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Effects of storms on primary productivity and air-sea CO_2 exchange in the subarctic western North Pacific: a modeling study

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Abstract

Biogeochemical responses of the open ocean to storms and their feedback to climate are still poorly understood. Using a marine ecosystem model, we examine biogeochemical responses to the storms in the subarctic western North Pacific. The storms in summer through early autumn enhance primary production by wind-induced nutrient injections into the surface waters while the storms in the other seasons reduce primary production by intensifying light limitation on the phytoplankton growth due to vertical dilution of the phytoplankton. The two compensating effects diminish the storm-induced annual change of primary production to only 1%. On the contrary, the storms enhance the annual sea-to-air CO_2 efflux by no less than 34%, resulting from storm-induced strong winds. Our results suggest that previous studies using climatological wind and CO_2 data probably underestimated the sea-to-air CO_2 efflux during storms in the subarctic western North Pacific, and therefore, that continuous observations are required to reduce uncertainties in the global oceanic CO_2 uptake.

1 Introduction

Episodic atmospheric disturbances such as storms reduce solar radiation and enhance wind-driven vertical mixing and upwelling in the surface waters (e.g. Price, 1981; Greatbatch, 1985; Cornillon et al., 1987; Shay and Elsberry, 1987; Sakaida et al., 1998; Hong et al., 2003). Such physical changes are expected to impact marine biogeochemistry. For example, decreases in solar radiation and downward transport of phytoplankton out of the euphotic zone are likely to increase light limitation on the phytoplankton growth. On the other hand, wind-induced nutrient injections into the surface waters allow for potentially more growth of phytoplankton.

However, biogeochemical responses of the open ocean to storms are still poorly understood (e.g. Babin et al., 2004). In situ ship-based sampling has greatly enhanced our understanding of the biogeochemistry, but rough weather prevents sampling during storms. Only a few cruises and mooring buoys have serendipitously encountered episodic strong wind events (e.g. Marra et al., 1990; Bates et al., 1998; Dickey et al., 1998; Nemoto et al., 1999). In most such cases, sudden decrease in the sea surface temperature (SST) and abrupt change in the partial pressure of CO_2 in seawater (pCO_{2sea}) have been observed. Recently satellite-derived estimates of wind speed, temperature and chlorophyll-a concentration in the surface waters have provided an opportunity to explore the physical and biological responses to episodic strong wind events (e.g. Babin et al., 2004). However, they cannot clarify whether the observed changes in chlorophyll-a concentration are the result of wind-induced nutrient injections or the result of entrainment of waters with high chlorophyll-a concentration. In addition, wind-induced change in carbon biogeochemistry, which is considered to greatly contribute to ecosystem dynamics and climate, cannot be estimated from observations by satellites at the present stage.

On the other hand, ecosystem modeling allows us to estimate the episodic storm-induced biogeochemical responses at any spatial and temporal scale. Therefore, the application of ecosystem models could significantly advance our understanding of the biogeochemical response to storm passage in the open ocean (e.g. Babin et al., 2004). Biogeochemical responses to storms have hardly been explored in the subarctic western North Pacific, which is considered one of the key regions impacting marine resources and uptake of anthropogenic CO_2 (e.g. Tsurushima et al., 2002). We therefore undertake this study to investigate the storm-induced biogeochemical responses in this region using a marine ecosystem model. We apply the model to time-series Station KNOT (Kyodo North pacific Ocean Time-series; 44° N, 155° E). More than ten storms capable of deepening the mixed layer depth (MLD) and affecting the biogeochemistry appear at Station KNOT on average each year (Table 1). We investigate the biogeochemical responses to the storms, especially focusing on the impacts to the phytoplankton dynamics and the air-sea CO_2 exchange.

