Physical behaviors of the iron-fertilized patch in SEEDS II

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ABSTRACT

Sulfur hexafluoride (SF6) tracer release experiments were carried out to trace the iron-fertilized water mass during the iron-fertilization experiments in the western North Pacific of Subarctic Pacific Iron Experiment for Ecosystem Dynamics Study II (SEEDS II) in 2004. A solution of Fe and SF6 tracer was released into the surface mixed layer over an 8 × 8 km area, and the fertilized patch was traced by onboard SF6 analysis for 12 days during each experiment. A Lagrangian frame of reference was maintained by the use of a drogued GPS buoy released at the center of the patch to reduce the advection effect on observations. The patch moved along the contour of sea-surface height (SSH) of a clockwise mesoscale eddy for 4 days after release. Then strong easterly winds dragged the patch across the contour of SSH. The patch behavior was affected by both the mesoscale eddy and surface winds. Apparent horizontal diffusivities were determined by the change of the distribution of SF6 concentrations. The averaged apparent horizontal diffusivity was about 49 m2 s⁻¹ during SEEDS II. It was larger than the one in SEEDS. Mixed-layer depth (MLD) was 8.5–18 m during SEEDS, and 12–33 m during SEEDS II. The larger horizontal diffusivity and deeper MLD in SEEDS II were disadvantages to maintain a high iron concentration in the surface layer compared to SEEDS. Temporal change of the MLD corresponded to the temporal change of chlorophyll-a concentration. Temporal change in the surface MLD was also important for the response of phytoplankton by iron fertilization.

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1. Introduction

Mesoscale iron-fertilization experiments have been carried out to test the iron-limitation hypothesis in the real ocean in a high-nutrient low-chlorophyll (HNLC) area. Subarctic Pacific iron Experiment for Ecosystem Dynamics Study (SEEDS II) was the first iron-fertilization experiment in the western subarctic Pacific (Tsuda et al., 2003). The response of phytoplankton during SEEDS was the largest and the mixed-layer depth (MLD) defining the light environment was shallowest compared to other experiments (de Baar et al., 2005). de Baar et al. (2005) suggested that the shallow mixed layer helped to maintain the high iron concentration and contributed to the large response in phytoplankton growth. In addition, they mentioned that lateral patch dilution, sea-surface irradiance, temperature and grazing are also important for the response of phytoplankton to the iron fertilization. Yoshie et al. (2005) pointed out that the response of phytoplankton depends on the species by a model simulation. The second iron-enrichment experiment (SEEDS II) was carried out in 2004 in the same area and season as SEEDS. The response of phytoplankton was about 8 times smaller than SEEDS. Tsuda et al. (2007) discussed the reasons why the responses of phytoplankton in SEEDS II were smaller than SEEDS. Neritic diatoms greatly increased in SEEDS, however no neritic diatoms were detected in SEEDS II. The MLD in SEEDS II was deeper than SEEDS. In addition, zooplankton grazing rate on phytoplankton in SEEDS II was larger than in SEEDS.

To discuss the different responses between SEEDS and SEEDS II, it is also important to examine the differences in physical conditions and their temporal changes between SEEDS and SEEDS II in detail. We traced the physical behavior of the iron-fertilized patch for continuous monitoring of the response to the artificial fertilization of iron. Sulfur hexafluoride (SF6) tracer was employed because its detection level is low and its behavior is not affected...
by geochemical and biogeochemical processes in the ocean (Ledwell and Watson, 1991). SF6 cannot be used as a tracer for more than 2 weeks because injected SF6 into the ocean is lost by air–sea gas exchange. The change of pCO2 is also useful to trace the patch and was used in the latter half of the experiment (Law et al., 2006).

The distributions of iron and SF6 tracer concentrations in the patch were relatively simple in SEEDS, and the temporal changes of the behavior were also small (Tsumune et al., 2005). More frequent measurements of SF6 tracer were employed to understand the detailed structure of the patch in SEEDS II. Physical parameters such as oceanic current, seawater density profile and wind, control the behavior of the iron-fertilized patch. In addition, these physical parameters partly control the response of phytoplankton to the iron fertilization. Here we discuss the differences in the physical conditions of both SEEDS and SEEDS II based on the behavior in the SF6 tracer release experiments, the in situ pCO2 observations, and the physical parameters to discuss the difference of the response between both experiments.

