Distribution of Oxygen Isotope Ratio of Precipitation in the Atlantic–Indian Sectors of the Southern Ocean

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Abstract

Herein, the spatial distribution of stable oxygen isotope ratios ($\delta^{18}O$) of precipitation in the Atlantic to Indian sectors of the Southern Ocean is examined using the results of in situ observations and numerical modeling. In situ observations of 59 precipitation events reveal poleward decrease of $\delta^{18}O$, with a larger meridional gradient south of 60°S. Moreover, the estimates from the observations and model (IsoGSM) agree reasonably well, with a mean absolute difference of 4.3‰. Thus, the IsoGSM results generally support the observed poleward increase in the meridional gradient. These results will prove valuable in investigating the atmospheric water cycle and in studying oceanic processes of water mass formation and transport.

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1. Introduction

The global hydrological cycle plays a vital role in characterizing the surface environment of the high-latitude Southern Hemisphere. Precipitation dominates evaporation over the Southern Ocean (e.g., Josey et al. 1999), contributing to the relatively fresh salinity at the ocean surface in the high latitudes (e.g., Talley 2002). Moreover, precipitation on the Antarctic continent supplies the fresh water that constitutes the vast ice sheet. This ice sheet slides outward to form ice streams and ice shelves, the terminuses of which are eventually melted and calved (e.g., Robin 1979), supplying continental freshwater to the ocean. In the Southern Ocean surrounding the Antarctic continent, the estimation of the abovementioned freshwater fluxes is important in understanding sea water property and hence global ocean circulation.

Several attempts have been made previously to estimate the spatial distribution and temporal change of the freshwater flux using satellite data and reanalysis output (e.g., Kanamitsu et al. 2002), although the resulting estimates above typically vary depending on the methods employed. Moreover, evaluation of the accuracy of these estimates is difficult owing to the lack of available data. Salinity of sea water represents the total effects of different freshwater sources, including local precipitation, continental ice and sea ice; however, it cannot provide information about contribution from each freshwater source. Thus, alternative approaches are required to estimate the validity of the fluxes and infer the characteristics of formation and transport processes of Antarctic water masses. The oxygen isotopic content in water ($H_2{}^{18}O$) is a useful tracer to identify the origin of fresh water, because it retains information about the history of water transport (e.g., Weiss et al. 1979). Using the oxygen isotope–salinity relationship, Meredith et al. (1999) concluded that advection from higher latitudes is important for the surface water offshore of South America. However, their approach was based on an assumption that the oxygen isotopic content of the mother freshwater (local precipitation east of Antarctic Peninsula) was −17‰, based on the isotope–salinity relationship; this was not confirmed by direct observations. Thus, further evidence is required to verify that this estimated value does in fact correspond to the oxygen isotopic content of annual precipitation in this high-latitude region.

The oxygen isotopic content in Antarctic precipitation has been investigated previously to understand isotopic variations in ice cores or to reconstruct paleotemperature. The resulting measurements have revealed seasonal and interannual variations at Antarctic coastal stations (Picciotto et al. 1960; Kato 1978; Ichiyanagi et al. 2002) and spatial variation from inland samplings, including those along traverse routes (Masson-Delmotte et al. 2008). Fricke and O'Neil (1999) compiled these observations and described a decreasing tendency of oxygen isotopic content toward the higher latitudes (the so-called "latitudinal effect"). However, these observations were obtained primarily over land, and few observations have been obtained over the Southern Ocean. Uemura et al. (2008) conducted intensive measurement of oxygen isotopes in water vapor along the ship track; however, measurements of oxygen isotopes in precipitation, which affects the ocean directly as influx, were not included in their study. Thus, overall, estimates of the oxygen isotope content of precipitation over the high-latitude ocean are limited, and further enhancement of the spatial and temporal coverage of observations is crucial.

Owing to the intrinsic difficulty of conducting in situ observations in this remote region, the observational coverage would inevitably be sparse both temporally and spatially, even if the number of observation opportunities could be increased substantially. Therefore, to obtain sufficient spatiotemporal coverage of oxygen isotopes in precipitation over the Southern Ocean, a reliable interpolation method with numerical modeling is required. Recently, several isotope-enabled GCMs have become available and can reproduce the general isotopic patterns of global precipitation reasonably well (e.g., Yoshimura et al. 2008). However, because of a lack of comparison with observation data, it is not yet clear whether these GCMs can successfully simulate the isotopic content in precipitation over the Southern Ocean. To address this, in the present study, we conducted observation to collect precipitation samples for isotope analysis and examine whether the isotope-enabled GCM is useful in estimating the spatiotemporal pattern of oxygen isotopes in precipitation over the Southern Ocean.

