Wintertime marine extreme temperature events modulate phytoplankton blooms in the North Pacific through subtropical mode water

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Abstract
Marine extreme temperature events (METs), including marine heatwaves (MHWs) and cold spells, have recently gained much attention owing to their vital influence on the marine ecosystem and social economy. Since METs can alter the upper ocean stratification and wintertime convective mixing in the northwestern North Pacific subtropical gyre (NPSG), their activities may modulate phytoplankton blooms by regulating entrainment of the subtropical mode water (STMW) with high NO−3. Furthermore, because STMW formed in the previous winter reemerges east of its formation site in the following winter, the METs activities imprinted in STMW affect phytoplankton blooms remote from its formation site. Here, we examined the relationship between the MET activities, STMW volume, and phytoplankton blooms using satellite observations and a data-assimilative coupled physical-biogeochemical model dataset. MET activities appearing in the STMW formation region during winter regulate the formation of STMW and the supply of NO−3 from the subsurface, with the latter controlling the spring/autumn blooms in that region under NO−3-limited conditions. Subsequently, this water mass is transported eastward in the subsurface within the northern flank of the NPSG before reemerging east of the STMW formation site the following spring. This process results in a negative lag-correlation between MET activities and surface chlorophyll in the reemergence region; for example, MHWs in winter at the STMW formation site tend to lower the surface chlorophyll concentration one year later in the reemergence region. Our study suggests that the oceanic processes allow one year of predictability of the marine ecosystems by monitoring METs in the STMW formation site.

1. Introduction

The North Pacific subtropical gyre (NPSG) is an expansive oligotrophic oceanic region with low chlorophyll [1]. Nevertheless, it plays an important role in carbon cycling by exporting approximately 40% of the total organic carbon in the global oceans from the upper ocean layers of subtropical gyres [2]. Recent observations have revealed that the annual mean depth-integrated gross primary production in the northwestern region of the NPSG is higher than that in the eutrophic subpolar gyre of the North Pacific Ocean [3]. Moreover, because subtropical gyres account for approximately 60% of the global ocean surfaces and are likely to expand poleward owing to global warming in the future [4], understanding the mechanisms underlying the primary production and its relationships with physical processes in the NPSG, as a representative oligotrophic gyre, is essential for improving the predictability of the global ecosystem in response to climate change.

In the western NPSG, where North Pacific subtropical mode water (STMW) is mainly formed, nitrate (NO−3) is a major limiting factor for primary production in the surface layer in all seasons except winter [5, 6]. Previous studies have reported various
types of new nitrogen inputs, such as convective mixing during winter, eddy-induced upwelling near the Kuroshio Extension region, nitrogen (N$_2$) fixation, and atmospheric deposition [5, 7–12]. Mino et al [5] reported that NO$_3^-$ mainly supplied by wintertime convective mixing, which accounts for 86%–93% of new primary production, is the main source of the spring bloom. Convective mixing in the northwestern North Pacific Ocean extending meridionally from 24° N to 35° N and zonally from 130° E to 175° E (a blue solid box in figure 1(b)) [13, 24]. The thickness of the STMW is greater than 250 m at the core of the formation site situated near 30° N, from 145° E to 155° E, and it mainly forms in the winter mixed layer, which is as deep as 150 m south of the Kuroshio Extension region (figure 1(b)). These criteria were applied to the monthly EN.4.2.1 objective analysis data with a horizontal resolution of 1° and 42 vertical levels [27], and the STMW volume in the formation region was computed for the years 1982–2020. The STMW moves eastward with the NPSG and affects the surface ocean conditions in the following winter/early spring through entrainment over the reemergence region that lies from 175° E to 160° W and spans the same latitudinal extent as the formation region (blue dashed box in figure 1(b)) [13, 28]. Results of passive tracer experiments performed by Tak et al [13] indicate that STMW can modulate MHW activity over the reemergence region for up to three years after its formation, although its water properties are altered while moving eastward.

