ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 29, NO. 5, 2012, 1111–1118

Circulation Indices of the Aleutian Low Pressure System: Definitions and Relationships to Climate Anomalies in the Northern Hemisphere

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(Received 11 October 2011; revised 23 December 2011)

ABSTRACT

In this study, a group of indices were defined regarding intensity (P), area (S) and central position (λ_c, ϕ_c) of the Aleutian low (AL) in the Northern Hemisphere in winter, using seasonal and monthly mean height field at 1000-hPa. These indices were calculated over 60 winter seasons from 1948/1949 to 2007/2008 using reanalysis data. Climatic and anomalous characteristics of the AL were analyzed based on these indices and relationships between the AL, and general circulations were explored using correlations between indices$P$, λ_c, and Pacific SST, as well as Northern Hemisphere temperature and precipitation. The main results are these: (1) AL is the strongest in January, when the center shifts to the south and west of its climatological position, and it is the weakest in December when the center shifts to the north and east. (2) AL intensity (P) is negatively correlated with its longitude (λ_c): a deeper low occurs toward the east and a shallower low occurs toward the west. On a decadal scale, the AL has been persistently strong and has shifted eastward since the 1970s, but reversal signs have been observed in recent years. (3) The AL is stronger and is located toward the east during strong El Niño winters and vice versa during strong La Niña years; this tendency is particularly evident after 1975. The AL is also strongly correlated with SST in the North Pacific. It intensifies and moves eastward with negative SST anomalies, and it weakens and moves westward with positive SST anomalies. (4) Maps of significance correlation between AL intensity and Northern Hemisphere temperature and rainfall resemble the PNA teleconnection pattern in mid-latitudes in the North Pacific and across North America. The AL and the Mongolian High are two permanent atmospheric pressure systems adjacent to each other during boreal winter over the middle and high latitudes in the Northern Hemisphere, but their relationships with the El Niño/La Niña events and with temperature and precipitation in the Northern Hemisphere are significantly different.

Key words: circulation indices, the Aleutian Low, definitions and relationships, climate anomalies

Citation: Wang, P. X., Julian X. L. Wang, H. Zhi, Y. K. Wang, and X. J. Sun, 2012: Circulation indices of the Aleutian low pressure system: Definitions and relationships to climate anomalies in the Northern Hemisphere. *Adv. Atmos. Sci.*, **29**(5), 1111–1118, doi: 10.1007/s00376-012-1196-7.

1. Introduction

The most significant decadal variations of the North Pacific ocean–atmosphere system in winter are the Aleutian low (AL), which has strengthened and moved eastward, while SST in the central North Pacific has cooled significantly since the late 1970s (Trenberth, 1990; Trenberth and Hurrell, 1994; Miller et al., 1997; Nakamura et al., 1997). Such changes are strongly correlated with ocean–atmosphere interaction

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over the tropical middle and eastern Pacific, and they are the main causes of climate anomalies from seasonal to decadal time scales over a vast region in the Northern Hemisphere (Latif and Barnett, 1996). Variabilities of the AL over the North Pacific are indicative of interannual and decadal variations of the atmospheric circulation, land surface temperature and sea surface temperature (SST; Overland et al., 1999). The previous results suggest that the AL may be a key factor for the coupling of the Arctic Oscillation (AO) and Pacific decadal oscillation. A strong AO can result in the AL deepening, and it can affect decadal oscillation of the ocean–atmosphere system in the North Pacific Ocean through mid-latitude ocean–atmosphere interaction in the Northern Hemisphere, and vice versa (Sun and Wang, 2006). Therefore, it is important to study the anomalies of the AL in the North Pacific.

