

# Temporal Variation in Iron Flux Deposition onto the Northern North Pacific Reconstructed from an Ice Core Drilled at Mount Wrangell, Alaska

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## Abstract

To quantify the atmospheric iron deposition on the northern North Pacific region, we measured concentrations of iron in ice cores drilled at Mount Wrangell, Alaska, in 2003 and 2004. The iron concentration profile from 1981 to 2003 showed seasonal peaks each spring. This variation was similar to the seasonal variation in the concentration of mineral dust in the atmosphere in the North Pacific region. The annual iron fluxes calculated from the ice core records ranged from 3.2 to 27.0 mg m<sup>-2</sup> yr<sup>-1</sup>, and the temporal variation in the iron flux was significantly correlated with the frequency of severe dust storms occurrence on the East Asian continent ( $r = 0.65$ ,  $p < 0.05$ ) and the total number of Kosa days observed in Japan ( $r = 0.64$ – $0.66$ ,  $p < 0.05$ ), but not with the precipitation amount in Alaska. We concluded that the amount of iron deposition onto the northern North Pacific is controlled mainly by the emission of dust from the east Asian continent and not by scavenging processes in Alaska.

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## 1. Introduction

Iron is an essential micronutrient controlling phytoplankton growth in the ocean, and several iron-enrichment experiments conducted in the subarctic Pacific Ocean have demonstrated this important role of iron (e.g., Tsuda et al. 2003; Boyd et al. 2004). Possible sources of the iron supplied to the surface water of the northern North Pacific are deposition of mineral dust from the atmosphere (e.g., Duce and Tindale 1991) and mesoscale oceanic intrinsic processes, such as vertical winter mixing and horizontal Fe-rich intermediate water transport (Nishioka et al. 2011). Several studies of mineral dust deposition using continuous multi-year observations have been conducted, especially in the Asian Continent and in Japan (e.g., Osada et al. 2011). However, in remote areas, where the main source of iron to the sea surface is atmospheric dust, only short-term or sporadic monitoring observations had been conducted (e.g., Uematsu et al. 1985). For the western side of North America, which is located downstream of Asian dust storms from the Asian Continent, studies on deposition of Asian dust are very limited. Zdanowicz et al. (2006) measured the insoluble dust concentration in snowpack on the surface of a glacier in the Yukon, Canada, during a major Asian dust event in 2001 and estimated the amount of dust deposition caused by the Asian dust event. Such studies of sporadic events have been reported, but continuous long-term monitoring data are scant.

Aerosols deposited onto the snow surface on top of a glacier

are preserved within the glacier unless summertime surface melting is significant. Therefore, profiles of chemical substances in ice cores obtained from glaciers are temporal records of deposited aerosols from the past to present. Alaska is located downstream of Asian dust flow, which is generated by strong winds in the Asian Continent and transported over the northern North Pacific. The iron profiles in ice cores obtained from alpine glaciers in Alaska can reflect temporal variation in iron deposition onto the northern North Pacific.

We obtained ice cores with lengths of 50 m and 212 m from Mount Wrangell in southern Alaska in 2003 and 2004, respectively (Shiraiwa et al. 2004; Matoba et al. 2014). Yasunari et al. (2007) showed seasonal variation in  $\delta D$ , tritium content, and insoluble dust in the 50-m ice core, and indicated that the insoluble dust showed peaks in spring and originated from Asian dust. In this study, we measured concentrations of iron in the ice cores obtained from Mount Wrangell, Alaska, reconstructed the annual deposition rate of iron onto the glacier, and examined the environmental factors controlling the amount of iron deposition.

## 2. Methods

### 2.1 Ice cores and drilling site

The drilling site of the ice cores was near the top of Mt. Wrangell, Alaska (62.00°N, 144.00°W, 4317 m, see Fig. 1). Mt. Wrangell is located in the Wrangell Mountains of southeastern Alaska. The glacier covers a caldera (6 × 4 km, 24 km<sup>2</sup>). We guess that the ice thickness at coring site is more than 500 m by topography around coring site (Shiraiwa et al. 2004). Yasunari and Yamazaki (2009a, 2009b) conducted analyses of backward trajectory of air mass to the coring site and showed that major air masses came from the North Pacific and adjacent continental regions, and that pollutants from spring Asian dust storms from east Asia and summer biomass burning from Siberia, Alaska and Canada can be easily transported. The 50.29- (ice core W03) and

