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A New Look at the Pacific/North American Index

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Abstract. This study examines inconsistencies in the Pacific/North American (PNA) index relative to atmospheric circulation over North America. Two types of atmospheric circulation were found to be associated with high PNA values. The first type is the true PNA pattern characterized by an amplified ridge-trough system. It appears to be related to the leading mode of sea surface temperature variability in the North Pacific. The second type is observed during El Niño events. It is characterized by a flattening of the polar jet stream and southward shift of the subtropical jet stream. The recognition of these two types of the PNA index improves our understanding of the relative role of to El Niño /Southern Oscillation events and sea surface temperatures in the North Pacific in affecting winter atmospheric circulation over North America.

1. Introduction

The Pacific/North American (PNA) teleconnection pattern has been recognized as a major mode of the atmospheric low-frequency variability over the Northern Hemisphere [*Wallace and Gutzler*, 1981]. The importance of the PNA for the North American climate arises from the fact that this pattern represents a departure from the mean tropospheric flow over the continent. In its normal mode, the PNA pattern features a climatological ridge over western North America and a trough over eastern North America. The PNA index measures an amplification (positive index) or damping (negative index) of this quasi-stationary wave [*Leathers and Palecki*, 1992]. The index is strongly correlated with monthly temperatures in many US climatic divisions, with the centers of highest correlation in the Pacific Northwest and the Southeast [*Leathers et al.*, 1991]. Correlations between the PNA index and precipitation are weaker and less extensive than they are for temperature, but large coherent regions of moderately high correlations are observed across the nation [*Leathers et al.*, 1991]. *Yarnal* and *Diaz* [1986] note, due to the importance of the PNA there is a tendency to explain all the variations with it, even though the observed pattern only vaguely resembles the classical PNA configuration [*Wallace* and *Gutzler*, 1986]. Some studies describe those situations as distortions of the PNA pattern. Thus, *Keables* [1992] identifies three types of the PNA-like circulation, distinct from one another with respect to the location of the anomaly centers and the resultant atmospheric circulation. Each of these types produces dramatically different spatial patterns of temperature and precipitation across the contiguous United States. Distorted PNA patterns are often revealed in Principal Components Analysis (PCA) of the 700-hPa or 500-hPa height fields [*Mo et al.*, 1998], with the centers of action shifted 10°-15° from the classical PNA pattern described by *Wallace and Gutzler* [1981]. To test the robustness of the PNA pattern, *Kushnir and Wallace* [1989] applied a rotated PCA (RPCA) analysis for two 19-year periods, 1947-1965 and 1966-1985. They found that the primary center of action over the North Pacific shifted 15° eastward and 5° southward from the first period to the second. In another experiment, they used the oblique rotation (instead of the conventional orthogonal rotation) of the first 15 eigenvectors of the correlation matrix for the entire 38-year period. The first two principal components on the interannual time scale resembled the PNA pattern, but were nearly in quadrature with one another. No explanation of this phenomenon was provided.

This study questions the ability of the PNA index to unambiguously characterize the flow pattern over North America. This question became particularly acute in our recent analysis of the relationship between the severity of winters in the Great Lakes basin and atmospheric teleconnection patterns [*Rodionov and Assel*, 2000]. Ironically, both the coldest (1976/77) and the warmest (1997/98) winters in this region during the 1949/50-1999/2000 period had the highest and second highest positive PNA index values, respectively. Our further analysis has revealed that the PNA index in its present form cannot unambiguously characterize the type of circulation over North America. Furthermore, it mixes together two distinctive types of circulation, one of which has little to do with (or even opposite to) the view of the PNA index as a measure of amplitude of the ridge-trough system over North America. The details of this analysis for the winter (DJF) season are presented below.