2 Model description and experimental design

We use a 16-compartment marine ecosystem model (Fig. 1; Fujii et al., 2002, 2005, 2007; Yamanaka et al., 2004). In this model, phytoplankton are categorized into two groups: diatoms (PL) and non-diatom small phytoplankton (PS) including coccolithophorids. Phytoplankton components utilize nitrate (NO_3) and ammonium (NH_4) in the process of photosynthesis and produce soft tissue in the form of particulate organic nitrogen (PON). Along with photosynthesis, diatoms utilize silicate ($Si(OH)_4$) to produce frustules of biogenic silica. Zooplankton are categorized into three groups: microzooplankton (ZS) including foraminifera, mesozooplankton (ZL) and predatory zooplankton (ZP). Seasonal vertical migration of mesozooplankton is taken into account: the mesozooplankton vertically migrate out of the model domain below 330 m-depth at the end of August, and 20% of the mesozooplankton return to the euphotic zone at the beginning of April every year, which is similar to the procedure used by previous studies (Kishi et al., 2001). Coccolithophorids and foraminifera produce hard shells of calcium carbonate ($CaCO_3$). Total alkalinity (TAlk) is calculated by balances of $CaCO_3$, NO_3 and NH_4. The TCO_2 is calculated by balances of TAlk, NO_3 and NH_4 (with a carbon: nitrogen ratio of 6.625; Redfield et al., 1963). Therefore, the pCO_{2sea} is calculated and the air-sea CO_2 flux can be estimated by this model. Values of biogeochemical parameters in the model are the same as those of Fujii et al. (2007).

The air-sea flux of CO_2 is calculated in the model using the transfer velocity-wind speed relationships of Wanninkhof (1992) as follows:

$$\text{Air-sea } CO_2\text{flux} = 0.31U^2\sqrt{660/\text{Sc}}\,\text{L}\{pCO_{2sea} - pCO_{2air}\}, \tag{1}$$

where U is the wind speed at the sea surface ($\text{m}\,\text{s}^{-1}$), Sc is the Schmidt number for CO_2, expressed as:

$$\text{Sc} = 2073.1 - 125.62\text{SST} + 3.6276\text{SST}^2 - 0.043219\text{SST}^3, \tag{2}$$

L is the solubility of CO_2 calculated from temperature and salinity (Weiss, 1974). The

pCO_{2air} is the partial pressure of CO_2 in the atmosphere and the monthly in situ observational data collected at Mauna Loa Observatory are used (Keeling et al., 1982).

The model is driven by the wind and solar radiation at the sea surface, and the temperature and salinity at the surface and at the bottom of the model domain (330 m). We use the National Centers for Environmental Prediction (NCEP) objectively analyzed data (Kalney et al., 1996) for the daily (every 6 h) wind and solar radiation at the sea surface, the Reynolds weekly data for the SST (Reynolds and Smith, 1995), and the KNOT time-series observations for the temperature at the bottom and the salinity at the surface and bottom (Fujii et al., 2002; Tsurushima et al., 2002).

We define storm events as those in which the wind speed is more than 2σ value from a 30-d running mean. To examine effects of storms on biogeochemistry, we carried out two experiments, namely Exp-1 (with storms) and Exp-2 (without storms). In Exp-1, the model is driven by the winds including more than 2σ values. In Exp-2, the model is driven by the winds in which more than 2σ values are filtered out. The simulation is calculated from 1982 to 2000, and the 19-y monthly-mean model results are presented below.

3 Results and discussions

The model well reproduces the observed seasonal changes of both physical environments and biogeochemistry at Station KNOT (Fig. 2; Imai et al., 2002; Tsurushima et al., 2002). The strong wind in winter causes the MLD, defined as the depth at which the vertical diffusive coefficient is $1.0\times10^{-4}\,m^2\,s^{-1}$, to deepen dramatically to more than 100 m in late winter (Fig. 2a, b). The strong wind and pCO_{2sea} elevated by storm-induced normalized TCO_2 ($NTCO_2$; normalized to a constant salinity of 35 pss) injections into the surface waters cause tremendous sea-to-air CO_2 efflux in late winter (Fig. 2a, d, e, f). The primary production is low in winter because of strong light limitation on the phytoplankton growth due to vertical dilution of the phytoplankton, along with low irradiance in this season (Fig. 2c). The primary production is relatively high in spring through early autumn when the light limitation on the phytoplankton growth is alleviated by high irradiance and stratification of the surface waters in these periods. The oceanic region functions as a sink of the atmospheric CO_2 in spring through autumn, supported by large biological uptake of CO_2, as reported by previous observations (e.g. Tsurushima et al., 2002).

