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# Influence of variations in extratropical wintertime teleconnections on Northern Hemisphere temperature

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**Abstract.** Pronounced changes in the wintertime atmospheric circulation have occurred since the mid-1970s over the ocean basins of the Northern Hemisphere, and these changes have had a profound effect on surface temperatures. The variations over the North Atlantic are related to changes in the North Atlantic Oscillation (NAO), while the changes over the North Pacific are linked to the tropics and involve variations in the Aleutian low with teleconnections downstream over North America. Multivariate linear regression is used to show that nearly all of the cooling in the northwest Atlantic and the warming across Europe and downstream over Eurasia since the mid-1970s results from the changes in the NAO, and the NAO accounts for 31% of the hemispheric interannual variance over the past 60 winters. Over the Pacific basin and North America, the temperature anomalies result in part from tropical forcing associated with the El Niño-Southern Oscillation phenomenon but with important feedbacks in the extratropics. The changes in circulation over the past two decades have resulted in a surface temperature anomaly pattern of warmth over the continents and coolness over the oceans. This pattern of temperature change has amplified the observed hemispheric-averaged warming because of its interaction with land and ocean; temperature changes are larger over land compared to the oceans because of the small heat capacity of the former.

## Introduction

Much attention has been given to the possibility that human activities might be responsible for significant changes in climate. At the core of the debate is the observation that global mean surface temperatures have risen between 0.3°and 0.6°C over the past century, including a warming of 0.2°to 0.3°C over the past four decades when the data are considered to be most reliable (IPCC 1995). The average warming has not been uniform, however, with differing decadal trends and marked seasonal and regional variations. Over the Northern Hemisphere (NH), average temperatures decreased from the late 1930s to the mid-1960s. Since the mid-1970s, NH temperatures have increased to record levels during the past decade. The recent warming has been largest during the winter and spring seasons over the continents between 40°N and 70°N, while weak cooling has occurred over the northern oceans (Fig. 1). The pattern of temperature change is related to observed decade-long changes in the circulation of the atmosphere and ocean. It is the purpose of this paper to illustrate and quantify the relationship between the circulation changes and surface temperature anomalies in the NH during winter using multivariate linear regression.



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## Circulation Indices

A large amount of evidence has emerged of a substantial change in the wintertime atmospheric circulation over the North Pacific that began in the mid-1970s and lasted throughout the 1980s. The changes involved the Pacific-North American (PNA) teleconnection pattern and corresponded to a deeper and eastward shifted Aleutian low pressure system which advected warmer and moister air along the west coast of North America and cooler and drier air over the central North Pacific (Trenberth and Hurrell 1994, hereafter TH94). Consequently, there were increases in temperatures and sea surface temperatures (SSTs) along the west coast of North America and Alaska but decreases in SSTs over the central North Pacific (Fig. 1). A simple index used to measure the variations over the North Pacific (NP) is the area-weighted mean sea level pressure (SLP) over the region 30°to 65°N, 160°E to 140°W (TH94). The NP index, averaged over the winter months from December through March, is shown in Fig. 2 since 1935 (the year corresponds to January). Pressures from 1977 to 1988 were lower by 2.2 mb relative to the 60-winter NP-area mean. The only previous period that comparable values occurred was for a much shorter interval in the early 1940s.

The decadal changes over the North Pacific have been linked to variations in the tropics (TH94), and several modeling studies have confirmed that North Pacific atmospheric variability is controlled in part by anomalous tropical Pacific SST forcing (e.g., Kumar et al. 1994). Fluctuations in tropical SSTs are related to changes in the Southern Oscillation (SO) and the occurrence of the El Niño–Southern Oscillation (ENSO) phenomenon. ENSO variability is evident in the NP index (Fig. 2), but feedback effects in the extratropics may serve to emphasize the decadal over interannual timescales relative to the tropics (TH94).

The relationships among tropical Pacific SSTs, the SO and ENSO have been examined by Trenberth and Hoar (1995). Variations in the SO can be measured through an index defined by the normalized Tahiti minus Darwin SLP anomalies, although problems exist in the quality and completeness of the Tahiti record prior to 1935. The SO index for the winter months illustrates a change toward more negative values and thus warmer tropical conditions since the mid-1970s (Fig. 2), including the prolonged warm conditions since 1990. The influence of ENSO extends to higher latitudes through wavelike patterns that change the jet stream and storm track locations, so that changes from one phase of the SO to another have a profound impact on regional temperatures.

