Phytoplankton decline in the eastern North Pacific transition zone associated with atmospheric blocking

5 authors, including:

Some of the authors of this publication are also working on these related projects:

Geodiversity as a surrogate of lake biodiversity and a measure of conservation value View project

Predicting Sargassum Blooms in the Caribbean and Lesser Antilles - PSB-CARIB project View project

PRIMARY RESEARCH ARTICLE

Global Change Biology WILEY

Phytoplankton decline in the eastern North Pacific transition zone associated with atmospheric blocking

Chengfeng Le[1] | Shuyu Wu[1] | Chuanmin Hu[2] | Marcus W. Beck[3] | Xuchao Yang[1]

[1]Ocean College, Zhejiang University, Hangzhou, China

[2]College of Marine Science, University of South Florida, St. Petersburg, FL, USA

[3]Southern California Coastal Water Research Project, Costa Mesa, CA, USA

Correspondence
Chengfeng Le and Xuchao Yang, Ocean College, Zhejiang University, Hangzhou, China.
Email: chengfengle@zju.edu.cn (C. L.) and yangxuchao@zju.edu.cn (X. Y.)

Abstract

Global climate change can significantly influence oceanic phytoplankton dynamics, and thus biogeochemical cycles and marine food webs. However, associative explanations based on the correlation between chlorophyll-*a* concentration (Chl-*a*) and climatic indices is inadequate to describe the mechanism of the connection between climate change, large-scale atmospheric dynamics, and phytoplankton variability. Here, by analyzing multiple satellite observations of Chl-*a* and atmospheric conditions from National Center for Environmental Prediction/National Center for Atmospheric Research reanalysis datasets, we show that high-latitude atmospheric blocking events over Alaska are the primary drivers of the recent decline of Chl-*a* in the eastern North Pacific transition zone. These blocking events were associated with the persistence of large-scale atmosphere pressure fields that decreased westerly winds and southward Ekman transport over the subarctic ocean gyre. Reduced southward Ekman transport leads to reductions in nutrient availability to phytoplankton in the transition zone. The findings describe a previously unidentified climatic factor that contributed to the recent decline of phytoplankton in this region and propose a mechanism of the top-down teleconnection between the high-latitude atmospheric circulation anomalies and the subtropical oceanic primary productivity. The results also highlight the importance of understanding teleconnection among atmosphere–ocean interactions as a means to anticipate future climate change impacts on oceanic primary production.

KEYWORDS
atmospheric blocking, Ekman transport, global change, jet stream, North Pacific transition zone, phytoplankton

1 | INTRODUCTION

The impact of climate variability on global oceanic ecosystems has been extensively discussed in recent decades (Behrenfeld et al., 2006; Doney et al., 2012; Hoegh-Guldberg & Bruno, 2010), but the descriptions of physical processes that link surface water properties to climate variability have differed. For example, the paradigm that climate warming is associated with a decline in phytoplankton productivity in nutrient-limited tropical and subtropical ocean gyres by strengthening ocean stratification is generally accepted (Behrenfeld et al., 2006; Boyce, Lewis, & Worm, 2010; Martinez, Antoine, D'Ortenzio, & Gentili, 2009; Moore et al., 2018). However, recent studies have demonstrated weak correlations between ocean stratification and primary productivity on interannual scales in different subtropical ocean gyres, and alternatively suggest that local and remote winds, buoyancy forcing, and the surface or subsurface

advective supply of nutrients may have more critical roles in affecting interannual variability in phytoplankton (Lozier, Dave, Palter, Gerber, & Barber, 2011; Palter, Lozier, & Barber, 2005; Whitney, 2015). Other physical process, such as mesoscale turbulence, may also influence interannual variability in phytoplankton productivity in several subtropical ocean gyres (Lévy, Resplandy, & Lengaigne, 2014; Liu & Levine, 2016; McGillicuddy, 2016). Various climatic phenomena, such as El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), North Pacific Gyre Oscillation, can further explain physical and biological fluctuation in global oceans (Behrenfeld et al., 2006; Di Lorenzo et al., 2008; Thomas, Ted Strub, Weatherbee, & James, 2012). However, climatic indices (e.g., ENSO, PDO) are responses of climatic phenomena such as wind anomalies and sea level pressure patterns (Anderson, Perez, & Karspeck, 2013; Bond, Cronin, Freeland, & Mantua, 2015; Nakamura, Tachibana, Honda, & Yamane, 2006), and thus, may not adequately describe specific mechanisms responsible for variation in biological productivity of surface waters. Thus, evaluating the linkage between direct measures of climate-related factors and biological fluctuation is a more practical approach to describe mechanisms of oceanic ecosystem response to climate change.

Recently, a substantial decline of interannual phytoplankton productivity, indicated by chlorophyll-*a* (Chl-*a*), was observed in the eastern North Pacific transition zone (Whitney, 2015). This zone is climatologically located at an approximate latitude of 32°N to 42°N and is an area of convergence between the southern region of the subarctic gyre and northern region of the subtropical gyre (Roden, 1991). A strong transition in phytoplankton biomass is observed at this location as a distinct Chl-*a* front (hereafter TZCF, transition zone chlorophyll-*a* front), defined as the 0.2 mg/m^3 surface Chl-*a* isopleth between the subtropical and subarctic gyres (Polovina, Howell, Kobayashi, & Seki, 2001). Ecologically, this area provides important migratory corridors and foraging habitat for a number of apex species, including tuna (albacore and other sp.), loggerhead turtles, pinnipeds, albatross, flying squid, sharks, and a variety of fishes (Brodeur & Ware, 1992). Consequently, variation of phytoplankton productivity in the transition zone and displacement of the TZCF can have widespread impacts across trophic levels (Polovina, Howell, Kobayashi, & Seki, 2017). For example, models consistently project 21st-century amplification of phytoplankton biomass declines at higher zooplankton trophic levels in low-latitude oceans (Chust et al., 2014; Kwiatkowski, Aumont, & Bopp, 2019).

Physical controls on the seasonal and interannual migration of the TZCF have been well studied (Ayers & Lozier, 2010; Bograd et al., 2004); vertical mixing and southern advection are the key factors driving the seasonal migration of TZCF. However, few studies have investigated both physical and climatic factors controlling interannual variability in phytoplankton productivity of this area. Although the low phytoplankton productivity in 2014 has been attributed to changes in the southern wind component that weakened nutrient transport in the eastern North Pacific (Whitney, 2015), the analysis was based only on a winter–spring period in 1 year, and the potential cause of the wind anomaly is unclear. Moreover, nutrient

sources supporting the high phytoplankton productivity in the transition zone are greatly affected by the westerly winds that force horizontal Ekman transport (Ayers & Lozier, 2010). Therefore, the physical cause of the decline and its associated climatic factors are unclear.

