



HOKKAIDO UNIVERSITY

Title	Effects of storms on primary productivity and air-sea CO ₂ exchange in the subarctic western North Pacific: a modeling study
Author(s)	Fujii, Masahiko; Yamanaka, Yasuhiro
Citation	Biogeosciences, 5(4), 1189-1197 https://doi.org/10.5194/bg-5-1189-2008
Issue Date	2008-08-27
Doc URL	https://hdl.handle.net/2115/56478
Rights	© Author(s) 2008. This work is distributed under the Creative Commons Attribution 3.0 License.
Rights(URL)	https://creativecommons.org/licenses/by/3.0/
Type	journal article
File Information	bg-5-1189-2008.pdf



Effects of storms on primary productivity and air-sea CO₂ exchange in the subarctic western North Pacific: a modeling study

M. Fujii^{1,2} and Y. Yamanaka^{2,3}

¹Sustainability Governance Project, Center for Sustainability Science, Hokkaido University, N9W8, Kita-ku, Sapporo, Hokkaido 060-0809, Japan

²Graduate School of Environmental Science, Hokkaido University, N10W5, Kita-ku, Sapporo, Hokkaido 060-0810, Japan

³Frontier Research System for Global Change, 3173-25 Showa-machi, Kanazawa-ku, Yokohama, Kanagawa 236-0001, Japan

Received: 13 November 2007 – Published in Biogeosciences Discuss.: 4 January 2008

Revised: 25 June 2008 – Accepted: 4 August 2008 – Published: 27 August 2008

Abstract. Biogeochemical responses of the open ocean to storms and their feedback to climate are still poorly understood. Using a marine ecosystem model, we examined biogeochemical responses to the storms in the subarctic western North Pacific. The storms in summer through early autumn enhance net community production by wind-induced nutrient injections into the surface waters while the storms in the other seasons reduce net community 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 net community production to only 1%. On the contrary, the storms reduce the annual oceanic uptake of the atmospheric CO₂ by 3%, resulting from storm-induced strong winds. Our results suggest that previous studies using climatological wind, sea level pressure, and CO₂ data probably overestimated the air-to-sea CO₂ influx during storms in the subarctic western North Pacific, and therefore, continuous high-frequency observations of these variables are required to reduce uncertainties in the global oceanic CO₂ uptake.

1 Introduction

Episodic atmospheric disturbances such as storms reduce incoming solar radiation, enhance wind-driven vertical mixing and upwelling, and decrease the temperature, in the surface waters (e.g. Iverson, 1977; Price, 1981; Greatbatch, 1985; Stramma et al., 1986; Cornillon et al., 1987; Sanford et al., 1987; Shay and Elsberry, 1987; Sakaida et al., 1998; Senjyu and Watanabe, 1999; Hong et al., 2003; Lee and Niller,

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., 1998a, b; Dickey et al., 1998; Nemoto et al., 1999; Wanninkhof et al., 2007). In most cases, sudden decrease in the sea surface temperature (SST) and abrupt change in the partial pressure of CO₂ in seawater ($p\text{CO}_{2\text{sea}}$) have been observed.

Recently satellite-derived estimates of wind speed, temperature, chlorophyll-a concentration, and nitrate concentration estimated from temperature in the surface waters have provided an opportunity to explore the physical and biological responses to episodic strong wind events (e.g. Stramma et al., 1986; Subrahmanyam et al., 2002; Lin et al., 2003; Babin et al., 2004; Davis and Yan, 2004; Platt et al., 2005; Son et al., 2006 and 2007). However, they cannot clarify whether the observed changes in chlorophyll-a concentration are the result of wind-induced nutrient injections or the result of horizontal advection 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.



Correspondence to: M. Fujii
(mfujii@ees.hokudai.ac.jp)

Table 1. Number of days on which the wind speed was more than 2σ or 3σ values from the 30-day 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
$>2\sigma$	10	14	15	8	22	19	13	12	12	12	12	14	15	10	11	15	9	10	16	249
$>3\sigma$	0	4	2	3	5	1	2	2	1	3	0	0	3	1	2	3	0	0	2	34

Several previous studies have demonstrated that ecosystem modeling allows us to estimate the episodic storm-induced biogeochemical responses at various spatial and temporal scales (e.g. McCreary et al., 2001; Soetaert et al., 2001; Kawamiya and Oschlies, 2004; Fujii et al., 2007; Wu et al., 2007). Therefore, the application of ecosystem models could significantly advance our understanding of the biogeochemical response to storm passage in the open ocean (Babin et al., 2004). However, the responses of the oceanic carbon cycling have not been discussed sufficiently because very few previous ecosystem models included the carbon cycling. Especially, the 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. Sabine et al., 2004).

