Interannual variations in atmospheric mass over liquid water oceans, continents, and sea-ice-covered arctic regions and their possible impacts on the boreal winter climate

Zhaoyong Guan1,2, Qian Zhang1,2, and Minggang Li1,2

1Key Laboratory of Meteorological Disaster of Ministry of Education, Nanjing University of Information Science and Technology, Nanjing, China, 2Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing, China

Abstract Using reanalysis data from National Centers for Environmental Prediction/National Center for Atmospheric Research, ERA-interim, and Hadley Centre Sea Ice and Sea Surface Temperature for the period of 1979–2012, the variations in atmospheric mass (AM) over liquid water oceans, continents, and sea-ice-covered Arctic regions during boreal winter are investigated. It is found that AM may migrate in a compensatory manner among these three types of surfaces on interannual time scales. There are two pairs of strong antiphase relations. One lies in a zonal orientation between the Eurasian continent and the midlatitude Pacific (referred to as Eurasian continent/Pacific antiphase relation) and exhibits a teleconnection pattern characterized by two strong correlation centers, one over Eurasia and one over the North Pacific. The other antiphase AM relation, referred to as ocean/ice-covered Arctic antiphase relation (OIAR), exhibits a meridional orientation between the ice-covered Arctic and liquid water oceans, including the Atlantic and Pacific. In the context of the OIAR, two teleconnection patterns are observed. One features three strong correlation centers, one each over the Mediterranean, Arctic, and North Pacific, and corresponds to AM fluctuations over liquid water oceans. The other is characterized by three strong correlation centers over the Mediterranean, the Arctic, and East Asia, and corresponds to AM fluctuations over the ice-covered Arctic. These teleconnections are the results of thermal contrasts among the three types of surfaces. Rossby waves and vertical circulations play important roles in the formation of these teleconnections. Interestingly, these teleconnections may have significant and widespread influences on the winter climate in the Northern Hemisphere, especially in regions near the Mediterranean, the northern Eurasia, parts of North America, and East Asia.

1. Introduction

As early as 1951, Lorenz [1951] developed his description of the air mass shift between the regions near 65°N and 35°N in the Northern Hemisphere (NH). This phenomenon of atmospheric mass (AM) migration in the meridional direction was later confirmed by Trenberth and Paolino [1981] and Christy and Trenberth [1985], who further demonstrated this north-south AM fluctuation to be even more evident over the Pacific and Atlantic, in a phenomenon now known as the Arctic Oscillation (AO) or the Northern Annular Mode [Thompson and Wallace, 1998, 2000; Wallace, 2000; Deser, 2000; Baldwin, 2001; Li and Wang, 2003], which is the dominant mode of atmospheric variation in the Arctic region. In fact, AM migrations are observed in atmospheric dynamical processes on a wide range of spatial-temporal scales and can be explored by investigating vertically integrated airflow [Lorenz, 1951], the surface air pressure [Christy and Trenberth, 1985; Christy et al., 1989; Toumi et al., 1999], and several other physical quantities, such as the equivalent potential temperature [e.g., Seo et al., 2015]. When AM migrates over a particular area above the Earth’s surface, the surface air pressure at that location will consequently change. This change in surface air pressure tends to induce surface winds and even changes in the weather/climate. Therefore, the ability to diagnose AM variations would be beneficial for gaining an improved understanding of the dynamics of general variations in circulation and related weather and climate anomalies.

In the NH, there are large expanses of continents and oceans, and the strong thermal differences between continents and oceans [e.g., Wu and Liu, 2003] play a role in redistributing AM over these regions. From the skin
temperatures provided by the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis [Kalnay et al., 1996], the area-averaged temperatures during boreal winter are found to be 19.8°C over liquid water oceans, −0.9°C over continents, and −26.9°C over ice-covered Arctic regions, indicating that oceans are relatively warm compared with continents, which causes the surface air pressure (SAP) to be lower over oceans than over continents. In fact, these thermal contrasts change with the cycle of the seasons, thereby causing the surface air pressure to change considerably with the seasons and inducing a striking seasonal shift in AM between land and sea [Gordon, 1953; Yang, 1956; Hu et al., 2014]. In atmospheric models, these AM redistributions can also be realistically simulated. For example, in 1993, Van den Dool and Saha [1993] simulated circulation variations using an atmospheric general circulation model, with an emphasis on the AM exchanges between land and sea in equinox seasons.

Since 1979, as a result of rapid progress in satellite development and data assimilation, increasingly reliable observations and reanalysis data have become available. These data are employed in quantitative research into global AM shifts [e.g., Guan and Yamagata, 2001; Trenberth and Smith, 2005; Trenberth et al., 2005]. Lu et al. [2008] revealed noticeable differences in AM excesses or deficits between land and sea. Hu et al. [2014] investigated seasonal variations in the AM redistribution between extensive ocean and landmass regions in the NH using the 1979–2011 NCEP/NCAR and ERA-40 reanalyses. Their results indicate that the distinct sea-land shift in AM is seasonally dependent as a result of the pronounced thermal contrast between land and sea in the NH.

Despite of the perceptible shift in AM between land and sea, further investigations are needed to understand the AM migration between ice-covered regions and both liquid water and land surfaces. In fact, ice-covered regions differ from ice-free regions in reflectivity, feedback, and thermal protective screening [Walsh, 1983; Houghton et al., 1996; Dieckmann and Hellmer, 2010]. The interactions of ice-covered regions with liquid water oceans and non-ice-covered continents via the atmosphere [Otto-Bliesner et al., 2006; Turner et al., 2009; Wu and Zhang, 2010; Screen et al., 2013] may play a crucial role in shaping our climate. Therefore, it is necessary to consider the interactions between ice-covered and water-covered ocean surfaces and between ice-covered and land surfaces based on the differences in their thermal properties.