Another teleconnection that has played a major role in the pattern of regional temperature change over the past two

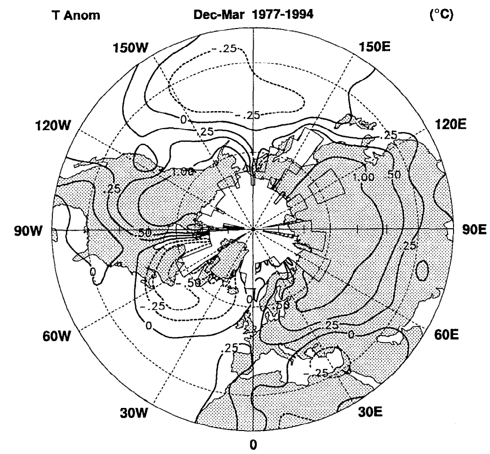


**Figure 1.** Eighteen winter average temperature anomalies expressed as departures from the 1951 to 1980 mean. The temperature data consist of land surface temperatures blended with SST data (Jones and Briffa 1992). Negative anomalies are dashed, and regions of insufficient data coverage are not contoured.

decades is the North Atlantic Oscillation (NAO). The NAO is associated with changes in the surface westerlies across the Atlantic onto Europe. A simple index of the NAO (Fig. 2) is defined as the difference of normalized pressures between Lisbon, Portugal and Stykkisholmur, Iceland, which are near the centers of the teleconnection during winter (Hurrell 1995). Positive values of the index indicate stronger-than-average westerlies over the middle latitudes associated with low pressure anomalies in the region of the Icelandic low and anomalously high pressures across the subtropical Atlantic. A striking feature of the NAO index (Fig. 2) has been the reversal from the weak meridional pressure gradient of the 1960s to strongly positive index values since 1980.

The changes in local surface temperatures and SSTs based on linear regression with the NAO, the NP and the SO indices are presented in Fig. 3. Changes of more than 1°C associated with a one standard deviation change in the NAO index occur over the northwest Atlantic and extend from northern Europe across much of Eurasia (Fig. 3a). Changes in temperatures over northern Africa and the southeast United States (U.S.) are also notable, but the pattern of change over the central

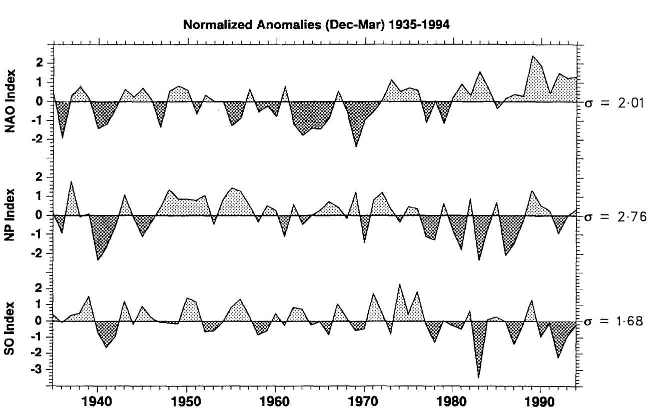


**Figure 2.** Time series of winter values of the NAO, the NP and the SO indices as defined in the text. Values are normalized relative to the mean from 1935 to 1994, and the standard deviations are plotted on the right axis.

