The Continuum and Dynamics of Northern Hemisphere Teleconnection Patterns

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ABSTRACT

This study presents an alternative interpretation for Northern Hemisphere teleconnection patterns. Rather than comprising several different recurrent regimes, this study suggests that there is a continuum of teleconnection patterns. This interpretation indicates either that 1) all members of the continuum can be expressed in terms of a linear combination of a small number of real physical modes that correspond to basis functions or 2) that most low-frequency patterns within the continuum are real physical patterns, each having its own spatial structure and frequency of occurrence.

Daily NCEP–NCAR reanalysis data are used that cover the boreal winters of 1958–97. A set of nonorthogonal basis functions that span the continuum is derived. The leading basis functions correspond to well-known patterns such as the Pacific–North American teleconnection and North Atlantic Oscillation. Evidence for the continuum perspective is based on the finding that 1) most members of the continuum tend to have similar variance and autocorrelation time scales and 2) that members of the continuum show dynamical characteristics that are intermediate between those of the surrounding basis functions. The latter finding is obtained by examining the streamfunction tendency equation both for the basis functions and some members of the continuum.

The streamfunction tendency equation analysis suggests that North Pacific patterns (basis functions and continuum) are primarily driven by their interaction with the climatological stationary eddies and that North Atlantic patterns are primarily driven by transient eddy vorticity fluxes. The decay mechanism for all patterns is similar, being due to the impact of low-frequency (period greater than 10 days) transient eddies and horizontal divergence. Analysis with outgoing longwave radiation shows that tropical convection is found to play a much greater role in exciting North Pacific patterns. A plausible explanation for these differences between the North Atlantic and North Pacific patterns is presented.

1. Introduction

One of the major challenges for long-range weather forecasting is to improve our understanding of the dynamical processes that drive low-frequency variability on time scales greater than 10 days. Midlatitude low-frequency variability is often described in terms of recurring, persistent teleconnection patterns (Wallace and Gutzler 1981; Barnston and Livezey 1987). Amongst these various patterns, most studies find that the North Atlantic Oscillation (NAO) and the Pacific–North American (PNA) teleconnection patterns are the two most dominant.

The goal of this study is to extend the results of previous teleconnection studies by attempting to generalize some of the dynamical characteristics of low-frequency variability. To achieve this, we first need to identify what are the physically relevant low-frequency patterns. For example, are the PNA and NAO the only real, physical patterns?

It is well known that there are one-point regression patterns associated with all Northern Hemisphere grid points (e.g., Wallace and Gutzler 1981). In this study, for low-pass-filtered data, we will refer to individual one-point regression patterns as low-frequency patterns and define the set of all one-point regression patterns as the continuum of low-frequency patterns. It appears to
be widely accepted that within this continuum, the PNA, NAO, and a few other spatial patterns are the only modes or recurrent regimes (see Wallace and Gutzler 1981, and references therein). All other low-frequency patterns are generally regarded as being noise. This perspective is illustrated by the studies of Kimoto and Ghil (1993) and Hsu and Zwiers (2001) who examined the probability density functions (PDFs) of various principal component time series. These studies identify modes as being those regions within the PDF space for which the frequency of occurrence exceeds the 90\% threshold for an AR(1) process, with the remainder of the parameter space being regarded as indistinguishable from a simple red noise process.

We will show that the variance and autocorrelation time scales (Metz 1991) are rather similar for most low-frequency patterns in the continuum. This will lead to two alternative interpretations of low-frequency variability. These are 1) that all members of the continuum can be represented by the linear combination of a small number of real physical modes or 2) that most, or perhaps all, low-frequency patterns within the continuum are real physical patterns, each with its own spatial structure and each with its own frequency of occurrence. With the techniques to be presented in this study, it is not possible to distinguish which of these two interpretations provides a better description of low-frequency variability. The first interpretation, which states that the continuum is represented by a small number of modes, or basis functions, was first suggested by Kushnir and Wallace (1989), who found that the leading low-frequency patterns occur in pairs that are in spatial quadrature with one another. For both of the above interpretations, although it is patterns such as the PNA and NAO that occur most often, none of the low-frequency patterns is regarded as being noise.\footnote{For patterns such as the PNA and NAO, for this continuum interpretation, there must be a very large number of PNA-like and NAO-like one-point regression patterns. Each of these particular patterns will explain less variance than the PNA and NAO patterns themselves.}

Support for our second interpretation that most or all members of the continuum of low-frequency patterns are real physical patterns comes from the lack of robustness of various teleconnection patterns, as the numerous papers published on this subject indicate a large range of variation in the structure of each teleconnection pattern. For example, in the rotated EOF analysis of Kushnir and Wallace (1989), they find that the structure of various teleconnections is very sensitive to the type of rotation used.