The AM over land/sea surfaces and ice-covered regions displays considerable discrepancies in heating behavior throughout the seasonal cycle. However, because of interannual variations in the physical properties of these surfaces, especially their thermal states, we can reasonably expect that the AM values over these different surfaces may vary differently from year to year. Thus, in the present paper, we investigate the interannual variations in atmospheric mass over liquid water oceans, continents, and ice-covered regions as well as their interrelations in the NH. The associated winter climate anomalies are also examined.

This study is organized as follows. A short description of the data sources and methodology employed in this study is provided in section 2. The AM variations over different types of surfaces and their interrelations are investigated in section 3. In section 4, the dynamics of the different teleconnections are presented. In section 5, the possible influences of AM variations on the boreal winter climate, including surface temperatures and precipitation, are examined. Section 6 follows with the concluding remarks and discussions.

2. Data and Methodology

2.1. Data

The data used are taken predominantly from the NCEP/NCAR reanalysis [Kalnay et al., 1996] and consist of the monthly mean surface pressure ($p_s$), the geopotential height ($h$), the wind speeds ($u$, $v$), the specific humidity ($q$), the temperature ($T$) at 17 isobaric levels, and the vertical speed ($\omega_z$) at 12 isobaric levels at a resolution of 2.5° × 2.5° latitude/longitude. Moreover, the land/sea surface temperatures ($skt$) on a Gaussian grid are also employed. The ice cover data are taken from the Hadley Centre Sea Ice and Sea Surface Temperature (HadiSST) data set [Rayner et al., 2003] and have a horizontal resolution of 1° × 1° latitude/longitude. The precipitation data used are from the CMAP (CPC Merged Analysis of Precipitation) data set [Xie and Arkin, 1997], which is available from the CMAP website at http://www.esrl.noaa.gov/psd/data/gridded/data.cmap.html.

The ERA-interim [Dee et al., 2011] surface pressures at a horizontal resolution of 1° × 1° from January 1979 to February 2012 are also employed for purposes of comparison.
The study period is from December of 1978 to February of 2012. The winter of a given year is defined as the period from the previous December to the current February (DJF) of that year, and hence, there are considered to be 34 winters between 1979 and 2012.

2.2. Methodology

The SAP ($p_s$) is an effective parameter for depicting the variations in AM of an air column above the Earth’s surface and is a very important indicator for describing climate variations [Toumi et al., 1999]. We use $p_{sa}$ to denote anomalies in AM or surface air pressure anomalies (SAPA); this quantity is defined as $p_{sa} = p_s - \bar{p}_s$, where $\bar{p}_s$ is the mean climatology of $p_s$ over the 34 winters of the 1979–2012 period.

Globally, AM is approximately conserved on interannual time scales, and it is able to oscillate between the boreal and austral hemispheres [Guan and Yamagata, 2001; Lu et al., 2008; Guan et al., 2010]. The correlation of the total AM in the Northern Hemisphere with that in the Southern Hemisphere during the study period is found to have been $-0.92$. This means that the total AM in the Northern Hemisphere varied in a nearly antiphase relation with the total AM in the Southern Hemisphere. It has been reported that certain localized, persistent anomalies in circulation, such as blocking events, may be related to interhemispheric AM exchanges [Trenberth, 1986; Christy et al., 1989; Carrera and Gyakum, 2003]. However, in the present study, to clearly observe the variations in AM over different types of surfaces in the NH, we must remove the effect of the AM Interhemispheric Oscillation (IHO) on the SAPA from $p_{sa}$. By regressing $p_{sa}$ onto a time series of the areal-weighted mean of SAPA in the NH, $p_i$, is obtained as follows:

$$ p_i = p_{sa} - \alpha M_{NH} \ldots (1) $$

Obviously, $p_i$ is defined as the difference between the SAPA and the IHO-related portion of the SAPA; consequently, it is statistically independent of the IHO in the NH. Because the IHO-related portion of the SAPA is small relative to $p_i$ [Guan and Yamagata, 2001], $p_i$ is the dominant component of the SAPA. Here in equation (1), $\alpha$ is the regression coefficient obtained by regressing $p_{sa}$ onto $M_{NH}$, where $M_{NH}$ is an integral of the areal-weighted $p_{sa}$ over the NH, i.e.,

$$ M_{NH} = \frac{1}{2\pi} \int_{NH} p_{sa} \cos \phi d\phi d\lambda \ldots (2) $$

Suppose that the air above land surfaces, ocean surfaces, and ice covers is heated differently, and therefore, shifts in AM occur among them. The $p_i$-based AM values over these surfaces can be calculated using the expressions below

$$ M_O = \int_{Ocean} p_i \cos \phi d\phi d\lambda / \int_{Ocean} \cos \phi d\phi d\lambda \ldots (3) $$

$$ M_L = \int_{Land} p_i \cos \phi d\phi d\lambda / \int_{Land} \cos \phi d\phi d\lambda \ldots (4) $$

$$ M_I = \int_{Seaice} p_i \cos \phi d\phi d\lambda / \int_{Seaice} \cos \phi d\phi d\lambda \ldots (5) $$

where $M_O$, $M_L$, and $M_I$ are the areal-averaged atmospheric masses over land, liquid water oceans, and ice-covered Arctic regions, respectively. The standard deviations of the time series of $M_O$, $M_L$, and $M_I$ for the study period are 0.34 hPa, 0.40 hPa, and 3.08 hPa, respectively. Note that the sum of the areas corresponding to the land, ocean, and sea-ice-covered regions over which the area-weighted averages of $p_i$ are computed is simply equal to the total area of the NH. It is observed that the areas corresponding to liquid water oceans and sea ice vary interannually because the edge of the sea ice varies by year, although these variations are fairly small. These interannual variations between regions of sea and ice cover are taken into account when we compute $M_O$, $M_L$, and $M_I$.

