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Variability in Mineral Dust Deposition over the North Pacific and Its Potential Impact on the Ocean Productivity

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Introduction

Deposition of wind-blown mineral dust particles, such as Asian dust, has been supposed to enhance oceanic phytoplankton growth, since they contain iron that serves as one of the micronutrients. Particularly for "high-nutrient low-chlorophyll (HNLC)" waters, where iron is considered to be a limitation factor for phytoplankton growth, one may expect that a significant amount of dust deposition to the ocean surface induces an increase in chlorophyll-a concentration.

In an attempt to assess the latent "iron-enrichment" effect caused by mineral dust input to the ocean, this study firstly compares the North Pacific mineral dust deposition estimates derived from the Spectral Radiation-Transport Model for Aerosol Species (SPRINTARS) with SeaWiFS-derived chlorophyll-a concentration (chl-a, henceforth) over the last decade. There are various factors which controls phytoplankton growth, and in order to minimize the variability in those factors resulting from different temporal and spatial conditions, we partition the North Pacific into about 200 subareas to conduct a regression analysis between dust deposition and chl-a for each subarea and for the same season (more specifically, month) of the year.

Secondly, we conduct a similar analysis on the Japan Sea data sets of SPRINTAR-based dust deposition, and satellite-derived chl-a, in consideration to the study of Jo *et al*. (2006). They noticed wet deposition of mineral dust particles, and reported that the wet deposition contributes to quickening the spring bloom at two study areas in the mid and north Japan Sea. While their wet deposition was based on the TOMS Aerosol Index (AI) and meteorological precipitation data, we use the SPRINTAR-derived wet deposition estimate, leading to a rather different conclusion.

Data and Methods

Mineral dust deposition data

SPRINTARS is a numerical model that has been developed for simulating the effects on the climate system, and the condition of atmospheric pollution, by atmospheric aerosols on the global scale (Takemura *et al*. 2000, 2002, 2005). Based on an atmospheric general circulation model developed by CCSR (Center for Climate System Research Center), NIES (National Institute for Environmental

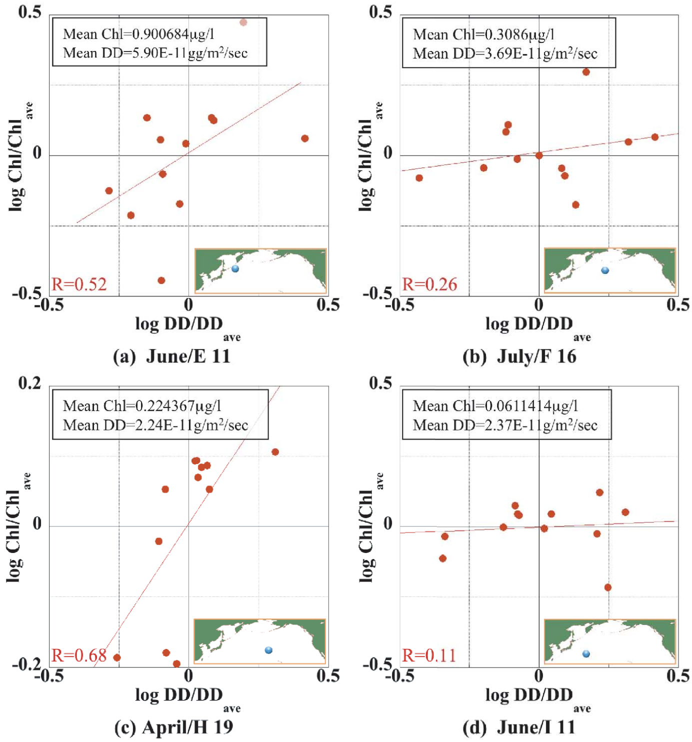

Fig. 1. Examples of areal month-wise comparison between SPRINTARS-derived monthly averages of dust deposition and of SeaWiFS-derived monthly average chl-a concentration.