2.2. Satellite chlorophyll-a data

Monthly mean surface chlorophyll-a data with a horizontal resolution of 9 km were obtained from the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer (MODIS)-aqua datasets from the periods 1998–2002 and 2003–2020, respectively [29]. Missing chlorophyll-a data were replaced with the nearest non-missing values. The surface chlorophyll-a concentrations in both the formation and reemergence regions have distinct seasonal variability with the spring bloom. The maximum concentration of 0.17 mg m$^{-3}$ in the reemergence region was observed in March, which was lower and appeared one month earlier than that in the formation region (0.23 mg m$^{-3}$) (figure 2(a)). Because the most vigorous primary production is observed during spring in northwestern North Pacific Ocean, we investigated the interannual variability of the surface chlorophyll-a concentration by averaging it from March to May against the MET and STMW values from January to March (main STMW formation period) [13, 16].

2.3. Estimation of METs

The MHW and MCS estimations were similar to those proposed by [22, 23, 30]. To identify MHWs and MCSs, daily SST values with 0.25° horizontal resolution were acquired from the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) satellite data [31] and climatological mean temperature and 90th and 10th percentile thresholds were calculated from 1982 to 2020 with an 11-day window centered on the day of interest. SSTs exceeding the 90th or
below the 10th percentile threshold for at least five days were identified as MHW and MCS, respectively. The monthly cumulative MHW and MCS intensities were computed as the integral of daily temperature anomalies during the MHWs/MCSs occurring in a particular month and employed as measures of MHW/MCS activity.

The horizontal distribution of MHW activities averaged from January to March was similar to that of MCS activities, and both displayed opposite patterns to the STMW thickness pattern (figure 1). The MHW and MCS activities were relatively weaker in the formation region than in the reemergence region because the STMW develops from the surface and reaches a depth of approximately 300 m, indicating a modest temperature anomaly in the formation region during winter and early spring (figure 1(b)). The fact that MHW activity can suppress STMW formation during winter/early spring suggests the possibility of a close relationship between
MCS activity and STMW formation. Thus, in this study, we defined MET activity as the summation of the monthly cumulative intensities of MHWs and MCSs. Interannual variations in the STMW volume and monthly cumulative MHW intensity, which were long-term detrended and averaged from January to March, had a significant negative correlation coefficient (r) of −0.65, and this negative relationship with the STMW volume improved to r = −0.69 after considering the MET activities. Also, interannual variability in the chlorophyll-a is more distinctly correlated with extreme temperature events than the variability in temperature anomaly (figure A1).

2.4. Retrospective analyses of ocean physical-biogeochemical fields

Historical estimates of ocean physical and biogeochemical fields were produced using a data-assimilative global earth system model (ESM) [32]. The ESM used in this study was developed at the National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory (NOAA-GFDL) and comprises dynamic atmosphere, ocean, land, sea ice, and biogeochemistry models [33]. The physical components in the ESM are based on GFDL’s Climate Model version 2.1, which is coupled online with the global ocean biogeochemical model, Carbon, Ocean Biogeochemistry, and Lower Trophics (COBALT) [34]. COBALT uses 33 tracers to represent global-scale biogeochemical cycles, including three phytoplankton and three zooplankton groups, bacteria and dissolved organic/inorganic matter. The data assimilation scheme coupled to ESM is the GFDL ensemble coupled data assimilation (ECDA) system [35]. Observed physical states in the ocean and atmosphere were assimilated into the ESM through the ECDA system to reproduce historical (1991–2017) ocean physical-biogeochemical fields. In other words, the ocean model of ESM was constrained by remotely sensed and in-situ temperature and salinity observations, including the daily NOAA optimum interpolation SST product and observed profiles from the Argo, World Ocean Database, and Global Temperature-Salinity Profile Program datasets [36–38]. The atmospheric model was constrained by six-hourly temperature and wind speed data from the National Centers for Environmental Prediction, Department of Energy Reanalysis 2 [39]. Notably, although the biogeochemical fields were not directly constrained by observations because of the lack of global-scale biogeochemical observations, they were indirectly updated by physical data assimilation within the ESM. This ESM-based assimilation system has been successfully tested in simulating historical ocean biogeochemical fields and used in a range of physical and biogeochemical predictions [32, 40–42].