The vertically integrated apparent heat source $<Q_1>$ and apparent vapor sink $<Q_2>$ [Nitta, 1972] are calculated in this work to analyze the anomalous heating over different regions. These quantities are

$$ <Q_1> = c_p \left( <\frac{\partial T}{\partial t}> + <V \cdot VT> + <\sigma \omega> \right) \ldots (6) $$

$$ <Q_2> = -L \left( <\frac{\partial q}{\partial t}> + <V \cdot Vq> + <\sigma \frac{\partial q}{\partial p}> \right) \ldots (7) $$
where \( \langle > = \frac{1}{L} \int_{p_0}^{p_f} \rho_l'(d)dp \), \( \rho_l \) denotes the pressure at the top isobaric level, and \( \sigma = \frac{T}{T_p} \frac{\sigma T}{C_p} \) is a parameter of atmospheric stability. The other symbols used have their conventional meanings.

The quantity \( \Delta Q = \langle Q_1 > - \langle Q_2 > \) can also be expressed in terms of the surface sensible heat flux, the thermal flux produced by vapor condensation, and the radiative forcing in an air column, as follows:

\[
\Delta Q = \langle Q_R > + Q_S + LE_S (\psi) \tag{8}
\]

where \( \langle Q_R > \) represents vertically integrated radiative heating (cooling), \( Q_S \) is the flux of surface sensible heat, \( L \) is the latent heat of condensation, and \( E_S \) is the surface evaporation rate.

The horizontal component of the wave activity fluxes for quasi-stationary Rossby waves can be computed by employing a formula proposed by Takaya and Nakamura [2001] in the framework of the approximate geostrophic theory. In pressure coordinates, this formula is expressed as

\[
W_r = \frac{1}{1 + U} \left[ \frac{\psi \psi' - \psi' \psi}{\psi^2} \right] \tag{9}
\]

where \( W_r \) denotes the wave activity flux (WAF) for quasi-stationary waves, \( U \) is the basic flow (\( U = U_i + V_j \)), and \( \psi' \) is the quasi-geostrophic stream function for waves. The wave energy propagated on an isobaric level is represented by the wave activity flux \( W_r \). At locations where \( W_r \) converges (diverges), the waves tend to intensify (weaken).

### 3. AM Variations and Their Interrelations

#### 3.1. Two Antiphase Relations

The AM fluctuates interannually over different types of surfaces. This can be clearly observed from the normalized time series of \( M_O \), \( M_L \), and \( M_I \) as derived from the NCEP/NCAR reanalysis (Figure 1). Upon cross checking these AM variations using the ERA-interim reanalysis, it is found that the normalized time series of \( M_O \), \( M_L \), and \( M_I \) as derived from the ERA data mimic the time series from the NCEP/NCAR reanalysis; the correlations between these two reanalyses are 0.98 for \( M_O \), 0.99 for \( M_L \), and 0.99 for \( M_I \). Therefore, in the following, only the results based on the NCEP/NCAR data are analyzed.

Physically, anomalous excesses or deficits of AM occurring over sea surfaces must be compensated by AM anomalies in regions of land and ice cover. In Figure 1a, an antiphase relation is found between \( M_O \) and \( M_I \) with a correlation of \( -0.82 \), suggesting that AM accumulates over liquid water oceans when it is lost over ice-covered regions. Together with the spatial distributions of SAPA (Figures 3a and 3c), this AM fluctuation in the meridional direction can be referred to as the liquid water ocean/ice-covered Arctic antiphase relation (OIAR). Another antiphase relation is evident between \( M_O \) and \( M_L \), with a correlation of \( -0.78 \) (Figure 1b). Similarly, this zonal pattern can be referred to as the Eurasian continent/Pacific antiphase relation (EPAR) when the spatial distributions of the SAPA shown in Figure 3b are taken into account.

The correlation of the AM over ice-covered regions (\( M_I \)) with that over land (\( M_L \)) is found to be positive but very weak (Figure 1c); the correlation coefficient is 0.29. This in-phase relation is, to some extent, related to
the simultaneous increase (decrease) in AM over land surfaces and ice-covered regions that is likely to be induced by an anomalous decrease (increase) in AM over ocean surfaces. This may be one reason why the AO-related SLP variations are stronger over both the Pacific and Atlantic Oceans [Thompson and Wallace, 1998] than they are over continents.

3.2. Periodicities in AM Variations

To obtain the periodicities of the anomalous variations in AM over different types of surfaces, the Morlet wavelet transforms [Torrence and Compo, 1998] and the power spectra are analyzed for the three time series, revealing their marked interannual variations. The well-known Morlet wavelet transform is a useful tool for analyzing local variations in power within a time series. By decomposing a time series into time-frequency space, one is able to determine both the dominant modes of variability and how those modes vary in time [Torrence and Compo, 1998]. The periodicities in each AM time series found in this manner are presented in Figure 2 and Table 1.

The AM values over different types of surfaces vary with different periodicities. Variations with periods of 8–9 years and 2–4 years that are significant at and above the 90% confidence level are observed in the time series of both $M_O$ and $M_L$ (Table 1); the former period is more perceptible from the end of the 1980s into the early part of the first decade of the new century, whereas the latter dominates between the end of that decade and the early 2010s (Figures 2a and 2b). It is found that $M_O$ exhibits its most striking quasi-4 year variations in the early 1990s (Figure 2a), corresponding to the 3–4 year periods of $M_I$ between the late 1980s and the middle-to-late 1990s (Figure 2c). In $M_L$ (Figure 2b), variations with periods of 3–5 (5–6) years are observed in the early 1980s (the mid-1990s). These periodicities of $M_L$ are very different from those of $M_O$, suggesting a weak correlation between them. Note that different periods that appear in the $M_O$, $M_L$, and $M_I$ data may be physically related to certain climate signals within the NH, such as the El Niño–Southern Oscillation and AO.

