SOLA, 2009, Vol. 5, 077-080, doi:10.2151/sola.2009-020

Origins of Air Masses over an Alaskan Glacier and Implications for Ice Core Studies in the North Pacific Region

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Abstract

Simulations of 10-day backward trajectories of air masses from Mount Wrangell, an Alaskan ice core site, were calculated for 11 years on a daily basis. Results were analyzed statistically in order to interpret monthly air mass contributions over the ice core site and to discuss implications for ice core studies in the North Pacific Region (NPR).

Increases in tropospheric air mass transport from EA in spring suggest favorable transport conditions for Asian dust during this season. The stratospheric air mass (< 300 hPa) over the ice core site increases in winter and that from East Asia (EA) to the North Pacific Ocean in late spring. The tritium peaks observed in the ice core in late spring were discussed in the context of the present results with two possibilities on the time lag of tritium transportation in the stratosphere and the seasonal variations of water vapor amount in the troposphere. Increases in air masses originating from Siberia, Alaska and Canada in summer-fall favor the transport of black carbon due to forest fires over the ice core site. These results allow advanced interpretation of the origin and transport processes of materials in the ice core proxies in the NPR.

1. Introduction

The North Pacific Region (NPR) is subject to seasonal variation in pollutants in the troposphere, such as Asian dust outbreaks in spring and black carbon from wildfires in summer in boreal forest regions such as Siberia, Alaska and Canada (e.g., Sun et al. 2001; Langmann et al. 2009). The trans-Pacific transport of aerosols including Asian dust and black carbon is well known (e.g., Darmenova et al. 2005; Hadley et al. 2007). In addition, stratospheric material intrusions into the troposphere associated with Asian dust storms in East Asia have also been discussed (Kim et al. 2002; Yasunari et al. 2007; Yasunari and Yamazaki 2009). Therefore, the NPR is an important region for understanding material circulation.

Ice cores provide direct information on past atmospheric material concentrations. Several ice cores have been drilled so far in the NPR. These ice core sites are Mount Logan (Holdsworth et al. 1992; Shiraiwa et al. 2003) and Eclipse ice field (Wake et al. 2002), Canada, Mount Ushkovsky and Mount Ichinsky, Russia (Shiraiwa et al. 2001; Matoba et al. 2007) and Mount Bona Churchill (Zagorodnov et al. 2005) and Mount Wrangell, Alaska (Shiraiwa et al. 2004; Yasunari et al. 2007). The ice cores at Mt. Logan, Mt. Wrangell, Mt. Bona Churchill and Eclipse ice field can be used to assess the variations in the trans-Pacific transport of materials in the NPR. The ice core sites are located close together in the NPR and synoptic weather changes may affect their sites simultaneously. However, it is difficult to directly obtain air mass and material origins from ice core proxies. Therefore, understanding the origins of transported air masses at the ice core sites in the NPR is essential, with implications for the interpretation of ice core proxies.

This study focuses on the Mount Wrangell ice core site, which is considered as a representative ice core site in the NPR, to investigate and discuss monthly air mass origins in this region. Although there have been some statistical trajectory analysis studies for understanding suspended material origins in the Alaskan atmosphere (e.g., Polissar et al. 1999), there have been few focusings on the NPR ice core sites for more than 10 years. In this study, useful information is provided for understanding monthly-seasonal air mass transport patterns over the Alaskan ice core site by statistical trajectory analysis, leading to progress in the interpretation of ice core proxies in the NPR.

2. Statistical backward trajectory analysis

A 10-day backward trajectory analysis was performed on a daily basis in order to understand the air mass origins over the ice core site of Mount Wrangell from 1992-2002 (11 years), the period over which the ice core extends (Yasunari et al. 2007). This trajectory model was constructed based on the Lagrangian tracking method (Yamazaki 1986). The validity of this trajectory model was verified in the case studies (Yasunari et al. 2007; Yasunari and Yamazaki 2009). A 10-day period was chosen as long enough for Asian dust to reach the site based on the result of Yasunari et al. (2007) (see supplementary text). Three-dimensional wind data from the ECMWF operational analysis data (2.5° × 2.5° horizontally; 15 layers vertically from Jan. 1992 to Mar. 1999 and 21 layers after Apr. 1999) for 01/1992-12/2002 were used for the calculations. The top level of the data is 1 hPa. The wind was linearly interpolated in the horizontal direction and interpolated with a cubic spline function in the vertical direction over time. Initial air parcels were set in the region 143.02°W-145.02°W, 60.59°N-62.59°N and 500-700 hPa in pressure level. This initial region (Wrangell Area) covers the