The AL is a subpolar cyclone over the North Pacific and one of the major semi-permanent atmosphere activity centers in the Northern Hemisphere winter. Numerous studies have been conducted on AL anomalies (Chen et al., 1992). Changes of its intensity and location are the main signs of atmospheric circulations over the North Pacific during the winter (Hartmann and Wendler, 2005; Rodionov et al., 2005), and they have important impacts on climatic change. For example, meridional flow position and intensity changes on the east and the west sides of its center directly impact the heat exchange between polar region and the mid-latitude Pacific Ocean, and the strength of westerly flow on the south side of its center effects westerly drift. Mantua et al. (1997) pointed out that the AL was significantly correlated with the Pacific Decadal Oscillation (PDO), and the warm phase of PDO corresponds to the strong AL, while the cold phase of PDO corresponds to the weak AL. On the decadal time scale, AL changes may be important external forcing mechanisms of PDO (Schneider and Cornuelle, 2005). In the study of the atmosphere circulation anomalies, indices are often used to describe concisely and quantitatively nature of the circulation system. To better describe anomalies of AL, different researchers defined several parameters to characterize AL intensity, area, and location. For example, Trenberth (1990) used regional average of sea level pressure (27.5°–72.5°N, 147.5°E–122.5°W) in the winter months to analyze AL strength; Overland et al. (1999) analyzed central values from sea level pressure field over the AL region (40°–60°N, 160°E–160°W) averaged for winter. Ren (1991) examined cumulative values weighted on each grid point within the 1010-hPa contour as the monthly AL intensity index.

Wang et al. (2007) defined a general method on circulation indices for a closed pressure system that includes three components: intensity (P), area (S), and center position $C(\lambda_c, \phi_c)$. To better describe center position distribution of a closed pressure system, Wang et al. (2008) defined a compression coefficient (μ) of a region, average distance (r) of a closed pressure system center from its climatological position, and a main abnormal direction (β). Wang et al. (2007, 2008) first defined and calculated monthly and seasonal AL circulation indices for 60 winters from 1948/1949 to 2007/2008. In the present study, the time-frequency characteristics of AL anomalies were analyzed, and relationships between AL indices P, λ_c and the Pacific SST anomalies, especially during El Niño/La Niña events, were evaluated.

2. Definition and calculation of the Aleutian Low circulation indices

The data used in this study include the following: (1) NCEP/NCAR reanalysis (Kalnay et al., 1996) global and monthly 1000-hPa geopotential height and temperature fields and precipitation ratio from January 1948 to December 2008; (2) NOAA Extended Reconstructed SST data (Smith et al., 2004) from January 1948 to December 2008; (3) NOAA Oceanic Niño Index (ONI), which is comprised of the 3-month moving average of Niño3.4 region SST data from January 1950 to December 2008.

Using the method of Wang et al. (2007), 1000-hPa seasonal and monthly mean AL circulation indices P, S and (λ_c,ϕ_c) were defined (online supplements) and calculated. The study area is represented by the pentagon surrounded by grid points of (20°N, 132.5°E); (20°N, 110°W); (60°N, 110°W); (75°N, 160°W); (60°N, 132.5°E) (online supplement Fig. S1). A characteristic contour line $f_0 = 70$ gpm approximates the interested region and separates the polar low and the AL.

3. Climatology and anomalies of the Aleutian Low indices

Each AL index time series was decomposed into time mean and anomalies (Lorenz, 1967). Statistical features of time mean $\overline{P}$ and $\overline{S}$ are shown in Table 1. It is clear that AL is the strongest and largest and that the center of the AL is located southernmost and westernmost in January.

Root mean square errors (σ) of the three circulation indices are shown in Table 2; they represent measurements of AL anomalies. Comparing the σ and time mean of S and P, its absolute ratios are $\sim$2/3 for P and 1/3 for S, indicating strong interannual anomalies of the circulation indices. It justifies utilizing these

Table 1. Time mean values of the AL circulation indices from 1948/49 to 2007/08.

	DJF	Dec	Jan	Feb
$\overline{S}$ (rad^2)	0.29	0.28	0.32	0.28
$\overline{P}$ (dagpm rad^2)	−1.36	−1.50	−1.81	− 1.56
$\overline{\lambda_c}$ (°E)	181.5	184.6	181.8	182.4
$\overline{\phi_c}$ (°N)	52.1	54.0	50.9	51.6

Table 2. Climatic variability (σ) of the AL circulation indices from 1948/49 to 2007/08 and the correlation coefficients (R) between size (S) and intensity (P).

	DJF	Dec	Jan	Feb
σ_S (rad ^{2})	0.08	0.09	0.11	0.11
σ_P (dagpm rad^2)	0.74	0.98	1.17	1.09
σ_λ (°)	6.64	8.73	9.22	10.32
σ_ϕ (°)	2.34	3.06	3.42	3.37
$R(S,P)$	−0.908	−0.923	−0.910	−0.924

parameters to analyze circulation anomalies.