3.3. Three Spatial Teleconnection Patterns

The spatial patterns of AM migrations can be explored based on the correlations of surface air pressure anomalies with each of the time series of $M_O$, $M_L$, and $M_I$. Note that the time series of $M_O$ and $M_L$
are areally averaged over continents and oceans, respectively, spanning from the equator to high-latitude regions in the NH. However, higher correlations of these time series with the SAPA are found at middle-high latitudes, indicating higher contributions of the SAPA variations to the variability of the \( M_O \) and \( M_L \) time series at middle-high latitudes compared with those at lower latitudes.

In the OIAR pattern, large positive significant correlations of \( p'_s \) with \( M_O \) are found over the North Pacific, North Atlantic, and Mediterranean regions at middle-low latitudes (Figure 3a). A small area of stronger positive correlation is observed in East Asia. Moreover, noticeable negative correlations are found near the Arctic ice cover. This teleconnection can be referred to as the Mediterranean-Arctic-North Pacific (MANP) pattern in the context of the OIAR. These findings indicate a considerable accumulation of AM over the North Pacific, North Atlantic, and Mediterranean, in contrast to a distinct anomalous deficit over the Arctic ice cover, suggestive of an AM fluctuation from the Arctic to middle-low latitudes related to the Arctic Oscillation.

With regard to the EPAR pattern, the absolute values of the correlation coefficients are greater than 0.6 in Northern Eurasia and the Pacific, as seen in Figure 3b. When \( M_L > 0 \), anomalous increase in AM occur over the extratropical land surfaces of the NH, including Eurasia, central North America, and the coastal bands of southern Greenland, with corresponding anomalous deficits over the North Pacific, the Bermuda Triangle, and the Mediterranean at middle-low latitudes (Figure 3b). This pattern looks quite different from the OIAR, indicating a predominant AM migration between Eurasia and the extratropical North Pacific.

The AM over Arctic ice-covered regions participates in exchanges in the meridional direction with that over the midlatitude northeast (NE) Pacific and the Atlantic as well as the Mediterranean and East Asia (Figure 3c). This pattern appears considerably different from those shown in Figure 3a for East Asia and the region to the south of the Aleutian Islands. It indicates that when AM accumulates in the circumpolar region, it is lost from northwestern Europe, East Asia, and northwestern America. The pattern depicted in Figure 3c may be referred to as the Mediterranean-Arctic-East Asia (MAEA) teleconnection in the context of the OIAR, implying some connection with winter climate variations and possibly with extreme events in the Mediterranean, western Europe, East Asia, and Arctic regions via this MAEA pattern.

4. Dynamics of AM Variations
4.1. Anomalous Flow of Air Mass

The AM variations over liquid water oceans, continents, and ice-covered Arctic regions are intrinsically linked by AM flows among these different types of surfaces. Figure 4 shows both the anomalous AM flow and its divergent component in layers below/above 500 hPa in association with AM variations. AM exchanges are evident between continents and oceans and between Arctic regions and oceans.

With regard to the MANP pattern, two anticyclonic circulations of atmospheric mass are apparent from Figures 4a and 4b in the midlatitude Atlantic and Pacific, partially stretching into continental regions. An anomalous cyclonic circulation, surrounded by these two anticyclonic circulations, appears over the Arctic.
Figure 4. Regressions of anomalous rotational winds (streamlines) integrated vertically from the Earth’s surface up to (a) 500 hPa and from 500 hPa up to (b) 10 hPa onto $M_0$ (contours with shades for absolute values larger than 0.3). Superimposed are the $M_0$-regressed divergent components of winds (in $10^5$ kg m$^{-1}$ s$^{-1}$) integrated vertically from surface up to (Figure 4a) 500 hPa and from 500 hPa up to (Figure 4b) 10 hPa. The black arrows are for those at/above 95% level of confidence using an $F$ test. (c and d) Same as in Figures 4a and 4b, respectively, but for $M_L$–related anomalies. (a and f) Same as in Figures 4a and 4b but for $M_I$–related anomalies.
These anomalous circulations indicate strong atmospheric interactions among continents, oceans, and Arctic regions via air mass migrations. In the vertical direction, the MANP pattern depicted in Figure 3a is also observed in Figures 4a and 4b, suggesting an equivalent barotropic structure of the anomalous circulation. This equivalent barotropic structure is similarly observed in the Arctic Oscillation [Thompson and Wallace, 1998].

The air mass flow converges over oceans above 500 hPa (Figure 4b), whereas it diverges in these regions below 500 hPa (Figure 4a). The maintenance of anomalously high SAPs over midlatitude oceans is apparently due to the atmospheric mass flow convergence above 500 hPa rather than to the divergence below 500 hPa. Notably, the airflow diverges over Arctic regions above 500 hPa (Figure 4b), facilitating the anomalously low SAPs in these regions and compensating for the increase in AM over middle- and high-latitude oceanic regions. Over the NE of Asia, weak convergence is observed in the lower troposphere, which is responsible for the air mass accumulation observed in this region. This anomalous convergence produces an anomalous positive vorticity, weakening the anticyclonic circulation below 500 hPa over East Asia.

With regard to the EPAR pattern, an anticyclonic circulation of atmospheric mass flows appears over high latitudes near 45°E (Figure 4c), which is related to the large anomalous cyclonic circulation over the midlatitude North Pacific. Note that although the EPAR pattern shown in Figure 3b looks considerably different from the MANP pattern (Figure 3a), the overall circulatory features in Figures 4c and 4d are surprisingly similar to those in Figures 4a and 4b at middle latitudes. However, in the polar region, no large anomalous polar vortex is observed, unlike what is seen in Figures 4a and 4b.

