Impact of Atmospheric Deposition on Carbon Export to the Deep Ocean in the Subtropical Northwest Pacific

Peng Xiu1,2,3 and Fei Chai4,5

1State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou, China, 2Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou), Guangzhou, China, 3Innovation Academy of South China Sea Ecology and Environmental Engineering, Chinese Academy of Sciences, Guangzhou, China, 4State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography, Ministry of Natural Resources, Hangzhou, China, 5School of Marine Sciences, University of Maine, Orono, ME, USA

Abstract The impact of atmospheric deposition on deep-ocean carbon export in the subtropical Northwest Pacific remains poorly evaluated. Using sediment trap data and a newly improved biogeochemical model, we show that iron deposition in winter and spring and nitrogen deposition in summer and fall are important drivers for the seasonal variability of deep-ocean particulate organic carbon (POC) export flux. Nitrogen deposition can stimulate pico-plankton growth in summer and fall, which leads to increases of microzooplankton and mesozooplankton. The increase of mesozooplankton exerts higher grazing pressure on diatoms in winter and early spring, which then reduces deep-ocean POC export due to the reduction of ballasting mineral of opal. Iron deposition only affects the region in winter and spring when nitrogen is not a limiting factor for phytoplankton growth; and it can increase deep-ocean POC export by stimulating diatom growth and opal production.

Plain Language Summary Atmospheric deposition is known to affect biogeochemistry in the upper ocean, while how it impacts carbon export to the deep ocean remains largely unknown. To evaluate the role of atmospheric deposition in deep-ocean carbon export, this research combined in-situ measurements from a moored sediment trap located at 4810 m and a newly improved biogeochemical model in the subtropical Northwest Pacific. We found that iron deposition increased deep-ocean POC export, while nitrogen deposition decreased POC export in winter and spring. Seasonal change of phytoplankton community structure was shown to be the driving mechanism for the opposite response of POC export to nitrogen and iron depositions.

1. Introduction

Atmospheric deposition is one of the major external nutrients sources for the open ocean (Duce et al., 1991; Jickells et al., 2005). Inorganic nutrients (nitrogen (N), phosphorus (P), and iron (Fe)) inputs due to atmospheric deposition can increase phytoplankton growth by alleviating macronutrient and/or micronutrient limitation (Duce et al., 2008; Young et al., 1991). Lithogenic particles associated with atmospheric deposition (e.g., dust), on the other hand, can remove soluble iron of water column via scavenging (Tagliabue et al., 2017). They are also involved in particle aggregation, and act as ballast for organic material export (Armstrong et al., 2002). Studies in the high-nutrient-low-chlorophyll region reported significant enhancements of phytoplankton biomass and particulate organic carbon (POC) due to the iron addition by dust (Bishop et al., 2002; Boyd et al., 1998). In oligotrophic waters, atmospheric deposition has been shown to enhance nitrogen fixation by supplying both iron and phosphorus in the eastern tropical North Atlantic (Mills et al., 2004), and also has the potential to change the phytoplankton community structure, depending on the local nutrient-limiting condition (Chien et al., 2016; Marañón et al., 2010; Ridame et al., 2014; Zhang et al., 2018).

The impact of atmospheric deposition on POC export has been recognized from the correlation between fluxes of minerals and POC sinking into sediment traps (Deuser et al., 1981; Francois et al., 2002). Atmospheric fertilization can induce growth of large phytoplankton with bigger cells, such as coccolithophores and diatoms, and productions of biogenic calcite and opal, prone to ballast higher POC flux (Honda &
In addition to the fertilization effect, the lithogenic ballast effect with aggregation and sorption processes between lithogenic particles and organic matter can lead to a strong POC export (Armstrong et al., 2002; Ittekkot, 1993; Le Moigne et al., 2013; Termon et al., 2010; van der Jagt et al., 2018). Neuer et al. (2004) suggested that iron deposition in winter can stimulate phytoplankton production in the eastern subtropical North Atlantic, which plays a more important role in driving particle export compared with the role of lithogenic matter as a ballasting agent. Bressac et al. (2014) demonstrated that the strength of ballast effect depends on biogeochemical conditions of the water column. Therefore, atmospheric deposition associated with both the ballast effect and fertilization effect can have important influences on ocean biogeochemistry and particle export flux.

