

A modified zonal index and its physical sense

Jianping Li

National Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG),
Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

Julian X. L. Wang

Air Resources Lab, NOAA, Silver Spring, MD, USA

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[1] A modified zonal index (ZI) for the Northern Hemisphere (NH) general circulation is defined as the normalized difference in zonal-averaged sea level pressure anomalies between 35°N and 65°N. The ZI is a measure of hemispheric-wide fluctuations in air mass between two annular belts of action (ABAs) over middle and high latitudes, centered near 35°N and 65°N, respectively. The spatial structure of the NH general circulation represented by the ZI is a zonally symmetric pattern, similar to the NH annular mode. Some physical features associated with the ZI are discussed and summarized as a concept model, and the analysis indicates that the Ferrel cell stands out as a dominant signal in the zonal-mean circulation anomalies related to the ZI, implying a strong dynamical property of the general circulation in the mid-high latitudes. *INDEX TERMS:* 3309

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1. Introduction

[2] To measure the intensity of the general zonal circulation of the Northern Hemisphere (NH) and describe its variability, Rossby *et al.* [1939] presented a simple index, the zonal index (ZI), which was defined by the zonally-averaged sea-level pressure (SLP) difference between 35°N and 55°N. The Rossby's zonal index (hereafter ZI_R) represents the intensity of the westerlies in the mid-latitude between 35°N and 55°N and was extensively used to study variations of the atmospheric general circulation [Namias, 1950; Wallace and Hsu, 1985; Kidson, 1985; Kass and Branstator, 1993; Gong and Wang, 1999]. However, the choice of 55°N in the ZI_R may not be optimal. In fact, the correlations in the zonally-averaged SLP anomalies between 35°N and 55°N are very weak at -0.13, -0.10 and -0.03 for monthly, seasonally and annual data, respectively, indicating a linear independence of the zonally-averaged SLP anomalies at the two latitudes. Moreover, the ZI_R may contain large noise since the signal-to-noise ratios [Trenberth, 1984] in it, which is defined as the ratio of the standard deviations of the sum of and difference between the zonal-mean SLP series at 35°N and 55°N, are small at 1.14, 1.11 and 1.03 for monthly, seasonally and annual data, respectively. The low signal-to-

noise in the ZI_R and the linear independence between the zonally averaged SLPs at 35°N and 55°N indicate that their linear combination as an index may not contain more information than their individual. This study is thus motivated to find an approach to define better the intensity of the NH zonal circulation, and tries to explore related physical features. The NCEP/NCAR reanalysis monthly data (1958–2000) [Kalnay *et al.*, 1996] are employed. The annual cycle of data was removed by subtracting the mean monthly values for the period 1958–2000.

2. A Modified ZI

[3] Figure 1 shows cross correlations between zonally averaged SLP anomalies at various latitudes in the NH. The outstanding features are significant negative correlations between mid- and high-latitudes, indicating a zonally symmetric, hemispheric north-south seesaw in air mass between temperate latitudes and high latitudes including the Arctic region, and in agreement with previous studies [Lorenz, 1951; Kutzbach, 1970; Wallace and Gutzler, 1981]. Apparently, this seesaw consists of two homogeneous zones centered around 35°N and 65°N, where the SLPs between

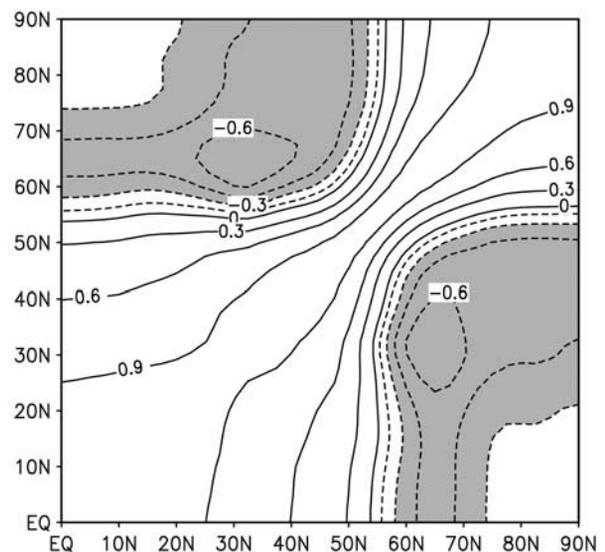


Figure 1. Correlation between annual zonally-averaged SLP anomalies in the NH (1958–2000). Critical negative values of the correlation at the 99.9% confidence level are shaded. The contour interval is 0.1 for negative values. Note that the map is symmetric about the diagonal.