By comparing the model results between Exp-1 (with storms) and Exp-2 (without storms), we find that pCO_{2sea} is the most sensitive biogeochemical parameter to the storms, and therefore, that the storms contribute significantly to air-sea exchange of CO_2 (Fig. 2e, f). The sea-to-air CO_2 efflux is enhanced by the storms in late spring, early summer and autumn. For example, the pCO_{2sea} abruptly increases by 42 μatm during a storm passage in mid-June 1994 in which the wind speed is more than 3σ value from the 30-day running mean (Fig. 3b). The pCO_{2sea} reaches one of its annual peaks during the storm, although the annual maximum generally appears in late winter in the subarctic western North Pacific (Fig. 2e; Tsurushima et al., 2002). The sea-to-air CO_2 efflux abruptly increases during the storm passage (Fig. 3c), accounting for no less than 10% of the annual sea-to-air efflux in 1994. The sudden increase in pCO_{2sea} results from the increase in $NTCO_2$ by 18 mmolC m^{-3} (Fig. 3a) because of the storm-induced vertical mixing, which dominates the counteracting effect of the storm-induced sea surface cooling of 0.8°C. This is consistent with a result based on mooring buoy data deployed in the East China Sea during the passage of three typhoons in 1995 that for changes in pCO_{2sea} the effect of TCO_2 increase dominated that of SST decrease (Nemoto et al., 1999).

On the contrary, the sea-to-air efflux is reduced slihjtly by the storms in late summer, because the primary production is enhanced by the storm-induced nutrient injections into the surface waters (Fig. 2c, f). The model result of the decrease in the pCO_{2sea} in late summer is consistent with a ship-based result of Bates et al. (1998), who observed a sudden decrease in pCO_{2sea} in the Sargasso Sea in the subtropical gyre during a hurricane passage in August 1995. However, the cause of the storm-induced decrease in the sea-to-air CO_2 efflux is different from this study: they observed only a slight increase in TCO_2, and the decrease in pCO_{2sea} was followed by a decrease in SST. The difference in responses of pCO_{2sea} to storms between this study and Bates et al. (1998) results from differences in the upper ocean structure and hydrographic conditions between the subarctic and subtropical gyres. In the subarctic gyre, the pycnocline is relatively shallow, and storms occasionally mix the surface waters with TCO_2-rich deep waters below the pycnocline. In the subtropical gyre, on the other hand, the pycnocline is usually deep and storm-induced vertical mixing does not reach to the deep waters. The magnitude of the sea surface cooling also depends on the upper ocean structure and hydrographic conditions, as noted in previous studies (e.g. Cornillon et al., 1987; Sakaida et al., 1998). Storm-induced sea surface cooling is more efficient in the subtropical ocean than in the subarctic ocean because of the permanently warm surface waters in the subtropical ocean.

The model result shows that the annual sea-to-air CO_2 efflux is higher in Exp-1 (244.55 [mmolC m^{-2} y^{-1}]) than in Exp-2 (160.60 [mmolC m^{-2} y^{-1}]) (Table 2), and therefore, that the storms enhance the annual sea-to-air CO_2 efflux by 34%. Previous studies, in which the flux was calculated using the climatological wind and pCO_{2sea} data, probably underestimated the effect of storm events on air-sea CO_2 exchange and overestimated the role of the entire subarctic western North Pacific in taking up oceanic CO_2.