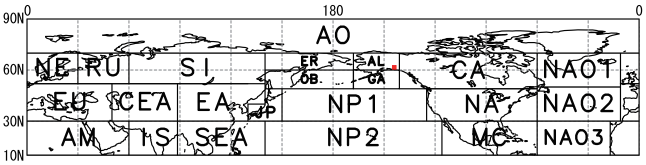

Fig. 1. Defined areas for the trajectory calculations (AO: Arctic Ocean; NE: Northern Europe; RU: Russia; SI: Siberia; ER: Eastern Russia; AL: Alaska; OB: Okhotsk & Bering Seas; GA: Gulf of Alaska; CA: Canada; NAO 1: North Atlantic Ocean 1; EU: Europe; CEA: Central Asia; EA: East Asia; JP: Japan; NP 1: North Pacific 1; NA: North America; NAO 2: North Atlantic Ocean 2; AM: Africa & Middle East; IS: Indian Sector; SEA: Southeast Asia; NP 2: North Pacific 2; MC: Mexico & Caribbean Sea; NAO 3: North Atlantic Ocean 3; OA: Other Areas including all areas other than those shown in Fig.1). The right and left edges at 0 degrees are connected. The red square denotes the initial region in the calculations (Wrangell Area).

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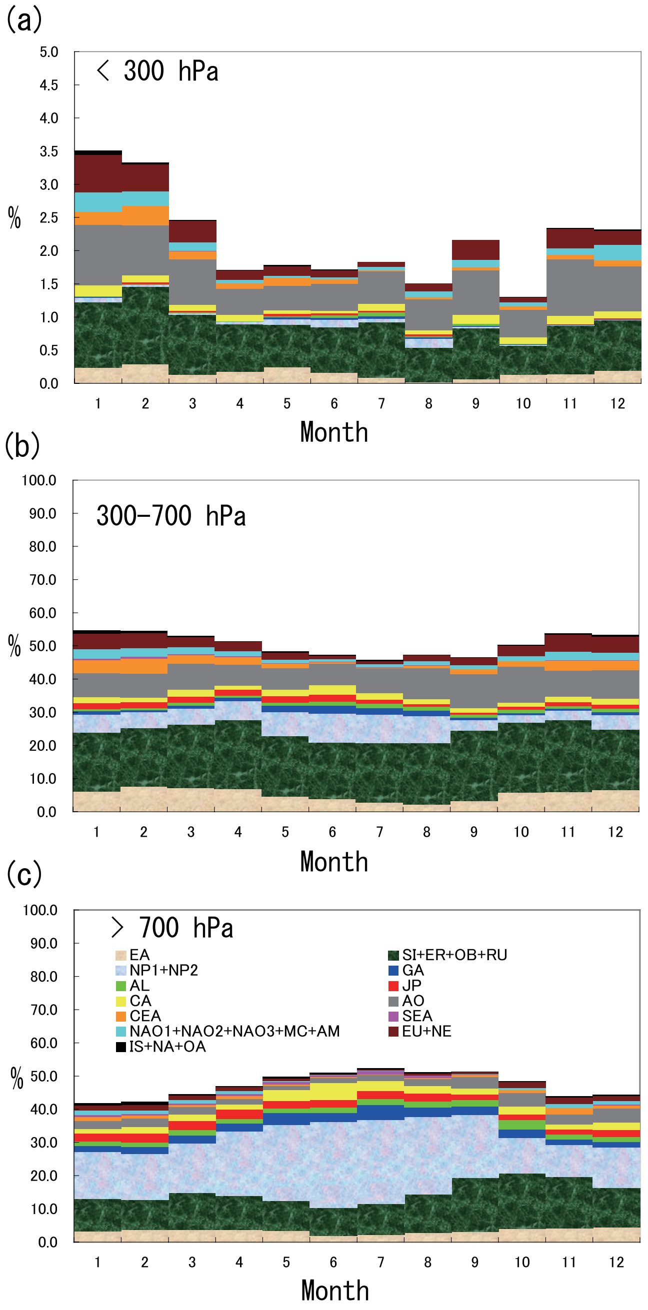