We therefore undertook this study to investigate the storm-induced biogeochemical responses in this region using a marine ecosystem model in which the carbon cycling is embedded. We applied the model to time-series Station KNOT (Kurodo North Pacific Ocean Time-series; 44°N , 155°E) located in the subarctic western North Pacific. The subarctic western North Pacific is known as the oceanic region of highest incidence rate of explosively developing extra-tropical cyclones (e.g. Roebber, 1984; Yoshida and Asuma, 2004). The extra-tropical cyclones rapidly decrease the sea level pressure, sometimes as low as during typhoons and hurricanes, and possibly enhance abrupt physical processes in the ocean. In addition, Kataoka (2003) revealed that 41 typhoons reached to nearby Station KNOT for 30 years from 1961 to 1990. As a result, more than ten days are under storm events which are capable of deepening the mixed layer depth (MLD) and affecting the biogeochemistry on average each year at Station KNOT (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 (16-state variable) marine ecosystem model coupled with a one-dimensional physical model (Fig. 1; Fujii et al., 2002, 2005, 2007; Yamanaka et al., 2004). The ecosystem model is based on NEMURO

(North Pacific Ecosystem Model for Understanding Regional Oceanography; e.g. Kishi et al., 2007). 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 ($\text{Si}(\text{OH})_4$) 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 liths of calcium carbonate (CaCO_3). Total alkalinity (TALK) is calculated by balances of CaCO_3 , NO_3 and NH_4 . Dissolved inorganic carbon (DIC) is calculated by balances of TALK, NO_3 and NH_4 (with a carbon:nitrogen ratio of 6.625; Redfield et al., 1963). Effects of the other materials and ions on TALK and DIC are relatively small and negligible. Partial pressure of CO_2 at the sea surface ($(p\text{CO}_2)_{\text{sea}}$) 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:

$$\text{Air-sea } \text{CO}_2 \text{ flux} = 0.31U^2 \sqrt{660/Sc} L \{ (p\text{CO}_2)_{\text{sea}} - (p\text{CO}_2)_{\text{air}} \}, \quad (1)$$

where U is the wind speed at 10 m height (m s^{-1}), Sc is the Schmidt number for CO_2 , expressed as:

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

L is the solubility of CO_2 calculated from temperature and salinity (Weiss, 1974). The $(p\text{CO}_2)_{\text{air}}$ is the partial pressure of CO_2 in the atmosphere and the monthly in situ observational data collected in the Shemya Island, Alaska, USA (SHM; 53°N , 174°E) are used (Keeling et al., 1982; Conway et al., 1994).

The model is driven by the wind and solar radiation at the sea surface, and the temperature and salinity at the surface

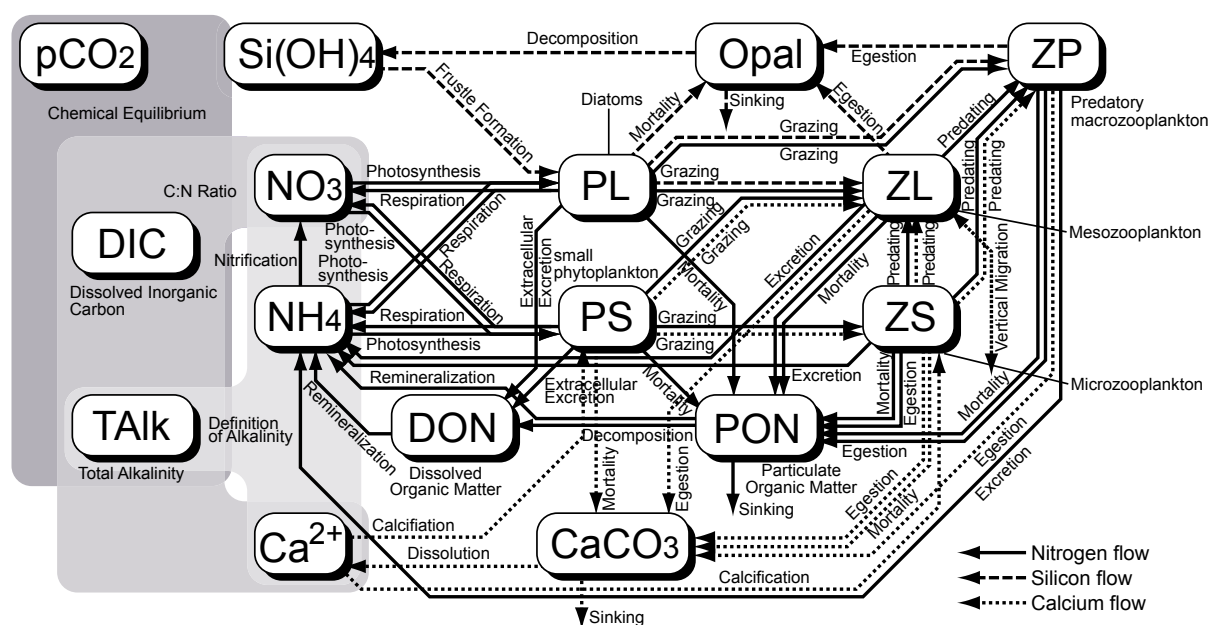


Fig. 1. Conceptual diagram of a 16-compartment (16-state variable) marine ecosystem model.

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 six hours) 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). The model performance of reproducing the observed results were double-checked by referring to observational data obtained by the joint Japan-Canada monitoring program using ships-of-opportunity (e.g. Nojiri et al., 1999; Wong et al., 2002a, b; Zeng et al., 2002; Chierici et al., 2006).

