Seasonal Variation of Moisture Transport in the Polar Regions
and the Relation with Annular Modes

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Abstract

The Seasonal variation of moisture transport and the relation between moisture transport and annular modes in the polar regions are investigated with ECMWF reanalysis data.

Over the Arctic, the strong moisture inflows from the Atlantic Ocean and Pacific Ocean exist in all seasons. Over the Antarctic, the strong moisture inflow exists around Antarctic Peninsula in all seasons and over the Bellingshausen Sea and the Amundsen Sea in austral autumn and winter. It is found that the seasonal variation of precipitation minus evaporation over the Arctic Ocean depends on the seasonal variation of precipitable water and that over the Antarctica depends on the cyclone activity.

Poleward and eastward moisture fluxes are positively correlated with annular modes in both polar regions. A positive polarity of the Arctic Oscillation is associated with a moisture inflow from Atlantic Ocean. On the other hand, a positive polarity of the Antarctic Oscillation is associated with moisture inflow around Antarctic Peninsula.
1. **Introduction**

The Arctic and Antarctic regions are moisture flux convergence areas and the atmospheric moisture transport is a primary input of water over the regions. The moisture transport directly or indirectly affects the snow, sea ice and ice sheet over the regions. The net input of water to the surface from the atmosphere is a difference between precipitation and evaporation ($P - E$). The $P - E$ is approximately equals to the moisture flux convergence for a long period. Therefore, atmospheric moisture transport is a critical factor for water balance especially over the polar regions. There are some studies on these estimations over the Arctic and the Antarctic. We have two estimation methods for $P - E$; one is an estimation from the atmospheric moisture budget using rawinsonde, objective analysis and satellite data (e.g. Peixoto and Oort, 1992, Bromwich et al., 1995, Groves and Francis, 2002), the other method is a direct calculation of $P$ and $E$ or $P - E$ from rain gage observations, snow depth measurements, objective analysis or model output data (e.g. Cullather et al., 1998, Bromwich et al., 2000). In general, the direct observation suffers from locality of precipitation. Moreover, the surface observations are not reliable over the Arctic Ocean and the Antarctica, because the observation network is very sparse and the accurate measurement is difficult over the Antarctica due to the severe climate and snow drift. Since $P$ from objective analysis data is obtained from a short-time integration of the forecast model, it suffers from a spin-up problem. Although $P$ from climate model output data dose not have the spin-up problem, it totally depends on the model performance and the performance is not so good in polar regions in
many models. Therefore, the moisture budget method is superior to the direct method in the Arctic and Antarctic regions.

Over the Arctic, the distribution of poleward moisture flux across 70°N that lead to the $P-E$ over the region was first investigated with rawinsonde data for 1974-1991 by Serreze et al. (1995) and the similar study was done for 1973-1995 by Serreze and Barry (2000). These studies discussed the seasonal variation and the distribution of poleward moisture flux across 70°N. To assess the fresh water balance of the Arctic Ocean, it is necessary to examine the moisture budget over the Arctic Ocean besides surface river runoff, fresh water exchange through ocean current and sea ice export. Cullather et al. (2000) and Bromwich et al. (2000) compared estimations from rawinsonde (Historical Arctic Rawinsonde Archive; HARA) with those from reanalysis data (European Centre for Medium-range Weather Forecasts; ECMWF, National Centers for Environmental Prediction and National Center for Atmospheric Research; NCEP-NCAR) and presented that the meridional moisture flux from rawinsonde is larger than that from reanalysis in boreal summer.

Over the Antarctic, Yamazaki (1992, 1994, 1997), Bromwich et al. (1995) and Cullather et al. (1998) estimated $P-E$ with operational numerical analysis data. Yamazaki (1992, 1994) found that $P-E$ is large in austral winter and suggested it is controlled by cyclone activity. Yamazaki (1997) presented the seasonal variation of zonal mean precipitable water and poleward moisture flux. Bromwich et al. (1995) compared the three operational numerical analyses (ECMWF, National Meteorological Center; NMC, Australian Bureau of
Kazuhiro Oshima

Meteorology; ABM) and rawinsonde data, and it was found that the ECMWF analysis provide good estimations for water budget.