2. Methods

2.1. Tracer release

The method of SF6 tracer release experiment was similar to the previous methods used in iron-fertilization experiments (Law et al., 1998; Tsumune et al., 2005). The saturated SF6 solution was prepared onboard R.V. Hakuo-Maru 2 days before release in the same area as the release area. Two 2000 L steel tanks were filled with seawater sampled at the experimental area. Therefore, the density of the solution was the same as seawater in the experimental area. SF6 solubility is very low in seawater; therefore we employed a method based on the previous experiment to make the SF6 solution effectively (Upstill-Goddard et al., 1990). Pure SF6 (99.9999%) gas was injected into seawater in tanks directly through air stones at a rate of 150–200 ml min\(^{-1}\). In addition, pure SF6 gas in the headspace was re-circulated by additional bubbling at the rate of 36 L min\(^{-1}\) by an airtight pump on R.V. Hakuo-Maru. To avoid contamination of SF6 in the ship, an exhaust line was extended behind the ship. The bubbling of SF6 was continued for 24 h for each tank. The bubbling time was enough to attain saturated SF6 concentration in seawater with a concentration in the order of 1 \times 10^{-4} M (Ledwell and Watson, 1991). During the release process of the SF6 tracer, a meteorological balloon within the airtight steel tank was filled with water to replace the volume of a headspace for preventing degassing of SF6.

A Lagrangian reference frame was employed for release and sampling of the Fe-enriched patch to minimize the effect of advection (Stanton et al., 1998). A GPS-navigation buoy attached to a drogue centered at 10 m depth was launched at 48° N, 166° E on the day before the iron addition. The first iron addition was carried out from 9:50 (local time) on 20 July to 9:00 (local time) on 21 July (Day 0). 10,800 L of seawater with 322 kg of Fe as FeSO\(_4\) (Nishioka et al., 2009) and 0.48 moles of SF6 tracer were released at about 6 m depth into the mixed layer over an area of 8 \times 8 km during about 23 h. The iron and SF6 release area should be square initially to discuss the following physical dispersion effect of the patch accurately, avoiding the advection effect during the injection time of about 23 h. The release area was from 48°28’ to 48°34’ N and from 164°53’ to 164°55’ E. The ship was navigated using the grid pattern as shown in Fig. 1 centered on the drogued center GPS buoy for about 23 h using the Lagrangian reference frame. The ship moved at a speed of 9.3 km h\(^{-1}\) to the south and north alternatively. Fig. 1(A) shows the trajectories of ship and the center buoy movement on the regular coordinate system. During the release of iron and SF6, the center GPS buoy moved clockwise during the period of about 12 h due to inertial oscillations. Ship track on the Lagrangian reference coordinate is shown in Fig. 1(B). Release-area was 8 \times 8 km on the Lagrangian reference coordinate system. The ship track was not straight because the ship maneuvered away from unexpected floating objects in the middle of the ship’s track. The surface MLD was 28 m at the

![Fig. 1](image-url)
release. XBT measurements were carried out six times during the tracer release. The surface MLD did not change during tracer release (data not shown). Initial SF$_6$ concentration was estimated to be 267 fM ($\text{SF}_6$) when SF$_6$ tracer would dilute in the surface mixed layer of the patch area immediately.

A second iron fertilization, 159 kg of Fe as FeSO$_4$ was released 6 days after first release on the ocean surface without SF$_6$ tracer from 15:00 (local time) on 26 July to 1:00 (local time) on 21 July (Day 6) on the area of the patch at Day 5 (See Fig. 2). pCO$_2$ signal was not detected and SF$_6$ was also not measured during the second iron fertilization. The ship speed was about 18.5 km h$^{-1}$ to cover a wider area with a shorter time than the first iron fertilization.