The subtropical region of the Northwest Pacific south of the Kuroshio Extension (Figure 1a) is an area with strong winter mixing (mixed layer depth [MLD] >150 m). As light is generally not a limiting factor in this region (Siswanto et al., 2015), phytoplankton blooms from winter to early spring, with diatoms occasionally dominating the phytoplankton community (Fujiki et al., 2016). This region is also frequently affected by Asian dust, with large deposition occurring in spring (Takemura et al., 2002; Tan et al., 2016; Uematsu et al., 2003). The deposition has been shown to increase chlorophyll concentration (Yoon et al., 2017) and enhance primary production (PP) (Taketani et al., 2018). Bioassay experiments demonstrated that a combination of nutrients (N, P, and Fe) associated with dust addition was responsible for phytoplankton growth (Zhang et al., 2018); and micro-phytoplankton (consisting of diatoms) appeared to benefit most from dust addition (Zhang et al., 2019, 2020). The coincidence of high POC export flux with Asian dust suggests a possible connection between the two (Li et al., 2004); however, detailed dynamics remain largely unexplored. Here, we use a newly improved biogeochemical model to evaluate the role of dust deposition in deep-ocean carbon export in the subtropical region of the Northwest Pacific.
2. Methods

2.1. Data

Data from a moored sediment trap were downloaded from the JAMSTEC website (Honda et al., 2002). The trap was deployed at station S1 (145°E, 30°N; Figure 1a). The water depth there is about 5,957 m. Time series of particles were collected at 200, 500, and 4,810 m from February 2010 to June 2014 (Honda et al., 2016). The total mass flux was estimated from the sample weight, collection area, and deployment period. Fluxes of opal, iron, and lithogenic materials were estimated by measuring concentrations of trace elements. More details can be found in Honda et al. (2016).

2.2. Models

In this study, a new biogeochemical model, CoSiNE-Fe, was developed, which includes a biological component, an atmospheric deposition component, and an iron cycling component (Figure S1). The biological component was based on the Carbon Silicate Nitrate Ecosystem (CoSiNE) model (Chai et al., 2002). The atmospheric deposition component with three size classes of lithogenic particles and the iron cycling component were constructed based on previous studies (Weber et al., 2007; Ye et al., 2009, 2011). Nitrogen fixation is not a major nitrogen source at S1 because both the bulk fixation rate (Shiozaki et al., 2010) and the abundance of diazotrophs observed with microscopy and flow cytometry are relatively low (Matsumoto et al., 2016). To focus on the seasonality of carbon export, especially during winter and spring, we do not include nitrogen fixation process in the model, but will consider it in our future studies. Model equations and parameters are presented as supporting information.

The physical model is based on a one-dimensional (1D) Regional Ocean Modeling system (ROMS) (Shchepetkin & McWilliams, 2005). The coupled ROMS-CoSiNE-Fe model was set up at station S1 with 300 vertical layers. The turbulent vertical mixing is based on the non-local K profile parameterization (KPP; Large et al., 1994). The model was initialized by the fields of the World Ocean Atlas (WOA09), and forced by 6-hourly wind, radiation, and precipitation from the NCEP/NCAR Reanalysis I data set from 2001 to 2016. The initial conditions for iron variables were interpolated from an updated version of the global iron data set of Tagliabue et al. (2012).

Atmospheric depositions of lithogenic particles, soluble iron (FeSol), nitrate (NO3), ammonium (NH4), and phosphate (PO4) are considered in the CoSiNE-Fe. The seasonal deposition flux data were obtained from Chien et al. (2016), with both dust and non-dust sources, and used to force the model. These fluxes were generated by a deposition model that considers both current and preindustrial emissions. Due to lack of real-time data, the climatological seasonal deposition fluxes are used in the model, which does not include episodic dust events. To evaluate the role of atmospheric deposition, four cases were simulated to compare with the control run (Ctl), which are without iron deposition (ZeroFe), without NO3 and NH4 deposition (ZeroN), without lithogenic particle deposition (ZeroLith), and without PO4 deposition (ZeroP). We also conducted a case forced by preindustrial deposition flux (Preind) to evaluate the anthropogenic impact. The relative change is calculated as (Ctl-case)/Ctl to quantify different treatments; for example (Ctl- ZeroN)/Ctl means the effect of adding N to the ocean (+N).

To examine horizontal advection process that may affect lithogenic material distribution in the water column, we conducted particle tracking numerical experiments. We used a three-dimensional (3D) circulation model, which was previously developed and validated against different sources of observations (e.g., Xiu et al., 2010, 2012). This 3D model was based on the ROMS, set up for the Pacific Ocean (99°E–70°W, 45°S–65°N) with the horizontal resolution of 1/8° and forced by the daily blended Seawinds (Zhang et al., 2006) and daily air-sea fluxes of heat and freshwater from the NCEP/NCAR Reanalysis I. The model outputs were used to drive a Lagrangian particle tracking model, the LTRANS (North et al., 2006), which allows adjustment of sinking particle speeds.
3. Results and Discussion

Station S1 is located south of the Kuroshio Extension with relatively weak eddy activities (Figure 1a). Measured POC export flux at 4,810 m was about 1.5 mg m$^{-2}$ d$^{-1}$ in summer and fall, and the flux can be higher than 8.0 mg m$^{-2}$ d$^{-1}$ in spring (i.e., March; Figure 1b). This strong spring peak of POC flux was also found in fluxes of opal, iron, and lithogenic materials. The high peak of opal was likely from diatom growth in the upper ocean, while the peak of lithogenic material may be induced by either atmospheric deposition or advection from continental margins. In the upper ocean, the highest depth-integrated PP over the euphotic zone has been reported to occur in February (Honda et al., 2016; Matsumoto et al., 2016).

