the area, with the absolute differences above 50% referring to 3.3% of the area and being by 94.4% increases.

Over a 50 km width area along the medicane's track and for the area of chlorophyll increase marked with P in Figure 1c, mean chl-a and SST values were computed for the time period 7 to 19 December. For the area along the track of 14 December (Figure 2a) SST decreased by 1.5 °C and chl-a increased by 36.4%; for the area along the track of 15 December (not shown) the decrease in SST was 1.6 °C and the increase in chlorophyll 52.6%; the P area (Figure 2b) presented a cooling of 2.5 °C and an increase in chlorophyll of 51.6%. In all cases the SST drop began before the main day of the event, became more abrupt just before or during it and continued after it; chlorophyll mainly increased during the event or just after it while an increasing trend 2 days before was also implied (Figure 2b).



(**a**) (**b**)

Figure 2. Mean chlorophyll concentration and SST for the time period centered on the event examined (**a**) For the 50 km width area along the cyclone's track on 14 December 2005; (**b**) For the area of chlorophyll increase marked with P in Figure 1c.

3.2. The Medicane of 4 December 2008

The cyclone of 4 December 2008 has been identified as a medicane with a minimum pressure of 990 hPa [14]. According to the model analysis used here, the minimum pressure was 986.7 hPa and the maximum 10 m wind speed 20.43 m/s; the pressure of 995 hPa was used for delineating the affected area. The phenomenon took place over the Ionian Sea between Italy and Greece; the cyclone was formed east of Sicily, gained its minimum pressure and moved north-northeastwards.

The study area of about 125,000 km^2 along with the track of the medicane and the 19-year monthly chlorophyll climatology map are shown in Figure 3a. The area studied here has been characterized, in general, as non-blooming with some intermittently blooming parts [33].

SST differences 3 days before and after the event (between 1 and 7 December 2008) are presented in Figure 3b; they revealed a decrease over 72.2% of the area, with values <−1 °C for 4.6% and <−1.5°C for 0.6% of the data. The SST decrease, in this case, was much smaller than the one of the previous case and did not present a concrete pattern.

Chlorophyll concentration differences between the maximum values of 5 days after the event (28 November–2 December 2008) and 5 days before it (5–9 December 2008) were increases for 79.1% of the area (Figure 3c), while 26.2% of the area presented increases >50% after the event and 6.7% more than doubled concentrations. Absolute chl-a differences >50% referred to 27.8% of the data and were by 94.1% increases; many of them were observed over the open sea area presenting oligotrophic climatic characteristics. Over 58.8% of the area of SST decrease (presented in Figure 3b), an increase in chlorophyll was observed. The maximum chlorophyll concentrations of the 5 days after the event, compared to December climatology (Figure 3d), were found higher for 73.1% of the area, with differences >50% for 13.3% and more than doubled values for 3.8% of the data; the absolute differences >50% referred to 13.4% of the data and they were increases by 96.0%. In this case, the increase in chlorophyll concentration was observed along the medicane's track as well as in some coastal areas; similar to the previous case examined, chlorophyll increases were found to be significant over the open sea. A region over the southwestern part of the study area presented a significant chlorophyll decrease; it is surprising that chl-a concentration after the event was still greater than the climatological value. The maximum 10 m wind speed during the event and the precipitation sum of 3 to 5 December 2008 are shown in Figure A3. It is noted that the highest rainfall amount was recorded on 3 December, i.e., one day before the cyclone gained its tropical characteristics. A large part of the open sea that presented a large increase in chlorophyll concentrations was affected by both strong winds and heavy precipitation, while the coastal areas mainly by large rainfall amounts. Taking in mind that the SST decrease, in this case, was quite low, the increase in chlorophyll could be mainly attributed to mixing processes due to the very strong winds plus nutrients from rain. For the open sea oligotrophic area, the difference of the mean chl-a concentration before and after the event was again statistically significant. The values were 0.083 mg/m^3 before and 0.110 mg/m^3 after the cyclone, revealing a 32.5% increase; however, SST mean dropped by only 0.1 °C.

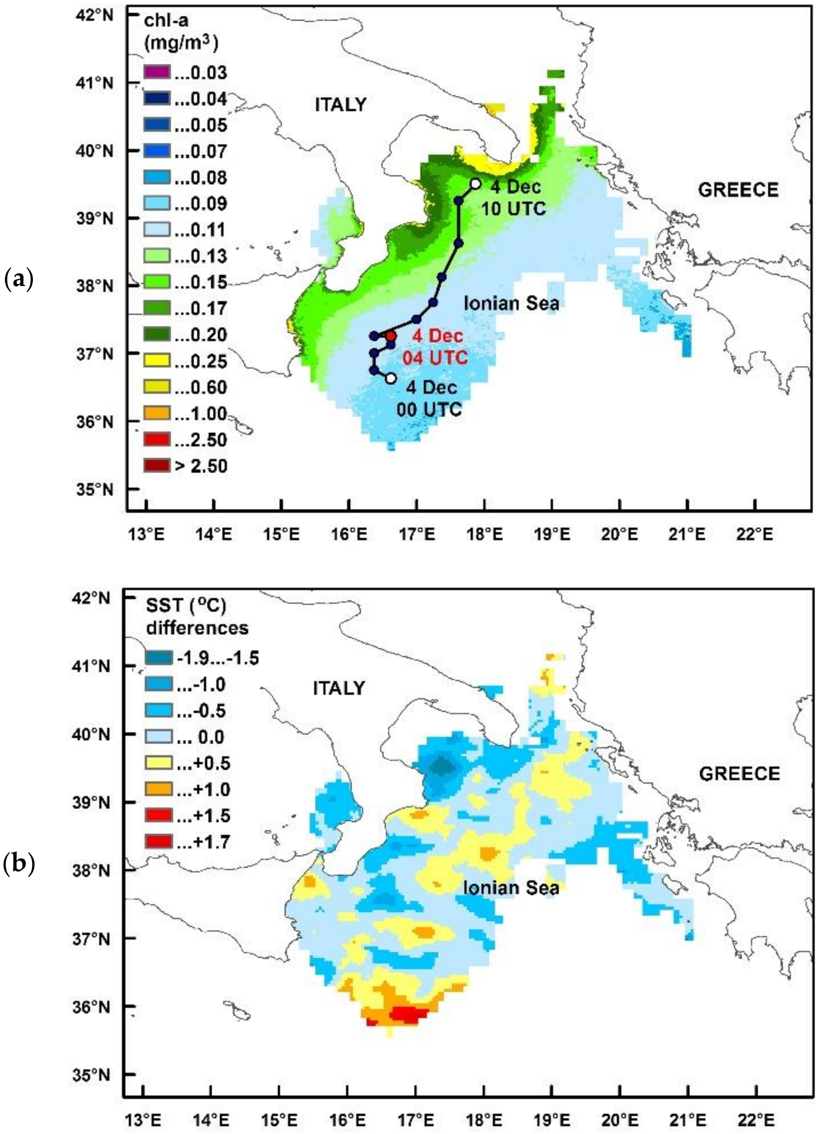
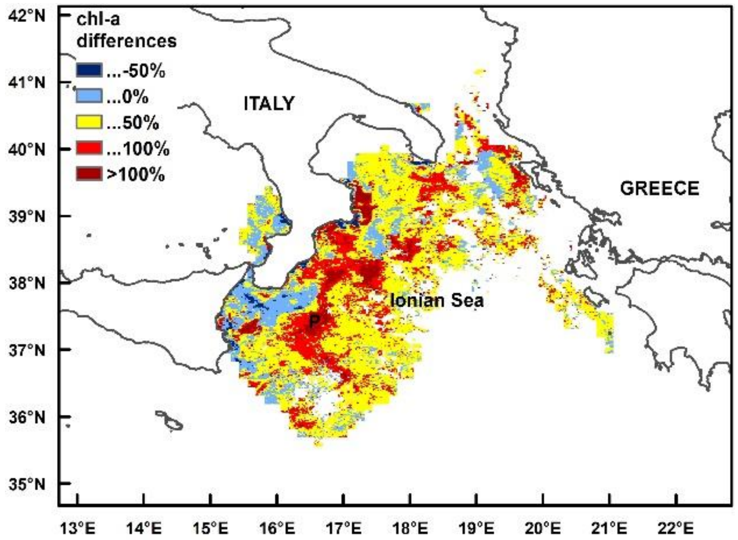


Figure 3 (a,b). (**a**) The study area together with the mean 1998–2016 chlorophyll-a concentration for December and the medicane's track. Day and hour refer to the white dots while the red dot denotes the minimum pressure; (**b**) SST differences between 1 and 7 December 2008.

(**c**)



(**d**)

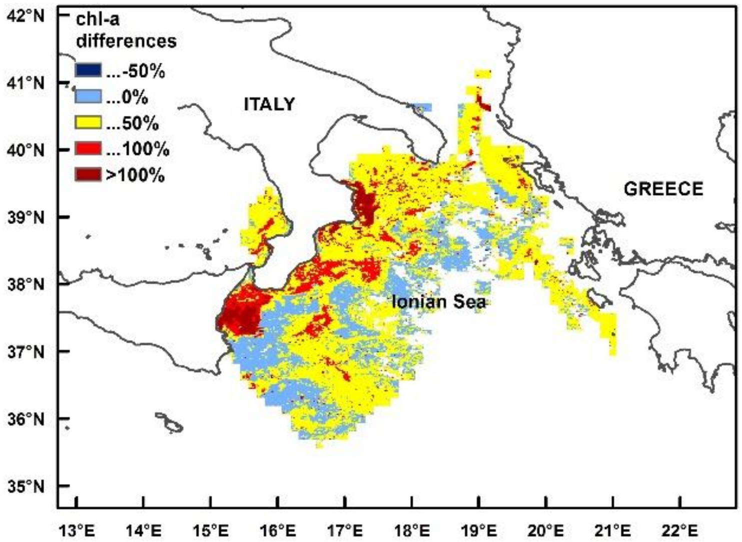
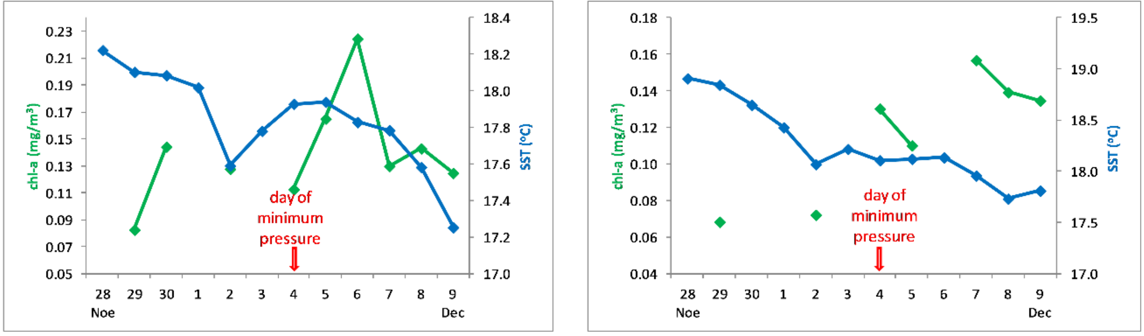


Figure 3 (c,d). (**c**) Chlorophyll percentage differences between the maximum concentrations of 5 days after the event (5–9 December 2008) and 5 days before (28 November–2 December 2008), P denotes the area of large chlorophyll increase referred in the text; (**d**) Same as (c) for the 5 days after the event and 1998–2016 December climatology.

The week after the medicane (10–17 December 2008) compared to the one of the event (2–9 December 2008) presented chlorophyll increases mainly over the neighboring areas to the track (Figure A4a). The observed increases covered 73.4% of the area, they exceeded 50% for 15.8% and referred to more than doubled concentrations for 4.2% of the area; the absolute differences >50% were present for 16.1% of the data and they were by 97.9% increases. Chlorophyll concentration differences of the week after the medicane and the one before (24 November–1 December 2008) (not shown) revealed an increase for 96% of the area (increases >50% for 55.2% and >100% for 12.2%, while the absolute differences exceeding 50% that referred to 55.2% of the data were all increases); however, the time difference between these two weeks is quite large. The chl-a concentrations of the week after the event compared to the climatological values (Figure A4b) were found higher for 83.6% of the area, and the increases exceeded 50% and 100% for 17.7% and 3.8% of the data, respectively; the absolute differences >50% referred to 17.8% of the data and they were by 99.5% increases.

Mean daily chl-a concentration and SST for the 50 km width area along the medicane's track and for the P area of Figure 3c were computed for the time period 28 November to 9 December. A decrease in SST of 1 °C plus an increase in chlorophyll of 55.6% for the along-track area and of 1.2 °C and 128% respectively for the P area were observed (Figure 4). The SST drop began a few days before the event while chlorophyll started increasing during it.



(**a**) (**b**)

Figure 4. Mean chlorophyll concentration and SST for the time period centered on the event examined (**a**) For the 50 km width area along the cyclone's track on 14 December 2008; (**b**) For the area of chlorophyll increase marked with P in Figure 3c.

3.3. The Medicane of 7–8 November 2014

The medicane of 7–8 November 2014 has been named Qendresa by the Free University of Berlin and has been studied several times [9,38]. It was formed south of Sicily on 7 November 2014 and made landfall at Malta on 7 November and at eastern Sicily on 8 November; a minimum mean sea level pressure of 984 hPa was recorded at Malta [38]. According to the model analysis used here the minimum pressure was 991.6 hPa and the maximum 10 m wind speed 23.15 m/s; for determining the study area the isobaric surface of 1,000 hPa was used.

In Figure 5a, the cyclone's track and the study area (about 160,000 km^2) along with the November chlorophyll climatology are shown; this area has been, in general, characterized as a non-blooming one [33].

SST differences between 4 and 10 November 2014—3 days before and after the event—presented a decrease for 96.9% of the area and they were <−1 °C for 49.9% and <−1.5 °C for 20.8% of the area (Figure 5b); these decreases were the largest of the cases examined in this paper, and the maximum ones were mainly observed over the right side of the cyclone's track.

The differences in maximum chl-a concentrations between 5 days after the event (9–13 November 2014) and 5 days before it (1–5 November 2014) that are shown in Figure 3c revealed an increase in chlorophyll for 91.1% of the study area; this increases exceeded 50% for 39.9% of the data, and the values were more than doubled for 10.5%. It is noted that over 89.4% of the area that presented SST decrease (presented in Figure 5b) an increase in chlorophyll was observed. The absolute chl-a differences >50% referred to 39.9% of the data and they were all increases. The chl-a concentrations of 5 days after the event compared to November climatology (Figure

5d) revealed higher values for 93.3% of the area, that were >50% and >100% for 29.1% and 4.4% of the data, respectively. The absolute chlorophyll differences >50% between the 5 days after the event and climatology were 29.1% of the data, and they were all increases. Both the above comparisons showed larger chlorophyll increases over the right side of the cyclone's track and over the oligotrophic open sea. The maximum 10 m wind speed during the event and the total precipitation for the period 6–8 November 2014 are given in figure A5; it is noted that the higher rainfall amounts were recorded the day before (6 November) the cyclone gained its tropical characteristics. The area of the larger increase in chlorophyll (on the right side of the track) coincided with the area of the stronger winds and the higher precipitation amounts; in this case, the increased chlorophyll concentrations should rather be attributed to both upwelling and mixing processes plus the favoring role of precipitation. The mean chl-a concentrations, for the open sea oligotrophic area, presented a statistically significant difference before and after the event; the averaged chlorophyll value was initially 0.075 mg/m^3 and reached 0.119 mg/m^3, revealing a 58.7% increase. The SST mean decreased by 1.1 °C.

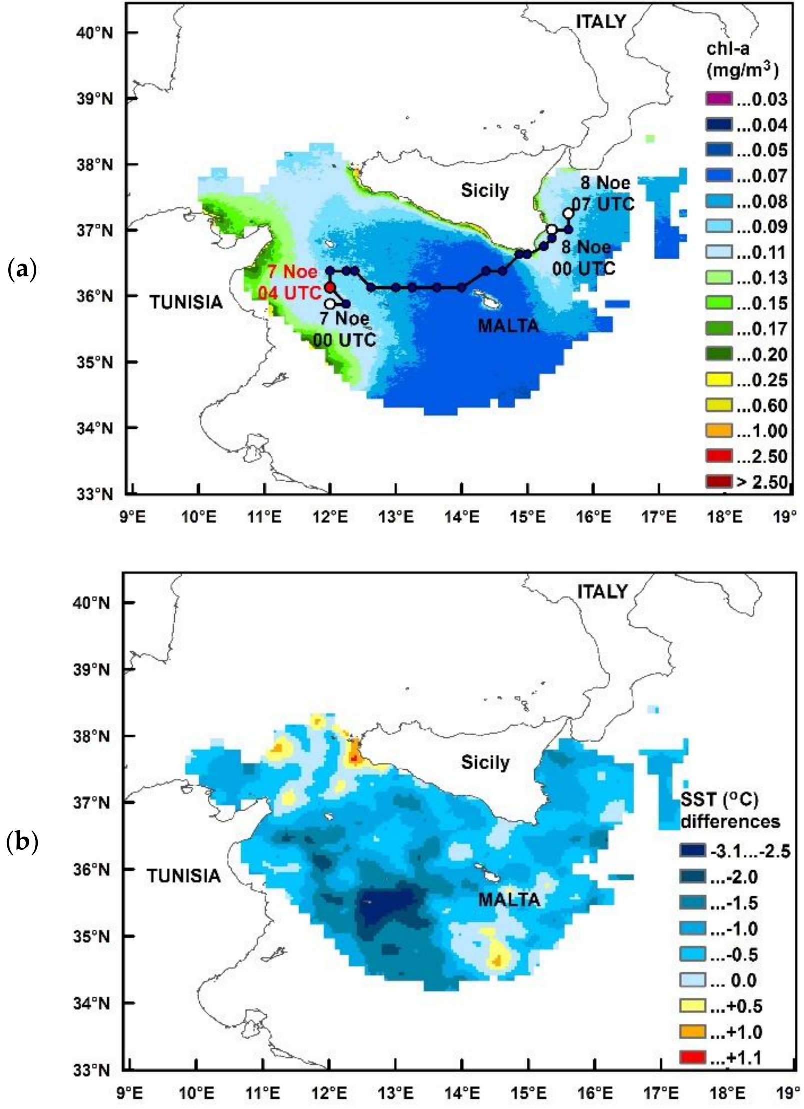


Figure 5 (a,b). (**a**) The study area together with the mean 1998–2016 chlorophyll-a concentration for November and the medicane's track. Day and hour refer to the white dots while the red dot denotes the minimum pressure; (**b**) SST differences between 4 and 10 November 2014.

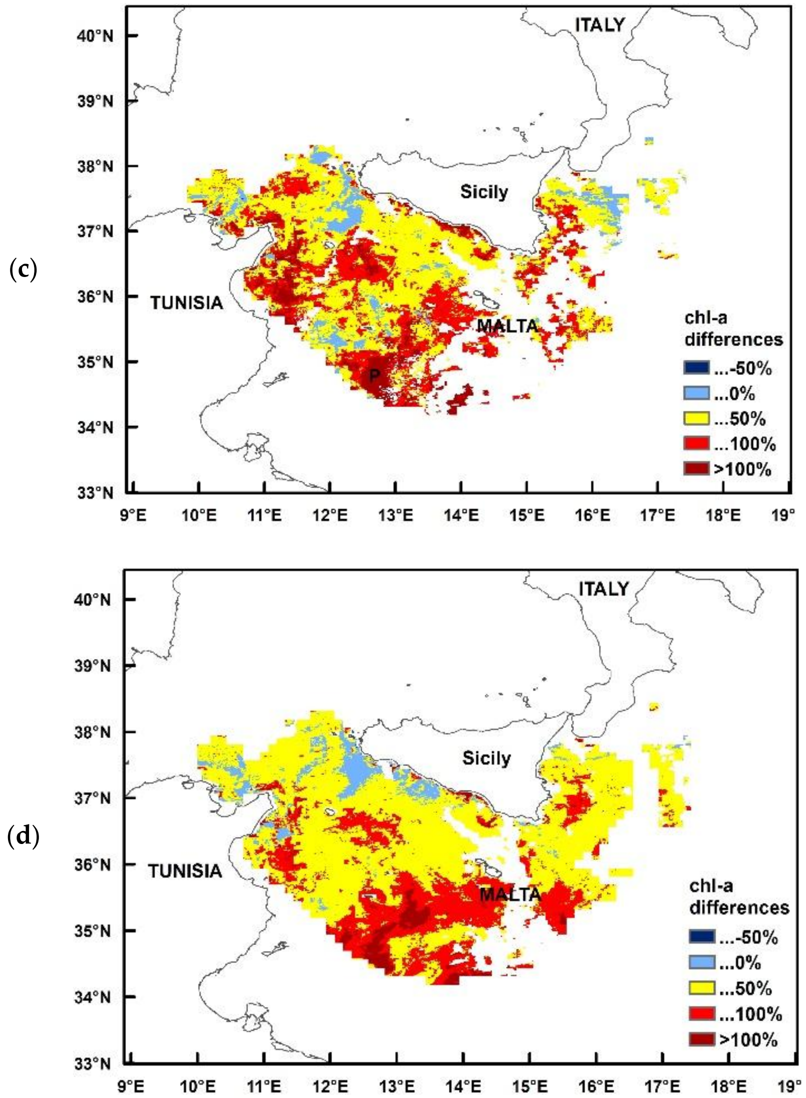
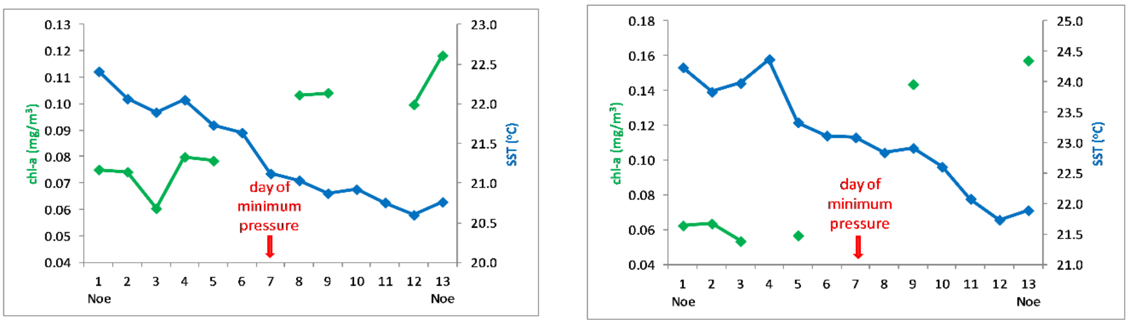


Figure 5 (c,d). (**c**) Chlorophyll percentage differences between the maximum concentrations of 5 days after the event (9–13 November 2014) and 5 days before (1–5 November 2014), P denotes the area of large chlorophyll increase referred in the text; (**d**) Same as (c) for the 5 days after the event and 1998–2016 November climatology.

The chlorophyll differences between the week after the event (9–16 November 2014) and the week of the event (1–8 November 2014) that are given in Figure A6a, revealed increases for 94.8% of the area. These increases were >50% for 41.3% of the data and >100% for 6.9%; the absolute percentage differences exceeding 50% referred to 41.3% of the data, and they were all increases. Comparing the chlorophyll concentrations of the week after the medicane with November climatology (Figure A6b), the values were higher for 95.5% of the area, with differences >50% for 18.8% of the data and >100% for 0.5%; the absolute percentage differences exceeding 50% referred to 18.8% of the area and they were all increases.

Over the 50 km width area along the cyclone's track on 7 December and for the P area of Figure 5c that presented a significant chlorophyll increase, mean values were computed for chl-a and SST on a daily basis for the time period 1–13 November. Over the along-track area (Figure 6a) SST decreased by 1.8 °C and chl-a increased by

47.5%; the P area (Figure 6b) presented a decrease of 2.5 °C in SST and a chl-a increase of 145%. In this case also, the SST drop began before the main day of the event and continued a few days after it; chlorophyll increased during and after the event.



(**a**) (**b**)

Figure 6. Mean chlorophyll concentration and SST for the time period centered on the event examined (**a**) For the 50 km width area along the cyclone's track on 7 November 2014; (**b**) For the area of chlorophyll increase marked with P in Figure 5c.

4. Discussion

In all three cases studied, a post-medicane increase in surface chlorophyll concentrations was observed over a large percentage of the affected area. This chlorophyll increase, during the time period after the medicanes' passage, was revealed by the calculations performed both on a daily and weekly basis. The comparison between the chlorophyll concentrations after the events and the respective monthly climatology revealed higher values after the events over large areas as well. The relevant results are summarized in Table 1. If absolute percentage chlorophyll differences exceeding 50% are considered as more reliable (their percentage of increases are given in parenthesis in Table 1), chlorophyll increases characterized the whole study areas. It is noted that the 7–8 November case presented the wider area of chlorophyll concentration increase after the event. Analogous results can be derived by the chlorophyll values averaged over the open sea oligotrophic areas, the along-track areas and the areas presenting enhanced chlorophyll increases (P areas); in Table 2 the percentage increases in chlorophyll for these areas, during an ~11-day time interval centered on the cyclone passage, are shown . A decrease in SST was also observed in all cases; the SST differences between the values 3 days before and after the event, presented a decrease over 95.5%, 72.2%, and 96.9% of the area, respectively for the three cases examined. SST, during these days, dropped by more than 1 °C over 40.6%, 4.6%, and 49.9% of the study area for the three cases. The averaged SST values over the track areas and the P areas, during the ~11-day time interval centered on the medicane, revealed a more pronounced SST decrease; these decreases are summarized for all cases in Table 2. Again, the larger SST decrease (as the increase in chlorophyll) referred to the 7–8 November 2014 case, although the 13–15 December 2005 event presented a comparable SST drop.