Studies), and FRCGC (Frontier Research Center for Global Change), it treats main tropospheric aerosols of both natural and anthropogenic sources and calculates the transport process of aerosols, including dry and wet deposition. For this study, we used a monthly and weekly average of mineral dust deposition data with a horizontal resolution of 1.125 degrees in latitude/longitude.

Satellite-derived chlorophyll-a data

The Sea-viewing Wide Field-of-View Sensor (SeaWiFS) was operated in orbit from August 1997 through December 2010, conducting ocean global color observation with a spatial resolution of 4 km by 4 km to produce standard Level 3 chl-a concentration data with a 9-km spatial resolution. In this study, monthly average chl-a data over September 1997 through February 2010 was used.

Analysis on the North Pacific Data Set

Data processing

We partitioned the North Pacific Ocean (20°–69°N) into subareas of 4° by 4° in latitude/longitude and prepared areal averages of the dust deposition and chl-a data. Then, to avoid a seasonal dependency effect, area-wise monthly data of the same month of the year were collected and subjected to a regression analysis. That is to say, each area-wise regression analysis of the dust deposition data of the month was conducted against chl-a data of the same month of the years 1998–2010 for the

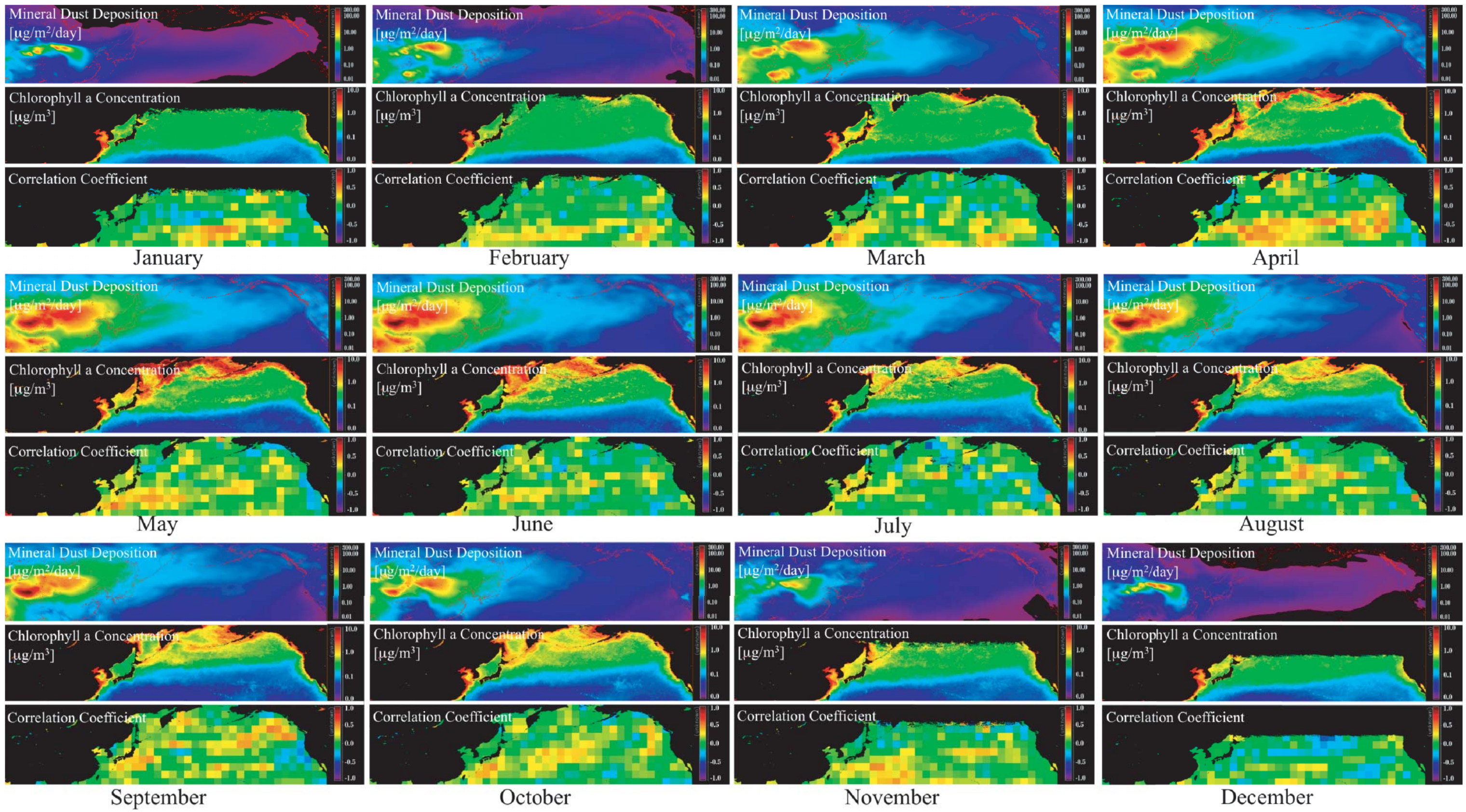

Fig. 2. Comparison between monthly average mineral dust deposition and chl-a concentration over the 1997–2010 period, with their areal time series correlation for each month. Mineral dust deposition was derived from the SPRINTARS model, while chl-a was derived from the SeaWiFS standard product.

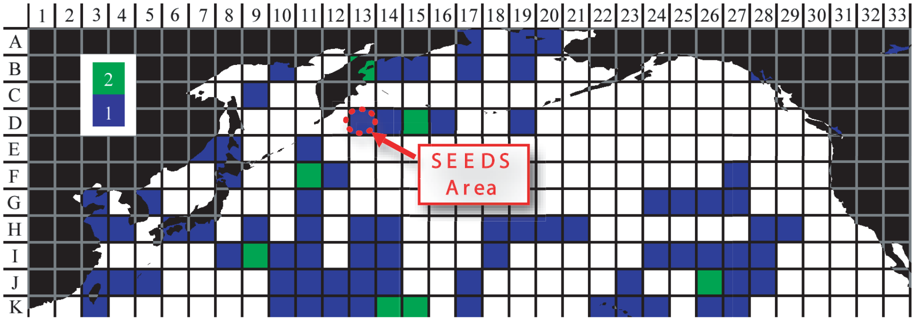

Fig. 3. Areas of "higher correlation" over April–July. Areas with high correlation are found more along the TZCF (transition zone of chlorophyll front) than in the sub-arctic HNLC area.