Fig. 2. Percentage of monthly mean air mass contributions over the Wrangell Area for 11 years from 1992 to 2002 from each area defined in Fig. 1 at (a) < 300 hPa, (b) 300–700 hPa, and (c) > 700 hPa levels.

summit of the Mount Wrangell ice core site (62°N; 144 °W; 4100 m above sea level, Fig. 1). A total of 125 air parcels were set in the initial region for the first time step. Then, the total number of air parcels after each 10-day calculation at each defined pressure level (> 700 hPa, 700–300 hPa, and < 300 hPa) in each defined area (Fig. 1) per month were counted. The arrival day of the air mass to the ice core site was used to classify trajectories into months. Then, the percentage of monthly air mass contributions was estimated by dividing by the total number of air parcels in each month. This method is similar to equation (6) in Polissar et al. (1999). The following days were excluded for the calculations due to model and data problems: 1992/1/1–1992/1/10; 1995/10/28; 1996/1/1–1996/1/10; 1997/2/5; 1998/9/1–1998/9/10; 1999/4/1–1999/4/10; 2001/12/31; 2002/2/9. However, the total number of calculations in each month was at least 20 days, presenting no problem for the statistical analyses in this study.

3. Results and discussions

3.1 Monthly origins of transported air mass

Monthly transported air mass frequency to the Mount Wrangell ice core site from each origin and altitude level was calculated as a percentage of the total number of air masses in each month (Fig. 2). Firstly, the results were checked for each defined area (not shown). Then, areas were combined into groups for easy comparison. Hereafter, we refer to the areas containing SI+ER+OB+RU as Group Russia (GrRU), NP1+NP2 as Group North Pacific (GrNP), NAO1+NAO2+NAO3+MC+AM as Group Atlantic (GrAT), EU+NE as Group Europe (GrEU) and IS+NA+OA as GrLess.

Air masses were mainly transported from adjacent sectors of the NPR (EA, GrRU, AL, GA, GrNP, JP, CA and AO) except for SEA, NA and MC in the troposphere (> 300 hPa). The contributions from GrAT and GrLess were relatively low (Fig. 2). Air masses were mostly transported to the ice core site from the middle troposphere (700–300 hPa) (Fig. 2b). The least contribution was from the upper troposphere to the stratosphere (< 300 hPa: Fig. 2a).

In spring, air masses from EA in the lower and middle troposphere increase and can easily transport Asian dust to the Mount Wrangell ice core site if Asian dust outbreaks occur (Figs. 2b and 2c). In fact, Asian dust outbreaks occur most frequently in spring (March, April and May) in EA (e.g., Sun et al. 2001; Kurosaki and Mikami 2003), suggesting that Asian dust may often suspend in the atmosphere in EA in spring. Therefore, spring is considered to be the most likely season for transport of Asian dust to the North Pacific ice core sites.

In summer-fall, air mass contributions from many areas decreased, but those from the North Pacific Ocean (GrNP and GA) increased (Fig. 2c). This indicates that sea-salt aerosols from the North Pacific Ocean may be easily transported to the ice core sites at this time of year. In a case study, sea-salt (sodium) was transported from GA to the King Col. ice core site Canada (Yalcin et al. 2006). However, for determining the factors affecting seasonal peaks of sea-salt proxies in ice cores, it is also important to consider snowfall amount and sea-salt scavenging processes on the way to the ice core sites. For instance, in the Eclipse ice core, Na+ decreases were mainly seen in summer (Wake et al. 2002). The sodium data for the Mt. Wrangell ice core has not been published and its seasonality is as yet unknown. The rainy season in southern Alaskan areas is summer-fall and then the snow accumulation at the Wrangell ice core site increases too (Manley and Daly 2005; Kanamori et al. 2008). The large amount of snowfall may dilute sea-salt proxies in summer in the ice cores in the NPR. Further discussion of the relationship between sea-salt peaks in the ice cores and amount of snowfall is required in future studies.