According to correlation coefficients R in Table 2, the area (S) and intensity (P) are closely associated with each other, only index P will be analyzed. Analyses in following sections are all based on normalized series of the AL intensity (P) and locations (λ_c, ϕ_c).

The decadal component was separated from seasonal and monthly mean P series using the period analysis method (Wang et al., 2007); this component is indicated by the thick solid line in Fig. 1. The F-test showed that the decadal component is only statistically significant in January at 95% confidence level. This component is generally positive before the middle of 1970s and is mainly negative afterward.

The anomalous time series of P was further analyzed using the wavelet power spectrum and an associated significance test method (Wang et al., 2008). The most prominent result was a significant decadal signal (p <0.05) around the 1970s (figure not shown).

On both seasonal and monthly scales, the AL centers were clustered in the North Pacific, and its merid-

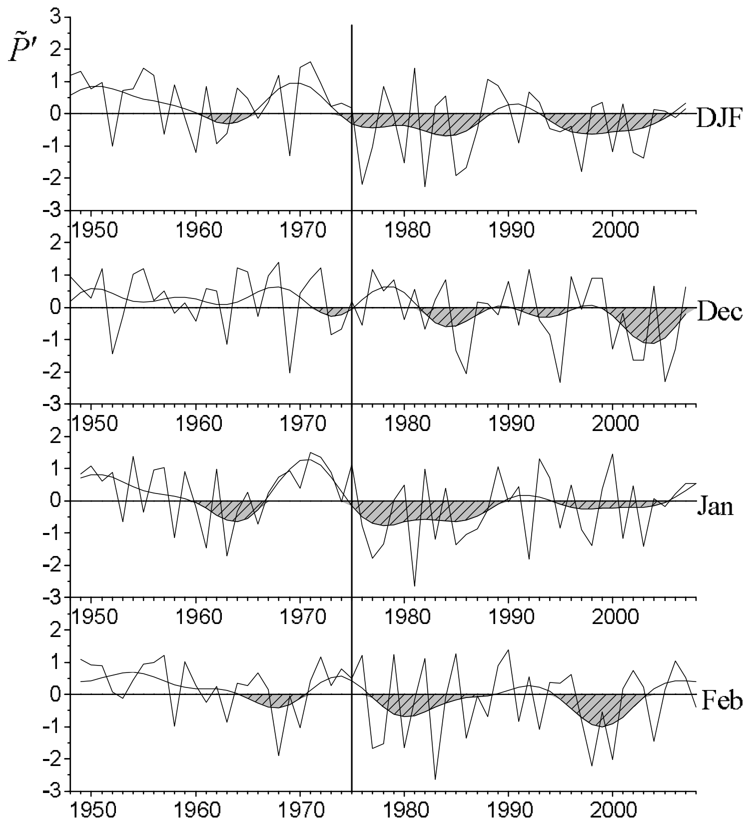

Fig. 1. Time series of standardized intensity index (P) of 1000 hPa Aleutian Low in winter, Dec., Jan., and Feb. from 1948/49 to 2007/08, the thick solid is the decadal component and the shaded areas show the stronger periods.

Table 3. Correlation coefficients (R) between the intensity index (P) with the center position indices (λ_c, ϕ_c).

	DJF	Dec	Jan	Feb
R (P, λ_c)	−0.720*	−0.331*	−0.421*	0.306*
R (P, ϕ_c)	0.182	0.172	0.137	0.320*

Notes: *denotes the values passing F-test at the significant level $\alpha = 0.05$.

ional displacement range ($\Delta\varphi_c$) was less than the zonal one ($\Delta\lambda_c$). The decadal component of λ_c and ϕ_c was also computed from its seasonal and monthly values, and the F-test shows that the decadal variations are significant. The AL center was displaced eastward for the 1970s, 1980s, and 1990s, and its meridional changes were less clear and consistent (figure not shown).

The data in Table 3 show a significant negative correlation between the intensity index P and the center position index λ_c on both seasonal and monthly scales, indicating that the AL intensification was accompanied by eastward movement.