2. Data and methods

We used data obtained from in situ sampling of precipitation and analyzed outputs of a modeling experiment to simulate realistic atmospheric circulation in the present study. We collected 59 precipitation samples (44 and 15 samples in summer and winter, respectively) during 7 research cruises (5 and 2 cruises in summer and winter, respectively; Table 1 and Fig. 1). In contrast to the relatively homogeneous distribution of summer data, winter samples were rather limited in extent and were biased toward two regions near the continent: around 50°W off the Antarctic Peninsula, and around 110−120°E off the coast of Wilkes Land. After the snowfall events, we sampled snows fallen on the ship's

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Table 1. Shipboard observations of oxygen isotope ratio δ^{18}O of precipitation.

Date	Samples	Ship	Project
20 Jan−4 Mar 2006	13	Aurora Australis	BROKE-West
6 Sep−15 Oct 2006	6	Polarstern	WWOS
14 Sep−5 Oct 2007	9	Aurora Australis	SIPEX
29 Dec 2007−1 Jan 2008	4	Umitaka maru	KARE13
17 Dec 2010−5 Jan 2011	9	Hakuho maru	KH10-5
25 Jan−14 Feb 2011	2	Shirase	JARE52
5 Jan−29 Jan 2012	16	Umitaka maru	KARE15

deck. Among the summer samples, 4 samples around 52°S, 140°E were rainfall; these were collected in a bucket. All samples were collected immediately after the precipitation events. Then, the snow samples were melted to fill 30 ml glass vials, which had inner caps and were sealed with Parafilm. The samples were then stored in refrigerators.

Isotope analysis was undertaken with a mass spectrometer (Finnigan DELTA plus) coupled with an equilibrium device, and the ratios of oxygen isotope contents of the samples (which are referred to as δ^{18}O) were determined with respect to Vienna Standard Mean Ocean Water (VSMOW). Thus, the ratios were obtained as follows:

$$\delta^{18}\mathrm{O} = \left\{ \frac{\left(\frac{^{18}\mathrm{O}}{^{16}\mathrm{O}}\right)_{sample}}{\left(\frac{^{18}\mathrm{O}}{^{16}\mathrm{O}}\right)_{vsmow}} - 1 \right\} \times 1000 \quad (‰)$$

Samples were shaken automatically for about 8 h in an 18°C water bath to equilibrate with CO_2. The accuracy of the analysis was estimated to 0.02‰ based on duplicated measurements (Nakamura et al. 2010).

As the output of an AGCM-based isotopic model, IsoGSM was used in the present study. IsoGSM was developed by Yoshimura et al. (2008) by incorporating the heavier water isotopologues in the Global Spectral Model originally developed by the National Center of Environmental Prediction (NCEP). A long-term simulation of IsoGSM from 1979 to 2012 was conducted using NOAA Optimum Interpolated (OI) sea surface temperature and sea ice distribution (Reynolds et al. 2002) and a global spectral nudging technique (Yoshimura and Kanamitsu 2008) toward atmospheric field variables (i.e., wind speed and temperature) of NCEP/DOE Reanalysis (the so-called NCEP Reanalysis 2; Kanamitsu et al. 2002). The horizontal resolution of the model is T62, which is equivalent to about 1.8° × 1.8°, whereas the vertical resolution is 28 levels. The typical output interval is 6 h. In the present study, the simulation result was collocated (i.e., the closest model grid to the ship location at a precipitation event was picked up).

Comparisons between the observations and model were conducted with the daily-mean output of IsoGSM. Zonal extent of the analysis domain is set to 55°W−140°E according to the in situ data distribution. The model estimates were obtained for 55 cases (40 in summer and 15 in winter), corresponding to 93% of the total 59 samples surveyed. Climatological characteristics of δ^{18}O distribution were studied for the 10-year-mean (2001−2010) field. The period from December to February (August to October) was defined as model summer (winter), according to the months when the observations were made.