We define storm events as those in which the wind speed is more than 2σ value from a 30-day 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-year monthly-mean model results are presented below.

3 Results and discussions

Most of storm events last for no more than one day, and there are no storm events that last for more than five days (Table 2). All the storms have the wind speed of more than $10 \text{ (m s}^{-1}\text{)}$ with the highest wind speed of $26.3 \text{ (m s}^{-1}\text{)}$ for the 19 years. However, the storm events which has the wind speed of more

Table 2. Number of storms which last for 1, 2, 3 and 4 days, respectively, from 1982 to 2000 at Station KNOT.

	1 day	2 days	3 days	4 days
$>2\sigma$	156	34	7	1
$>3\sigma$	23	4	1	0

than $25 \text{ (m s}^{-1}\text{)}$ are very limited (Table 3), which is different from situations in the subtropical regions in which typhoons and hurricanes have higher wind speeds more than $30 \text{ (m s}^{-1}\text{)}$ (e.g. Bates et al., 1998a, b; D'Asaro and McNeil, 2007; Wanninkhof et al., 2007).

The model reproduces well the observed seasonal changes of both physical environments and biogeochemistry at Station KNOT (Fig. 2). 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 $p\text{CO}_{2\text{sea}}$ elevated by storm-induced DIC (normalized to a constant salinity of 35 psu) injections into the surface waters cause tremendous sea-to-air CO_2 efflux in late winter (Fig. 2a, d, e, f). The net community 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 net community production is relatively high in spring through early autumn when the light limitation on the phytoplankton growth is alleviated by high irradiance and stratification

Table 3. Hours for which storms had the wind speed of 10~15 m s⁻¹, 15~20 m s⁻¹, 20~25 m s⁻¹ and (4) >25 m s⁻¹, respectively, from 1982 to 2000 at Station KNOT. Percentage shows the ratio to total duration of the storms.

	10~15 m s ⁻¹	15~20 m s ⁻¹	20~25 m s ⁻¹	>25 m s ⁻¹
>2σ	6488 h (40.0%)	8850 h (54.5%)	888 h (5.5%)	6 h (0.0%)
>3σ	795 h (23.4%)	1752 h (51.5%)	847 h (24.9%)	6 h (0.2%)