2.2. Propeller survey

Continuous sampling of surface waters during the underway survey, propeller survey, was conducted to determine the position and shape of the patch using the ship’s pumping system, which had an intake at 6 m below the surface for measurements of SF$_6$ and pCO$_2$. The propeller surveys were carried out just after the tracer release (Day 1 on 21st July), and then 3, 4, 5, 7, 9 and 12 days (Days 3, 4, 5, 7, 9 and 12, respectively) by R.V. Hakuho-Maru, and 13 days (Day 13), 14 days (Day 14), 15 days (Day 15), 17 days (Day 17) by R.V. Kilo-Moana, and 22 days (Day 22) by R.V. Hakuho-Maru after the tracer release. According to the measurement of the distribution of SF$_6$ concentration and pCO$_2$, the ship track was determined to describe the contours of the tracer patch. It took 8–10 h for the propeller survey to determine the patch structure. The GPS buoy location was employed to reduce the effect of advection during the sampling. SF$_6$ concentration was measured using a sparge and cryogenic trap system based on Upstill-Goddard et al. (1990) and Watanabe et al. (2003). Seawater was pumped to the laboratory continuously and supplied to the glass sparge tower. SF$_6$ was trapped using two Parapak Q traps in combination and determined using an Electron Capture Detector.

Fig. 2. SF$_6$ color contour on Day 1, Day 3, Day 4, Day 5, Day 7, Day 9 on the Lagrangian coordinate system based on the center buoy. White plus marks show the sampling points of SF$_6$. Zero axis is the location of the center buoy. Note that the center buoy was reset on Day 6. Color contour scales are different for each figure.
SF6 concentration was measured at intervals of 6 min. The detection level of SF6 concentration was 2 fM.

The PCO2 was measured by a system with a bubbling equilibrator with an open air flow and a non-dispersive infrared analyzer (Nojiri et al., 1999). PCO2 signals were measured at intervals of 1 min on both R.V. Hakuho-Maru and R.V. Kilo-Moana with the same analytical systems.

To reduce the effect of advection, we employed the Lagrangian coordinate system based on the center GPS buoy. Based on the SF6 concentrations and PCO2 at the observed points, contours of SF6 concentration were described by a natural neighbor interpolation method (NCAR Command Language, NCL). Mesh size was 500 m × 500 m to create the contours. The SF6 patch area was defined as the area where the SF6 concentration was over 2 fM because background concentration of SF6 was about 0.5 fM. The PCO2 patch area was defined as the area where the PCO2 was less than 364 ppm because background PCO2 was about 370 ppm.

Patch radius based on the second moment of the patch distribution, Wr2, was calculated using Eq. (1) (Martin et al., 2001)

\[ W_t^2 = \frac{M_2}{M_0} - \left( \frac{M_1}{M_0} \right)^2 \]  \hspace{1cm} (1)

where

\[ M_0 = \sum_i C(r_i), M_1 = \sum_i C(r_i)r_i, M_2 = \sum_i C(r_i)r_i^2 \]

and C(r_i) and r_i are the SF6 concentration and radius from the center of patch, respectively, for the ith datum. Patch configuration was idealized as circular to simplify this analysis and to compare with SEEDS (Tsumune et al., 2005). Horizontal diffusion coefficient is obtained by dividing the second moment of the patch distribution, Wr2, by time from fertilization. SF6 concentration in surface seawater decreases by horizontal diffusion, vertical diffusion, and the loss due to air–sea gas exchange. So the apparent horizontal diffusion was calculated. The effect of horizontal diffusion to the decrease of SF6 concentration was larger than the one by vertical diffusion and the loss due to air–sea gas exchange.

2.3. Monitoring of vertical structure of the patch

2.3.1. Vertical profile of SF6 concentration

Vertical water samplings with CTD Carousel multi-sampling system were carried out by both R.V. Hakuho-Maru and R.V. Kilo-Moana in the iron-fertilization patch for a total of 12 times. To acquire vertical profiles of SF6 concentration, SF6 concentrations were measured from sampled water in 500 ml glass bottles after the research cruise. Ten vertical profiles were obtained from 2 to 150 m.

2.3.2. Mixed-layer depth

Potential density was calculated from the measured temperature and salinity by CTD. The equation for MLD defined by World Ocean Atlas (Levitus, 1982) is

\[ \sigma_b(D_{\text{max}}) = \sigma_b(0) - 0.125 \]  \hspace{1cm} (2)

\[ \sigma_b = (1 - \rho)1000 \]  \hspace{1cm} (3)

where, \( \rho \) is density of seawater (kg m\(^{-3}\)) calculated from temperature and salinity, \( D_{\text{max}} \) is MLD (m).