4. Relationships between the Aleutian Low indices and SST anomalies

It is well known that the existence of the AL in winter is due to forcing of zonal temperature difference between ocean and land. Therefore, Latif and Barnett (1996) thought that the SST anomalies in the North Pacific would lead to a regional circulation anomaly through the mid-latitude unstable ocean–atmosphere interaction. On the other hand, thermal anomalies in the tropical Pacific Ocean also play a forcing role on the mid-latitude circulation anomalies (Lau, 1997; Graham et al., 1994; Deser et al., 2004), such as El Niño or La Niña impacts. Horel and Wallace (1981) proposed the Pacific North American teleconnection pattern (PNA) and pointed out that remote atmospheric responses to forcing sources and its low-frequency behavior manifested a wave train similar to the great circle path. Theoretical studies of Hoskins and Karoly (1981) posited a dynamic mechanism for the PNA teleconnection. Based on the AL circulation indices, this study provides an alternative explanation for low-level circulation over the mid-latitude North Pacific Ocean and its relationships with mid-latitude SSTs of the North Pacific and El Niño and La Niña events.

Figure 2 shows the correlation coefficients between P and the North Pacific SST. For seasonal means (Fig. 2a), significant positive correlations are centered on the central North Pacific (170°W, 40°N), with a significant negative correlations on its northeastern, eastern, and southeastern flank. For monthly means

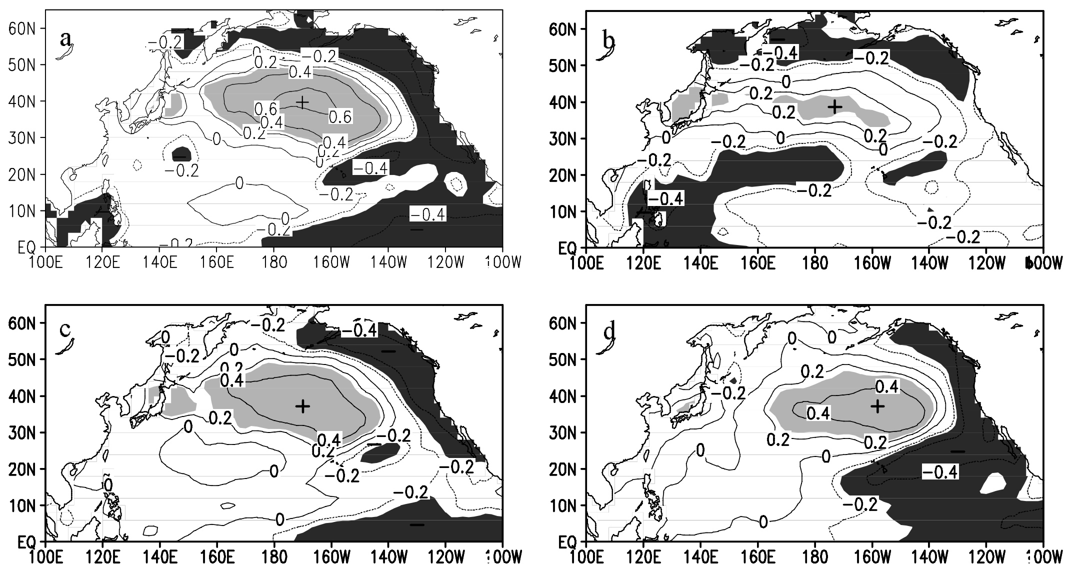

Fig. 2. The correlation coefficients (R) between intensity index (P) of Aleutian Low and the SST in the same period. (a) winter; (b) Dec; (c) Jan; (d) Feb.. The shaded area is $|R| \geqslant R_{0.05}$, the dark is the positive correlation, and the plain is the negative correlation.

Table 4. Correlation coefficients between ONI index and AL indices P, λ_c, and ϕ_c.

	DJF	Dec	Jan	Feb
R (P, ONI)	−0.292*	−0.163	−0.338*	−0.297*
R (λ_c, ONI)	0.347*	0.202	0.337*	0.261*
R (ϕ_c, ONI)	−0.218*	−0.249	−0.022	0.093

Notes: * denotes the values passing significant F-test at the confidence level $\alpha = 0.05$.