Table 1. Chlorophyll increases in percentages of the affected area for the three medicanes, as revealed by the 5-day (5d) and the weekly (w) chlorophyll data before and after the event. The percentages of absolute chlorophyll differences exceeding 50% that were increases are given in parenthesis.

Medicane	Chlorophyll Increase after-before (Area %)	Chlorophyll Increase after-Climatology (Area %)
13–15 December 2005	5d: 77.5 (95.3) w: 81.7 (95.7)	5d: 63.0 (96.2) w: 46.3 (94.4)
4 December 2008	5d: 79.1 (94.1) w: 73.4 (97.9)	5d: 73.1 (96.0) w: 83.6 (99.5)
7–8 November 2014	5d: 91.1 (100) w: 94.8 (100)	5d: 93.3 (100) w: 95.5 (100)

Table 2. Chlorophyll percentage increase and SST decrease of their averaged daily values during a time period of ~11-days centered on the event, for the oligotrophic open sea area, the 50 km width along-track area, and the areas of positive chlorophyll differences (P-areas).

Medicane/Areas	Chlorophyll Increase (%)	SST Decrease (°C)
13–15 December 2005		
14 Dec track area	36.4	1.5
15 Dec track area	52.6	1.6
P area	51.6	2.5
Open sea area	24.3	1.1
4 December 2008		
4 Dec track area	55.6	1.0
P area	128	1.2
Open sea area	32.5	0.1
7–8 November 2014		
7 Nov track area	47.5	1.8
P area	145	2.5
Open sea area	58.7	1.1

Over near coast regions, characterized by higher chl-a climatological values than the rest of the study area, a significant decrease in chlorophyll concentrations was locally recorded in two cases (December 2005 and December 2008). Such a decrease has also been observed in a similar study for a coastal Pacific region [28], and the destruction of phytoplankton cells caused by the strong cyclone shear has been proposed as a possible reason [39]. Low chlorophyll concentrations have also been resulted for shelf regions from a model simulation study and have been attributed to upwelling of water originating below the mixed layer and characterized by decreased chl-a content [40]. A credible explanation could also be that water from the open sea is transferred into these areas due to the extreme phenomenon and reduces chlorophyll concentrations [41] or that the reinforced prevailing winds shift waters of high chlorophyll to the open sea. Concerning SST, it has been documented that hurricanes cause a decrease of several degrees by deepening the MLD some tens of meters [32]. They are expected to induce the largest SST drop on the right side of their track (northern hemisphere), where the winds are more intense, and the upwelling is maximized [31,32,42,43]. Such a pattern has been the result of a model study along with the maximum MLD [40] and has been observed in studies of tropical cyclones in respect to their influence on chlorophyll concentrations [22,25] coinciding with the regions presenting higher chlorophyll increases. Similarly, in all cases studied here, the stronger winds were also found on the right side of the medicanes’ track; however, the maximum cooling was observed over this area in two out of the three cases. In the case of 4 December 2008 where the above characteristic was absent, the lower SST drop was induced over the affected area. In addition, this medicane moved rather faster compared to the others. For the tropical cyclones has been suggested that their speed is negatively related to their cooling effect [44], while model results have shown that slower moving storms induce deeper mixed layers [40]. An analogous pattern, with larger chlorophyll increases on the right side of the track, is implied by the results of this study and is clear enough for the 7–8 November case. It is noted that a quite large portion of the areas exhibiting a decrease in SST presented an increase in chlorophyll as well, 76%, 58.8%, and 89.4% for the three cases, respectively; the lower value refers to the 4 December 2008 case which was characterized by the smaller SST drop. In tropical cyclone cases, an abrupt SST drop coincides with the passage of the storm and SST continues decreasing after it. In the cases studied here, SST started decreasing some days before the event. This fact could be anticipated since upper-level disturbances that bring colder air masses pre-exist the formation of medicanes; another reason could be the mixing caused by the strong winds that prevail before the cyclone center reaches an area.

Comparisons in chlorophyll variations between the results of the present study and the ones for tropical cyclones could be made with the hurricane cases that have affected oligotrophic Atlantic regions. In a study of 13 hurricanes, for values averaged over the along-track area (a much wider area than the one examined here), chlorophyll increase exceeded 50% for only three of them [23]. These values are comparable with the results of the current study, even for the wide oligotrophic open sea areas (Table 2). However, while in hurricanes’ cases, the maximum chlorophyll concentrations have been locally found much higher than the averaged values, the latter is not observed here. It is noted that in the same study [23], the largest SST drop was 2.6 °C; such a value was observed here over the P areas of two cases (Table 2). In addition, a cooling of 2 °C and a chlorophyll increase of 26.1%, averaged over a large area of maximum changes, has been reported for a hurricane that affected the northeast Atlantic oligotrophic area [27], similar to the results of the present study. All the above mentioned indicate that tropical-like Mediterranean cyclones can also cause significant chlorophyll increases; these increases are comparable to the ones caused by hurricanes, though on smaller scale likewise the intensity of medicanes compared to the one of hurricanes.

Although there is a lack in the daily available chlorophyll data (especially for the day before the event), chlorophyll seems to start increasing during the medicanes’ approach, passage or just after it. Increased chlorophyll concentrations were observed the days after the event in a large portion of the affected area, revealed as well by the relevant calculations of the week that followed. An increase in chlorophyll that initiated during the hurricanes’ passage with the high chl-a values lasting for the following weeks have also been reported for cases in oligotrophic Atlantic waters [23]. It is also noted that model experiments have shown that the center of the storm lags the area of increased chl-a by several kilometers [40].

The open sea areas, where a large percentage of chlorophyll increase was observed, were usually impacted by both strong winds and high precipitation amounts; regarding the P areas examined, the one of the 13–15 December 2005 case was mainly affected by strong winds. The open sea areas presented a decrease in SST by more than 1 °C and the P areas up to 2.5 °C. The role of precipitation in increasing chlorophyll by adding nutrients from the atmosphere seems more significant over coastal areas that were also affected by land runoff and river discharges.

The main mechanisms that have been proposed to explain the increased chlorophyll concentrations following tropical cyclones, are the cyclone-induced upwelling and the wind mixing; they cause a breakdown of the water column stratification and deepen the mixed layer, resulting in inducing nutrients from deeper layers to layers near sea surface, enhancing, therefore, phytoplankton growth. It has been found that the amount of nutrients (e.g., nitrate) that are brought from the deeper layers under the influence of a storm and can further support primary production and chl-a increase is smaller for faster moving, less intense, and less extensive storms [40]. The procedures of upwelling and mixing, mentioned above, have also been proposed for hurricanes affecting the oligotrophic Atlantic waters [23], where the highest chlorophyll increases have been found in September and October, i.e., in time periods when the stratification starts breaking down; in a November case, when the MLD is the deepest of the hurricane season, a chl-a increase <20% has been found. The MLD of the region examined in the above-mentioned study is up to ~40 m in September, up to ~60 m in October and ~80 m in November [45]. The mechanisms of cyclone induced upwelling and wind mixing could also be valid here. The MLD is ~40–100 m for the study area of 13–15 December 2005 event, ~40–70 m for the area affected by the 4 December 2008 cyclone and ~20–50 m for the one of 7–8 November 2014 [46,47]. In the medicanes' affected regions studied, the water column stratification also starts collapsing mainly by the end of fall and the beginning of winter; the MLD is in general maximized during February while it is still quite shallow during the time periods studied here [46,47]. Under these circumstances, it is possible that the MLD deepens under the influence of the cyclone-induced upwelling and the strong winds' mixing, causing the SST to drop and importing nutrients to the upper layers from below, enhancing primary production. Note that in the case of 7–8 November 2014, characterized by the shallower MLD, the most pronounced chl-a increases were observed.

An additional cause that has been documented for the increased chlorophyll concentrations caused by a hurricane's passage is an upward phytoplankton entrainment from the deep chlorophyll maximum (DCM) [22–24]. The above is further supported by the model study of [40] where the initial chlorophyll increase has been resulted from its redistribution within the mixed layer; the significance of the quite comparable depths of the DCM and the after-storm MLD for larger chl-a increases has been highlighted. Since Mediterranean is characterized almost all year long (with the exception of the end of winter) by a DCM in depths of 30 m in its western parts and up to 120 m in its eastern parts [48], such a procedure could have also taken part here. The favoring role of heavy rainfall in chlorophyll increase that has also been proposed in some studies [22,27] cannot be underestimated here since in many areas of increased chl-a concentrations large precipitation amounts were recorded; this is especially valid for the coastal areas as mentioned earlier.

5. Conclusions

The main results of this paper where three tropical-like Mediterranean cyclones (one November case and two December cases) were examined in respect to their influence on surface marine chlorophyll concentrations, could be summarized as follows:

(a) An increase in chlorophyll concentration was observed after the medicanes' passage in all cases exceeding 73.4% of the study area;

(b) Chlorophyll post-medicane values that were greater than the climatological ones referred at least to 46.3% of the affected area and in most cases to much wider regions, showing the significant influence of medicanes on the Sea's phytoplankton abundance and primary production;

(c) The above percentages were extremely high when absolute chlorophyll differences exceeding 50% were concerned;

(d) A drop in SST was observed which initiated some days before the event;

(e) The November 2014 case presented the largest chlorophyll increases, that were mainly observed on the right side of the cyclone's track, and the most pronounced SST cooling;

(f) The possible mechanisms for the observed chlorophyll increase caused by medicanes could be the cyclone induced upwelling and the wind mixing processes, a possible chl-a entrainment from the DCM plus a complementary favoring role of heavy precipitation at places;

(g) The increase in chlorophyll was comparable, though on smaller scale, to the one caused by hurricanes in oligotrophic environments.

The present study explored for the first time the influence of the tropical-like Mediterranean cyclones on the Sea's surface chlorophyll concentration. The findings showed that, though medicanes are of lower intensity compared to hurricanes, they also cause significant chlorophyll increases.

Author Contributions: Conceptualization, D.K. (Dionysia Kotta); Data curation, D.K. (Dionysia Kotta); Formal analysis, D.K. (Dionysia Kotta); Investigation, D.K. (Dionysia Kotta); Methodology, D.K. (Dionysia Kotta); Project administration, D.K. (Dionysia Kotta) and D.K. (Dimitra Kitsiou); Resources, D.K. (Dionysia Kotta); Supervision, D.K. (Dionysia Kotta) and D.K. (Dimitra Kitsiou); Validation, D.K. (Dionysia Kotta) and D.K. (Dimitra Kitsiou); Visualization, D.K. (Dionysia Kotta); Writing—original draft, D.K. (Dionysia Kotta); Writing—review and editing, D.K. (Dionysia Kotta) and D.K. (Dimitra Kitsiou).

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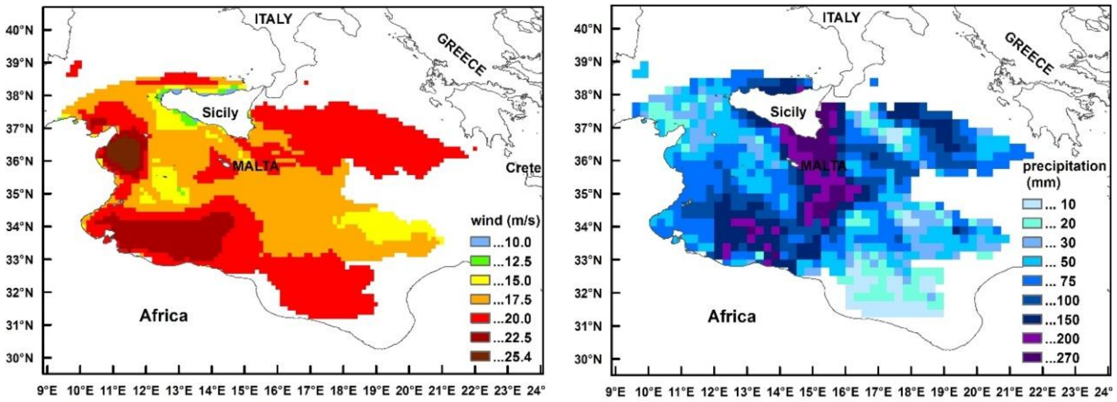
Conflicts of Interest: The authors declare no conflict of interest.

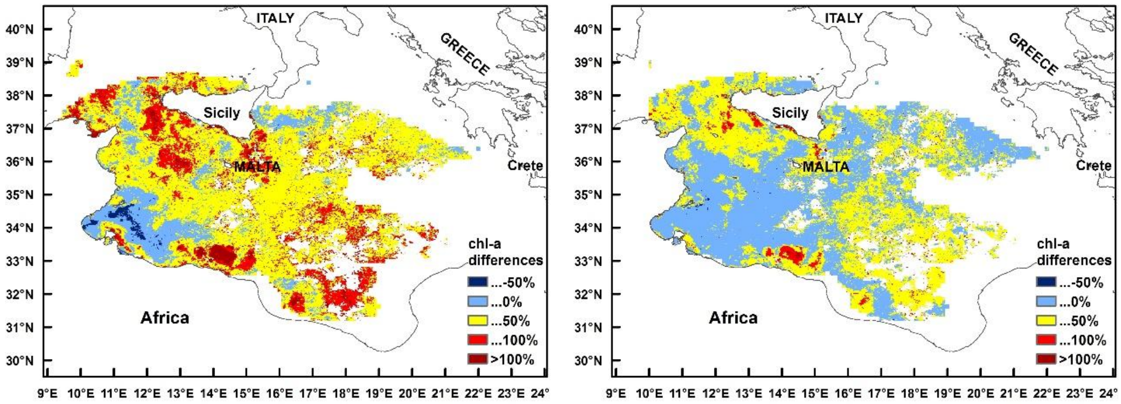
Appendix A

Here are given the maximum 10 m wind speed during the events, the total precipitation (of one day before each event till one day after) and the chlorophyll differences of the week after each medicane from the one before or during the event as well as from the monthly climatology.



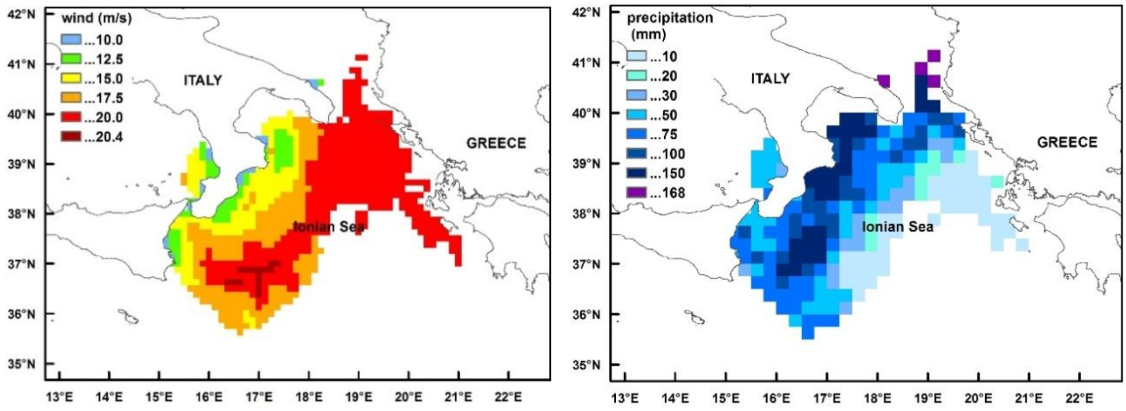
(**a**) (**b**)

Figure A1. (**a**) Maximum 10 m wind speed during the medicane of 13–15 December 2005; (**b**) Precipitation sum for 12–16 December 2005.



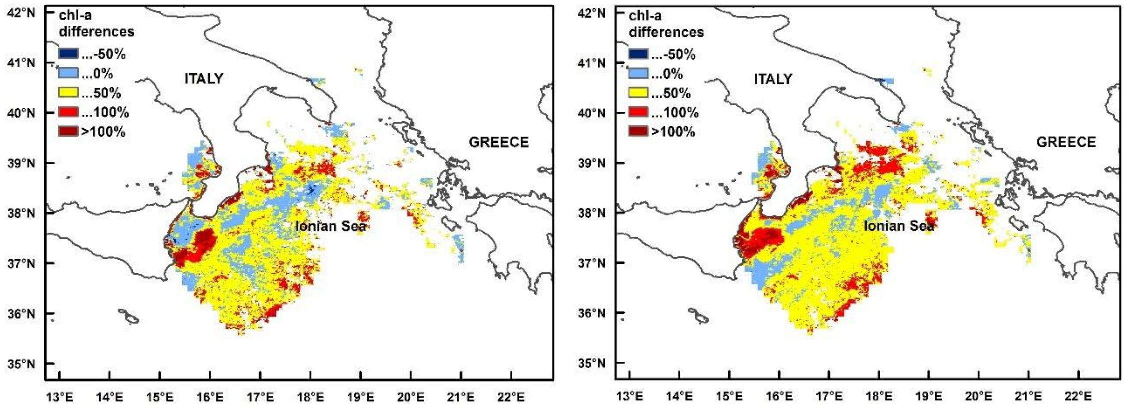
(**a**) (**b**)

Figure A2. (**a**) Chlorophyll percentage differences between the week after the event (19–26 December 2005) and the week before the event (3–10 December 2005); (**b**) Chlorophyll percentage differences between the week after the event (19–26 December 2005) and the climatological mean values for December.



(**a**) (**b**)

Figure A3. (**a**) Maximum 10 m wind speed during the medicane of 4 December 2008; (**b**) Precipitation sum for 3–5 December 2008.



(**a**) (**b**)

Figure A4. (**a**) Chlorophyll percentage differences between the week after the event (10–17 December 2008) and the week of the event (2–9 December 2008); (**b**) Chlorophyll percentage differences between the week after the event (10–17 December 2008) and the December climatological mean values.

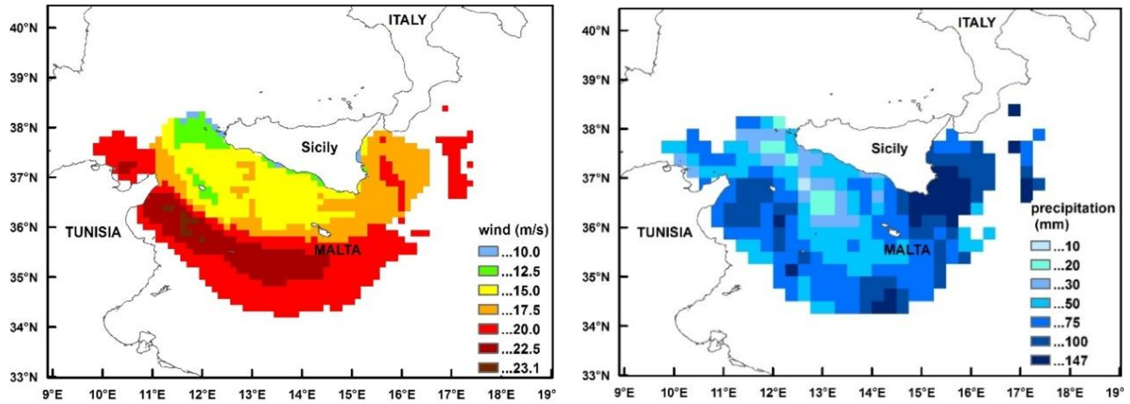
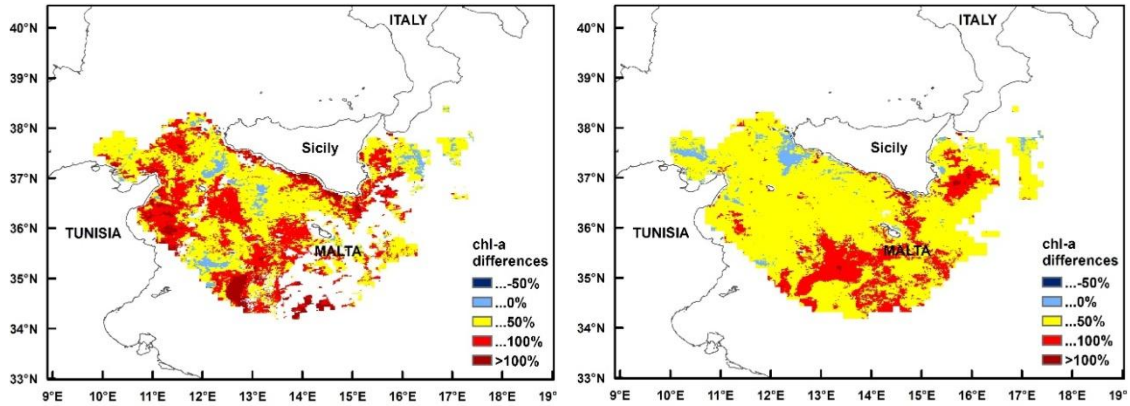


Figure A5. (**a**) Maximum 10 m wind speed during the medicane of 7–8 November 2014; (**b**) Precipitation sum for 6–8 November 2014.



(**a**) (**b**)

Figure A6. (**a**) Chlorophyll percentage differences between the week after the event (9–16 November 2014) and the week of the event (1–8 November 2014); (**b**) Chlorophyll percentage differences between the week after the event and the November climatological mean values.

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5. Relations between Sea Surface Chlorophyll Concentrations and Meteorological Parameters on a Monthly Basis

5.1. Introduction

This part refers to the possible relations between sea surface chlorophyll concentration and selected meteorological parameters.

As a first step the examination of two regions characterized by different chlorophyll regimes, the Rhodes Gyre and the Cyclades Plateau, was performed. The chlorophyll variations were assessed in respect to the parameters of SST, wind speed, temperature, precipitation and MSL pressure, for a 10-year period and the month of March. The study was published in a peer-reviewed journal.

A limited relevant study was also carried out referring to the winter period of 2014 and 2015 that were characterized by different weather conditions. Although it formed part of a preliminary research, this study was presented in an international conference.

Based on the findings of the above mentioned work, the research ended up with a more ‘climatic approach’ in assessing the possible relations between meteorological factors and sea surface chlorophyll concentrations. It took advantage of the longest available (1998–2016) homogenous time series of satellite derived chlorophyll data plus a reanalysis dataset for the meteorological variables. Correlations between chlorophyll and meteorological parameters were estimated for the Eastern Med Sea, discriminating between seasons and including the rarely studied parameters of wave height, MSL pressure and precipitation. The trends of all parameters were also calculated. However, the period examined, determined by the chlorophyll data availability, is far from what is called the “average of weather” or climate in Meteorology. According to the World Meteorological Organization (WMO), a 30-year period is at least needed for describing the behavior of the atmosphere and the distribution of meteorological parameters including anomalous events (http://www.wmo.int/pages/prog/wcp/ccl/documents/GUIDELINESONTHEDEFINTIONANDMONITORINGOFEXTREMEWEATHERANDCLIMATEEVENTS_09032018.pdf, assessed on 15/7/2019).

5.2. Chlorophyll-a variations in terms of meteorological forcing: The Rhodes Gyre and Cyclades region

ABSTRACT

In the eastern Mediterranean Sea, characterized in general as an oligotrophic area, there are regions like the Rhodes Gyre revealing strong early spring blooms and others like the Cyclades plateau where no blooms are observed but gradual chlorophyll-a increase from autumn to spring, with maximum values usually reached in March. Meteorological factors such as wind and precipitation are considered to influence marine productivity. The above mentioned regions are examined for the last decade - focusing on March - in order to assess chlorophyll-a variations in terms of meteorological forcing. Monthly satellite data for chlorophyll-a concentrations and meteorological datasets were used and processed in the framework of a Geographical Information System (GIS). Cases of extended blooms over Rhodes Gyre and of small but significant chlorophyll-a variations over Cyclades region were detected. Precipitation, wind speed, air temperature, sea surface temperature and mean sea level pressure were investigated as factors affecting chlorophyll-a increase and some of them were found to have important and complementary influence. High wind speed values and considerable precipitation amounts, combined with low mean sea level pressure and quite low sea surface temperatures were revealed as prerequisites for high chlorophyll-a concentrations and blooms. In addition, the absence of precipitation or very low wind speed values could prevent the formation of a bloom.

KEYWORDS: satellite data, precipitation, wind, temperature, mean sea level pressure, GIS

Kotta D. and Kitsiou D. (2014) Chlorophyll-a variations in terms of meteorological forcing: The Rhodes Gyre and the Cyclades region. Fresenius Environmental bulletin, 23(12a): 3131-3139.

1. INTRODUCTION

Phytoplankton which provides a sink for atmospheric CO_2 through photosynthesis, is a particularly good indicator of climate change in the marine environment [1]. It has been also proven to be an indicator for assessing marine ecosystems' response to external forcing [2]. Its variability influences all higher trophic levels, since shifts in climatic conditions can generate changes in marine communities [3, 4], leading to economic and financial impacts. Therefore, chl-a concentrations on water masses, which indicate the presence of phytoplankton species, their alterations and the related reasons are a matter of continuous research. During the last decades, satellite sensors measure ocean colour, providing information up to a few tens of meters depth [5], estimating chl-a [6] as a good proxy for primary production [7], therefore making data available over extended areas that is impossible to acquire with *in situ* measurements.