Atmospheric blocking is a phenomenon characterized by a quasi-stationary, large-scale anticyclone observed in the upper-level geopotential height fields at middle to high latitudes that can persist for several days or longer. This event can block the ambient westerly winds and weather systems, or divert the westerly flow when it situated off dominant storm tracks or the jet stream (Berrisford, Hoskins, & Tyrlis, 2007). As such, atmospheric blocking substantially influences downstream weather patterns and climate conditions (Carrera, Higgins, & Kousky, 2004; Cattiaux et al., 2010). High-latitude atmospheric blocking over Greenland was linked to changes in surface water conditions of the North Atlantic by altering wind patterns (Hakkinen, Rhines, & Worthen, 2011; Woollings, 2011). Since 2000, an increasing trend in atmospheric blocking over Alaska has been reported (McLeod, Ballinger, & Mote, 2017), with the highest blocking in 2013 and 2014 coincident with the lowest Chl-*a* in the eastern North Pacific transition zone (Whitney, 2015). However, mechanistic linkages between phytoplankton variability and blocking events in the North Pacific have yet to be shown.

Here, using a long-term time series of satellite observations along with climate datasets, we evaluate trends to (a) investigate variation of Chl-*a* in the eastern North Pacific transition zone in the past two decades from 1998 to 2017, (b) examine physical dynamics forcing the phytoplankton variations, and (c) explore the potential link between atmospheric blocking over Alaska and the remarkable decline of phytoplankton in the subtropical transition zone. These analyses address the hypothesis that interannual variation in Chl-*a* in the TZCF is coupled with regional wind patterns that influence oceanic horizontal Ekman transport, and secondarily, changes in phytoplankton are linked to broad scale climatic patterns through teleconnection. We focus only on describing trends in the spring during peak Chl-*a* in the transition zone and when a positive trend of Alaskan blocking has been observed (Howard, Emerson, Bushinsky, & Stump, 2010).

2 │ DATASET AND METHODS

Chl-*a* (in mg/m^3) were estimated at 9 km resolution in the eastern North Pacific (Figure 1a) using the monthly mean ocean color index algorithm (Hu, Lee, & Franz, 2012) with imagery obtained from NASA's Ocean Color website (http://oceancolor.gsfc.nasa.gov/). These data were generated from SeaWiFS (September 1997 to December 2010) and MODIS/Aqua (July 2002 to December 2017) observations using the SeaWiFS Data Analysis System software (SeaDAS, Version 7.0) with up-to-date calibration coefficients and algorithms. Monthly mean Chl-*a* was extracted from a subregion encompassing the transition zone (32°N to 42°N, and 180°W to
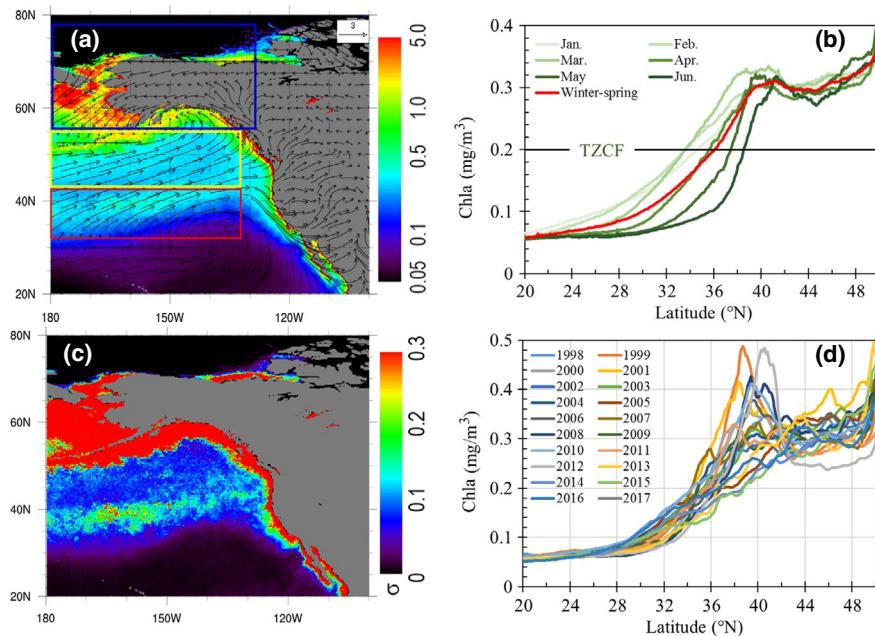
FIGURE 1 Spatial and temporal variations of chlorophyll-*a* concentration (Chl-*a*) in the eastern North Pacific. (a) The 1998–2017 climatological winter–spring Chl-*a* with a noticeable transition zone chlorophyll-*a* front (TZCF) in the subtropical transition zone (red box). (b) The 1998–2017 climatological monthly Chl-*a* along 20°N to 50°N averaged between 130°W and 180°W, and from 1998 to 2017 for the months January to June. (c) The standard deviation of spring Chl-*a* in the eastern North Pacific for the period 1998–2017 with distinctive high values in the subtropical transition zone. (d) The 1998–2017 interannual variability of spring Chl-*a* along 20°N to 50°N averaged between 130°W and 180°W. The boxes in (a) indicate the area used to calculate Alaska Blocking Index (blue), southward horizontal Ekman transport (ET) anomaly (yellow), and the subtropical transition in the eastern North Pacific (red)

130°W, red box in Figure 1a). Monthly Chl-*a* anomalies relative to climatological monthly means were calculated as:

$$Xa(i) = \frac{X(i) - Xm(i)}{Xm(i)} \times 100 \qquad (1)$$

where *Xa*(*i*) is the Chl-*a* anomaly for month *i*, *Xm*(*i*) is the climatological monthly mean Chl-*a*, and *X*(*i*) is the monthly mean Chl-*a*. Images from December, January, and February were used for the winter Chl-*a* anomalies and images from March, April, and May were used for the spring Chl-*a* anomalies.

Strong westerly winds during winter and spring transport subarctic nutrient-rich surface waters southward into the subtropical gyre, supporting relatively high primary productivity in the TZCF (Ayers & Lozier, 2010). Relevant climatic variables covering the period of 1948–2017 were downloaded from the United States National Center for Environmental Prediction/National Center for Atmospheric Research website (reanalysis 1 dataset, www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html). These data included global daily 500 hPa geopotential height estimates (500 hgt in m) and surface (10 m) zonal (U) wind speed. An Alaska Blocking Index (ABI) was calculated from the climate data following McLeod et al. (2017) to evaluate dynamics of the mid-tropospheric circulation field across Alaska and the possible teleconnections to climate and environmental changes in the eastern North Pacific Ocean. Briefly, the ABI is defined as the monthly anomaly of 500 hgt centered over the Alaska region (54°–76°N and 125°–180°W, blue box in Figure 1a). The north–south component of the horizontal Ekman transport (in kg m^{-1} s^{-1}) was calculated from the

daily wind dataset. Finally, regional mean Ekman transport in the middle latitudes of the North Pacific (43°–54°N, 130°–180°W, yellow box in Figure 1a) was extracted to further evaluate factors associated with Chl-*a* variability in the subtropical transition zone.