If the continuum perspective is an appropriate framework from which to examine low-frequency variability, then a better understanding of low-frequency variability would require that we examine all members of the continuum, which is clearly not feasible. One approach for dealing with this concern is to objectively find a set of basis functions that spans the entire continuum, and then to concentrate one’s research on the most important basis functions. In other words, the streamfunction field, $\psi(s, t)$, where $s$ denotes the grid point and $t$ the time, would be written as

$$
\psi(s, t) = \sum_{m=1}^{M} a_{m}^{ET}(t) e_{m}(s),
$$

where $M$ is the number of grid points in the domain and the $a_{m}^{ET}(t)$ are the time-varying amplitudes of the $e_{m}(s)$ basis functions. As will be seen in section 2, if we allow the $e_{m}(s)$ to be a nonorthogonal basis, then it can be shown that the dominant $e_{m}(s)$ correspond to well-known teleconnection patterns, including the NAO and PNA.

The approach that we use to obtain the $e_{m}(s)$ are based on a small modification of the empirical orthogonal teleconnection (EOT) methodology of Van den Dool et al. (2000). Very briefly, among all base points, $e_{1}(s)$ is the one-point regression pattern with the maximum variance. After subtracting $e_{1}(s)$ from $\psi(s, t)$, the one-point regression pattern with the largest variance becomes $e_{2}(s)$. This procedure of calculating the one-point regression pattern with largest variance followed by its subtraction leads to the determination of all $e_{m}(s)$. In this study, we will refer to the $e_{m}(s)$ as empirical teleconnection (ET) patterns (the acronym ET, rather than EOT, is used because, as we will see, the $e_{m}(s)$ are nonorthogonal in space and time). This approach combines the advantages of empirical orthogonal functions, and that of both teleconnection maps and rotated EOFs, since the $e_{m}(s)$ are basis functions that closely resemble observed spatial patterns.

In this study, we will first verify that the well-known teleconnection patterns correspond to basis functions, and then present evidence supportive of either inter-
pretation for the continuum view for low-frequency patterns. Because the entire continuum of low-frequency patterns is spanned by the ET patterns, we will address questions that deal with general characteristics of the continuum by focusing on the dynamical properties of the ET patterns themselves. The answers to these questions do not depend upon which of the above two interpretations better describes low-frequency variability. The questions that we will examine include: 1) Are the life cycle dynamics within some parts of the continuum determined by linear processes and in other parts of the continuum by nonlinear processes? 2) To what extent does anomalous tropical convection excite low-frequency patterns in different parts of the continuum? 3) Does the climatological stretching deformation field play an important role in determining whether the life cycle of low-frequency patterns is linear or nonlinear? 4) Is the presence of a much stronger subtropical jet in the North Pacific related to differences between North Pacific and North Atlantic low-frequency variability? 5) Can some or all ET patterns be related to the dominant patterns of zonal mean flow variability?

In section 2, we describe the data and analysis methods, followed by the analysis of the ET patterns in section 3. In section 4, we discuss the dynamical forcing processes and in section 5 the relation between the ET patterns and the climatological flow. Section 6 discusses the role of tropical convection, and the summary is presented in section 7.

2. Data and methodology

a. Data

The daily (0000 UTC) National Centers for Environment Prediction–National Center for Atmospheric Research (NCEP–NCAR) 300-hPa streamfunction, wind, and vorticity fields are used. These quantities are obtained by logarithmic interpolation from sigma onto pressure surfaces. These data cover the years 1958 to 1997 for the months of November through March. To examine the impact of tropical convection on low-frequency variability, we use outgoing longwave radiation (OLR) data, which is produced by the National Oceanic and Atmospheric Administration. For all data, the seasonal cycle is removed at each grid point. The seasonal cycle is obtained by taking the calendar mean for each day and applying a 20-day low-pass digital filter. Except for OLR, all data are truncated at rhomboidal 30 resolution on a Gaussian grid. The OLR analysis is performed on a 2.5° latitude × 2.5° longitude grid.

Digital filters are used to distinguish between high- and low-frequency variability. The high-frequency filter captures fluctuations with periods less than 10 days and the low-frequency filter retains fluctuations with periods of more than 10 days with the time mean subtracted (Feldstein 2002, 2003).

b. Streamfunction tendency equation

To investigate which processes are responsible for the growth, maintenance, and decay of the ET patterns, we use the streamfunction tendency equation (Cai and Van den Dool 1994; Feldstein 1998, 2002, 2003; Franzke et al. 2000, 2001). This equation can be written as

$$\frac{\partial \psi^L}{\partial t} = \sum_{i=1}^{8} \chi_i + R, \quad (2)$$

where $\psi$ is the streamfunction, $\chi_i$ the various forcing terms (see appendix A), $R$ the residual, and the superscript $L$ denotes a low-pass-filtered variable. It has to be kept in mind that (2) can only be used diagnostically; therefore, no causal relationships can be rigorously determined.

c. Empirical orthogonal teleconnections

As discussed in section 1, a modification of the EOT method (Van den Dool et al. 2000) is used to determine the ET patterns. The ET patterns comprise regression coefficients between a base point and all other grid points in the Northern Hemisphere. As in Van den Dool et al. (2000), the base point of the first ET pattern is defined as the grid point whose regression pattern explains the largest variance. The fields are weighted to account for the reduction in unit area with increasing latitude. In contrast to the normal setup of Van den Dool et al. (2000), who specifies the amplitude time series of the first EOT pattern to be the time series of the variable of interest at the base point, in this study $\alpha_1^{ET}(t)$ is calculated by projecting the first ET spatial pattern, $e_i(\lambda, \phi)$, onto the daily 300-hPa streamfunction field.

$$\alpha_1^{ET}(t) = \sum_j \psi(\lambda, \phi, t) e_j(\lambda, \phi) \cos \phi.$$  \quad (3)

where $\lambda$ and $\phi$ denote longitude and latitude, respectively. The dataset is then reduced by subtracting $\alpha_1^{ET}(t) e_i(\lambda, \phi)$ from the streamfunction field, $\psi(\lambda, \phi, t)$. The same procedure of calculating the pattern of largest variance following by its subtraction is repeated to determine each of the $\alpha_m^{ET}(t)$.