The Mediterranean basin is one of the less productive seas of the world, especially in its eastern part [8], and follows the subtropical model for primary production, which is nutrient-limited over its largest part [9]. Thus, among the important factors for phytoplankton growth, such as temperature, light and nutrients, the latter is considered to be of high importance. The basin presents high biodiversity and undergoes alterations due to climate change and human pressure [10]. Quite recent results showed that phytoplankton abundance was significantly affected by temperature changes [11]. Since the area has been identified as a ”hot spot” regarding climate change projections [12], research on chl-a concentrations in relation to meteorological factors and environmental variables is of great importance.

A wide range of studies have assessed the relationship between meteorological conditions and phytoplankton blooms locally over Mediterranean [13-17], in particular over coastal and near shore areas. Sea surface temperature (SST) has been widely used to identify areas of high primary production [18, 19]. Negative correlations between high chl-a concentrations and SST were detected [20] and related to potential fishery locations [21]. Winds influence primary productivity in the Mediterranean [14,16], especially through wind-induced upwelling [22, 23]. Precipitation has been identified as a factor affecting phytoplankton, mainly due to nutrient input from atmosphere and/or land into sea water [24, 25], thus favouring its growth. However, precipitation's effect on primary production has been mainly studied over coastal areas and the nutrient input has been attributed to agricultural [26] and river runoff [23, 27]. In addition, statistical methods have been applied to identify relationships between chlorophyll concentration and environmental variables in the Mediterranean [28], suggesting that atmospheric forcing varies depending on the area and the temporal and spatial scale.

The aim of the present study was the detection of relationships between chl-a concentrations and selected meteorological parameters in the marine environment; locally, over different areas and on a specified and significant for the primary production time period. In order to minimize the influence of other parameters, the study was focused on areas characterized by low human and land pressure. The meteorological impact was assessed in two contrasting areas during the high productive period. The first area was the Rhodes Gyre in the Levantine basin that is one of the most productive regions of the Mediterranean Sea, revealing a sporadic late winter/early spring bloom [29]. The second area was the Cyclades plateau in the

Aegean Sea which represented a typical oligotrophic area [29]. The study was carried out over a 10-years period for the month of March, when the Rhodes Gyre bloom is observed and relatively high chl-a concentrations characterize the Cyclades area [30, 31]. The meteorological parameters of precipitation, 10m wind speed, 2m air temperature and mean sea level (msl) pressure as well as SST were selected for assessing their possible impact on primary productivity. According to authors' knowledge, such different regions have not been examined in terms of meteorological forcing on primary production in the past. In addition, there is limited bibliography on the influence of the msl pressure on chl-a variations, especially at local scales.

2. MATERIALS AND METHODS

2.1 Study areas

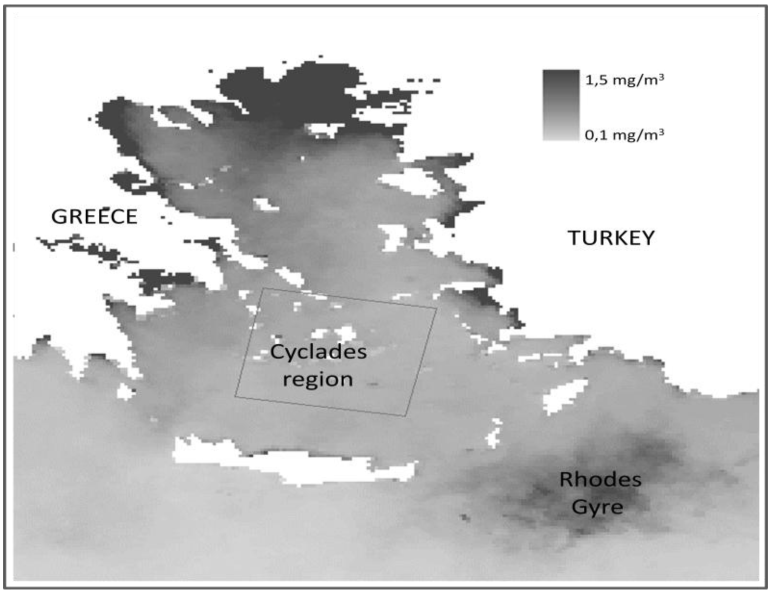

FIGURE - 1. The study areas of Rhodes Gyre and Cyclades region as seen upon a March chl-a climatology map.

The study areas are shown in Fig. 1. The Rhodes Gyre is a cyclonic feature of the eastern Mediterranean circulation, where upwelling of nutrient-rich deep waters cause higher primary production. It is characterized by a strong early spring bloom which has a short lifetime, and its annual primary production is comparable to the productive north-western Mediterranean [31]. The region's maximum chl-a concentrations was detected in March based on SeaWiFS data sets (1998–2003) [30], and the latter was confirmed by MODIS 2003 - 2012 monthly climatology data in the current study (not shown). On the other hand, the Cyclades region is characterized by a gradual chl-a increase from autumn to early spring [30]. It is worth-mentioning that the area is minimally affected by riverine nutrient loads as well as by anthropogenic ones, as there is no significant agricultural activity and the population is quite limited, especially during winter. Rhodes Gyre was classified as an "intermittently blooming" area, based on K-means cluster analysis [29], as intermittently blooms are observed in early spring – March, while Cyclades is a "non-blooming" area. The present study focused on March during the period 2003-2012.

2.2 Datasets

The satellite chl-a data were retrieved from myOcean project (www.myocean.eu), specifically the monthly interpolated means of surface chlorophyll (resolution 1.1 km). In addition, the standard monthly and monthly climatology products from Level 3 Browser of Aqua MODIS chlorophyll concentration (resolution 4 km) were acquired from the NASA OceanColor Website (http://oceancolor.gsfc.nasa.gov). Although the latter are affected by a calibration problem in the Mediterranean Sea, their use for detecting monthly trends could not affect the results significantly [29, 32]. For the Rhodes Gyre, data from both myOcean and OceanColor led to similar conclusions; the results presented herein are from the processing of Ocean-Color datasets. For the Cyclades region, where the chl-a variations are small, the finer resolution myOcean data are presented here.

The meteorological data are numerical weather products from the ERA Interim Re-analysis project (grid $0{,}125^o$ x $0{,}125^o$) of the European Centre for Medium-Range Weather Forecasts (ECMWF - www.ecmwf.int). Monthly means of daily means data were used for 10m wind speed, sea surface temperature (SST), 2m temperature and msl pressure, and monthly means of daily forecast accumulations for precipitation. In addition, Hellenic National Meteorological Service (HNMS) station data were used to reveal trends of the meteorological parameters and their interconnections.

The parameters of SST and 2m temperature were selected as proxies of the water column stratification – high temperatures could lead to strong stratification preventing nutrient supply from deeper layers, thus altering the main factor for phytoplankton growth. Precipitation was selected because it is also related to nutrient input. Wind speed was studied, since it is considered as an important factor influencing marine primary production. Finally, msl pressure was also included in the analysis as a possible factor affecting chl-a variations at local scales.

2.3 Methodology

The monthly satellite and meteorological data sets for every March of the 10-years period 2003 – 2012 were organized and processed in a GIS environment. For each area and for all parameters, maps of the 10-years mean (hereafter climatology) were computed. The mean monthly values of each parameter over both areas were calculated and used for the detection of possible relationships between chl-a concentrations and meteorological factors. For chl-a concentrations, a reclassification was performed and the percentage of pixels with values higher than climatology mean and climatology maximum was determined for each March, in order to detect the spatial extent of the blooming area.

Cases with important differences, such as high chl-a concentrations and extended bloom area (compared to climatology), or very low chl-a values and limited bloom area, were initially detected for the Rhodes Gyre. Possible relationships between chl-a concentrations and meteorological parameters were assessed and further studied in other cases.

Pearson’s correlation coefficients between meteorological parameters’ mean values and chl-a concentrations as well as the percentage of pixels with chl-a values higher than climatology mean, as a measure of the extent of the bloom, were calculated. A pixel-by-pixel correlation was performed only for precipitation in the Rhodes Gyre area.

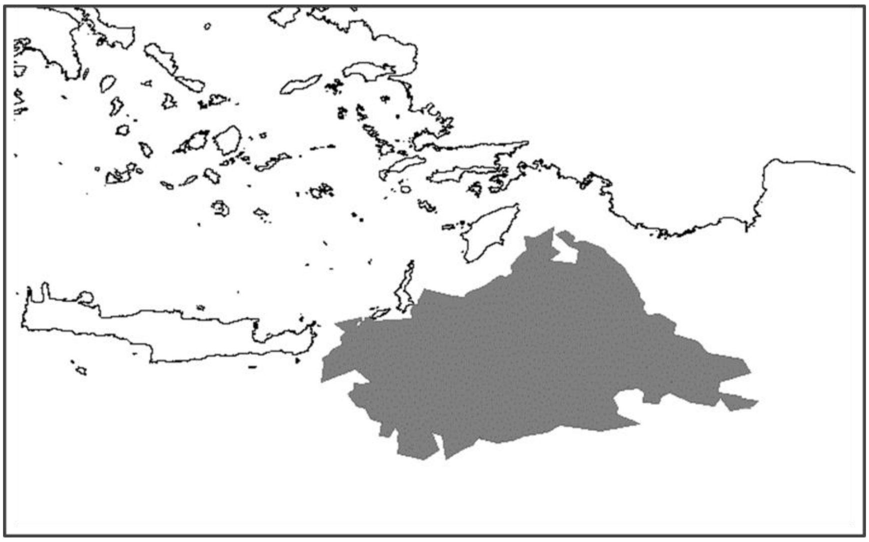

FIGURE - 2. The Rhodes Gyre region as defined by setting the condition of chl-a pixel values greater than 0.25 mg/m^3 at least for two years in March over the study period.

It should be noted that while the Cyclades plateau is geographically determined, the extent of the Rhodes Gyre was determined as the area where chl-a values were higher than 0.25 mg/m^3, at least for two years in March during the 10-years' study period (Fig. 2).

3. RESULTS

3.1 The Rhodes Gyre

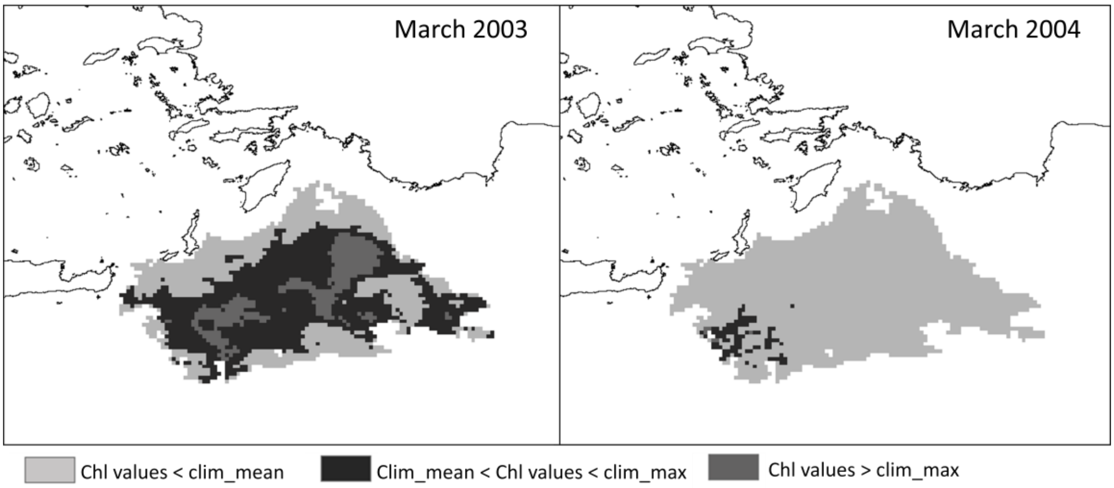

FIGURE - 3. Chl-a concentrations, reclassified in respect to climatology mean and maximum values, revealing the important differences between March 2003 and March 2004 that could be attributed to different meteorological conditions.

Chl-a concentrations in March 2003 were notably high and the bloom was particularly extended, while in March 2004, there was no bloom (Fig. 3); also observed by [29]. In

March 2003, the precipitation was by far higher than climatology, 10m wind speed was higher, and msl pressure, 2m temperature and SST were lower. At the first place, one could assume that extensive blooms might be related to such meteorological parameters' values.

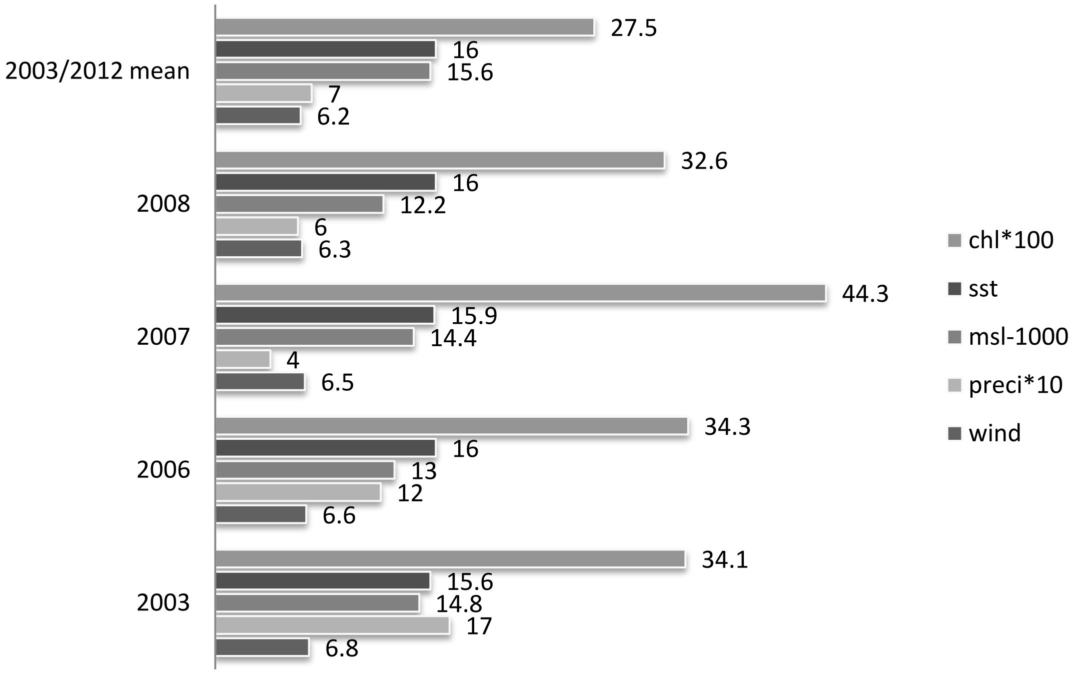

FIGURE - 4. Mean values of meteorological parameters and chl-a for the years of extended blooms in the Rhodes Gyre, in respect to 2003-2012 climatology mean.
(chl-a: mg/m^3, SST: ^{o}C, msl: hPa, precipitation: mm/day, 10m wind speed: m/s)

There were four cases in the study period characterized by extensive blooms: 2003, 2006, 2007 and 2008, where the mean chl-a value for the area was higher than climatology. In addition, more than 50% of the area exceeded the mean climatology value, while at least 12% exceeded the maximum. In Fig. 4, the mean chl-a and meteorological parameters' values (except 2m temperature) are presented, together with the mean climatology values of the 10-years' period. In all cases, 10m wind speed values were higher than climatology, msl pressure lower, SST lower or equal, and the precipitation almost equal or higher (except for March 2007). A clear relation with 2m temperature was not revealed. It could be concluded that for an extended area where high chl-a concentrations are observed, the following conditions are fulfilled: high wind speed values, low msl pressure, SST not exceeding the climatology value and, at least, some precipitation amount.

In Figs. 5 and 6, all the chl-a data and the mean values of the meteorological parameters of 10m wind speed, precipitation and msl pressure are presented, along with their mean 10-years' climatology values and the percentage of pixels with chl-a values exceeding climatology mean. For March 2005, the low mean chl-a concentrations and the limited blooming area could be attributed to the low wind speed value (as all the other conditions were fulfilled) and considered as a limiting factor for bloom development. In addition, in March 2010, the very limited blooming area could rather be attributed to the absence of precipitation and not to the fact that

SST was 0.5 ^{o}C higher than climatology (not shown) considering it as another limiting factor.

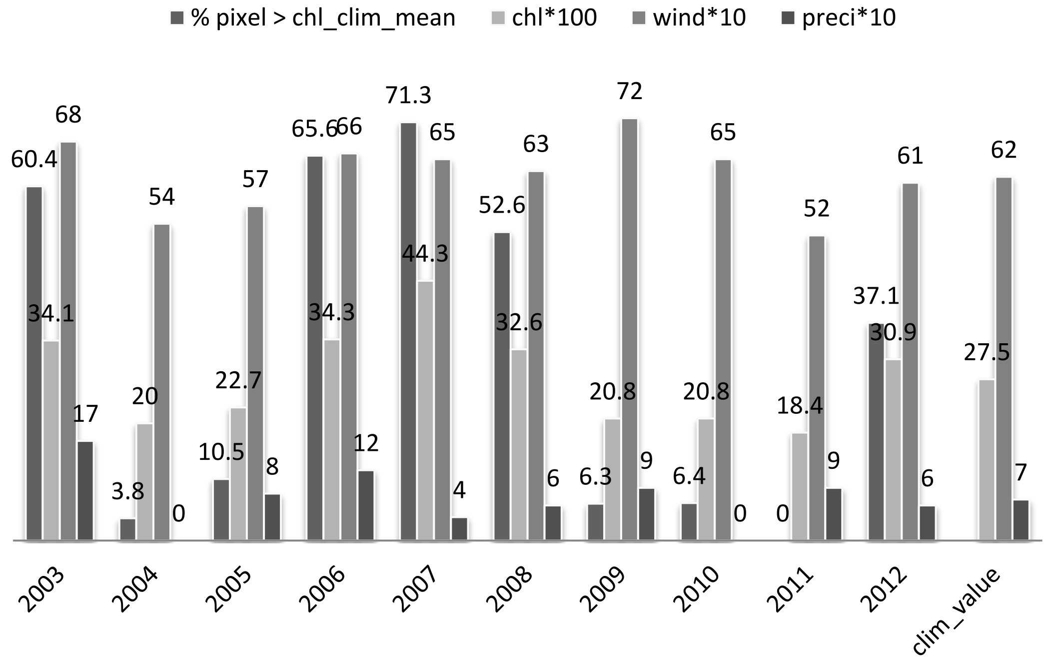

FIGURE - 5. The % number of pixels with chl-a values higher than the climatology mean, the mean chl-a values (mg/m^3) and the mean values of 10m wind speed (m/s) and precipitation (mm/day) for the study period along with climatology values.

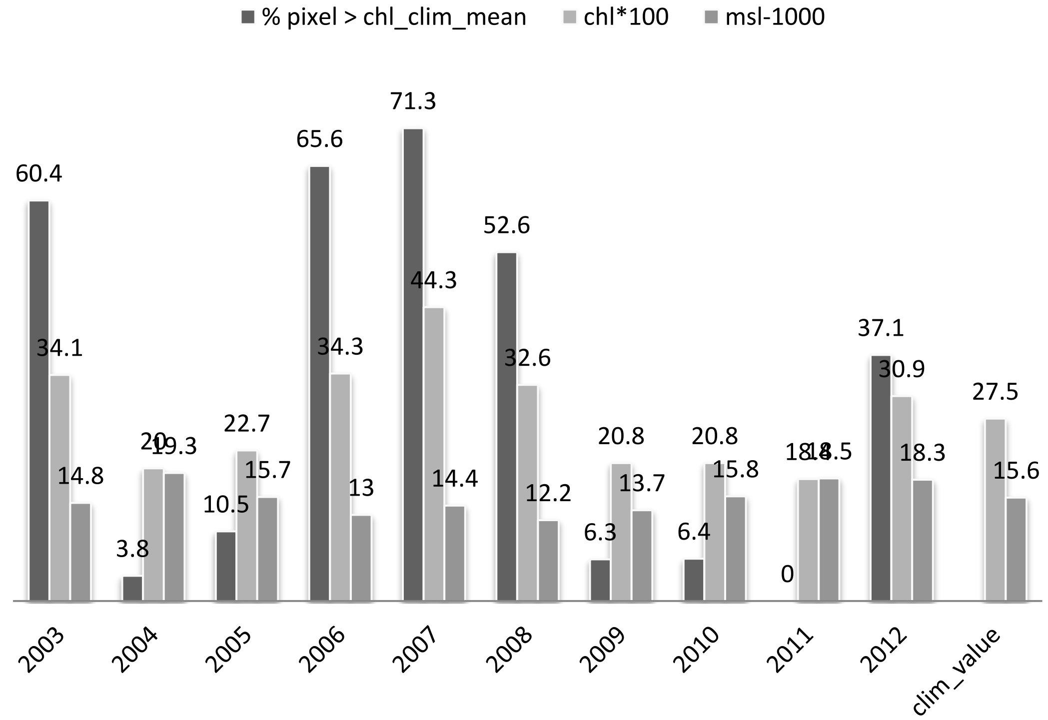

FIGURE - 6. As in Fig. 5 but for the meteorological parameter of msl pressure (hPa).

Though the extended blooms of the study period always fulfill the conditions mentioned above, there is the case of March 2009 where all the conditions were fulfilled but practically no bloom occurred. Therefore, these conditions seem to be necessary but not sufficient for the occurrence of a bloom.

The Pearson correlation coefficient between chl-a and meteorological parameters' mean values resulted, as expected, in positive correlations with precipitation (0.26) and wind speed (0.42) and negative ones with msl pressure (-0.5) and SST (-0.5). Small and negative was also the correlation with 2m temperature. The correlations regarding the percentage of pixels with chl-a values higher than climatology - the measure of the extent of the bloom – and the meteorological parameters were even greater. The correlations were higher when the March of 2009 was excluded. The pixel-by-pixel correlation performed between chl-a values and precipitation resulted in positive correlations for the 75% of the area with the 10% being above 0.5.

3.2 The Cyclades region

Over this low productive area, only three cases, 2006, 2007 and 2008, presented higher than climatology chl-a values over more than the 75% of the area. In Fig. 7, the mean chl-a and meteorological parameters' values (except 2m temperature) are presented together with the mean climatology value of the 10-years' period. In all cases, msl pressure and SST were lower than climatology, while 10m wind speed and precipitation were higher or almost equal. It is possible that the very high precipitation value of March 2006 played a complementary role to the lower than climatology wind speed, resulting in high chl-a values. The conditions identified in the Rhodes Gyre area were fulfilled for the Cyclades area as well.

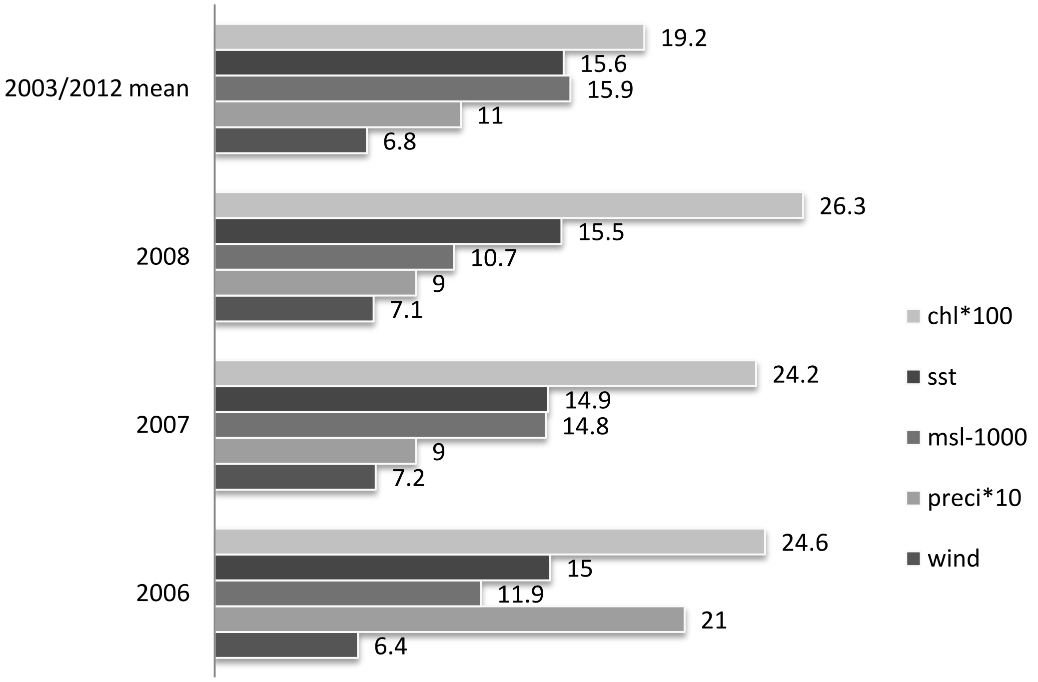

FIGURE - 7. Mean values of meteorological parameters and chl-a for Cyclades area, in respect to 2003-2012 climatology mean.
(chl-a: mg/m^3, SST: ^{o}C, msl: hPa, precipitation: mm/day, 10m wind speed: m/s)

The Pearson correlation coefficients, for all the study period, of mean chl-a concentrations or the percentage of pixels with chl-a values higher than climatology, were negative with SST, positive with precipitation, and negative and particularly important with msl pressure (-0.7). Surprisingly, correlations with wind speed were rather insignificant, while with 2m temperature were positive.