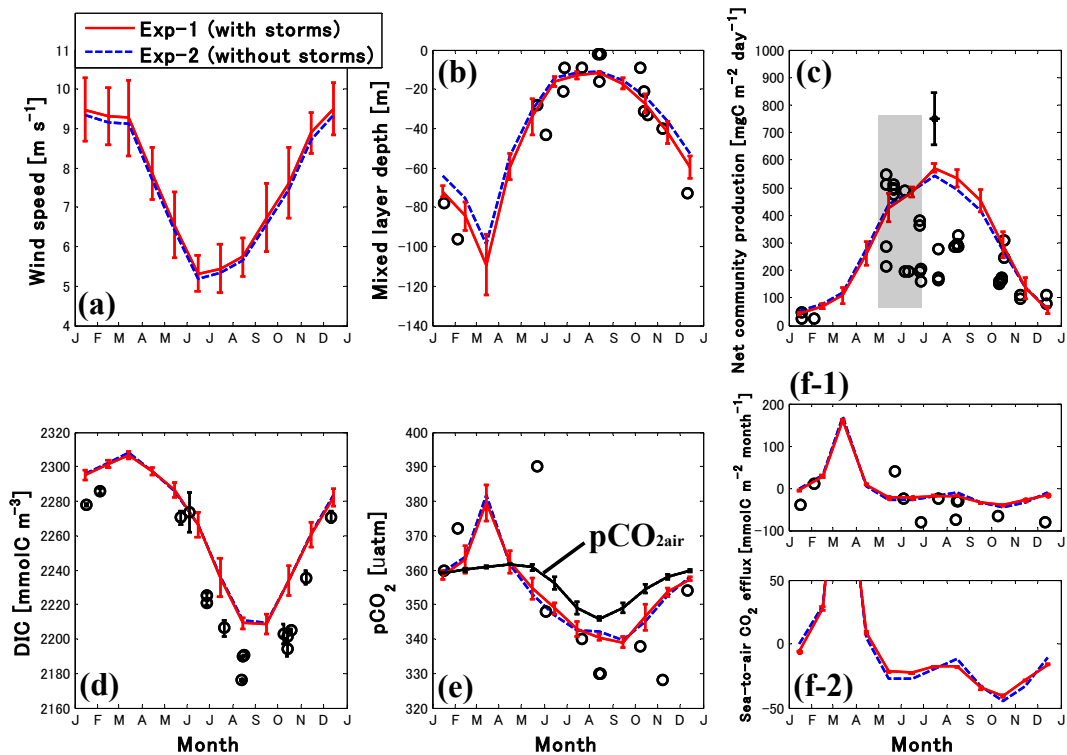


Fig. 2. Nineteen-year (1982–2000) averaged seasonal changes of (a): wind speed [m s⁻¹], (b): MLD [m], (c): net community production [mgC m⁻² day⁻¹], (d): surface DIC [mmolC m⁻³], (e): $p\text{CO}_{2\text{sea}}$ and $p\text{CO}_{2\text{air}}$ [μatm], and (f-1) and (f-2): sea-to-air CO₂ flux [mmolC m⁻² day⁻¹] (positive upward), for Exp-1 (with storms; in solid red lines) and Exp-2 (without storms; in dotted blue lines) at Station KNOT. Error bars represent 1σ values. Open circles in (b), (c), (d), (e) and (f-1) denote observational data from 1998 to 2000 (from Imai et al. (2002) for net community production and Tsurushima et al. (2002) for the others). An asterisk in (c) shows observed net community production in July from Shiimoto et al. (1998). A shaded domain in (c) denotes a range of observed net community production in May and June of 1993–1995 (from Shiimoto, 2000) but excluding data at Station 9 in 1993 which are considered to be affected by the coastal waters with extremely high net community production. Note that (f-1) and (f-2) are identical but are drawn in different scales of y-axis.

of the surface waters in these periods. The oceanic region functions as a sink of the atmospheric CO₂ in spring through autumn, supported by large biological uptake of CO₂, 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 the storms contribute to air-sea exchange of CO₂ (Fig. 2f). The sea-to-air CO₂ efflux is enhanced by the storms in late spring, early summer and autumn (Fig. 2f-2). For example, the $p\text{CO}_{2\text{sea}}$ abruptly increases by 51 μatm during a storm pas-

sage in mid-June 1994 in which the wind speed is more than 3σ value from the 30-day running mean (Fig. 3b). The $p\text{CO}_{2\text{sea}}$ 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 CO₂ flux abruptly increases during the storm passage (Fig. 3c), accounting for 3% of the annual sea-to-air efflux in 1994 for two days. The sudden increase in $p\text{CO}_{2\text{sea}}$ results from the increase in DIC by 22 mmolC m⁻³ (Fig. 3a) because of the storm-induced vertical mixing, which dominates the counteracting effect of the

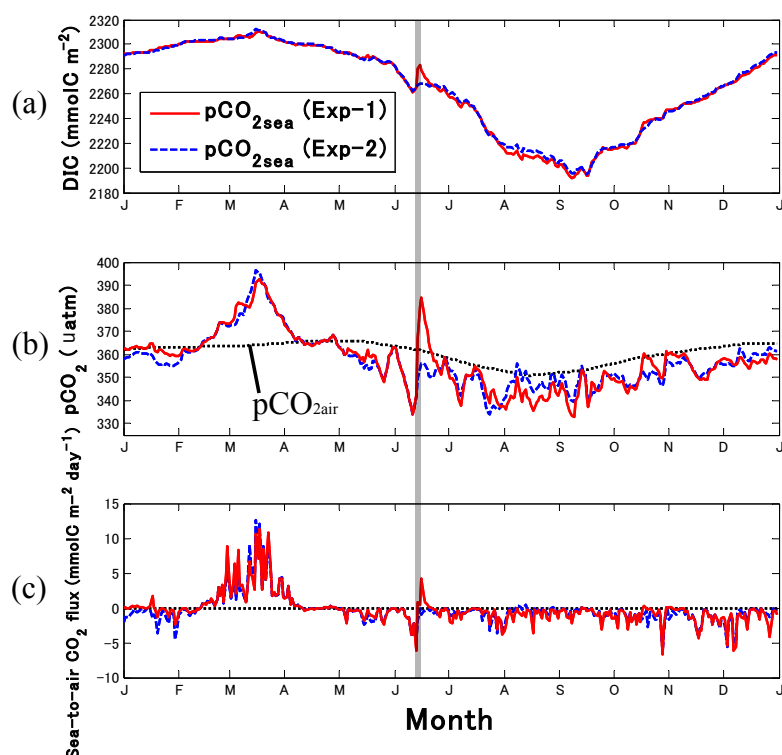


Fig. 3. Modeled (a): surface DIC [mmolC m⁻³], (b): $p\text{CO}_{2\text{sea}}$ and $p\text{CO}_{2\text{air}}$ [μatm], and (c): sea-to-air CO₂ flux [mmolC m⁻² day⁻¹] (positive upward) for Exp-1 (with storms; in red solid lines) and Exp-2 (without storms; in blue dotted lines) in 1994 at Station KNOT. A storm with the wind speed more than 3σ value from the 30-day running mean passed during the hatched period (mid-June).

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 $p\text{CO}_{2\text{sea}}$ the effect of DIC increase dominated that of SST decrease (Nemoto et al., 1999).