The fact that the $e_m(\lambda, \phi)$ form a nonorthogonal basis is verified analytically by showing that the $e_m(\lambda, \phi)$ are linearly independent (see appendix B). A numerical calculation also finds that the difference between the
variance of the streamfunction field, $\psi(\lambda, \phi, t)$, and the variance of $\sum_n a_{m}^\text{ET}(t) e_n(\lambda, \phi)$ as successive terms are retained, reduces to zero as $m$ approaches $M$ in (1). Furthermore, the streamfunction field reconstructed from the $e_n(\lambda, \phi)$ has an error that is very close to zero. Even though this procedure does not have any orthogonality constraints, the resulting spatial patterns and time series are close to being orthogonal. The maximal pattern correlation between the various ET patterns is less then 0.2, and the maximal temporal correlation is less then 0.1 and is not significant.

For this study, we will investigate the characteristics of the first eight ET patterns. We selected the first eight patterns both because they encompass most of the well-known teleconnection patterns and because together they span a sizeable fraction of the hemispheric variance.

d. Regression analysis

To reveal the relationship between the ET patterns and the terms on the right-hand side of the streamfunction tendency equation, a time-lagged regression analysis is performed between the various $a_m^\text{ET}$ time series and $\chi_t$ terms in (2). For this calculation, the $a_m^\text{ET}$ anomaly is always specified to be one standard deviation. A concise method for examining the temporal evolution of the ET patterns is to project the various lag-regressed forcing terms in the streamfunction tendency equation onto the respective lag-regressed streamfunction pattern (Feldstein 1998, 2002, 2003; Franzke 2002).

3. The ET analysis

a. ET patterns

The first eight ET patterns of the low-pass-filtered 300-hPa streamfunction field are presented in Figs. 1 and 2. To determine if these ET patterns correspond to well-known teleconnection patterns, each of the ET amplitude time series is linearly correlated with the various teleconnection pattern time series from the Climate Prediction Center (CPC). These CPC teleconnection patterns are the leading modes of a rotated EOF analysis of the monthly mean 700-hPa geopotential height field during the 1950–2000 period. The CPC provides both daily and monthly mean time series [Daily: PNA, NAO; Monthly: PNA, Southern Oscillation Index (SOI), NAO, West Pacific (WP), East Atlantic (EA), East Atlantic/West Russia (EA/WR), Tropical/Northern Hemisphere (TNH), and Scandinavia (SCA)]. The CPC acronyms are based upon Barnston and Livezey (1987), with the exception of the SCA and EA/WR patterns, which they designated as the EU1 and EU2 patterns, respectively. To compare the daily ET amplitude time series with the monthly mean CPC time series, a new time series is generated that consists of monthly means of the daily ET amplitude time series.

Figures 1 and 2 show spatial patterns that resemble those from numerous previous teleconnection pattern studies [see Barnston and Livezey (1987) and references cited]. A comparison of the centers of action of these patterns with those of Barnston and Livezey (1987), and also Horel and Wallace (1981), together with the corresponding correlation values, which all exceed 99% confidence level for a two-sided $t$ test, allows us to identify each of the ET patterns (see Table 1, which also includes values of explained variance and autocorrelation time scale). We identify the first eight ET patterns as the PNA, SOI, NAO, WP, EA, EA/WR, TNH, and SCA, respectively. The regression pattern identified with the SOI (Fig. 1b) has a spatial structure that resembles the linear correlation of seasonal mean 700-hPa geopotential height with the Southern Oscillation index [see Fig. 9 of Horel and Wallace (1981)] and the leading EOF of monthly mean 300-hPa streamfunction found in observational and GCM data [see Figs. 9 and 15 of Branstator (2002)]. We interpret this pattern as the atmospheric response to ENSO. Such a relatively short time scale atmospheric response to ENSO has also been found by Barsugli et al. (1999) and Feldstein (2000). Considering the different methodology (rotated EOF versus ET), variables selected (geopotential height versus streamfunction), levels used (700 hPa versus 300 hPa) and time scales (the CPC teleconnection patterns are all derived from monthly mean data whereas we are using daily low-pass-filtered data), the association of our patterns with the well-known teleconnection patterns seems to be justified.

b. Continuum perspective

A compact method for illustrating the existence of the continuum is with joint probability distribution