3. Results and discussion

3.1. Relationship of MET activity and STMW with phytoplankton blooms

A previous study reported that the annual variability in the spring bloom magnitude has a positive relationship with the NO$_3^-$ concentration at the bloom onset [43]. Because NO$_3^-$ in the northwestern NPSG is mainly supplied to the surface mixed layer by convective mixing [5], the MET activity may control the NO$_3^-$ level at the surface layer. In this case, annual variation in the spring bloom was modulated by MET activities. The time series of the MET activities and springtime surface chlorophyll-a concentration indicated strong negative relationships in both formation and reemergence regions with r of −0.63 and −0.62, which are statistically significant under 95% confidence level, respectively. METs occurring in the formation region are irrelevant to chlorophyll-a in the reemergence region, indicating that the variation in chlorophyll-a in the reemergence region is independent of MET activity in the formation region (figure 2(d)).

The time-lagged correlation, however, suggests a connection between MET activities in the formation region and spring bloom in the reemergence region because of the reemergence of STMW. Figure 3 depicts the significant positive correlation of the STMW volume formed during winter in the formation region with surface chlorophyll-a during spring in that region. This positive relationship suggests that wintertime convective mixing causes the STMW formation and concurrently supplies high NO$_3^-$ to the water, implying that vigorous convective mixing in winter can intensify the subsequent spring bloom (figure 3(a)). A positive correlation peak in autumn indicates that the isolated STMW with high NO$_3^-$ in the subsurface owing to seasonal stratification starts to be entrained into the mixed layer in autumn. In contrast, significant negative correlations were observed between wintertime MET activities and chlorophyll-a during spring and autumn in the same region. This suggests that wintertime MET activities suppress phytoplankton blooms in spring and autumn by modulating the entrainment of STMW, which can be synchronous with the high NO$_3^-$ in the water.

According to previous studies [13, 28], STMW moves eastward because of the anticyclonic NPSG and reemerges into the surface ocean the following winter while experiencing alteration in its properties. Because STMW formation is proportional to the NO$_3^-$ inventory in STMW [19], there is a high chance that the reemergence of STMW supplies NO$_3^-$ to the mixed layer in the reemergence region. The time-lagged correlation between STMW volume and surface chlorophyll-a in the reemergence region clearly
Figure 3. Time-lagged correlation coefficients of the surface chlorophyll-a concentration in the (a) formation and (b) reemergence regions, with the STMW volume (red) and MET activity (blue) in the formation region averaged from January to March. The chlorophyll-a data were filtered using the three-month moving median filter and the correlation was calculated for 1998–2020. The dashed magenta lines indicate a 95% confidence level \((r = \pm 0.41)\), and closed circles indicate significant correlations with chlorophyll-a. The X-axes represent a time lag when upcoming years are denoted by positive values in parentheses.

indicates this mechanism. Chlorophyll-a in the reemergence region has significant negative and positive correlations with wintertime MET activities and STMW volume in the formation region, respectively, with 14 months of time lag. This time-lag correlation corresponds to that between the STMW volume in the formation region and MHW activities in the reemergence region [13]. However, STMW formation and MET activities have a statistically significant correlation with chlorophyll-a in the reemergence region only in the following year, whereas STMW formation can lead to MHW activities in the remote region for up to three years. This difference may stem from the fact that NO\textsubscript{3} concentration can be altered even in the subsurface layer because of physical as well as biogeochemical processes such as primary production, and nitrogen fixation, nitrification, and the biological pump. These active processes undermine the biological memory at the onset of STMW formation faster than passive tracers.

Time-lagged correlation maps of chlorophyll-a with MET activities and STMW volume suggest the propagation of the signal eastward (figure 4), which is similar to the pattern observed between MHW activity and STMW volume presented by Tak et al [13]. MET activity and STMW volume exhibited significant negative and positive correlations, respectively, with the surface chlorophyll-a concentration in spring in the south of the formation region. After eight months, significant patches still appeared in the formation region in the autumn. The patches shifted eastward to the reemergence region in the following spring. The correlation maps confirmed that MET activities occurring during winter in the formation region can modulate the phytoplankton blooms in spring, autumn and those in the reemergence region in the following spring through the reemergence of STMW. Significant patches with the chlorophyll-a also appear south of 24° N in spring and autumn (figure 4). According to previous studies, STMW formed in the formation region is advected to the reemergence region or southwestward after its formation owing to the Kuroshio countercurrent, which is part of the Kuroshio anticyclonic recirculation system [44, 45]. It suggests that the spreading of STMW could affect the phytoplankton blooms south of 24° N, although the significant relationship disappears in the next year.