In this study, seasonal variations of atmospheric moisture budget over the Arctic and the Antarctic regions are investigated by using ECMWF reanalysis data not only for the region poleward from 70° (hereafter called polar cap region) but also for the Arctic Ocean and the Antarctica.

The Arctic Oscillation (AO) is a dominant mode of atmospheric variability in the wintertime Northern Hemisphere (Thompson and Wallace, 1998, 2000). The AO is a seesaw of sea level pressure between the Arctic region and midlatitudes, which shows an annular pattern. Thus it is also named the Northern Hemisphere annular mode (NAM). The Southern Hemisphere counterpart of the AO/NAM is called the Antarctic Oscillation (AAO) or the Southern Hemisphere annular mode (SAM) (Gong and Wang, 1999, Thompson and Wallace, 2000). When the phase of the annular mode (AO or AAO) is positive, westerly winds around 60° are enhanced and those around 35° are reduced. Although the annular modes exist throughout the year, they are active during cold seasons.

Moisture transport is also related with the annular modes (AO and AAO). The zonal mean meridional moisture flux at high-latitudes has a positive correlation with the AO and AAO (Rogers et al. 2001, Boer et al. 2001). Although these studies show the zonal mean moisture flux associated with the annular modes, they didn’t describe the horizontal pattern of moisture flux, which will be examined in this paper.
In section 2, we describe the data and method used in our analysis. The results are presented in section 3. We summarize with some discussions in section 4.

2. Data and method

Two reanalysis data sets are used to estimate the moisture flux over the polar regions. The main data is ECMWF reanalysis (ERA, 1979-1993), the supplementary one is National Centers for Environmental Prediction - Department of Energy (NCEP-DOE) reanalysis-2 (NCEP R2, 1979-2002). We present horizontal fields of moisture flux and seasonal variations of the precipitation minus evaporation ($P-E$) over both the Arctic Ocean and the Antarctica. These regions are defined with ERA land-sea mask data (Fig. 1). $P-E$ is estimated by atmospheric moisture budget equation, shown as follows,

$$\frac{dPW}{dt} = -\nabla < qv > + E - P,$$

where $PW$ is the precipitable water, $q$ is the specific humidity, $v$ is the horizontal wind vector and $<qv>$ is the vertically integrated moisture flux:

$$\langle qv \rangle = \frac{1}{g} \int_{300hPa}^{surface} \frac{qv}{dp} dp.$$  

When we calculate an average over a long time period (i.e., seasonal mean), the time rate of change of $PW$, the left hand side of Eq. (1) can be neglected and Eq. (1) is rewritten as:

$$P - E \approx -\nabla < qv >$$

$$\approx -\frac{1}{A} \int < qv > \cdot n \ dl,$$

where $A$ is the area of the region, $l$ is the length along the boundary of the region and $n$ is the
unit vector normal to the boundary of the region. \( P-E \) is estimated from moisture flux divergence, and moisture transport is based on the vertically integrated moisture flux.

To clarify the relation between annular modes and moisture flux, we calculate the correlation coefficients between Arctic and Antarctic Oscillation indices and zonal mean moisture flux and also show the regression patterns for moisture flux upon the indices. The regression patterns indicate moisture flux signatures of annular modes. AO index and AAO index available at NOAA Climate Prediction Center are used, in this study.

3. Results

3.1. Climatology

The annual mean moisture flux fields over the Arctic and the Antarctic are shown in Fig. 2 and the annual mean \( PW \) and wind fields at 850 hPa are shown in Fig. 3. Over the Arctic, there are strong moisture inflows from the Atlantic Ocean and the Pacific Ocean. It is also clear that moisture is transported from the Atlantic Ocean to the interior of Siberia and from the Pacific Ocean to the interior of North America (Fig. 2a). These moisture fluxes are caused by the mean wind at the lower troposphere (Fig. 3a). Over the Antarctic, the eastward flux is strong over the Antarctic Sea surrounding the Antarctica. The westward moisture flux exists along coastline to the East Antarctica (Fig.2b). These transports are related to the mean wind at the lower troposphere (Fig. 3b). The poleward flux is strong around Antarctic Peninsula and over the Bellingshausen and the Amundsen Sea. Such flows are not seen in Fig. 3b and these
fluxes must be related to transport with cyclones. The poleward fluxes also appear off Wilkes Land, and around Syowa Station. It corresponds to the mean wind. These features are almost consistent with Yamazaki (1992, 1994, 1997).