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2 For nonorthogonal spatial patterns, it is important to note that the explained variance arises both from individual patterns and also from the interaction between each of the patterns. Therefore, it is not possible to unambiguously define the variance of any particular ET pattern. Notwithstanding this limitation, we define the explained variance to be that due to each ET pattern by itself and do not consider the variance arising from the interactions amongst ET patterns. Since the ET patterns are nearly orthogonal in space and nearly uncorrelated in time, the variance from the interaction amongst ET patterns is likely to be small.
functions (PDFs) (e.g., Kimoto and Ghil 1993; Hsu and Zwiers 2001) of various ET amplitude time series. Two joint PDFs are shown, one whose axes are the PNA and WP amplitude time series (Fig. 3a) and the other with the axes being the NAO and EA amplitude time series (Fig. 3b). As can be seen, both PDFs show unimodal characteristics. The shape of the PDFs imply that the flow projects more frequently onto the PNA than the WP and with about the same frequency for the NAO and EA. The PDFs also indicate that patterns that project simultaneously onto two ETs tend to occur at frequencies similar to those of the ET patterns themselves.

PDFs with similar types of characteristics are found for the other ET patterns.

The properties of the continuum are further demonstrated by focusing on low-frequency patterns whose base point is located midway between those of two different ET patterns. We consider two examples, one with its base point located halfway between that of the PNA and WP patterns (53°N, 158°W) and the other with its base point halfway between that of the NAO and EA patterns (57°N, 38°W). The one-point regression patterns for these base points are referred to as the PNA/WP and NAO/EA patterns, respectively. We be-
gin by showing that the PNA/WP and NAO/EA patterns project mostly onto their corresponding ET patterns. For the PNA/WP pattern, the correlation with the PNA is 0.84 and with the WP it is 0.52. The remaining correlations are all less than 0.1. For the NAO/EA pattern, the correlation with the NAO is 0.76, and 0.57 with the EA. All other correlations are less than 0.2.

We next calculate the explained variance and autocorrelation time scale of the PNA/WP and NAO/EA patterns. The explained variance of the PNA/WP and NAO/EA patterns are found to be 6.5% and 4.2%, respectively. For the PNA/WP this value is closer to that for the PNA, and for the NAO/EA pattern it is almost the same as that for the EA. Similar variance calculations were performed with other base points located along a line connecting the PNA and WP base points and along another line connecting the NAO and EA base points. For the line between the PNA and WP base points, the variance increases monotonically toward the PNA base point. For the line between the NAO and EA base points, the variance values are rather uniform increasing more rapidly toward the NAO base point. Extending these variance results to other patterns suggests that the frequency of occurrence and/or amplitude of all low-frequency patterns are not very different. The autocorrelation time scales

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**Fig. 2.** Same as in Fig. 1, except (a) ET5 (EA) 4.2%, (b) ET6 (EA/WR) 3.7%, (c) ET7 (TNH) 3.7%, and (d) ET8 (SCA) 3.4%.
(Metz 1991) for the PNA/WP and NAO/EA patterns are found to be 9 and 8 days, respectively, similar to that of all the ET patterns (Table 1) and to those found by Feldstein (2000). These values for the autocorrelation time scales correspond to decay that is significantly slower than the time scale associated with synoptic scale waves, that is, approximately 4 days. Together with the above joint PDFs, this also suggests that each member of the continuum of low-frequency patterns can be regarded as being part of a signal of low-frequency variability rather than simply being noise.

4. Lag-regression analysis

For the purpose of revealing the dynamical processes associated with the continuum of low-frequency patterns, we begin by investigating the dynamics of the ET patterns themselves since it is these patterns that span the continuum. As will be shown, the various ET patterns are driven by different terms on the rhs of (2), the streamfunction tendency equation. Some ET patterns are driven and maintained primarily by $\chi_3$ [see (A12)], a linear term which represents the interaction of the low-frequency anomalies with the climatological stationary eddies. In this study, we will refer to $\chi_3$ as stationary eddy advection. Other ET patterns are found to be driven and maintained by $\chi_5$ and/or $\chi_{50}$ (A14) and (A15), nonlinear terms that correspond to forcing by low- and high-frequency transient eddy vorticity fluxes, respectively. The divergence term, $\chi_4$ (A13) is also found to play an important role.

To identify these dynamical processes, we calculate lag regressions of various terms on the rhs of (2), the streamfunction tendency equation, against the ET amplitude time series. The magnitude and sign of the influence of these tendency terms are then determined by projecting the lag-regression tendency terms onto the lag-regression streamfunction fields. The extent to which (2) is balanced has been examined by Franzke (2002) and Feldstein (2002, 2003). These studies found that the streamfunction tendency is much larger than the residual, $R$, in (2). A similar degree of balance is found in this study (not shown).

We closely examine projections for the ET patterns corresponding to the PNA, NAO, WP, and EA. For ET1 (PNA), we see that its growth and maintenance is primarily due to stationary eddy advection and that its decay results from the impact of both the divergence term and the low-frequency eddy advection (see Fig. 3).
The impact of planetary vorticity advection by the low-frequency flow ($\chi_p$) and relative vorticity advection associated with the zonal mean flow ($\chi_r$) is relatively small, as these two terms tend to cancel one another. These characteristics for the stationary eddy advection and divergence term can also be seen in the regression patterns (Fig. 5). Most of this behavior closely resembles that of the PNA life cycle shown in Feldstein (2002). [Other studies that find stationary eddy advection to be important for low-frequency variability include Frederiksen (1983), Simmons et al. (1983), Branstator (1990, 1992), and Cash and Lee (2001).] The primarily difference between this result and that of Feldstein (2002) is that the maximum anomalous divergence occurs several days earlier in this study. Such behavior may be consistent with the con-
tinuum idea, which implies that there are many different PNA-like patterns. Amongst the other ET patterns, only the North Pacific ET2 (SOI) and ET7 (TNH) patterns are found to undergo growth primarily by stationary eddy advection (not shown).