The storms enhance the primary production in summer through early autumn (Fig. 2c), because the nutrient limitation on the phytoplankton growth is alleviated by the storm-induced nutrient injections into the surface waters. This is consistent with previous observation-based results of the oligotrophic subtropical ocean (e.g. Babin et al., 2004), but not as much as in the subtropical ocean, because of higher pre-storm surface nutrient concentrations, and therefore, less nutrient limitation on the phytoplankton growth, in the subarctic ocean than in the subtropical ocean. On the contrary, the storms reduce the primary production in the other seasons, because the storm-induced vertical mixing increases the light limitation on the phytoplankton growth. This result shows that the effect of storms on the phytoplankton dynamics changes with pre-storm conditions such as the irradiance and nutrient concentrations in the surface waters. The two compensating effects diminish the storm-induced annual change of primary production at Station KNOT to only 1% (Table 2).

4 Conclusion and remarks

Using a marine ecosystem model, we examine the biogeochemical responses to storms at Station KNOT, located in the subarctic western North Pacific. In the simulation, the storms significantly affect both ecosystem dynamics and air-sea CO_2 exchange, and the effects change with the irradiance, upper ocean structure, hydrographic conditions and nutrient concentrations.

The storms enhance the primary production in summer through early autumn because of the storm-induced nutrient injections into the surface waters. On the contrary, the primary production in the other seasons is reduced by the storm-driven vertical mixing and subsequent intention of the light limitation on the phytoplankton growth. The two compensating effects diminish the storm-induced annual change of primary production to only 1%.

The storms enhance the sea-to-air CO_2 efflux in late spring, early summer and autumn by the strong wind, whereas the storms reduce the sea-to-air CO_2 efflux in late summer because of large biological uptake of CO_2 stimulated by the storm-induced nutrient injections into the surface waters. The storms are estimated to enhance the annual sea-to-air CO_2 flux by 34% in this region.

During storms, pCO_{2sea} tends to increase more in the subarctic ocean because of the storm-induced increase in surface $NTCO_2$, whereas pCO_{2sea} tends to decrease in the subtropical ocean because of the storm-induced decrease in the SST. Therefore, it is necessary to perform direct measurements during storm passage in various oceanic regions to elucidate which effects dominate the storm-induced pCO_{2sea} change in each region. Previous studies that calculated the air-sea CO_2 flux using climatological wind and pCO_{2sea} data probably underestimated the significant contribution of storms to the air-sea CO_2 exchange. Therefore, to reduce uncertainties in the global oceanic CO_2 uptake, changes in the pCO_{2sea} caused by episodic atmospheric disturbances should be measured continuously.

While climate changes associated with global warming may influence the frequency and intensity of storms (e.g. Emanuel, 1987, 2005; Saunders and Harris, 1997; Sugi et al., 2002; Yoshimura and Sugi, 2005; Webster et al., 2005; Yoshimura et al., 2006), storm-induced biogeochemical activity may also contribute to climate. Therefore, to predict future climate change, it is essential that we elucidate the biogeochemical responses to storms. Although it is difficult to conduct direct observations during the rough weather, we would very much like to have high-frequency, in-situ biogeochemical observations with which we could conduct more accurate simulations.

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Table 1. Number of days on which the wind speed was more than 2σ or 3σ values from the 30-d running mean in each year from 1982 to 2000 at Station KNOT.

Year	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	Total
>2σ	8	10	8	9	10	15	11	12	9	14	8	14	12	6	12	12	10	10	13	203
>3σ	0	2	0	0	0	0	1	2	0	1	0	0	1	0	0	0	0	0	0	7

Table 2. Annual-mean values of the wind speed, MLD, primary production, pCO_{2sea} and sea-to-air CO_2 efflux (positive upward) for Exp-1 (with storms), Exp-2 (without storms), differences between the experiments (Exp-1 minus Exp-2), and ratios of the differences to the values for Exp-1, at Station KNOT.

