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Anomalous 2022 deep water formation and intense phytoplankton bloom in the Cretan area

Anna Teruzzi[1], Ali Aydogdu[2], Carolina Amadio[1], Emanuela Clementi[2], Simone Colella[3], Valeria Di Biagio[1], Massimiliano Drudi[4], Claudia Fanelli[3], Laura Feudale[1], Alessandro Grandi[4], Pietro Miraglio[2], Andrea Pisano[3], Jenny Pistoia[2], Marco Reale[1], Stefano Salon[1], Gianluca Volpe[3], Gianpiero Cossarini[1]

[1]National Institute of Oceanography and Applied Geophysics - OGS, Trieste, 34142, Italy
[2]Ocean Modelling and Data Assimilation Division, Euro-Mediterranean Centre on Climate Change (CMCC) Foundation, 40127, Bologna, Italy
[3]Istituto di Scienze Marine – Consiglio Nazionale delle Ricerche, Roma, 00133, Italy
[4]Ocean Predictions and Applications Division, Euro-Mediterranean Centre on Climate Change (CMCC) Foundation, 73100 Lecce, Italy

Correspondence to: Anna Teruzzi (ateruzzi@ogs.it)

Abstract. The Mediterranean Sea is a quasi-permanently stratified and oligotrophic basin with intense late-winter early-spring phytoplankton blooms typically limited to few regions (i.e., northwestern Mediterranean Sea, the Southern Adriatic Sea and the Rhodes gyre). In these areas, blooms are sustained by nutrients injection to surface layers by winter vertical mixing and convective processes. A markedly intense bloom was predicted in spring 2022 in an unusual area of the southeastern Mediterranean Sea (i.e., southeastern of Crete) by the Med-MFC system, the production centre of the Copernicus Marine Service for the Mediterranean Sea. Combining Copernicus modelling and observation products, the 2022 event and a number of driving and concurrent features have been investigated in a multidisciplinary way. A noticeable cold spell that occurred in eastern Europe at the beginning of 2022 has been identified as the main driver of an intense deep water formation event, with associated high nutrient concentrations in the surface layers. Consequently, an extreme phytoplankton bloom that was 50% more intense than usual occurred in the area southeast of Crete, starting nearly one month later than usual and lasting for 3-4 weeks. Impacts on primary production were also relevant in the 2022 event area, being 35% higher than the climatological annual primary production. Further, the documented link between primary productivity and fish catches suggests possible consequences along the whole food chain up to the marine ecosystem in the eastern Mediterranean Sea.

1 Introduction

The Mediterranean, the main regional sea of southern Europe, is a semi enclosed basin located between midlatitude and subtropical climate regimes (Coppini et al., 2023; Siokou-Frangou et al., 2010; Lazzari et al., 2012; Cossarini et al., 2019). The Mediterranean Sea is an almost permanently stratified and oligotrophic basin with few areas exhibiting recurrent late-

https://doi.org/10.5194/sp-2023-30
Preprint. Discussion started: 10 October 2023

winter/early-spring phytoplankton blooms: the northwestern Mediterranean, the Rhodes gyre, and the southern Adriatic Sea (Siokou-Frangou et al., 2010). In these regions, the blooms are driven by deep winter convective mixing, which brings nutrients into the surface layer, and by the subsequent stratification, when the phytoplankton is no longer diluted across the water column. At this moment, conditions are suitable for the surface phytoplankton bloom onset since in the surface layer both light and nutrients are available (Mayot et al., 2017; Habib et al., 2022; D'Ortenzio and Ribera d'Alcalà, 2009).

The Eastern Mediterranean experiences particularly sharp oligotrophic conditions, and productive areas are limited to the Rhodes gyre, where deep water mixing and related bloom events typically occur (Varkitzi et al., 2020), and to the Turkish coast (Kubin et al., 2019).

Current evidence suggests that the Mediterranean Sea is facing an increase in marine heat waves and a decrease in cold spell events (Simon et al., 2022) as a potential consequence of changes in regional climate. However, in March 2022 a strong and unusual atmospheric cold spell affected the eastern Mediterranean region (Demirtaş, 2023), with strong surface air negative anomalies recorded over southeastern Europe (up to -3 °C according to Copernicus Climate Change Service bulletin; C3S monthly climate bulletin explorer, 2023; Surface air temperature for March 2022 | Copernicus, 2023).