2. Calculation of the PNA Index

There are two different methods to calculate the PNA index. The first method was offered by *Wallace and Gutzler* [1981], who defined the PNA index as a linear combination of the normalized 500-hPa height anomalies (z^*) at the four pattern centers:

$$\text{PNA} = \tfrac{1}{4}\,[z^*(20°\text{N}, 160°\text{W}) - z^*(45°\text{N}, 165°\text{W}) + z^*(55°\text{N}, 115°\text{W}) - z^*(30°\text{N}, 85°\text{W})].$$

Positive values of the index are associated with an amplified wave pattern, while negative values correspond to a more zonally-oriented flow. However, the subtropical center (20°N, 160°W) is often omitted to emphasize the wave energy propagation through the mid-latitudinal belt, which appears to be more appropriate when studying the effect of the PNA on the surface climate of the United States [*Leathers et al.*, 1991]. The difference between the PNA indices calculated using 3 (PNA_3) and 4 (PNA_4) centers, however, is negligible. For example, in the case of mean winter (DJF) values for the period 1949/50-1999/2000 the correlation coefficient between the PNA_3 and PNA_4 is 0.96.

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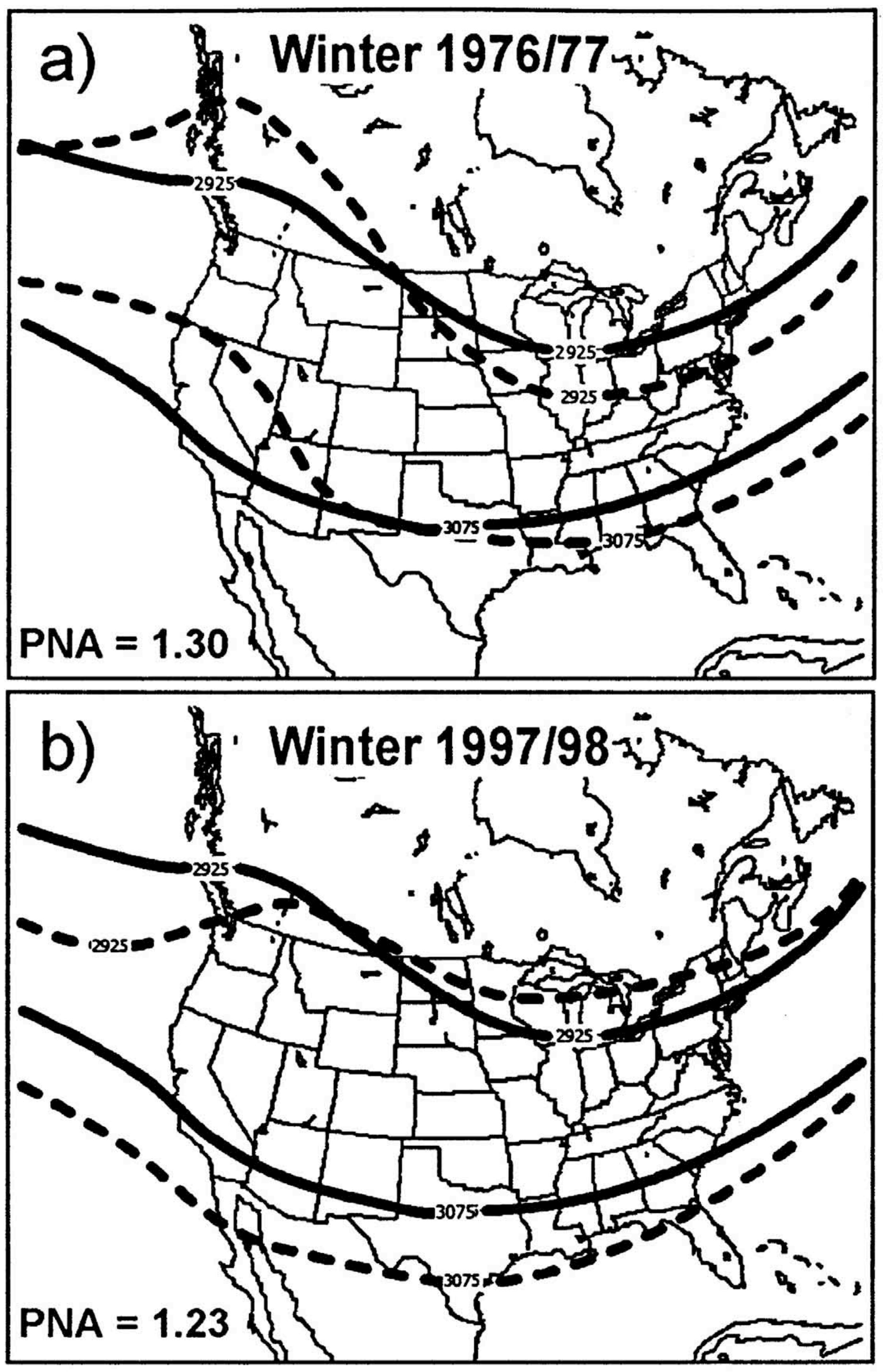