3.2. The Arctic

Figure 4 presents the seasonal mean moisture flux fields over the Arctic and Figure 5 presents the seasonal mean $PW$ and wind fields at 850 hPa. There are primary moisture inflow from the Atlantic Ocean and the secondary from the Pacific Ocean in all seasons, as seen in the annual mean field (Fig. 2a). The flux pattern in summer (JJA) is different from that in other seasons. In summer, moisture fluxes are strong due to summer moisture increase. The $PW$ in summer is about five times larger than that in winter (Fig. 5). The inflow from the Pacific to the Arctic Ocean through Alaska is largely enhanced, but the subsequent outflow through Canadian Archipelago is also enhanced. The counterclockwise flow also appears over the Arctic Ocean. These flows are seen in Fig. 5 and correspond to the mean wind. Since the poleward wind from the Atlantic Ocean is weak in the mean wind fields, the moisture inflow in this region is considered to be caused by cyclone activity. On the other hand, in other season, moisture is transported from the Atlantic Ocean to the interior of Siberia and from the Pacific Ocean and Alaska to the interior of North America. The former flow is related to the mean wind, and the latter flow is related to cyclone activity. In winter (DJF), the wind field shows a cross-Arctic flow in the Arctic Ocean (Fig 5a), but such flow is not seen in moisture flux (Fig. 4a) due to small $PW$ in this season.
To examine the seasonal variation of poleward moisture flux more clearly, monthly mean meridional moisture flux across 70°N is shown in Figure 6. There is poleward moisture flux at most of longitudes throughout the year. The inflow and outflow are enhanced in summer, especially in July and August. In Atlantic sector (20°W-30°E), the poleward moisture flux can be seen throughout the year and it shows semi-annual variation in strength with winter and summer peaks. As for the poleward flux from the Pacific (180°-150°W), it shows a strong peak in July, which is accompanied with a strong peak of equator-ward flux through Canadian Archipelago (120°-90°W). There are also enhanced poleward fluxes in summer around west Siberia (80°-100°E) and west of Greenland (50°W). These two inflows show the maxima in August. These fluxes are concerned with the moisture flux convergence over the Arctic region. Figure 7 shows the seasonal variation of $P-E$ over the Arctic Ocean and the polar cap region. The $P-E$ over the Arctic Ocean is large in summer, June to September, and it is almost constant in other seasons. The maximum appears in July and the minimum in December. This variation is similar to that over the north polar cap. The result for the polar cap is consistent with previous studies (Cullather et al., 2000, Bromwich et al., 2000), which estimated with reanalysis data.

3.3. The Antarctic

Figure 8 presents the seasonal mean moisture flux fields over the Antarctic and Figure 9 presents the seasonal mean $PW$ and wind fields at 850 hPa. There is large eastward flux over the Antarctic Sea surrounding the Antarctica in all seasons. This basically corresponds to the
mean wind field at the lower troposphere. The poleward flux is strong around Antarctic Peninsula. It is not clearly seen in wind fields and this is caused by the cyclone activity. In summer (DJF), the moisture flux parallel to the coastline is enhanced to the East Antarctica and weak in other seasons, because the mean wind corresponding to the flux is strong in summer and the \( PW \) in summer is a few times larger than in winter. In autumn (MAM) and winter (JJA), poleward flux is enhanced over the Bellingshausen Sea and the Amundsen Sea. Since such flow is not seen in the mean wind field, it is related to the cyclone activity. The enhanced poleward fluxes in autumn and winter are not clear in Yamazaki (1992, 1994).