2.3.3. Vertical shear

To estimate the vertical shear, vertical profiles of ocean current velocity were measured with a bottom-mounted ADCP (R.D. Instruments, 38 kHz) of R.V. Hakuho-Maru. The ADCP current profiles were obtained under 22.7 m depth at every 8 m. Time interval was 2 min. The root mean square of eastward current shear and northward current shear, \( |dV/dz| \), is calculated as follows:

\[ |dV/dz| = \sqrt{(u_{\text{up}} - u_{\text{lo}}/\Delta z)^2 + (v_{\text{up}} - v_{\text{lo}}/\Delta z)^2} \]  \hspace{1cm} (4)

where \( u \) and \( v \) are eastward and northward velocities, respectively, and the subscript \( \text{up} \) and \( \text{lo} \) mean upper layer and lower layer. \( |dV/dz|_1 \) was calculated with velocities at a depths of 32.7 \( (V_{\text{up}}) \) and 40.7 m \( (V_{\text{lo}}) \) and \( |dV/dz|_2 \) with those at a depth of 40.7 \( (V_{\text{up}}) \) and 48.7 m \( (V_{\text{lo}}) \). The current speed showed much interference noise caused by the movement of the ship therefore the vertical shear was calculated from current velocities averaged over 20 min during periods when the ship moved at the speed of less than 0.5 m s\(^{-1}\).

3. Results

3.1. Patch evolution

The patch evolutions are summarized in Fig. 2 with the same coordinate system and different color scale to indicate the concentration of SF6. The zero axis point is the location of the

![Fig. 3. (A) Temporal change of the patch area calculated from the contours in Fig. 2. (B) Temporal change of total amount of SF6 in the patch.](image-url)
center buoy. White plus mark shows the observation points for SF6. There were two high-concentration cores in the contours on Day 1 because the ship track was not straight during SF6 tracer release. The patch area was about 98 km² on Day 1. The patch area on Day 1 was a little larger than the initial area (64 km²). The patch area on Day 3 expanded to 172 km². The shape of patch extended to the south-west. The patch area on Day 4 reduced to 167 km². The reduction of area from Day 3 to Day 4 was probably due to the lack of the sampling points of SF6 concentration. The center GPS buoy moved out of the patch on Day 4 due to the strong wind shear affecting the part of the center GPS buoy protruding from the sea surface. The patch area on Day 5 expanded to 172 km². And the patch extended to the south-west to more than 20 km. The patch had two high-concentration cores. On Day 6, we reset the center buoy at approximately the center of the patch. The patch area at Day 7 expanded to 228 km². The shape of the patch stretched southward. There was a single high-concentration core in the patch on Day 7 due to the lack of the sampling points. On Day 9, the patch area expanded to 254 km². The shape of patch stretched to the south-west, and the maximum concentration was reduced to 10 fM. Two high-concentration cores were clearly shown in the patch on Day 9. The area of patch increased from 64 km² on Day 0 to 254 km² on Day 9. Fig. 3(A) shows the temporal change of area from Day 0 to Day 12 (Contour of Day 12 is shown in Fig. 8). The area of patch defined by the SF6 concentrations increased by horizontal diffusion and decreased by the loss of SF6 by air–sea gas exchange. The apparent area decreased from Day 9 to Day 12 due to the loss of SF6 by air–sea exchange. Fig. 3(B) shows the observed temporal change of total amount of SF6 in the patch. Horizontal distribution of SF6 concentration.

Fig. 4. Temporal change of the range of concentration of SF6 in the patch (values from all sampling points plotted).

Fig. 5. The movement of the center of patch for the first 22 days in relation to the sea-surface height contours. The points show Days 0, 1, 3, 4, 5, 7, 9, 12, 13, 14, 15, and 22, respectively from north to south.

Fig. 6. The behavior of the patch and buoy for the first 12 days. Diamonds show the movement of the center of patch. Color lines show the movement of the buoy. Each color indicates a different day.
concentration was obtained by the propeller survey (Fig. 2). Total amount of SF6 was obtained by multiplying the SF6 concentration, mesh area, and the MLD. Observed total amount of SF6 decreased by the loss due to air–sea gas exchange. The effect of the loss of SF6 tracer due to air–sea gas exchange was still negligible before Day 4, and increased after Day 9.