For ET3 (NAO), the projection by the high-frequency transient eddy vorticity flux is always positive and peaks at lag 0 (Fig. 4b), and the projection by the low-frequency transient eddy vorticity flux is positive while the NAO anomaly is growing and negative during its decay. As can be seen from Fig. 4b, these results imply that it is the combination of both the high- and low-frequency transient eddy vorticity fluxes that together drives the NAO growth and that, after the NAO anomaly has attained its maximum amplitude, the high-frequency vorticity flux continues to maintain the anomaly pattern, while both the low-frequency vorticity flux and the divergence term contribute toward the NAO decay. For the high-frequency eddy fluxes, such behavior is consistent with these eddy fluxes maintaining the NAO anomaly through a positive feedback process (e.g., Egger and Schilling 1983; Lau 1988; Metz 1989, 1991; Branstator 1992; Ting and Lau 1993; Franzke et al. 2000, 2001; Franzke 2002). Each of the

![Figure 5. Lag regressions of forcing terms against ET1 (PNA) amplitude time series: (a) $\chi_1$ at lag -1 day (contour interval 10 m$^2$ s$^{-2}$), (b) $\chi_1$ at lag -5 days (contour interval 10 m$^2$ s$^{-2}$), (c) $\chi_1$ at lag +6 days (contour interval 5 m$^2$ s$^{-2}$), and (d) $\chi_1$ at lag +3 days (contour interval 5 m$^2$ s$^{-2}$). Dark (light) shading indicates positive (negative) values of the regressed streamfunction anomaly at the corresponding lag.](image)
above characteristics can also be seen in the regression patterns in Fig. 6. These findings are in agreement with the NAO life cycle results of Feldstein (2003). Both the ET4 (WP) and ET5 (EA) patterns exhibit a life cycle that appears to be intermediate between that of the PNA and NAO (Figs. 4c, 4d, 7, and 8). The temporal evolution of the high- and low-frequency eddy vorticity fluxes resemble those for the NAO during both their growth and their decay, and stationary eddy advection does contribute to the growth and maintenance. Similar behavior was also found for the ET6 (EA/WR) and ET8 (SCA) patterns (not shown). Among these four “mixed” patterns, it is only the EA for which stationary eddy advection plays a greater role than does the driving by the transient eddy vorticity fluxes.

The impact of the low-frequency planetary vorticity advection and relative vorticity advection associated with the zonal mean flow is illustrated in Fig. 4 for the NAO, WP, and EA patterns. As can be seen, unlike for the PNA, these terms do not cancel each other. Similar behavior is found in Feldstein (2003) for the NAO, as the linear terms for that teleconnection pattern tend to
balance the driving by the transient eddy vorticity fluxes, rather than each other.

The primary purpose for examining the dynamical processes that drive the various ET patterns has been to use the basis function property of these patterns to infer the dynamical processes associated with the continuum of low-frequency patterns. To test whether this basis function perspective extends to the life-cycle dynamics associated with the continuum, we examine whether the projections for the PNA/WP and NAO/EA patterns share the projection properties of the corresponding ET patterns (see Fig. 9). Even though the spatial structure of these mixed patterns (e.g., PNA/WP and NAO/EA) consists of a linear combination of the surrounding ET patterns, it is not clear a priori that they should exhibit clearly defined life-cycle dynamics. An examination of the projections of these mixed patterns shows that the dynamical characteristics of the PNA/WP and NAO/EA patterns are indeed intermediate between those of the ET patterns onto which they most strongly project. (Additional projections were performed for patterns with base points along a line connecting the

Fig. 7. Lag regressions of forcing terms against ET4 (WP) amplitude time series: (a) $\chi_3$ at lag $-2$ days (contour interval 10 m$^2$ s$^{-2}$), (b) $\chi_4$ at lag $-2$ days (contour interval 10 m$^2$ s$^{-2}$), (c) $\chi_5$ at lag $-4$ days (contour interval 5 m$^2$ s$^{-2}$), and (d) $\chi_6$ at lag $+1$ day (contour interval 5 m$^2$ s$^{-2}$). Dark (light) shading indicates positive (negative) values of the regressed streamfunction anomaly at the corresponding lag.
Fig. 8. Lag regressions of forcing terms against ET5 (EA): (a) $\chi_3$ at lag +2 days, (b) $\chi_4$ at lag +1 day, (c) $\chi_5$ at lag −5 days, (d) $\chi_6$ at lag +4 days, and (e) $\chi_7$ at lag 0 days. Dark (light) shading indicates positive (negative) values of the regressed streamfunction anomaly at the corresponding lag.
PNA and WP base points and another line connecting the NAO and EA base points. Intermediate properties between the corresponding ET patterns were again found.) Since for the North Pacific (Atlantic) three of the four ET patterns are dominated by stationary eddy advection (transient eddy flux driving), the above findings lead to the suggestion that most low-frequency patterns in the North Pacific tend to be driven by stationary eddy advection and that most low-frequency patterns in the North Atlantic are driven by transient eddy vorticity fluxes.