To examine the possibility of lithogenic material observed at the trap site is induced by advection from continental margins, we continuously seeded particles at the bottom layer along the continental margins off Japan (water depth <500 m) on day 1 of every month from 2010 to 2014. Five particle sinking speeds (0.5, 2, 10, 50, and 100 m d$^{-1}$) were tested (Grabowski et al., 2019; Honda et al., 2013; Lerner et al., 2016). We tracked trajectories of these particles and calculated their probabilities entering the 4° × 4° box surrounding station S1 (Figure S2). The probability was calculated as the percentage ratio of the number of particles ever entering the box to the number of total particles released in the experiments. With the slow sinking speed of 0.5 m d$^{-1}$, the chances of those particles entering the box were about 0.75%; and their chances were much lower (~0.03%) at sinking speed of 100 m d$^{-1}$. Generally, the higher the sinking speed, the lower the chances. By calculating the rate of attenuation of POC flux, Honda (2020) estimated the sinking velocity of POC at 4,810 m to be ~110 m d$^{-1}$. Honda et al. (2013) estimated the sinking velocity to be higher than 180 m d$^{-1}$ by using different parameters. The low probability that a continental particle ends up in the study region does not necessarily mean low supply flux (e.g., Conte et al., 2019; Lamborg et al., 2008). Strontium isotopes in surface sediments near the study region suggested a mixture of dust and volcanic materials from the island arcs (Asahara et al., 1995). However, it is difficult to estimate the contribution of lateral flux with trap samples (Honda, 2020). In this study, we focus on the role of seasonal atmospheric deposition in affecting POC export. The seasonal variability of POC fluxes observed by sediment traps at 200, 500, and 4,810 m all synchronized with that of surface primary productivity (Honda, 2020; Uchimiya et al., 2018). Since the seasonal variability of lateral transport flux is not clear in this region, we assume that the observed seasonal variability at 4,810 m was largely attributed to the local process.

At station S1, the coupled model captured observed variations of sea surface temperature, sea surface salinity, and MLD at both seasonal and interannual time scales (Figure S3). The MLD can reach 150 m in winter, and shoals to about 20 m in summer. The model also reproduced seasonal changes of nutrient profiles, including nitrate, silicate, and phosphate (Figure S4). Modeled vertical distribution of dissolved iron was in a reasonable range of measurements from Nishioka et al. (2020) and Tagliabue et al. (2012) (Figure S5). The modeled winter-spring peaks of surface chlorophyll concentration are larger than satellite-derived, but agree well with in situ-measured (Figure S6). The modeled seasonal pattern of depth-integrated PP also compares well with those of satellite PP and in situ-measured PP. The model can reproduce the seasonal variability of POC flux at different depths (Figure S7). For POC export at 4,810 m, the modeled flux shows strong peaks (~8.0 mg m$^{-2}$ d$^{-1}$) in spring and low values in the other seasons, which is consistent with trap observations (Figure 1c). These model-data comparisons suggest that the model is reasonably constrained and is capable of simulating key biogeochemical processes in this region at the seasonal time scale.

In the model, phytoplankton growth rate is modeled as a minimum function of potentially limiting nutrients, in addition to light. For diatom, the potentially limiting nutrients are silicate (Si), nitrate + ammonium (N), P, and Fe, whichever is the lowest will determine diatom growth rate. At S1, diatoms at the surface were generally limited by N in summer and fall, and by Fe in winter and spring (Figure S8). A similar pattern is found for pico-plankton. The seasonal change in limiting nutrients is caused by strong winter mixing that supplies sufficient N and P from subsurface to the upper layer and alleviates the N limiting condition in winter and spring. It also implies that the importance of different external nutrients in stimulating biological production may vary with season.

We conducted different cases to evaluate the role of atmospheric deposition in affecting PP and export flux. In the ZeroN case, PP is mostly decreased (Figure 2a). The difference of PP between ZeroN case and Ctl reaches about 20% of Ctl’s, and this difference decreases to near zero in winter-spring (Figure 2b), suggesting...
different contributions of N deposition in different seasons. Similarly, PP is also decreased in the ZeroFe case; however, its difference from Ctl is larger in winter-spring than in the other seasons. The relative difference of PP between ZeroFe case and Ctl can reach about 40%, larger than that between ZeroN case and Ctl. For lithogenic particle deposition (ZeroLith) and P deposition, their influences on PP in this region are very small. Overall, on the annual mean basis, the effects of N and Fe depositions are positive to PP (11.6% increase with N, 14.4% increase with Fe), which means more deposition will lead to higher PP in this region.