Observed SF6 concentrations in the patch are shown in Fig. 4. Maximum SF6 concentration was about 85.2 fM on Day 1. Maximum SF6 concentration in each day decreased to 8.3 fM on Day 12. Dilution rates from the initial SF6 concentration on Day 0 were roughly estimated to be 0.32, 0.18, 0.13, 0.11, 0.04, and 0.03 on Days 1, 3, 4, 5, 7, 9 and 12, respectively, in the center of the patch.

3.2. Patch movement

Fig. 5 shows the movement of the center of patch on the sea-surface height contour for 22 days. The sea-surface height map was obtained from the Colorado Center for Astrodynamics Research in the University of Colorado [http://argo.colorado.edu/~realtime/welcome/]. The iron patch moved south-westward at around 7.6 km d$^{-1}$ from Day 1 to Day 4 along the contour of sea-surface height in the clockwise eddy by geostrophic current, and moved south-eastward at around 14 km d$^{-1}$ from Day 4 to Day 5 due to the strong winds. After the strong winds, the patch moved southward across the contour of sea-surface height at around 5 km d$^{-1}$ to Day 9 and moved along the sea-surface height between two clockwise eddies with a lower speed.

The behavior of the patch and buoy for the first 12 days is shown in Fig. 6 to understand the patch movement in more detail. From Day 4 to Day 5, stronger easterly winds blew at a speed of over 14 m s$^{-1}$ (Fig. 7). The center buoy was dragged westward by the strong winds. The movement of the patch changed to a south-westward direction across the contour of the sea-surface height.

3.3. Comparison between SF6 and pCO2 patch

The pCO2 in surface sea water decreased due to the response of phytoplankton by iron fertilization. Iron was released two times on Day 0 and Day 6. The second iron fertilization was carried out on the area of the patch on Day 5 without monitoring the SF6 concentration and pCO2 signal. We compare the SF6 contour with pCO2 contour on Day 12 in Fig. 8 to confirm the overlap between the first and the second iron fertilizations. The pCO2 patch corresponded to the SF6 patch. Note that the pCO2 patch in the western area was caused by a natural bloom because there were no measurable SF6 concentrations in this area. The patch area defined by SF6 concentrations decreased to 154 km$^2$ because SF6 was lost from the ocean surface by air–sea gas exchange (Fig. 3(B)). The patch area defined by SF6 concentrations was smaller than the actual iron-fertilized patch area. The patch area defined by the pCO2 signal was about 684 km$^2$ on Day 12. After Day 12, the pCO2 measurement was employed for the propeller survey to define the center of patch.

Fig. 9 shows the evolution of the pCO2 patch on Days 12, 13, 14, 15, 17, and 22. The area of the pCO2 patch was 684, 942, 923, 1057, and 830 km$^2$ on Days 12, 13, 14, 15, and 22, respectively. The contours were not closed for Day 17. It is difficult to quantitatively understand the patch evaluation by the pCO2 signal. We found that the patch area increased from 64 to about 1000 km$^2$ over the

Fig. 7. Temporal change of (A) wind speed and (B) wind direction. Each color corresponds to the color of the day in Fig. 6.

Fig. 8. SF6 contours and pCO2 contours on Day 12 on the Lagrangian coordinate system based on the center buoy. Color contours show the SF6 patch. White lines show the pCO2 patch. Yellow points show the sampling points of pCO2 every minute. The sampling points of SF6 were every 6 min. Zero axis is the location of the center buoy.
The maximum biomass of phytoplankton was observed between Days 12 and 13 (Tsuda et al., 2007).

### 3.4. Mixed-layer depth

The MLD during the experiment is one of the important factors to determine the response of phytoplankton to the iron fertilization (de Baar et al., 2005). The MLD just after iron fertilization was 28 m. Fig. 10 shows the temporal change of the MLD, which increased to 33 m between 5 and 8 days after the iron fertilization. After that, the MLD decreased to 20 m between Days 9 and 13, and then increased to 28 m between Days 15 and 19. Finally, the MLD decreased to less than 15 m.