Monthly mean mixed layer depth (MLD) data, covering January 1998 to December 2017, were downloaded at www.science.oregonstate.edu/ocean.productivity (Behrenfeld et al., 2015). This dataset includes MLD values from the HYbrid Coordinate Ocean Model, a multi-institutional effort sponsored by the National Ocean Partnership Program, as part of the U.S. Global Ocean Data Assimilation Experiment. The global model GLBu0.08 hindcast results were used in this study. MLD is defined as the depth where density is 0.125 kg/m^3 greater than the surface value.

3 | RESULTS

The climatological and interannual variability in winter–spring Chl-*a* over the North Pacific Ocean are shown in Figure 1. The North Pacific transition zone is seen slightly south of the yellow box delineating the westerly winds over the middle latitudes (red box in Figure 1a). A local Chl-*a* maximum is observed running east to west and bounded by approximately 38–41°N (Figure 1b), with a peak value of 0.32 mg/m^3 for the climatological mean value. The TZCF boundary of 0.2 mg/m^3 varies seasonally from ~34°N in January to ~40°N in June, consistent with previous studies (Ayers & Lozier, 2010;

Bograd et al., 2004). Phytoplankton in the transition zone show greater interannual variation than in the subtropical and subarctic gyres (Figure 1c). A local maximum of standard deviation (σ) is also apparent in the transition zone, with $\sigma > 0.2$ mg/m^3 in the winter and spring. The location of the TZCF and Chl-*a* peak varied interannually (Figure 1d). The spring TZCF location migrated from 33°N in 2010 to 38°N in 2015. The two highest Chl-*a* peaks were observed in 1999 and 2012, with values of ~0.49 and 0.48 mg/m^3, respectively. A significant but weak linear relationship was found between the regional mean Chl-*a* and regional mean TZCF locations, with $R^2 = 0.24$ ($p = 0.03$, $N = 20$).

Regional mean Chl-*a* in the transition zone was extracted from the satellite time series observations to investigate the interannual variation in phytoplankton. MLD and the horizontal Ekman transport were previously proposed as key forcing variables for Chl-*a* variability in subtropical oceans (Dave & Lozier, 2010, 2013; Doney, 2006). The regional means of MLD and horizontal Ekman transport were extracted from the transition zone and subarctic gyre region, respectively, to examine their roles in determining variation of Chl-*a*. Regional mean Chl-*a* concentrations in the transition zone declined significantly in the spring from 1998 to 2017 (Figure 2a), with a decrease of 0.0034 mg m^{-3} year^{-1} ($R^2 = 0.41$, $p < 0.05$). The MLD showed a clear increasing trend ($R^2 = 0.32$, $p < 0.05$; Figure 2b), although the trend was driven by the 2013 and 2014 observations. No apparent interannual variation in MLD was observed from 1999 to 2007. No significant trend was observed for the Ekman transport, although the interannual variation correlated with Chl-*a* variation, that is, positive (negative) anomalies in Ekman transport always occurred in years with positive (negative) Chl-*a* anomalies (Figure 2c).
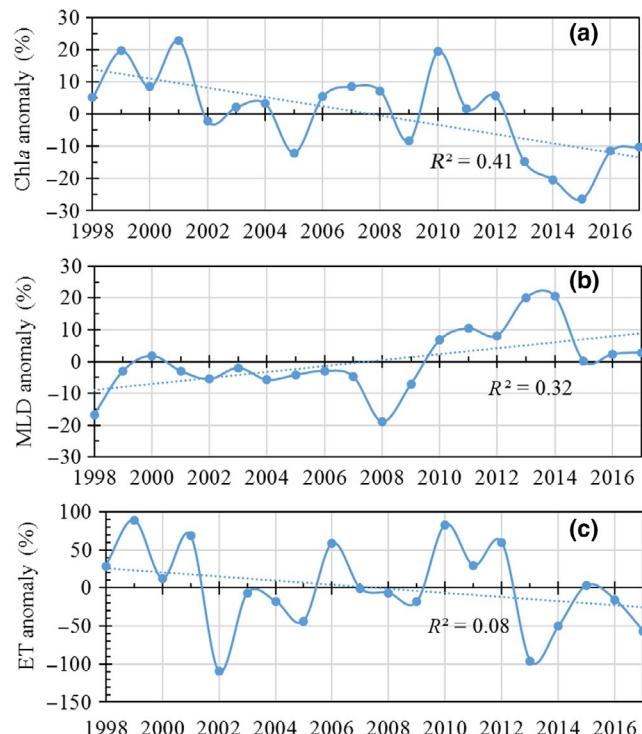
FIGURE 2 The interannual variability in spring (a) chlorophyll-*a* concentration (Chl-*a*), (b) mixed layer depth (MLD), and (c) the Ekman transport

The relationships between the Chl-*a* anomaly with MLD and Ekman transport was further analyzed to determine physical forcing effects on the phytoplankton variation. No significant relationship was found between the interannual Chl-*a* anomaly and MLD variation ($R^2 = 0.16$, $p = 0.2$; Figure 3a), implying that vertical mixing has a limited role in forcing interannual spring phytoplankton variation. In contrast, interannual variability in the spring Chl-*a* anomaly was positively correlated with the southward Ekman transport anomalies estimated in the subarctic gyre. A strong relationship was found between the Chl-*a* anomaly and Ekman transport variation by excluding two outlier years in 2002 and 2015 ($R^2 = 0.75$, $p < 0.01$; Figure 3b). The two outlier years were primarily caused by circulation patterns in prior winters (discussed later). The relationship was still significant, but slightly weaker with these outlier years included in the analysis ($R^2 = 0.54$, $p < 0.01$). Despite the outliers, the strong positive relationship between subtropical Chl-*a* and subarctic horizontal Ekman transport supports previous findings that subarctic nutrient-rich waters are the primary nutrient source that maintains high phytoplankton in the transition zone (Ayers & Lozier, 2010). This further suggests that changes in westerly wind are a likely factor influencing spring phytoplankton variation in the transition zone because of the influence on southward horizontal Ekman transport (Figure 3c). This was supported by the strong relationship between Chl-*a* anomaly and U wind variation (excluding 2002 and 2015; $R^2 = 0.72$, $p < 0.01$; Figure 3d).

The correlation between ABI and the westerly wind over east North Pacific subarctic gyre was further analyzed to establish the potential link between atmospheric blocking over Alaska and phytoplankton variation in subtropical transition zone. A dramatic decrease of phytoplankton in the transition zone was observed in 2014 when a positive 500 hgt anomaly occurred over Alaska. This blocking event was associated with an eastward wind anomaly over subarctic gyre, which further decreased the westerly wind and resultant Ekman transport (Figure 4a). Following the blocking event, a large negative Chl-*a* anomaly occurred in the transition zone in the following spring (Figure 4b). The linkage was further confirmed by the strong correlation between ABI and U wind variation, in addition to the strong relationship between ABI and Chl-*a* anomaly observed in the long-term time series (Figures 5 and 6). The ABI was significantly and negatively correlated with U wind variation over eastern North Pacific subarctic gyre (Figure 5a, $r = -0.87$ for the interannual correlation from 1998 to 2018). A similar result was yielded for the longer time series from 1948 to 2017 (Figure 5b). As expected, spring Chl-*a* anomalies in the transition zone are significantly correlated with the ABI (Figure 6a). Strong year-to-year relationships were also found between the regional mean spring Chl-*a* anomaly and spring ABI (Figure 6b). The regression coefficient between ABI and Chl-*a* anomalies was −0.49, which suggests that a 10 m ABI anomaly could cause a 5% decline of phytoplankton productivity.