On the contrary, the sea-to-air efflux is reduced slightly by the storms in late summer, because the net community production is enhanced by the storm-induced nutrient injections into the surface waters (Fig. 2c, f-2). The model result of the decrease in the $p\text{CO}_{2\text{sea}}$ in late summer (Fig. 2e) is consistent with a ship-based result of Bates et al. (1998b), who observed a sudden decrease in $p\text{CO}_{2\text{sea}}$ in the Sargasso Sea in the subtropical gyre during hurricane Felix passage in August, 1995. Wanninkhof et al. (2007) also showed a decrease in $p\text{CO}_{2\text{sea}}$ by 12 μatm over a period of hurricane Frances passage in the Caribbean Sea in September, 2004. However, the cause of the storm-induced decrease in the sea-to-air CO₂ efflux is different from these studies in the subtropical regions: They observed only a slight increase in DIC, and the decrease in $p\text{CO}_{2\text{sea}}$ was followed by a decrease in SST. The difference in responses of $p\text{CO}_{2\text{sea}}$ to storms between this study and Bates et al. (1998b) and Wanninkhof et al. (2007) 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 DIC-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 air-to-sea CO₂ influx is lower in Exp-1 (211 [mmolC m⁻² yr⁻¹]) than in Exp-2 (218 [mmolC m⁻² yr⁻¹]) (Table 4), and therefore, that the storms reduce the annual oceanic uptake of the atmospheric CO₂ efflux by 3%. It is possible that previous studies, in which the flux was calculated using the climatological wind, sea level pressure (which is necessary in converting $x\text{CO}_{2\text{air}}$ to $p\text{CO}_{2\text{air}}$) and $p\text{CO}_{2\text{sea}}$ data (e.g. Takahashi et al., 2002; Tsurushima et al., 2002), underestimated the effect of storm events on air-sea CO₂ exchange and overestimated the role of the entire subarctic western North Pacific in taking up atmospheric CO₂.

Our model results also suggest that storm events, tropical or extra-tropical, could potentially have a large effect on

Table 4. Nineteen-year (1982–2000) averaged annual-mean values of the wind speed, MLD, net community production, $p\text{CO}_{2\text{sea}}$ and air-to-sea CO_2 influx 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 minus Exp-2)	Ratio ((Exp-1)–(Exp-2))/(Exp-1) [%]
Wind speed [m s^{-1}]	7.7	7.5	0.2	1.9
MLD [m]	45.5	40.7	4.8	10.6
Net community production [$\text{mgC m}^{-2} \text{day}^{-1}$]	286.4	283.2	3.2	1.1
$p\text{CO}_{2\text{sea}}$ [μatm]	353.9	353.8	0.1	0.0
Air-to-sea CO_2 influx [$\text{mmolC m}^{-2} \text{yr}^{-1}$]	211.2	218.1	6.8	3.2

interannual air-sea CO_2 flux variability globally, which is consistent with Bates et al. (1998a) and Bates (2002). However, Wanninkhof et al. (2007) induced an opposite conclusion of minimal influence of storms on annual CO_2 flux. Therefore, long-term monitoring of the air-sea CO_2 flux is required in various oceanic regions to assess quantitatively the role of storm events in the interannual air-sea CO_2 flux.

The storms enhance the net community 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 net community 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 net community production at Station KNOT to only 1% (Table 4).

4 Conclusion and remarks

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

The storms enhance the net community production in summer through early autumn because of the storm-induced nutrient injections into the surface waters. On the contrary, the net community production in the other seasons is reduced by the storm-driven vertical mixing and subsequent inten-

tion of the light limitation on the phytoplankton growth. The two compensating effects diminish the storm-induced annual change of net community 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 reduce the annual oceanic uptake of the atmospheric CO_2 flux by 3% in this region.

During storms, $p\text{CO}_{2\text{sea}}$ tends to increase more in the subarctic ocean because of the storm-induced increase in surface DIC, whereas $p\text{CO}_{2\text{sea}}$ 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 $p\text{CO}_{2\text{sea}}$ change in each region. Previous studies that calculated the air-sea CO_2 flux using climatological wind, sea level pressure and $p\text{CO}_2$ data probably underestimated the contribution of storms to the air-sea CO_2 exchange. Therefore, to reduce uncertainties in the global oceanic CO_2 uptake, changes in these parameters 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; Beersma et al., 1997; Saunders and Harris, 1997; Sugi et al., 2002; Geng and Sugi, 2005; 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. We thank Michio J. Kishi, S. L. Smith and two anonymous reviewers for providing helpful and constructive comments, and M. N. Aita for providing data necessary for this study. M. Fujii was supported by MEXT through Special Coordination Funds for Promoting Sciences and Technology.