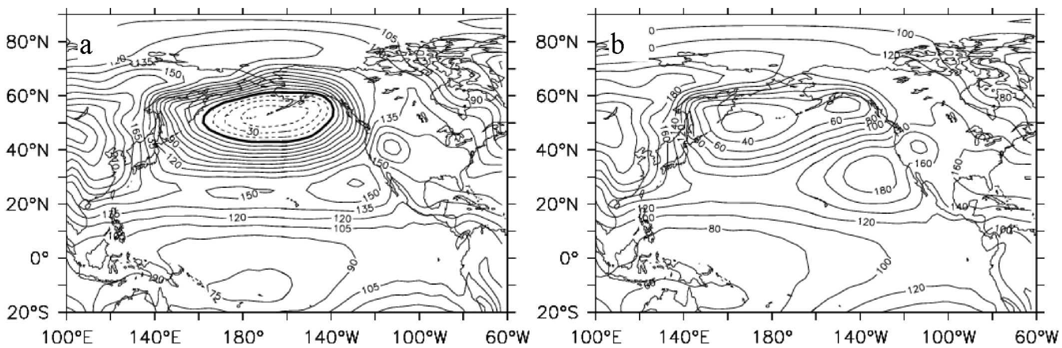

Fig. 3. The 1000 hPa height composite in winter (12, 1, 2), (a) during El Niño, (b) during La Niña.

(Figs. 2b–d), it tends to resemble the seasonal map (Fig. 2a) with some variations. The positive correlations are strongest in January and weakest in December, while the negative correlations increase from December to February. These correlations suggest that positive SST anomalies in the North Pacific are associated with a weakened AL, and vice versa. However, when positive SST anomalies appeared in the Northern Pacific, offshore of North America coasts, and subtropical Eastern Pacific, the Aleutian Low intensified toward these regions.

Table 4 shows the correlation coefficients of three AL circulation indices with the ONI index defined by NOAA. The negative correlations between P and ONI as well as the positive correlations between λ_c and ONI indicate that the AL strengthens and drifts eastward during El Niño events, whereas it weakens and drifts westward during La Niña events (Fig. 3).

5. Relationships between the Aleutian Low indices and temperature and precipitation anomalies

Figure 4 shows the correlation coefficient maps between P and the Northern Hemisphere temperature. Significant correlation areas are located in the central North Pacific, the northwestern coasts and southeastern region of the North America. Notably, these correlation centers resemble the PNA wave train along the great circle path. There are also negative correlations covering large area of tropics and subtropics, with considerable month-to-month variations. Notably, there is no obvious relationship between the AL intensity (P) and temperature over the East Asia. In contrast, the intensity of the Mongolian High pressure system is significantly correlated with temperature over East Asia but not with temperature over the North Pacific and North America (Liu et al., 2011). Although the AL and the Mongolian High are adjacent atmospheric activity centers over Asian-Pacific mid-latitudes, their dramatically different global influences warrant further exploration.

Figure 5 shows the correlation coefficient maps between P and Northern Hemisphere precipitation. Significant correlation patterns exhibit similar wave train characteristics. Differences include positive correlations in the North Pacific, extending westward to mid-latitudes of the East Asia and much less correlation between P and tropical rainfall.

There are another two positive correlation areas in the tropical central Pacific centered near Hawaii and in the tropical western Atlantic to Caribbean Sea, and the latter seems to be extension of the PNA wave train.

6. Summary

In this study, we defined the seasonal and monthly mean indices for AL intensity, area or coverage, and central location during the Northern Hemisphere winter. We calculated the time series of several indices