Similar to the relationships of Chl-*a* with Ekman transport and U wind anomalies, 2002 and 2015 were also outlier years related to atmospheric conditions in the preceding winters. For example, in the winter of 2002, a strong negative 500 hgt anomaly occurred over east Alaska

FIGURE 3 The relationships of (a) chlorophyll-*a* concentration (Chl-*a*) anomaly with the mixed layer depth (MLD) in the transition zone; (b) Chl-*a* with southward Ekman transport anomaly over the subarctic gyre; (c) the southward Ekman transport anomaly with U wind anomaly over the subarctic ocean gyre; and (d) U wind anomaly in the subarctic oceanic gyre and Chl-*a* in the transition zone. The two outliers in the years 2002 and 2015 (highlighted in red) are excluded from the regression in (a), (b), and (d)
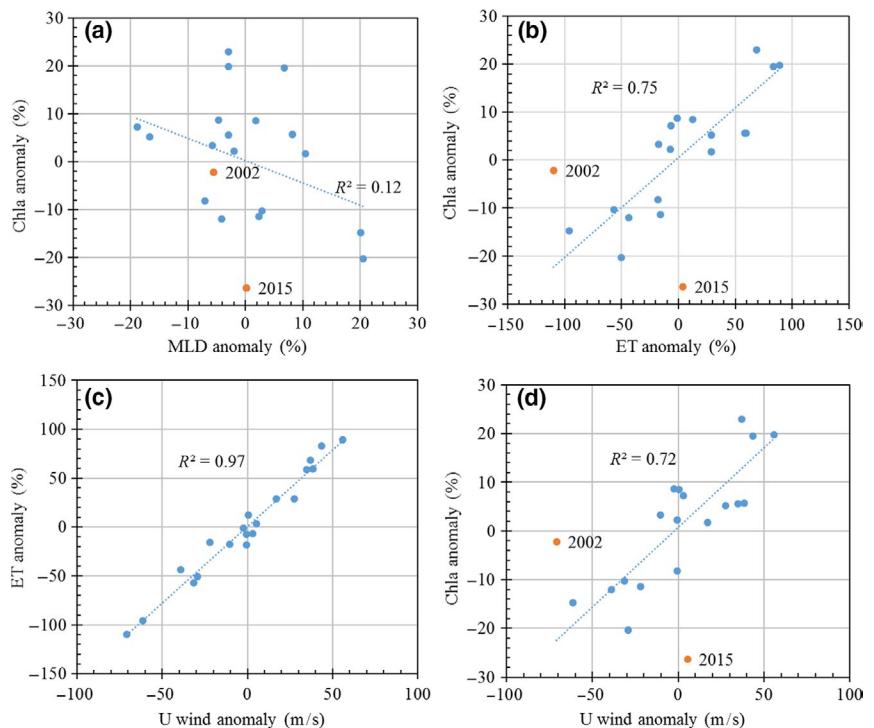
FIGURE 4 (a) The wind (arrows) and 500 hgt anomalies (1998–2017 base period, shown with color scale) over the eastern North Pacific Ocean in spring 2014; (b) the chlorophyll-*a* concentration anomaly in spring 2014
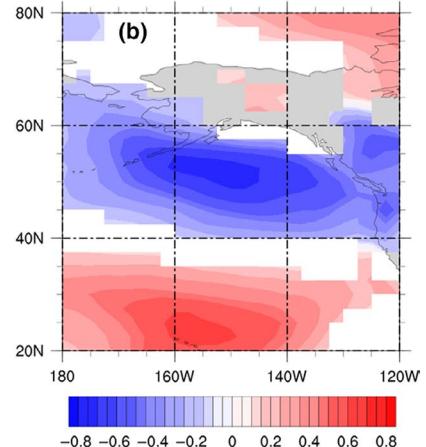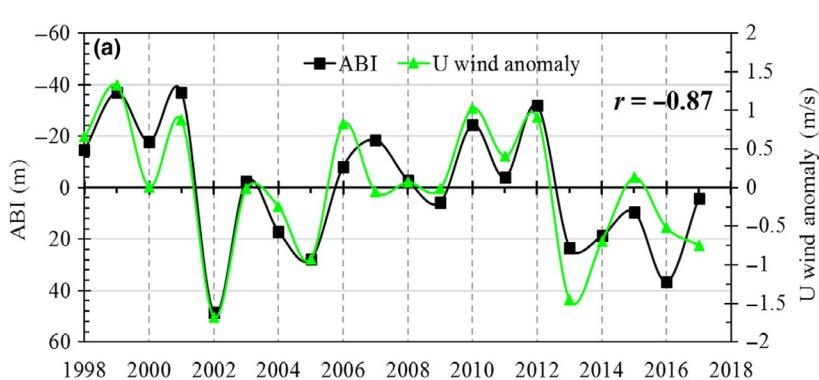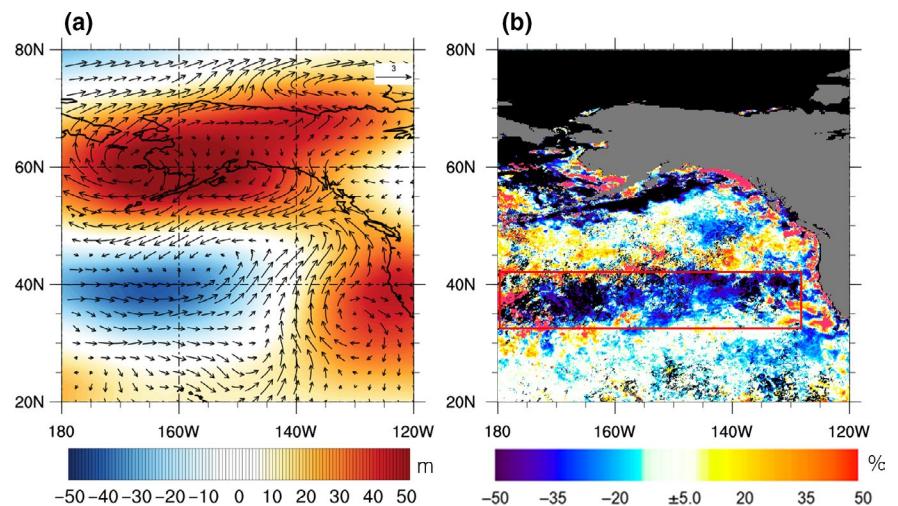
FIGURE 5 (a) Correlations between the regional averaged spring Alaska Blocking Index (ABI) and zonal wind from 1998 to 2017; (b) the correlation pattern of spring ABI and zonal wind from 1948 to 2017 over the eastern North Pacific Ocean