In summer-fall, wildfires in boreal forest regions such as SI, AL and CA are active (e.g., Langmann et al. 2009). The mean 1000–700 hPa air mass contributions from these areas (Fig. 3) increased in summer-fall. This implies that air masses from areas of wildfire in SI, Al or CA may easily reach the Mount Wrangell ice core site and other such ice core sites in the NPR in summer-fall. This supports the case of the transportation of soot from Alaskan wildfires (Kim et al. 2005). In conclusion, forest fire proxies such as black carbon are most likely to impact on ice cores in the NPR in summer-fall.

In fall-winter, air masses of various continental origins contributed to the ice core site, including EA,

Table 1. Estimated seasonal mean concentrations of fine dust and tritium from Mount Wrangell ice core flux data in 1992–2002 by Yasunari et al. (2007).

Particle	ES-LS	LS-SU	SU-FA	FA-WI	WI-ES	Unit
Fine dust	59405	42995	35794[a]	40235	46998[b]	(Particles/mL)
Tritium	11.92	10.17	6.45	4.78	7.55[b]	(TU)

ES, LS, SU, FA and WI denote Early spring, Late spring, Summer, Fall, and Winter, respectively.

[a] Data in 1992 was excluded due to large dust contributions from the Mt. Spurr eruption.

[b] Data in 1992–1993 and 1998–1999 were excluded due to very low seasonal snowfall (< 0.1 m w.e.) resulting in much higher concentrations.

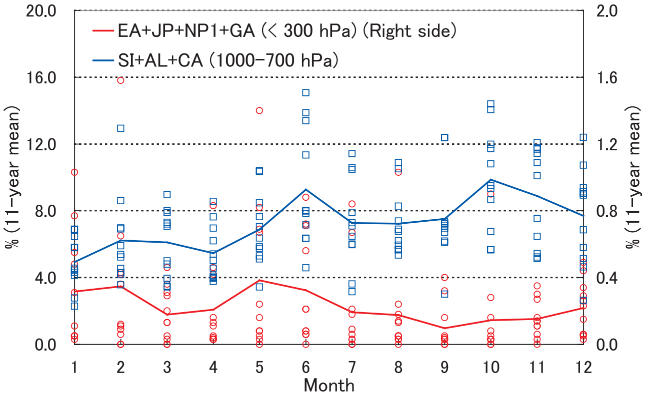

Fig. 3. Mean contributions by air masses to the Mount Wrangell ice core site (bold lines) from 1000–700 hPa levels in SI+AL+CA and < 300 hPa levels in EA+JP+NP+GA (on the right side). Blue squares and red circles denote monthly mean data in each year (1992-2002) for SI+AL+CA and EA+JP+NP+GA (on the right side), respectively.

GrRU, CEA, GrEU, GrAT and AO at the > 700 hPa and 700–300 hPa levels (Figs. 2b and 2c). Long range transportation of aerosols from these regions and mixing may occur in this season. Hence, interpretation of ice core proxies in fall-winter may be more difficult than in other seasons.

In winter, stratospheric air increased from EA, GrRU, CEA, GrAT, AO and GrEU areas (Fig. 2a). However, tritium in dense concentration may not reach the tropopause in this season and these winter increases in air do not necessarily explain tritium peaks in late spring as mentioned in Section 3.3.

Air mass contributions to the ice core site from GrAT and GrLess are relatively low. This indicates that probability of aerosols and other material transport from these regions are very low. Over the event scale, however, aerosol transport from these regions cannot be ignored, such as the case of African dust transport to Western Canada (McKendry et al. 2007). In terms of a monthly or seasonal mean data set of ice core proxies, aerosol and other material information from these areas may be diluted.

3.2 Implication for dust and black carbon variations

Yasunari et al. (2007) and Yasunari and Yamazaki (2009) verified Asian dust transport from EA from case studies, finding an increase in fine dust concentration in ice cores in the NPR in spring (Table 1). There seems to be no increasing trend of fine and coarse dust variation over 1992–2002 in Mt. Wrangell ice core (Yasunari et al. 2007). The fine and coarse dust particles were highly correlated and had seasonal cycles. In general, black carbon particles are fine and less than 1 μm in size (e.g., Moteki et al. 2007). As Yasunari et al. (2007) discussed, fine dust particles (insoluble particles) in the Mount Wrangell ice core may include black carbon from forest fires in SI and AL. They found a fine dust peak in the summer of 1998, likely corresponding to forest fires (Yasunari et al. 2007). The result shown in Fig. 3 supports black carbon contributions due to wildfires.