Edited by: Y. Prairie

References

- Babin, S. M., Carton, J. A., Dickey, T. D., and Wiggert, J. D.: Satellite evidence of hurricane-induced phytoplankton blooms in an ocean desert, *J. Geophys. Res.*, 109, C03043, doi:10.1029/2003JC001938, 2004.
- Bates, N. R.: Interannual variability in the global uptake of CO₂, *Geophys. Res. Lett.*, 29(5), 1059, doi:10.1029/2001GL013571, 2002.
- Bates, N. R., Knap, A. H., and Michaels, A. F.: Contribution of hurricanes to local and global estimates of air-sea exchange of CO₂, *Nature*, 395, 58–61, 1998a.
- Bates, N. R., Takahashi, T., Chipman, D. W., and Knap, A. H.: Variability of pCO₂ on diel to seasonal timescales in the Sargasso Sea near Bermuda, *J. Geophys. Res.*, 103, 15 567–15 585, 1998b.
- Beersma, J. J., Rider, K. M., Komen, G. J., Kaas, E., and Kharin, V. V.: An analysis of extra-tropical storms in the North Atlantic region as simulated in a control and 2 × CO₂ time-slice experiment with a high-resolution atmospheric model, *Tellus A*, 49(3), 347–361, 1997.
- Chierici, M., Fransson, A., and Nojiri, Y.: Biogeochemical processes as drivers of surface fCO₂ in contrasting provinces in the subarctic North Pacific Ocean, *Global Biogeochem. Cy.*, 20, GB1009, doi:10.1029/2004GB002356, 2006.
- Conway, T. J., Masarie, K. A., and Zhang, Ni: Evidence for inter-annual variability of the carbon cycle from the National Oceanic and Atmospheric Administration/Climate Monitoring and Diagnostics Laboratory Global Air Sampling Network, *J. Geophys. Res.*, 99(D11), 22 831–22 855, 1994.
- Cornillon, P., Stramma, L., and Price, J. F.: Satellite measurements of sea surface cooling during hurricane Gloria, *Nature*, 326, 373–375, 1987.
- D'Asaro, E. D. and McNeil, C.: Air-sea gas exchange at extreme wind speeds measured by autonomous oceanographic floats, *J. Mar. Syst.*, 66, 92–109, 2007.
- Davis, A. and Yan, X.-H.: Hurricane forcing on chlorophyll-a concentration off the northeast coast of the U.S., *Geophys. Res. Lett.*, 31, L17304, doi:10.1029/2004GL020668, 2004.
- Dickey, T. D., Frye, D., McNeil, J., Manov, D., Nelson, N., Sigurdson, D., Jannasch, H., Siegel, D., Michaels, A. F., and Johnson, R. J.: Upper-ocean temperature response to Hurricane Felix as measured by the Bermuda Testbed Mooring, *Mon. Weather Rev.*, 126, 1195–1201, 1988.
- Emanuel, K. A.: The dependence of hurricane intensity on climate, *Nature*, 326, 483–485, 1987.
- Emanuel, K.: Increasing destructiveness of tropical cyclones over the past 30 years, *Nature*, 436, 686–688, doi:10.1038/nature03906, 2005.
- Fujii, M., Nojiri, Y., Yamanaka, Y., and Kishi, M. J.: A one-dimensional ecosystem model applied to time series station KNOT, *Deep-Sea Res. II*, 49, 5441–5461, 2002.
- Fujii, M., Yamanaka, Y., Nojiri, Y., and Kishi, M. J.: Comparison of seasonal characteristics in biogeochemistry among the subarctic North Pacific stations described with a NEMURO-based marine ecosystem model, *Ecol. Modell.*, 202, 52–67, 2007.
- Fujii, M., Yoshie, N., Yamanaka, Y., and Chai, F.: Simulated biogeochemical responses to iron enrichments in three high nutrient, low chlorophyll (HNLC) regions, *Prog. Oceanogr.*, 64, 307–324, doi:10.1016/j.pocean.2005.02.017, 2005.
- Geng, Q.-Z. and Sugi, M.: Possible change of extratropical cyclone activity due to enhanced greenhouse gases and sulfate aerosols – Study with a high-resolution AGCM, *J. Climate*, 16, 2262–2274, 2003.
- Greatbatch, R. J.: On the role played by upwelling of water in lowering sea surface temperatures during the passage of a storm, *J. Geophys. Res.*, 90(C6), 11 751–11 755, 1985.
- Hong, C. H. and Yoon, J. H.: A three-dimensional numerical simulation of Typhoon Holly in the northwestern Pacific Ocean, *J. Geophys. Res.*, 108, 3282, doi:10.1029/2002JC001563, 2003.
- Imai, K., Nojiri, Y., Tsurushima, N., and Saino, T.: Time series of seasonal variation of primary productivity at station KNOT (44° N, 155° E) in the sub-arctic western North Pacific, *Deep-Sea Res. II*, 49, 5395–5408, 2002.
- Iverson, R. I.: Mesoscale oceanic phytoplankton patchiness caused by hurricane effects on nutrient distribution in the Gulf of Mexico, in: *Oceanic Sound Scattering Prediction*, edited by: Andersen, N. R. and Zahuranec, B. J., Plenum Press, New York, 767–776, 1977.
- Kalney, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., and Joseph, D.: The NCEP/NCAR 40-year reanalysis project, *B. Am. Meteorol. Soc.*, 77, 437–471, 1996.
- Kataoka, K.: Tracks of tropical cyclones in the mid-latitudes of the western North Pacific, *Tenki*, 50(9), 705–714, 2003 (in Japanese with English abstract).
- Kawamiya, M. and Oschlies, A.: Simulated impact of intraseasonal variations in surface heat and momentum fluxes on the pelagic ecosystem of the Arabian Sea, *J. Geophys. Res.-Oceans*, 109, C03016, doi:10.1029/2003JC002107, 2004.
- Keeling, C. D., Bacastow, R. B., and Whorf, T. P.: Measurements of the concentration of carbon dioxide at Mauna Loa Observatory, Hawaii, in: *Carbon Dioxide Review: 1982*, edited by: Andersen, N. R. and Zahuranec, B. J., Oxford University Press, New York, 377–385, 1982.
- Kishi, M. J., Kashiwai, M., Ware, D. M., Megrey, B. A., Eslinger, D. L., Werner, F. E., et al.: NEMURO – a lower trophic level model for the North Pacific marine ecosystem, *Ecol. Modell.*, 202, 12–25, 2007.
- Kishi, M. J., Motono, H., Kashiwai, M., and Tsuda, A.: An ecological-physical coupled model with ontogenetic vertical migration of zooplankton in the northwestern Pacific, *J. Oceanogr.*, 57, 499–507, 2001.
- Lee, D. and Niller, P.: Ocean responses to typhoon Rusa in the south sea of Korea and in the East China Sea, *J. Korean Soc. Oceanogr.*, 38(2), 60–67, 2003.
- Lin, I., Liu, W. T., Wu, C.-C., et al.: New evidence for enhanced ocean primary production triggered by tropical cyclone, *Geophys. Res. Lett.*, 30(13), 1718, doi:10.1029/2003GL017141, 2003.