4. DISCUSSION

Chl-a and SST were negatively correlated in this study. Negative statistically significant correlations were found between these two parameters in the Mediterranean [28] as well as significant negative linear relationships were detected at local scales [33]. In the Aegean Sea, higher values of chlorophyll concentration corresponded to lower temperatures, although their variations were not closely linked [34]. This inverse relationship was also revealed in the present study, confirming that low phytoplankton abundance is related to water column stratification corresponding to high SST over intermittently or non blooming areas [35]. On the other hand, in the absence of stratification, the extent of the mixed layer depth has a strong impact on phytoplankton dynamics, since it determines both nutrient and light availability [36]. For the Rhodes Gyre, it was stated that the reduced cooling resulted in shallower mixed layers and thus in weaker blooms [31]; in addition, chl-a maximum values were detected about a month after the mixed layer depth maximum [37]. Therefore, in the present study, SST and chl-a could have possibly presented a stronger inverse relationship, if examined with a monthly gap. For Cyclades region, where the maxima of mixed layer depth and chl-a are concurrent, the concluded results of the current study on this relation are safer.

In some cases over the Mediterranean, air temperature presented a negative correlation with chl-a concentrations [28], while over the Aegean Sea no correlation was found [34]. No significant correlation was revealed between chl-a and 2m temperature in the present study: for the Rhodes Gyre region, a small negative correlation, while over Cyclades the correlation was small and positive. The latter could be explained through the complementary role of rainfall in primary production, that in March is usually accompanied by southern winds rising air temperature (HNMS data base).

Wind speed values were found to be higher than the climatology means in all cases of increased chl-a concentration. That was not surprising, mainly for the Rhodes Gyre, as wind is considered to be the most relevant factor influencing phytoplankton blooms, especially with the presence of cyclonic structures [29]. The two parameters showed positive correlation at local scales over the Mediterranean [28], since strong winds can disturb the stratification of the water column and favour its mixing, increasing primary production by importing nutrients into the euphotic zone. Chl-a concentration and wind-mixing index (the cube of wind speed) were also found positively correlated, implying the importance of the wind-induced mixing processes [33]. In the present study, the two parameters were positively correlated over the Rhodes Gyre area, where stronger correlations were detected between the extent of the bloom and wind speed. In the centre of the Gyre, more nutrients from the deeper layers are brought to the surface due to upwelling, i.e. nitrate was found much higher [38], and could be transferred by wind induced waves to greater distances over the adjacent areas; this fact could explain the stronger correlation between wind speed and the extent of the bloom. On the contrary, the correlation of the two parameters over Cyclades was rather insignificant; probably due to the quite stable wind regime of the area (HNMS station data).

Precipitation amounts higher or equal to climatology values for almost all cases of high chl-a concentrations and positive correlation between the two parameters were found. Precipitation over the Mediterranean usually presents a positive correlation with chl-a (at least in the long run) which is attributed to nutrient supply through rainfall into the upper layers [28]. In Eastern Mediterranean, atmospheric inputs of N and P, leading to increase of primary production [39], are an alternative to the vertical mixing source of nutrients. In addition, the role of precipitation has been indicated to be significant for nutrient limited areas [40]. Very high precipitation values might have mostly triggered the chl-a increase over the Cyclades area (March 2006), since for this quite moderate (and at places mainly over its eastern part) upwelling area [22], nutrients from precipitation seem to be of great importance.

The very limited blooming area over the Rhodes Gyre (March 2010) could probably be attributed to the absence of precipitation and, therefore, to low atmospheric nutrient supply into the upper layers. For the areas studied, chl-a concentration increase could be also related to the Saharan dust wet deposition - with nutrients essential for primary production - which peaks over the Eastern Mediterranean in spring [41].

Chl-a has been related to the sea level pressure of all northern hemisphere in order to reveal large-scale atmospheric and teleconnection patterns driving its distribution in the Mediterranean [28]. In the present study, this relation was investigated at local scales and it is worth mentioning that in all cases, low msl pressures were observed along with high chl-a concentrations, especially over the Cyclades region. The latter could be attributed to rain and strong winds related to low msl pressure patterns over the area (HNMS data base), and needs to be further examined.

In the present study, it was revealed that wind speed, msl pressure and SST values, higher, lower, equal or lower than climatology, respectively, and considerable precipitation amounts were related to high chl-a concentrations. However, in the case of March 2009, though all the above-mentioned conditions were fulfilled, no bloom occurred over the Rhodes Gyre region. Therefore, these conditions could rather be characterized as necessary but not sufficient to lead to high chl-a concentrations or blooms. It should be also noted that for the oligotrophic Cyclades area no such a deviation was detected. In addition, low msl pressure values along with precipitation were identified as the most important factors for this region.

HNMS station data for Naxos and Milos (Cyclades area) of the period 1955-2013 during March reveal that temperature presents an increasing trend, precipitation a slightly decreasing one, while wind speed presents no trend. During last decades, there is a warming trend in the Aegean Sea along with a decreasing one in monthly chlorophyll values [34], and a positive sea level pressure trend over the Mediterranean [42]. According to global and regional climate models and all IPCC (Intergovernmental Panel on Climate Change) scenarios, for both areas the trends for future changes are a small decrease of wind speed [43], an increase of sea level pressure [44] especially over the Cyclades area, an increase of temperature over Cyclades, and no significant trend over the Rhodes Gyre area [45], along with small to large decrease of precipitation [44]. Thus, all conditions identified in the present study and related to high chlorophyll concentrations are rather expected not to be fulfilled in the future; a fact, that could lead to significant alteration in primary production.

5. CONCLUSIONS

The study of the chl-a variations, in respect to selected meteorological parameters, over an intermittently blooming and a non blooming area, during 10 years focusing on the increased primary production time period, led to the identification of the following conditions to be satisfied for high chl-a values over extended areas: higher wind speed, lower msl pressure, lower or equal SST values compared to climatology, and considerable precipitation amount. Possible complementary roles of wind speed and precipitation were detected, in cases where the values of one parameter deviated from the conditions, but not significantly. Low wind speed values as well as very low values or absence of precipitation were considered as limiting factors for chl-a increase. Low msl pressure was always related to high chl-a concentrations, especially over the oligotrophic area. The conditions revealed by the present study seem to be necessary but not sufficient to lead to high chl-a values or blooms and, therefore, should be further assessed over more areas, more extended time series and at seasonal level, especially in the light of possible climate changes.

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5.3. Variation of Chlorophyll *α* Concentrations Related to Winter Weather Conditions

Extended abstract

The Hellenic Seas (Eastern Mediterranean) are in general characterized by low primary production with chlorophyll *α* concentration - the indicator of phytoplankton abundance - being higher in winter and/or early spring. Weather conditions could influence marine primary production, affecting in some extent the necessary components of the procedure: light and nutrients; therefore it is considered important to assess their impact on chlorophyll *α* concentration.

In this paper, the variation of chlorophyll *α* concentrations in the Hellenic Seas has been studied in relation to the different weather conditions of winters 2014 and 2015. January and February 2014 were milder than 2015, the latter being colder, windier and especially during February rainier, as revealed by Hellenic National Meteorological Service data. Chlorophyll *α* variations were examined through satellite derived datasets from My Ocean project, based on Mediterranean Ocean Color algorithms. Air temperature, wind speed and precipitation represented the weather conditions; the data used were monthly means from the European Center of Medium-Range Weather Forecasts (ECMWF) Era-Interim reanalysis. Chlorophyll *α* variations were also examined in relation to satellite sea surface temperature. All datasets were stored in a spatial database and processed in the framework of a Geographical Information System (GIS). The differences of chlorophyll *α* concentrations between winter 2014 and 2015 and of the weather related parameters were calculated pixel-by-pixel for the study area.

In general, it was found that chlorophyll *α* concentration was higher during winter 2015 than 2014. In particular, almost all the important (above 35%) chlorophyll *α* concentration differences between the two years represented increase for 2015. These differences were beyond 50% over many regions and were positively related to the higher precipitation amounts and stronger winds detected over most of these areas. Chlorophyll *α* concentration increases above 70% for 2015 were also observed; over the more productive region of the North Aegean Sea, over many coastal areas - fact that could probably be attributed to terrestrial nutrient input increase due to higher rainfall - and over the cyclonic Rhodes Gyre region. Variations of chlorophyll *α* and sea surface temperature did not show any clear relation.

The results indicated that weather conditions could play an important role in the variation of chlorophyll *α* concentrations and furthermore to the primary production, since large increases in precipitation and stronger winds were related to higher chlorophyll *α* concentrations.

Keywords: precipitation, wind speed, temperature, satellite data, GIS, Aegean Sea

Kotta D. and Kitsiou D. (2015) Variation of chlorophyll *α* concentrations related to winter weather conditions. 18th International MESAEP Symposium on Environmental Pollution and its Impact on Life in the Mediterranean Region, Crete, Greece. Abstract Book, p.270. *(Poster presentation)*

Introduction

The Hellenic Seas (Eastern Mediterranean) are in general characterized by low primary production with high chlorophyll *a* concentrations observed in winter and/or early spring [Barale et al. 2008]. Weather conditions could influence marine primary production in some extent, therefore it is considered important to assess their impact on the variation of chlorophyll *α* concentrations [Katara et al. 2008].

In Greece, January and February 2014 were milder than in 2015; the latter being colder, windier and especially during February rainier. The variation of chlorophyll *α* concentrations in the Hellenic Seas has been studied related to weather conditions during these winters.

Chlorophyll *α* variations were examined through satellite derived datasets from My Ocean project based on Mediterranean Ocean Color algorithms (www.myocean.eu). Wind speed and precipitation represented the weather conditions in the study area; they derived from the European Center of Medium-Range Weather Forecasts (ECMWF - www.ecmwf.int) Era interim re-analysis monthly data. Chlorophyll *α* variations were also examined in relation to satellite sea surface temperature. All datasets were stored in a spatial database, processed in the framework of a Geographical Information System (GIS) and analyzed in a statistical package.

Results

Chlorophyll mean values for the whole study area and for both months between 2015 - 2014 were found statistically significant through a statististical paired t-test.

For January, chl-a concentrations differences (above 35%) represented, in general, increased values for 2015 in respect to 2014; the larger ones (exceeding 70%) refered only to increases. These increases seem related to higher precipitation amounts and/or stronger winds over most of the areas. The expected inverse relationship between chl-α and sea surface temperature [Katara et al., 2008] is not clearly shown (Fig.1).

For February, chl-a differences (above 35%) and the higher differences (exceeding 70%) showed again increases for 2015 over most of the areas. They seem, in general, related to higher precipitation amounts and/or stronger winds, as found in other studies [Kotta and Kitsiou 2014]. An inverse relationship between chl-α and sea surface temperature was implied (Fig.2).

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Noticeable chl-a variations were observed: over the more productive region of the North Aegean Sea; over many coastal areas that could probably be attributed to terrestrial nutrient input due to higher rainfall; and over the cyclonic Rhodes Gyre region [D’Ortenzio and d’Alcalà 2009].

Over the Northern Aegean Sea, chl-a mean value differences for both months between 2015 and 2014 were statistically significant. A positively, low but statistically significant correlation (0.21) was found between chlorophyll and precipitation, especially during February. Wind speed presented low (0.17) positive correlation with chlorophyll. Increases in chl-a were observed along with sea surface temperature decreases only locally and mainly for February.

For the near coast area of the Ionian Sea, which includes the islands, the mean chlorophyll was not statistically significant different between the two years; for the oligotrophic Ionian, chl-a variations were mainly identified over the coastal areas. However, the correlation of chl-a with precipitation as well as with wind speed were both found statistically significant, positive and low (<0.2). Lower sea surface temperatures were only locally connected to higher chl-a concentrations.

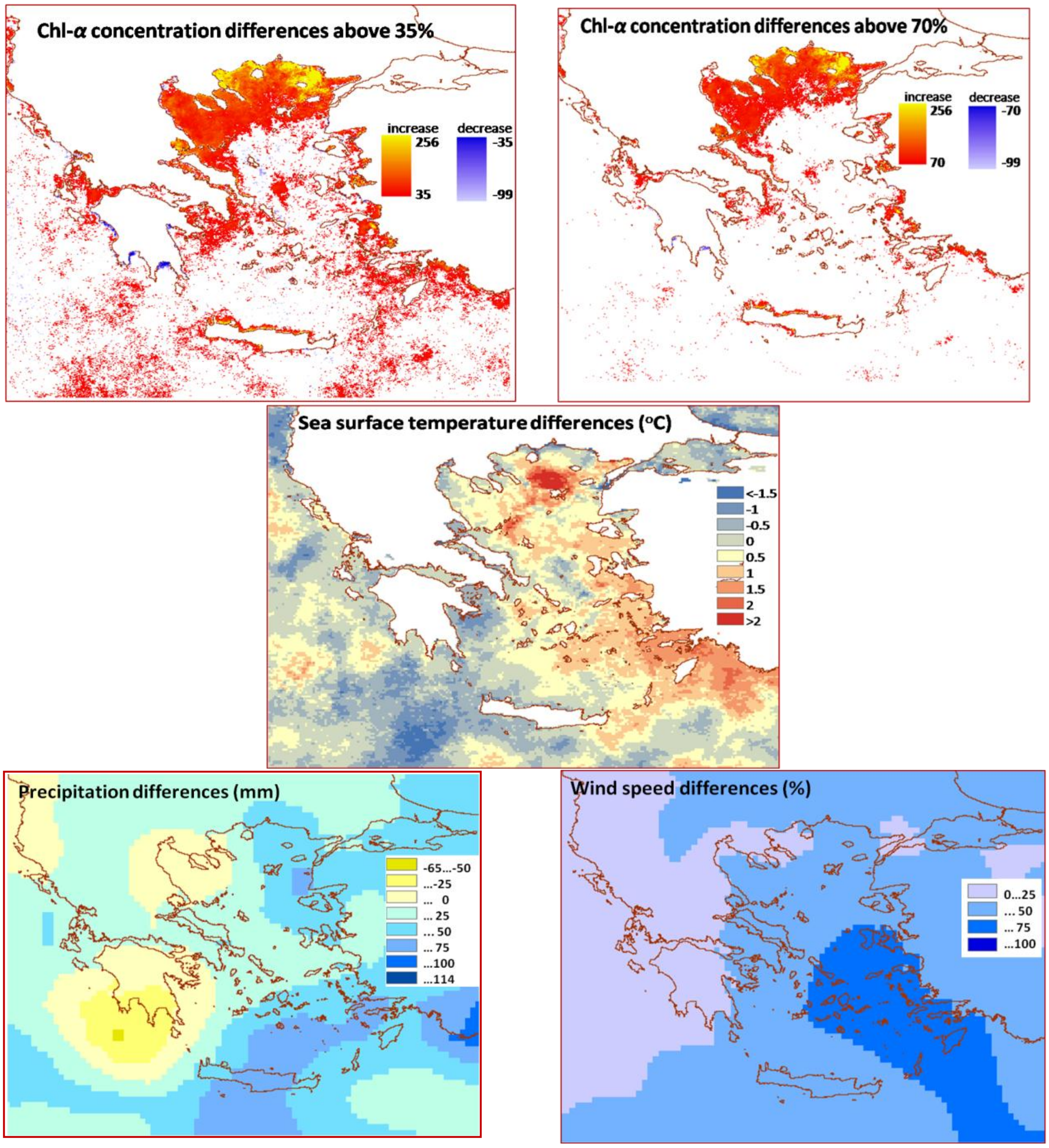

Fig.1. January 2015-2014 differences for: chl-a concentrations, SST, precipitation and 10m wind speed.

Conclusion

The findings of the current study indicated that winter weather conditions could play an important role in the variation of chlorophyll α concentrations and furthermore to primary production, even in the oligotrophic areas of the Hellenic Seas. Increase in precipitation as well as in wind speed was in general related to higher chl-a values.

Sea surface temperature and chl-a values were found inversely related only locally and mainly for February.

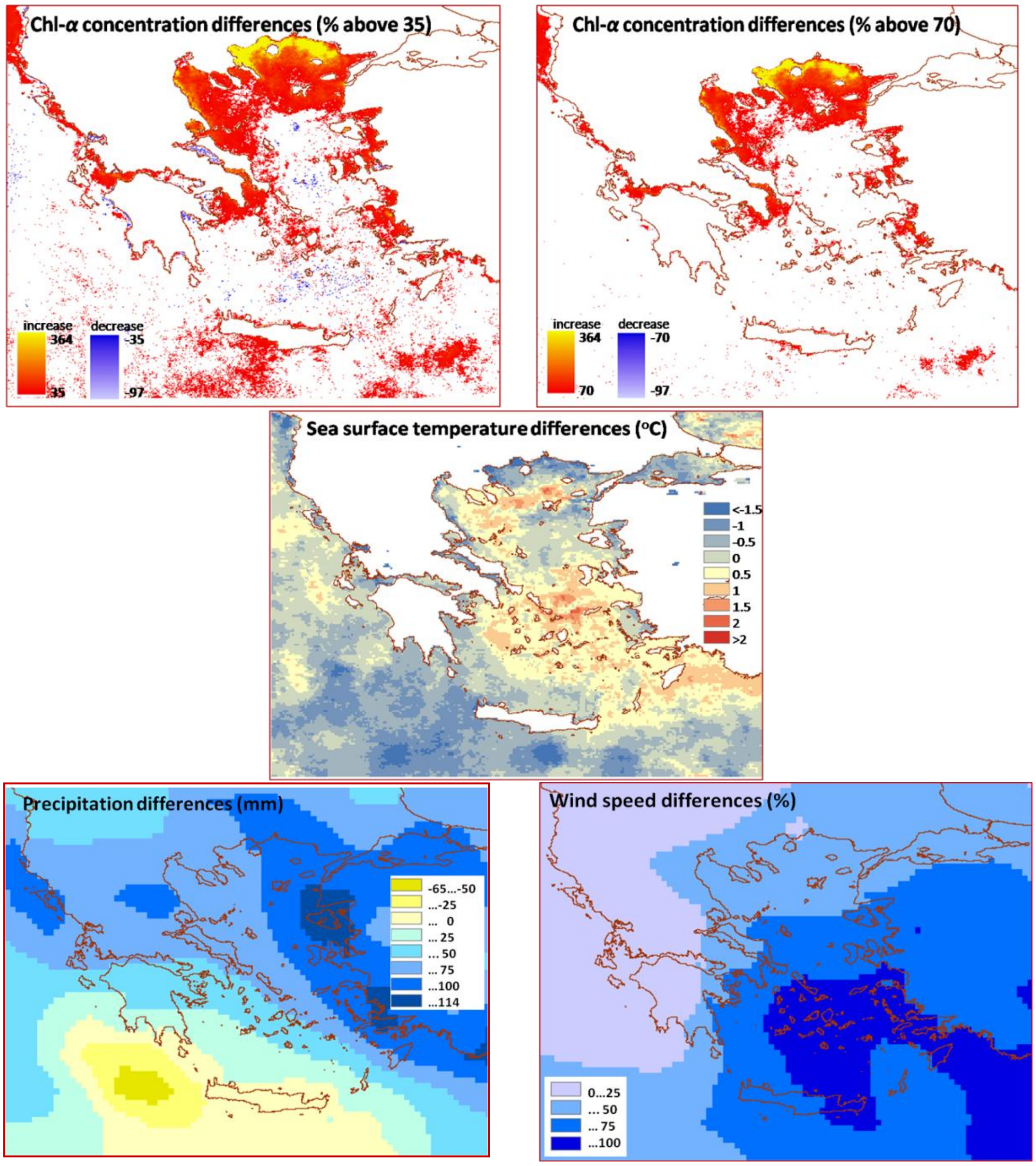

Fig.2. February 2015 – 2014 differences for: chl-a concentrations, SST, precipitation and wind speed.

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5.4. Chlorophyll in the Eastern Mediterranean Sea: Correlations with Environmental Factors and Trends

Abstract: The research on marine chlorophyll concentrations, as indicators of phytoplankton abundance, their relations with environmental parameters, and their trends is of global interest. It is also crucial when referring to oligotrophic environments where maintenance or increase in primary production is vital. The present study focuses on the Eastern Mediterranean Sea that is in general oligotrophic. Its primary goal is to explore possible relations between surface chlorophyll-a concentrations and environmental factors. The involved parameters are the sea surface temperature, the wind speed, the wave height, the precipitation, and the mean sea level pressure; their relation with chlorophyll is assessed through the calculation of the relevant correlation coefficients, based on monthly satellite-derived and numerical model data for the period 1998–2016. The results show that chlorophyll relates inversely with sea surface temperature; in general positively with wind speed and wave height; positively, although weaker, with precipitation; and negatively, but area and season limited, with mean sea level pressure. These correlations are stronger over the open southern part of the study area and strongly dependent on the season. A secondary aim of the study is the estimation of chlorophyll trends for the same time interval, which is performed separately for the low and the high production periods. The statistically significant results reveal only increasing local chlorophyll trends that, for each period, mainly characterize the eastern and the western part of the area, respectively.

Keywords: Sea surface temperature (SST); wind; wave height; precipitation; mean sea level (MSL) pressure; ocean color data; ERA interim; geographic information system (GIS).

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1. Introduction

The role of phytoplankton in Earth's system is critical; they are not only responsible for half of the planet's primary production [1], being in the base of the marine food web [2], but they also play a major role in the global carbon cycle, affecting climate change in this way [3,4]. Their growth is mainly controlled by nutrients and light [5], and they quickly react to environmental factors [4]. An indicator for phytoplankton abundance that is widely used, due to its major role in photosynthesis, is chlorophyll-a (chl-a). Its surface concentrations can be derived through the ocean color property from satellite measurements and they have been proved good phytoplankton proxies [6,7]. The availability of satellite derived chl-a data has led to extensive related research that is still ongoing and includes chlorophyll's trends and possible relations with environmental variables.

The Mediterranean Sea is an oligotrophic marine environment due to the limited nutrient availability for phytoplankton growth that is enhanced from west to east [8]. The Eastern Mediterranean (E Med) Sea, which is the study area here, presents non-blooming characteristics (i.e., smooth changes in chlorophyll from its lower concentrations during summer to the higher ones in winter) over a majority of its area; only a few areas have been identified as intermittently blooming (i.e., presenting years of blooming and non-blooming characteristics) or exhibit a coastal behavior [9]. Eutrophication is a rare case for E Med and characterizes very few inshore and nearby offshore areas exposed to river outflows and land discharges with intense anthropogenic influence [10]. The Sea follows the subtropical model for primary production, according to which, it is the nutrient level and not the light availability that controls phytoplankton growth [11]. As a result, the variability of the Sea's mixed layer depth (MLD) is the main controller for the nutrient influx from the deeper layers to the euphotic ones, and as a consequence, for phytoplankton growth and the observed chlorophyll concentrations. In general, winter is characterized by the highest chl-a values and summer by the lowest [11], coinciding with the deepest and shallowest MLDs [12,13]. The broader Med area has been characterized as a "hot-spot" for climate change [14] and atmospheric forcing has been proposed to play a determinant role in the Sea's production [11]. Consequently, it is important that the possible relations between chlorophyll concentrations and environmental parameters are studied and revealed. On the other hand, chlorophyll trends of this oligotrophic Sea are also important as they represent the trends of its trophic state.

Sea surface temperature (SST) and wind are considered as the key environmental variables controlling the MLD variability [5] and thus the nutrient availability which, in turn, determines phytoplankton's abundance and chlorophyll concentrations. In tropical and subtropical oceans, where primary production is controlled by the availability of nutrients and not by light, chlorophyll is negatively correlated with SST [5] and positively with wind speed [5,15]; this also applies for the Med as mentioned above. In the study of Katara et al. [16], it has been found that the statistically significant correlations between SST and chl-a are negative. In addition, areas with low SST-high chlorophyll have been proposed as regions of enhanced primary production in E Med [17]. Since higher SSTs have a direct effect on the stratification of the water column, they can result in the reduction of the MLD and the limitation of nutrients, causing phytoplankton and chlorophyll decreases [18]. Wind has been proposed as one of the major controllers for the Sea's production [9]. Chlorophyll and wind have been investigated for the whole Mediterranean [16] and specific locations

[19] and have been found presenting a positive relationship. These results are interpreted through wind induced vertical mixing and upwelling processes, which inversely influence the MLD [15] and the stratification of the water column, and in turn, the imported nutrients to the euphotic layer. Waves can be another factor influencing chl-a concentrations; since they act upon the sea in a similar way as the wind does, they are expected to present positive correlations with chlorophyll in the Med. Although the MLD is significantly influenced by other factors as well, such as net heat fluxes, and to a lesser degree by the differences between evaporation and precipitation, the parameters of SST and wind stress (resembling wind and waves) mentioned here are crucial for its variations. Precipitation has been identified as a factor with a positive influence on marine primary production in low nutrient areas, as seen through chlorophyll increases; this is mostly valid for areas near coasts, especially with the complementary effect of strong winds [20]. A positive correlation of precipitation and chlorophyll has been referred to in Katara et al. [16] and a favoring effect of precipitation on chlorophyll has been proposed in a study of specific regions [19]. Increased chl-a concentrations have also been observed over areas affected by high rainfall amounts through episodic and extreme events [21,22]. The reason for chl-a increases after rainfall events can be the added nutrients from the atmosphere. It is noted that for the E Med, the atmospheric inputs have been identified as the secondary nutrient source that can increase primary production [23]. Mean sea level (MSL) pressure has been referred to as an important variable related to marine production [24]. It has been examined in the Med with respect to its possible influence on chl-a concentrations through teleconnection patterns [16] and at local scales in distinct areas where low MSL pressure has been observed, along with higher chl-a values [19]. In addition, the E Med and especially the Ionian Sea, is often affected by low pressure systems, such as tropical like cyclones [25], that have been found to induce chl-a increases [26]. It is noted that all studies based on satellite-derived data refer to surface chlorophyll concentrations and disregard the photosynthetic activity of the sub-surface layers that are not captured by the remote sensors.