In the present work, implications on marine physical and biogeochemical dynamics of the unusual 2022 cold spell are investigated exploiting the products of the Copernicus Marine Service (Home | CMEMS, 2023). We use both models and observations to highlight the interplay between biogeochemical and physical processes considering that intense cold spells usually drive deep water column mixings and consequent nutrients injections in the surface layer and onset of phytoplankton blooms (Auger et al., 2014). In order to describe the exceptionality of the 2022 event and its possible implications on the Mediterranean ecosystem, its spatial and temporal extent are defined based on phytoplankton bloom anomaly, and its characteristics in terms of sea surface temperature, mixed layer depth, surface chlorophyll, nutrient concentrations and primary production are investigated.

2 Methods

The occurrence and mechanism of the anomalous deep convection and phytoplankton bloom episode southeast of Crete (eastern Mediterranean Sea) in spring 2022 was investigated using both model and satellite-based products. The Copernicus Marine Service Mediterranean forecasting centre (Med-MFC) provides 3D ocean biogeochemical and physical variables at 1/24 ° resolution (product ref. 1, 2, 4 and 5; Table 1). Sea surface temperature (SST) and surface layer chlorophyll concentration are provided by the Copernicus Marine Sea Surface Temperature and Ocean Colour Thematic Assembly Centre (SST TAC and OC TAC, respectively) (Product ref. 3 and 6; Table 1). Both near real time and multi-year products are used to characterise the 2022 event.

https://doi.org/10.5194/sp-2023-30
Preprint. Discussion started: 10 October 2023

Product ref. no.	Product ID & type	Data access	Documentation
1	MEDSEA_ANALYSISFORECAST_BGC_006_014, Numerical models	EU Copernicus Marine Service Product (2022a)	Quality Information Document (QUID): Feudale et al. (2022), Product User Manual (PUM): Lecci et al. (2022a)
2	MEDSEA_MULTIYEAR_BGC_006_008, Numerical models	EU Copernicus Marine Service Product (2022b)	Quality Information Document (QUID): Teruzzi et al. (2022), Product User Manual (PUM): Lecci et al. (2022b)
3	OCEANCOLOUR_MED_BGC_L3_NRT_009_141, Satellite observations	EU Copernicus Marine Service Product (2022c)	Quality Information Document (QUID): Colella et al. (2022a), Product User Manual (PUM): Colella et al. (2022b)
4	MEDSEA_ANALYSISFORECAST_PHY_006_013, Numerical models	EU Copernicus Marine Service Product (2022d)	Quality Information Document (QUID): Goglio et al. (2022), Product User Manual (PUM): Lecci et al. (2022c)
5	MEDSEA_MULTIYEAR_PHY_006_004, Numerical models	EU Copernicus Marine Service Product (2022e)	Quality Information Document (QUID): Escudier et al. (2022), Product User Manual (PUM): Lecci et al. (2022d)
6	SST_MED_SST_L4_REP_OBSERVATIONS_010_021, Satellite observations	EU Copernicus Marine Service Product (2022f)	Quality Information Document (QUID): Pisano et al. (2022a), Product User Manual (PUM): Pisano et al. (2022b)
7	OMI_VAR_EXTREME_WMF_MEDSEA_area_averaged_mean, Numerical models	EU Copernicus Marine Service Product (2023g)	Quality Information Document (QUID): Lyubartsev et al. (2023), Product User Manual (PUM): Lyubartsev and Clementi (2022)
8	ECMWF AST	ECMWF: IFS Documentation CY47R3, E.: IFS Documentation CY47R3 https://doi.org/10.21957/eyrpir4vj, 2021.	ECMWF (2021)

Table 1. Datasets used in the present work, with references and doi.

A daily climatology based on the 1999-2019 Med-MFC Biogeochemistry Reanalysis (Cossarini et al., 2021; Teruzzi et al., 2022; product ref. 2, Table 1) was calculated following Hobday et al. (2016) for a subset of variables (surface chlorophyll concentration, nutricline depth, average phosphate concentration above the nutricline, primary production integrated in the 0-200 m layer). In particular, for each variable a set of percentiles is calculated to identify specific thresholds (i.e., 1st, 25th, 50th, 75th, 99th percentile) using a ten-day window centred on each date of the climatological year. Comparing the 2022 Med-MFC Analysis and Forecast (Salon et al., 2019; Feudale et al., 2022; product ref. 1, Table 1) with the corresponding climatology in the time window of the bloom (20 March - 30 April), the chlorophyll concentrations in all the surface grid points of the investigated area (22-32 °E, 32-35 °N) resulted above the 99th percentile for at least 20% of the time period, indicating that the whole area was interested by intense and anomalous bloom conditions. In order to define the region mostly interested by the anomalous 2022 bloom, following Hobday et al. (2016), the maximum difference with respect to