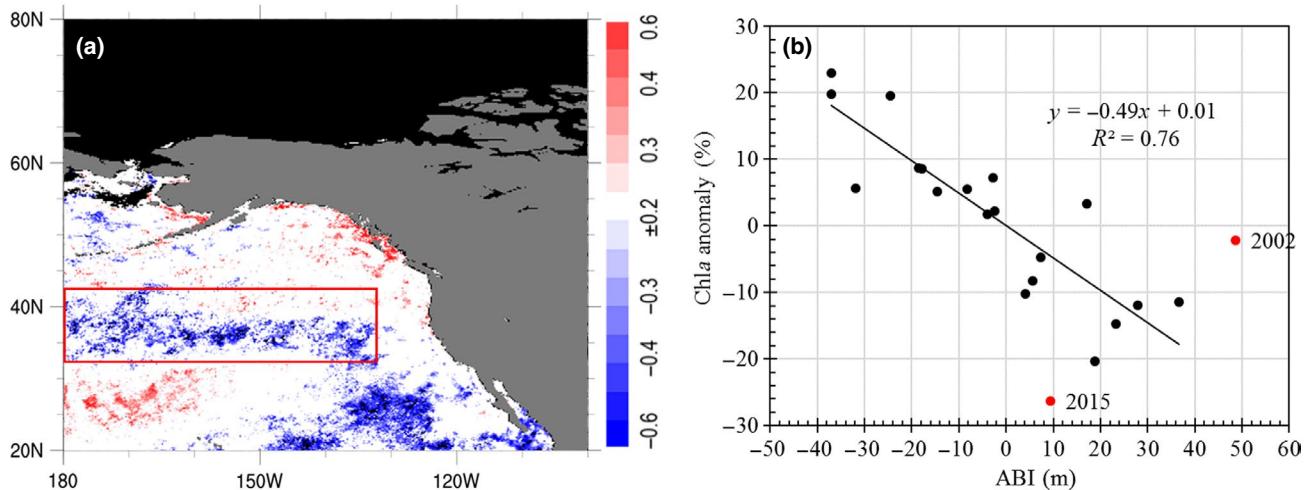
FIGURE 6 (a) The correlation between spring chlorophyll-*a* concentration (Chl-*a*) anomalies and Alaska Blocking Index (ABI) in the eastern North Pacific. (b) The interannual relationship between ABI and the Chl-*a* anomalies in the subtropical transition zone (red box). The two outliers in the years 2002 and 2015 (highlighted in red) are excluded from the regression
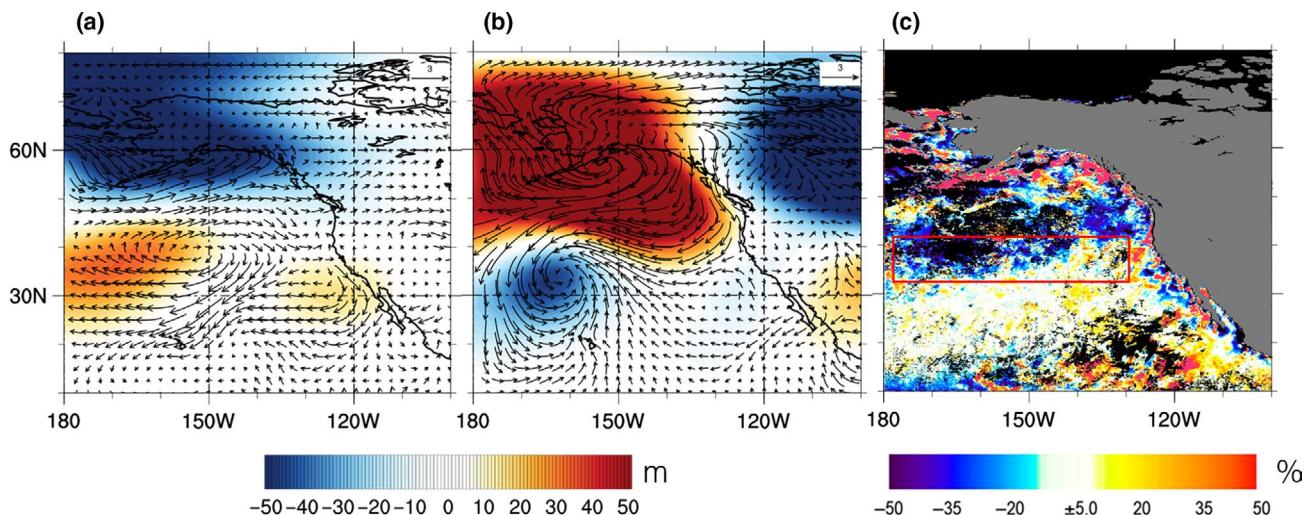
FIGURE 7 The wind (arrows) and 500 hgt anomalies (1998–2017 base period, shown as left color scale) over the eastern North Pacific Ocean in (a) winter 2002 and (b) in spring 2002; (c) the chlorophyll-*a* concentration anomaly in spring 2002 (shown as right color scale)
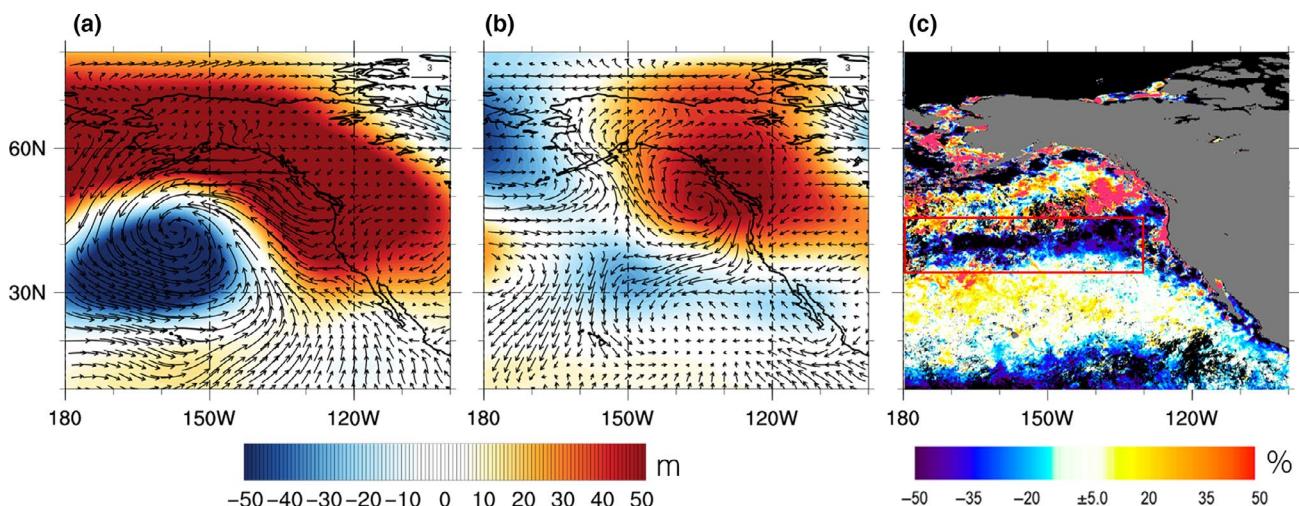
FIGURE 8 The wind (arrows) and 500 hgt anomalies (1998–2017 base period, shown as left color scale) over the eastern North Pacific Ocean in (a) winter 2015 and (b) in spring 2015; (c) the chlorophyll-*a* concentration anomaly in spring 2015 (shown as right color scale)
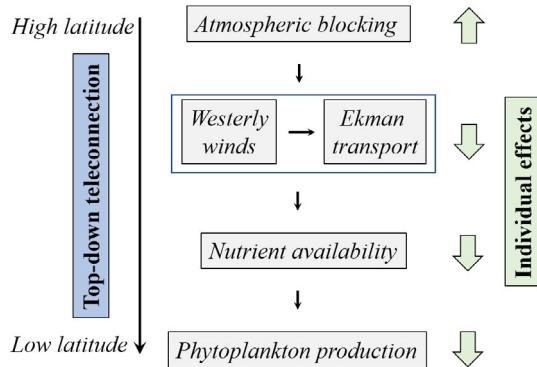
FIGURE 9 A conceptual model describing the mechanism of the top-down teleconnection between the high-latitude atmospheric blocking and the subtropical oceanic primary production. The green arrows show the trends of individual parameters that were demonstrated by the analyses