With regard to the MAEA pattern, two anomalous cyclonic circulations are observed over western Europe and East Asia, along with an anticyclonic circulation over the polar region, exhibiting the equivalent barotropic structure (Figures 4e and 4f). The anomalous divergence of the AM flow over the Mediterranean in the upper troposphere (Figure 4f) is compensated by a convergence of atmospheric mass in the same region in the lower troposphere, which thus maintains the lower than normal SAP observed in this location (Figure 3c).

Note that an anomalous AM convergence in the lower troposphere must be balanced by an anomalous AM divergence in the upper troposphere. That is, when AM anomalously converges below a reference isobaric level \( p_n \), it diverges above \( p_n \). This relation can be roughly interpreted based on the continuity equation. Using the hydrostatic approximation, the continuity equation can be rewritten as the following equation of the SAP tendency:

\[
\frac{\partial \rho_i}{\partial t} \approx - \int_{p_n}^{p_0} \nabla h \cdot V dp.
\]

For the DJF mean, \( \frac{\partial \rho_i}{\partial t} \approx 0 \), which means that the SAPA locally remains nearly unchanged during boreal winter. Hence, \( \int_{p_n}^{p_0} \nabla h \cdot V dp = - \int_{p_n}^{p_0} \nabla p \cdot V dp \). This indicates that the amount of AM inflow below \( p_n \) in an air column is exactly equal to the amount of AM outflow above \( p_n \), suggesting that vertical circulations can be found between two neighboring correlation centers, although the horizontal circulations are equivalent barotropic. This is precisely what is observed in Figure 4.

### 4.2. Role of Rossby Waves in the MANP, EPAR, and MAEA Patterns

The teleconnection patterns displayed in Figure 3 form as a result of AM redistributions among regions with different types of surfaces, and anomalous AM flows (Figure 4) play a crucial role in connecting different SAPA centers. However, because the AM flow patterns exhibit wave-like structures in both the upper and lower troposphere, Rossby waves are expected to play an important role in the formation of the MANP, EPAR, and MAEA patterns. To examine this possibility, Figure 5 shows the wave activity fluxes [Takaya and Nakamura, 2001] superimposed on the geopotential height anomalies. It is again observed from Figure 5 that the MANP, EPAR, and MAEA patterns display barotropic structures at middle and high latitudes. For the quasi-stationary waves, the wave activity fluxes show clear connections among the correlation centers of geopotential height anomalies with different indices (Figure 5).

For the MANP pattern, at 500 hPa (Figure 5b), the wave activity fluxes (WAFs) reveal the propagation of wave energy southward from the polar region into the Mediterranean region. From this region, the WAFs extend eastward into East Asia, clearly suggesting the zonal propagation of Rossby wave energy along the westerly
In NE Asia, the WAF vectors indicate the polarward propagation of wave energy. Based on these scenarios of Rossby wave propagation, the MANP pattern can be regarded as a triangular teleconnection with three centers, one each in the Mediterranean, East Asia, and the polar region, which are linked by Rossby wave energy dispersion. At 850 hPa (Figure 5a) and 200 hPa (Figure 5c), similar scenarios are observed. Note that over the northern Atlantic, there is another center of anomalous geopotential height.

Figure 5. Correlations of $M_\Omega$ with geopotential height anomalies in region north of 10°N at (a) 850 hPa, (b) 500 hPa, and (c) 200 hPa. The critical absolute value of correlation coefficient at 95% (99%) level of confidence using a t test is found to be 0.34 (0.44). Superimposed vectors are the associated wave activity fluxes at the corresponding pressure level. (d–f) Same as in Figures 5a–5c, respectively, but for $M_L$–related anomalies. (g–i) Same as in Figures 5a–5c but for $M_I$–related anomalies.
equation can be written as follows:

\[ \text{equation (12)} \]

Generally, for variables averaged over the December-January-February period, the thermal dynamical land surfaces and between liquid water and ice act to promote air mass exchanges between these surfaces. In addition to latent heat release, the striking differences in anomalous diabatic heating between sea and because a positive (negative) marked relationship is evident between the diabatic heating over a land surface and that over ice cover.

\[ \text{Parameter} \]

\[ \text{parameters in question and resulting in an air mass shift. To examine this phenomenon, the anomalous diabatic heating} \]

\[ \text{The anomalous heating (cooling) of air over sea/land surfaces and ice cover drives a rise (drop) in temperature and air column expansion (contraction), causing the atmosphere to diverge (converge) over the region} \]

\[ \text{With regard to the EPAR pattern, WAF vectors are observed between the positive correlation center over high latitudes and the negative center over the midlatitude Pacific, revealing a southward propagation of wave energy over Eurasia and a similar northward propagation over the North Pacific (Figure 5e). Similar features can be found in both the lower (Figure 5d) and upper (Figure 5f) troposphere. This phenomenon suggests that these two centers of geopotential height anomalies in the EPAR pattern may form and interact with each other in correlation with Rossby wave dispersion. Again, in the EPAR pattern, no typical raypath of wave propagation is identified.} \]

\[ \text{For the MAEA pattern in the context of the OIAR, the wave propagation features exhibited by the WAFs appear similar to those in the MANP pattern except for the lack of significant negative correlations of geopotential height anomalies with } M_1 \text{ over the North Pacific (Figures 5g, 5h, and 5i). This teleconnection pattern, which includes the polar region and Eurasia, is more confined in domain compared with the MANP pattern. From western Europe to East Asia, wave energy propagates eastward along the waveguide of the westerly jet stream. Weak propagations in the meridional direction are observed between the polar region and the negative correlation center over the Mediterranean and between the polar region and the negative correlation center over East Asia.} \]

\[ \text{4.3. Diabatic Heating Related to AM Migration} \]