https://doi.org/10.5194/sp-2023-30
Preprint. Discussion started: 10 October 2023

climatology between 20 March and 30 April is calculated (Imax) and the event area is defined as composed by all the surface grid points with Imax higher than its 90th percentile (0.23 mg chl m^{-3}) (Fig. 1). The characteristics of the anomalous convection and bloom event are investigated considering marine physical and biogeochemical properties averaged over the event area contoured in Fig. 1. Moreover, a daily sea surface temperature (SST) climatology derived from the Mediterranean SST multi-year product over the period 1982-2021 (Pisano et al., 2022a, 2022b; product ref. 6, Table 1) is used to compare surface temperatures (i.e., first layer of the Med-MFC SST; product ref. 4) during the 2022 event time window.

Finally, the Copernicus Marine Ocean Monitoring index (Lyubartsev et al., 2023; product ref.7, Table 1), computed from the Mediterranean Sea Physics Reanalysis (Escudier et al., 2021; product ref. 6, Table 1), which provides water mass formation rates in the Mediterranean Sea is considered to analyse the 2022 event. In particular the Levantine Deep Waters (LDW) formation index is calculated for 2022 and compared with values that occurred in the past (from 1987 onwards).

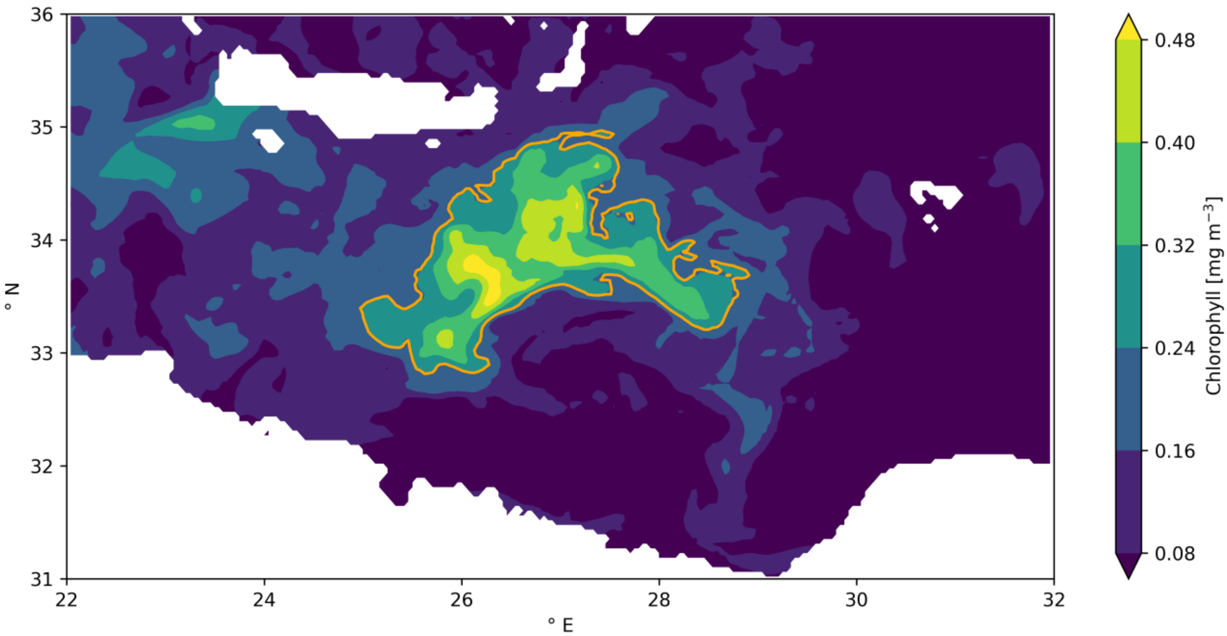

Figure 1: Mediterranean Sea Analysis and Forecast product (product ref. 1, Table 1): filled contours of the maximum intensity of surface chlorophyll concentration between 20 March and 30 April 2022, and line contour of the 90th percentile of the maximum intensity (0.23 mg chl m^{-3}).