Figure 1. Mean-winter (DJF) positions of the 2925 m and 3075 m isohypses (dashed lines) at the 700-hPa surface during the winters of a) 1976/77 and b) 1997/98. Solid lines are the mean positions of these isohypses for the period 1949/50 – 1999/2000.

The second method to calculate the PNA index is based on the RPCA procedure [*Barnston and Livezey*, 1987]. It is considered to be superior to the method based on a combination of geopotential height anomalies in the centers of action, in that the teleconnection patterns are identified based on the entire flow field, and not just from height anomalies at a few selected locations. Both methods, however, produce comparable values. The correlation coefficient between the RPCA-based index (PNA_{RPCA}) and PNA_3 is 0.88, and between PNA_{RPCA} and PNA_4 is 0.86. Therefore, for this analysis we used only the PNA_{RPCA} values available from the National Oceanic and Atmospheric Administration, *Climate Prediction Center* (http://www.cpc.noaa.gov/data/indices/tele_index.nh).

3. Ambiguity of the PNA

As mentioned above, the PNA indices for both the winter of 1976/77 and the winter of 1997/98 were highly positive. Nevertheless, atmospheric circulation during these two winters had little in common (Fig. 1). To characterize atmospheric circulation we used, for the sake of simplicity, only two isohypses, 2925 m and 3075 m, at the 700-hPa surface. These isohypses can serve as indirect measures of the spatial variability (not the exact position) of the polar and subtropical jet streams respectively. A schematic representation of the mean meridional circulation in the northern hemisphere during winter, including the position of the polar and subtropical jets is given in Reiter (1961) and at http://www.britannica.com/bcom/eb/article/1/0,5716,109111+9,00.html. The winter of 1976/77 (Fig. 1a) is characterized by a well-developed ridge-trough system over North America, that is, enhanced meridional circulation. This situation is what is typically considered as the positive phase of the PNA [*Wallace and Gutzler*, 1981]. Over the eastern North Pacific and western North America (110°W-135°W), the 2925 m isohypse was shifted northward for more than one standard deviation (σ), with the maximum deviation along the Pacific coast reaching 2σ. This amplified ridge over the West was accompanied by a strong trough over the East, with the maximum southern excursion of the 2925 m isohypse (2.8σ) over the Midwestern United States. This type of circulation was associated with frequent intrusions of bitterly cold arctic air along the eastern periphery of the ridge (or western periphery of the trough), and well-below-normal temperatures dominated the eastern half of the United States mainland [*Namias*, 1978].

In the winter of 1997/98 (Fig. 1b), despite the high value of the PNA index, the ridge-trough system over North America was flattened, which is characteristic of zonal type of circulation. The anomalously weak climatological trough over the East and, as a result, practical absence of cold air outbreaks from the north contributed to the extreme warmth over most of North America. Record or near-record temperatures were observed across central Canada and large portions of the central and northeastern United States [*Bell et al.*, 1999]. Another interesting feature in Fig. 1b is a substantial (of more than one standard deviation) southward shift of the 3075 m isohypse. The most significant deviation was observed over Texas, where it exceeded 3σ. This southward shift of the 3075 m isohypse was consistent with a strengthening and shift of the subtropical jet in the same direction [*Bell et al.*, 1999]. It was also accompanied by enhanced cyclonic activity and precipitation across the southern tier of the United States [*Bell et al.*, 1999; *Smith and Ledridge*, 1999].