The POC flux at 4,810 m in the ZeroN case is lower (15%–45%) than that in Ctl in both summer and fall, but is as much as 50% higher than that in Ctl in winter-spring (Figures 2c and 2d). The POC flux in the ZeroFe case shows a different pattern. The difference of POC flux between ZeroFe case and Ctl is small in both summer and fall. In winter and spring, however, the POC flux in the ZeroFe case is lower than that in Ctl, which is opposite to the ZeroN case. The difference of POC flux between ZeroFe and Ctl can also reach ∼50% of the Ctl. For lithogenic particle deposition of the ZeroLith case, its influence on POC flux in this region is small because of the small magnitude of deposition flux.

Distributions of phytoplankton and zooplankton in the upper 200 m were examined. Here, we show the differences between Ctl and an individual case (Ctl minus case). For example, the difference of Ctl-ZeroN shows the effect of adding N (+N) from the atmosphere to the ocean. With N addition, pico-plankton chlorophyll concentration increases all year round, with large enhancements occurring in the subsurface in summer and fall (Figure 3a). Diatom chlorophyll concentration, however, shows a clear decrease from surface down to 150 m during late winter and early spring (Figure 3b). Microzooplankton that graze on pico-plankton generally follow the change of pico-plankton (Figure 3e). Mesozooplankton graze on microzooplankton, diatom, and detritus. In summer and fall, mesozooplankton increase with N addition, attributable to the increased microzooplankton (Figure 3f). During late winter and spring, mesozooplankton also increase, while the change of mesozooplankton is generally opposite to that of diatoms (Figures 3b and 3f), suggesting a top-down control of diatoms by mesozooplankton.

With Fe addition (+Fe), pico-plankton in the water column increase in winter and spring (Figure 3c). In summer and fall, pico-plankton decrease in the upper layer and increase in the subsurface. In this region, diatoms typically grow in winter and spring. With Fe addition, the large change of diatoms is mostly in winter and spring (Figure 3d). Diatoms increase in winter and tend to bloom earlier in spring. Microzooplankton follow the change of pico-plankton, and mesozooplankton follow the changes of microzooplankton and diatoms (Figures 3g and 3h). It is noteworthy that the change of mesozooplankton in winter and spring is in the same direction as that of diatoms, suggesting a bottom-up control of mesozooplankton due to diatoms.

These results clearly demonstrate different roles of N and Fe depositions in stimulating diatom growth in winter and spring. Production of opal is associated with diatom growth, and opal can serve as ballast of deep-ocean POC export. Therefore, N and Fe depositions in different seasons may have different impacts on deep-ocean POC export. As the subtropical gyre is in an N-limiting condition for phytoplankton, N deposition with a relatively slow rate in these seasons can increase pico-plankton growth (Figure 4a). The growth of pico-plankton then leads to increases of microzooplankton and mesozooplankton. Increase of mesozooplankton exerts higher grazing pressure on diatoms, which can persist to winter and early spring. The grazing pressure from mesozooplankton thus suppresses the growth of diatoms in spring, which results in the reduction of deep-ocean POC export. As the region is in an N-limiting condition in...
summer and fall, Fe deposition only takes effect in winter and spring when strong vertical mixing brings subsurface N to the upper layer. Then, with Fe deposition, both pico-plankton and diatoms grow, which leads to increases of zooplankton concentration, opal production, and deep-ocean POC export.

The atmospheric deposition flux includes both dust and non-dust sources due to significant anthropogenic contributions in this region (Ito, 2013; Ito & Shi, 2016). It has been documented that Asian sources of

Figure 3. Modeled vertical distributions of differences of pico-plankton chlorophyll concentration (a, c; mg m^{-3}), diatom chlorophyll concentration (b, d; mg m^{-3}), microzooplankton concentration (e, g; mmol m^{-3}), and mesozooplankton concentration (f, h; mmol m^{-3}) between Ctl and individual cases from 2011 to 2014. Here, the difference between Ctl and ZeroN runs (Ctl-ZeroN) is denoted by +N, representing adding nitrogen; and the difference between Ctl and ZeroFe runs (Ctl-ZeroFe) is denoted by +Fe, representing adding iron.
non-dust Fe are likely to impact the upper-ocean biogeochemistry of the North Pacific (Hamilton et al., 2020; Ito et al., 2020). Compared with the preindustrial deposition, atmospheric supplies of both N and Fe are increased in the current climate (Brahney et al., 2015; Luo et al., 2008). It results in increased PP throughout the year (∼13%) in the current climate compared with the preindustrial time (Figure S9a). Deep-ocean POC export in the current run is generally higher than that in the preindustrial run (Figure S9b). However, the increase of POC export is small in spring, especially in April when POC export shows lower values in the current run than in the preindustrial run. This seasonal pattern of POC change is similar to the result of +N treatment (Figure 2d), implying a relatively larger impact from anthropogenic N deposition than from Fe deposition to the seasonal variability of POC export.