3 Results

The signal of the 2022 cold outbreak over Eastern Europe (Demirtaş, 2023) is clearly detectable in the atmospheric surface temperature (AST) extracted from the ECMWF analysis products (ECMWF 2021; product ref. 8, Table 1). In the second half of January 2022 the AST daily time series reaches a relative minimum (nearly 15° C), and it is followed by two minima in the March-April time window (Fig. 2a). Accordingly, with a less noticeable variability, sea surface temperature (SST)

https://doi.org/10.5194/sp-2023-30
Preprint. Discussion started: 10 October 2023

gradually decreases in the area of interest (Fig. 2a). The satellite SST (Pisano et al., 2022a; product ref. 6, table 1) shows a constantly negative anomaly of winter 2022 with respect to its climatology (-0.46 °C on average) from the beginning of January to the end of March, indicating the sea surface cooling as the most likely driver of an anomalous deep convection event. Even lower SST values are provided by the Med-MFC Analysis and Forecast (Goglio et al., 2022; product ref. 4, Table 1) with a minimum in the second half of March, followed by a relatively sharp increase towards the SST satellite climatology. According with the relatively low SST and similarly to the typical winter mixing conditions in the Rhodes gyre area (Kubin et al., 2019), in the 2022 event area (Fig. 1) the maximum mixed layer (MLD; calculated as depth where the density increases by 0.01 kg m^{-3} compared to density at 10 m depth; product ref. 4, Table 1) is relatively deep (deeper than 1000 m on average; Fig. 2b) from the end of January to the beginning of March, when maximum MLD gets shallower (up to 50 m). Consistently with the strong March 2022 sea surface cooling, the mixed layer deepens again down to 1000 m until the end of March. Differently from the beginning of 2022, in March the maximum MLD is constantly deeper than 1000 m without strong oscillations. The sequence of oscillating and persistent deep convection results in an intense and protracted deepening of the mixed layer that starts in January and holds until the end of March 2022 and that is quite unusual for the investigated area.

Considering the Copernicus Marine Ocean Monitoring index (Lyubartsev et al., 2023; product ref. 7, Table 1), in the Levantine basin a large dense water formation rate of approximately 1.3 Sv is documented (not shown[1]) in the winter of 2022. Confirming the relevant effects on physical marine processes of the 2022 cold outbreak, the same LDW formation index was higher only during the noteworthy Eastern Mediterranean transient (EMT; 1992-1993), when the formation rate reached up to 1.8 Sv. After that, the LDW formation index showed only two maxima in 2008 and 2012 with relatively low values (0.7 Sv and 1.0 Sv, respectively).

Slightly later with respect to AST minima and during the strong March 2022 MLD deepening, in the event area southeast of Crete (Fig. 1) the nutricline depth (NCLD; depth of the maximum nitrate vertical gradient; Salon et al., 2019) is deeper than 400 m and of the NCLD climatology 99th percentile, with two peaks that go down to nearly 600 m (Fig. 2b). The March 2022 anomalous deepening of the nutricline is preceded in February by a more typical event with deepening of the nutricline that stays within its climatology 99th percentile and goes down to nearly 400 m.

[1] The Ocean Monitoring index on the water mass formation will be extended to 2022 and published on Copernicus Marine catalogue by 2024.