### 3.5. Vertical profile of SF6 concentrations

All the vertically stratified water samples for SF6 analyzed by a CTD-Carousel multi-sampling system on R.V. Hakuho-Maru were unfortunately contaminated. Atmospheric SF6 concentration in R.V. Hakuho-Maru was quite high during the cruise because the SF6 saturated water was made onboard. We acquired only one vertical profile of the SF6 tracer concentration on Day 17 by the sampling of R.V. Kilo-Moana. Fig. 11 shows the vertical profile of SF6 concentrations on Day 17. Maximum SF6 concentration was 22 fM at the depth of 30 m. Note that the iron concentration was low in the same sample water (Nishioka et al., 2009). SF6 concentration was lower in the surface layer due to the loss at ocean surface by air–sea gas exchange. By propeller survey it was not possible to trace the behavior of the patch after Day 12 but it was possible for more than 17 days when the water sampling was carried out from a deeper layer. SF6 concentrations below the MLD were the same as the background level.

### 3.6. Vertical shear

Fig. 12 shows the time series of the vertical shear, $|\frac{dV}{dz}|_{1,2}$, from 21 July to 29 July 2004. $|\frac{dV}{dz}|_{1}$ was calculated with velocities at a depth of 32.7 m ($V_{up}$) and 40.7 m ($V_{lo}$) and $|\frac{dV}{dz}|_{2}$ with those at a depth of 40.7 m ($V_{up}$) and 48.7 m ($V_{lo}$). The vertical shear was calculated using the following equation:

$$|\frac{dV}{dz}| = \sqrt{\left(\frac{dV}{dz}\right)^2 + \left(\frac{dW}{dz}\right)^2}$$
shear was strong from about 24 July, 22:00 to about 25 July, 3:00 when wind speeds were strong from Day 4 to Day 5 (Fig. 7).

Strong vertical shear due to the strong winds of Day 4–5 might have separated the surface mixed layer and deeper layer at the depth of 30 m. We supposed that this strong vertical shear might have separated the iron-fertilized water mass vertically from the deeper water, which would have some particulate iron exported from the surface mixed layer. As a result, SF$_6$ concentrations below the MLD were the same as the background level on Day 17 (Fig. 11).

4. Discussion

4.1. Apparent horizontal diffusion coefficient

Decrease of SF$_6$ concentrations in the patch was caused by horizontal diffusion, vertical diffusion and air–sea gas exchange. The apparent horizontal diffusion coefficient includes all three factors. Horizontal diffusion was larger than other two factors. Apparent horizontal diffusion coefficient in SEEDS II was estimated from the second moment of the patch distribution, $W_r^2$, based on the distance from center of patch to compare with SEEDS. On the other hand, Martin et al. (2001) employed the distance from the center of a mesoscale eddy. In SEEDS II, the distance from the center of the mesoscale eddy was not employed because the patch movement was affected by both geostrophic current and wind stress.

The second moment of the patch distribution, $W_r^2$, versus time is shown in Fig. 13. Diffusion coefficients were calculated from the slope of $W_r^2$. The apparent horizontal diffusion coefficient in SEEDS II was estimated to be $4.9 \times 10^7$ m$^2$s$^{-1}$. The dispersion of $W_r^2$ values during SEEDS II was large for the radius from center of patch. The estimated minimum and maximum apparent horizontal diffusion coefficients were 2.3 and $13 \times 10^7$ m$^2$s$^{-1}$, respectively. Uncertainty for the estimation of apparent horizontal diffusion coefficients was large because the patch structure was not circular. Apparent diffusion coefficients in SEEDS were estimated to be $9.0 \times 10^7$ m$^2$s$^{-1}$ before Day 10 and $5.0 \times 10^7$ m$^2$s$^{-1}$ from Day 10 to Day 12 (Tsumune et al., 2005). Note that the effect of the loss of SF$_6$ tracer due to air–sea gas exchange was large on the apparent diffusion coefficient after Day 10. The minimum apparent horizontal diffusion coefficient during SEEDS II was larger than the one during SEEDS. Larger diffusion coefficient was one of the disadvantages to maintain high iron concentrations in the patch. This was one of the reasons why chlorophyll-a concentration in SEEDS II was smaller than SEEDS.
4.2. Vertical structure

The MLD during SEEDS II was deeper than the one of SEEDS, which was 8.5 m (Tsuda et al., 2005). The initial SF6 concentrations in SEEDS II were lower than the concentrations during SEEDS because the surface mixed layer in SEEDS II was deeper than the one in SEEDS. This also was one of disadvantages to maintain the high iron concentrations during the experiment. de Baar et al. (2005) summarized the relationship between maximum chlorophyll-a concentration and the MLD. Initial MLD at the iron fertilization in SEEDS II was 28 m and maximum chlorophyll-a concentration was 2.8 μg L⁻¹. Maximum chlorophyll-a concentration was lower than the estimated value of 5.6 μg L⁻¹ by the empirical equation of de Baar et al. (2005). This difference may suggest an alternative cause of low accumulation of phytoplankton biomass, such as mesozooplankton grazing (Tsuda et al., 2007).