The anomalous heating (cooling) of air over sea/land surfaces and ice cover drives a rise (drop) in temperature and air column expansion (contraction), causing the atmosphere to diverge (converge) over the region in question and resulting in an air mass shift. To examine this phenomenon, the anomalous diabatic heating parameters \(< Q_1 >, < Q_2 >, \text{ and } \Delta Q' > \text{ are calculated to identify the correlations between any two of these three types of surfaces (Table 2).} \]

Significant negative correlations between these underlying surfaces arise in anomalous diabatic heating. No marked relationship is evident between the diabatic heating over a land surface and that over ice cover. Because a positive (negative) \(\Delta Q'\) indicates that the air column is undergoing net diabatic heating (cooling) in addition to latent heat release, the striking differences in anomalous diabatic heating between sea and land surfaces and between liquid water and ice act to promote air mass exchanges between these surfaces.

\[ \text{Generally, for variables averaged over the December-January-February period, the thermal dynamical equation can be written as follows:} \]

\[ < Q_1 > \approx < C_p V \cdot \nabla_b T > + < C_p V \cdot \nabla_b T > + < C_p \pi \omega' > . \]  

If we multiply equation (11) by \(p'_s\) for a particular winter, we obtain

\[ p'_s < Q_1 > \approx p'_s ( < C_p V \cdot \nabla_b T > + < C_p V \cdot \nabla_b T > ) + p'_s < C_p \pi \omega' > . \]  

Obviously, if each term in equation (12) is averaged over 34 winters, then the multiyear mean covariance \(p'_s < Q_1 >\) will be balanced by the sum of the covariances of the two terms on the right-hand side of

<table>
<thead>
<tr>
<th>Surface Type</th>
<th>Ocean</th>
<th>Land</th>
<th>Sea Ice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean</td>
<td>1</td>
<td>-0.75** (-0.54**)</td>
<td>-0.4 (0.33)</td>
</tr>
<tr>
<td>Land</td>
<td>1</td>
<td>0.06 (0.17)</td>
<td>1</td>
</tr>
<tr>
<td>Sea Ice</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This theory was successfully used to explain the wintertime teleconnections on a sphere [e.g., Wallace and Gutzler, 1981; Sea and Son, 2012]. Typically, teleconnection centers are found to lie approximately along such a great circle. However, for the MANP pattern, the propagations of quasi-stationary Rossby waves among the three centers are found to be highly complex; the three centers of geopotential height anomalies do not lie along a great circle. Although these interactions of atmospheric disturbances between the midlatitude and polar regions are very complex, Rossby wave energy propagation can still be clearly observed between any two of the three centers.

In 1981, Hoskins and Karoly [1981] proposed a geostrophic theory suggesting that Rossby wave energy tends to propagate along a raypath in a “great circle.”
Theoretically, where there is an anomalous low-pressure center with \( p_s' < 0 \), an ascending motion of the air will occur as a result of Ekman pumping. Therefore, the last term in equation (12) tends to be negative for negative correlations between \( p_s' \) and \( Q_1' \). The correlation of \( p_s' \) with the advection term \( \langle C_p V \cdot \nabla_h T \rangle + \langle C_p V \cdot \nabla_h T' \rangle \) also contributes, to a certain extent, to the term \( p_s' < Q_1' \). However, several studies have demonstrated that the dynamical heating due to convection is relatively large compared with the contribution due to horizontal advection [e.g., Rodwell and Hoskins, 1996; Guan and Yamagata, 2003]. Here in Figure 6, we present rough estimates of the two terms on the right-hand side of equation (12). It is clear that the dynamic heating anomalies due to vertical motion are, overall, larger than those due to horizontal advection at almost all latitudes, with the exception of 55°N. Therefore, \( < Q_1' > \) and \( p_s' \) can be reasonably expected to be negatively correlated. Nevertheless, the negative correlation of diabatic heating anomalies between liquid water oceans and ice-covered Arctic regions and that between liquid water oceans and continents, as seen in Table 2, are largely responsible for the negative correlations between \( M_O \) and \( M_I \) and between \( M_O \) and \( M_L \) that are seen in Figure 1.

Based on the discussion above, it can be concluded that the MANP, EPAR, and MAEA teleconnection patterns are modulated by both vertical circulation and Rossby waves. The differences in thermal forcing among oceans, continents, and ice-covered Arctic regions drive the atmosphere to either diverge or converge over these regions and henceforth cause AM shifts among these three types of surfaces. Vertical circulations connect neighboring strong correlation centers. These vertical circulations are typically expected to be very weak because the quasi-stationary disturbances at middle-high latitudes are, as is well known, equivalent barotropic. Besides of these thermally driven air movements, Rossby waves also play an important role in modulating the teleconnections and AM redistributions. As seen in Figure 3 and Figure 5, several pairs of neighboring anticorrelation centers are linked by wave activity fluxes, indicating the propagation of Rossby wave energy between these two centers. Such wave energy dispersions can be found in all of the MANP, EPAR, and MAEA patterns, although they appear complex.

5. Climate Anomalies Related to AM Migration

The AM fluctuations over the different types of surfaces discussed above in the NH are intrinsically related to the circulation anomalies that dominate the winter climate variations over different regions. These AM-climate relations can be explored by investigating the correlations (regressions) of different quantities with (onto) the AM variation indices over different types of surfaces (Figure 7).