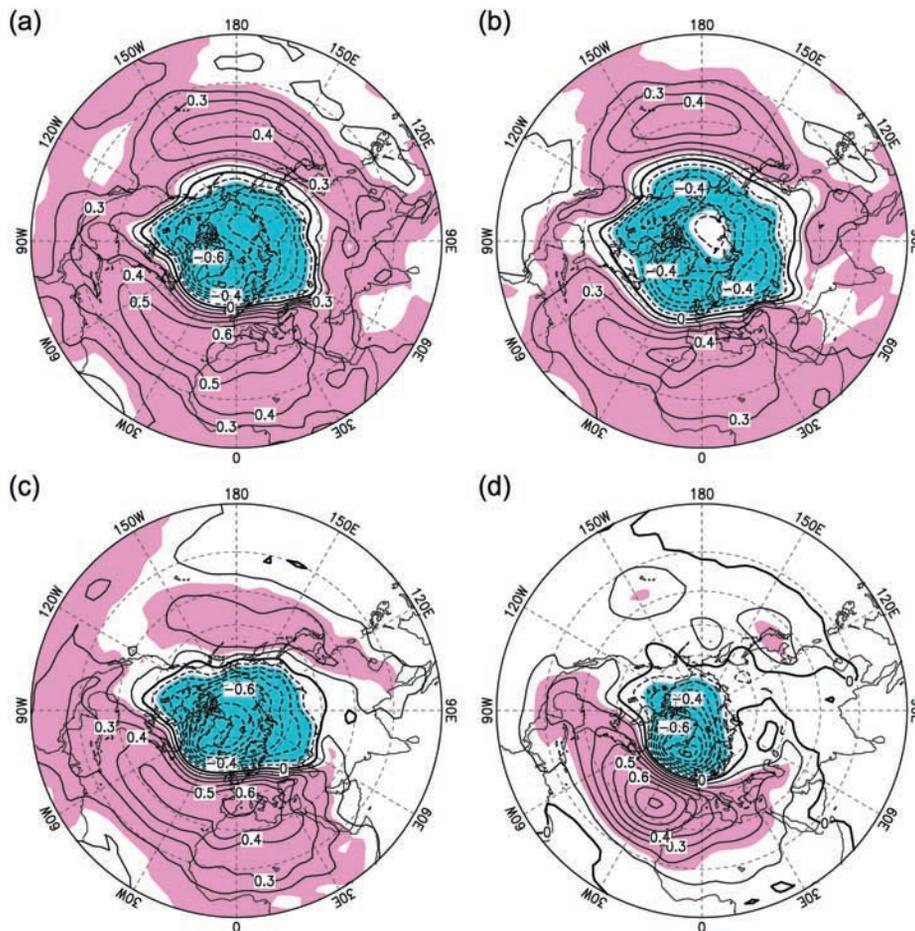


Figure 2. Correlation maps between monthly SLP anomalies in the NH (1958–2000) and (a) the ZI, (b) ZI_R [Rossby *et al.*, 1939], (c) AO index [Thompson and Wallace, 1998] and (d) NAO index [Rogers, 1984]. The contour interval is 0.1. The red (blue) shading indicates significant at the 99.9% confidence level. The latitude lines are at 15 degree intervals starting with the equator at the edges.

them are most strongly negative correlated. In this paper, we define these two zones as the annular belts of action (ABAs), which are separated by a narrow transition zone between 50–55°N (Figure 1). The SLPs within the transition zone tend to be uncorrelated with those in the ABAs. The SLPs within the two ABAs represent the relative strengths of the subtropical high and sub-polar low, respectively. Therefore, a new simple ZI can be defined as the difference in the normalized monthly zonal-mean SLP (\hat{P}) between the two ABAs as follows:

$$ZI = \hat{P}_{35^{\circ}N} - \hat{P}_{65^{\circ}N} \quad (1)$$

The ZI is a measure of the hemisphere-wide fluctuations in surface air mass between the two ABAs. The signal-to-noise ratios in the ZI for the monthly, seasonal and annual data are 1.80, 1.85 and 2.31, respectively, which are far more than those in the ZI_R , suggesting larger signal in the ZI.