	Exp-1	Exp-2	Difference ((Exp-1)−(Exp-2))	Ratio ((Exp-1)−(Exp-2)) /(Exp-1) [%]
Wind speed [$m\,s^{-1}$]	7.65	7.50	0.15	1.92
MLD [m]	45.46	40.66	4.80	10.55
Primary production [$mgC\,m^{-2}\,d^{-1}$]	286.35	283.16	3.19	1.12
pCO_{2sea} [μatm]	357.45	357.33	0.12	0.03
Sea-to-air CO_2 efflux [$mmolC\,m^{-2}\,y^{-1}$]	244.55	160.60	83.95	33.63

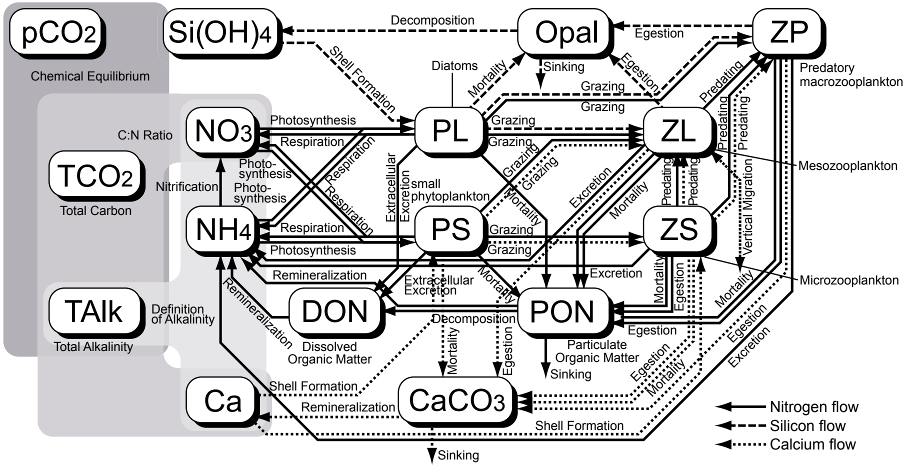

Fig. 1. Schematic view of a 16-compartment marine ecosystem model (from Fujii et al., 2002, 2005, 2007 and Yamanaka et al., 2004).

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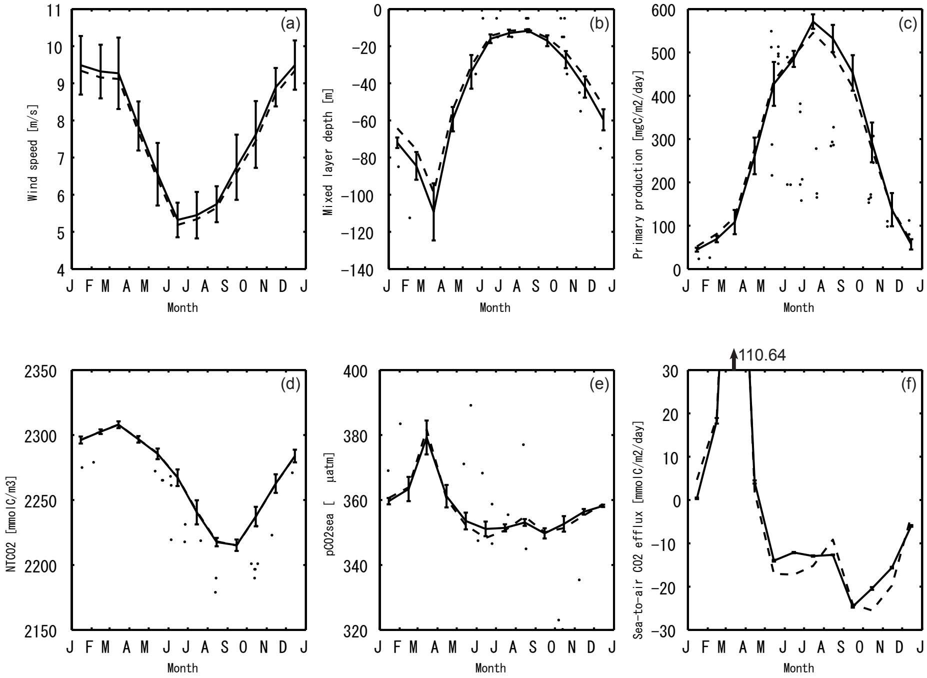