A large anomalous anticyclonic circulation pattern at 850 hPa is found over the Pacific and in regions from the Atlantic to western Europe at middle latitudes, whereas a large cyclonic circulation pattern is observed over the Urals and the Eurasian region at 105°E–135°E over the Arctic zone (Figure 7a) when an anomalous air mass excess (\( M_O > 0 \)) occurs over the ocean surface at middle latitudes. On the northwestern flank of this anomalous anticyclonic circulation pattern over the Atlantic and in the western portion of the cyclonic
Figure 7. Correlations of $M_O$ with anomalous skin temperature at the land surface and with anomalous sea surface temperature (contours with shades for values larger than 0.3). Superimposed are the $M_O$-regressed winter winds in m s$^{-1}$ at (a) 850 hPa, and the divergent component of $M_O$-regressed vapor fluxes (in 10$^3$ kg m$^{-1}$ s$^{-1}$) integrated vertically from the Earth’s surface up to 300 hPa along with correlations of winter rainfall anomalies with (b) $M_O$. The critical value of correlation coefficient at 95% (99%) level of confidence using a $t$ test is found to be 0.34 (0.44). The shown arrows are for those at/above 95% level of confidence using an $F$ test. (c and d) Same as in Figures 7a and 7b, respectively, but for $M_L$–related anomalies. (e and f) Same as in Figures 7a and 7b but for $M_I$–related anomalies. Results derived from Global Precipitation Climatology Project rainfall and Goddard Institute for Space Studies surface temperature display similar patterns as in Figure 7.
Table 3. Regions Where the Surface Winter Climate Is Possible Significantly Influenced by MANP, EPAR, and MAEA Teleconnection Patterns

<table>
<thead>
<tr>
<th>Climate Conditions</th>
<th>( M_0 &gt; 0 )</th>
<th>( M_1 &gt; 0 )</th>
<th>( M_2 &gt; 0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warmer temperature</td>
<td>Europe to central Siberia, East Asia, and regions around the Gulf of Mexico</td>
<td>Alaska, coastal regions to east of Pacific</td>
<td>Regions around Mediterranean and North Africa, Alaska, and NE of North America, Indo-China Peninsula</td>
</tr>
<tr>
<td>Colder temperature</td>
<td>Alaska, northeast (NE) of North America to Greenland, North Africa</td>
<td>NE of Asian continent including east of China, regions surrounding the Gulf of Mexico</td>
<td>Eurasian continent at high latitude, NE of China and Korean Peninsula, regions around the Gulf of Mexico</td>
</tr>
<tr>
<td>More rainfall</td>
<td>The zonal rainbelt in middle-high latitudes of Eurasia, northwest of China</td>
<td>Southern Europe, NE of North America and regions to northwest of Tibetan Plateau</td>
<td>Southern Europe, north of Indian Peninsula</td>
</tr>
<tr>
<td>Less rainfall</td>
<td>Southern Europe, NE of North America</td>
<td>North of Europe to west Siberia and the central Plains</td>
<td>Scandinavian Peninsula, central Siberia, Alaska and regions to the east of Tibetan Plateau</td>
</tr>
</tbody>
</table>

The circulation pattern, the southerly wind flows bring warmer and moister air from the sea, producing higher than normal temperatures over regions from Europe eastward into central Siberia. On the southern flank of the anomalous anticyclone over the midlatitude northern Pacific, the anomalous easterly airflow blows westward onto the eastern Asian seaboard, where the flow then turns toward the northwest. Because of this warmer and moister airflow, significantly higher than normal temperatures are induced over a large area that includes Japan, the Korean peninsula, and northeastern China north of 40°N. This warmer area connects to the high-temperature belt of extratropical Eurasia near Lake Baikal. Higher than normal temperatures are also observed on the seaboard of the Gulf of Mexico, possibly as a result of the anomalous southerly wind on the western edge of the anomalous anticyclone over the midlatitude Atlantic. By contrast, several lower than normal temperature anomalies are observed over the Gulf of Alaska, including its coastal mountainous area and the tropical eastern Pacific as well as the south side of the coastal regions. These anomalies may be induced by the northerly wind that brings cold air from higher latitudes in the conjunction region of the anticyclone over the northeastern Pacific. Interestingly, anomalous low temperatures are also observed in regions of the low-latitude Atlantic and North Africa, which may similarly be attributed to the anomalous cold advection of the north winds on the southwestern flank of the anomalous anticyclone over the Atlantic and western Europe. Negative temperature anomalies are also observed in regions around Greenland and the northeastern part of North America, as well as in the western part of the continent at higher latitudes when \( M_0 > 0 \). The reverse occurs when \( M_0 < 0 \).

When \( M_0 > 0 \), less than normal rainfall is received over the NE Pacific and in a zone from the NE Atlantic to western Europe near 40°N as a result of the divergence of the water vapor in those regions. Because the water vapor converges at middle-high latitudes on the Eurasian continent and at lower latitudes in the central Pacific, more than normal rainfall is received in these regions. Note that more rainfall is also observed in the northwestern part of China, although the vapor convergence is relatively weak. When \( M_0 < 0 \), the rainfall anomaly and vapor transport scenarios are opposite to those observed when \( M_0 > 0 \).

However, when AM accumulates over continents in the NH, both the temperature and rainfall anomalies are nearly the inverse of those that occur when AM accumulates over open oceans. This can be clearly seen in Figures 7c and 7d. Note that the significant temperature anomalies disappear in the regions around the Mediterranean and the middle of Russia in Figure 7c, revealing certain asymmetries compared with their counterparts in Figure 7a. A similar situation is also observed in the anomalous rainfall distributions; several significant correlations of rainfall with \( M_1 \) vanish in the northern part of China in Figure 7d in comparison with those in Figure 7b.

The \( M_1 \)-related winter climate anomalies exhibit a similar pattern to that of the \( M_0 \)-related anomalies, although their signs are opposite because of the different definitions of \( M_1 \) and \( M_0 \). This can be clearly observed in Figures 7e and 7f. The surface air temperatures are significantly affected by the MAEA teleconnection in regions around the Mediterranean, the higher latitudes of Eurasia, the Aleutian Islands, and the eastern part of Canada. Rainfall anomalies are also strongly influenced in those regions, as seen in Figure 7b.