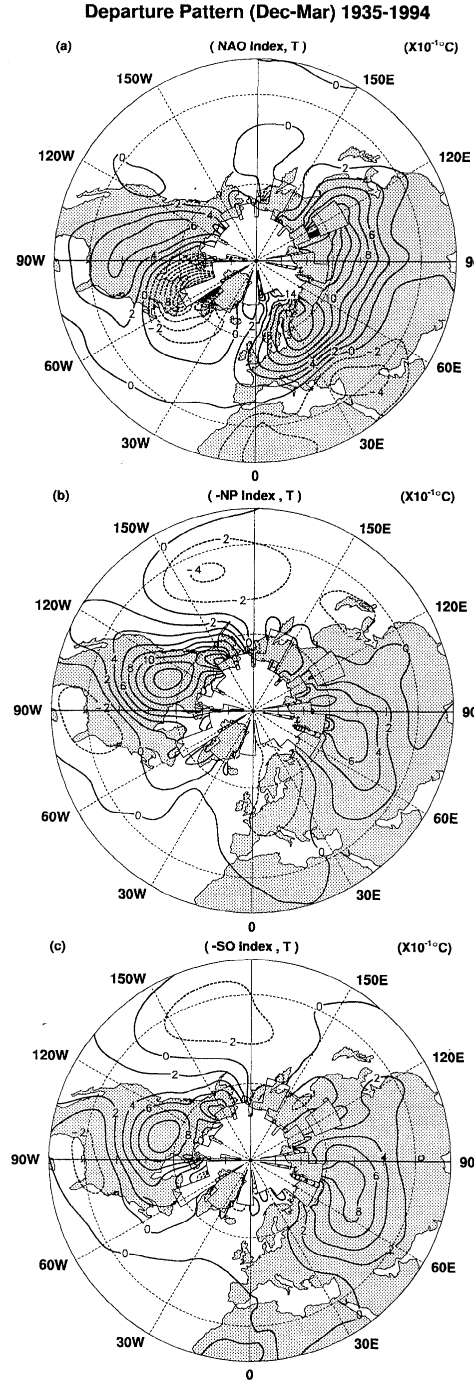


**Figure 3.** Changes in temperatures ($\times 10^{-1}$°C) corresponding to unit deviations of the (a) NAO index, (b) NP index, and (c) SO index computed over the winters from 1935 to 1994. The NP and the SO indices were multiplied by minus one. Regions of insufficient data are not contoured.

and western U.S. occurs in a region of statistically insignificant correlation and is not evident when the relationship is examined farther back in time (Hurrell 1995). It is evident that the changes in circulation over the Atlantic (Fig. 2) have contributed much to the recent wintertime warmth across Europe, the coolness over the eastern Mediterranean, and to the very cold conditions over the northwest Atlantic (Fig. 1).

The pattern of temperature change associated with the NP index (Fig. 3b) shows that the North Pacific basin anomalies since the mid-1970s (Fig. 1) are consistent with the longer record: below normal NP values are associated with below-normal temperatures over the North Pacific and above normal surface temperatures along the west coast of North America extending into Alaska and across most of Canada. The departure pattern during winter also reveals below-normal temperatures over the southeast U.S., which illustrates the PNA teleconnection and occurs in opposition to the temperature changes associated with NAO (Fig. 3a). Also, it is clear from Figs. 3b and 3c that the NP and the SO indices explain much of the same surface temperature variance.

The relationships shown in Fig. 3 were also explored as a function of various lags. Simultaneous correlations explained the most variance, although more detailed analyses examining both the SO and NP influences spatially has found differing lags, depending on location and season, to be more appropriate (e.g., Halpert and Ropelewski 1992; TH94). The different lag times relate to the different heat capacities of land and ocean. Land surfaces equilibrate more rapidly with the temperature of the overlying air mass, so that temperature changes tend to be amplified over the continents in response to changes in circulation (e.g., Wallace et al. 1995).

## Regression Analysis

The previous results have illustrated that hemispheric averages of temperature anomalies are the residual of strong regional patterns of change. The effect of the circulation changes on temperature can be quantified through multivariate linear regression. Previously, the most common application of linear regression has been to remove the linear influence of ENSO from hemispheric and global temperature time series (e.g., Jones 1994). The indices in Fig. 2 were regressed upon the NH extratropical (20°N to 90°N) temperature anomalies for each winter since 1935. The results can be extended farther back in time, but only with the tradeoff of less reliable NP and SO indices (TH94) and less reliable estimates of surface temperature and SST (Trenberth et al. 1992).

The regression model using all three indices explains 47% of the NH extratropical surface temperature variance (Table 1), and the leading regression coefficient is associated with the NAO index. The strong relation between the NP and the SO indices is readily apparent: the two are correlated at 0.51 (the 1% significance level is ≈ 0.33), and this contributes to the relatively high standard errors of the regression coefficients associated with the two indices. The partial correlation coefficients in Table 1 show the actual variance explained by a circulation index when the effects of the other indices are eliminated. For instance, while the correlation of the SO index with NH temperature anomalies is −0.40, the partial correlation coefficient is −0.29 when the NP index is held fixed.