5. Barotropic deformation

To gain insight into why stationary eddy advection is more important for some low-frequency patterns, but not for others, we examine the relationship between the climatological barotropic deformation field (Mak and Cai 1989; Black and Dole 2000) and the ET patterns. The barotropic stretching deformation, which can be written as

$$
\frac{1}{a \cos \phi} \frac{\partial u}{\partial \phi} - \frac{1}{a} \frac{\partial v}{\partial \phi} - \frac{v}{a} \tan \phi,
$$

where $u$ and $v$ are the climatological zonal and meridional winds, is displayed in Fig. 10. We also overlay the PNA, NAO, WP, and EA patterns on the climatological deformation field. As can be seen, the PNA and EA patterns are close to being in spatial quadrature with the climatological barotropic stretching deformation field. On the other hand, the NAO and WP patterns are primarily spatially in phase with the stretching deformation. These phase relationships are in concordance with the stationary eddy advection being relatively large (small) for the PNA and EA (NAO and WP) patterns. The importance of this phase relationship can be understood by decomposing stationary eddy advection into various components. It is found that this term is dominated by the advection of the anomalies by the climatological stationary eddy meridional wind. As this particular wind field is close to zero along the axis of the jet, only those anomalies located away from the jet axis and in quadrature with the background deformation field can grow via stationary eddy advection.

6. Tropical convection

We next examine whether tropical convection impacts the continuum of low-frequency patterns by calculating the regression of OLR against the various ET amplitude time series. These regressions are averaged over the seven-day interval between lag $-10$ days and lag $-4$ days in order to capture the OLR signal while the respective teleconnection pattern is growing. For this calculation, the OLR field is truncated at zonal wavenumber 4.
The OLR lag regressions show that it is only the North Pacific ET patterns that are strongly impacted by tropical convection (see Fig. 11). For the first two ET patterns (PNA and SOI), the anomalous OLR field associated with both patterns has a zonally oriented dipole structure that extends across the tropical Indian and western Pacific Oceans. The OLR dipole anomaly associated with the PNA pattern is located about 30° to the west of that associated with the SOI pattern. These OLR anomalies are statistically significant above the 95% confidence level. The TNH is associated with weaker, but still statistically significant, tropical OLR anomalies (not shown), whereas there are no statistically significant OLR anomalies found for the WP pattern. This is consistent both with the PNA/WP joint PDF, which shows that the PNA takes place more frequently than the WP, and with our interpretation that the PNA is not necessarily an atmospheric mode, but that it may simply be the pattern within the continuum that is most frequently excited by tropical convection. For the North Atlantic ET patterns, no statistically significant OLR anomalies are found.

7. Discussion and conclusions
The aim of this study has been to investigate general characteristics of low-frequency variability. We first
used our modification of the EOT method (Van den Dool et al. 2000) to show that most of the well-known teleconnection patterns can be understood as being part of a nonorthogonal set of basis functions. We also presented two alternative interpretations for the continuum of low-frequency patterns. These are 1) that all members of the continuum can be represented as a linear combination of a small number of real physical modes that correspond to basis functions or 2) that most or all low-frequency patterns within the continuum are real physical patterns, each with its own spatial structure and frequency of occurrence. Following these perspectives, we examined the dynamical processes that account for the growth and decay of the ET patterns with the aim of using the basis function properties of the ET patterns to examine the dynamics of the continuum. For this study, the primary approach has been to investigate the temporal evolution of various terms in the streamfunction tendency equation during the life cycle of each ET pattern.

The analysis indicates that some ET patterns (PNA, SOI, TNH) are driven mostly by stationary eddy advection, that the NAO is the only ET pattern driven almost entirely by transient eddy vorticity fluxes, and that the remaining four ET patterns, the WP, EA, EA/WR, and SCA, are driven by both stationary eddy advection and transient eddy vorticity fluxes. When stationary eddy advection is dominant, it is found that this process also contributes toward the maintenance of the anomalies. For patterns that are primarily influenced by transient eddy fluxes, the high-frequency fluxes drive and maintain the anomalies, and the low-frequency fluxes first contribute toward anomaly growth and then toward anomaly decay. Because of the basis function property of the ET patterns, these findings lead to the suggestion for the continuum that North Pacific (Atlantic) low-frequency patterns are primarily driven by stationary eddy advection (transient eddy vorticity fluxes). In turn, these results imply that the life cycles for North Pacific (Atlantic) low-frequency patterns is mostly determined by linear (nonlinear) processes. The behavior of the high- and low-frequency eddy fluxes can be understood from the fact that the NAO originates from synoptic scale waves (Benedict et al. 2004; Franzke et al. 2004). As these high-frequency waves evolve into the NAO they break and the remnants of these breaking waves form the NAO. This breaking of high-frequency waves generates the low-frequency waves that comprise the NAO (Benedict et al. 2004). The NAO finally decays by mixing, which also projects onto the low-frequency waves.