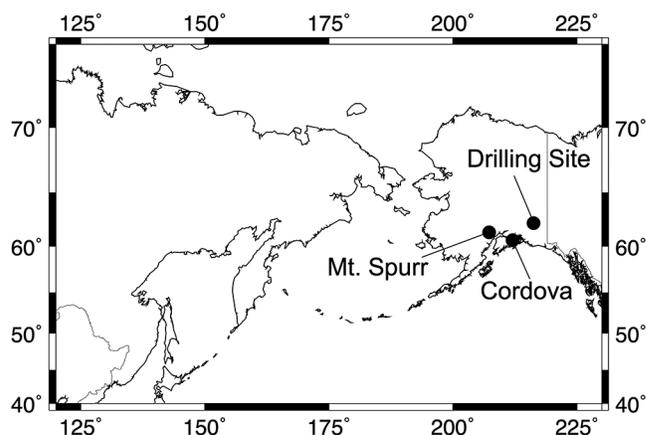


Fig. 1. Map of the observation site.

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the 216-m (ice core W04) depth ice cores were drilled in June 2003 (Shiraiwa et al. 2004; Matoba et al. 2014) and June 2004 (Kanamori et al. 2008), respectively. After drilling, the diameter, length, and weight of each segment of ice core were measured for density calculation. The density of the ice was used for calculation of the fluxes of chemical substances. The 10-m temperature in the borehole was approximately  $-18^{\circ}\text{C}$ , which corresponded to the annual mean air temperature at the drilling site. The annual snow accumulation rate estimated by a snow pit observation and in situ snow height observations by recording the burial times of temperature sensors mounted on a specially constructed tower during the accumulation year June 2005 to June 2006 was  $2.75\text{ m water equivalent yr}^{-1}$  ( $\text{m w.e. yr}^{-1}$ , Kanamori et al. 2008). The high accumulation at the drilling site allowed retrieval of high-temporal-resolution data. The ice cores were kept frozen and transported to Japan, where they were stored in the cold room at the Institute of Low Temperature Science, Hokkaido University.

## 2.2 Analysis and measurement of the iron concentration

In this study, we used ice core from 0 to 50.3 m from core W03 and 52.61 to 100.1 m from core W04. Thick volcanic ash layers were found at 47.1 m in core W03 and at 52.6 m in core W04. Yasunari et al. (2007) indicated that the ash layer in core W03 originated from an eruption of Mt. Spurr ( $61.30^{\circ}\text{N}$ ,  $152.26^{\circ}\text{W}$ ) in 1992. The ice core data from cores W03 and W04 were combined using the ash layer from Mt. Spurr as a chronostratigraphic marker to join to the two cores. The ice cores were divided lengthwise into four parts using a band saw. A sample of the four parts was used for measurement of iron concentration. The surfaces of the samples were shaved off gradually using a ceramic knife to remove contamination attached to the ice core surface. The width of the removed part of subsample surface was approximately 20 mm. Only the remaining center parts of the ice cores (diameter of 20 mm) were used for iron measurement. Vertical intervals of sampling were approximately 250 mm. All of these procedures were conducted on a clean bench in a cold clean room (class 10,000) at ILTS. The samples were melted in Teflon containers at ambient temperature and then poured into 15 ml polypropylene bottles, and acidified by 60% ultra-pure grade of nitric acid (Kanto Chemical), resulting in volumetric concentration of 1.0% acid. The acidified samples were still for more than one week until the concentration of acid-soluble iron was constant. We also confirmed that the concentrations of iron did not change 1 month later from the acidification. Then, the iron concentration was measured with a polarized Zeeman atomic absorption spectrophotometer (Hitachi model Z-2100). The analytical condition was general settings, and the detection limit was  $0.5\text{ }\mu\text{g L}^{-1}$ . The deposition rate of iron was calculated from the iron concentration of the sample and the length and density of the ice sample.

## 2.3 Dating

Dating of the ice cores was done by counting annual  $\delta\text{D}$  layers.  $\delta\text{D}$  showed clear seasonal cycles, with high (low) values in summer (winter) (Fig. 2b, Yasunari et al. 2007). We counted the winter (low  $\delta\text{D}$ ) layer as the start depth of each annual layer. The result showed that the interval from 0 m of core W03 to 100.1 m of core W04 corresponded to AD 2003 to AD 1979. We also determined the date of the ice core using the reference horizon of the visible dust layer at 26.824–26.873 m w.e. from the Mount Spurr eruption of 1992 (Yasunari et al. 2007).