Atmospheric deposition fluxes used in this study were obtained from a previous modeling study (Chien et al., 2016); however, validating these fluxes are challenging due to the multitude and complexity of the forms under which elements (N, P, and Fe) are emitted to the atmosphere, as well as the variety of processes that alter the properties during their transports through the atmosphere (e.g., Baker & Croot, 2010). To evaluate the robustness of the results, we conducted another sensitivity run forced by a different Fe deposition flux data set that was derived from multi-model ensemble mean (Myriokefalitakis et al., 2018). Although there are differences in Fe deposition flux between the two data sets, the modeled relative changes of deep-ocean POC export under +N and +Fe treatments are generally consistent (Figure S10). Most of the differences of POC export flux between the two data sets occur in spring when export flux is high.

The model used in this study does not simulate coccolithophores associated with CaCO₃ production. Both CaCO₃ and opal are important ballasting minerals, with comparable densities and sinking velocities (e.g., Ploug et al., 2008; Thomalla et al., 2008). For the western subarctic Pacific gyre, Honda and Watanabe (2010) showed that about 67% and 17% of POC in the deep sea were transported by opal and CaCO₃, respectively. At station S1, the mean opal flux is 7.0 ± 2.9 mg m⁻² d⁻¹ (Honda et al., 2018), which is lower than the CaCO₃ flux (20.4 ± 6.1 mg m⁻² d⁻¹). The seasonal pattern of CaCO₃ flux is similar to that of opal flux, both with enhanced values in winter and spring due to strong mixing that supplies subsurface nutrients and triggers phytoplankton blooms (Mino et al., 2020). The ballasting mechanism in the model assumes that a portion of the POC sinks with the same velocity of opal. Inclusion of CaCO₃ would then introduce another portion of POC sinking associated with CaCO₃ (e.g., Gloege et al., 2017). With similar sinking velocities of opal and CaCO₃, it is possible that the mechanism of deep-ocean POC export in response to dust deposition

Figure 4. Conceptual diagram illustrating different mechanisms by which atmospheric deposition affects deep-ocean carbon export. In summer and fall, nitrogen deposition (blue arrows) increases concentrations of pico-plankton, microzooplankton, and mesozooplankton, which exerts high grazing pressure on diatom and reduces deep-ocean carbon export in winter and spring. In winter and spring, iron deposition (red arrows) increases concentrations of pico-plankton, diatom, microzooplankton, and mesozooplankton, which further enhances carbon export to the deep ocean.
remains at the seasonal time scale. Previous studies attempted to model coccolithophores explicitly; however, parameters associated with coccolithophores dynamics were difficult to constrain due to insufficient in-situ observations (Fujii & Chai, 2007; Xiu & Chai, 2014). Coccolithophores and CaCO₃ production are thus often simulated implicitly as a variable fraction of the small phytoplankton group in biogeochemical models (Lima et al., 2014; Moore et al., 2004). Nevertheless, the relative importance of opal and CaCO₃ to deep-ocean POC export needs to be considered in future studies.

In the subtropical Northwest Pacific, the dominant mechanism for nutrient supply is winter convective mixing (Mino et al., 2020). In the stratified seasons when surface nutrient concentrations are low, Honda et al. (2018) and Sukigara et al. (2014) reported that mesoscale eddies can facilitate vertical transports of nutrients into the euphotic zone. Inoue and Kouketsu (2016) tracked about 7.5 (6.5) cyclonic (anticyclonic) eddies per year passing the vicinity of station S1 during 2010–2013. As these eddies are generally episodic and their occurrences do not show a clear seasonal pattern, they are not considered in our 1D model, which focuses on seasonal dynamics and may underestimate vertical nutrient flux induced by eddies (Inoue et al., 2016).

4. Conclusions

Atmospheric deposition is known to affect biogeochemistry in the upper ocean. Using a newly improved biogeochemical model, we obtained important results regarding deep-ocean POC export in relation to atmospheric deposition. The model results illustrate that iron deposition in winter and spring and nitrogen deposition in summer and fall are important drivers for the seasonal variability of deep-ocean POC export flux. Nitrogen deposition can stimulate pico-plankton growth in summer and fall. The growth of pico-plankton then leads to increases of microzooplankton and mesozooplankton. The increase of mesozooplankton exerts higher grazing pressure on diatoms in winter and early spring, which consequently reduces deep-ocean POC export due to the reduction of ballasting mineral of opal. Iron deposition only affects the system in winter and spring when nitrogen is not a limiting factor for phytoplankton growth, and can increase deep-ocean POC export by stimulating diatom growth and opal production. The dynamic processes proposed here are not specific to the subtropical Northwest Pacific, and can be applied to other seasonal oligotrophic waters. This study also highlights the importance of considering seasonal background environment when conducting bioassays.

Data Availability Statement

The measurements at station S1 were obtained from the “K2S1 database” from the JAMSTEC (http://www.jamstec.go.jp/e/). The global iron data set of Tagliabue et al. (2012) was obtained online (https://www.bodc.ac.uk/geotraces/data/historical/). The model outputs in this study are available online (http://doi.org/10.5281/zenodo.4255185).