North-Pacific study, while weekly (or "8-day", precisely) average Level 3 chl-a data was used in the Japan Sea study.

Examples of areal data distribution

To give some insight into the variability of dust deposition and chl-a data, scatter diagrams of monthly-averaged dust deposition and chl-a concentration for selected areas are shown in Fig. 1. Each data point is a pair of average dust deposition and chl-a for the area and for the month, for a particular year. As an example, Fig. 1(a) is a June result for the area near the southern tip of Kamchatka peninsula (Row E and Column 11 area in Fig. 3), showing factorial deviation around the average in dust deposition (abscissa) and in chl-a concentration (ordinate). Since the plot is in a log scale, the range in dust deposition (or in chl-a concentration) covers $10^{-0.5}$~$10^{0.5}$ factorial variability. Thus, the areal average of chl-a concentration varies from about 0.3~3.0 μg/l level, for this area in June.

Among other areas, Fig. 1(b) shows another case of an HNLC area ("F-16" area in Fig. 3) while panels (c) and (d) correspond to the so-called Transition Zone of Chlorophyll Front (TZCF) areas ("H-19" and "I-11"). Note that the correlation coefficient significantly varies depending on the area and the month.

Areal correlation map

The month-wise areal correlation distribution is shown in Fig. 2, where the average dust deposition [μg/m^2/day] and chl-a concentration [μg/l] are also shown. In terms of mineral dust deposition, the amount remains a minimum during the November–February period. Otherwise the amount ranges between 0.1 to 5 μg/m^2/day, and the deposition is widely spread over the North Pacific. For SeaWiFS-derived chl-a, a strong front line is observed in the 20°–40°N area, corresponding to TZCF.