## 3. Results and discussion

Figure 2a shows a profile of the iron concentration in the ice core. The iron concentration showed clear seasonal variation, with peaks in spring (firn/ice) layers and minimum values in summer (firn/ice) layers. The seasons were identified from the ice core layers using the seasonal variation in  $\delta\text{D}$  (Yasunari et al. 2007). The seasonal variation in iron concentration in the ice core is similar to the seasonal variations in the frequency of Kosa dust events observed in Japan (e.g. Arao et al. 2003) and sandstorms on

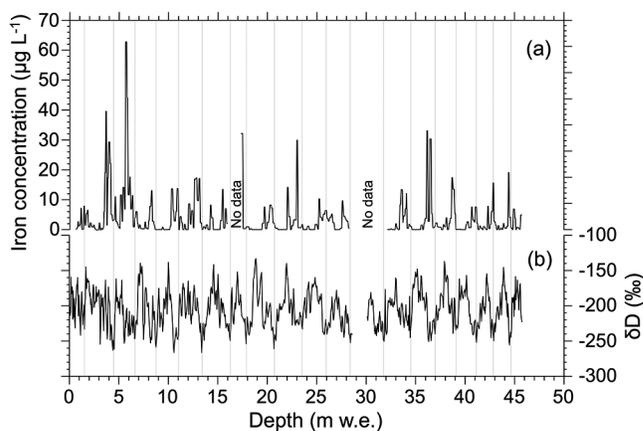


Fig. 2. (a) Iron concentration and (b)  $\delta\text{D}$  plotted against water equivalent depth. Thin lines indicate winter seasons as identified by seasonal variation in  $\delta\text{D}$ .

the Asian continent (Lim and Chun 2006), as well as the concentration of atmospheric dust in the North Pacific region (e.g., Duce and Tindale 1991). The iron concentration in the ice core showed remarkable peaks of more than  $60\text{ }\mu\text{g L}^{-1}$  at 3.8 m w.e. and 4.0 m w.e. The ice core ages of these peaks were AD 2002 and AD 2001, years when major Kosa dust events were observed in Japan and East Asia (e.g., Jaffe et al. 2003). Therefore, iron in the ice core must have originated from Asian dust.

The broad iron peaks in the ice core revealed several events in each year. Therefore, we assumed that the concentration of iron in the atmosphere over Mount Wrangell increases during a certain period of spring and that the iron is removed from the atmosphere by precipitation, which deposits it onto Mount Wrangell.

We calculated the annual iron flux to assess the iron profile of the ice core quantitatively (Fig. 3). The highest annual iron fluxes were  $18.2\text{ mg m}^{-2}\text{ yr}^{-1}$  (2002) and  $27.0\text{ mg m}^{-2}\text{ yr}^{-1}$  (2001). Excluding the years for 2001 and 2002, the annual iron flux was in the range of  $3.2\text{--}15.1\text{ mg m}^{-2}\text{ yr}^{-1}$ . This value is consistent with the annual iron fluxes over the North Pacific reported by previous studies (e.g., Duce and Tindale 1991; Jickells et al. 2005).

First, we compared the annual iron flux of the ice core with dust emission events in the East Asian continent. Lim and Chun (2006) divided the 11 types of dust phenomena in a GTS SYNOP report (WMO 1974) into three groups (Floating dust: FD, Blowing sand: BS, and Dust storm: DS, in order of strength), and reported the temporal variation and spatial distribution of each of the three types of dust phenomena from 1993 to 2003. The annual iron flux was correlated with only the annual frequency of DS ( $r = 0.65$ ,  $p < 0.05$ ,  $n = 11$ ). Therefore, the frequency of larger dust events, after long transport over the North Pacific, was correlated quantitatively with recorded iron in the studied ice cores.

Second, to clarify the relationship between dust transportation over Pacific ocean and dust deposition on Alaska, we compared the annual iron flux of the ice core with the dust phenomena during transport from the Asian continent to Alaska. The Japan Meteorological Agency (JMA) defines Kosa as aeolian dust uplifted by frontal activity from the semi-arid areas of the East Asian continent and transported to Japan by westerly winds. JMA certifies Kosa days when dust, including Asian dust, is visually observed in the atmosphere at any of 59 meteorological stations. The annual total number of Kosa days is the total number of stations at which Kosa is observed in a year. The annual total number of Kosa days reflects the frequency of Kosa as well as the spatial extent of one Kosa dust event. There was also a significant correlation between annual iron flux and the total number of Kosa days ( $r = 0.64$ ,  $p < 0.05$ ,  $n = 11$ , 1993–2003;  $r = 0.66$ ,  $p < 0.05$ ,  $n = 22$ , 1981–2003).

