The Continuum of North Pacific Sea Level Pressure Patterns: Intraseasonal, Interannual, and Interdecadal Variability

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ABSTRACT

This study combines k-means cluster analysis with linear unidimensional scaling to illustrate the spatial and temporal variability of the wintertime North Pacific sea level pressure (SLP) field. Daily, wintertime SLP data derived from the NCEP/NCAR reanalysis are used to produce 24 SLP anomaly patterns that represent a discretized approximation of the continuum of North Pacific SLP patterns. This study adopts the continuum perspective for teleconnection patterns, which provides a much simpler framework for understanding North Pacific variability than the more commonly-used discrete modal approach.

The primary focus of this research is to show that variability in the North Pacific, on intraseasonal, interannual, and interdecadal timescales, can be understood in terms of changes in the frequency distribution of the cluster patterns that comprise the continuum, each of which has a time scale of about 10 days. This analysis reveals 5-7 Pacific/North American-like (PNA-like) patterns for each phase, as well as dipoles and wave trains. A self-organizing map (SOM) analysis of coupled SLP and outgoing longwave radiation data shows that many of these patterns are associated with convection in the tropical Indo-Pacific region. On intraseasonal timescales, the frequency distribution of these patterns, in particular the PNA-like patterns, is strongly influenced by the Madden-Julian Oscillation (MJO). On interannual timescales, the El Niño-Southern Oscillation (ENSO) impacts the North Pacific continuum, with warm ENSO episodes resulting in the increased frequency of easterly displaced Aleutian low pressure anomaly patterns, and cold ENSO episodes resulting in the increased frequency of southerly displaced Aleutian high pressure anomaly patterns. In addition, the results of this analysis
suggest that the interdecadal variability of the North Pacific SLP field, including the well known “regime shift” of 1976/77, also results from changes in the frequency distribution within the continuum of SLP patterns.
1. Introduction

The wintertime North Pacific sea level pressure (SLP) field exhibits substantial variability over a wide range of timescales. Over periods of days to weeks, these fluctuations are associated with synoptic-scale eddies and with lower frequency teleconnection patterns. The North Pacific SLP field also exhibits pronounced variability on much longer timescales. Numerous studies, including Trenberth (1990), Trenberth and Hurrell (1994), Latif and Barnett (1996), Mantua et al. (1997), Zhang et al. (1997), and Deser et al. (2004) among others, have described interannual and interdecadal climate fluctuations associated with changes in the intensity of the atmospheric circulation over the North Pacific. These interdecadal fluctuations have produced significant climate impacts over western North America (Dettinger and Cayan 1995; Cayan et al. 2001) as well as substantial physical and biological impacts over the North Pacific (Miller et al. 1994; Mantua et al. 1997; Peterson and Schwing 2003).

A sizeable fraction of the variability in the North Pacific SLP field is closely associated with that of large-scale teleconnection patterns, particularly that of the Pacific/North American (PNA) pattern. The PNA encompasses four centers of action in the mid- and upper-tropospheric height field, two centers of the same sign over the North Pacific and southeast United States and two centers of the opposite sign near Hawaii and along the west coast of North America (Wallace and Gutzler 1981). The surface signature of the PNA, however, is largely confined to the North Pacific in the vicinity of the Aleutian Islands (Wallace and Gutzler 1981).