Acknowledgments

This study was supported by the National Key Research and Development Program of China (2016YFC1401604), the National Natural Science Foundation of China (41730536 and 41890805), the Key Special Project for the National Natural Science Foundation of China (41730536 and 2016YFC1401604), and the Innovation Foundation of China (41730536 and 2016YFC1401604).

References

Armstrong, R., Lee, C., Hedges, J., Honjo, S., & Wakeham, S. (2002). A new, mechanistic model for organic carbon fluxes in the ocean based on the quantitative association of POC with ballast minerals. Deep-Sea Research II, 49, 219–236. https://doi.org/10.1016/S0967-0645(01)00101-1

Asahara, Y., Tanaka, T., Kamioka, H., & Nishimura, A. (1995). Asian continental nature of 87Sr/86Sr ratios in north central Pacific sediments. Earth and Planetary Science Letters, 133, 105–116. https://doi.org/10.1016/0012-821x(95)00048-h

Baker, A. R., & Croot, P. L. (2010). Atmospheric and marine controls on aerosol iron solubility in seawater. In A. R. Baker, P. L. Croot, & S. G. T. Turner (Eds.), Iron in the ocean: Sources, distributions, and biogeochemical effects (pp. 369–400). https://doi.org/10.1029/2010CM000367

Boyd, P. W., Wong, C. S., Merrill, J., Whitney, F., Snow, J., Harrison, P. J., & Gower, J. (1998). Atmospheric iron supply and enhanced vertical carbon flux in the NE subarctic Pacific: Is there a connection? Global Biogeochemical Cycles, 12, 429–441. https://doi.org/10.1029/97GC03150

Bressac, M., Guieu, C., Doxaran, D., Bourrin, F., Desboeufs, K., Leblond, N., & Ridame, C. (2014). Quantification of the lithogenic carbon pump following a simulated dust-deposition event in large mesocosms. Biogeosciences, 11, 1007–1020. https://doi.org/10.5194/bg-11-1007-2014
Li, T., Masuzawa, T., & Kitagawa, H. (2004). Seasonal variations in settling fluxes of major components in the oligotrophic Shikoku Basin, the western North Pacific: coincidence of high biogenic flux with Asian dust supply in spring. Marine Chemistry, 91, 187–210. https://doi.org/10.1016/j.marchem.2004.06.010

Lima, I. D., Lam, P. J., & Doney, S. C. (2014). Dynamics of particulate organic carbon flux in a global ocean model. Biogeochemistry, 11, 1177–1198. https://doi.org/10.1007/s10533-011-9605-2

Luo, C., Mahowald, N., Bond, T., Chuang, P. Y., Artaxo, P., Siebert, R., et al. (2008). Combustion iron distribution and deposition. Global Biogeochemical Cycles, 22. GB1012. https://doi.org/10.1029/2007GB002964

Marañón, E., Fernández, A., Mouríño-Carballido, B., Martínez-García, S., Teira, E., Cereño, P., et al. (2010). Degree of oligotrophy controls the response of microbial plankton to Saharan dust. Limnology and Oceanography, 55, 2339–2352. https://doi.org/10.4319/lo.2010.55.6.2339

Matsumoto, K., Abe, O., Fujiki, T., Sukigara, C., & Mino, Y. (2016). Primary productivity at the time-series stations in the northwestern Pacific Ocean: is the subtropical station unproductive? Journal of Oceanography, 72, 359–371. https://doi.org/10.1007/s10872-016-0354-4

Mills, M. M., Ridame, C., Davey, M., La Roche, J., & Geider, R. J. (2004). Iron and phosphorus co-limit nitrogen fixation in the eastern tropical North Atlantic. Nature, 426, 292–294. https://doi.org/10.1038/nature02550

Mino, Y., Sukigara, C., Honda, M. C., Wakita, M., Sasaoka, K., et al. (2020). Seasonal and interannual variations in nitrogen availability and particle export in the northwestern North Pacific subtropical gyre. Journal of Geophysical Research: Oceans, 125, e2019JC015600. https://doi.org/10.1029/2019JC015600

Moore, J. K., Doney, S. C., & Lindsay, K. (2004). Upper ocean ecosystem dynamics and iron cycling in a global three-dimensional model. Global Biogeochemical Cycles, 18. https://doi.org/10.1029/2004GB002229

Myriokefalitakis, S., Ito, A., Kanakidou, M., Nenes, A., Krol, M. C., Mahowald, N. M., et al. (2018). Reviews and syntheses: The GESAMP atmospheric iron deposition model intercomparison study. Biogeochemistry, 15, 6659–6684. https://doi.org/10.1007/s10533-015-9659-2

Neuer, S., Torres-Padrón, M. E., Gelado-Calaballo, M. D., Rueda, M. J., Hernández-Brito, J., Davenport, R., & Wefer, G. (2004). Dust deposition pulses to the eastern subtropical North Atlantic gyre: Does ocean's biogeochemistry respond? Global Biogeochemical Cycles, 18. https://doi.org/10.1029/2004GB002228