3. Results

3.1 Distribution of precipitation δ^{18}O from in situ observations

The spatial distribution of observed δ^{18}O of precipitation was found to exhibit a general trend, with lower (higher) values in the higher (lower) latitudes (Fig. 1). Although anomalously high values (−5−0‰) occurred around 60°S, 140°E in January 2012, the estimates equatorward of 60°S are typically approximately −10−0‰. The lowest value (−25‰) was found in October 2006 around 65°S, east of the Antarctic Peninsula. The standard deviation (std) of all summer (winter) measurements is 7.1‰ (8.3‰).

The meridional gradient of isotopes is not, however, monotonous (Fig. 2a). The observed rate of decrease is relatively low from the lower latitudes to around 60°S, whereas the meridional gradient of δ18O was found to increase poleward from 60°S toward the Antarctic continent. In particular, a quadratic curve fitted to all data, including those in both summer and winter, reveals a decrease of 5.5‰ from 60°S to 65°S, with a negligible decrease obtained from 55°S to 60°S.

Simple seasonal averages were also found to be different between summer and winter. When averaged south of 55°S, the summer average (−8.1 ± 5.5‰ (std) at an average latitude of 63.0°S) is higher by about 8‰ than the winter average (−16.4 ± 7.0‰ at an average latitude of 63.4°S). This magnitude of seasonal difference, 8‰, is about half or more of the seasonal range obtained at Antarctic coastal sites around 70°S (around 12 and 15‰ at Baudouin (70.4°S) and Syowa (69.0°S) station, respectively; Picciotto et al. 1960; Kato 1978), although caution is advised when interpreting the limited and inhomogeneous spatial data available, particularly in winter.

3.2 Evaluation of model output with in situ observations

The performance of IsoGSM was examined through comparison with the observation data. The nearest grid data from the observation site on the observation date were chosen from the model output and then compared with the observed oxygen isotopic values. The model output shows a good agreement with the observations (Fig. 3a): the correlation coefficient is 0.64, which is statistically significant at a 99.9% two-tail confidence interval, and the absolute mean difference is 4.3‰. The high values around 60°S, 140°E in observations are reasonably reproduced by the model. Histograms of the difference between model and observations show no obvious systematic bias in summer (Fig.

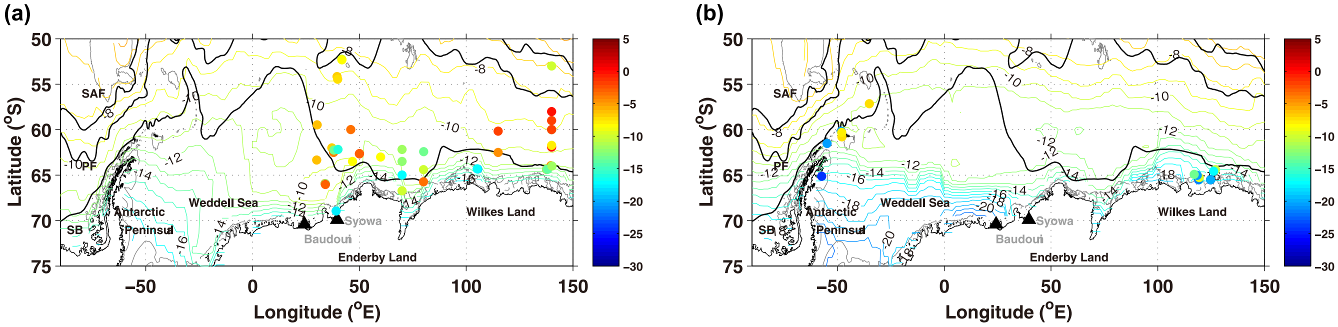

Fig. 1. Distributions and estimates (circle color) of oxygen isotope ratios of precipitation derived from in situ observations in a) summer (from December to February) and b) winter (from August to October). Contours indicate climatological mean (2001−2010) estimates of oxygen isotope ratios of precipitation derived from IsoGSM for each season. Triangles denote the available Antarctic coastal stations. Solid lines denote the positions of the Sub-Antarctic Front (SAF), Polar Front (PF), and Southern Boundary (SB) of the Antarctic Circumpolar Current (Orsi et al. 1995) to roughly illustrate the surface oceanic current regimes.