The PNA pattern undergoes a life cycle of growth and decay within a time span of approximately two weeks (Feldstein 2000; Cash and Lee 2001). On slightly longer
timescales, variability over the North Pacific has exhibited coherence with tropical convection associated with the 30-60 day Madden-Julian Oscillation (MJO) (e.g., Liebmann and Hartmann 1984; Weickmann et al. 1985; Lau and Phillips 1986; Knutson and Weickmann 1987; Lau and Phillips 1986; Ferranti et al. 1990; Kiladis and Weickmann 1992; Hsu 1996; Higgins and Mo 1997; Matthews et al. 2004; Zhang 2005; Lin et al. 2007; Mori and Watanabe 2008), whereas on interannual timescales, North Pacific variability has been linked with tropical convection associated with the El Niño-Southern Oscillation (ENSO) (e.g., Bjerknes 1969; Horel and Wallace 1981; Branstator 1985; Rasmusson and Mo 1993; Hoerling et al. 1997). On interdecadal timescales, many studies have focused on the abrupt, step-like “regime shift” after 1976 (Trenberth 1990) whereby the strength of the wintertime SLP field over the North Pacific, which can be measured by the North Pacific Index (NPI)\(^1\), dropped 2 hPa from that of the previous three decades and remained low for more than one decade. Other studies (Mantua et al. 1997; Minobe 1997; Zhang et al. 1997) identified similar abrupt shifts in 1925 and 1947, and analyses of North American tree-ring data (Minobe 1997; D’Arrigo et al. 2005) suggest that North Pacific interdecadal variability likely has extended back at least a few centuries. Based on recent physical and ecological changes over the North Pacific Ocean, a few studies (Bond et al. 2003; Chavez et al. 2003; Peterson and Schwing 2003) suggest that another regime shift may have occurred in the late 1990s. Several studies (e.g., Trenberth and Hurrell 1994; Graham 1994; Deser et al. 2004; D’Arrigo et al. 2005; Deser and Philips 2006) provide strong evidence that recent Pacific regime shifts have

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\(^1\) Trenberth and Hurrell (1994) defined the NPI as the area-weighted mean SLP over the region 30°N to 65°N, 160°E to 140°W. Because the surface contribution to the PNA is largely confined to the North Pacific, the NPI may serve as a proxy record for the PNA index, as evidenced by the correlation of -0.91 between the winter mean (November – March) NP and PNA indices for the period of 1947-1991 (Trenberth and Hurrell 1994).
involved remote forcing from the tropics, though some modeling studies suggest that such interdecadal variability can originate in the North Pacific itself (e.g. Latif and Barnett 1996; Latif 2006).

Although North Pacific variability is closely related to that of the PNA, Feldstein (2002) notes that no single spatial pattern may be considered the PNA because the geographic locations of the PNA anomaly centers vary with the dataset and the PNA definition used. Consistent with this finding, recent works (Kushnir and Wallace 1989; Franzke and Feldstein 2005; Johnson et al. 2008) have developed the continuum perspective of teleconnection patterns, which suggests that the PNA actually consists of many spatially varying PNA-like patterns instead of a single pattern with spatially fixed anomaly centers. In this study, we use a similar approach to that of Johnson et al. (2008) to illustrate the continuum of wintertime North Pacific SLP patterns, which, as we demonstrate, includes the continuum of PNA-like patterns.

In this study, we use k-means clustering combined with linear unidimensional scaling (LUS; Hubert and Arabie 1986) to illustrate the continuum of North Pacific SLP patterns. The k-means cluster analysis produces a spectrum of SLP patterns, and the unidimensional scaling organizes the patterns along a single dimension such that similar patterns are located closely together, and distinct patterns are more widely separated. This method of describing a continuum of patterns in a spatially ordered way is similar to the method of self-organizing maps (SOMs; Kohonen 2001; Hewitson and Crane 2002; Liu et al. 2006; Johnson et al. 2008) but with one notable difference: whereas SOM analysis typically organizes the patterns in two dimensions, the organization of the patterns along a single dimension in this study allows the second dimension to illustrate
the temporal evolution of the frequency of occurrence for each pattern. In addition to
describing the temporal evolution of the North Pacific continuum, in section 3, we also
present a SOM analysis that illustrates coupled variability between the North Pacific SLP
field and outgoing longwave radiation (OLR) in the tropical Indo-Pacific region in order
to shed light on the relationship between the North Pacific continuum and tropical
convection.