The distribution of the area-wise correlation between dust deposition and chl-a also changes significantly with season. Although one may expect a high correlation in the sub-arctic HNLC region (around 45°N), more areas with an even higher correlation ($R > 0.4$) are found in the temperate TZCF. This can be interpreted as a "wind effect", i.e. the wind works in favor of both dust transportation, and mixing, in the upper ocean layer. It should be noted that the correlation coefficient is not necessarily high in the HNLC areas throughout the year: there are even some areas that have negative correlation coefficients.

If dust deposition is to contribute to phytoplankton growth, the slope of the regression should be significantly positive. Hence, we conducted a statistical significance test (t-test) for the positivity of the

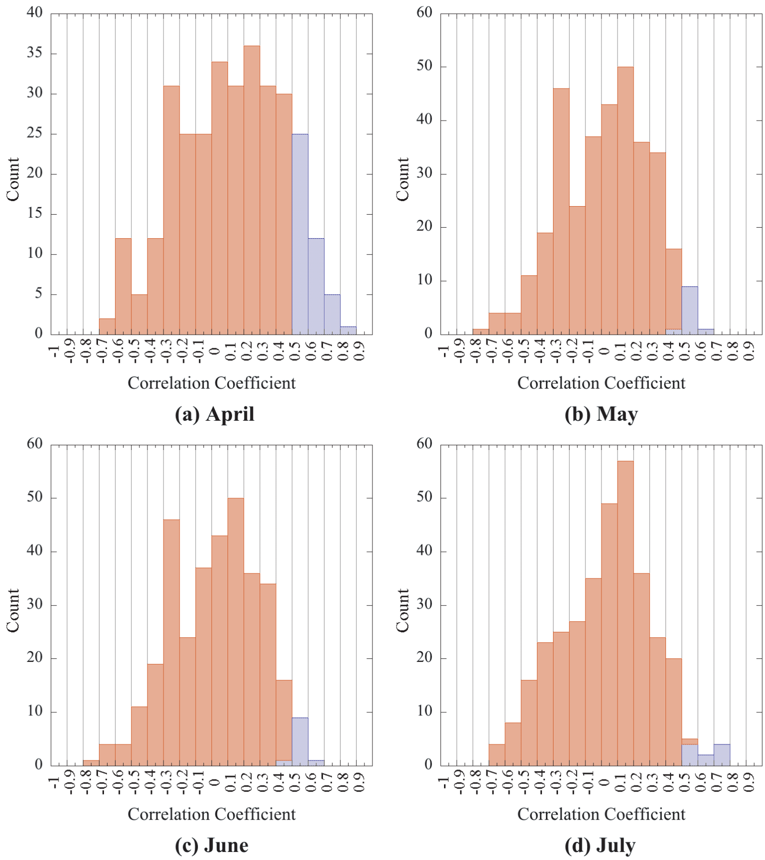

Fig. 4. Frequency distribution of month-area-wise correlation. The blue bars correspond to the areas with a statistically significant positive correlation.

regression slope for each area/month. Note that this test is equivalent to the one for the "positivity of the correlation coefficient." Figure 3 summarizes the area-wise result for the April–July data altogether, where green areas (blue areas) mean that the slope recorded a 5% statistically-significant positivity twice (once). As shown in the figure, it is clear that there are much more "significantly-high slopes" instances in the TZCF area, although some HNLC areas also record significantly positive slopes.