Significant correlation patches of chlorophyll-a in spring with both MET activities and STMW volume were observed south of 30° N, which has a relatively thin STMW layer (figures 1(b) and 4(a, d)). In regions north of 30° N, with a large STMW formation, other factors are likely to limit primary production because NO\textsubscript{3} is sufficiently supplied into the surface layer as the insignificant correlation between the surface chlorophyll-a and NO\textsubscript{3} concentrations in spring in these regions (figure A4). Previous studies have proposed that mesoscale eddies and turbulent mixing limit primary production because they modulate the residence time of phytoplankton in the euphotic zone south of the Kuroshio–Oyashio Confluence region [7, 43]. In addition, there is a possibility that the Kuroshio Current transports high-nutrient water into the STMW formation region so that MHW activities can promote spring bloom by relaxing light limitation in that region [4, 46].

3.2. Reemergence of STMW with high nitrate and its modulation of the phytoplankton blooms

The time-lagged correlation map suggests that MET activities in winter modulate the spring bloom in the STMW formation region and that in the reemergence region the following spring. This indicates that the oceanic teleconnection associated with the reemergence of STMW may influence the upper ocean marine ecosystem as well as its physical conditions.
Figure 4. Correlation maps of the satellite-derived surface chlorophyll-a concentration in each grid cell with MET activities (a)–(c) and STMW volume from EN4.2.1 (d)–(f), averaged from January to March and integrated in the formation region (solid box), with (a) and (d) one, (b) and (e) eight, (c) and (f) fourteen months of lag. The chlorophyll-a data were filtered using the three-month moving median filter and the correlation was calculated for the period 1998–2020. Colored solid and dashed boxes denote the formation and reemergence regions, respectively. Red and blue shadings represent the positive and negative coefficients while black dots denote coefficients above the 95% confidence level ($r = \pm 0.41$).

[13, 28]. Because NO$_3^-$ is the main limiting factor for primary production in NPSG [5, 6], we anticipate that the NO$_3^-$ level in the reemerging water mass plays a critical role (figure A4). Hence, we examined the changes in NO$_3^-$ with respect to the reemergence of STMW using the physical-biogeochemical coupled model.

The data-assimilative coupled physical-biogeochemical model results suggest that the modulation of NO$_3^-$ associated with STMW is the key to the changes in chlorophyll-a. The surface NO$_3^-$ concentration in March was clearly positively correlated with the volume at which STMW is heavily formed (figures 1(b) and 5(a)). The vertical sections of the correlation between the NO$_3^-$ concentration and the volume of the STMW formed in winter exhibit a dipole pattern such that the NO$_3^-$ in the upper 200 m has a positive correlation with the STMW volume, whereas there is a negative correlation in the lower layers between 300 m and 400 m (figure 5(d)–(f)). This dipole pattern suggests that wintertime convective mixing enhances the formation of STMW and synchronously supplies NO$_3^-$ to the upper ocean. A positive correlation patch present at the surface layer disappeared in summer (not shown), but reappeared in autumn and winter (figure 5(b)). The recurring patch in the formation region can be attributed to the vertical mixing in the formation region that entrains the NO$_3^-$. The anomalously large STMW formation in March enriches the top 200 m depth, where higher levels of nutrients persist below the euphotic zone during summer. This water mass surfaces after summer because convection results in a positive NO$_3^-$ anomaly. The persistence of the pattern for at least a year in the vertical section of the formation region supports this idea. Hence, the intensity of STMW formation and the associated NO$_3^-$ level can modulate not only the spring bloom but also the growth of phytoplankton during autumn and early winter (figures 3(a) and 4(e)). Notably, phytoplankton blooms during winter are mainly limited by light conditions [19], resulting in insignificant relationship between the surface chlorophyll-a concentration and STMW volume for winter (figure 3(a)).