Chlorophyll trends, giving a strong sign for phytoplankton abundance trends, have been computed at global scales, usually together with SST co-variations [24,27,28], as well as for the Med [11,29–32], with controversial results dependent on the study period. The recent study of Salgado-Hernanz et al. [32], analyzing 17 years' worth of data, has not only discriminated chlorophyll variations in seasonal, irregular, and interannual components before computing the trends, but has also estimated trends of phenological indices such as the timing of chlorophyll peak.

The primary aim of the present work was to explore possible relations between surface chl-a concentration and the environmental factors of SST, 10 m wind speed, wave height, precipitation, and MSL pressure focusing on the open sea oligotrophic waters of the E Med. For this goal, the correlation coefficients between chlorophyll and the environmental parameters were estimated and separately calculated for each season. These calculations were based on the compilation of robust and concise relevant data sets; they involved one of the longest monthly data series (1998–2016) for chlorophyll studied so far, while all environmental data were homogeneous in the sense that they were all products of the same numerical model. The statistically significant correlations between surface chl-a and the studied parameters were: negative with SST; mainly positive with wind speed and wave height; positive, although weaker, with precipitation; and negative, but area and season limited, with

MSL pressure. It is noted that the relationships between chl-a, SST, and wind have also been addressed in global studies that included the Med through the co-variations of chlorophyll or primary production and SST [24,27,28], as well as through the correlations of chl-a with SST and wind [15]. However, the environmental factors of precipitation and MSL pressure have been scarcely involved; they have mainly been considered in studies conducted at local scales or for episodic weather events (e.g., References [21,26]). Consequently, the novelty of this part of the present work relies on: the inclusion of precipitation, MSL pressure, and wave height; the discrimination of the examined correlations between seasons; and especially on the employment of the longest time series of robust data sets used until now for such a research, which can be considered as an asset of this study.

The use of this long time series for the estimation of chlorophyll trends in the E Med was a secondary goal of this study since the analysis of chlorophyll trends for the entire Med has already been addressed several times [11,29–32]. For this aim, chl-a trends were computed with the use of a simple methodology, and separately for the low and the high production periods. The main intention was their comparison with the trends of the environmental parameters that were also calculated in order to check the results for possible inconsistencies regarding their correlation coefficients. In addition, the chl-a trends found here were compared to those derived from studies where more sophisticated methods have been used. The statistically significant results of the present study showed locally increasing surface chlorophyll trends that mainly characterize the western part of the E Med during the high production period and its eastern part for the low production period.

2. Materials and Methods

E Med is the study area in this work, which is shown in Figure 1, along with the mean yearly chlorophyll climatology, as computed for the examined period 1998–2016.

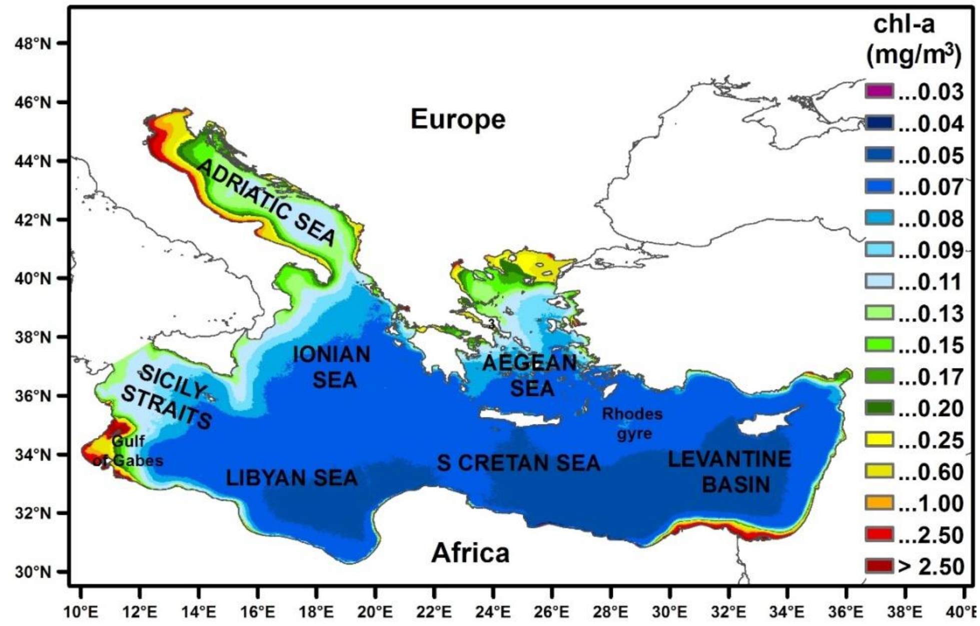


Figure 1. The study area (Eastern Mediterranean Sea) along with the mean yearly chlorophyll climatology as computed from the Copernicus Marine Environment Monitoring Service (CMEMS) data for the period 1998–2016.

The chlorophyll data used were the Copernicus Marine Environment Monitoring Service (CMEMS) product OCEANCOLOUR_MED_CHL_L4_REP_OBSERVATIONS_009_078; these involve the reprocessed surface chlorophyll concentrations (at a 1 km resolution) from multi-satellite observations (SeaWiFS, MODIS-Aqua, MERIS, and VIIRS sensors). This CMEMS product is developed based on regional ocean color algorithms that differentiate between case-1 and case-2 waters [33–36]. The applied algorithms have increased the accuracy of the resulting products, especially for the low chlorophyll values that characterize the major part of the E Med. It is noted that surface chlorophyll concentrations derived with the use of global ocean color algorithms over-estimated the Med's low chl-a in situ field and were characterized by an absolute percentage difference from the in situ observations that exceeded 100%. The use of the regional-Med algorithm MedOC4 [35] significantly reduced these over-estimations and resulted in absolute percentage differences below 50% from the in situ field. As a consequence, for a study like as the present one that focuses on the oligotrophic E Med waters, this chlorophyll product is considered the most suitable. The environmental data of the study were the numerical products of the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA Interim reanalysis; their spatial resolution is approximately 80 km, but they can be retrieved bilinear interpolated at 0.125°. Specifically, the data retrieved were: the monthly means of daily means for 10 m wind speed, MSL pressure, and SST; the monthly means of daily forecast accumulations for precipitation; and the four analyses per day of the significant height of combined wind waves and swell that were used for computing its monthly means. It is noted that the major part of this study was performed in the framework of a Geographic Information System (GIS).

Monthly averages, as in other studies [5,15,30], were computed for all variables in a 1° × 1° grid of the study area for the study period; that is, 158 points covering the E Med Sea with 216 values each. It should be noted that such a coarse analysis was selected for several reasons: the present study was mainly focused on the open sea oligotrophic area, the absolute percentage errors even of the most suitable chlorophyll product used were still quite large and the native resolution of the numerical model was small. Consequently, the results were more accurate for the open sea that is characterized by less abrupt changes in chlorophyll concentrations. Means of the parameters were also calculated for each month in order to produce the monthly climatology. Based on this climatology for chlorophyll concentrations that is presented in Appendix A, the year was separated into two periods: the "high production period" (November–April) and the "low production period" (May–October) characterized by higher and lower chlorophyll values, respectively; the mean values for these periods were also computed for each year. The above is consistent with the study of Salgado-Hernanz et al. [32] where chlorophyll peaks were identified for the E Med from January to April and the initiation of chl-a growing period was not found before November even for areas of a highly possible secondary bloom in autumn.

Data's seasonality was removed by subtracting each month's climatology value from the mean monthly value to produce the "anomalies" of the parameters, as is usually implemented [11,16]. The maximum anomalies observed for the parameters during the study period were checked in order to define the extent of their variations.

The selected parameters (SST, 10 m wind speed, wave height, precipitation, and MSL pressure) with respect to their possible influence on chl-a are described in the introduction section. It is noteworthy that the wave height was also selected here, as it is an environmental factor that is quite similar to the wind but has a greater ability to describe the wind-mixing potential. The significant wave height for a fully developed sea is proportional to the second power of wind speed [37], quite similar to the wind stress, which mainly determines the wind-mixing and upwelling procedures [15]. According to the authors' knowledge, the wave height is studied here for the first time as an environmental parameter possibly related to chlorophyll concentration.

For detecting possible relationships between surface chl-a and the selected environmental parameters, the correlations between their anomalies were calculated. Although correlations do not ensure a cause–effect relationship, they can be used together with other findings to reach useful conclusions. Chlorophyll data, as well as other parameters' data (especially for precipitation), were not normally distributed for several points. Since the Spearman rank correlation coefficient is quite unaffected by the data distribution (as well as by outliers), it was selected for estimating the correlations between the anomalies of chl-a and the examined environmental factors. These correlations were calculated for all data and separately for the data of the high production period (November–April) and the low production period (May–October); they were also extracted on a seasonal basis for winter (December–February), spring (March–May), summer (June–August), and autumn (September–November). Their values were considered low (small) up to 0.3, moderate between 0.3 and 0.5, and strong (high) when exceeding 0.5. They were considered significant at a confidence level >95% (p-value < 0.05) and only the relevant results are presented.

Chlorophyll trends were computed for the mean values of the high and the low production periods of each year. The idea for such a discrimination originated from the study of Coppini et al. [29] where a chl-a trend calculation was conducted for the summer (May–September) period aiming toward the development of an indicator for eutrophication based on ocean color data that monitors eutrophication trends. In addition, the above mentioned feature differentiates the present study from the several others addressing this topic. First, Spearman rank correlation was applied in order to detect the points presenting significant trends at a confidence level of 95%. Then, for these points, the linear trend was estimated. Trends of the environmental factors examined were also calculated for the time period studied and with the same method for comparison purposes. It is noted that, Spearman rank correlation has been identified as a useful tool for detecting trends with time, giving quite similar results with the Mann–Kendall test [38,39], while linear trends are, in general, estimated [11,31].

3. Results

The main characteristics of the monthly climatology for the E Med Sea, as computed from the CMEMS monthly product for the period 1998–2016 (Appendix A) were: the ultra-oligotrophic condition of the southern open sea and especially of the Levantine Basin, which was extremely enhanced during July, August, and September; the highest chl-a values of the NW Adriatic, the gulf of Gabes, and the Nile river plume (NE Africa) coastal regions, which were maintained all year long; the more "productive" regions of the W Libyan Sea, the Sicily Straits, the Adriatic Sea, the W Ionian Sea, and the N Aegean; the Rhodes gyre, which was strongly shown through the monthly climatology during spring; and the specific behavior of the southern Adriatic gyre, which had lower chl-a values than the nearby regions throughout the year, except for March when it showed higher values, presenting blooming characteristics. In general, the E Med was characterized by a high production period that extended from November to April when the higher chlorophyll concentrations were observed (the highest were observed in February for most of the areas) and a low production one from May to October; the chlorophyll climatological mean values for these two periods are given in Figure 2.

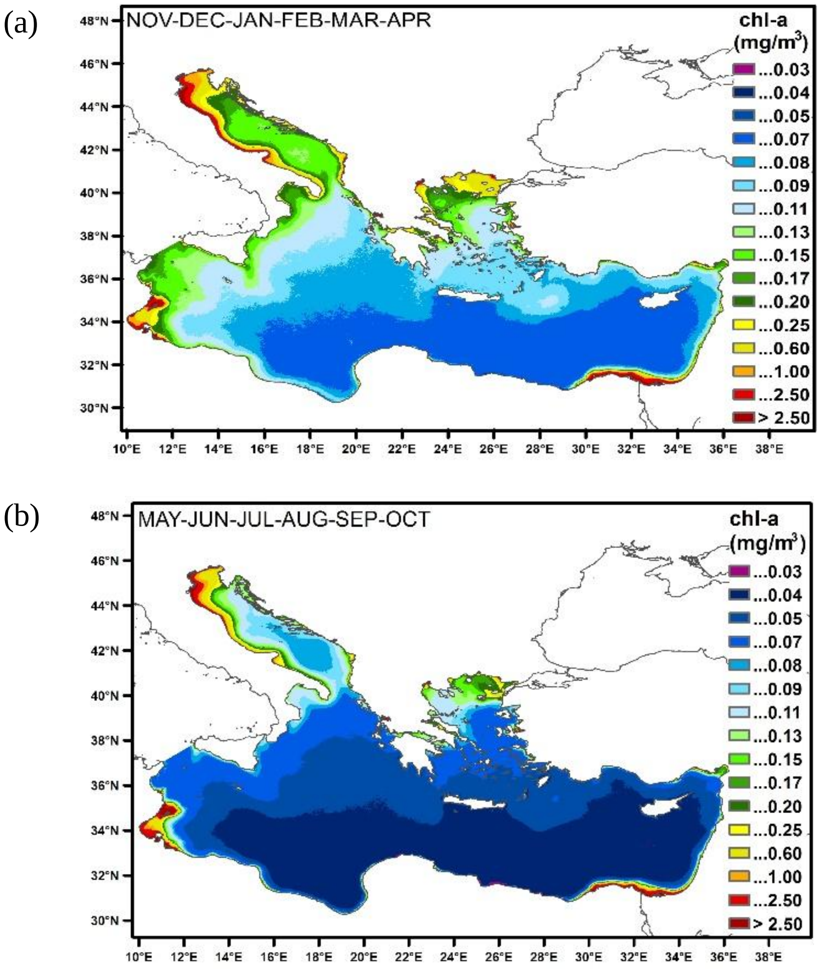


Figure 2. Chlorophyll climatology for the high (**a**) and the low (**b**) production periods as computed from the CMEMS data for the period 1998–2016.

During the high production period (November–April): SST presents a N–S increasing gradient of 12.4–19.6 °C; the stronger winds were found over the western open sea area, but also in the Aegean; higher waves were present over the open sea, especially over its western part and mainly in the Ionian; lower precipitation amounts were observed over the southern part of the study area, while the Adriatic Sea, the Ionian Sea, the E Aegean, and the northern and eastern parts of the Levantine Basin presented higher values. During the low production period (May–October): SST ranged from 20.0 to 26.3 °C, with the higher values encountered in the E Levantine Basin; stronger winds were found in the Aegean; the area extending from the central Aegean down to Africa was characterized by higher waves; the precipitation was much lower and its higher values were found in the Adriatic, the E Ionian, and the N Aegean.

All the above were derived from the relevant climatology which was computed with the use of the ERA Interim dataset for the period 1998–2016 and they are shown in Appendix B for the 158 points studied here.

3.1. Chlorophyll Correlations with Environmental Factors

The Spearman rank correlation coefficients between the monthly anomalies of chl-a and the environmental factors of SST, 10 m wind, wave height, and MSL pressure are presented here. It is worth mentioning the maximum anomalies of the examined parameters throughout the study period, which were calculated as a measure of their variability. Chlorophyll anomalies (Figure 3), presented their higher values over the Adriatic and the N Aegean Seas, as well as for several near-shore points, exceeding 80% and even 100% of the climatological mean value. For the open sea, they usually ranged between 20 and 60% of the climatological mean depending on the season (and for a few points between 10 and 20%, especially during summer); however, they were larger for the spring period ranging between 30 and 80% of the climatological mean value and even exceeding it, especially for points of the Rhodes gyre region and the Sicily Straits. SST presented lower anomaly values in winter and spring seasons, ranging from 0.5 to 1.5 °C; for the summer and autumn periods, the anomalies were found to be higher over the western and the eastern parts of the study area, respectively, exceeding 2 °C in many places. Wind anomalies were found to be 10–40% of the climatological mean with a few exceptions up to 50% for all seasons. Wave height anomalies were found to be 30–70% of the climatological value for the winter period, while for the other seasons, they were smaller, except for the N Aegean during summer. They presented their higher values for the Adriatic and the Aegean Seas, and the lower ones over the southern open sea and especially its central parts. Precipitation was the parameter with the greatest anomalies; they exceeded 50% of the climatological mean in all seasons, while over large areas, they were 2–3-fold greater that the climatological average, even during the low production period when the E Med is characterized by low rainfall amounts. MSL pressure anomalies presented a NW–SE decreasing gradient. For the high production period and especially during winter when the higher values were observed, they exceeded 10 hPa over the N Adriatic Sea and went down to 4 hPa over the eastern parts of the Levantine Sea. For the low production period, the anomalies were much smaller, with a higher value of 5 hPa observed for the N Adriatic in October. The amplitude of the parameters' observed anomalies showed that it was worth studying their relations.

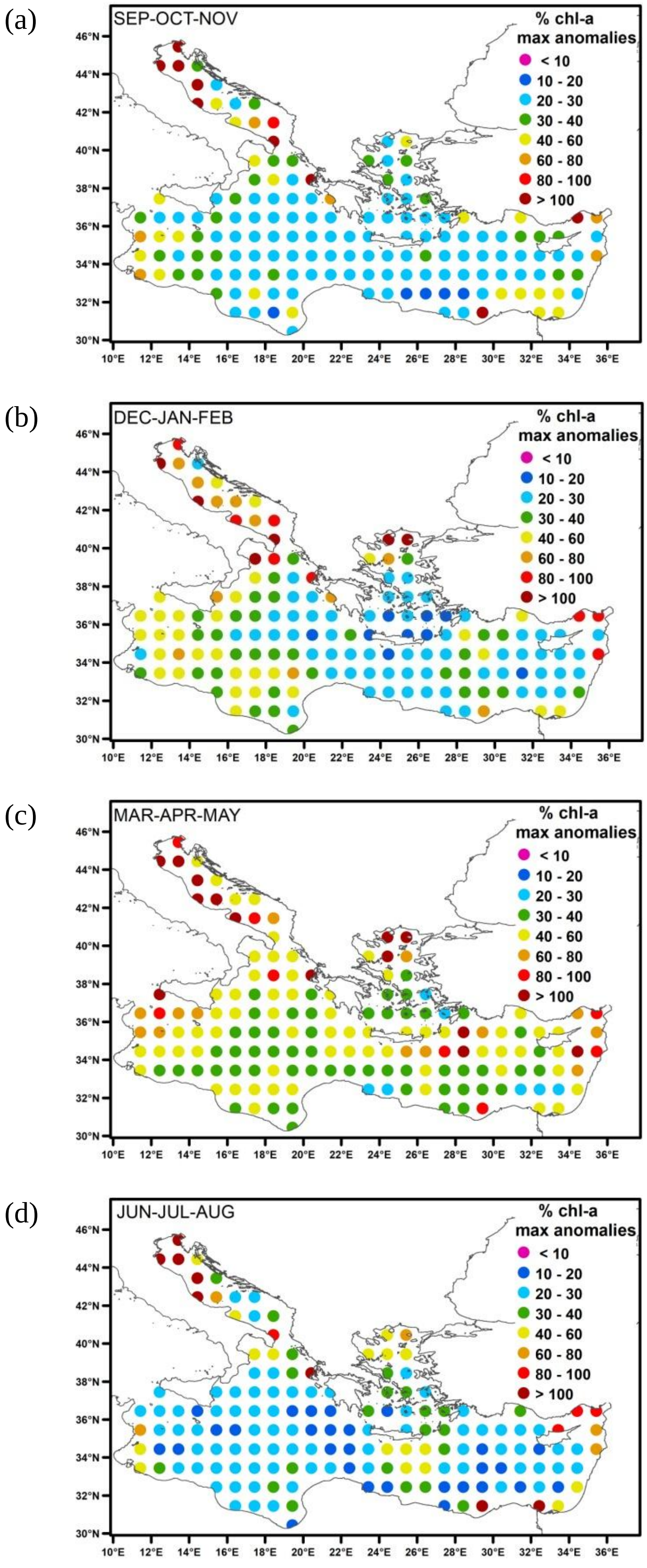
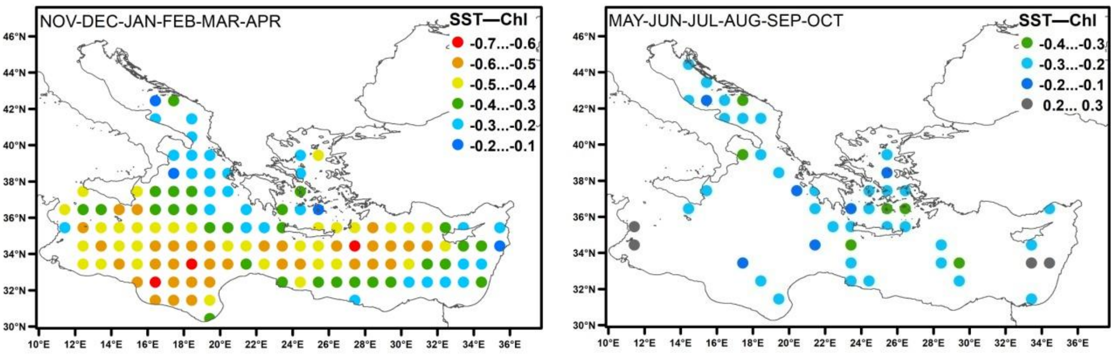


Figure 3. Maximum chlorophyll anomalies observed each season for the time period 1998–2016 for: (**a**) autumn, (**b**) winter, (**c**) spring, (**d**) summer.

For the high production period, the significant correlations between chl-a and SST were all found to be negative and referred to the majority (81.6%) of the points (Figure 4a); only the N Adriatic Sea, the north and east Aegean parts, and several near-shore points were excluded. They were higher, even reaching −0.7, for the open sea (SSW part of the study area), i.e., excluding the eastern Levantine Basin, which presented low to moderate correlations. For the low production period, the points that presented a significant relation between the two parameters were much fewer (53 out of 158), while four of these points even presented positive correlations (over the gulf of Gabes and the eastern part of the Levantine Basin). During this period, the observed negative correlations were small in general (up to −0.4), and they were mainly observed over the northern parts of the study area (Adriatic, E Ionian, and Aegean Seas) (Figure 4b). The seasonal-based calculations are presented in Figure 5. In autumn, 68 out of the 158 points presented significant negative correlations of chl-a and SST, with moderate to high values for the central parts of the study area (SE Adriatic, E Ionian, Aegean, S Cretan, W Levantine, and E Libyan Seas). During winter, 80 points were found with statistically significant negative correlations between the two parameters, presenting moderate to strong relationships over the south and mainly the southwest parts of the E Med; this was especially true for the Libyan Sea where the correlations were up to −0.7. However, seven points with positive correlations were also found over the SE Aegean and the N Levantine near-shore regions. Spring was characterized by moderate and strong relationships between chl-a and SST for most (88%) of the E Med, mainly excluding the N Adriatic and the northern Aegean. For the summer period, 10 points out of 158 presented negative correlations and 12 points presented positive ones; low negative correlations characterized 43% of the Adriatic Sea and three points of moderate negative relationships were found over the E Levantine Basin, while the points presenting positive correlations were mainly found near the gulf of Gabes. The inverse relation between chl-a and SST was clear, characterized at almost every part of the E Med Sea depending on the season, except for summer, and it was more pronounced in spring. This inverse relationship was also observed for the data throughout the year for 135 out of 158 points that presented statistically significant correlations, especially over the central parts of the south E Med (Figure A3a), i.e., the W Libyan, the S Cretan, and the E Levantine Seas.



(**a**) (**b**)

Figure 4. Spearman rank correlation coefficients between chl-a and SST monthly anomalies for the high (**a**) and the low (**b**) production periods. Only significant correlations are shown.