Another example of ambiguity of the PNA index is the relationship between severity of winters in the Great Lakes basin and atmospheric circulation. The winter severity was estimated as an average of normalized mean-winter (DJF)

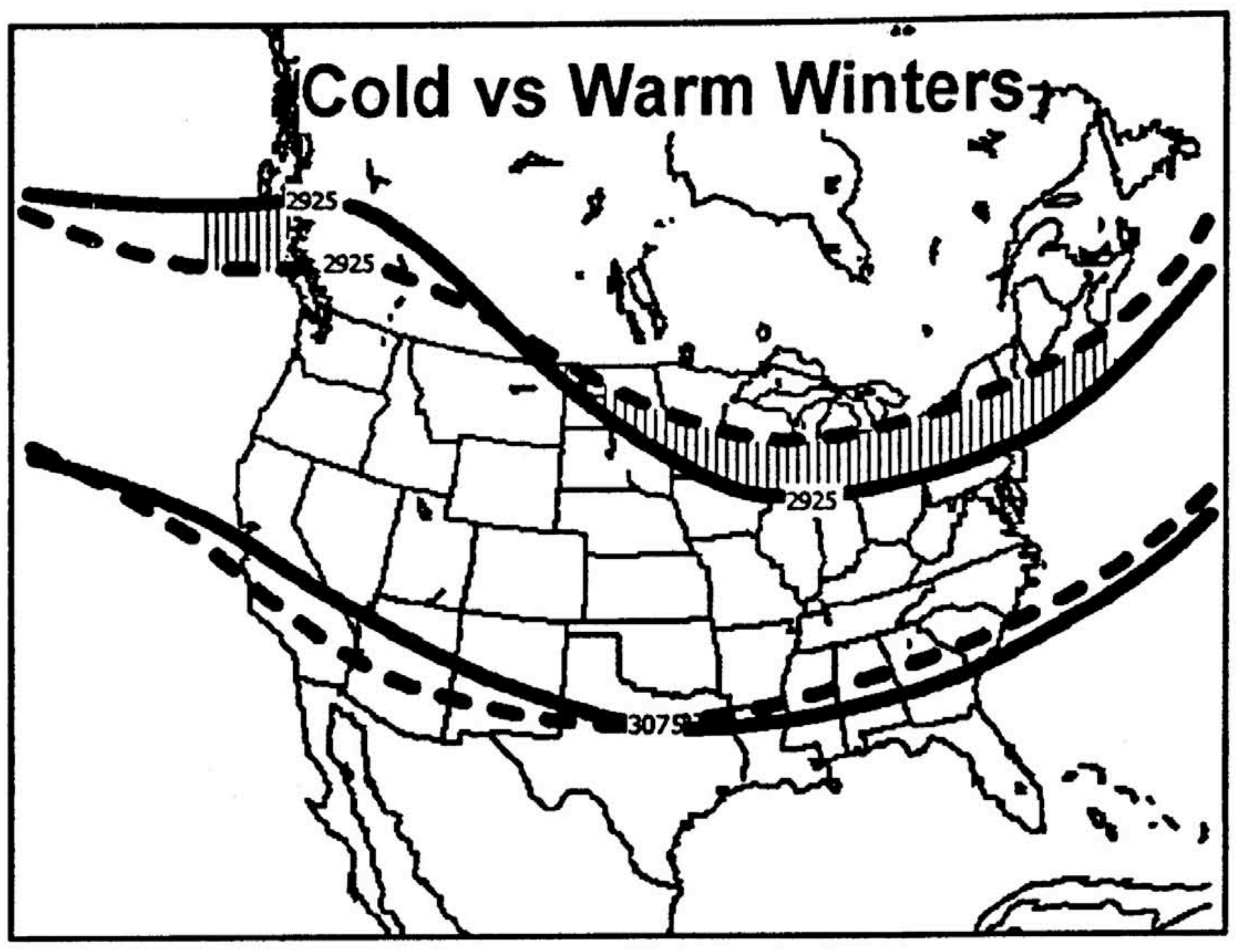

Figure 2. Mean-winter (DJF) positions of the 2925 m and 3075 m isohypses averaged for cold (solid lines) and mild (dashed lines) winters in the Great Lakes basin (see text). Vertical lines indicate significant (at the 5% level) difference between the isohypses.