In addition, a positive correlation patch was observed in the reemergence region with a 14-month lag (figure 5(c)). The vertical section of the correlation between the STMW volume and NO$_3^-$ in December, ten months after STMW formation (figure 5(e)), suggests a subsurface origin of the signal. This positive correlation patch initially appeared at the STMW formation site in the previous March (figure 5(d)). It moved eastward to the reemergence region in the subsurface layer between 100 m and 200 m depths during
summer and autumn, which is evident by the positive correlation patch in figure 5(d, f). The model results confirm that the positive NO$_3^-$ anomaly associated with higher STMW formation can enhance the spring bloom in the formation region in March and in the reemergence region the following spring, and that eastward propagation and entrainment are the responsible processes. The eastward propagation of the positive NO$_3^-$ anomaly was clearly presented in figure A5, and it was stretched southwestward due to the Kuroshio countercurrent, resulting in diagonal significant correlation patches in figure 4. The negative lagged correlation between STMW volume and MHW activities in the formation region as well as the MHW activities in the reemergence region can be attributed to these processes [13]. Hence, we argue that MET activities in winter can modulate the biogeochemical environment as well, as shown by a negative correlation between the surface chlorophyll and METs using satellite observations; furthermore, numerical simulation results revealed that the change in nutrient supply through entrainment is a key process. MET activities during winter control the STMW formation and supply of NO$_3^-$ from the subsurface, with the latter modulating the spring bloom in the formation region under NO$_3^-$-limited conditions.

4. Summary and concluding remarks

METs, including MHWs and MCSs, have recently attracted considerable interest owing to their critical impact on the marine ecosystem and the social economy. According to a previous study [13], MHW activity during winter can suppress the formation of STMW in the northwestern NPSG by stabilizing the water column. In turn, smaller STMW volume provides favorable conditions for MHW occurrence by creating relatively warm surface conditions. In this study, we demonstrated that MET activities in winter can modulate the biogeochemical environment as well, as shown by a negative correlation between the surface chlorophyll and METs using satellite observations; furthermore, numerical simulation results revealed that the change in nutrient supply through entrainment is a key process. MET activities during winter control the STMW formation and supply of NO$_3^-$ from the subsurface, with the latter modulating the spring bloom in the formation region under NO$_3^-$-limited conditions.

Figure 5. Correlation maps between simulated surface NO$_3^-$ concentration in each grid cell and STMW volume during winter with (a) one, (b) ten, and (c) fourteen months of lag. Vertical correlation sections between NO$_3^-$ concentration across 30° N in each grid and STMW volume during winter with (d) one, (e) ten, (f) fourteen months of lag. The STMW volume was averaged from January to March and integrated in the formation region (purple solid box), and the correlation was calculated for 1998–2017. Purple solid and dashed boxes in (a)–(c) denote the formation and reemergence regions, respectively. Dashed line in (d)–(f) indicates a boundary between the formation and reemergence regions and black contours represent climatological vertical temperature sections of 16 °C–19 °C at 1 °C intervals across 30° N averaging model results from 1998 to 2017. Red and blue shadings represent the positive and negative coefficients while black dots denote coefficients above the 95% confidence level ($r = ±0.44$).
The METs can even affect phytoplankton blooms east of their site one year later. During summer, the water mass with a positive NO$_3$ anomaly associated with larger STMW formation is isolated from the euphotic zone by seasonal stratification; it then reappears in the surface ocean and again affects the growth of phytoplankton in autumn. Meanwhile, this water mass with a higher NO$_3$ concentration continues traveling eastward in the subsurface owing to the NPSG before reemerging east of the STMW formation region and provides a higher level of NO$_3$ in the following spring, which promotes the spring bloom. The NO$_3$ anomaly associated with STMW can affect the growth of phytoplankton for only up to one year, which is in contrast to the signal in temperature that persists for up to three years [13]. Our study revealed that this oceanic teleconnection based on the NPSG is a significant factor in predicting the thermal and biogeochemical conditions in the surface ocean. In other words, precise simulation of NPSG and dynamics of the reemergence of STMW can improve the predictability of MET activity and lower trophic levels of the marine ecosystems in the North Pacific.