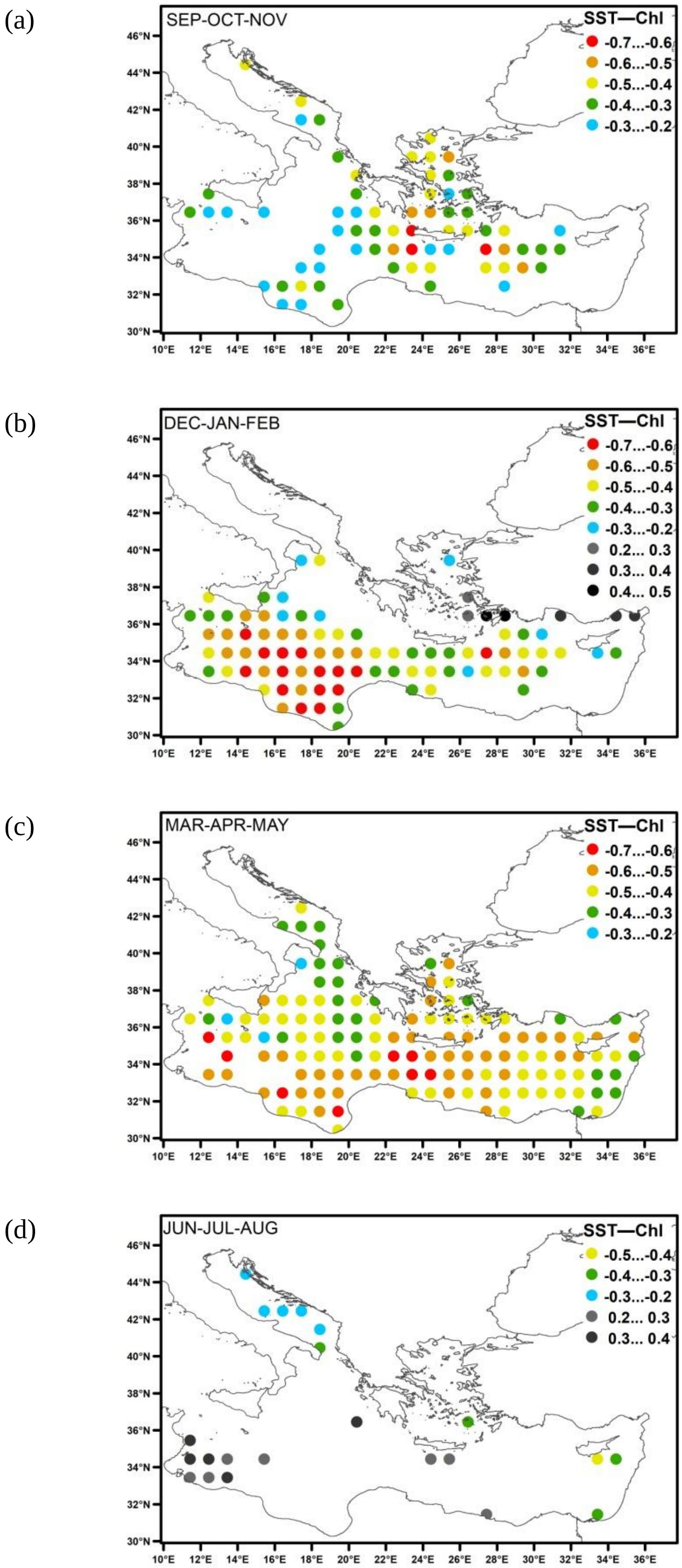
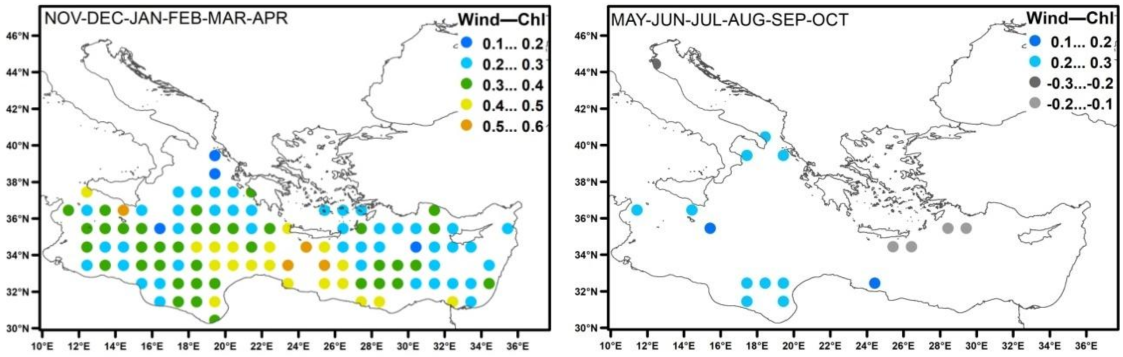


Figure 5. Spearman rank correlation coefficients between chl-a and SST monthly anomalies on a seasonal basis: (**a**) autumn, (**b**) winter, (**c**) spring, and (**d**) summer. Only significant correlations are shown.

Chlorophyll and 10 m wind speed correlations were found to be positive and significant for 111 out of the 158 points during the high production period (November–April) over the southern parts of the study area and larger for the central parts (E Libyan and S Cretan Seas) where they were moderate to strong (Figure 6a). For the low production period (May–October), the correlations were very few and low, with 17 points presenting significant values and 5 of them negative ones (Figure 6b). When data throughout the year were considered, the results were similar to the ones of the high production period, with 102 points presenting statistically significant positive relationships, but with lower correlations (Figure A3b). The seasonal results are shown in Figure 7. For the autumn period, only 18 out of the 158 points were found with significant and positive correlations between the two parameters, mainly over the E Libyan Sea and the west part of S Cretan Sea with moderate values. The majority of the points (102 out of 158) presenting significant and positive correlations between chl-a and 10 m wind speed were found in winter. They were mainly observed over the southern part of the study area and the higher values (up to 0.8) were found for the S Cretan Sea. In spring, 36 points presented low to moderate positive correlations and their moderate values were found over the S Cretan Sea and the eastern part of the Levantine Basin. For the summer period, only 2 points were found with positive correlations and 10 with negative relations between the two parameters; the latter were mainly found over the southern part of the study area. In conclusion, positive significant correlations between chl-a and 10 m wind speed were calculated for the south seas, excluding summer, and were mainly found in winter, with the S Cretan Sea presenting the higher values.



(**a**) (**b**)

Figure 6. Spearman rank correlation coefficients between chl-a and 10 m wind speed monthly anomalies for the high (**a**) and the low (**b**) production periods. Only significant correlations are shown.

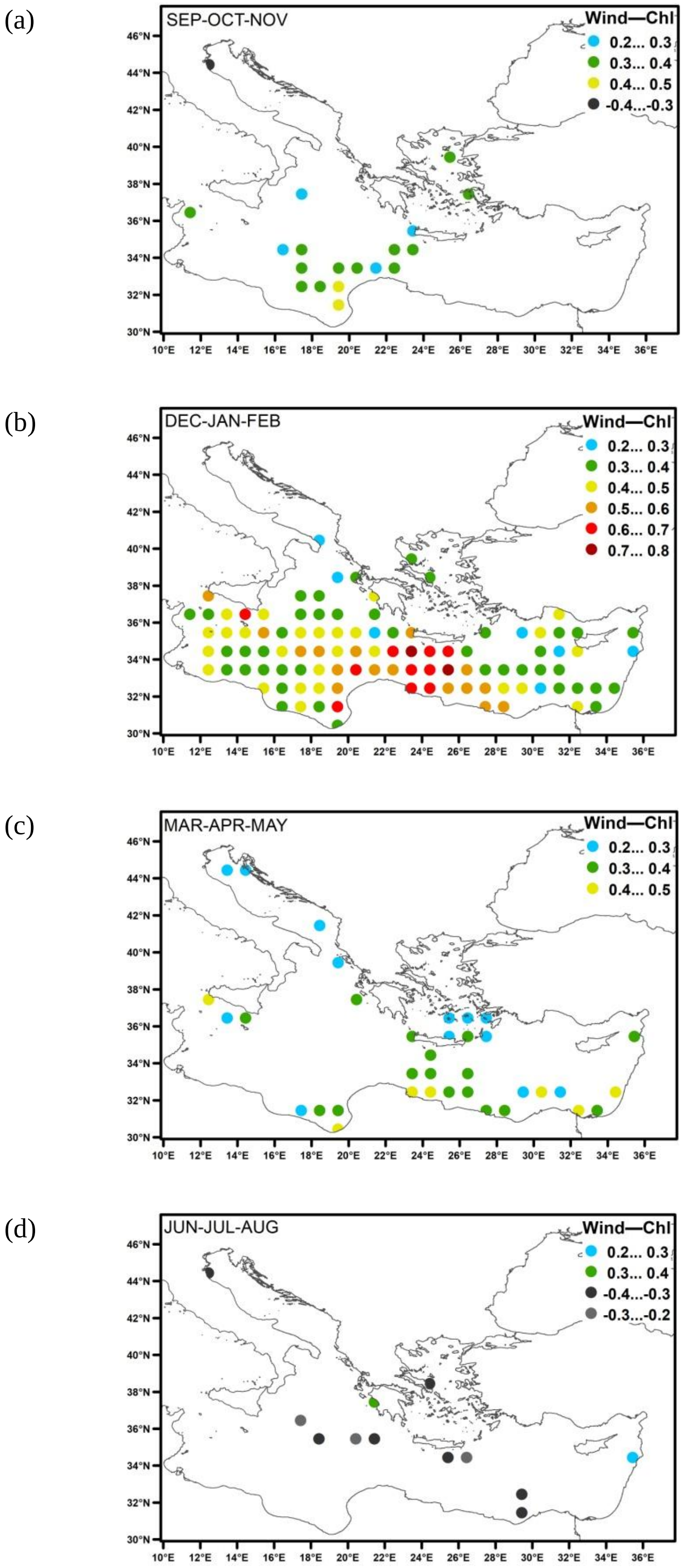
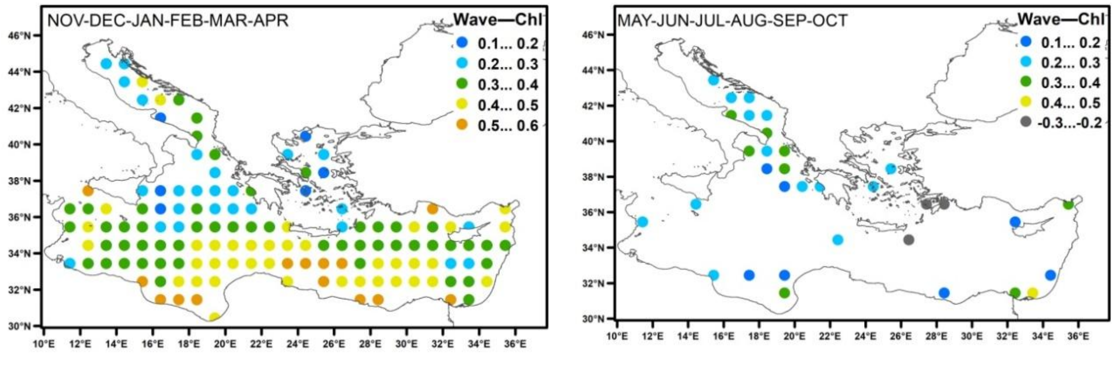


Figure 7. Spearman rank correlation coefficients between chl-a and 10 m wind speed monthly anomalies on a seasonal basis: (**a**) autumn, (**b**) winter, (**c**) spring, and (**d**) summer. Only significant correlations are shown.

The correlations of chl-a and wave height for the high production period (Figure 8a) were found to be positive and significant over a major part (88%) of the area, i.e., for 139 out of the 158 points. The higher values were calculated for the southern part of the area and mainly in its central parts (E Libyan, S Cretan, and W Levantine regions) where they were moderate to strong, while the Adriatic Sea presented moderate correlations over its eastern and southern parts. During the low production period (Figure 8b), the positive correlations were few (30 points) and lower, with the S Adriatic and the N Ionian forming a compact region of quite high (up to 0.4) values. The seasonal results for the correlations between wave height and chlorophyll are shown in Figure 9. For the autumn period, 75 out of the 158 points presented low to moderate positive correlations; their moderate values were mainly found over the south-central part of the study area (E Libyan and western parts of S Cretan and W Levantine regions) and the Aegean Sea. For the winter season, the correlations were like the ones of the high production period but with higher values: 135 points presented significant correlations and only 11 of them presented low values; 47 of these points over the southern part of the sea were characterized by strong correlations, especially over the S Cretan Sea where the values were up to 0.8. In spring, 69 points were found with positive correlations presenting higher values for the southern part of the study area and the Adriatic Sea, while stronger correlations (up to 0.6) were observed for the central Adriatic Sea and the southern part of the Levantine Basin. For the summer period, the correlations over the southern parts of the area resulted in negative values for 29 points, and only parts of the Adriatic, the N Ionian and the E Levantine presented low to moderate positive values (13 points in total). The year-round results (Figure A3c) were like the ones found for the high production period but with lower values, with 136 points presenting positive correlations and up-to-moderate values found for the central Adriatic Sea and the south-central parts of the study area (E Libyan Sea, S Cretan Sea, and locally over the Levantine Basin). These correlations, compared to the ones between chl-a and 10 m wind speed, presented similar patterns but resulted in higher values and included more parts of the study area, especially the Adriatic Sea.



(**a**) (**b**)

Figure 8. Spearman rank correlation coefficients between chl-a and wave height monthly anomalies for the high (**a**) and the low (**b**) production periods. Only significant correlations are shown.

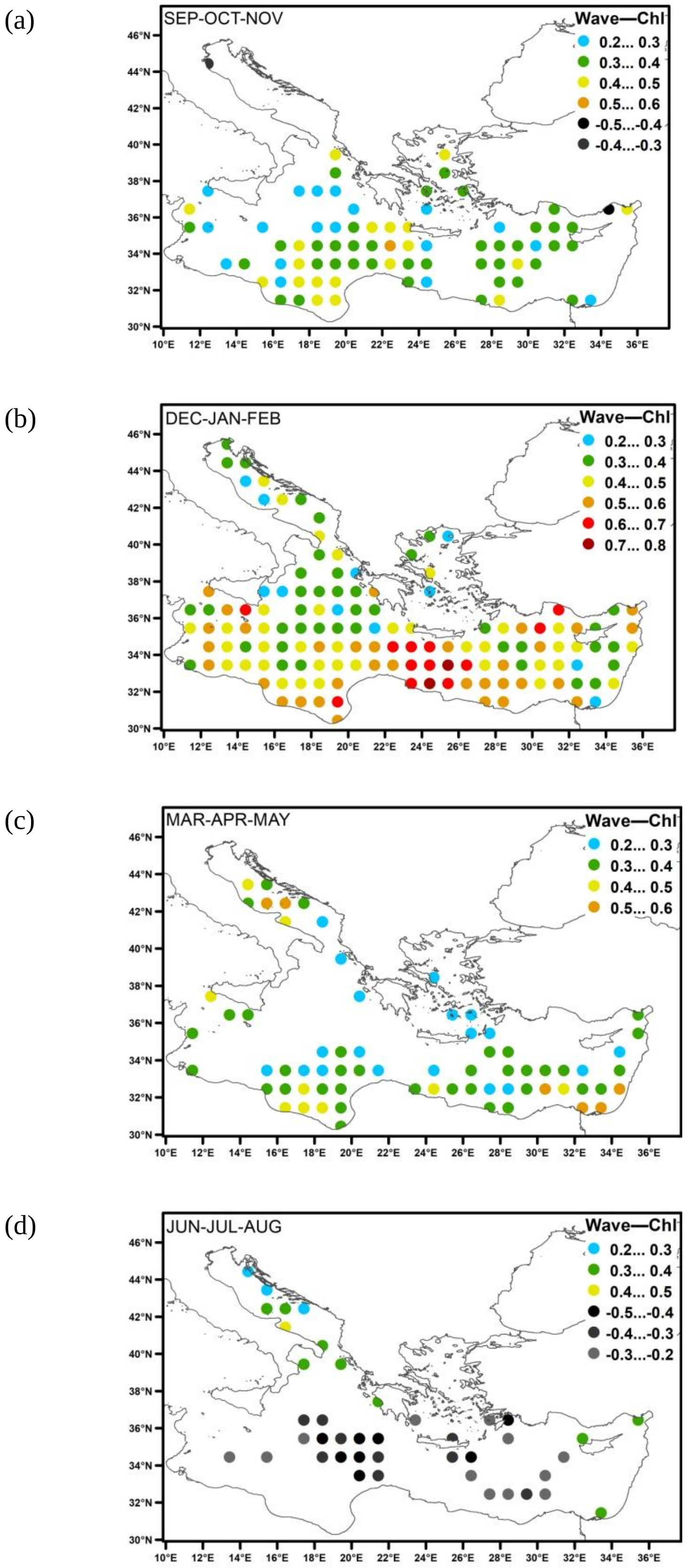
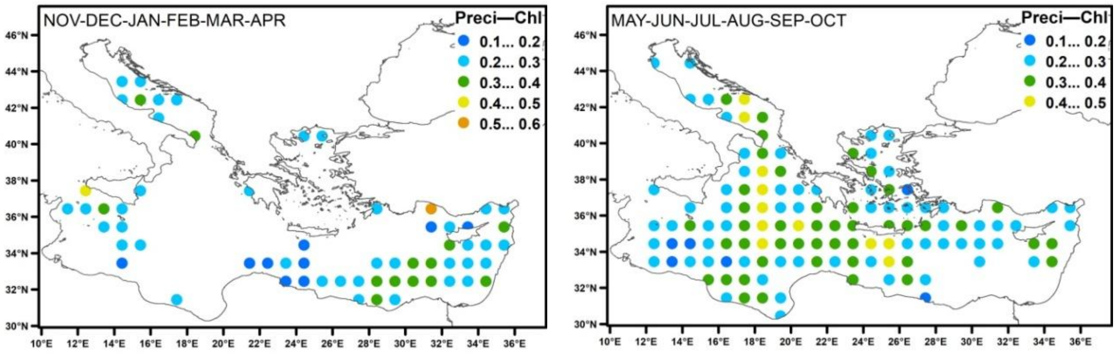


Figure 9. Spearman rank correlation coefficients between chl-a and wave height monthly anomalies on a seasonal basis: (**a**) autumn, (**b**) winter, (**c**) spring, and (**d**) summer. Only significant correlations are shown.

Chlorophyll and precipitation were found to be positively correlated. Low to moderate correlations were calculated for the high production period (November–April) for 62 out of the 158 points over the SSW parts of the study area, especially over the Levantine Basin, near the Sicily Straits and locally over the Adriatic Sea (Figure 10a). For the low production period (May–October) these positive correlations (observed for 123 points) covered a wide part of the E Med, mainly with the exception of the SW and SE parts; their values showed moderate correlations, with the higher ones (0.4–0.5) for the S Adriatic, the Ionian, the E Libyan, and the S Cretan Seas (Figure 10b). When data throughout the year were considered (Figure A3d), the positive correlations referred to 111 points and they were low in general with a few exceptions of moderate values, mainly for the Levantine Sea. According to the seasonal results (Figure 11), moderate to strong (up to 0.6) positive correlations were found for the central and the southern Adriatic Sea in the spring and summer periods and locally over the N Aegean in the autumn–winter period. The open sea presented low to moderate correlations: over the Ionian in autumn and its west part during summer; locally over the Libyan Sea during all seasons except winter, mainly in summer; over the S Cretan Sea in winter; and the Levantine Sea presented such values during all seasons except summer, mainly in winter. For the winter season and for the other seasons, 63 and 38 out of the 158 points, respectively, were found to present positive relationships between chlorophyll and precipitation. In conclusion, positive significant correlations between chl-a and precipitation were calculated for the eastern parts in winter and for the western parts during the other seasons, mainly in summer.



(**a**) (**b**)

Figure 10. Spearman rank correlation coefficients between chl-a and precipitation monthly anomalies for the high (**a**) and the low (**b**) production periods. Only significant correlations are shown.

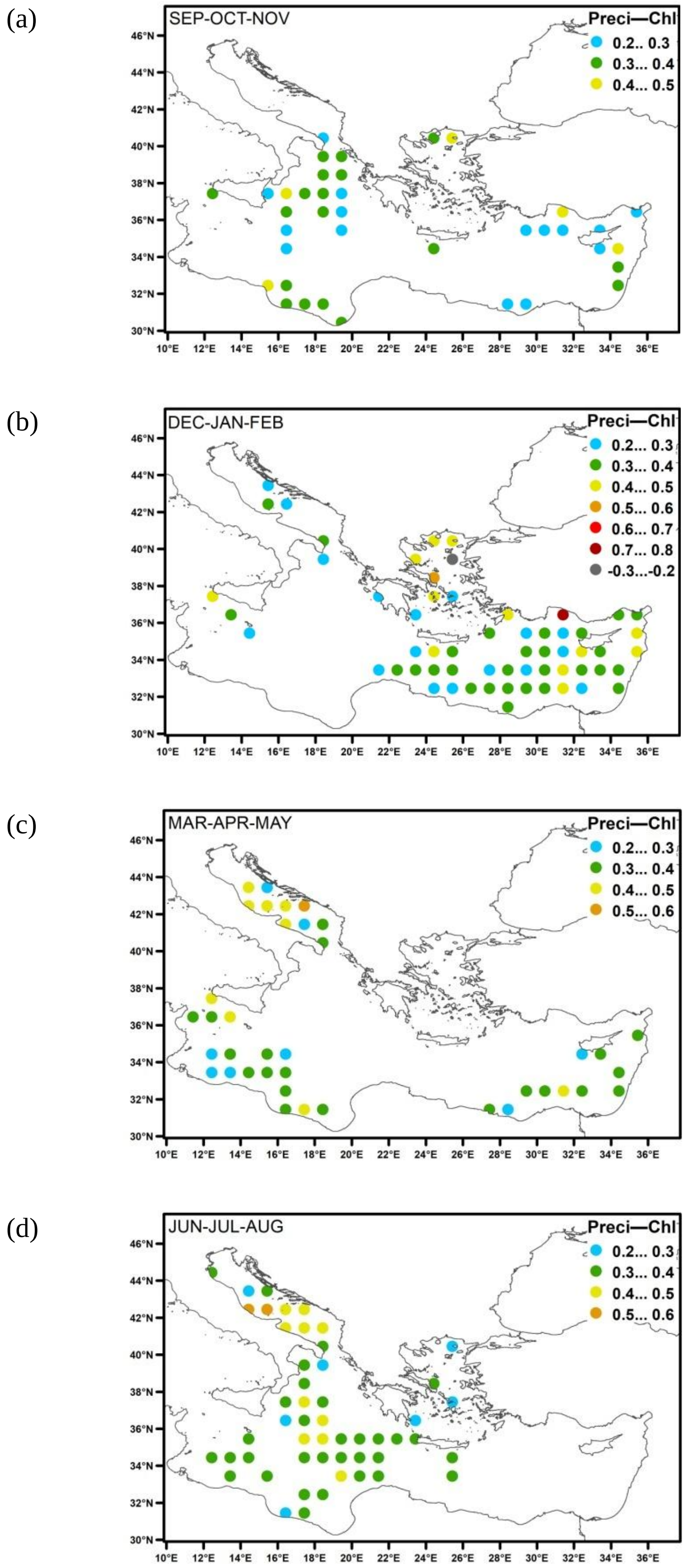


Figure 11. Spearman rank correlation coefficients between chl-a and precipitation monthly anomalies on a seasonal basis: (**a**) autumn, (**b**) winter, (**c**) spring, and (**d**) summer. Only significant correlations are shown.

Stronger correlations between chl-a and the environmental parameters were found over the southern open sea, where the results of this study can be considered more accurate due to the coarse analysis. They were negative for chlorophyll and SST over the SW part in winter and all southern parts in spring, and positive between 10 m wind speed and wave height with chl-a over the central S parts and all southern parts, respectively, in winter. Quite interesting were the negative low to moderate correlations between chl-a and wave height that were observed for several points in summer. The correlations of chlorophyll with precipitation were up to moderate and they were found to the eastern part in winter and to the west part during the other seasons. The high production period was characterized by the correlations of chl-a with SST, 10 m wind speed and wave height, while the correlations between chlorophyll and precipitation were present mainly during the low production period, except for the S Levantine parts where they were observed for the high production period.

The correlations between chl-a and MSL pressure were very few in general, low and scattered for the low production period and the seasons of spring, summer, and autumn (not shown). The winter season (Figure 12a) presented significant negative correlations for 58 out of the 158 points; moderate to strong correlations over the western parts of the study area, near the Sicily Straits and locally over the Adriatic and the Ionian Seas; and up to moderate correlations over the S Cretan Sea, the N Levantine Sea, and at places in the Aegean. The correlations were fewer (they referred to 23 points) and lower when all the high production period was considered, with their higher values mainly near the Sicily Straits (Figure 12b).

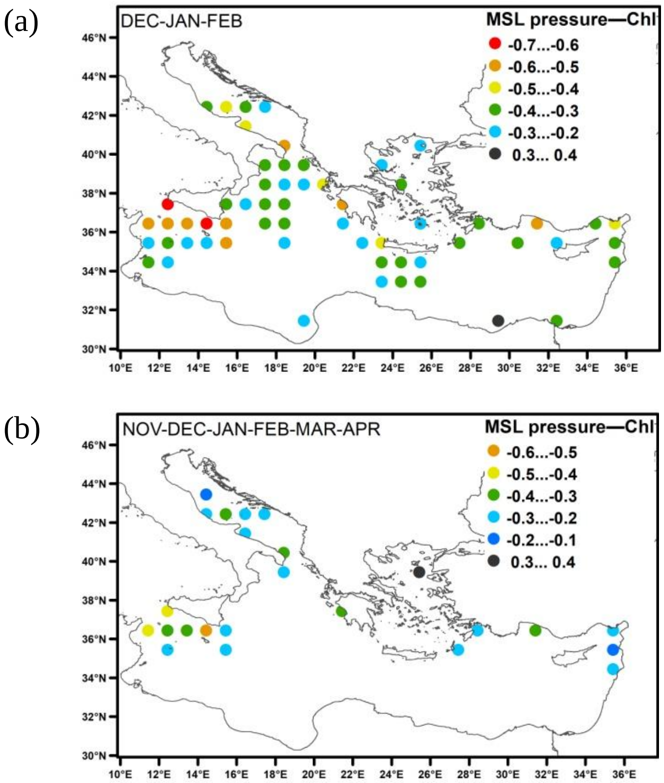


Figure 12. Spearman rank correlation coefficients between chl-a and MSL pressure monthly anomalies for the high production period (**a**) and for the winter season (**b**). Only significant correlations are shown.