The regions in which the winter climate may be influenced by the MANP, EPAR, and MAEA patterns are listed in Table 3.
6. Conclusions and Discussion

Distinct thermal contrasts form among the different types of Earth’s surfaces, including liquid water oceans, continents, and ice-covered Arctic regions, during boreal winter. The AM is driven to migrate among these surfaces on interannual time scales. It is found that the air mass shifts remarkably between sea and land surfaces and between surfaces of liquid water and ice, leading to two strong antiphase relationships of SAPA between these two pairs of regions.

The teleconnection patterns of AM migrations, including the MANP, EPAR, and MAEA patterns, were observed for the period of 1979–2012. The MANP pattern is characterized by anomalous changes in AM predominantly over Eurasia, central North America, and southern Greenland to balance the AM variations over the Pacific, Bermuda Triangle, and Mediterranean at middle latitudes. Longitudinally, strong exchanges occur between the Arctic ice cover and the midlatitude northeastern Pacific, the Atlantic-Mediterranean region, and East Asia. The EPAR mainly exhibits seesaw-like SAPA variations between the Eurasian continent and the northern Pacific south of the Aleutian Islands. The MAEA pattern, although it appears somewhat similar to the MANP pattern, is largely driven by strong SAPA connections among the Mediterranean, western Europe, the Arctic, and East Asia.

The anomalous diabatic heating patterns vary with an antiphase relationship between liquid water oceans and continents and between liquid water oceans and sea-ice-covered Arctic regions, driving anomalous AM exchanges between these regions. Vertical circulations and quasi-stationary Rossby waves play important roles in connecting those strong correlation centers and thus are partially responsible for the formation of the MANP, EPAR, and MAEA patterns.

The winter climate in the NH, including surface air temperatures and precipitation, may be influenced by AM migrations among these three types of surfaces. In association with the MANP pattern, strong variations in surface air temperature and rainfall are observed, mainly in regions around the Mediterranean Sea, at middle-high latitudes on the Eurasian continent, and in the eastern part of North America. The MAEA teleconnection has an influence similar to that of the MANP pattern, although it differs in North America and the western part of China. The EPAR influences air temperatures predominantly over Russia, the northern part of China, Japan, and the western USA and at high latitudes east of Greenland. Rainfall may also be affected by this pattern in the northern coastal regions of the Mediterranean Sea, the zonal region around the Ural Mountains, and other scattered areas. Moreover, because surface climate anomalies in the NH such as rainfall and air temperature are significantly and highly correlated with the AM variations over these three different types of Earth’s surfaces (Figure 7), the time series of areal averages of SAPA, including $M_D$, $M_L$, and $M_I$, can serve as good indicators for the simultaneous monitoring of climate conditions throughout a wide area in the Eurasia-Pacific sector.

Note that the OIAR, in the context of which the MANP and MAEA patterns are observed, appears to be strongly related to the AO because the overall signatures of the OIAR and the AO pattern are similar. Although the AO is sometime believed to be strongly related to the North Atlantic Oscillation [Ambaum et al., 2001] and the paradigm of the Northern Annular Mode [Wallace, 2000; Wallace and Thompson, 2002], it is well known as the strongest signal of interannual variability in the extratropical regions of the NH [Thompson and Wallace, 1998; Baldwin, 2001] and has strong impacts on boreal weather/climate [Thompson and Wallace, 2001; Gong et al., 2001; McAfee and Russell, 2008; Mao et al., 2011]. Following the definition of the AO [Thompson and Wallace, 1998], an empirical orthogonal function (EOF) analysis was conducted on the winter SAPA data from the 1979–2012 period to obtain the AO index indicated by the time series of coefficients of the leading EOF mode. The correlations of the AO index with $M_D$ and $M_L$ were found to be 0.82 and −0.87, respectively. These two high correlations suggest that the MANP and MAEA patterns may form part of the AO. This is a reasonable expectation because of the meridional shifts of AM between the Arctic and its surrounding regions. The EPAR pattern, however, is linked to the AO with a weaker but still significant correlation of −0.42. The reason that this correlation is weaker remains unclear. Moreover, these patterns may also be related to various other known teleconnection patterns, such as the Eurasian (EU) and Pacific/North American patterns identified by Wallace and Gutzler [1981] or the Aleutian-Icelandic seesaw reported by Honda et al. [2001]. The EU pattern is one of the major teleconnections during boreal winter and is characterized by a west-east-oriented wave train over Eurasia in the middle troposphere. Therefore, we expect that the EPAR pattern may be related to the EU pattern. In fact, the correlation of $M_I$ with the EU
index was found to be 0.65, suggesting a possible relation to the EU teleconnection. Therefore, the EPAR pattern and its differences from the MANP and MAEA patterns deserve more extensive investigation in the future.

Note that the OIAR and EPAR can be successfully simulated using most models from phase 5 of the Coupled Model Intercomparison Project (CMIP5). However, the very weak positive correlation of $M_1$ with $M_2$ is not properly simulated in approximately half of CMIP5 models; the simulated correlations are positive but too strong. This shortcoming of CMIP5 models also requires further investigation.

Acknowledgments

The authors are very grateful to the anonymous reviewers for their helpful comments. The NCEP/NCAR reanalysis data used here were obtained from the NOAA-CIRES Climate Diagnostics Center and are accessible at http://www.esrl.noaa.gov. The ECMWF data were obtained from the European Centre for Medium-Range Weather Forecasts (http://apps.ecmwf.int/datasets/), and the HadISST data, obtained from the Met Office Hadley Centre, are available at http://www.metoffice.gov.uk/hadobs/hadisst/data. This work was supported by the National Natural Science Foundation of China (41175062 and 41330425) and the Creative Program of Science and Technology of Jiangsu (KYZZ_0239 [Zhang] and CXZZ12_0485 [Li]). The graphs were plotted using the software packages GrADS and NCL.

References

Lorenz, E. N. (1951), Seasonal and irregular variations of the Northern Hemisphere sea-level pressure field, J. Meteorol., 8, 52–59.