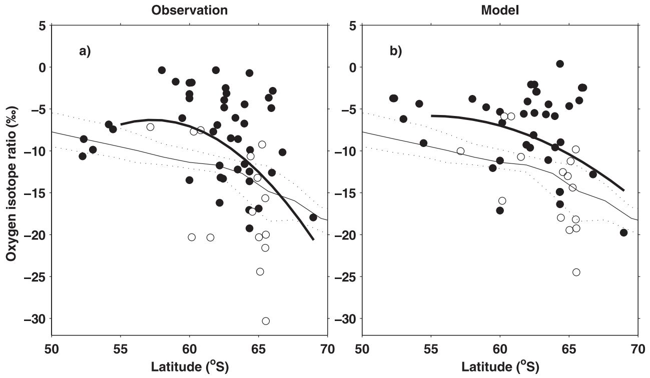

Fig. 2. Meridional distribution of the oxygen isotope ratio of precipitation obtained from a) observations and b) model. Closed (open) circles are the samples taken in summer (winter). Thick solid lines indicate the second-order polynomial curve fitted to the estimates. Solid (broken) lines indicate the regional climatological mean (maximum and minimum) values of IsoGSM for the 2001−2010 period.

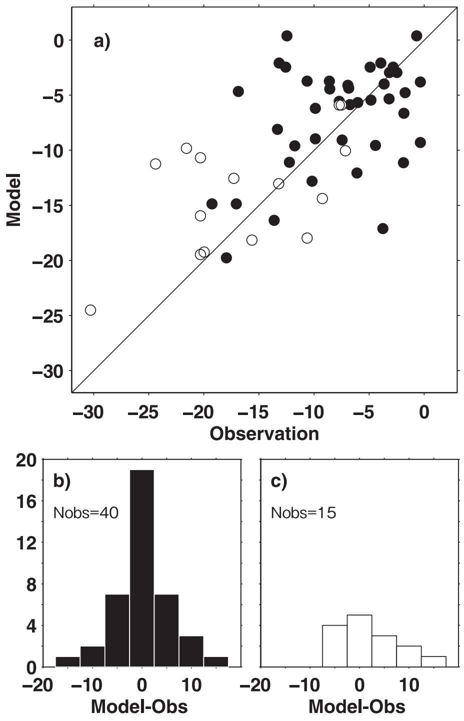

Fig. 3. a) Comparison of oxygen isotope ratio of precipitation between observation and IsoGSM. Dots (circles) are the samples taken in summer (winter). Histogram of difference between model and observation in b) summer and in c) winter.

3b), whereas model values in winter slightly overestimate the corresponding observations (Fig. 3c): the difference of means in winter is 2.4‰, which is larger than the 1.2‰ difference in all seasons. This may partly reflect the inadequate sampling in winter. The overall good agreement here indicates that the model output should be capable of reproducing the general signal of meridional gradient (around 5‰ per 5°) derived from in situ observations.

Next, the simulated meridional gradient was compared with that of observations (Fig. 2b). The obtained meridional variation is expressed as a similar decrease toward higher latitudes and an increase in gradient south of around 60°S. The simulated decrease at high latitudes (from 60°S to 66°S), however, is slightly underestimated (about 60% that of the observations) owing to an overestimation near the Antarctic coast, when the quadratic curve is fitted in the same manner adopted for the observations. The seasonal difference found for observation samplings was also detected by IsoGSM: the mean value in summer south of 55°S is higher (−7.0 ± 4.9‰) than that in winter (−13 ± 5.3‰). Thus, the characteristic distribution derived from the observations was retrieved similarly by the model, providing further support for the general fidelity of IsoGSM.

3.3 Characteristics of precipitation δ^{18}O from model output

The spatial distribution of the 10-year climatological mean δ^{18}O distribution of IsoGSM clearly shows the gradual decreasing trend of the oxygen isotopic content toward the Antarctic continent in both summer and winter (underlying contours in Fig. 1). In addition, the zonal distribution of oxygen isotopes is not homogeneous from 60°W to 150°E: δ^{18}O is generally higher in the eastern region than in the western region east of the Antarctic Peninsula, particularly in the lower latitude region. Along 60°S, for example, annual average δ^{18}O is higher by about 2‰ at 140°E than at 30°E. Since precipitation δ^{18}O is sensitive to the factors including air temperature, wind, sea ice cover, and precipitation amount in the high-latitude Southern Ocean (Ichiyanagi et al. 2002), spatial variation in these environmental conditions are likely contributed to the obtained zonal distribution of δ^{18}O.