(Figure 7a), which enhanced the westerly wind and resultant southward Ekman transport over the Gulf of Alaska. This enhanced Ekman transport may have mitigated the effects of intensive blocking the following spring on phytoplankton productivity (Figure 7b). Furthermore, Chl-*a* has a large negative anomaly in the transition zone in May 2002 (Figure 7c). In 2015, a positive 500 hgt anomaly occurred from Alaska to California, along with a strong negative 500 hgt anomaly over northeast North Pacific (Figure 8a). These events caused a broad anticyclonic anomaly in surface circulation, which dramatically decreased the westerly wind and Ekman transport. This strong blocking in addition to a weakened blocking in spring (Figure 8b) contributed to the lowest observed spring Chl-*a* in the transition zone in 2015. Overall, the strong correlation of the subtropical transition zone Chl-*a* anomaly with the horizontal Ekman transport, including the correlation of the westerly wind anomaly with the ABI, suggest a top-down linkage between the high-latitude atmospheric blocking to low-latitude phytoplankton variation in the eastern North Pacific transition zone (Figure 9). The high-latitude atmospheric blocking over Alaska significantly reduced westerly winds over the subarctic gyre in the northeast Pacific through blocking. As a result, southward horizontal Ekman transport was reduced, resulting in lower nutrient availability to phytoplankton in the transition zone and a reduction of phytoplankton.

4 | DISCUSSION

Climatic effects on the variation in oceanic phytoplankton productivity has been widely observed from in situ measurements, satellites observations, and model simulations (Behrenfeld et al., 2006; Boyce et al., 2010; Moore et al., 2018); however, physical controls and climatic factors forcing the variability differ regionally and at different time scales (Gregg, Conkright, Ginoux, O'Reilly, & Casey, 2003; Thomas et al., 2012). Here, using satellite observations, we found a remarkable decline of spring phytoplankton in the eastern North Pacific transition zone, which is primarily caused by the variability in horizontal Ekman transport. This result supports

previous findings that advection is a critical factor controlling the phytoplankton variability in this area. We further linked the decline of phytoplankton to recent increases in atmospheric blocking over Alaska (McLeod et al., 2017). This linkage of the subtropical phytoplankton variability to high-latitude mid-tropospheric atmospheric circulation has been previously unreported in any global oceans.

Although novel, the linkage described here is not unexpected given previous studies documenting atmospheric blocking and upper ocean condition relationships. Atmospheric blocking could significantly interrupt zonal flow through blocking or diversion that, consequently, decreases the middle latitude westerly winds (Berrisford et al., 2007). Atmospheric blocking over Greenland has been shown to influence the eddy-driven jet stream (Woollings, Hannachi, & Hoskins, 2010), which in turn influences oceanic circulation patterns, sea surface temperatures, and salinity in the North Atlantic ocean (Hakkinen et al., 2011). Alaskan atmospheric blocking also has broad effects on near surface wind and SST over the Northeastern Pacific (Carrera et al., 2004; Hartmann, 2015; McLeod et al., 2017). Our results provide additional evidence of the effects of large-scale atmospheric circulation anomalies on subtropical phytoplankton by establishing a strong linkage with Chl-*a* variation in the eastern North Pacific transition zone (Figure 4). A critical process of this connection is the variability in westerly winds, which determine the southward Ekman transport from the subarctic ocean gyres and the high phytoplankton in the subtropical transition zone. Conversely, the westerly wind responds negatively to Alaska blocking, which decreases phytoplankton in the subtropical transition zone. Because ABI has recently increased (McLeod et al., 2017), its relationship with the Chl-*a* anomalies suggests a direct mechanisms for the recent decline in phytoplankton in the eastern North Pacific transition zone.

Additional climatic factors, such as ENSO, PDO, and Pacific–North American pattern (PNA), have been linked to the southward horizontal Ekman transport and could provide additional explanation for the interannual Chl-*a* variability in the TZCF (Bograd et al., 2004; Polovina et al., 2017). Regression analyses were conducted to further evaluate these factors that may explain the long-term variation in westerly wind over the North Pacific. In contrast to the strongly negative correlation of ABI with U wind speed anomalies (Figure 5), no significant correlations were found between U wind anomalies and Multivariate ENSO Index, PNA, or PDO. This provides evidence that the Alaskan atmospheric blocking is the dominant factor influencing the westerly wind and the resultant southward horizontal Ekman transport over the middle latitudes of the North Pacific Ocean. Consequently, the Alaskan atmospheric blocking could mechanistically describe variations in phytoplankton in the subtropical transition zone.

There are important implications from the findings here, beyond the interpretations of the recent decline of phytoplankton in the transition zone. Specifically, high-latitude atmospheric blocking has been previously associated with Arctic amplification (Barnes & Screen, 2015; Cattiaux et al., 2010; Kug et al., 2015). Arctic amplification is a phenomena of rapid surface warming over the Arctic that occurs faster than that at other latitudes under greenhouse forcing. This rapid warming can influence continental weather patterns and ecosystem

function at mid-latitudes (Barriopedro, Fischer, Luterbacher, Trigo, & Garcia-Herrera, 2011; Cattiaux et al., 2010; Cohen et al., 2014; Kim et al., 2017; Kug et al., 2015). However, the effects of Arctic amplification on mid-latitude and low-latitude oceanic ecosystems have not yet been evaluated. Understanding connections between Arctic warming and subtropical oceanic regions at a global scale would undoubtedly improve our ability to assess how climate change will affect phytoplankton productivity and future climate-system feedbacks. The linkage established here provides insights for further evaluation of large-scale atmospheric circulation patterns and their connections with climate change–atmosphere–ocean interactions.