Frequency distribution of areal correlation

The value of the areal monthly correlation coefficient varies from almost –1.0 to +1.0, and we are interested in the distribution of the coefficients. Figure 4 depicts the month-wise frequency distribution of the areal correlation for April through July, the typical period for the seasonal phytoplankton bloom. In April (Fig. 4(a)), the number of areas with a statistically-significant positive correlation (blue bars) occupies 14% of the total area, which is the maximum through all months of the year. It is also noticeable that the frequency distribution is more weighted on the positive side, although in December, January and February, the weight moves into the negative correlation area, suggesting the pres-

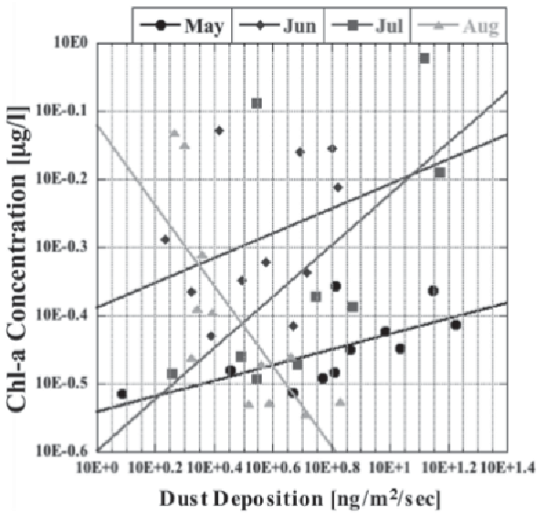

Fig. 5. Dust deposition vs. chl-a concentration in the SEEDS/SEEDS-II area over May–August.

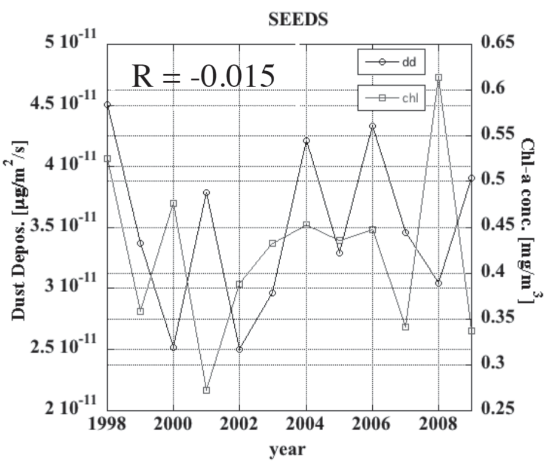

Fig. 6. Annual time series of model-predicted dust deposition and satellite-derived chl-a concentration.

ence of some mechanism other than "iron enrichment". The grand average of the areal correlation coefficients is a slightly-positive value of 0.033.

Discussion on the North Pacific data analysis

Figure 5 shows the scatter diagram of the monthly/areal average chl-a concentration vs. that of the SPRINTAR-derived dust deposition over the SEEDS/SEEDS-II area (Tsuda *et al*. 2007) for the May–August period. Note that while the May–July regressions show positive correlations, the August case does not. Other instances with a negative correlation are of-

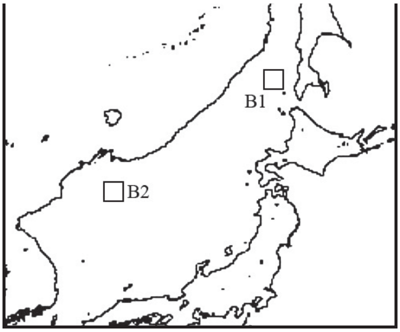

Fig. 7. Study area. B1: near Wakkanai, B2: near Chongjin.

ten found in the typical HNLC waters, clearly suggesting that dust deposition does not contribute directly to the blooming. On the other hand, the varying correlation factors may be considered due to the fact that the iron in the dust particle is not in a soluble form, necessitating a fairly long time before the particulate iron changes itself into that which can be easily utilized by phytoplankton. Hence, taking the SEEDS/SEEDS-II area, we reanalyze the data to compare the two time series of the annual average chl-a concentration and that of the model-predicted dust deposition. The result, however, does not show any statistically-significant correlation, as shown in Fig. 6. It is also noted that there is no obvious tendency that a higher chl-a is preceded by a higher average dust deposition.

From these discussions, we consider that the dust deposition for the North Pacific does not contribute directly, or on a short time scale, to phytoplankton blooming, in the sense that the effect is rather invisible.