The long memory of the ocean extends the temporal and spatial ranges of the influence of METs occurring in winter and spring by greater than a year and a few thousand kilometers. Although we investigated the only predictability of nutrient supply and surface chlorophyll using METs and associated STMW formation in the North Pacific, other biogeochemical variables may exhibit similar responses to wintertime METs. For example, the subsurface chlorophyll-a concentration that cannot be measured using satellites may also be negatively correlated with METs. The supply of carbon-rich water from the subsurface may be suppressed by MHWs, similar to that of nutrients, which can lower the partial pressure of carbon dioxide. In addition, the mechanism presented here can be applied to other subtropical gyres with the formation of STMW, which should be further investigated using observations or a realistic physical-biogeochemical coupled model.

Data availability statement

SeaWiFS and MODIS-aqua data were provided by NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group. Dataset accessed (20 January 2022, 27 July 2021) from https://doi.org/10.5067/ORBVIEW-2/SEAWIFS/L3M/CHL/2018 and https://doi.org/10.5067/AQUA/MODIS/L3M/CHL/2018, respectively. EN4.2.1 data was obtained from the Met Office Hadley Centre and downloaded at http://metoffice.gov.uk/hadobs/en4/download-en4-2-1.html. AVHRR dataset was provided by GHRsst and the NOAA National Centers for Environmental Information. Dataset accessed (25 June 2021) from https://doi.org/10.5067/PATHF-MOD50. The data generated and/or analyzed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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Appendix. Validation of reconstructed historical ocean states using a 3D physical-biogeochemical coupled model

The interannual variability of the surface chlorophyll-a in the formation region from February to April correlates better with marine extreme temperature events than when all SST anomalies are considered (figure A1). Colored dots denote monthly mean SST anomalies over the 90th percentile (red) and under the 10th percentile (blue) of SST anomalies from February to April, which shows the correlation coefficient of $-0.74$ with the chlorophyll-a anomalies. This value exceeds the correlation coefficient between all chlorophyll-a and SST anomalies ($r = -0.46$).

Seasonal variations observed in STMW volume and surface chlorophyll-a concentrations in the formation and reemergence regions from the model results were compared with EN4.2.1 and satellite data, including SeaWiFS and MODIS-aqua datasets (figure A2a, c)). The model satisfactorily simulated the seasonal variations in both STMW volume and chlorophyll-a concentration although the simulated volume was larger than that in EN4.2.1 data, and the simulated chlorophyll-a values during winter and spring were approximately twice those in the satellite data. This indicates that the simulated STMW formation and its dissipation with seasons are nearly comparable with those in EN4.2.1 data, and the biological processes in the model, such as NO$_3$ uptake by phytoplankton and its life cycle, are properly simulated in the northwestern NPSG. A comparison of climatological horizontal distributions of chlorophyll-a during spring between the satellite data and model result suggests similar concentrations in the NPSG but a significantly higher concentration in the model over the north of the chlorophyll front (figure A2e, f)). This indicates that the model bias for the chlorophyll-a is mainly restricted over the north of the chlorophyll front. Satellite-derived surface chlorophyll-a concentration anomaly shows a positive anomaly in both the formation and
Figure A1. Scatter plot between normalized monthly mean satellite-derived surface chlorophyll-a concentration and SST anomalies in the formation region from February to April. Red and blue dots denote monthly mean SST anomalies over the 90th percentile (red dashed line) and under the 10th percentile (blue dashed line) of the SST anomalies from February to April, respectively. Correlation coefficients ($r$) of the chlorophyll-a concentration anomaly with all SST data (cyan) and METs (black) from February to April are indicated at the lower left corner of the plot.

Reemergence regions (figure A2(g, h)). Irregular negative anomalies near the Kuroshio–Oyashio Confluence region is mainly owing to the meandering of the Kuroshio current and eddy activities.

In addition, the large blooms in the model may have been caused by the overestimated formation of STMW because overestimated vertical mixing will lead to STMW formation and NO$_3^-$ entrainment from the subsurface, and consequently to increased primary production. However, annual variation in the STMW formation during winter and surface chlorophyll-a concentration in the remote region during spring have significant correlation coefficients of $r = 0.58$ and $r = 0.72$, respectively, with the observations (figure A2(b, d)). The insignificant correlation of $r = 0.42$ in the formation region could be caused by the overestimation of chlorophyll-a north of 27° N in the model.