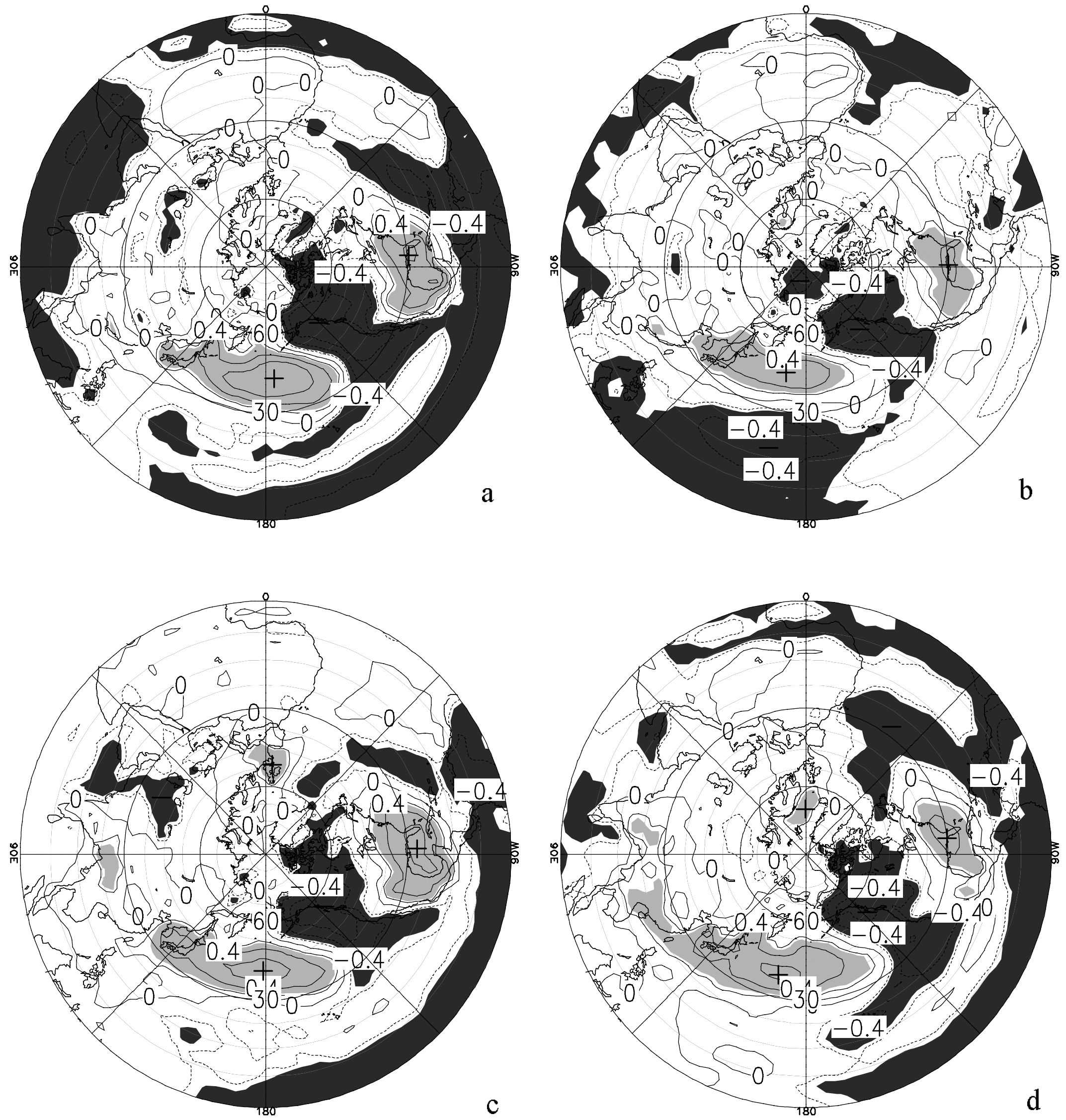

Fig. 4. The correlation coefficients (R) between the intensity index (P) of the Aleutian Low and the temperature in the Northern Hemisphere during the same period (1948/49–2007/08). (a) DJF; (b) Dec.; (c) Jan.; (d) Feb., the shaded area is $|R| \geqslant R_{0.05}$, the light-shaded is the positive correlation, and the dark-shaded is the negative correlation.

using reanalysis data from 60 winters from 1948/49 to 2007/08. The climatic and anomalous characteristics of the AL were analyzed based on correlations between these circulation indices and the Pacific SST, the Northern Hemisphere temperatures, and precipitation. The main results were these: (1) The AL is the strongest in January, with its center located south and west of its climatological position. (2) There is a strong correlation between the intensity of the AL and its zonal displacement; it drifts eastward while intensifying and drifts westward while weakening. On a decadal scale, the AL has been consistently strong and has drifted eastward since the 1970s, but reversal signals have been observed in more recent years. (3) The AL is stronger and shifts eastward in the strong El Niño years and reverses in strong La Niña years, which are particularly evident after 1975. AL intensity is significantly correlated with the North Pacific SST: it strengthens and moves eastward during years with negative SST anomalies, and vice versa. (4) The significant correlation patterns between AL intensity and Northern Hemisphere temperature and precipi-