Analysis on the Japan Sea Data Set

Objectives

Jo *et al*. (2006) reported that wet deposition of Asian dust particles contributes to quickening the onset of the spring blooms, by about one month, at two stations in the Japan Sea, even when the Mixed Layer Depth (MLD) is still deep. They estimate the days with a "wet dust event" from TOMS/AI data in conjunction with precipitation data of local meteorological stations. In an attempt to verify their result, we conduct a similar analysis using a SPRINTAR-derived wet dust deposition estimate to compare the time series of satellite-derived chl-a concentration and of the model-derived wet dust deposition in the same study areas as those of Jo *et al*. (2006).

Data processing and analysis

We used SPRINTAR-derived daily wet deposition (WDD) data to compose 8-day (or "weekly") averaged WDD data to spatially and temporarily collocate with the SeaWiFS Weekly Level 3 data over the Japan Sea, and over the study period from January, 1998, through December, 2002. Then, the time series of both WDD and chl-a were extracted at the specific location for comparison. In this report, we show the time series comparison result at the same locations as those studied by Jo *et al.* (2006).

Results and discussion

Figure 7 depicts the two study areas defined in Jo *et al.* (2006), while Fig. 8 reproduces their results. They stated that at B1 in 2001 and in 2002, as well as at B2 in 2001, the "wet dust event" occurrences had induced about a month-earlier bloom onset compared to other years. In comparison, Fig. 9 shows the SPRINTAR-derived WDD time series together with the SeaWiFS-derived weekly average chl-a transition. The MLD curve taken from Jo *et al.* (2006) is also shown for reference. Note that, in Fig. 9, the temporal axis is the "start day of the 8-day week", which is slightly different from that of Fig. 8. The chl-a curves look also different because Jo

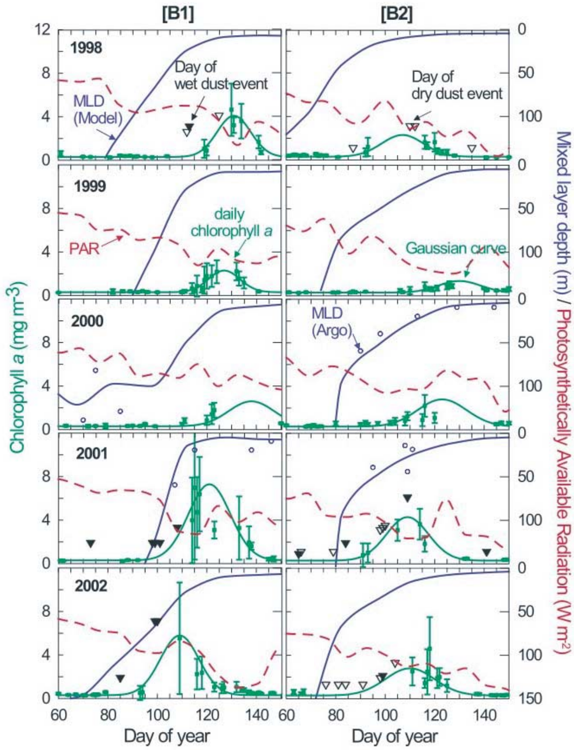

Fig. 8. Temporal variations of the daily and Gaussian curve-fitted chl-a concentrations (green lines), MLD from the ESROM (blue lines) and Argo (blue circles), PAR (red lines), and the days of wet (black triangles) and dry (white triangles) dust events. Error bars mean standard deviation of daily chlorophyll a concentrations. (Reproduced from Jo *et al.* (2006).)

et al. (2006) drops all the daily data obtained within a few days before, or after, the "dust event" predicted from the TOMS/AI data, based on their decision not to include dubiously high chl-a data potentially brought about by the optical effect of the Asian dust aerosol.