3.2. Chlorophyll Trends

All significant surface chlorophyll trends, as calculated for the period 1998–2016, based on the mean chl-a values of each year and separately for the high and the low production periods were found to be positive. They are shown in Figure 13 as percentages of their respective climatological value per year. The Adriatic Sea presented positive chl-a trends for the high production period (1–2% of the climatological value per year). For both the high and the low production periods, significant trends were found for the area near the Sicily Straits (with greater values, 1–2% of the climatological value per year, for the high production period) and the central and south Aegean parts (ranging in general from 0.5 to 1% of the climatological value per year), as well as to a few points of the Ionian and the Libyan Seas. The the S Cretan and the Levantine Seas presented increasing chl-a trends, mainly for the low production period (0.5–1% of the climatological value per year in most cases). In summary: during the high production period, 35 out of the 158 points presented statistically significant increasing trends, up to 2.8% of the climatological value per year, and mainly characterized the western part of the E Med ; for the low production period, the significant trends were observed for more points (58 out of 158), they were again all increases of 0.4–2.5% of the climatological value per year, and they were mainly found in the eastern part of the study area.

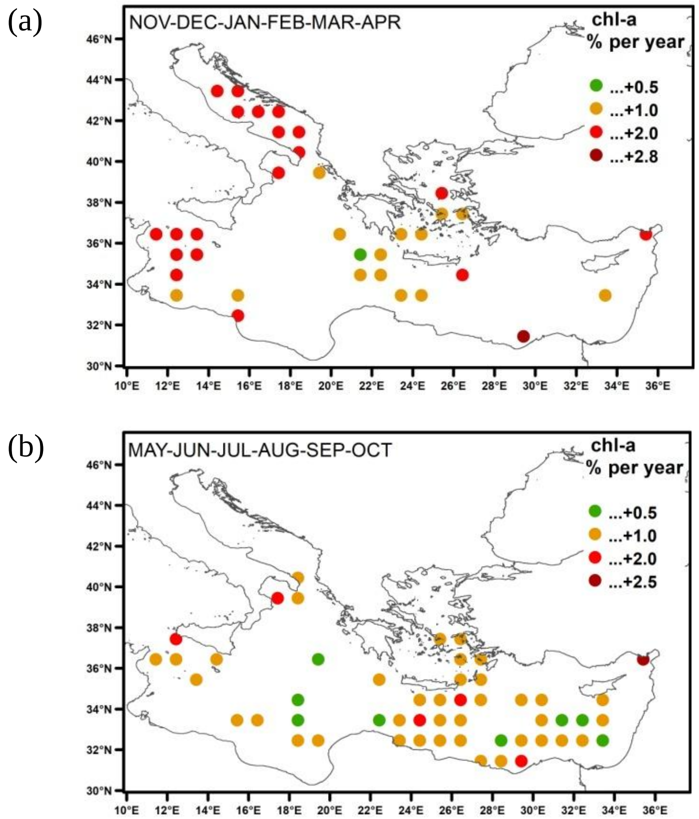


Figure 13. Chlorophyll trends (% of the climatology per year) during 1998–2016 for the high (**a**) and the low (**b**) production periods. Only significant trends are shown.

For the same time period, the trends of the environmental factors SST, 10 m wind speed, wave height, and precipitation are presented in Appendix D. SST presented an increasing trend over a large part of the Ionian Sea for the high production period and over the southern part of the Levantine Sea for both periods (Figure A4). These areas were characterized by the absence of a correlation or low correlation between SST and chl-a, and only locally coincide with increasing chl-a trends. For the wave height, a large area of positive trends was found for both periods over the Adriatic Sea, the Ionian, the west part of the Cretan Sea, the N Aegean, and the northern part of the Levantine Sea; a negative trend was calculated for the SE Aegean (Figure A5). Over the Adriatic Sea, chl-a presented an increasing trend, and for this area, the correlations between wave height and chlorophyll were moderate mainly during the high production period; similar was the case locally over the Ionian Sea and over the western part of the S Cretan Sea where the two parameters presented strong correlations for the high production period (November–April); over the N Aegean, no increasing trend was found for chlorophyll and its correlations with wave height were found to be low; over the north Levantine Basin, chlorophyll did not show an increasing trend, while the relevant correlations were moderate; over the SE Aegean, where the wave height showed a negative trend, chl-a presented a positive one, and the correlations between them were found to be negative or absent for the low production period. Precipitation and 10 m wind speed did not present significant trends for the high production period. For the low production period, wind presented an increasing trend for the S Adriatic, the Ionian, and locally over the E Levantine, as well as a decreasing one for the SE Aegean (Figure A6a); for these regions, no correlation with chl-a was found. A positive trend for precipitation was calculated for the central Adriatic, the E Ionian, the W Aegean, the S Cretan, and the N Levantine (Figure A6b). The similar trends for chlorophyll coincide only for the S Cretan Sea where up to moderate positive correlations with precipitation were found. For the majority of the points where chlorophyll trends were met together with trends of other parameters, the results did not contradict- their estimated correlations.

In Appendix E, the chlorophyll concentrations for the high and the low production periods of November 1998–April 1999, November 2015–April 2016, May–October 1998, and May–October 2016 are given in order showing changes in concentrations based on ocean color data, which can be compared to in situ observations.

4. Discussion

4.1. Correlations among Chlorophyll and Environmental Variables

The SST presented an inverse significant relationship with chl-a, which characterized the major part of the study area during the high production period and in spring; this relation was minimized and even inversed in summer. In the study of Katara et al. [16] for the whole Mediterranean Sea, it was found as a preliminary result that all statistically significant correlations between chl-a and SST were negative. The two parameters were also found to be negatively correlated for the Aegean basin [40] and an inverse relation between them was revealed for specific areas of the E Med [19]. This kind of relationship supports the outcome that the strength of stratification, as inferred from the SST, is a major controller of phytoplankton abundance for the nutrient-limited Med Sea. Higher SSTs, representing stronger water column stratification, produce reduced vertical mixing and low nutrient amounts for the surface layer leading to low chl-a concentrations. Such a relation between SST and chl-a was detected for the non-blooming and the intermittently-blooming areas of the entire Med, such as the ones of its eastern part (i.e., the whole Basin except for some coastal parts) [12]. The results found here gave further evidence for the above through the higher inverse correlation of the parameters during the transitional periods of spring and autumn (for the northern part), when the mixed layer begins to become shallow or deepen, respectively [13,41]. With lower SST values denoting a deeper MLD, the later MLD starts to decrease in spring and the sooner it starts to increase again in autumn, the larger the positive influence it can have on phytoplankton, as seen through chlorophyll concentrations. This was also the case for the SSW part of the study area during winter, according to the MLD of the region. In addition, for the winter season (for the northern part) characterized by the deepest MLD and for the summer when the shallowest MLD was observed [13,41], the relative correlations were absent. Furthermore, the inverse correlation between SST and chlorophyll was minimized and even reversed for the summer season, showing the marginal or absent effects of SST decreases in an already nutrient-poor environment. It should also be noted that, although such an inverse relationship was anticipated between SST and chlorophyll or net primary production for the larger part of the oceans [24,27], this was not always the case, even for the Med. The two parameters were found presenting opposite trends for the major part of the E Med Sea for the period 1999–2004 in the global study of Behrenfeld et al. [24]. However, areas showing decreases in both SST and net primary production were also found in the same study, especially over the Levantine Basin. For the same time period, the results for the E Med showed decreases in SST along with both positive and negative variation for chlorophyll in another global study [27]. For a longer interval, December 2002–January 2015, the E Med was found to have increases for both chl-a and SST [28]. The latter studies point to the conclusion that SST alone cannot describe chl-a variations [28].

The significant correlations between chlorophyll and 10 m wind speed were all found to be positive (with the exception of a few points during summer). This positive relation of the parameters mainly characterized the southern parts of the E Med for the high production period and the winter season. The mechanism behind these positive correlations is the wind-induced mixing, which by deepening the MLD, could result in increased nutrient fluxes from the deeper layers to the surface, and as a consequence, to increased chlorophyll concentrations. Such correlations were found for the two parameters in the Med [16] and this inverse relationship was also identified for the Rhodes Gyre area [19]. The most relevant study was the global one of Kahru et al. [15] for the period November 1996–October 2009 on correlations between chlorophyll and wind satellite data throughout the year, which resulted in a similar pattern with the one of the present study: all the significant correlations were found to be positive and they were also mainly recorded over the southern open sea. In addition, the same areas as here were characterized by the higher correlations and comparable values were observed; however, more areas over the Levantine Basin were found to have significant correlations [15]. In the above-mentioned study [15], such correlations were found for areas with relatively shallow MLDs and nutrients were pointed out as the main limiting factor for phytoplankton growth. This was also the case here for the winter season when the MLD over the southern E Med is, in most parts, shallower than the one of the northern parts [13,41]; it is more likely for the wind mixing to deepen a shallower MLD, resulting in more available nutrients for the surface layers. The opposite result was observed during summer, when the deepening of the MLD decreased chl-a [15]. The few positive correlations between wind and chlorophyll that were found here for the summer period could be explained this way. Since the area is characterized by a deep chlorophyll maximum during this season [42], any deepening of the MLD could only diffuse the limited available nutrients leading to chl-a decreases or to a redistribution of the chlorophyll content down to depths where it is not detected by the ocean color measurements. The absence of correlations between chl-a and wind in the summer period over the Aegean Sea was also consistent with the results of other studies [40,43]. The prevailing summer winds in the Aegean Basin are northerlies and cause upwelling events over its eastern part that do not influence surface chlorophyll concentrations [40,43]; although the present study dealt with the wind speed and not with its direction, no significant correlations of the two parameters were found. All significant correlations between wave height and chlorophyll were positive (except for several points over the S Med during summer). This relationship mainly characterized the high production period and the winter season. In general, these correlations presented, as expected, similar patterns with the ones between wind and chlorophyll. However, their values were higher and more points presented significant positive correlations over the northern parts of the E Med and mainly for the Adriatic Sea. The number of points with significant negative relations between the parameters, for the summer period over the southern part of the study area, were also higher. The mechanism through which higher waves can result in increased chlorophyll concentrations (and decreased ones during summer) are the same as for the wind speed described above. Nevertheless, the wind influence on the sea surface can be better described through the wave height, especially for non-open seas, such as the Adriatic and the Aegean Seas; wind needs fetch to produce higher waves that can mix the water column. In addition, the waves respond to the wind stress, which better describes the wind mixing and upwelling procedures [15]. The results of the wave–chlorophyll correlations found here, which included more areas with significant results than the ones of the wind–chlorophyll relation, point to the conclusion that the wave height is more suitable than the wind speed, especially in cases of non-open sea areas, in studying possible relations with chl-a concentrations.

The significant correlations between chlorophyll and precipitation were all positive and were mainly found during the low production period, with the exception of the southern parts of the Levantine Basin, which presented such correlations in the high production period; in general, low to moderate values were found. An exception of moderate to strong positive correlations was found in the central and southern Adriatic Sea in the spring–summer period. The eastern parts of the study area presented these correlations in winter, while the western parts presented them in the other seasons, mainly in summer. Positive correlations between these parameters were found in the Med Sea [16] and larger precipitation amounts were related with higher chlorophyll values in specific areas of the E Med [19]. Considerable short-lived chl-a increases were recorded after extreme rainfall events during the early autumn and summer periods over the Hellenic Seas and mainly for the E Ionian and the N Aegean Seas; they were attributed to the atmospheric deposition of nutrients into the sea [21,22]. It is noted that the atmosphere was identified as an additional nutrient source for the E Med [23], especially during the low production period; the relevant correlations found here characterize a wide area during this period. In addition, the study area is subject to dust deposition that was found to be positively correlated with chlorophyll [44], and in its wet form can result in significant chl-a increases [45,46].

MSL pressure and chlorophyll were found to have significant negative correlations over quite a large area only for the winter season, mainly over the western part of the E Med where these correlations were larger. It is noted that MSL pressure monthly anomalies also had higher values over the western part where the majority of these correlations were found. One could argue that the areas presenting significant inverse correlations between the two parameters are also affected by deep barometric lows [25] that induce strong winds and high rainfall amounts.

4.2. Temporal Trends in Chlorophyll Concentrations

All the significant surface chlorophyll trends, estimated separately for the high and the low production periods of 1998–2016, were found to be positive. They mainly characterized the western part of the study area during the high production period and the eastern part for the low production period. They were not contradictory to the trends of the other parameters when seen together with their relevant correlations. In a recent study of the same time period, only increasing chlorophyll trends were found [31]. Despite the different approaches followed, i.e., the present study was conducted using a much coarser analysis and it discriminated between the high and the low production periods, similar results in defining both the areas presenting significant trends and the trend magnitude were found. The results here, compared to another long-term study of Salgado-Hernanz et al. [32] for the time period 1998–2014, were in partial agreement regarding the increasing chlorophyll trends in the Adriatic Sea and the Sicily channel. On the other hand, in the above-mentioned study [32], a low decreasing trend was found for the rest of the E Med, which was not observed in the present work. For the E Med, the results of several studies presented considerable differences: mainly decreasing chlorophyll trends were found for 1998–2003 [11]; from 1979–1983 to 1998–2002 increasing trends for both SST and chl-a were observed, while for 1999–2004, a decreasing trend for SST along with increasing and decreasing chlorophyll trends were found [27]; for the May–September period of 1998–2009, positive and negative chl-a trends were calculated [29]; both decreasing and increasing chl-a trends were estimated for the period 1998–2009, along with much greater trend magnitudes [30]; and only increasing trends for both chl-a and SST were found for December 2002 to January 2015 [28], similar to the present study. Such different estimations were also found in studies referring to other parameters, i.e., for SST trends [27,28,47] and precipitation trends [48,49], when comparing them and in respect to the present work. However, for SST, most of them resulted in increasing trends [28,47]. The results of the studies mentioned above [11, 27-32] were described so briefly because it is obvious that the trend estimation is highly dependent on the time period studied. Much longer time series are needed for the detection of trends in order to reach safer results, exceeding 30 years, which is the usual practice for meteorological parameters; this has also been proposed for phytoplankton’s climate-driven trends [50].

Regarding environmental variables’ future changes that have been predicted by climate models for the Med, e.g., an increase for SST [47] and a decrease in precipitation [14,49], it is crucial to reveal the possible relations between these variables and chlorophyll concentrations. The estimation of the relevant correlations can unveil aspects of these relations. According to the results of the present study, the predicted future increase in SST and decrease in precipitation mentioned above could lead to chlorophyll decreases. However, the respective studies are quite scarce, especially for precipitation, upon which more work needs to be done. In addition, studies over long time series, such as the one conducted here, but with higher spatial resolution, are proposed. As far as the chlorophyll trends are concerned, which have been more extensively studied with controversial results, longer and more homogenous time series are required to be built.

5. Conclusions

The main results of this work can be summarized for the study area of the E Med and the period 1998–2016 as follows: SST was inversely related to surface chl-a in the major part of the Sea; this relation was more pronounced in spring and not valid for the summer season. Wind speed and mainly wave height were positively correlated with chlorophyll, especially over the southern open part of the Sea; however, during the summer period, a negative relation was observed. For precipitation and chl-a, all the significant correlations were positive and mainly valid for the low production period. MSL pressure and chl-a presented significant negative correlations for the winter season and mainly over the western part of the Sea. All the significant surface chlorophyll trends were found to be positive; nevertheless, the trend estimation requires much longer time series than the available ones.

Author Contributions: Conceptualization, Dionysia Kotta; Data curation, Dionysia Kotta; Formal analysis, Dionysia Kotta; Investigation, Dionysia Kotta; Methodology, Dionysia Kotta; Project administration, Dionysia Kotta and Dimitra Kitsiou; Resources, Dionysia Kotta; Supervision, Dionysia Kotta and Dimitra Kitsiou; Validation, Dionysia Kotta and Dimitra Kitsiou; Visualization, Dionysia Kotta; Writing–original draft, Dionysia Kotta; Writing–review and editing, Dionysia Kotta and Dimitra Kitsiou.

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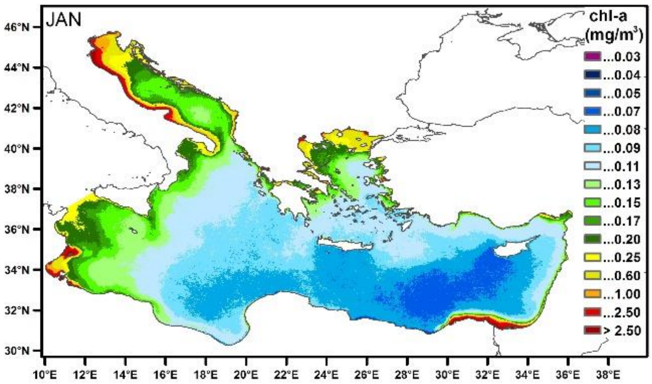
Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

The monthly chlorophyll climatology, as computed for the 1998–2016 time period, is given here.

(a)



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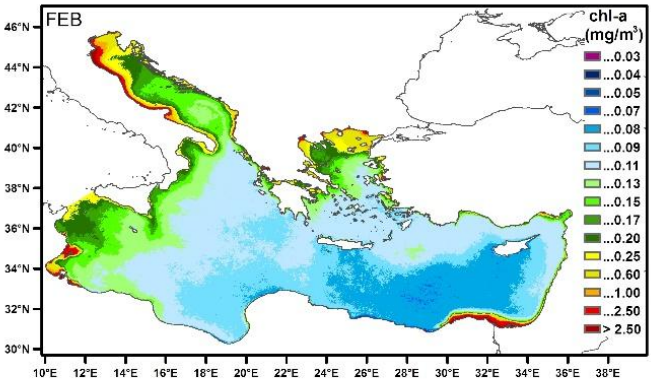

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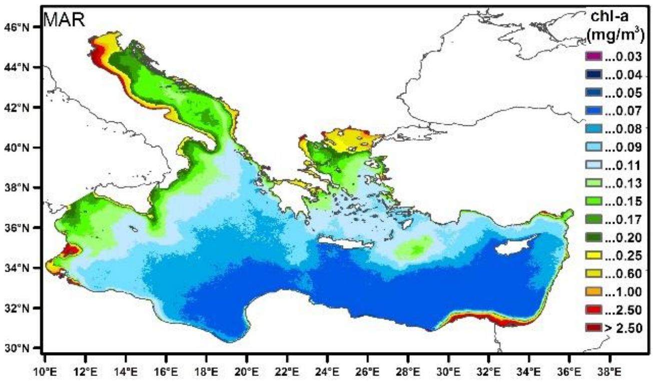
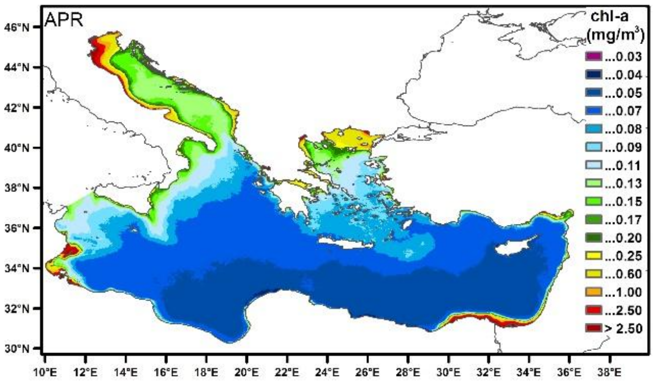
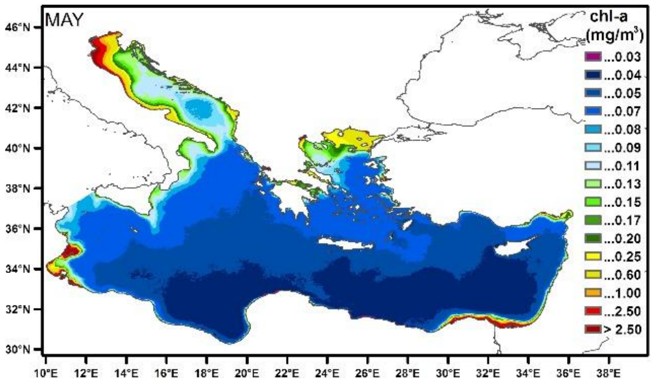


(d)



(e)


MAY
chl-a (mg/m^3)
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46°N 44°N 42°N 40°N 38°N 36°N 34°N 32°N 30°N
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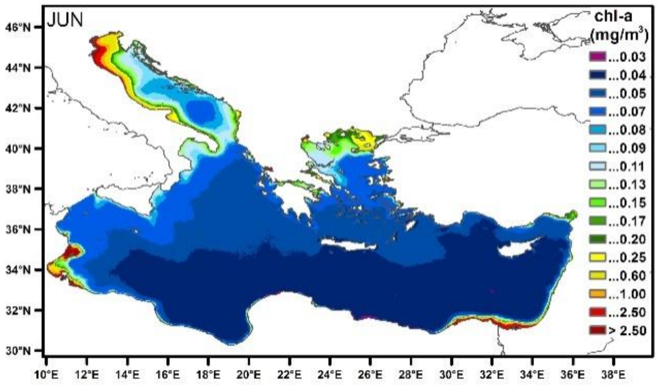
(f)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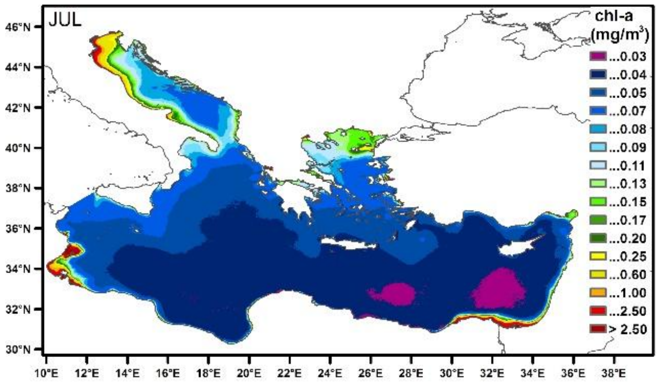
(g)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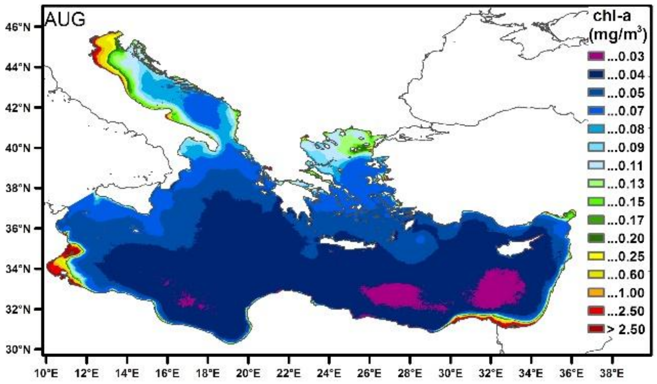
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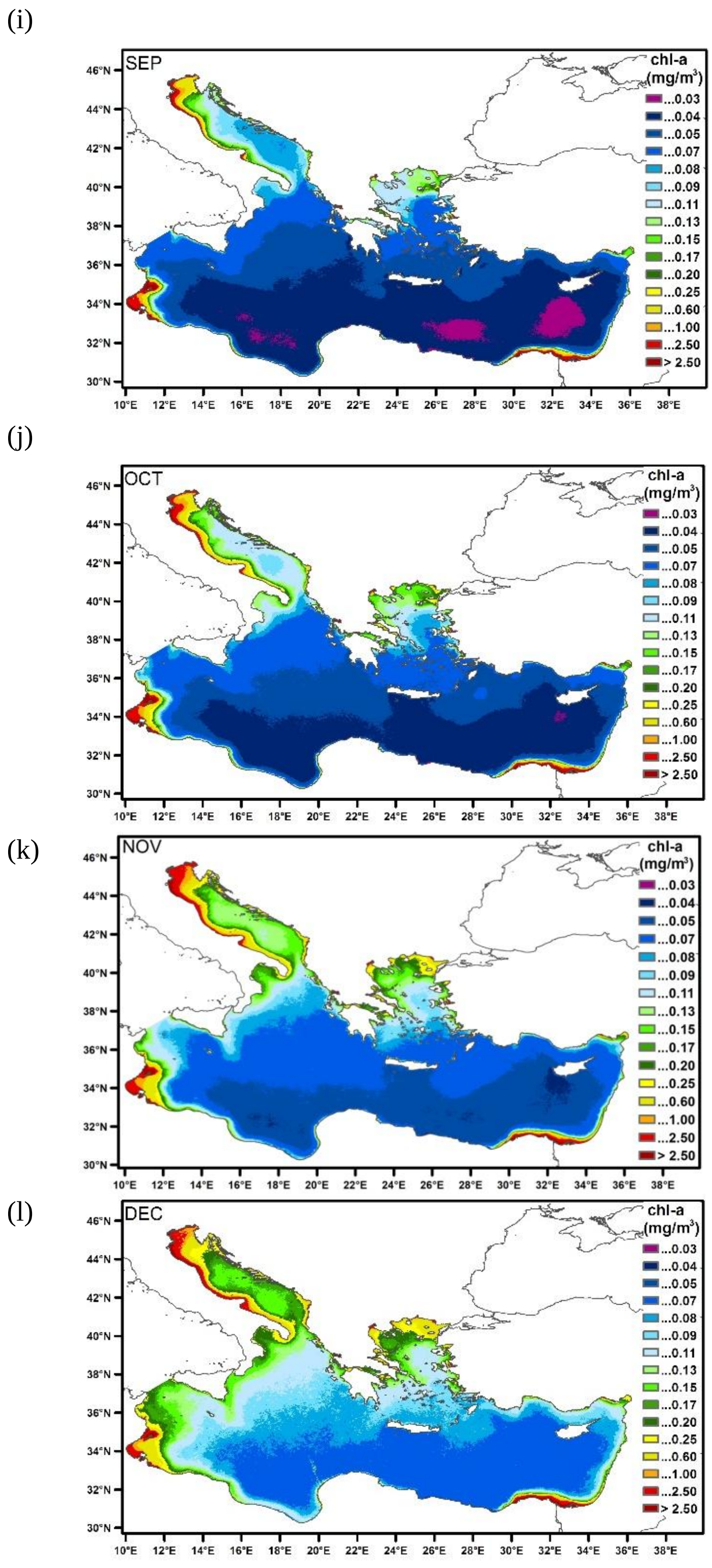
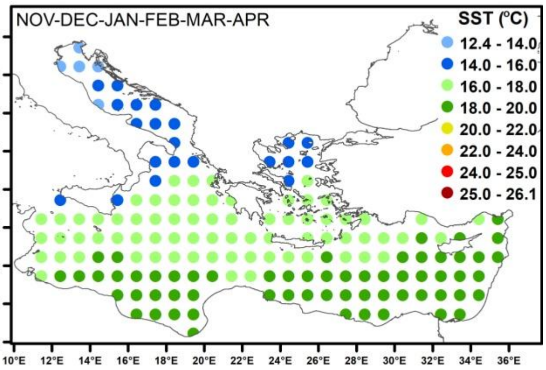


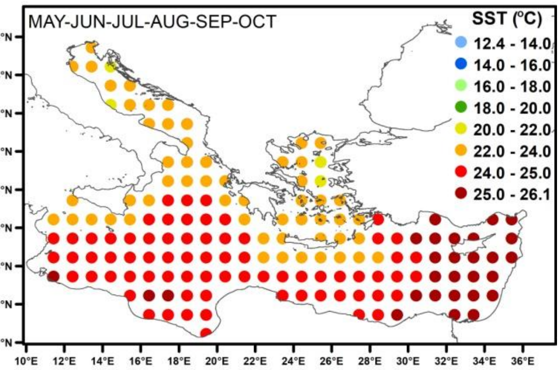
Figure A1. Chlorophyll monthly climatology as computed for the period 1998–2016 for January (**a**) to December (**l**).