When only the NAO and the SO indices are used in the regression more confidence can be placed in the estimated coefficients, and 44% of the variance of the extratropical NH temperatures is explained (Table 2). Shown in Fig. 4 are the temperature changes since 1935 associated with the NAO, the SO and their sum. Also shown are the mean NH temperature anomalies relative to the 60-winter mean and the residual time series after the removal of the temperature contributions by the two circulation indices. Over the entire period, variations of temperature associated with the NAO account for 31% of the hemispheric interannual variance, while the SO accounts for 16% of the interannual variance (Table 1). Both the NAO and the SO indices can account linearly for much, but not all, of the hemispheric warming over the past two decades. Over the period 1977 to 1994, the NH extratropical temperature

**Table 1.**
Summary statistics from the multivariate regression using the NAO, the NP and the SO indices as the independent variables and NH (20°N to 90°N) temperature anomalies as the dependent variable. Also shown is the correlation matrix and the partial correlation coefficients. The index that is held constant is indicated by the subscript.

| Regression Coefficient | Estimate | Standard Error | $t$-Statistic | Probability of Larger $\lvert t \rvert$ |
|---|---|---|---|---|
| NAO | 0.53 | 0.09 | 5.5 | 0.000 |
| NP | -0.20 | 0.11 | -1.9 | 0.069 |
| SO | -0.25 | 0.11 | -2.3 | 0.026 |
| $R^2 = 0.47$ | | | | |

| Correlation Matrix | | | | | Partial Correlation Coeffiecients | |
|---|---|---|---|---|---|---|
| NAO | 1.00 | | | | $(NAO,T)_{NP}$ = | 0.59 |
| NP | 0.01 | 1.00 | | | $(NAO,T)_{SO}$ = | 0.57 |
| SO | -0.07 | 0.51 | 1.00 | | $(NP,T)_{NAO}$ = | -0.40 |
| T | 0.55 | -0.33 | -0.40 | 1.00 | $(NP,T)_{SO}$ = | -0.16 |
| | NAO | NP | SO | T | $(SO,T)_{NAO}$ = | -0.43 |
| | | | | | $(SO,T)_{NP}$ = | -0.29 |

**Table 2.**
Same as for Table 1, but for only the NAO and the SO indices.

| Regression Coefficient | Estimate | Standard Error | $t$-Statistic | Probability of Larger $\lvert t \rvert$ |
|---|---|---|---|---|
| NAO | 0.52 | 0.09 | 5.30 | 0.000 |
| SO | -0.36 | 0.09 | -3.75 | 0.001 |
| $R^2 = 0.44$ | | | | |

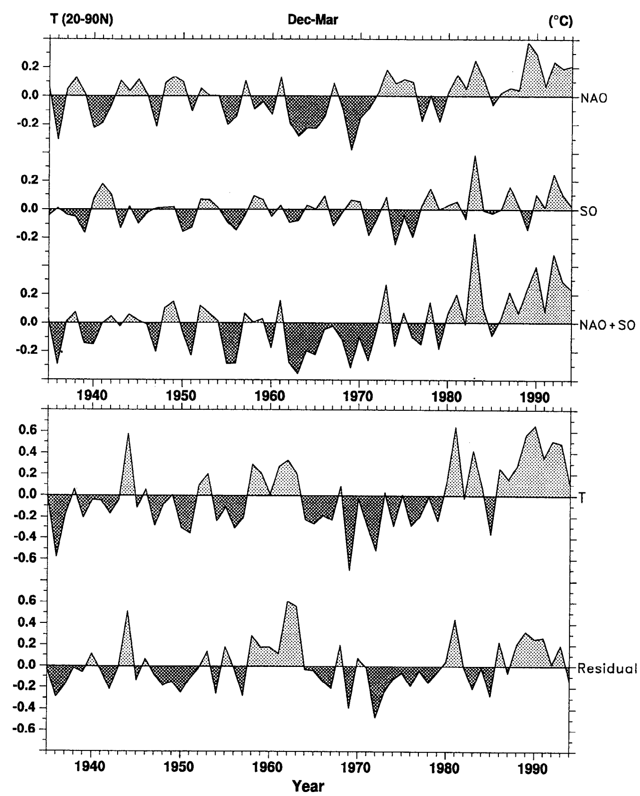


**Figure 4.** Temperature changes associated with the NAO, the SO and their sum averaged from 20°N to 90°N. The NH extratropical temperature anomalies relative to the 1935 to 1994 mean, and the residual after removing the linear effects of the NAO and SO are shown in the lower panel.