This correlation indicates that severe dust events in the Asian continent, which are observed as Kosa in Japan, can transport

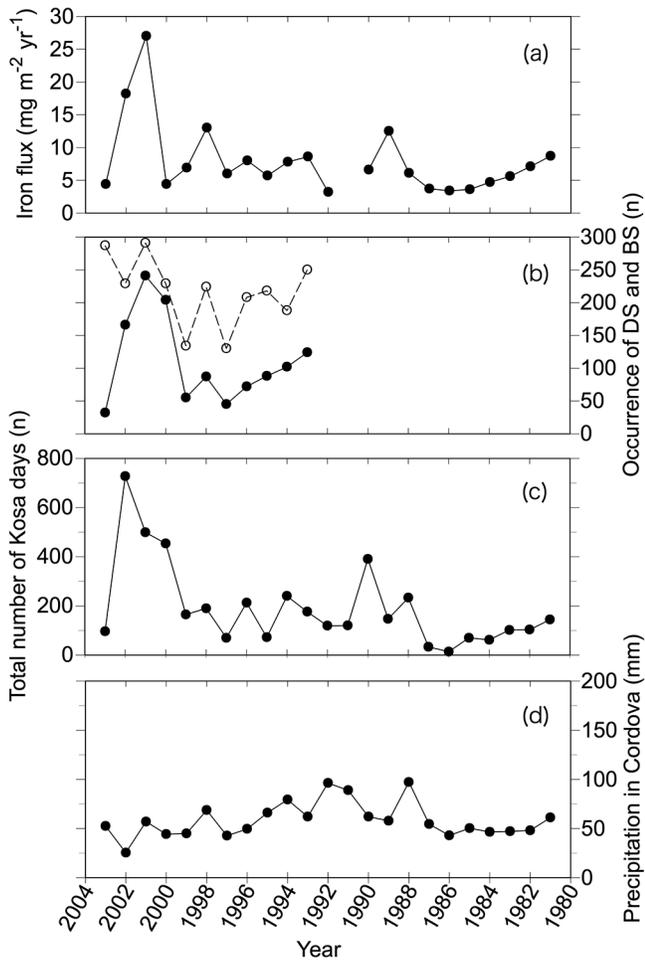


Fig. 3. (a) Temporal variation in annual flux of iron in the ice core, (b) frequency of occurrence of Blowing sand (BS; dashed line) and Dust storm (DS; solid line), as defined by Lim and Chun (2006), (c) total number of Kosa days, and (d) precipitation amount at Cordova.

Asian dust to Alaska across the northern North Pacific. As mentioned above, the concentration of iron in the atmosphere over Mount Wrangell increases during a certain period in every spring.

Third, we investigated the relationship between the iron flux in the ice core and the precipitation that mainly affects wet deposition of aeolian dust from the atmosphere. Osada et al. (2011) reported that the wet deposition of Asian dust in Japan is affected by the frequency of precipitation during dust seasons. Figure 3d shows the temporal variation in the precipitation amount during spring (February to March) observed at the Cordova station from the GHCN-Daily dataset (Manne et al. 2012). The timing of snowfall at Mount Wrangell correlated well with the precipitation record at Cordova (Kanamori et al. 2008). However, the iron flux was not correlated with the precipitation amount at Cordova (FMA:  $r = -0.26$ ,  $P > 0.05$ ,  $n = 22$ , MAM:  $r = -0.03$ ,  $P > 0.05$ ,  $n = 22$ ). Consequently, the iron flux is controlled quantitatively by the amount of mineral dust emitted by severe dust storms on the East Asian continent, but does not depend on wet scavenging processes in Alaska.

#### 4. Concluding remarks

We measured concentrations of iron in ice cores obtained from Mount Wrangell, Alaska, and reconstructed annual iron fluxes. The annual iron fluxes from 1981 to 2003 ranged from 3.2 to 27.0  $\text{mg m}^{-2} \text{yr}^{-1}$ .

Nishioka et al. (2011) explained that iron is supplied constantly from the middle layer to the surface layer of the North Pacific Ocean by upwelling and that atmospheric iron is supplied in the short-term and/or intermittently by sporadic dust events. However, the results of this study showed that the iron flux is controlled mainly by the emission amount of dust from the East Asian continent and does not depend on irregular wet deposition. The atmospheric iron was deposited constantly, 3.2–15.1  $\text{mg m}^{-2} \text{yr}^{-1}$ , even in years other than 2001 and 2002, when remarkable severe dust events occurred. If 3.2–15.1  $\text{mg m}^{-2}$  of atmospheric iron was deposited onto the eastern subarctic Pacific (Station Papa), where winter maximum of mixing layer depth (MLD) is 80 m (Nishioka et al. 2001), and is dissolved with 1.2–2.2% solubility (Ooki et al. 2009) without any effects of scavenging processes in ocean, concentration of dissolved iron in MLD from atmospheric iron is 0.009–0.075 nM, corresponding to 8.2–68% of dissolved iron concentration in winter MLD. This speculation includes uncertain factors of solubility and residence time of dissolved iron in ocean, and further studies are needed for precise quantitative estimation of the effect of atmospheric iron on ocean ecosystem.

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