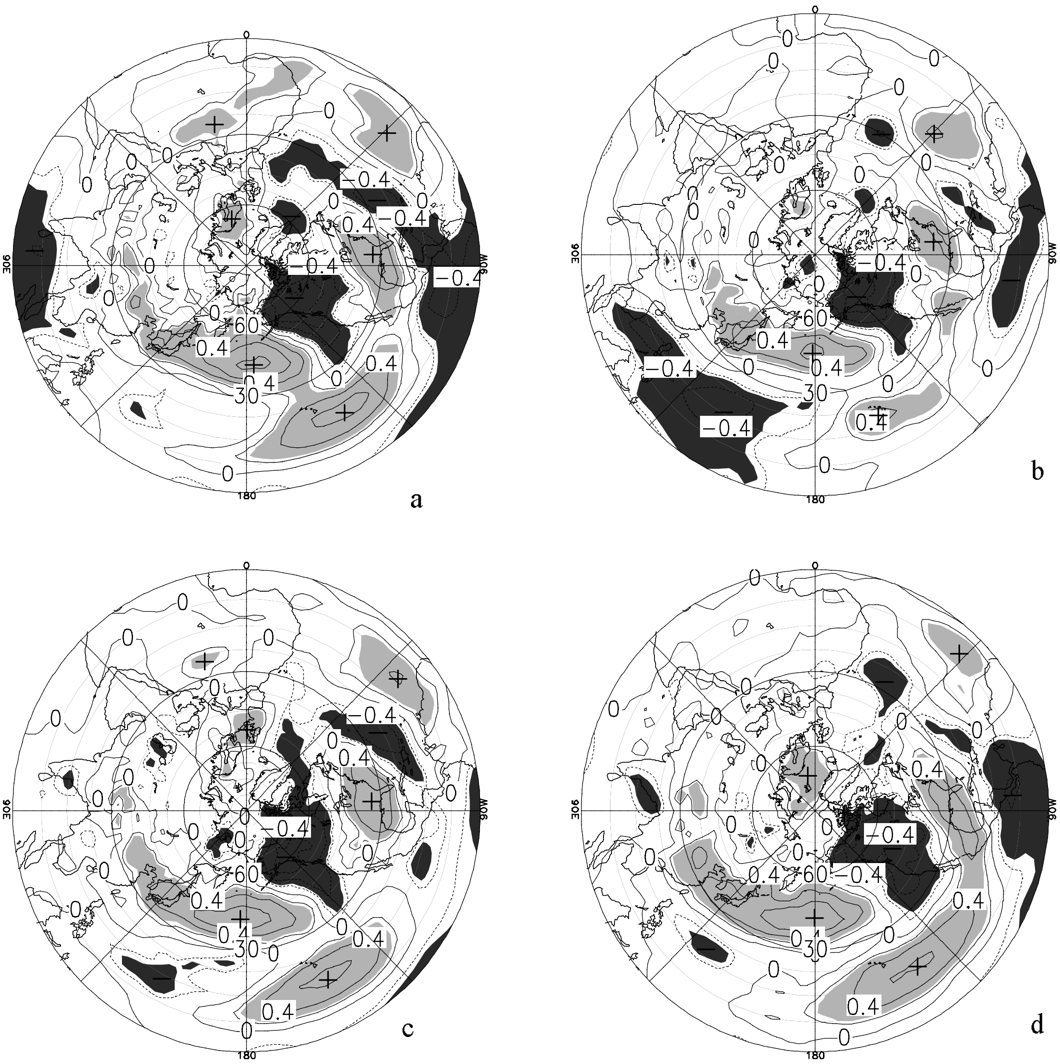

Fig. 5. The correlation coefficients (R) between the intensity index (P) of Aleutian Low and the precipitation in the Northern Hemisphere during the same period (1948/49 to 2007/08). (a) DJF; (b) Dec; (c) Jan; (d) Feb., the shaded area is $|R| \geqslant R_{0.05}$, the light-shaded is the positive correlation, and the dark -shaded is the negative correlation.

tation exhibit characteristics of the great circle wave train, and they resemble the PNA teleconnection mode over the mid- and high-latitudes of the Northern Hemisphere. The AL and the Mongolian High are two adjacent atmospheric activity centers during winter season; however, their relationships with El Niño/La Niña events, and with Northern Hemisphere temperature and precipitation are significantly different, which deserves further study.

Acknowledgements. The authors gratefully acknowledge the helpful suggestions and comments from two anonymous reviewers. This project is supported by National Key Technology Research and Development Program (Grant No. 2007BAC29B02), the National Basic Research Program of China's 973 Program (Grant Nos. 2010CB950502 and 2010CB428904), the project funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD).

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