https://doi.org/10.5194/sp-2023-30
Preprint. Discussion started: 10 October 2023

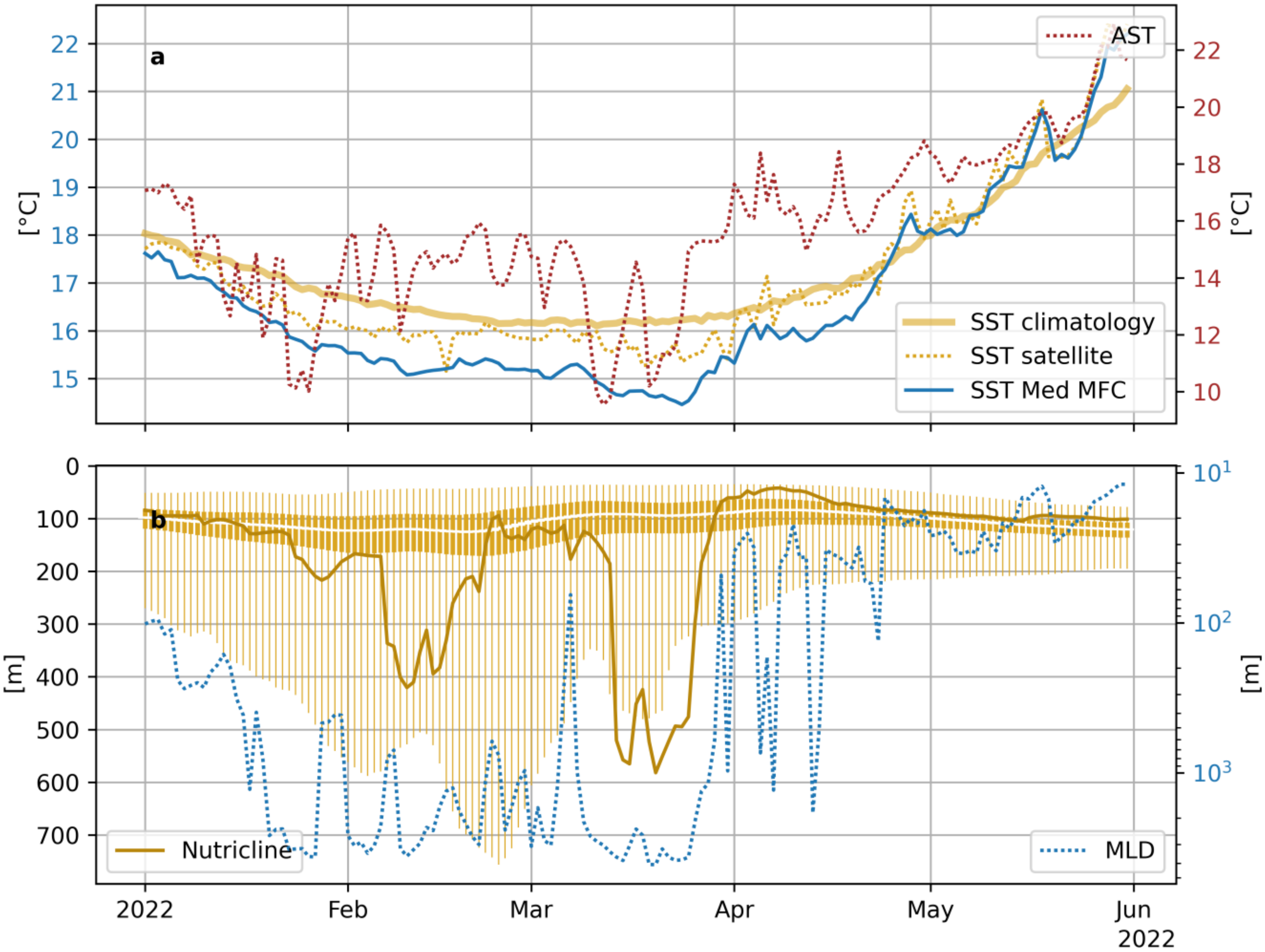

Figure 2: Daily time series - spatially averaged over the event area (Fig. 1) - from January to May 2022 of (a) air surface temperature (AST), sea surface temperature for satellite (SST satellite, product ref. 6, Table 1) and model (SST Med MFC, product ref. 4, Table 1), and SST satellite climatology; and (b) mixed layer depth (MLD: product ref. 4. Table 1) and nutricline (product ref. 1, Table 1) with climatological percentiles (thin vertical line: 1st and 99th percentiles, thick vertical line: 25th and 75th percentiles, white marker: median).

At the bloom peak (8 April) the mean surface chlorophyll concentration in the event area (Feudale et al., 2022; Fig. 1, product ref. 1, Table 1) is higher than 0.4 mg m^{-3}, i.e., more than double of the climatological 99th percentile (Fig. 3a). Chlorophyll concentrations are higher than the 99th climatological percentile from 2 to 10 April, indicating that the 2022 bloom event is anomalous both in terms of intensity and timing. In fact, according to the chlorophyll climatology, typical late-winter/early-spring chlorophyll peaks occur in the first half of March. With similar timing of the anomalous surface chlorophyll concentration, primary production integrated over the 0-200 m layer largely exceeds the 99th climatological percentile (Fig. 3b). Related to the strong mixing event occurred in the late winter of 2022 and to the deepening of the nutricline (Fig. 2), the mean phosphate concentration above the nutricline is higher than the 99th percentile in the month

https://doi.org/10.5194/sp-2023-30
Preprint. Discussion started: 10 October 2023

preceding the phytoplankton bloom with a rapid decrease during the bloom-establishing phase (Fig. 3c). The delay between large availability of nutrients in the surface layer and the bloom peak is consistent with the Sverdrup theory (Mayot et al., 2017), according to which surface bloom starts when the MLD becomes shallower than the euphotic layer. Indeed, when the mixing is limited to the surface, phytoplankton is no longer diluted over the water column but remains in the surface layer where both light and nutrients (brought to the surface by the previous deep mixing) are available and favourable to the bloom onset.