Fig. 2. Seasonal changes of **(a)** wind speed [$\mathrm{m\,s^{-1}}$], **(b)** MLD [m], **(c)** primary production [$\mathrm{mgC\,m^{-2}\,d^{-1}}$], **(d)** $\mathrm{NTCO_2}$ [$\mathrm{mmolC\,m^{-3}}$], **(e)** $\mathrm{pCO_{2sea}}$ [μatm], and **(f)** sea-to-air $\mathrm{CO_2}$ efflux [$\mathrm{mmolC\,m^{-2}\,d^{-1}}$] (positive upward) for Exp-1 (with storms; in solid lines) and Exp-2 (without storms; in dotted lines) at Station KNOT. Error bars represent 1σ values in Exp-1. Dots: observational data from 1998 to 2000 (Imai et al., 2002; Tsurushima et al., 2002).

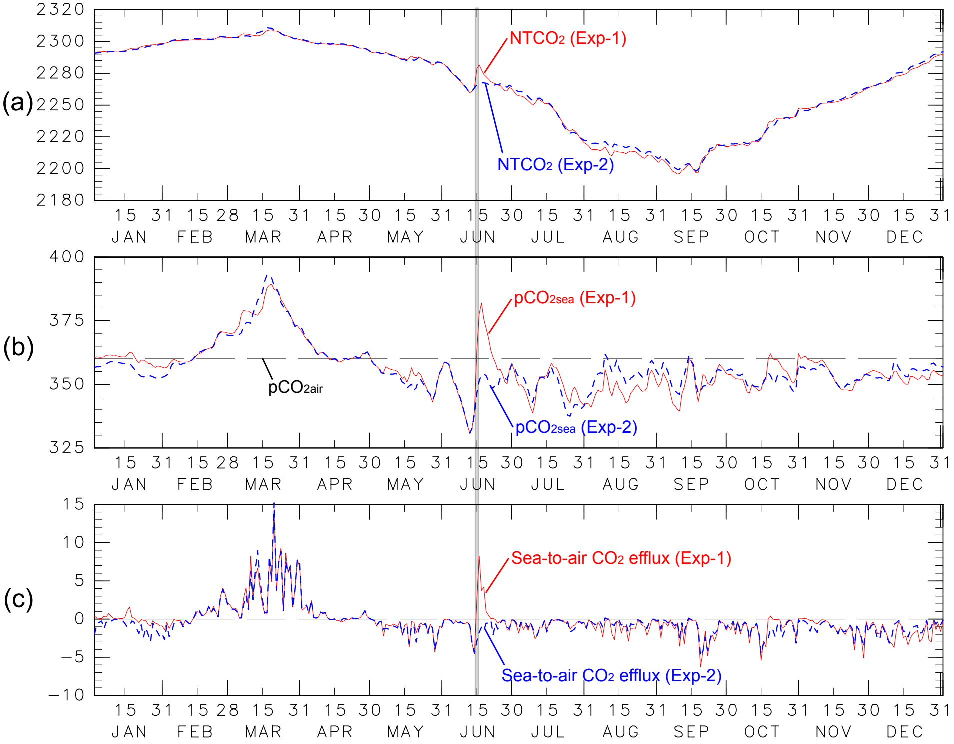

Fig. 3. Modeled **(a)** surface $NTCO_2$ [mmolC m^{-3}], **(b)** pCO_{2sea} and pCO_{2air} [μatm], and **(c)** sea-to-air CO_2 efflux [mmolC m^{-2} d^{-1}] (positive upward) for Exp-1 (with storms; in red solid lines) and Exp-2 (without storms; in blue dotted lines) in 1994 at Station KNOT. The storm with the wind speed more than 3σ value from the 30-d running mean passed during the hatched period (mid-June).