Although anthropogenic total black carbon emission from China has been increasing since about 1970 (e.g., Novakov et al. 2003), no clear increasing trend of fine dust concentration has been seen in the ice core in the 1990s (Yasunari et al. 2007). Clear peaks in fine dust concentration in spring associated with coarse dust peaks were interpreted as seasonal cycles. Hence, spring dust peaks in the ice core of Yasunari et al. (2007) may mainly be associated with continental sources and are considered to mainly be Asian dust since Asian dust outbreaks and air mass transport from EA both increase in spring (Figs. 2b and 2c). In conclusion, transport of Asian dust impacts on the ice core sites every spring in the NPR.

In addition, dust concentration in the ice core of Yasunari et al. (2007) decreased in summer-fall (Table 1). This may be attributed to a lower contribution from continental regions to the ice core site, especially from East Eurasia (Fig. 2) and also the rainy season in southern Alaska (Manley and Daly 2005; Kanamori et al. 2008).

3.3 Implication for tritium variation

It is well known that tritium is made by cosmic rays in the stratosphere and is transported to the troposphere. The transport of air mass from the stratosphere to the troposphere shows a January maximum (Fig. 2a). However, tritium concentration in the Mount Wrangell ice core shows a late-spring maximum (Table 1). This discrepancy requires explanation.

One possible explanation is the tritium concentration just above the tropopause may peak in spring. The concentration of tritium is higher in the upper-middle stratosphere and lower in the lower stratosphere (Ehhalt et al. 2002). The tritium in dense concentration may be transported toward the tropopause during winter, likely taking about two months to reach tropopause in spring.

Another possible explanation is related to the meridional gradient of tritium. Tritium mainly may exist in a form of water vapor (HTO) and its concentration may decrease with latitude. In winter, the stratospheric air mostly comes from high latitudes where water vapor is low and possibly ineffective at transporting tritium to the ice core site. The effective transport route is considered to be along lower-latitude East Asian storm-track. The transport of tritium from EA to the North Pacific Ocean at < 300 hPa peaks in May (Fig. 3). It may cause efficient tritium depositions by snowfall at the ice core site.

Since few observations of tritium in the lower stratosphere and the troposphere have been made, further observational and modeling studies are required to explain the seasonal variation of tritium at the ice core site.

4. Conclusion

In this study, air mass origins at an Alaskan ice core site and their seasonal variation were modeled. Simulations of 10-day backward trajectories of air masses were made on a daily basis from 1992–2002, corresponding to the period covered by the Mount Wrangell ice core by Yasunari et al. (2007). Major air masses affecting the ice core site were found to come from the North Pacific Ocean and adjacent continental regions. However, care must be taken when discussing material origins since source intensity, distributions, seasonality and wet and dry deposition processes should also be taken into account. In addition, results depend on the period to some extent. The model does not include cumulus effects and the turbulent mixing effect and those will be future studies. Thus, the results presented in this study should be taken as a rough estimate of material origins.

This study has shown that pollutants from spring Asian dust storms in EA and summer biomass burning in SI, AL and CA can easily reach the ice core sites in the NPR. The air mass transport above the 300 hPa level increases in winter and that from the EA+JP+NP1+GA region increases in late spring. The tritium peak observed in the ice core in late spring was discussed in the context of the present results with two possibilities on the time lag of tritium transportation in the stratosphere and the seasonal variations of water vapor amount in the troposphere.

In conclusion, this study provides information clarifying the origins of ice core proxies in the NPR and is useful for understanding material circulation in the NPR.

Acknowledgments

The ECMWF data were provided by the Course in Atmosphere-Ocean & Climate Dynamics of the Graduate School of Environmental Science, Hokkaido University, Japan. Calculations for and the drafting of Fig. 1 were carried out using the GFD DENNOU Library.

Supplement

1. The reason why we chose 10-day backward trajectory analysis in this study and points to notice to use the results of statistical trajectory analysis are included as supplementary text.

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Manuscript received 25 December 2008, accepted 20 April 2009
SOLA: http://www.jstage.jst.go.jp/browse/sola/