More striking differences were found for the relationship between the ET patterns and tropical convection. A regression analysis involving OLR suggests that tropical convection has a much stronger influence on North Pacific low-frequency patterns, as statistically significant OLR anomalies are associated with three of the four North Pacific ET patterns and with none of the North Atlantic ET patterns. A plausible explanation for tropical convection having a greater impact on North Pacific low-frequency patterns is simply that these patterns are geographically closer to the convection.

A calculation of the variance of both the climatologi-
cal stationary eddy advection and the climatological transient eddy vorticity flux driving reveals that the variance of the former term is larger in the North Pacific and that of the latter term is greater in the North Atlantic. These results are consistent with our findings, and that of many other studies, that the dominant teleconnection patterns in the North Pacific and the North Atlantic, the PNA and the NAO, are driven by stationary eddy advection and transient eddy vorticity fluxes, respectively (Fig. 12). These differences between the North Pacific and North Atlantic can be interpreted within the context of the results of Lee and Kim (2003), which show that when the subtropical jet is strong (weak) the midlatitude eddy-driven jet is weak (strong). Therefore, in the North Atlantic, where the eddy-driven jet is strong and highly variable, the low-frequency patterns tend to be eddy driven. In contrast, in the North Pacific, where the less variable subtropical jet is dominant, the low-frequency patterns are mostly driven by stationary eddy advection.

A basic question is why are the dominant ET patterns concentrated over the ocean basins downstream of the jet maxima. A plausible answer to this question is that ET patterns are driven and maintained by both stationary eddy advection and high-frequency eddy vorticity flux divergence, and the extrema in the variance of these two quantities lie in these regions over the two ocean basins (see Fig. 12). The regions of large stationary eddy advection variance overlap with the negative maxima in the barotropic stretching deformation field (Fig. 10), allowing for ET patterns to gain their energy barotropically from the climatological flow. The regions of largest variance in the high-frequency eddy vorticity flux divergence overlap with the Northern Hemisphere storm tracks (Blackmon 1976). This suggests that it is the location of both the barotropic stretching deformation and the storm track eddies that accounts for the location of the dominant ET patterns.

The ranking of the ET patterns in both the North Atlantic and North Pacific Oceans bears resemblance to that seen for the observed zonal mean flow variability. As has been shown in Lorenz and Hartmann (2001), the first EOF of the zonal mean flow represents meridional displacements in the latitude of the zonal mean jet, that is, the so-called zonal index, and the second EOF corresponds to a pulsation in the strength of the zonal mean jet. Furthermore, in their idealized model study, Lee and Feldstein (1996) show that the primary factor that determines whether zonal index or jet pulsation dominates is the width of the jet. For wide jets, Lee and Feldstein (1996) find that the zonal index variance exceeds that due to jet pulsation, whereas for narrow jets it is jet pulsation that has more variance. They interpret this behavior in terms of the stabilization characteristics of baroclinic eddies. In the North Atlantic, where the jet is relatively broad, the ET pattern with the largest variance, the NAO, does indeed represent shifts in the latitude of the jet maxima (Fig. 1c). Note that in Figs. 1 and 2 the contours indicate anomalous 300-hPa streamfunction and the shading denotes 300-hPa zonal wind. In the North Pacific, where the jet
is relatively narrow, the dominant PNA pattern coincides with jet pulsation (Fig. 1a). Furthermore, consistent with the above properties for zonal mean flow variability, the second most prominent pattern in the North Atlantic, the EA, corresponds to jet pulsation (Fig. 2a), and the second strongest North Pacific pattern, the WP, resembles the zonal index (Fig. 1d). Therefore, over both ocean basins, the ET patterns locally show characteristics that resemble those for zonal mean flow variability.

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APPENDIX A

A Streamfunction Tendency Equation

The streamfunction tendency equation can be written as

$$\frac{\partial \psi^L}{\partial t} = \sum_{i=1}^{n} \chi_i + R,$$

(A1)

where $\psi$ is the streamfunction, $\chi_i$ the various forcing terms, and $R$ the residual. The $\chi_i$ are written as

$$\chi_1 = \nabla^{-2}(-u^L \cdot \nabla \bar{f}),$$

(A2)

$$\chi_2 = \nabla^{-2}(-[u^H] \cdot \nabla \bar{f} - u^L \cdot \nabla [\bar{f}]),$$

(A3)

$$\chi_3 = \nabla^{-2}(-[u^H] \cdot \nabla \bar{f} - u^L \cdot \nabla [\bar{f}]),$$

(A4)

$$\chi_4 = \nabla^{-2}(-[f + \bar{\zeta}] \nabla \cdot u^L - \bar{\zeta}^2 \nabla \cdot u),$$

(A5)

$$\chi_5 = \nabla^{-2}(-[\nabla \cdot (u^H \bar{\zeta})]^L),$$

(A6)

$$\chi_6 = \nabla^{-2}(-[\nabla \cdot (u^H \bar{\zeta})]^L),$$

(A7)

$$\chi_7 = \nabla^{-2}(-[\nabla \cdot (u^H \bar{\zeta} + u^H \bar{\zeta})]^L),$$

(A8)

$$\chi_8 = \nabla^{-2}(-k \cdot \left( \nabla \times (\frac{\partial u}{\partial \bar{p}}) \right)^L).$$