[4] Figure 2a illustrates the spatial structure in SLP field represented by the ZI. The zonally symmetric pattern is a predominant characteristic in the map. The ZI is positively correlated with SLP anomalies over the subtropical and mid-latitudes, and is strongly negative correlation with SLP

anomalies over the high latitudes and polar region, implying an out-of-phase relationship in SLP anomalies between the two ABAs. From Figures 2a and 2b, the ZI demonstrates a more robust structure and a stronger correlation with SLP anomalies than the ZI_R . Besides, the ZI_R shows a very weak correlation with SLP anomalies over the polar cap poleward of 75°N as well as over the mid-latitude North American and Asian continents (Figure 2b). Therefore, the ZI indeed reflects better the action belts found in the SLP field than the ZI_R .

[5] In a certain degree the spatial pattern represented by the ZI is similar to the NH annular mode (NAM) or Arctic Oscillation (AO) defined by the leading empirical orthogonal function (EOF) pattern of monthly SLP anomalies [Thompson and Wallace, 1998]. In fact, there is good relationship between the ZI and the time series of the leading EOF mode (AO index). All correlations between them (1958–2000), whether 12 calendar months and 4 seasons or monthly, seasonal and annual data, are significant above the 99.9% confidence limit, range from 0.61, the lowest in May, to 0.91, the highest in January. However, parts of the annular ring over land masses shown by the AO index in Figure 2c are missing [Kerr, 1999], whereas the ZI forms a complete ring (Figure 2a). Moreover, the AO