Nishioka, J., Obata, H., Ogawa, H., Ono, K., Yamashita, Y., Lee, K., et al. (2020). Subpolar marginal seas fuel the North Pacific through the intermediate water at the termination of the global ocean circulation. Proceedings of the National Academy of Sciences of the USA, 117(23), 12665. https://doi.org/10.1073/pnas.2006581117

North, E. W., Hood, R. R., Chao, S.-Y., & Sanford, L. P. (2006). Using a random displacement model to simulate turbulent particle motion in a baroclinic frontal zone: A new implementation scheme and model performance tests. Journal of Marine Systems, 60, 365–380. https://doi.org/10.1016/j.jmarsys.2005.08.003

Pabortsava, K., Lampitt, R. S., Benson, J., Crowe, C., McLachlan, R., Le Moigne, F. A. C., et al. (2017). Carbon sequestration in the deep Atlantic enhanced by Saharan dust. Nature Geoscience, 10(3), 189–194. https://doi.org/10.1038/ngeo2899

Ploug, H., Iversen, M. H., Koski, M., & Buitenhuis, E. T. (2008). Production, oxygen respiration rates, and sinking velocity of copepod fecal pellets: Direct measurements of ballasting by opal and calcite. Limnology & Oceanography, 53(2), 469–476. https://doi.org/10.4319/lo.2008.53.2.0469

Ridame, C., Dekaezemacker, J., Guieu, C., Bonnet, S., I’Helguen, S., & Mulien, F. (2014). Contrasted Saharan dust events in LNLC environments: impact on nutrient dynamics and primary production. Biogeosciences, 11(17), 4783–4800. https://doi.org/10.5194/bg-11-4783-2014

Schepetkin, I. F., & McWilliams, J. C. (2005). The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topography-following-coordinate ocean model. Ocean Modelling, 9, 347–404. https://doi.org/10.1016/j.ocemod.2004.08.002

Shiozaki, T., Furuya, K., Kodama, T., Kitajima, S., Takeda, S., Takemura, T., & Kanda, J. (2010). New estimation of N2fixation in the western and central Pacific Ocean and its marginal seas. Global Biogeochemical Cycles, 24. https://doi.org/10.1029/2009GB003620

Siswanto, E., Matsumoto, K., Honda, M. C., Fujiki, T., Sasaoka, K., & Saino, T. (2015). Reappraisal of meridional differences of factors controlling phytoplankton biomass and initial increase preceding seasonal bloom in the Northwestern Pacific Ocean. Remote Sensing of Environment, 159, 44–56. https://doi.org/10.1016/j.rse.2014.11.028

Sukigara, C., Suga, T., Toyama, K., & Oka, E. (2014). Biogeochemical responses associated with the passage of a cyclonic eddy based on shipboard observations in the western North Pacific. Journal of Oceanography, 70, 435–445. https://doi.org/10.1007/s10754-014-0244-6

Tagliafuore, A., Bowie, A. R., Boyd, P. W., Buck, K. N., Johnson, K. S., & Saito, M. A. (2017). The integral role of iron in ocean biogeochemistry. Nature, 541, 51–59. https://doi.org/10.1038/nature21058

Tagliafuore, A., Mistral, A., Aumont, O., Bowie, A. R., Klunder, M. B., Roychoudhury, A. N., & Swart, S. (2012). A global compilation of dissolved iron measurements: focus on distributions and processes in the Southern Ocean. Biogeochemistry, 9, 2333–2349. https://doi.org/10.1016/j.bioge.2011.10.001

Takemura, T., Uno, I., Nakajima, T., Hirugashi, A., & Sano, I. (2002). Modeling study of long-range transport of Asian dust and anthropogenic aerosols from East Asia. Geophysical Research Letters, 29(24), 11. https://doi.org/10.1029/2002GL016251

Taketani, F., Aita, M. N., Yamaji, K., Sekiya, T., Ikeda, K., Sasaoka, K., et al. (2018). Seasonal response of northwestern Pacific marine ecosystems to deposition of atmospheric inorganic nitrogen compounds from east Asia. Scientific Reports, 8, 9324. https://doi.org/10.1038/s41598-018-27523-w

Tan, S., Li, J., Gao, H., Wang, H., Che, H., & Chen, B. (2016). Satellite-observed transport of dust to the east China Sea and the North Pacific Subtropical Gyre: Contribution of dust to the increase in chlorophyll during spring 2010. Atmosphere, 7, 152. https://doi.org/10.3390/atmos7110152

Ternon, E., Guieu, C., Loje-Pilot, M.-D., Leblond, N., Bosc, E., Gasser, B., et al. (2010). The impact of Saharan dust on the particulate export in the water column of the North Western Mediterranean Sea. Biogeosciences, 7, 809–826. https://doi.org/10.5194/bg-7-809-2010