temperature anomalies for four stations: Duluth (MN), Sault Ste. Marie (MI), Detroit (MI), and Buffalo (NY). Figure 2 shows mean positions of the 2925 m and 3075 m isohypses for the 17 mildest (upper tercile) and the 16 coldest (lower tercile) winters for the period 1949/50-1999/2000. The significance of the difference between the positions of the isohypses for these two groups of winters was estimated using the standard two-tailed Student's t-test. For the 2925 m isohypse, the difference is statistically significant at the 5% significance level over coastal Pacific waters off British Columbia (and over the eastern half of the United States). The difference in the positions of the 3075 m isohypse is not statistically significant. Figure 2 clearly demonstrates that cold winters in the Great Lakes basin are associated with an amplified ridge-trough system in the middle latitudes (positive phase of the PNA), while during mild winters the wave structure is flattened (negative phase of the PNA). However, the actual numerical correlation coefficient between winter temperatures in the basin and the PNA index for the 1949/50-1999/2000 period is close to zero ($r = 0.05$), similar to results of Leathers et al. (1991).

4. El Niño/Southern Oscillation and the PNA

Numerous studies have documented that the PNA pattern is the dominant extratropical response to El Niño/Southern Oscillation (ENSO) forcing mechanism affecting the circulation over North America (see a review in *Mo et al.* [1998]). Those studies suggest that during ENSO warm events PNA index values have a tendency to be positive, and there is a preference for negative index values during cold events. It is also often emphasized that strong PNA patterns can be produced in non-ENSO years, while a strong warm or cold event does not always give the expected PNA response.

Figure 3 shows mean-winter positions of the 2925 m and 3075 m contours for El Niño and La Niña winters. Those winters were determined using the Multivariate ENSO Index (MEI) introduced by *Wolter and Timlin* [1998]. Unlike the more popular Southern Oscillation Index (SOI), the MEI is positive during El Niño events and negative during La Niña events. Here El Niño winters were defined as those winters when the MEI was greater than 0.8. La Niña winters were those when the MEI was less than –0.8. For the period 1949/50-1999/2000, there were 10 such El Niño winters (1957/58, 1963/64, 1965/66, 1972/73, 1982/83, 1986/87, 1987/88, 1991/92, 1994/95, 1997/98) and 12 La Niña winters (1949/50, 1950/51, 1955/56, 1956/57, 1961/62, 1962/63, 1970/71, 1973/74, 1975/76, 1988/89, 1998/99, 1999/2000).