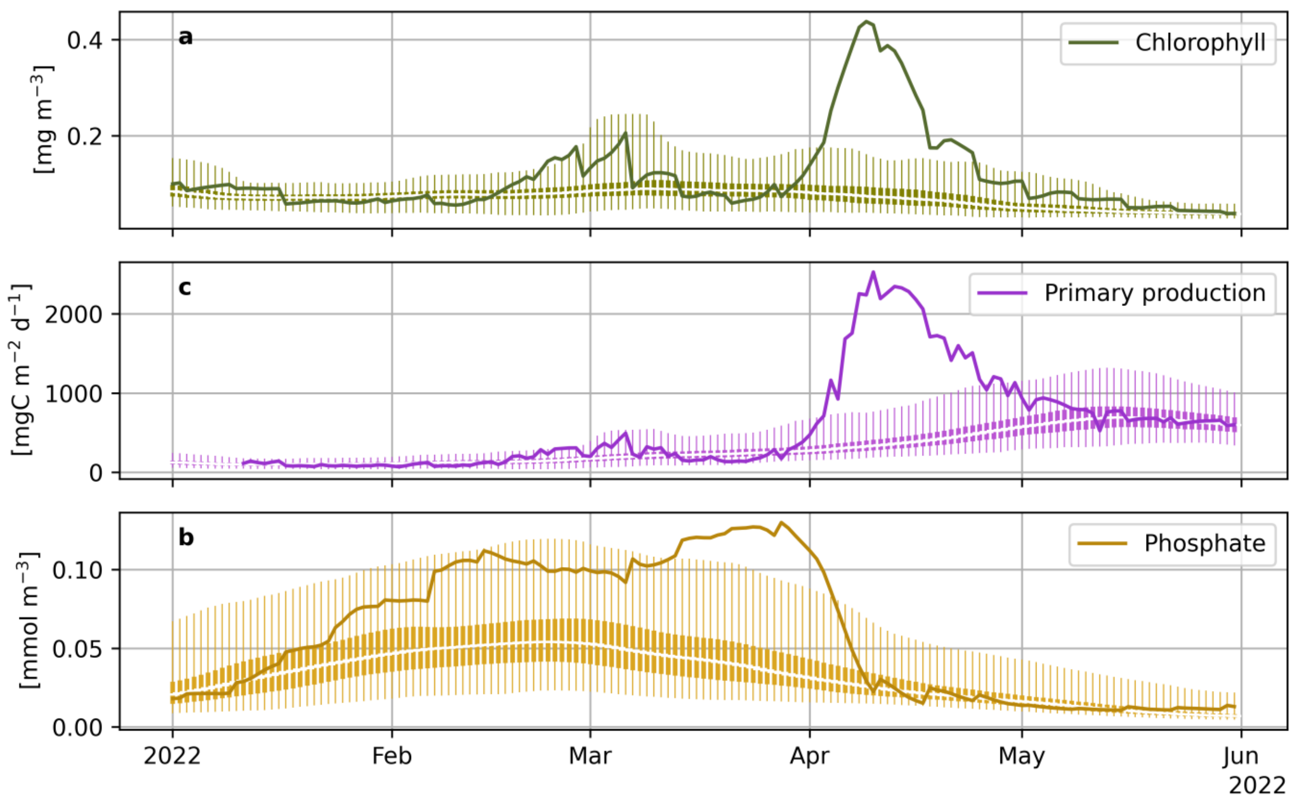

Figure 3: Daily time series of variables based on product ref. 1 (continuous line) and of climatology percentiles (thin line: 1st and 99th percentiles, thick line: 25th and 75th percentiles, white marker: median) spatially averaged over the event area (Fig. 1) for (a) surface chlorophyll concentration; (b) mean concentration of phosphate above the nutricline; and (c) primary production integrated in the 0-200 m layer.