In summary, we present strong evidence of a link between the subtropical phytoplankton variation in the eastern North Pacific transition zone and the high-latitude atmospheric blocking over Alaska. This provides critical insights on how large-scale atmospheric variability affects phytoplankton in the subtropical ocean gyres under climate change scenarios. Because the previous literature provides a basic understanding of the dynamic processes associated with atmospheric blocking, and the latter can be hindcasted or predicted using numerical models, the linkage established herein provides useful information for forecasting seasonal primary production in the study area. Specifically, our findings can facilitate projections of long-term phytoplankton variation in the transition zone because of the availability decadal-to-centennial atmospheric forecasts based on reanalysis data using herein or anticipated model simulations (e.g., Coupled Model Intercomparison Project Phase 5 CMIP5 Earth System Models (Barnes, Dunn-Sigouin, Masato, & Woollings, 2014; Masato, Hoskins, & Woollings, 2013). However, we caution that the linkage is based on limited observations in the specific region and future work is needed to further support our analyses. For example, atmospheric blocking can occur at high and middle latitudes throughout all seasons (Barriopedro, García-Herrera, Lupo, & Hernández, 2006), whereas the current study only focused only on spring observations from the eastern North Pacific Ocean. Further evaluation of the connection between atmospheric blocking and phytoplankton in other seasons and ocean basins (e.g., North Atlantic) is needed.

ORCID

Chengfeng Le (iD) https://orcid.org/0000-0002-4536-1913

Shuyu Wu (iD) https://orcid.org/0000-0003-2252-2013

REFERENCES

Anderson, B. T., Perez, R. C., & Karspeck, A. (2013). Triggering of El Niño onset through trade wind-induced charging of the equatorial Pacific. *Geophysical Research Letters*, 40(6), 1212–1216. https://doi.org/10.1002/grl.50200

Ayers, J. M., & Lozier, M. S. (2010). Physical controls on the seasonal migration of the North Pacific transition zone chlorophyll front. *Journal of Geophysical Research*, 115(C5), https://doi.org/10.1029/2009jc005596

Barnes, E. A., Dunn-Sigouin, E., Masato, G., & Woollings, T. (2014). Exploring recent trends in Northern Hemisphere blocking. *Geophysical Research Letters*, 41(2), 638–644. https://doi.org/10.1002/2013gl058745

Barnes, E. A., & Screen, J. A. (2015). The impact of Arctic warming on the midlatitude jet-stream: Can it? Has it? Will it? *Wiley Interdisciplinary Reviews: Climate Change*, 6(3), 277–286. https://doi.org/10.1002/wcc.337

Barriopedro, D., Fischer, E. M., Luterbacher, J., Trigo, R. M., & Garcia-Herrera, R. (2011). The hot summer of 2010: Redrawing the temperature record map of Europe. *Science*, 332(6026), 220–224. https://doi.org/10.1126/science.1201224

Barriopedro, D., García-Herrera, R., Lupo, A. R., & Hernández, E. (2006). A climatology of northern hemisphere blocking. *Journal of Climate*, 19(6), 1042–1063. https://doi.org/10.1175/jcli3678.1

Behrenfeld, M. J., O'Malley, R. T., Boss, E. S., Westberry, T. K., Graff, J. R., Halsey, K. H., … Brown, M. B. (2015). Revaluating ocean warming impacts on global phytoplankton. *Nature Climate Change*, 6(3), 323–330. https://doi.org/10.1038/nclimate2838

Behrenfeld, M. J., O'Malley, R. T., Siegel, D. A., McClain, C. R., Sarmiento, J. L., Feldman, G. C., … Boss, E. S. (2006). Climate-driven trends in contemporary ocean productivity. *Nature*, 444(7120), 752–755. https://doi.org/10.1038/nature05317

Berrisford, P., Hoskins, B. J., & Tyrlis, E. (2007). Blocking and Rossby wave breaking on the dynamical tropopause in the southern hemisphere. *Journal of the Atmospheric Sciences*, 64(8), 2881–2898. https://doi.org/10.1175/jas3984.1

Bograd, S. J., Foley, D. G., Schwing, F. B., Wilson, C., Laurs, R. M., Polovina, J. J., … Brainard, R. E. (2004). On the seasonal and interannual migrations of the transition zone chlorophyll front. *Geophysical Research Letters*, 31(17). https://doi.org/10.1029/2004gl020637

Bond, N. A., Cronin, M. F., Freeland, H., & Mantua, N. (2015). Causes and impacts of the 2014 warm anomaly in the NE Pacific. *Geophysical Research Letters*, 42(9), 3414–3420. https://doi.org/10.1002/2015gl063306

Boyce, D. G., Lewis, M. R., & Worm, B. (2010). Global phytoplankton decline over the past century. *Nature*, 466(7306), 591–596. https://doi.org/10.1038/nature09268

Brodeur, R. D., & Ware, D. M. (1992). Long-term variability in zooplankton biomass in the subarctic Pacific Ocean. *Fisheries Oceanography*, 1(1), 32–38. https://doi.org/10.1111/j.1365-2419.1992.tb00023.x

Carrera, M. L., Higgins, R. W., & Kousky, V. E. (2004). Downstream weather impacts associated with atmospheric blocking over the northeast pacific. *Journal of Climate*, 17(24), 4823–4839. https://doi.org/10.1175/jcli-3237.1

Cattiaux, J., Vautard, R., Cassou, C., Yiou, P., Masson-Delmotte, V., & Codron, F. (2010). Winter 2010 in Europe: A cold extreme in a warming climate. *Geophysical Research Letters*, 37(20), L20704. https://doi.org/10.1029/2010gl044613

Chust, G., Allen, J. I., Bopp, L., Schrum, C., Holt, J., Tsiaras, K., … Irigoien, X. (2014). Biomass changes and trophic amplification of plankton in a warmer ocean. *Global Change Biology*, 20(7), 2124–2139. https://doi.org/10.1111/gcb.12562

Cohen, J., Screen, J. A., Furtado, J. C., Barlow, M., Whittleston, D., Coumou, D., … Jones, J. (2014). Recent Arctic amplification and

extreme mid-latitude weather. *Nature Geoscience*, 7(9), 627–637. https://doi.org/10.1038/ngeo2234

Dave, A. C., & Lozier, M. S. (2010). Local stratification control of marine productivity in the subtropical North Pacific. *Journal of Geophysical Research*, 115(C12), https://doi.org/10.1029/2010jc006507

Dave, A. C., & Lozier, M. S. (2013). Examining the global record of interannual variability in stratification and marine productivity in the low-latitude and mid-latitude ocean. *Journal of Geophysical Research: Oceans*, 118(6), 3114–3127. https://doi.org/10.1002/jgrc.20224

Di Lorenzo, E., Schneider, N., Cobb, K. M., Franks, P. J. S., Chhak, K., Miller, A. J., ... Rivière, P. (2008). North Pacific Gyre Oscillation links ocean climate and ecosystem change. *Geophysical Research Letters*, 35(8), https://doi.org/10.1029/2007gl032838

Doney, S. C. (2006). Plankton in a warmer world. *Nature*, 444, 695. https://doi.org/10.1038/444695a