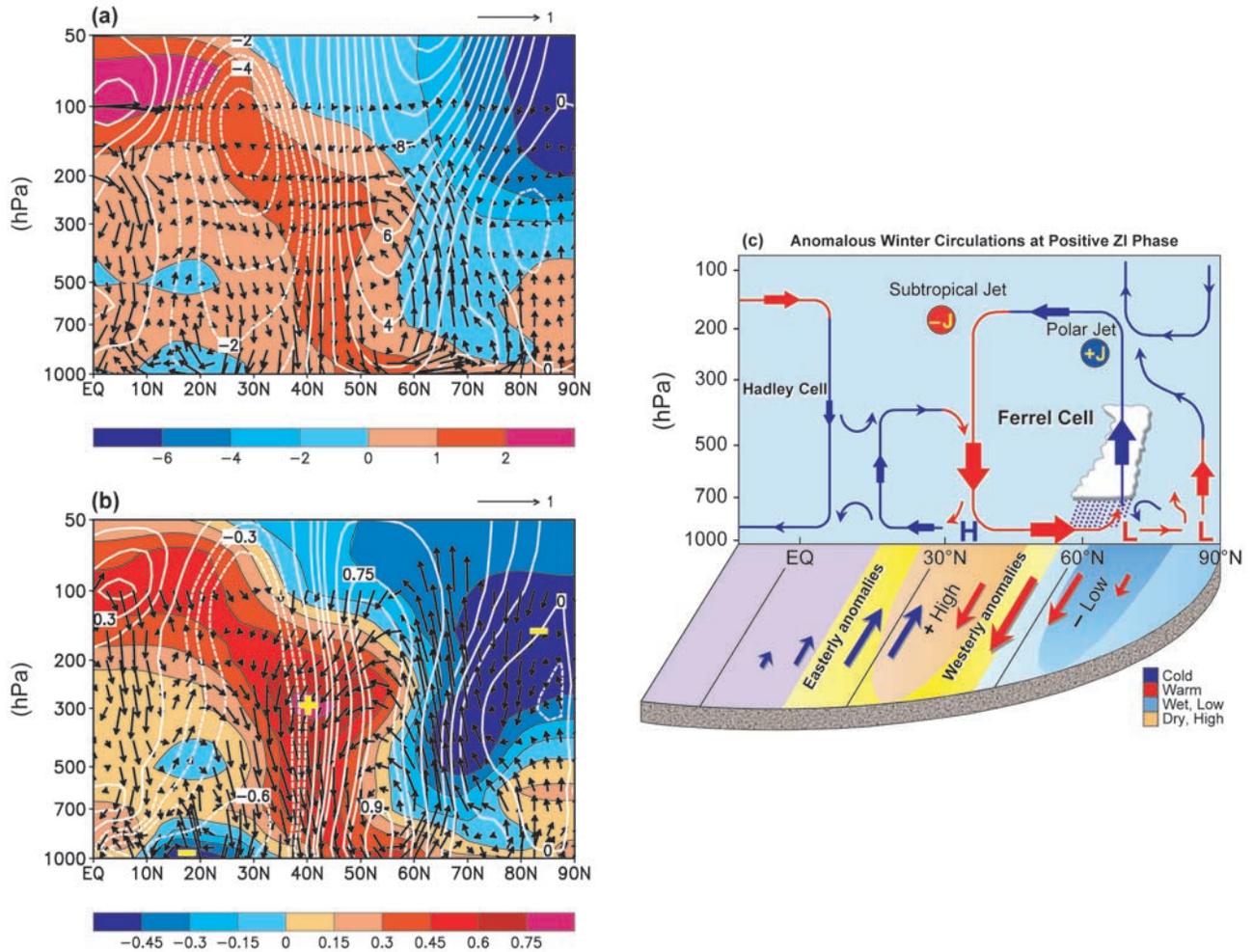


Figure 3. (a) Composite difference patterns in anomalous zonal-mean zonal wind (white lines), meridional circulation (vectors) and temperature (shaded) between winters with a ZI $> +1$ SD of the index and those with a ZI < -1 SD (high index minus low index winters) since 1958; (b) Correlations between the ZI and anomalous zonal-mean wind (white lines), meridional circulation (vectors) and temperature (shade) in winter (1958–2000) (The vector here is a vector of correlations whose two components are the correlation coefficients between the ZI and anomalously zonal-mean meridional wind and between the ZI and anomalously zonal-mean vertical velocity, respectively); (c) Schematic of NH anomalous winter circulations at positive ZI phase (Note that the part of the image shown below the abscissa down to the curved boundary at the bottom is the pictorial of horizontal motions and pressure anomalies at the earth surface). Contour intervals for zonal wind are 1.0 m s^{-1} (a) and 0.15 (b), vectors (a) in units of m s^{-1} for the meridional wind and cm s^{-1} for the vertical velocity. The yellow marks + and - in (b) denote the centers of positive and negative correlations between the ZI and zonal-mean temperature.

correlation pattern shown in Figure 2c has far more asymmetry around the globe at 30° – 40°N than does the ZI correlation in Figure 2a with the biggest differences in the Pacific Basin. These evidently indicate that the ZI demonstrates a much-pronounced annular ring structure than the AO index. The north-south seesaw structure implied by the ZI is thus called the NH annular oscillation. Besides, comparing with the NAO index [Rogers, 1984], the spatial feature represented by the NAO index accentuates a sectoral pattern over the North Atlantic sector (Figure 2d).

3. Related Physical Features to the ZI

[6] Vertical structures of circulation pattern associated with the ZI are determined from the composite and correlation analyses. Figure 3a is the composite difference between winters (DJF mean) with a ZI value greater than

one standard deviation (SD) of the index and those with a ZI value less than one negative SD. Both the numbers of positive and negative ZI years used to construct the composite are six. Figure 3b is a correlation map between the ZI and related circulation variables. A few key characteristics associated with the positive ZI winters, as shown in Figures 3a and 3b, are listed below:

[7] (1) Strong westerly anomalies over the higher latitudes between 45° – 75°N in the troposphere and poleward of 45°N in the stratosphere and easterly anomalies over the subtropical latitudes between 15° – 40°N (Figure 3a), which are indicative of a weakened subtropical jet, a strengthened polar jet and an enhancement in polar vortex strengths. The strongest correlation between the ZI and zonal-mean zonal wind anomalies is centered around 55°N (Figure 3b), and such a relationship exists in all seasons (not shown). Moreover, the significant correlations beyond the level of

0.05 between them at the surface are located between 45°N and 65°N, suggesting that the ZI reflects the intensity of the surface zonal wind anomalies over latitudes within the range.