IsoGSM also reproduced the seasonal difference, with higher (lower) δ^{18}O in summer (winter), although the simulated climatological seasonal variation is much smaller than that obtained from the limited observations. Moreover, the magnitude of the seasonal variation increases toward the higher latitudes: it is 4.3‰ (between −15.4‰ in summer and −19.7‰ in winter) at 70°S but 1.5‰ (−11.4‰ in summer and −12.9‰ in winter) at 64°S. This difference from the observations can be attributed to both observational and modeling deficits (as discussed below).

4. Discussion

In situ observations and model output of precipitation δ^{18}O were found to exhibit reasonable agreement in the high-latitude Southern Ocean. In both outputs, the zonally averaged meridional δ^{18}O distribution was found to exhibit a gradual decrease toward the Antarctic continent, and the meridional gradient was found to increase suddenly at around 60°S.

The meridional distribution obtained in the present study is broadly consistent with the "latitudinal effect" derived from previous observational results, with clear evidence of a discontinuity in the gradient. In addition, the high values of δ^{18}O poleward of around 60°S implies there are driving processes other than the "latitudinal effect" (a.k.a. Rayleigh effect); i.e., the source area of the precipitation is close and/or the existence of kinetic process during evaporation from ocean surface or from falling raindrop. The agreement between observations and model partly guarantees these processes.

The simulated large seasonality is supported by year-long observation records at Antarctic coastal stations: at Syowa (Baudouin) station, the monthly average range of seasonal variation was approximately 15‰ (12‰), ranging from −12‰ to −30‰ (from −15‰ to −27‰), in 1974 (1958). The climatological range at the nearest model grid was found to be around 5‰ (8‰), ranging from −11‰ to −16‰ (from −16‰ to −24‰); this indicates an overestimation of the winter depletion, in particular. This may be attributable, at least in part, to the fact that isotopic AGCMs typically fail to reproduce the observed depleted values of inland Antarctica (Masson-Delmotte et al. 2008), owing partly to the wet bias of IsoGSM (Frankenberg et al. 2009). Therefore, validation and improvement of the model performance near (and in inland) Antarctica in winter will be required in future to ensure reliable estimates of seasonal variation.

5. Conclusions

The obtained meridional distribution of precipitation δ^{18}O has implications for ocean water mass formation and transport.

The indirect estimation of precipitation δ^{18}O from surface sea water by Meredith et al. (1999) is consistent with both the direct observations and model interpolation results of the present study. Thus, the present study lends support to inferences based on sea water near the surface, suggesting that such data can also be extrapolated across broader regions and justifying the use of local precipitation at 52°S (which was extrapolated from island data). Using the same method with Meredith et al. (1999), Nakamura et al. (2010) derived the fresh water end member of about −17‰ for the region off the Enderby Land. The present estimation of local precipitation δ^{18}O is helpful in differentiating its effect from glacial and sea ice contributions.

In the isotopic studies of the water cycles between atmosphere and ocean, the data of hydrogen isotope, together with the oxygen isotope, is also important and will be useful. This is especially true on the continental margin where the multiple freshwater sources can contribute. The simultaneous analysis of both isotopes becomes much easier owing to the recent development of laser spectroscopy systems. Hence in situ data sampling should be extended to both isotopes in the future studies.

Future application of the data presented here to sea water δ^{18}O will provide clues to help differentiate between the various causes of on-going freshening of the Southern Ocean (Durack and Wijffels 2010; Aoki et al. 2013). Possible reasons for freshening in this region include geographic variations in precipitation increases associated with enhancement of the hydrological cycle (Held and Soden 2006), accelerated melting of the ice shelves of Western Antarctica (Rignot et al. 2008; Jacobs et al. 2011), and changes in the transport and production of sea ice (Comiso et al. 2011; Tamura et al. 2008). When combined with data describing changes in salinity, continuous measurements of seawater δ^{18}O can provide useful tracer information that will be beneficial in determining the mechanisms underlying environmental change in the Antarctic region.

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