Fig. 14 shows the temporal change of the MLD in comparison with the temporal change of chlorophyll-a concentration during SEEDS II. The MLD just after the first iron fertilization was 28 m. The MLD increased to 3.3 m between Day 4 and Day 6. Increase rate of the MLD was about 2.5 m day⁻¹ during Days 2–4. Iron concentrations decreased due to the strong vertical mixing and were lost from the surface mixed layer due to the enhancement of cohesion and sedimentation (Nishioka et al., 2009). The chlorophyll-a concentrations increased but the response was not so large (Tsuda et al., 2007). Therefore, the second iron fertilization was carried out on Day 6. In the period between Days 8 and 10, the surface MLD was shallow, the Fv/Fm was high and the grazing pressure was moderate (Tsuda et al., 2007). On the other hand, increase of chlorophyll-a concentration was small after the second iron fertilization. The effect of large horizontal diffusivity may be large to reduce the iron concentration and response of phytoplankton. After Day 10, grazing pressure increased (Tsuda et al., 2007). After Day 12, the surface MLD increased with a rate of 2.0 m day⁻¹. After Day 13, the decrease of the Fv/Fm and dissolved iron concentration indicated iron deficiency (Tsuda et al., 2007; Nishioka et al., 2009). The processes after Day 10 indicate that the bloom was effectively terminated. Temporal change of the MLD corresponds to the temporal change of chlorophyll-a concentration. On the other hand, the MLD was 8.5 m during SEEDS and gradually increased to 18 m over 12 days (Tsume et al., 2005). The rate of increase of the mixed layer was about 0.6 m day⁻¹ during SEEDS. It was about 25% observed rate in SEEDS II. The rate of increase of the mixed layer in the first period of iron-fertilization experiment directly affected the dilution rate of iron in the patch. We suppose that a smaller rate of increase of the MLD might have enabled the large response of phytoplankton in SEEDS. Temporal change of the MLD was also important for the response of phytoplankton by iron fertilization.

5. Conclusions

We traced the iron-fertilized patch for 22 days by monitoring the SF6 concentration before Day 12 and the pCO2 signal after Day 12. Comparisons between SEEDS II and SEEDS are summarized in Table 1. The horizontal structure of the iron-fertilized patch in SEEDS II was more complex than the one for SEEDS. There were two high-concentration cores in the SEEDS II patch because the ship track was not straight during the iron and tracer release. The iron-fertilized patch moved by geostrophic current along the sea-surface height and strong wind shear occurred on Day 4 to Day 5 in SEEDS II. The strong wind moved the patch away from the geostrophic current. On the other hand, the patch of SEEDS moved along the contour of sea-surface height without being significantly affected by strong winds (Tsumune et al., 2005). Patch behavior in SEEDS II was more complex than SEEDS.

Mixed-layer depth in SEEDS II was deeper than SEEDS, and the rate of increase of MLD in SEED II was larger than SEEDS. These were disadvantages to maintain the high iron concentrations in the surface layer in SEEDS II. Temporal change of the MLD corresponded to the response of phytoplankton. Apparent diffusion coefficient in SEEDS II was larger than SEEDS. Larger

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<tr>
<td>Change of mixed layer depth</td>
<td>Increase (1.0 m day⁻¹)</td>
</tr>
<tr>
<td>Apparent diffusion coefficient</td>
<td>4.9 × 10⁻² m² s⁻¹ (minimum value: 9.0 m² s⁻¹ before Day 10)</td>
</tr>
</tbody>
</table>
diffusivity in SEEDS II was also one of the physical disadvantages to maintain the high iron concentration and high phytoplankton biomass compared with SEEDS.

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References


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