Appendix B

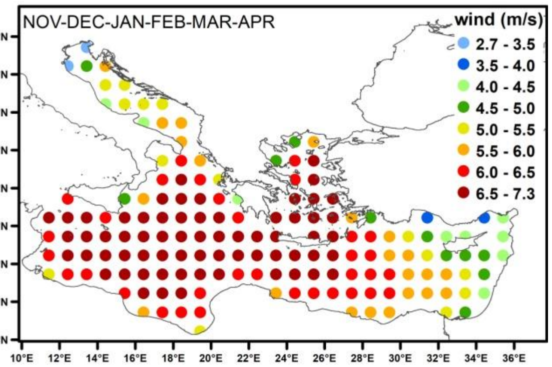
The climatology of the high and the low production periods for SST, 10 m wind speed, and precipitation as computed with the use of the ERA Interim dataset for the period 1998–2016 is shown in this appendix.



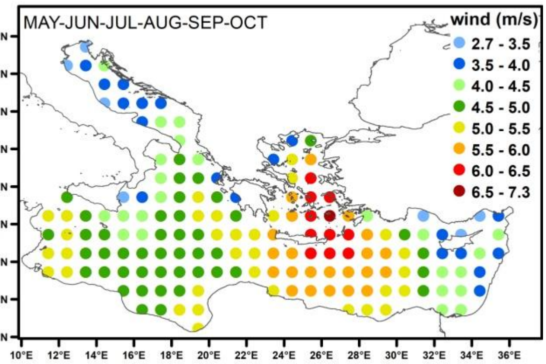
(**a**)



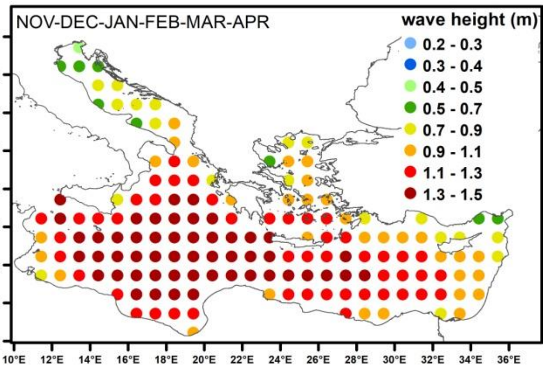
(**b**)



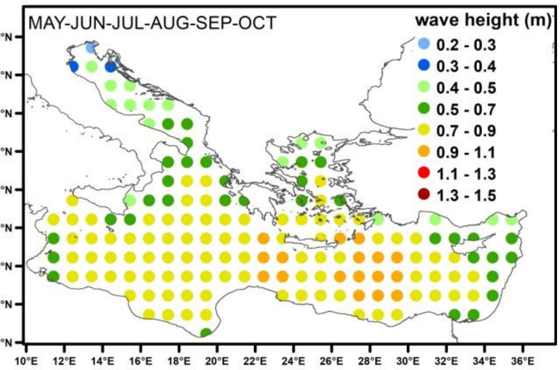
(**c**)



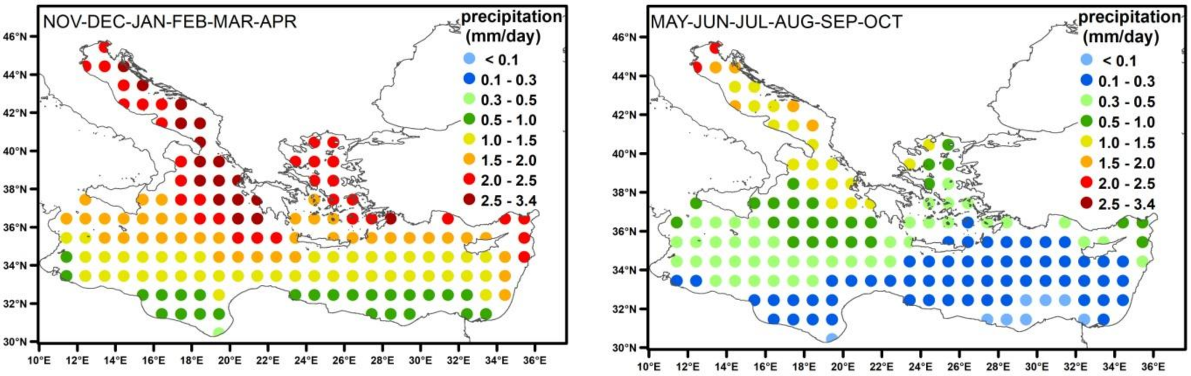
(**d**)



(**e**)



(**f**)

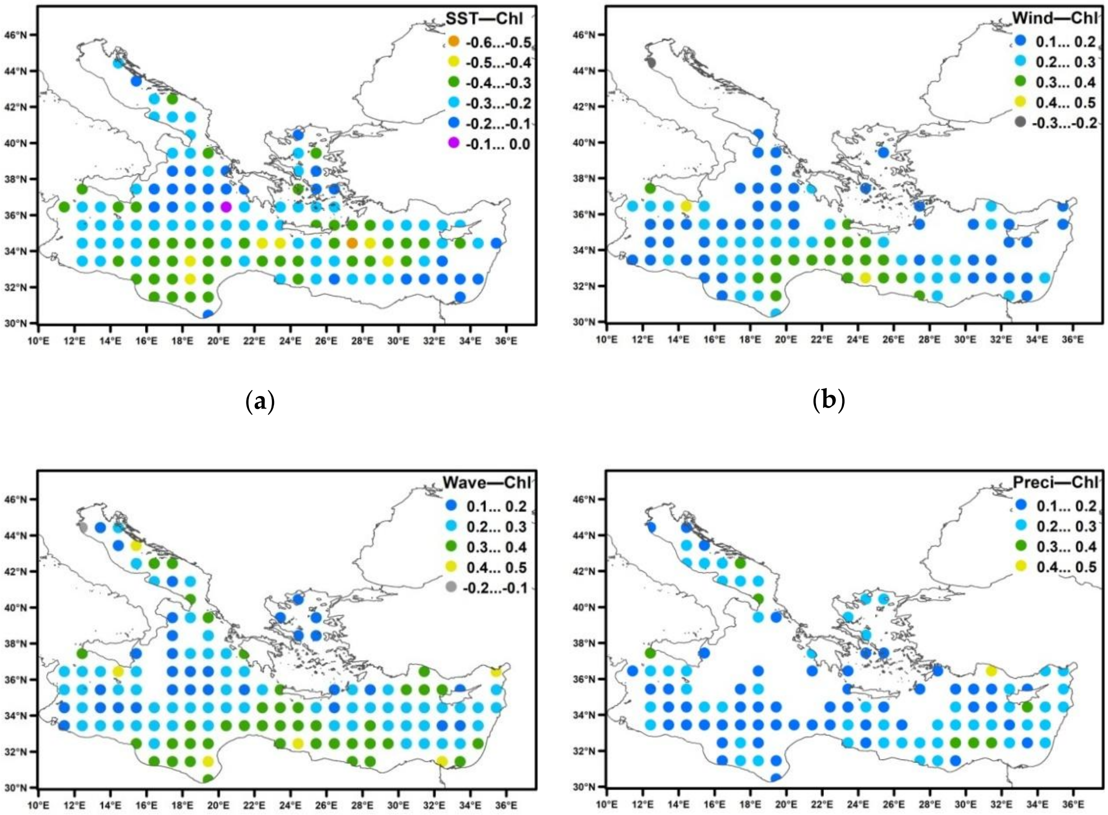


(**g**) (**h**)

Figure A2. SST (**a**,**b**), 10 m wind speed (**c**,**d**), wave height (**e**,**f**), and precipitation (**g**,**h**) climatology for the period 1998–2016 of the 158 points studied here for the high (November–April) and the low (May–October) production periods, respectively, as derived from the ERA Interim data set.

Appendix C

Spearman rank correlation coefficients between the monthly anomalies of chl-a and the environmental factors examined on a yearly basis are presented in this appendix.



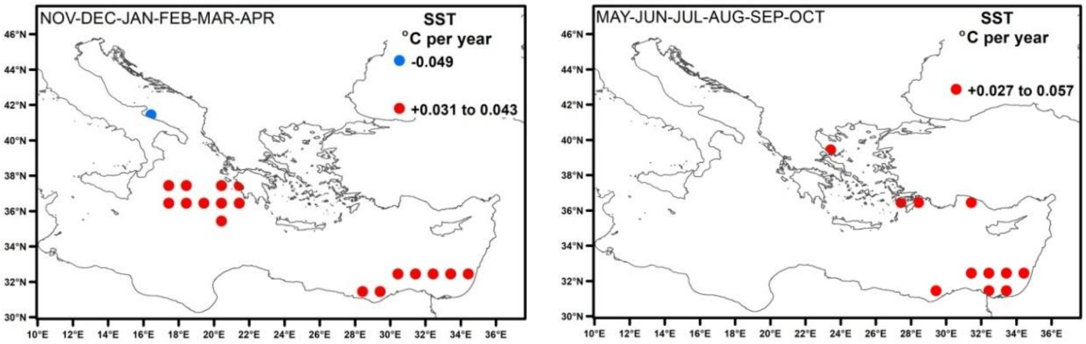
(**a**) (**b**)

(**c**) (**d**)

Figure A3. Spearman rank correlation coefficients throughout the year between the monthly anomalies of chl-a with: (**a**) SST, (**b**) 10 m wind speed, (**c**) wave height, and (**d**) precipitation. Only significant correlations are shown.

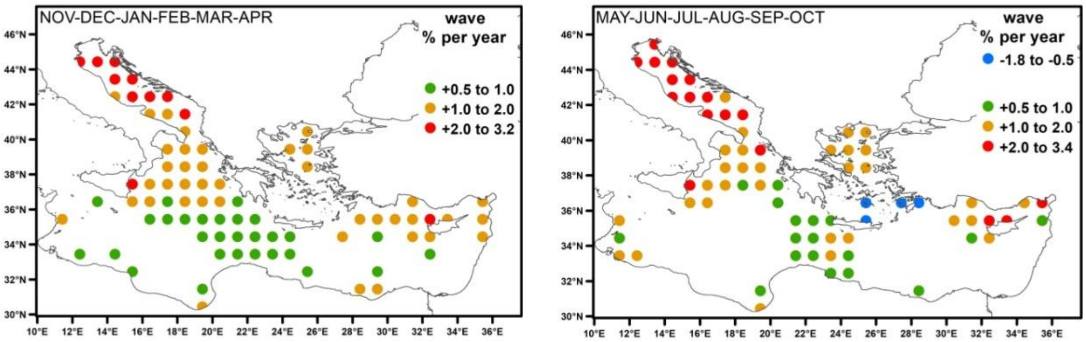
Appendix D

The trends of the environmental factors of SST, 10 m wind speed, wave height, and precipitation for the period 1998–2016 are given here. It is noted that these results are not representative for climate studies since they refer to a limited time period.



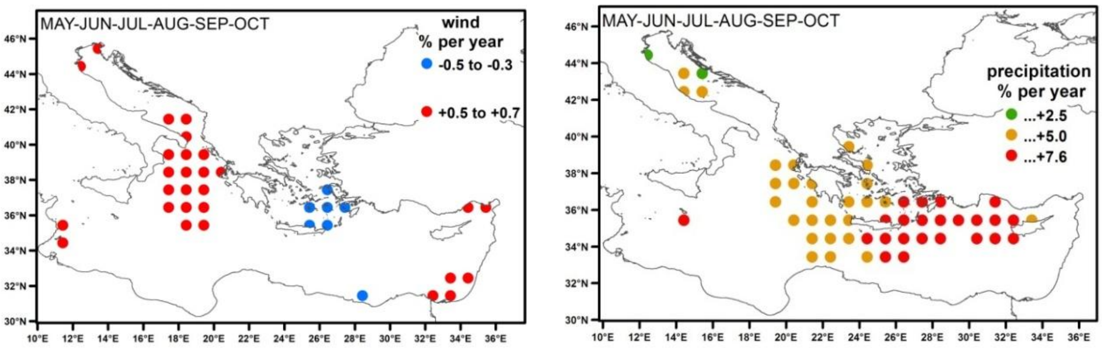
(a) (b)

Figure A4. SST trends (°C per year) during 1998–2016 for the high (**a**) and the low (**b**) production periods. Only significant trends are shown.



(a) (b)

Figure A5. Wave height trends (% of the climatology per year) during 1998–2016 for the high (**a**) and the low (**b**) production periods. Only significant trends are shown.

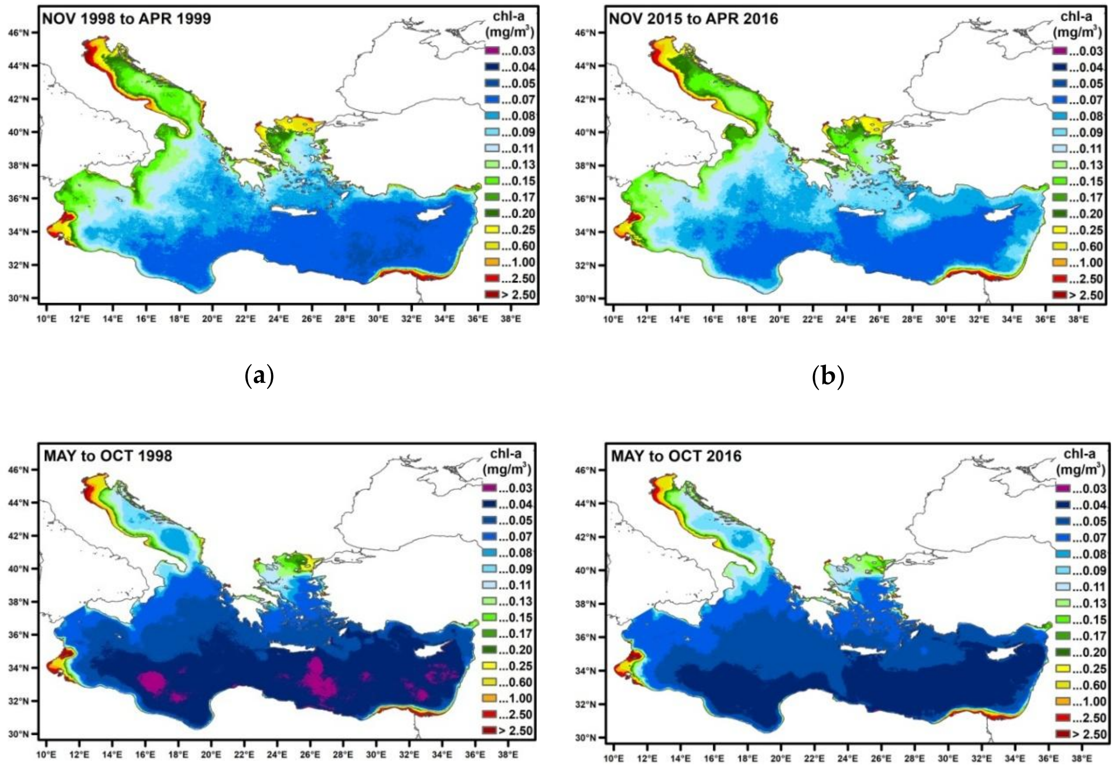


(a) (b)

Figure A6. The 10 m wind (**a**) and precipitation (**b**) trends (% of the climatology per year) during 1998–2016 for the low production period. Only significant trends are shown. For the high production period, no significant trends were detected.

Appendix E

The chlorophyll concentrations for the high and the low production periods of November 1998–April 1999, November 2015–April 2016, May–October 1998, and May–October 2016 are given in this appendix for comparison purposes.



(**a**) (**b**)

(**c**) (**d**)

Figure A7. Chlorophyll concentrations for the high production periods of November 1998–April 1999 (**a**) and November 2015–April 2016 (**b**), and the low production periods of May–October 1998 (**c**) and May–October 2016 (**d**).

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6. Summary of the main Results and Proposals for Future Work

6.1. Summary of the main Results

In this thesis, the possible influence on sea surface chlorophyll of the meteorological conditions of desert dust episodes and extreme weather events, as well as of the parameters of SST, 10 m wind speed, SWH, precipitation and MSL pressure was examined in the Eastern Mediterranean Sea; the study focused on the Hellenic seas in many cases. The research was mainly based on satellite derived chlorophyll concentrations and numerical model products.

The study of the 'dust fertilization effect' was carried out by the assessment of specific dust episodes and for extended sea areas; five out of the six examined events affected the Hellenic Seas. This study resulted in no safe conclusions since both sign (positive and negative) chlorophyll differences were observed after the dust events. Nevertheless, the significant chlorophyll differences, i.e. the ones exceeding 50% which is the absolute percentage difference between satellite derived chlorophyll data and *in situ* measurements, pointed to the direction that dust has a fertilizing role in phytoplankton growth, especially during the low productive period. The weekly chlorophyll mean values were also found statistically significantly higher after the events for the areas that presented the above mentioned significant chlorophyll variations; however, these variations corresponded to a restricted amount of data. A more favouring role of wet dust deposition was also implied. In addition, it was difficult to discriminate between the possible effects of dust and the ones of other meteorological factors, such as strong winds and heavy rainfall, on the observed chlorophyll variations.

The results of the research upon the influence of extreme weather events on sea surface chlorophyll concentrations were clear: extreme events, in general, favoured primary production. Chlorophyll increased, in most cases, by more than 50% over a large part of the impacted sea areas. Even during the summer period, extreme rainfall seemed able to induce chlorophyll increases of temporary character. Medicanes, the tropical-like Mediterranean cyclones that induce extreme weather conditions, were found triggering chlorophyll increases that were also observed over extended open sea areas. The post-medicane chlorophyll values that were higher than those before, and even higher than the climatological monthly values, referred to large proportions of the affected areas; when absolute chlorophyll differences exceeding 50% were concerned, the chlorophyll increases characterized quite the whole areas. Area averaged chlorophyll concentrations presented increases that were comparable to the ones caused by Atlantic hurricanes in oligotrophic environments, even for the open sea oligotrophic area. The mechanisms that have been proposed to explain hurricanes' favourable influence on chlorophyll concentration seemed to be valid for medicanes as well.

The last part of the present thesis, which assessed the possible relations between sea surface chlorophyll concentration and meteorological parameters, identified SST, wind speed, wave height, precipitation and, in cases, MSL pressure as important factors influencing phytoplankton growth. Higher wind speeds, relatively low SST, considerable precipitation amounts and lower MSL pressure compared to climatological values, were revealed as possible prerequisites for higher chlorophyll α concentrations during March for the regions of the Rhodes Gyre and the Cyclades Plateau. Correlations between chlorophyll and the environmental variables were calculated through their monthly anomaly values for the long period 1998-2016 for the Eastern Mediterranean. All correlations were strongly dependent on the season. Chlorophyll was found inversely correlated with SST in the major part of the Basin especially during spring; nevertheless, this relation was not valid for the summer season. Positive correlations of chlorophyll with wind speed and more pronounced ones with wave height were found, both presenting their higher values over the open sea (south part of the study area); however, negative correlations were locally found between these parameters for the summer period. The correlations between chlorophyll and wind speed presented similar patterns with the ones between chlorophyll and wave height; nevertheless, the latter were higher and covered larger areas. The correlations of chlorophyll with precipitation were lower, always positive and mainly valid during the low production period; the southern parts of the Levantine Basin presented such correlations for the high production period. Negative correlations between chlorophyll and MSL pressure were found for the winter season and especially for the western part of the study area. Considering the period 1998-2016 and as far as the chlorophyll trends in the Eastern Mediterranean are concerned, only increasing and local ones were detected.

6.2. Conclusions and Proposals for Future Work

The possible dust fertilizing effect on marine primary production, as revealed by sea surface chlorophyll concentrations, remains a questionable issue for the Eastern Mediterranean Sea. Since the majority of the studies regarding the dust impact on chlorophyll were based on experiments, more *in situ* measurements after real dust events could shed light on this issue. A problem raised by the present thesis was the difficulty in disentangling between the possible influence of dust and the one of other meteorological conditions. Thus, further studies involving long time series of both dust and chlorophyll data as well as of meteorological parameters' data, processed using statistical techniques, is proposed.

Extreme weather events play a key role in meteorological forcing on the Eastern Mediterranean Sea inducing increases in sea surface chlorophyll concentrations. Medicanes cause chlorophyll increases, even over the large open sea affected areas, comparable to the ones of hurricanes in Atlantic oligotrophic waters. In the Mediterranean, the studies carried out so far regarding the relation of extreme events and chlorophyll referred to near coast areas; thus, such events should be further examined with emphasis on the open sea. A relative study referring to deep depressions (lows) over the open sea could be a subject for future research.

In the Eastern Mediterranean, sea surface chlorophyll is, in general, negatively correlated with SST, negatively but locally with MSL pressure, and positively with wind speed, wave height and precipitation. The correlations of chlorophyll with SST, wind speed and wave height characterize the high productive period, while the ones between chlorophyll and precipitation mainly occur during the low production period. Chlorophyll presents increasing and local trends in the Basin for the period 1998-2016. Since the parameters of wave height, MSL pressure and precipitation have been minimally involved in relevant studies, further research could be carried out. Additionally, correlation studies at higher temporal and spatial resolution are suggested. It is noted that the detection of trends requires much longer time series for safe results; thus, this research could be continued in the future as more satellite chlorophyll data become available.

List of Acronyms and Abbreviations

AERONET	AErosol RObotic NETwork
AOD	Aerosol Optical Depth
AOT	Aerosol Optical Thickness
ASCAT	Advanced Scatterometer
AVHRR	Advanced Very High Resolution Radiometer
CAMS	Copernicus Atmosphere Monitoring Service
CDF	Cumulative Distribution Function
CDOM	Colored Dissolved Organic Matter
CDS	Climate Data Store
Chl	Chlorophyll
DCM	Deep Chlorophyll Maximum
CMEMS	Copernicus Marine Environment Monitoring Service
ECMWF	European Centre for Medium-Range Weather Forecasts
EFI	Extreme Forecast Index
ENS	Ensemble
EPS	Ensemble Prediction System
ERA5	the latest ECMWF reanalysis project
ERA Interim	the ECMWF reanalysis project up to Aug 2019
GCOS	Global Climate Observing System
GIS	Geographic Information System
GPM	Global Precipitation Measurement
HNLC	High-Nutrient Low-Chlorophyll
HNMS	Hellenic National Meteorological Service
HRES	High Resolution
IFS	Integrated Forecasting System
LIW	Levantine Intermediate Water
LNLC	Low-Nutrient Low-Chlorophyll
MACC	Monitoring Atmospheric Composition and Climate
MBR	Maximum Band Ratio
Medicane	Mediterranean hurricane
Med	Mediterranean
MERIS	MEdium Resolution Imaging Spectrometer
MLD	Mixed Layer Depth
MODIS	MODIS Moderate Resolution Imaging Spectroradiometer
MSL	Mean Sea Level
NOA	National Observatory of Athens
NRT	Near Real Time
NWP	Numerical Weather Prediction
OCTAC	Ocean Colour Thematic Assembly Centre
OLCI	Ocean and Land Colour Instrument
PAR	Photosynthetically Active Radiation
PM	Particulate Matter
REP	Reprocessed
Rrs	Remote Sensing Reflectance
SeaWiFS	Seaviewing Wide Field-of-view Sensor

SWH	Significant Wave Height
SST	Sea Surface Temperature
TRMM	Tropical Rainfall Measuring Mission
VIIRS	Visible Infrared Imager Radiometer Suite
WMO	World Meteorological Organization