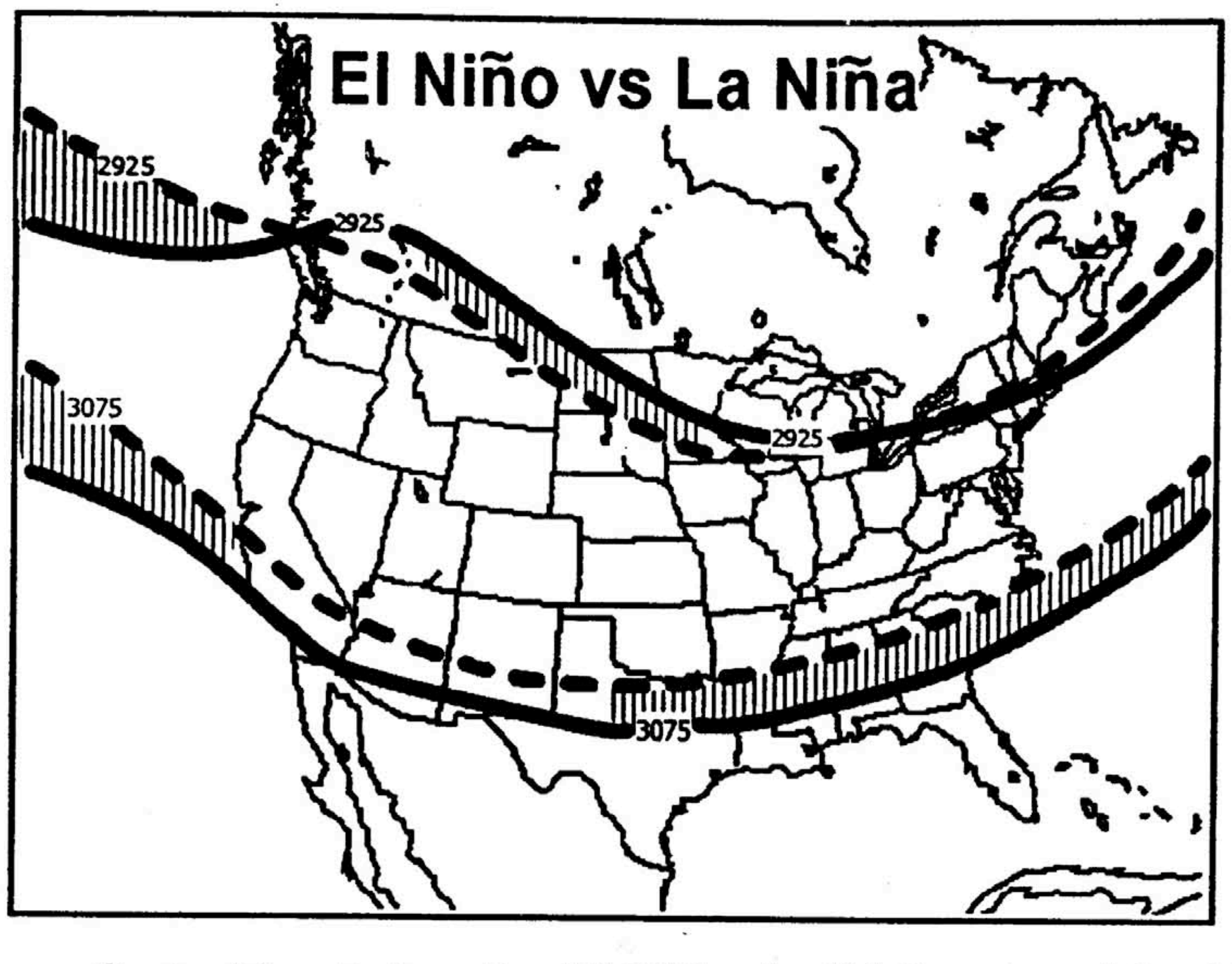

Figure 3. As Fig. 2, but for El Niño (solid lines) and La Niña (dashed lines) winters.

The average values of the PNA index for these El Niño and La Niña winters are 0.40 and –0.50 respectively. The position of the 2925 m isohypse in Fig. 3 suggests that the trough over the eastern North Pacific and the ridge over the Rockies are stronger during El Niño winters than during La Niña winters. The position of the trough over eastern North America, however, is approximately the same for both types of winters and corresponds to its long-term mean position.

The difference in the position of the 3075 m isohypse suggests a characteristic southward shift of the subtropical jet stream during El Niño events [*Bell et al.*, 1999]. This difference is statistically significant (at the 5% significance level) over the eastern North Pacific and from Texas eastward to the Sargasso Sea. It is interesting to note that for both the 2925 m and 3075 m isohypses the deviation from their long-term positions is more substantial during El Niño winters than during La Niña winters. El Niño winters are also characterized by a generally less vigorous westerly flow over the United States due to a larger distance between the 2925 m and 3075 m isohypses, and hence, a weaker north-south gradient.

Figure 3 implies that high values of the PNA index during El Niño winters are a result of a deeper than normal trough over the eastern North Pacific, stronger than normal ridge over the Rockies, and negative geopotential height anomalies over the Southeast due to a southward excursion of the subtropical Jet stream. Those values, however, are misleading because the polar jet stream does not form a trough over eastern North America as it normally does during such classical PNA winters as the winter of 1976/77 (Fig. 1a).

5. Relative Effect of ENSO and Sea Surface Temperatures in the North Pacific

It is relevant to note that ENSO is not the only source responsible for exciting the PNA pattern. Some observational and modeling studies indicate that the atmospheric response to the extratropical sea surface temperature (SST) anomalies is even stronger than the response to the tropical SST anomalies (e.g., *Wallace and Jiang*, [1992]). The relative impact of tropical and midlatitude SST anomalies on atmospheric variability was recently studied by *Mo et al.* [1998], *Wang and Fu* [2000] and others. *Zhang et al.* [1996], for example, have shown that, although the ENSO-related SST anomalies over the tropical Pacific may have significant influence on the extratropical atmospheric circulation, a large amount of variability in the 500-hPa height in the wintertime Northern Hemisphere is also strongly coupled with extratropical SST anomalies that are linearly independent of the ENSO signal.