Thomalla, S. J., Poulton, A. J., Sanders, R., Turner-Stokes, R., Holligan, P. M., & Lucas, M. L. (2008). Variable export fluxes and efficiencies for calcite, opal, and organic carbon in the Atlantic Ocean: A ballast effect in action? Global Biogeochemical Cycles, 22. https://doi.org/10.1029/2007GB002982

Uchimiy, M., Fukuda, H., Wakita, M., Kitamura, M., Kawakami, H., Honda, M. C., et al. (2018). Balancing organic carbon supply and consumption in the ocean's interior: Evidence from repeated biogeochemical observations conducted in the subarctic and subtropical western North Pacific. Limnology & Oceanography, 63, 2015–2027. https://doi.org/10.1002/lno.10821

Uematsu, M., Wang, Z., & Uno, I. (2003). Atmospheric input of mineral dust to the western North Pacific region based on direct measurements and a regional chemical transport model. Geophysical Research Letters, 30(6), 1342. https://doi.org/10.1029/2002GL016645
van der Jagt, H., Friese, C., Stuut, J.-B. W., Fischer, G., & Iversen, M. H. (2018). The ballasting effect of Saharan dust deposition on aggregate dynamics and carbon export: Aggregation, settling, and scavenging potential of marine snow. *Limnology & Oceanography*, 63, 1386–1394. https://doi.org/10.1002/lno.10779

Weber, L., Völker, C., Oschlies, A., & Burchard, H. (2007). Iron profiles and speciation of the upper water column at the Bermuda Atlantic Time-series Study site: a model based sensitivity study. *Biogeochemistry*, 4, 689–706. https://doi.org/10.5194/bg-4-689-2007

Xiu, P., & Chai, F. (2014). Connections between physical, optical and biogeochemical processes in the Pacific Ocean. *Progress in Oceanography*, 122, 30–53. https://doi.org/10.1016/j.pocean.2013.11.008

Xiu, P., Chai, F., Shi, L., Xue, H., & Chao, Y. (2010). A census of eddy activities in the South China Sea during 1993-2007. *Journal of Geophysical Research*, 115, C03012. https://doi.org/10.1029/2009JC005657

Xiu, P., Chai, F., Xue, H., Shi, L., & Chao, Y. (2012). Modeling the mesoscale eddy field in the Gulf of Alaska. *Deep Sea Research Part I: Oceanographic Research Papers*, 63, 102–117. https://doi.org/10.1016/j.dsr.2012.01.006

Ye, Y., Völker, C., & Wolf-Gladrow, D. A. (2009). A model of Fe speciation and biogeochemistry at the Tropical Eastern North Atlantic Time-Series Observatory site. *Biogeochemistry*, 6, 2041–2061. https://doi.org/10.5194/bg-6-2041-2009

Ye, Y., Wagener, T., Völker, C., Guieu, C., & Wolf-Gladrow, D. A. (2011). Dust deposition: iron source or sink? A case study. *Biogeochemistry*, 8, 21070–22124. https://doi.org/10.5194/bg-8-2107-2011

Yoon, J. E., Kim, K., Macdonald, A. M., Park, K. T., Kim, H. C., Yoo, K. C., et al. (2017). Spatial and temporal variabilities of spring Asian dust events and their impacts on chlorophyll-a concentrations in the western North Pacific Ocean. *Geophysical Research Letters*, 44, 1474–1482. https://doi.org/10.1002/2016gl072124

Young, R. W., Carder, K. L., & Betzer, P. R., Costello, D. K., Duce, R. A., DiTullio, G. R., et al. (1991). Atmospheric iron inputs and primary productivity: Phytoplankton responses in the North Pacific. *Global Biogeochemical Cycles*, 5, 119–134. https://doi.org/10.1029/91gb00927

Zhang, C., Gao, H., Yao, X., Shi, Z., Shi, J., Yu, Y., et al. (2018). Phytoplankton growth response to Asian dust addition in the northwest Pacific Ocean versus the Yellow Sea. *Biogeochemistry*, 15(3), 749–765. https://doi.org/10.5194/bg-15-749-2018

Zhang, C., He, J., Yao, X., Mu, Y., Guo, X., Ding, X., et al. (2020). Dynamics of phytoplankton and nutrient uptake following dust additions in the northwest Pacific. *Science of the Total Environment*, 739, 139999. https://doi.org/10.1016/j.scitotenv.2020.139999

Zhang, C., Yao, X., Chen, Y., Chu, Q., Yu, Y., Shi, J., & Gao, H. (2019). Variations in the phytoplankton community due to dust additions in eutrophic, LNLC and HNLC oceanic zones. *The Science of the Total Environment*, 669, 282–283. https://doi.org/10.1016/j.scitotenv.2019.02.068

Zhang, H.-M., Bates, J. J., & Reynolds, R. W. (2006). Assessment of composite global sampling: Sea surface wind speed. *Geophysical Research Letters*, 33, L17713. https://doi.org/10.1029/2006GL027086