- 2003.
- Marra, J., Bidigare, R. R., and Dickey, T. D.: Nutrients and mixing, chlorophyll and phytoplankton growth, *Deep-Sea Res.*, 37, 127–143, 1990.
- McCreary, J. P., Kohler, K. E., Hood, R. R., Smith, S., Kindle, J., Fischer, A. S., and Waller, R. A.: Influences of diurnal and intraseasonal forcing on mixed-layer and biological variability in the central Arabian Sea, *J. Geophys. Res.*, 106, 7139–7155, 2001.
- Nemoto, K., Takatani, S., Ogawa, K., Umeda, T., Oyama, J., Midorikawa, T., Kimoto, T., and Inoue, H. Y.: Continuous observations of atmospheric and oceanic CO₂ using the moored buoy in the East China Sea, in: *Proceedings of the 2nd International Symposium CO₂ in the Oceans*, CGER/NIES, Tsukuba, 545–553, 1999.
- Nojiri, Y., Fujinuma, Y., Zeng, J., and Wong, C. S.: Monitoring of pCO₂ with complete seasonal coverage utilizing a cargo ship M/S Skaugran between Japan and Canada/US, in: *Proceedings of the 2nd International Symposium CO₂ in the Oceans*, CGER/NIES, Tsukuba, 17–23, 1999.
- Platt, T., Bouman, H., Devred, E., Fuentes-Yaco, C., and Sathyendranath, S.: Physical forcing and phytoplankton distributions, *Sci. Mar.*, 69(1), 55–73, 2005.
- Price, J. F.: Upper ocean response to a hurricane, *J. Phys. Oceanogr.*, 11, 153–175, 1981.
- Redfield, A. C., Ketchum, B. A., and Richards, F. A.: The influence of organisms on the composition of seawater, in: *The Sea*, edited by: Hill M. H., Wiley, New York, 26–77, 1963.
- Reynolds, R. W. and Smith, T. M.: A high resolution global sea surface temperature climatology, *J. Climate*, 8, 1571–1583, 1995.
- Roebber, P. J.: Statistical analysis and updated climatology of explosive cyclones, *Mon. Weather Rev.*, 112, 1577–1589, 1984.
- Sabine, C. L., Feely, R. A., Key, R. M., Lee, K., Bullister, J. L., Wanninkhof, R., Wong, C. S., Wallace, D. W. R., Tilbrook, B., Millero, F. J., Peng, T.-H., Kozyr, A., Ono, T., and Rios, A. F.: The oceanic sink for anthropogenic CO₂, *Science*, 305(5682), 367–371, 2004.
- Sakaida, F., Kawamura, H., and Toba, Y.: Sea surface cooling caused by typhoons in the Tohoku Area in August 1989, *J. Geophys. Res.*, 103, 1053–1065, 1998.
- Sanford, T. B., Black, P. G., Hausteine, J. R., et al.: Ocean response to a hurricane, Part I: observations, *J. Phys. Oceanogr.*, 17, 2065–2083, 1987.
- Saunders, M. A. and Harris, A. R.: Statistical evidence links exceptional 1995 Atlantic hurricane season to record sea warming, *Geophys. Res. Lett.*, 24, 1255–1258, 1997.
- Senjyu, T. and Wanatabe, T.: A sudden temperature decrease along the Sanin coast induced by a typhoon, *UmitoSora*, 75, 1–8, 1999 (in Japanese with English abstract).
- Shay, L. K. and Elsberry, R. L.: Near-inertial ocean current response to Hurricane Frederick, *J. Phys. Oceanogr.*, 17, 1249–1269, 1987.
- Shiomoto, A.: Chlorophyll-a and net community production during spring in the oceanic region of the Oyashio Water, the north-western Pacific, *J. Mar. Biol. Ass. U.K.*, 80, 343–354, 2000.
- Shiomoto, A., Ishida, Y., Tamaki, M., and Yamanaka Y.: Net community production and chlorophyll a in the western Pacific Ocean in summer, *J. Geophys. Res.*, 103(C11), 24 651–24 661, 1998.
- Soetaert, K., Herman, P. M. J., Middelburg, J. J., Heip, C., Smith, C. L., Tett, P., and Wild-Allen, K.: Numerical modeling of the shelf break ecosystem: reproducing benthic and pelagic measurements, *Deep-Sea Res. II*, 48, 3141–3177, 2001.
- Son, S., Platt, T., Bouman, H., Lee, D., and Sathyendranath, S.: Satellite observation of chlorophyll and nutrients increase induced by Typhoon Megi in the Japan/East Sea, *Geophys. Res. Lett.*, 33, L05607, doi:10.1029/2005GL025065, 2006.