To examine the seasonal variation of poleward moisture flux more clearly, monthly mean meridional moisture flux across 67.5°S is shown in Figure 10. We chose 67.5°S instead of 70°S, because the latitude circle of 70°S passes the East Antarctica. As same as the Arctic, there is poleward moisture flux at most of longitudes throughout the year. Note that the negative value means poleward flux. There is large poleward flux in summer and small flux in winter around Antarctic Peninsula (80°-60°W). However there is large poleward flux in early winter and small flux in summer over the Bellingshausen Sea and the Amundsen Sea (150°-100°W). The large inflow exists around Syowa Station (20°-50°E) in late summer, January to March. The small outflow appears around 60°E throughout the year and the sector between 45°W and 10°E in late summer.

The seasonal variation of \( P-E \) over the Antarctica and south polar cap is presented in Figure 11. The \( P-E \) varies gently. In spite of large \( PW \) in summer and small \( PW \) in winter, the
Kazuhiro Oshima

$P-E$ is large in winter and small in summer, the maximum appears in July and the minimum in January. The $P-E$ over the south polar cap has the maximum in May and the minimum in January. The present result for the Antarctica and the south polar cap agrees with Bromwich et al. (1995).

3.4. Atmospheric Moisture Budget

Table 1 shows the seasonal mean $P-E$ over the polar regions, derived from ERA. Over the Arctic Ocean, the annual mean $P-E$ is 184 mm/year, the summer (JJA) mean is 291 mm/year and the winter (DJF) mean is 135 mm/year. Over the Antarctica, the annual mean $P-E$ is 168 mm/year, the summer (JJA) mean is 126 mm/year and the winter (DJF) mean is 200 mm/year. Therefore seasonal variation is large over the Arctic Ocean and small over the Antarctica.

Table 2 and 3 present the annual mean $P-E$ over the Arctic Ocean and over the Antarctica, respectively, showing together with results from previous studies. Compared with previous studies, the values of $P-E$ over both Arctic and Antarctic regions in this study are reasonable. The $P-E$ from NCEP R2 is a little larger than that from ERA. This is consistent with Cullather et al. (2000). The $P-E$ over the Antarctica region which is not including Antarctic Peninsula is approximately 10 mm/year smaller than that over the Antarctica which is defined in this study. It suggests the $P-E$ over the Antarctica depend on the choice of the region.

3.5. Moisture flux and Annular modes
It is known that there is a relation between annular modes (AO and AAO) and moisture flux (Rogers et al., 2001, Boer et al., 2001). Figure 12a shows correlation coefficient between AO index and zonal mean moisture flux. They have significant correlations. For zonal flux, it shows the maximum of 0.66 at 57.5°N and minimum of -0.53 at 27.5°-30°N. These correlations are reasonable because the AO accompanies the similar zonal wind variation. For meridional flux, it shows the maximum of 0.59 at 60°-65°N and minimum of -0.50 at 32.5°N. The meridional flux variation related to the AO is partly explained by the AO-related poleward wind variation in the lower troposphere. The variation of transient moisture flux is also contributed to this good correlation between the meridional moisture flux and the AO (Bore et al., 2001).

On the other hand, Figure 12b shows correlation coefficient with AAO index and zonal mean moisture flux. They also have significant correlations. For the zonal flux, it shows the maximum of 0.83 at 55°-60°S and minimum of -0.64 at 35°S. For the meridional flux, it shows the maximum of 0.20 at 35°-37.5°S and minimum of -0.44 at 57.5°S. The similar discussion as the AO can be applied to the AAO for the meridional flux. The correlation coefficient between meridional moisture flux and AAO become zero at 75°S and remains small poleward of 75°S. This indicates that AAO is not associated with meridional flux in the interior of the Antarctica. In contrast, the correlation coefficient at 75°N is 0.4 and the effect of AO is extended more poleward compared with that of AAO.

