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M. Fujii, Y. Yamanaka. Effects of storms on primary productivity and air-sea CO2 exchange in the subarctic western North Pacific: a modeling study. Biogeosciences Discussions, 2008, 5 (1), pp.65-81. hal-00297957

## HAL Id: hal-00297957 https://hal.science/hal-00297957

Submitted on 18 Jun 2008

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# Effects of storms on primary productivity and air-sea CO<sub>2</sub> exchange in the subarctic western North Pacific: a modeling study

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Received: 13 November 2007 – Accepted: 29 November 2007 – Published: 4 January 2008

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BGD

5, 65-81, 2008

Modeling biogeochemical responses to storms



### 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<sub>2</sub> efflux by no less than 34%, resulting from storm-induced
- the annual sea-to-air CO<sub>2</sub> 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 sub-arctic western North Pacific, and therefore, that continuous observations are required to reduce uncertainties in the global oceanic  $CO_2$  uptake.

#### 15 **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 un-<sup>25</sup> derstood (e.g. Babin et al., 2004). In situ ship-based sampling has greatly enhanced our understanding of the biogeochemistry, but rough weather prevents sampling dur-

## BGD

5, 65-81, 2008

### Modeling biogeochemical responses to storms

M. Fujii and Y. Yamanaka



ing 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

- <sup>5</sup> (pCO<sub>2sea</sub>) 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
- <sup>10</sup> 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-<sup>15</sup> 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 re-
- sources and uptake of anthropogenic CO<sub>2</sub> (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 biogeo-
- chemistry 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<sub>2</sub> exchange.

## BGD

5, 65-81, 2008

#### Modeling biogeochemical responses to storms

M. Fujii and Y. Yamanaka



#### 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 coccol-

- ithophorids. 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)<sub>4</sub>) 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 meso-10 zooplankton 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
- <sup>15</sup> carbonate (CaCO<sub>3</sub>). Total alkalinity (TAlk) is calculated by balances of CaCO<sub>3</sub>, NO<sub>3</sub> and  $NH_4$ . The TCO<sub>2</sub> 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<sub>2sea</sub> is calculated and the air-sea CO<sub>2</sub> 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<sub>2</sub> is calculated in the model using the transfer velocity-wind 20 speed relationships of Wanninkhof (1992) as follows:

Air-sea CO<sub>2</sub>flux=0.31
$$U^2\sqrt{660/\text{ScL}\{\text{pCO}_{2\text{sea}}-\text{pCO}_{2\text{air}}\}}$$
, (1)

where U is the wind speed at the sea surface (m s<sup>-1</sup>), Sc is the Schmidt number for  $CO_2$ , expressed as:

Sc=2073.1-125.62SST+3.6276SST<sup>2</sup>-0.043219SST<sup>3</sup>,

L is the solubility of CO<sub>2</sub> calculated from temperature and salinity (Weiss, 1974). The 68

(2)

BGD

5, 65-81, 2008

Modeling

biogeochemical

responses to storms

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 $pCO_{2air}$  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).

- <sup>5</sup> 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).
- <sup>10</sup> We define storm events as those in which the wind speed is more than  $2\sigma$  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  $2\sigma$  values. In Exp-2, the model is driven by the winds in which more than  $2\sigma$  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  $1.0 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$ , to deepen dramatically to more than 100 m in late winter (Fig. 2a, b). The strong wind and pCO<sub>2sea</sub> elevated by storm-induced normalized TCO<sub>2</sub> (NTCO<sub>2</sub>; normalized to a constant salinity of 35 pss) injections into the surface waters cause tremendous sea-to-air CO<sub>2</sub> 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



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).

5

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, <sup>10</sup> early summer and autumn. For example, the  $pCO_{2sea}$  abruptly increases by  $42 \mu$ atm during a storm passage in mid-June 1994 in which the wind speed is more than  $3\sigma$  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<sub>2</sub> by 18 mmolC m<sup>-3</sup> (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<sub>2sea</sub> the effect of TCO<sub>2</sub> increase dominated that of SST decrease (Nemoto et al., 1999).