- Son, S., Platt, T., Fuentes-Yaco, C., Bouman, H., Devred, E., Wu, Y., and Sathyendranath, S.: Possible biogeochemical response to the passage of Hurricane Fabian observed by satellites, *J. Plankt. Res.*, 29(8), 687–697, 2007.
- Stramma, L., Cornillon, P., and Price, J. F.: Satellite observations of sea surface cooling by Hurricanes, *J. Geophys. Res.*, 91, 5031–5035, 1986.
- Subrahmanyam, B., Rao, K. H., Rao, N. S., et al.: Influence of a tropical cyclone on chlorophyll-a concentration in the Arabian Sea, *Geophys. Res. Lett.*, 29, 2065, doi:10.1029/2002GL015892, 2002.
- Sugi, M., Noda, A., and Sato, N.: Influence of the global warming on tropical cyclone climatology: an experiment with the JMA global model, *J. Meteor. Soc. Japan*, 80, 249–272, 2002.
- Takahashi, T., Sutherland, S. C., Sweeney, C., Poisson, A., Metzl, N., Tilbrook, B., Bates, N., Wanninkhof, R., Feely, R. A., Sabine, C., Olafsson, J., and Nojiri, Y.: Global sea-air CO₂ flux based on climatological surface ocean pCO₂, and seasonal biological and temperature effects, *Deep-Sea Res. II*, 49, 1601–1622, 2002.
- Tsurushima, N., Nojiri, Y., Imai, K., and Watanabe, S.: Seasonal variations of carbon dioxide system and nutrients in the surface mixed layer at station KNOT (44°N, 155°E) in the subarctic western North Pacific, *Deep-Sea Res. II*, 49, 5377–5394, 2002.
- Wanninkhof, R.: Relationship between wind speed and gas exchange, *J. Geophys. Res.*, 97(C5), 7373–7382, 1992.
- Wanninkhof, R., Olsen, A., and Trinanes, J.: Air-sea CO₂ fluxes in the Caribbean Sea from 2002–2004, *J. Mar. Syst.*, 66, 272–284, 2007.
- Webster, P. J., Holland, G. J., Curry, J. A., and Chang, H.-R.: Changes in tropical cyclone number, duration, and intensity in a warming environment, *Science*, 309, 1844–1846, 2005.
- Weiss, R. F.: Carbon dioxide in water and seawater: The solubility of a non-ideal gas, *Mar. Chem.*, 2, 203–215, 1974.
- Wong, C. S., Waser, N. A. D., Nojiri, Y., Johnson, W. K., Whitney, F. A., Page, J. S. C., and Zeng, J.: Seasonal and interannual variability in the distribution of surface nutrients and dissolved inorganic carbon in the Northern North Pacific: Influence of El Niño, *J. Oceanogr.*, 227–243, 2002a.
- Wong, C. S., Waser, N. A. D., Nojiri, Y., Whitney, F. A., Page, J. S., and Zeng, J.: Seasonal cycles of nutrients and dissolved inorganic carbon at high and mid latitudes in the North Pacific Ocean during the Skaugran cruises: determination of new production and nutrient uptake ratios, *Deep-Sea Res. II*, 49, 5317–5338, 2002b.
- Wu, Y., Platt, T., Tang, C., et al.: Short-term changes in chlorophyll distribution in response to a moving storm – a modeling study, *Mar. Ecol. Prog. Ser.*, 335, 57–68, 2007.
- Yamanaka, Y., Yoshie, N., Fujii, M., Aita, M. N., and Kishi, M. J.: An ecosystem model coupled with Nitrogen-Silicon-Carbon cycles applied to Station A7 in the Northwestern Pacific, *J. Oceanogr.*, 60, 227–241, 2004.
- Yoshida, A. and Asuma, Y.: Structures and environment of explo-

- sively developing extratropical cyclones in the northwestern Pacific region, *Mon. Weather Rev.*, 132, 1121–1142, 2004.
- Yoshimura, J. and Sugi, M.: Tropical cyclone climatology in a high-resolution AGCM –Impact of SST warming and CO₂ increase, *SOLA*, 1, 133–136, 2005.
- Yoshimura, J., Sugi, M., and Noda, A.: Influence of global warming on tropical cyclone frequency, *J. Meteor. Soc. Japan*, 84, 405–428, 2006.
- Zeng, J., Nojiri, Y., Murphy, P. P., Wong, C. S., and Fujinuma, Y.: A comparison of $\Delta p\text{CO}_2$ distributions in the northern North Pacific using results from a commercial vessel in 1995–1999, *Deep-Sea Res. II*, 49, 5303–5315, 2002.