The anomalous bloom event is clearly detectable in surface chlorophyll observations (Colella et al., 2022; product ref. 3, Table 1) reaching values comparable to those simulated by the Analysis and Forecast system (Fig. 4). On the other hand, the sequence of satellite maps suggests that the model bloom is spatially (i.e., approximately 100 km north-eastwards) and temporally (i.e., anticipated by maximum 10 days) shifted with respect to the satellite observations (Fig. 4). Since the 2022 anomalous surface bloom is the result of a sequence of processes (cold outbreak, sea surface cooling, vertical mixing, fertilisation and subsequent stratification), uncertainties in the representation of each of these dynamics by the atmospheric-

https://doi.org/10.5194/sp-2023-30
Preprint. Discussion started: 10 October 2023

ocean and biogeochemical models may combine and result in inaccuracies in the spatio-temporal representation of the bloom.

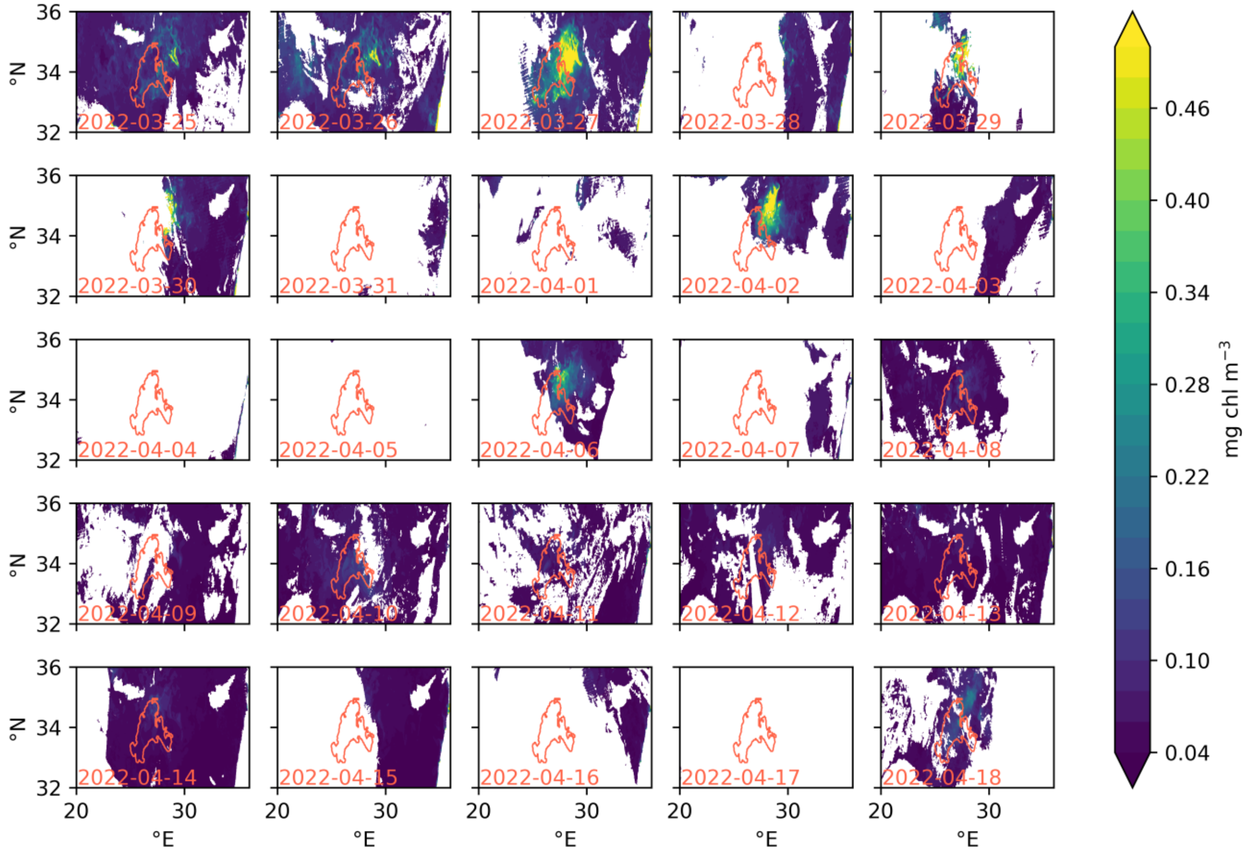

Figure 4: Daily maps of satellite surface chlorophyll concentration [mg m^{-3}] (product ref. 3, Table 1) from 25 March (upper left panel) to 18 April 2022 (lower right panel), and orange line contour of the event area (Fig. 1).