[8] (2) Large positive temperature anomalies over the subtropics and mid-latitudes in the troposphere, extending to tropical lower stratosphere, while negative anomalies over mid-high latitudes north of 55°N from mid-troposphere to lower stratosphere (Figures 3a and 3b). In addition, there are weak warm anomalies over the polar cap poleward of 80°N below 500 hPa level, accompanying an anomalous rising flow over the Arctic region, therefore a weakened polar cell.

[9] (3) The most significant feature in the anomalous meridional circulation is an obvious enhancement of the Ferrel cell (Figure 3a). The cell consists a strong anomalous ascending flow poleward of 55°N with a maximum near 65°N, a subsidence over mid-latitudes between 35°–55°N with a minimum between 35°–40°N near the surface, a northerly flow between 35°–70°N in upper troposphere, and a strong southerly between 40°–80°N near the surface. The ascending and descending branches of the Ferrel cell are the strongest of the whole NH circulations and are corresponding to anomalous low- and high-pressure centers. Moreover, the strongest correlation between the ZI and zonal-mean vertical velocity anomalies is located near 65°N (Figure 3b). While the strong ascending branch of the Ferrel cell at 65°N extends deep into the stratosphere, the descending flow predominated in the lower troposphere (~40°N) induces a shallower and secondary tropical cell to its south (15°–35°N), resulting in a split in the anomalies in the Hadley cell. The strong southerly wind from 55° to 80°N in the near surface layer transports heat from lower latitudes to higher latitudes, which raises surface temperature in mid-high latitudes including the polar cap and weakens polar cell (Figures 3a and 3b). The predominant strength of the Ferrel cell in the anomalous meridional circulation makes it as a primary candidate for underlying physics and dynamics associated with the NH annular oscillation. Changes in the intensity and latitudinal displacement of the Ferrel cell directly effect the distribution of pressure, temperature, and rainfall over a vast area of the NH.

[10] A schematic diagram synthesized from Figures 3a and 3b is shown in Figure 3c and illustrates key circulation features and dynamic components associated with the positive ZI phase. It is characterized by 1) surface low-pressure anomalies over high latitude and throughout the polar region, centered near 65°N, and surface high-pressure anomalies across the subtropics and mid-latitudes, centered near 35°N, 2) stronger-than-normal westerlies across the mid-latitudes, centered around 55°N, 3) abnormally warm temperatures at the surface of mid-high latitudes, 4) abnormally strong Ferrel cell, which plays a predominant role in the vertical circulation, with a strong southerly at the surface over mid-high latitudes and cold (warm) air rising (sinking) to its north (south) and with a maximum anomalous ascent near 65°N (minimum anomalous descent between 35°–40°N), which is corresponding to the position of the polar front, 5) strengthening of polar jet with a cold condition and weakening of subtropical jet with a warm condition, 6) a diminishing polar cell with warm air rising at the Arctic region, 7) a split Hadley cell anomaly in subtropics. The negative ZI phase shows the opposite conditions (not shown) to those described above.

4. Summary

[11] Based on the result that the NH general circulation contains two ABAs over middle and high latitudes, centered around 35°N and 65°N, respectively, a modified ZI for the NH general circulation is defined as the normalized difference in zonal-averaged SLP anomalies between 35°N and 65°N. The ZI is a measure of hemispheric-wide fluctuations in air mass between the two ABAs and represents the overall intensity of the surface westerly anomalies over middle latitudes. The spatial structure of the NH general circulation represented by the ZI is an annular seesaw between the two ABAs, i.e., the NH annular oscillation, which is similar to the NAM [Thompson and Wallace, 2000] and closely associated with internal atmospheric dynamics. The analysis suggests that the Ferrel cell may play an important role in the basic physical processes of the NH annular oscillation. In addition, the physical concept diagram related to the ZI summarized in this paper is similar to that the Southern Hemisphere general zonal circulation including the Antarctic Oscillation (AAO) [Gong and Wang, 1998, 1999].

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J. P. Li, LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China. (ljp@lasg.iap.ac.cn)

J. X. L. Wang, Air Resources Lab, NOAA, Silver Spring, MD 20910, USA. (julian.wang@noaa.gov)