For the model to simulate the response of chlorophyll-a to the reemergence of STMW, the time-lagged correlation maps, as shown in figure 4(d)–(f) except for the model results, are presented in figure A3. Overall, the positive correlation patch calculated from the model was smaller than that calculated from the observations. However, the response of chlorophyll-a to the entrainment of STMW with NO$_3^-$ occurred in the formation region in October with an eight-month lag and in the reemergence region in the following spring with a fourteen-month lag. Thus, the model simulation appropriately captured not only the changes in the surface ocean conditions owing to the reemergence of STMW but also the adjustment of chlorophyll-a to the changes.

Data-assimilative coupled model results show NO$_3^-$-limited regions during spring in the Northwestern NPSG. Correlation map between the surface chlorophyll-a and NO$_3^-$ concentrations presents that NO$_3^-$ is the main limiting factor in an area south of 30° N in the formation region and the entire reemergence region (figure A4). Insignificant correlation appearing north of 30° N in the formation region indicates that other factors mainly regulate growth of phytoplankton during spring.

A positive anomaly of NO$_3^-$ concentration at a depth of 150 m occurs north of 30° N in the STWM formation region in February 2001 and it moves eastward with time and it finally reaches the reemergence region the following winter (figure A5). Due to the Kuroshio countercurrent, the anomaly occurring south of 30° N moves westward and it results in that the anomaly is stretched southwestward and diagonal significant correlation patches with MET activities and STMW volume (figure 4).
Figure A2. (a) Monthly mean time series of STMW volume ($\times 10^{14} \text{ m}^3$) in the formation region averaged from 1998 to 2017 obtained from EN4.2.1 data and model results (red and blue lines, respectively). Vertical bars indicate ±1 standard deviation. (b) Annual variation in STMW volume ($\times 10^{14} \text{ m}^3$) in the formation region averaged from January to March obtained from EN4.2.1 data and model results (red and blue lines, respectively). (c) Same as (a), except for the surface chlorophyll-a concentration (mg m$^{-3}$) obtained from satellite datasets (SeaWiFS and MODIS-aqua) and model result (red and blue lines, respectively). (d) Same as (b), except for the surface chlorophyll-a concentration (mg m$^{-3}$) obtained from satellite datasets (SeaWiFS and MODIS-aqua) and model results (red and blue lines, respectively). Solid and dashed lines in (c, d) denote values in the formation and reemergence regions, respectively. Horizontal distributions of climatological surface chlorophyll-a concentration (mg m$^{-3}$), averaged monthly from March to May and yearly from 1998 to 2017, obtained from (e) satellite datasets (SeaWiFS and MODIS-aqua) and (f) model results. Horizontal distributions of satellite-derived surface chlorophyll-a concentration anomalies (mg m$^{-3}$), averaged monthly from March to May in (g) 2004 and (h) 2005. Red solid and dashed boxes in (e)–(h) denote the formation and reemergence regions, respectively.
Figure A3. Correlation maps between simulated surface chlorophyll-a concentration in each grid and STMW volume during winter with (a) one, (b) eight, (c) fourteen months of lag. Purple solid and dashed boxes denote the formation and reemergence regions, respectively. The STMW volume was averaged from January to March and integrated in the formation region, and the correlation was calculated for 1998–2017. Red and blue shadings represent the positive and negative coefficients while black dots denote coefficients above the 95% confidence level ($r = \pm 0.44$).

Figure A4. Correlation map between modeled surface chlorophyll-a and NO$_3^-$ concentrations averaged from February to April. The correlation was calculated for the period 1998–2017. Purple solid and dashed boxes denote the formation and reemergence regions, respectively. Red and blue shadings represent the positive and negative coefficients while black dots denote coefficients above the 95% confidence level ($r = \pm 0.44$).
Figure A5. Horizontal distributions of monthly mean NO$_3^-$ concentration anomaly ($\mu$M) at a depth of 150 m in (a) February, (b) April, (c) June, (d) August, (e) October, (f) December 2001, (g) February and (h) April 2002, respectively. Red and blue shadings denote positive and negative anomalies of the NO$_3^-$ concentration.

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