5 Discussion and conclusions

An anomalous deep mixing and bloom event in the south-eastern Mediterranean in the 2022 late-winter early spring period was detected by means of the Copernicus Marine Med-MFC products. In this region, intense phytoplankton blooms related to vertical mixing processes are usually located in the Rhodes gyre area (Varkitzi et al., 2020; Siokou-Frangou et al., 2010), while the 2022 event was located southeast of Crete (Fig. 1). In this work we analysed and described the main 2022 event traits and its drivers.

The deep convection and the phytoplankton bloom events in the Cretan area are consistent with the anomalous cooling that occurred in southeastern Europe at the beginning of 2022, showing a dynamics similar to the one of the Mediterranean marine cold spell events described in Simon et al. (2022). Furthermore, the connection between the 2022 atmospheric

https://doi.org/10.5194/sp-2023-30
Preprint. Discussion started: 10 October 2023

conditions and sea cooling is corroborated considering the impacts of atmospheric modes of variability on Mediterranean Sea surface heat exchange discussed by Josey et al. (2011) and Reale et al. (2020). Indeed, both the East Atlantic/Western Russia and the East Atlantic pattern indexes, that are associated with negative heat fluxes in the eastern Mediterranean, were relatively high in March 2022 (Index of /cwlinks, 2023).

The frequency and the impacts of marine extreme events in recent years have been investigated in the Mediterranean Sea (Darmaraki et al., 2019; Dayan et al., 2023; Simon et al., 2022; Martínez et al., 2023; McAdam et al., 2023) also proposing innovative techniques to analyse prolonged episodes in marine ecosystems (Di Biagio et al., 2020). Together with the relatively high number of variables exceeding their 99th percentile during the event (Fig. 2 and 3), the recent decrease in the occurrence of cold marine extremes in the Eastern Mediterranean (Simon et al., 2022) further highlights the exceptionality of the 2022 event.

Our study documents the importance of the value chain composed by atmospheric, ocean and biogeochemical prediction models in detecting anomalies with respect to the typical state and variability. In particular, the strong anomaly in phytoplankton bloom intensity revealed to be a suitable descriptor to define the 2022 event localization, extent and duration. Moreover, the evaluation of the spatial and temporal mismatch of the simulated event with respect to the Copernicus Marine ocean colour product provides an assessment of the capability of the prediction chain to simulate specific events.

Considering that previous anomalous cooling events (1992-1993) were among the drivers of the EMT that impacted the whole Mediterranean Sea dynamics (e.g., Theocharis et al., 2002; Roether et al., 2007; Pinardi et al., 2019) with consequences on other marine compartments (e.g., nutrients and productivity, biodiversity, and acidification; Tsiaras et al., 2012; Touratier and Goyet, 2011; Stratford and Haines, 2002; Civitarese and Gacic, 2001; Danovaro et al., 2004), the 2022 event and the related deep water formation might be worth further investigation.

Our results show that the 2022 anomalous event increased by 35% the annual primary production in an area of approximately 35000 km^2 (i.e., 11% and 1.4% of the Levantine basin and Mediterranean Sea surface, respectively). As a consequence of the increased organic matter synthesis, a non-negligible impact along the whole food chain might have occurred, given the well proven link between productivity and fish catches (Canu et al., 2022; Colloca et al., 2017; Conti and Scardi, 2010; Piroddi et al., 2017). Due to the relative time proximity of the event and to the non-trivial work needed to collect fishing catches data, it was not possible to gather quantitative information on this aspect. Even if personal communication from the local fishery community reported increased catches and effects on the biogeochemical realms were clearly detected, the impact of the 2022 anomalous on the higher trophic level deserves a closer look.

Data availability

Publicly available datasets were analysed in this study. Modelling and in situ data can be found at the Copernicus Marine Service, with references and DOIs indicated in the Table 1 of the manuscript.

https://doi.org/10.5194/sp-2023-30
Preprint. Discussion started: 10 October 2023

Author contribution

AT, AA and GC conceived the idea. AT, AA, CF and SC conducted the analysis. AT, AA and GC wrote the first draft, with contributions from the other co-authors. All the authors discussed and reviewed the submitted manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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