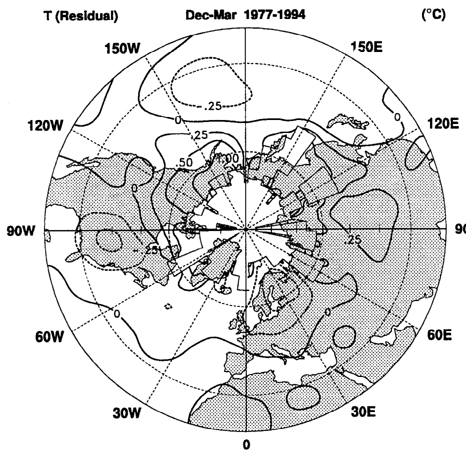


**Figure 5.** Same as Fig. 1, but for the surface temperature and SST anomalies after the linear effects of the NAO and the SO have been removed.

anomaly relative to the 60-winter mean was 0.21°C, while the anomaly of the residual series was 0.06°C. Of the 0.15°C difference, the NAO-related warming was 0.10°C. Similarly, the NAO remained in a negative phase during much of the 1960s (Fig. 2), a period during which wintertime blocking events were frequent over the Atlantic basin. From 1962 to 1971, the NH extratropical temperature anomaly was −0.13°C and the NAO-related anomaly was −0.17°C. The 10-winter average of the residual temperature anomaly was 0.06°C. While the selection of these periods is arbitrary, the above examples serve to illustrate the importance of the NAO, in addition to the role of circulation changes associated with ENSO, in determining the hemispheric temperature anomalies.

Regression was also performed locally using the NAO and the SO indices as the independent variables. The anomalies of the residual temperatures averaged over the winters since 1977, recomputed relative to a 1951-1980 base period, reveal that the distinctive regional features evident in Fig. 1 are linearly related to variations in these two indices (Fig. 5). Most notable is the reduction of the warm anomalies over the NH extratropical landmasses and the elimination of the strong cooling over the northwest Atlantic. The residual coolness over the North Pacific, the warmth over Alaska and the coolness over the southeast U.S. is partially related to the exclusion of the NP index from the regression. Note that the residual coolness over the eastern U.S. and Europe resembles the signal of aerosol forcing (Kiehl and Rodhe 1995). It should also be recognized that the residual anomalies in Figs. 4 and 5 probably reflect the exclusion of other teleconnection indices that affect patterns of interannual temperature variability in the NH (Gutzler et al. 1988), and that linear regression techniques do not account for feedback (nonlinear) effects. The claim of this study is not that the NAO and the SO indices provide the best fit to NH extratropical anomalies; rather, the indices were selected because they relate to well-understood circulation anomalies that have persisted for much of the past two decades.

It is worth noting that elements of the temperature anomaly pattern since the mid-1970s (Fig. 1) resemble the greenhouse warming fingerprint predicted by some general circulation models (IPCC 1995). However, it is difficult to assess whether the observed changes are in response to greenhouse gas forcing, or whether the changes are part of a natural decadal-timescale variation in the circulation (see also Wallace et al. 1995). Trenberth and Hoar (1995) have argued that the recent changes in ENSO, especially in the context of the prolonged 1990-1995 warming of the tropical waters, are unlikely to be part of a natural variation. On the other hand, recent analyses of Greenland ice-core data have revealed abrupt changes in the North Atlantic on decadal time scales that may be related to fluctuations in the NAO (Barlow et al. 1993). Regardless of cause, the changes in circulation since the mid-1970s have resulted in a particular surface temperature anomaly pattern that has amplified the hemispheric-averaged warming because of its interaction with land and ocean. Because anomalies over oceans are more subdued due to the large heat capacity of water, the hemispheric mean surface air temperature is largely determined by the temperature of the continents.

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