(A9)

The superscripts $L$ and $H$ refer to low- and high-pass-filtered quantities, respectively. The overbar defines the winter (November–March) time mean. The bracket indicates a zonal average, the asterisk deviations from the zonal average, $\zeta$ the vorticity, $t$ time, $u$ the horizontal wind vector, $\omega$ the vertical velocity, $k$ the unit vector in the vertical direction, $p$ pressure, and $f$ the Coriolis parameter; $\nabla$ is the divergence operator, $\nabla \times$ the rotation operator, and $\nabla^{-2}$ the inverse Laplacian.

The dynamical meanings of the $\chi_i$ terms are as follows. Very briefly, $\chi_1$ corresponds to the planetary vorticity advection by the low-frequency flow, $\chi_2$ ($\chi_3$) to the interaction of the zonal mean (zonally asymmetric) time mean flow with the low-frequency anomalies, $\chi_4$ the low-frequency contribution to the divergence term; $\chi_5$ ($\chi_6$) the self-interaction among the low-frequency (high frequency) eddies, $\chi_7$ the interaction between the low- and high-frequency eddies, and $\chi_8$ the sum of the tilting terms and the vertical vorticity advection.

Analysis of the streamfunction budget requires the subtraction of the seasonal cycle. For the linear terms ($\chi_1 - \chi_4$) the seasonal cycle of the respective variable is subtracted, whereas for the nonlinear terms the seasonal cycle of the flux is subtracted. The equation with the seasonal cycle removed can be written as

$$\chi_1 = \nabla^{-2}(-[u - u^S]) \cdot \nabla \bar{f},$$

(A10)

$$\chi_2 = \nabla^{-2}(-[u] \cdot \nabla \bar{f} - [u - u^S]) \cdot \nabla \bar{f},$$

(A11)

$$\chi_3 = \nabla^{-2}(-[u^S] \cdot \nabla \bar{f} - [u - u^S]) \cdot \nabla \bar{f},$$

(A12)

$$\chi_4 = \nabla^{-2}(-[f + \bar{\zeta}] \nabla \cdot [u - u^S] - (\bar{\zeta}^2 \nabla \cdot u)$$

(A13)

$$\chi_5 = \nabla^{-2}(-[\nabla \cdot (u^H \bar{\zeta})] - [\nabla \cdot (u^H \bar{\zeta})]^S)^L,$$

(A14)

$$\chi_6 = \nabla^{-2}(-[\nabla \cdot (u^H \bar{\zeta} + u^H \bar{\zeta})] - [\nabla \cdot (u^H \bar{\zeta})]^S)^L,$$

(A15)

$$\chi_7 = \nabla^{-2}(-[\nabla \cdot (u^H \bar{\zeta} + u^H \bar{\zeta})] - [\nabla \cdot (u^H \bar{\zeta})]^S)^L,$$

(A16)

$$\chi_8 = \nabla^{-2}(-k \cdot \left( \nabla \times (\frac{\partial u}{\partial \bar{p}}) \right)^L).$$

(A17)

The superscript $S$ indicates the seasonal cycle. The streamfunction tendencies are calculated as centered differences, except for the first (last) time step where a forward (backward) finite-difference scheme is used. A time step of $\Delta t = 24$ h is used.

APPENDIX B

Linear Independence of the $e_{i\mu} (\lambda, \phi)$

The expression for $e_{i\mu}^{TE}(\lambda, \phi)$ in (3) implies that $e_{i\mu}(\lambda, \phi)$ is orthogonal to $\psi_{\text{reduced}}(\lambda, \phi, t) = \psi(\lambda, \phi, t) - a_{i\mu}^{TE}(t)e_{i\mu}(\lambda, \phi)$. Therefore, the only solution for the coefficients $c_{1a}$ and $c_{1b}$ in
\[ c_{1a}e_1(\lambda, \phi) + c_{1b}\psi_{\text{reduced} 1} = 0 \]  
(B1)

is \( c_{1a} = c_{1b} = 0 \).

An analogous orthogonality relation occurs for each \( m \). Therefore, the only solution for the coefficients \( c_{ma} \) and \( c_{mb} \) in

\[ c_{ma}e_m(\lambda, \phi) + c_{mb}\psi_{\text{reduced} m} = 0 \]  
(B2)

is \( c_{ma} = c_{mb} = 0 \).

The summation of the above \( M \) equations yields

\[ \sum_{m=1}^{M} (c_{ma}e_m(\lambda, \phi) + c_{mb}\psi_{\text{reduced} m}) = 0, \]  
(B3)

A rearrangement of terms and a redefining of coefficients leads to

\[ \sum_{m=1}^{M} (c_m e_m(\lambda, \phi)) = 0, \]  
(B4)

whose only solution must be that all \( c_m = 0 \). This implies that the \( e_m(\lambda, \phi) \) are linearly independent, which in turn indicates that the \( e_m(\lambda, \phi) \) form a nonorthogonal basis.

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