Doney, S. C., Ruckelshaus, M., Emmett Duffy, J., Barry, J. P., Chan, F., English, C. A., ... Talley, L. D. (2012). Climate change impacts on marine ecosystems. *Annual Review of Marine Science*, 4, 11–37. https://doi.org/10.1146/annurev-marine-041911-111611

Gregg, W. W., Conkright, M. E., Ginoux, P., O'Reilly, J. E., & Casey, N. W. (2003). Ocean primary production and climate: Global decadal changes. *Geophysical Research Letters*, 30(15), https://doi.org/10.1029/2003gl016889

Hakkinen, S., Rhines, P. B., & Worthen, D. L. (2011). Atmospheric blocking and Atlantic multidecadal ocean variability. *Science*, 334(6056), 655–659. https://doi.org/10.1126/science.1205683

Hartmann, D. L. (2015). Pacific sea surface temperature and the winter of 2014. *Geophysical Research Letters*, 42(6), 1894–1902. https://doi.org/10.1002/2015gl063083

Hoegh-Guldberg, O., & Bruno, J. F. (2010). The impact of climate change on the world's marine ecosystems. *Science*, 328(5985), 1523–1528. https://doi.org/10.1126/science.1189930

Howard, E., Emerson, S., Bushinsky, S., & Stump, C. (2010). The role of net community production in air-sea carbon fluxes at the North Pacific subarctic-subtropical boundary region. *Limnology and Oceanography*, 55(6), 2585–2596. https://doi.org/10.4319/lo.2010.55.6.2585

Hu, C., Lee, Z., & Franz, B. (2012). Chlorophyll a algorithms for oligotrophic oceans: A novel approach based on three-band reflectance difference. *Journal of Geophysical Research*, 117. https://doi.org/10.1029/2011JC007395

Kim, J.-S., Kug, J.-S., Jeong, S.-J., Huntzinger, D. N., Michalak, A. M., Schwalm, C. R., ... Schaefer, K. (2017). Reduced North American terrestrial primary productivity linked to anomalous Arctic warming. *Nature Geoscience*, 10(8), 572–576. https://doi.org/10.1038/ngeo2986

Kug, J.-S., Jeong, J.-H., Jang, Y.-S., Kim, B.-M., Folland, C. K., Min, S.-K., & Son, S.-W. (2015). Two distinct influences of Arctic warming on cold winters over North America and East Asia. *Nature Geoscience*, 8(10), 759–762. https://doi.org/10.1038/ngeo2517

Kwiatkowski, L., Aumont, O., & Bopp, L. (2019). Consistent trophic amplification of marine biomass declines under climate change. *Global Change Biology*, 25(1), 218–229. https://doi.org/10.1111/gcb.14468

Lévy, M., Resplandy, L., & Lengaigne, M. (2014). Oceanic mesoscale turbulence drives large biogeochemical interannual variability at middle and high latitudes. *Geophysical Research Letters*, 41(7), 2467–2474. https://doi.org/10.1002/2014gl059608

Liu, X., & Levine, N. M. (2016). Enhancement of phytoplankton chlorophyll by submesoscale frontal dynamics in the North Pacific Subtropical Gyre. *Geophysical Research Letters*, 43(4), 1651–1659. https://doi.org/10.1002/2015GL066996

Lozier, M. S., Dave, A. C., Palter, J. B., Gerber, L. M., & Barber, R. T. (2011). On the relationship between stratification and primary productivity in the North Atlantic. *Geophysical Research Letters*, 38(18). https://doi.org/10.1029/2011GL049414

Martinez, E., Antoine, D., D'Ortenzio, F., & Gentili, B. (2009). Climate-driven basin-scale decadal oscillations of oceanic phytoplankton. *Science*, 326(5957), 1253–1256. https://doi.org/10.1126/science.1177012

Masato, G., Hoskins, B. J., & Woollings, T. (2013). Winter and summer northern hemisphere blocking in CMIP5 models. *Journal of Climate*, 26(18), 7044–7059. https://doi.org/10.1175/jcli-d-12-00466.1

McGillicuddy, D. J. Jr. (2016). Mechanisms of physical-biological-biogeochemical interaction at the oceanic mesoscale. *Annual Review of Marine Science*, 8, 125–159. https://doi.org/10.1146/annurev-marine-010814-015606

McLeod, J. T., Ballinger, T. J., & Mote, T. L. (2017). Assessing the climatic and environmental impacts of mid-tropospheric anticyclones over Alaska. *International Journal of Climatology*, 38(1), 351–364. https://doi.org/10.1002/joc.5180

Moore, J. K., Fu, W., Primeau, F., Britten, G. L., Lindsay, K., Long, M., ... Randerson, J. T. (2018). Sustained climate warming drives declining marine biological productivity. *Science*, 359(6380), 1139–1143. https://doi.org/10.1126/science.aao6379

Nakamura, T., Tachibana, Y., Honda, M., & Yamane, S. (2006). Influence of the Northern Hemisphere annular mode on ENSO by modulating westerly wind bursts. *Geophysical Research Letters*, 33(7), https://doi.org/10.1029/2005gl025432

Palter, J. B., Lozier, M. S., & Barber, R. T. (2005). The effect of advection on the nutrient reservoir in the North Atlantic subtropical gyre. *Nature*, 437(7059), 687–692. https://doi.org/10.1038/nature03969

Polovina, J. J., Howell, E., Kobayashi, D. R., & Seki, M. P. (2001). The transition zone chlorophyll front, a dynamic global feature defining migration and forage habitat for marine resources. *Progress in Oceanography*, 49(1), 469–483. https://doi.org/10.1016/S0079-6611(01)00036-2

Polovina, J. J., Howell, E. A., Kobayashi, D. R., & Seki, M. P. (2017). The transition zone chlorophyll front updated: Advances from a decade of research. *Progress in Oceanography*, 150, 79–85. https://doi.org/10.1016/j.pocean.2015.01.006

Roden, G. I. (1991). Subarctic-subtropical transition zone of the North Pacific: Large-scale aspects and mesoscale structure. In J. A. Wetherall (Ed.), *Biology, oceanography, and fisheries of the North Pacific* (pp. 1–38). Silver Spring, MD: NOAA.

Thomas, A. C., Ted Strub, P., Weatherbee, R. A., & James, C. (2012). Satellite views of Pacific chlorophyll variability: Comparisons to physical variability, local versus nonlocal influences and links to climate indices. *Deep Sea Research Part II: Topical Studies in Oceanography*, 77–80, 99–116. https://doi.org/10.1016/j.dsr2.2012.04.008

Whitney, F. A. (2015). Anomalous winter winds decrease 2014 transition zone productivity in the NE Pacific. *Geophysical Research Letters*, 42(2), 428–431. https://doi.org/10.1002/2014GL062634

Woollings, T. (2011). Ocean effects of blocking. *Science*, 334(6056), 612–613. https://doi.org/10.1126/science.1214167

Woollings, T., Hannachi, A., & Hoskins, B. (2010). Variability of the North Atlantic eddy-driven jet stream. *Quarterly Journal of the Royal Meteorological Society*, 136(649), 856–868. https://doi.org/10.1002/qj.625