On the contrary, the sea-to-air efflux is reduced slihitly 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<sub>2sea</sub> in late summer is consistent with a ship-based result of Bates et al. (1998), who observed a sudden decrease in pCO<sub>2sea</sub> 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<sub>2</sub> efflux is different from this study: they observed only a slight in-

### BGD

5, 65-81, 2008

#### Modeling biogeochemical responses to storms



crease in TCO<sub>2</sub>, 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 rel-

- <sup>5</sup> atively shallow, and storms occasionally mix the surface waters with TCO<sub>2</sub>-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;
- <sup>10</sup> 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<sup>-2</sup> y<sup>-1</sup>]) than in Exp-2 (160.60 [mmolC m<sup>-2</sup> y<sup>-1</sup>]) (Table 2), and there-

- fore, 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

## BGD

5, 65-81, 2008

#### Modeling biogeochemical responses to storms

M. Fujii and Y. Yamanaka



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

20

- <sup>5</sup> 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<sub>2</sub> 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

 $_{\rm 25}$  regions to elucidate which effects dominate the storm-induced pCO<sub>2sea</sub> change in each region. Previous studies that calculated the air-sea CO<sub>2</sub> flux using climatological wind and pCO<sub>2sea</sub> 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 p $CO_{2sea}$  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.

Acknowledgements. The authors wish to thank M. N. Aita for providing data necessary for this study. Thanks are extended to S. L. Smith for his proofreading of the English manuscript.
 M. Fujii was supported by MEXT through Special Coordination Funds for Promoting Science
 and Technology. A figure was produced by the GFD-DENNOU Library.

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BGD						
5, 65–8	1, 2008					
Modeling biogeochemical responses to storms M. Fujii and Y. Yamanaka						
Title Page						
Abstract	Introduction					
Conclusions	References					
Tables	Figures					
14	۶I					
•	•					
Back Close						
Full Screen / Esc						
Printer-friendly Version						
Interactive Discussion						
EGU						

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5, 65-81, 2008

#### Modeling biogeochemical responses to storms

M. Fujii and Y. Yamanaka

Title Page						
Abstract	Introduction					
Conclusions	References					
Tables	Figures					
14	N					
•	•					
Back Close						
Full Screen / Esc						
Printer-friendly Version						
Interactive Discussion						
Interactive	Discussion					

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## BGD

5, 65-81, 2008

#### Modeling biogeochemical responses to storms

Title Page						
Abstract	Introduction					
Conclusions	References					
Tables	Figures					
14	•					
•	•					
Back	Close					
Full Screen / Esc						
Printer-friendly Version						
Interactive Discussion						

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Modeling biogeochemical responses to storms M. Fujii and Y. Yamanaka **Title Page** Abstract Introduction Conclusions References Figures **Tables** .∎◀ < Back Close Full Screen / Esc **Printer-friendly Version** Interactive Discussion

BGD

5, 65-81, 2008

5, 65-81, 2008

#### Modeling biogeochemical responses to storms

M. Fujii and Y. Yamanaka

Title Page						
Abstract	Introduction					
Conclusions	References					
Tables	Figures					
	►I					
•	•					
Back	Close					
Full Screen / Esc						
Printer-friendly Version						
Interactive Discussion						

EGU

**Table 1.** Number of days on which the wind speed was more than  $2\sigma$  or  $3\sigma$  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
>20	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

5, 65-81, 2008

#### Modeling biogeochemical responses to storms

M. Fujii and Y. Yamanaka

Title Page						
Abstract	Introduction					
Conclusions	References					
Tables Figures						
I	۶I					
•	•					
Back	Close					
Full Screen / Esc						
Printer-friendly Version						
Interactive Discussion						

EGU

**Table 2.** Annual-mean values of the wind speed, MLD, primary production,  $pCO_{2sea}$  and seato-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 <sup>-1</sup> ]	7.65	7.50	0.15	1.92
MLD [m]	45.46	40.66	4.80	10.55
Primary production [mgC m <sup>-2</sup> d <sup>-1</sup> ]	286.35	283.16	3.19	1.12
pCO <sub>2sea</sub> [µatm]	357.45	357.33	0.12	0.03
Sea-to-air $CO_2$ efflux [mmolC m <sup>-2</sup> y <sup>-1</sup> ]	244.55	160.60	83.95	33.63

5, 65-81, 2008

#### Modeling biogeochemical responses to storms





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



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

5, 65-81, 2008

Modeling biogeochemical responses to storms

M. Fujii and Y. Yamanaka





**Fig. 3.** Modeled **(a)** surface NTCO<sub>2</sub> [mmolC m<sup>-3</sup>], **(b)**  $pCO_{2sea}$  and  $pCO_{2air}$  [ $\mu$ atm], and **(c)** seato-air CO<sub>2</sub> efflux [mmolC m<sup>-2</sup> d<sup>-1</sup>] (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  $3\sigma$  value from the 30-d running mean passed during the hatched period (mid-June).