To evaluate the effect of extratropical SST anomalies on the PNA pattern we used the Pacific Decadal Oscillation (PDO) index, which is defined as the leading principal component of North Pacific monthly SST variability (poleward of 20°N) [*Mantua et al.*, 1997]. For the period 1949/50-1999/2000, the correlation between mean-winter (DJF) values of the PDO and PNA indices is 0.72, significant at the 99% level (Table 1). Although the correlation coefficient between the MEI and PNA indices ($r = 0.46$) is also significant at this level, the latter is substantially lower than the former.

To better characterize the ridge-trough structure over North America, we constructed a Ridge-Trough Index (RTI) that was defined as the difference in normalized deviations (φ^*) of the 2925 m isohypse from its long-term position over the Rocky Mountains (115°W) and over the East Coast (75°W) in degrees latitude:

Table 1. Correlation coefficients between the PNA, MEI, PDO, and RTI indices for the entire data set (1949/50 – 1999/2000) and MEI partitioned subsets.

Data Set[a]	PNA, MEI	PNA, PDO	RTI, MEI	RTI, PDO
All data (51)	**0.46**[b]	**0.72**[b]	0.22	**0.55**[b]
MEI ≥ 0.8 (10)	0.51	0.44	**-0.74**[b]	-0.06
-0.8 < MEI < 0.8 (29)	0.06	**0.70**[b]	0.18	**0.70**[b]
MEI ≤ -0.8 (12)	0.07	**0.72**[b]	0.36	0.23

a The numbers of observations are given in parentheses.
b Correlation coefficients significant at the 99% level are shown in bold.

$$RTI = \frac{1}{2}\,[\varphi^*(115°W) - \varphi^*(75°W)].$$

For the entire time series (1949/50-1999/2000) the RTI is better correlated with the PDO than it is with the MEI (0.55 vs. 0.22). These correlation coefficients, however, are weaker than the corresponding correlation coefficients for the PNA index r(PNA, PDO) = 0.72 and r(PNA,MEI) = 0.46. The difference between the PNA and RTI indices becomes especially apparent during El Niño years (MEI ≥ 0.8). The correlation between the PNA and MEI remains positive and even somewhat higher than for the entire data set, but the correlation between the RTI and MEI is strongly negative. The latter means that the stronger the El Niño event, the flatter the ridge-trough system. An analysis of the components of the RTI shows that this flattening occurs primarily due to a northward excursion of the polar jet stream over eastern North America, which was particularly significant during the 1982/83 and 1997/98 El Niño events.

A comparison of the correlation coefficients *r*(PNA, MEI) and *r*(PNA, PDO) conditioned by the MEI index reveals a change in relative effect of ENSO and extratropical SSTs on the PNA pattern. During El Niño events (MEI ≥ 0.8) the ENSO effect appears to surpass that of the PDO (0.51 vs. 0.44), but the PDO prevails both during non-ENSO (-0.8 < MEI < 0.8) winters (0.70 vs. 0.06) and La Niña (MEI ≤ -0.8) winters (0.72 vs. 0.07). Strong positive correlation coefficients *r*(PNA, PDO) and *r*(RTI, PDO) for non-ENSO winters suggest that the PDO is associated with the true PNA pattern described as the ridge-trough system over North America.

6. Conclusion

The analysis has demonstrated that the PNA index in its present form cannot unambiguously characterize the type of atmospheric circulation over North America. In fact, it mixes together two distinct types of circulation. The first type of circulation is the true PNA pattern characterized by an amplification of the ridge-trough system in its positive phase. It appears to be associated with the distribution of SST anomalies in the North Pacific. The second type of circulation is associated with strong El Niño events. It is characterized by a flattening of the polar jet and a southward shift of the subtropical jet. The recognition of these two types of the PNA index improves our understanding of the relative role of EL Nino/Southern Oscillation events and sea surface temperatures in the North Pacific in affecting winter atmospheric circulation over North America.

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