AO and AAO regression patterns for moisture flux are shown in Fig. 13. A positive
polarity of the AO is related to the enhanced poleward moisture flux from the Atlantic Ocean and counterclockwise flux over the Arctic Ocean. Similarly, a positive polarity of the AAO is related to the enhanced eastward moisture flux over the Antarctic Sea surrounding the Antarctica and cyclonic flux over the Bellingshausen Sea and the Amundsen Sea. The vector in the interior of the Antarctica is very small. It corresponds to the low correlation coefficient at the latitudes. Figure 14 shows AO regression patterns for moisture flux for four seasons. A positive polarity of the AO is associated with an enhanced poleward moisture flux from Atlantic Ocean in all seasons. It is also associated with an enhanced poleward flux in central Eurasia and an enhanced equator-ward flux though Canadian Archipelago in boreal summer (JJA) and autumn (SON). It is seen the counterclockwise flux over the Arctic Ocean is enhanced in boreal spring (MAM), summer and autumn. Especially in summer, these fluxes are enhanced. Note that the arrow scale in summer is three times larger than other maps in Fig. 14. Figure 15 shows AAO regression patterns of moisture flux for four seasons. A positive polarity of the AAO is associated with eastward flux over the Antarctic Sea surrounding the Antarctica and cyclonic flux over the Bellingshausen Sea and the Amundsen Sea. This flux is enhanced especially in austral summer (DJF) and autumn (MAM).

4. Discussion and Conclusions

We investigated the seasonal variation of moisture transport over the Arctic and the Antarctic region with ERA and NCEP R2 and clarified the relation between annular modes
and moisture transport.

Over the Arctic, there are strong moisture inflows from the Atlantic Ocean and Pacific Ocean in all seasons and strong outflow through Canadian Archipelago in boreal summer. These inflow and outflow are especially enhanced in boreal summer due to the summer moisture increase. On the other hand, over the Antarctic, the strong moisture inflow exists around Antarctic Peninsula in all seasons and over the Bellingshausen Sea and the Amundsen Sea in austral autumn (MAM) and winter (JJA). The most of moisture inflows have the maximum peak in austral summer and the minimum peak in winter, but the inflows over the Bellingshausen Sea and the Amundsen Sea have the maximum peak in winter and the minimum peak in summer. The seasonal variation of $P-E$ shows large values in winter and small values in summer. Therefore, the moisture inflow over the Bellingshausen Sea and the Amundsen Sea, which is controlled by cyclone activity, contributes to the large $P-E$ in winter.

In this way, the seasonal variation of $P-E$ over the Arctic Ocean primarily depends on the seasonal variation of $PW$ and that over the Antarctica primarily depends on the cyclone activity. The annual mean $P-E$ over the Arctic Ocean and the Antarctica are 184 mm/year and 168 mm/year, respectively.

The Arctic Oscillation (AO) and zonal mean meridional moisture flux have a significant positive correlation. This is connected with the poleward moisture flux from the Atlantic Ocean. The Antarctic Oscillation (AAO) has same relation with the poleward moisture flux. This is connected with the poleward flux around Antarctic Peninsula. It is also found that the
AAO is not associated with meridional flux in the interior of the Antarctica. A positive polarity of the AO is associated with a poleward moisture flux from Atlantic Ocean in all seasons, counterclockwise flux in boreal spring (SON), summer (DJF) and autumn (MAM), and equator-ward flux through Canadian Archipelago in boreal summer and autumn. A positive polarity of the AAO is associated with eastward moisture flux over the Antarctic Sea surrounding the Antarctica and cyclonic flux over the Bellingshausen Sea and the Amundsen Sea, especially in austral summer (DJF) and autumn (MAM). Although, in austral summer, westward moisture flux along coastline at the East Antarctica exists in annual mean flux field, a positive polarity of AAO is associated with the eastward flux along the coastline.

The results from NCEP R2 are almost the same as those from ERA. Over the Arctic, the $P-E$ from NCEP R2 is a little smaller than that from ERA. This is consistent with Bromwich et al. (2000), but they compared ERA with NCEP-NCAR data set. The $P-E$ over the Antarctic from NCEP R2 is also smaller than that from ERA. This agrees with Bromwich et al. (1995). It is considered that these differences are caused by differences in performance and horizontal resolutions of the models.

These estimations of atmospheric moisture budget and the clarification of the relations between annular modes and moisture transports are helpful to assess the water cycle over the entire polar regions.

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Kazuhiro Oshima

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