The two results given in Figs. 8 and 9 compare, in part, very well. In Fig. 9 at B1 in 2001, for example, a high WDD is observed at around day 70 when the MLD is quite deep, while chl-a reached its peak after day 115, corresponding well to the time series shown in Fig. 8. On the other hand, there are many differences in the two figures. Firstly, while Fig. 8 shows no WDD event in 1999 and 2000, significantly high WDD instances are present in both years. Secondly, Fig. 9 indicates that high WDD during a deep MLD period does not necessarily induce earlier bloom, or any bloom. For example, the high WDD at B1 in 2001 is observed at around days 80 and 100, associated with no quickened bloom onset, although the chl-a concentration after the bloom is high. A similar example is the case at B2 in 1999, where WDD is high at around day 70, but with no significant chl-a increase afterwards.

From these results, we consider that it is difficult to validate that wet dust deposition during the deep MLD period has any

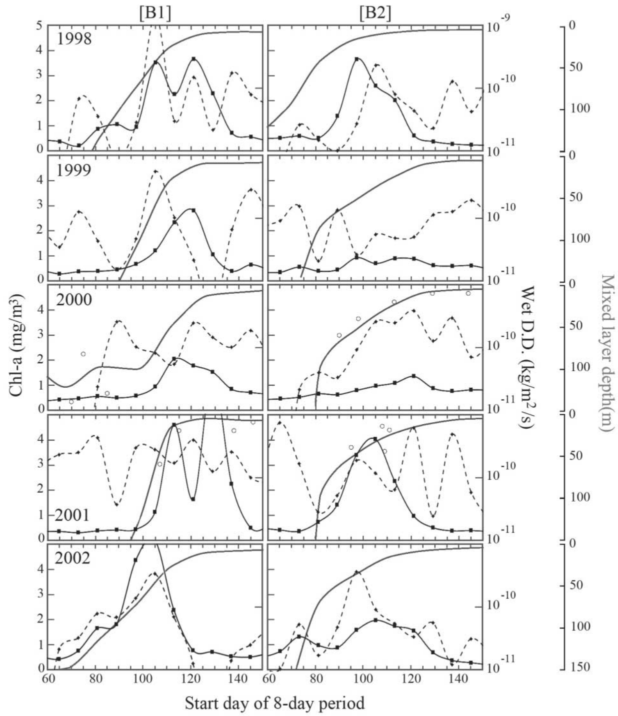

Fig. 9. Results of this study. Time series of weekly wet dust deposition (broken line), chl-a concentration (solid line), and mixed-layer depth (MLD) (gray solid line) taken from Jo *et al.* (2006).

direct and immediate effect on phytoplankton bloom.

Conclusion

As is well known, a high correlation does not always indicate an actual cause-effect relation, but, if dust deposition really contributes to phytoplankton growth, a significantly positive correlation would be observed. In that sense, our effort in this study can be regarded as a check as to whether this necessary condition holds, or not.

In this study, we firstly analyzed the north Pacific data set of satellite-derived chl-a and model-derived WDD concentrations, and we conducted area-month-wise regressions. To summarize the results, the overall percentage of month-areas with a 5% level statistically-significant positive regression slope is about 7%, with a maximum of 14% recorded in April. The grand average of the correlation coefficient is slightly positive, but the presence of a strongly negative correlation necessitates further study for some other physical processes regarding phytoplankton growth. On the contrary, the cause of the high correlation in the temperate TZCF region should be further studied. Although the possibility of iron limitation in the region cannot be denied at the present stage, one possible interpretation would be the inter-annual shift wind system that may affect nutrient conditions, as well as dust transport. On the other hand, the relatively-weak correlation in the HNLC areas suggests a rather-low efficiency of dust-transported iron to serve as a micronutrient for phytoplankton growth.

We analyzed a similar data set over the Japan Sea in an attempt to verify the result reported by Jo *et al*. (2006), who stated that the wet dust deposition to the Japan Sea could quicken the spring bloom onset by about one month. While their analysis was based on TOMS/AI and precipitation records, the current study with SPRINTAR-derived wet dust deposition does not positively affirm their statement.

Acknowledgements

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