We have organized this article in the following manner. Section 2 describes the
data and analysis procedures. In section 3, we illustrate the continuum of wintertime
North Pacific SLP anomaly patterns together with a description of the intraseasonal,
interannual, and interdecadal variability of each SLP pattern within the continuum. We
conclude with a brief discussion in Section 4.

2. Data and Analysis Methods

To determine the predominant North Pacific SLP anomaly patterns, we analyze
daily, wintertime (December – March) SLP data derived from the NCEP-NCAR
reanalysis dataset (Kalnay et al. 1996) for the period of 1958-2005. We consider the 2.5°
x 2.5° latitude-longitude grid centered over the North Pacific that is bounded by 20° N
and 90° N and by 120° E and 120° W. For the purpose of examining the connection
between the North Pacific SLP patterns and convection in the tropical Pacific, we also
analyze daily OLR data obtained from the National Oceanic and Atmospheric
Administration (Liebmann and Smith 1996). We use winter OLR data from 1974-2005
except for a period of approximately six weeks in 1978 when data are missing. We
examine OLR data on the 2.5° x 2.5° latitude-longitude grid bounded by 20° S and 20° N
and by 20° E and 60° W. For both the SLP and OLR datasets, we have subtracted the seasonal cycle at each grid point, and the resulting quantities are referred to as anomalies. Because the SLP and OLR fields are on a sphere, we weight the data by the square root of cosine of latitude in all subsequent analyses to account for the dependence of grid point density on latitude.

2a. K-means cluster analysis and linear unidimensional scaling

We obtain a set of representative North Pacific SLP patterns through the method of k-means cluster analysis (e.g., Anderberg 1973; Michelangeli et al. 1995). The k-means algorithm clusters each object in a dataset into $K$ partitions by attempting to minimize the squared error

$$J = \sum_{c=1}^{K} \sum_{z \in S_c} \| z - m_c \|^2$$

(1)

where $\| z - m_c \|$ is a distance measure, usually Euclidean distance, between the data vector $z$ and the nearest cluster center $m_c$, and $S_c$ is the set of all data vectors that have $m_c$ as the nearest cluster center. In this case, we may consider $z$ as an $n$-dimensional vector that corresponds with the daily SLP field with $n$ grid points, and the cluster center $m_c$ corresponds with a representative SLP pattern that most closely resembles $z$. Through the minimization of the squared error function in (1), each daily SLP field becomes associated with a similar representative pattern, and, thus, the $K$ representative patterns provide a discretized approximation of the continuum of SLP patterns, as explained more thoroughly in Johnson et al. (2008) for the conceptually similar method of SOMs.
The choice of the number of clusters $K$ is arbitrary, so we choose values of $K$ that range from 16 to 32. For each value of $K$, we repeat the algorithm 10 times with different initial, randomly selected cluster centers, and then choose for the final result the clustering with the smallest squared error. We perform these repetitions to ensure that we choose a solution that has converged near the global minimum rather than a substantially larger local minimum of the squared error function, though we find the sensitivity of the error to choice of initial cluster centers to be quite small. We obtain qualitatively similar results with both small and large $K$, but we choose to illustrate results from the 24-pattern analysis as a balance between economy and the degree of resolved detail in the patterns. Because we focus on the continuum perspective of North Pacific SLP patterns, we have chosen not to focus on an optimal number of clusters, as in other exploratory studies that have focused on the identification of discrete clusters or quasi-stationary regimes.

Unlike in the SOM method discussed in Johnson et al. (2008), the k-means algorithm does not organize the $K$ representative patterns in any particular manner. In order to achieve an ordering whereby similar patterns tend to be grouped together and dissimilar patterns tend to be widely separated, we apply the LUS method. We may describe the task of LUS as follows: given a set of $K$ clusters and a symmetric $K \times K$ matrix $D = \{d_{ij}\}$ of Euclidean distances between each of the cluster centroids, we arrange each of the cluster centroids along a single dimension such that each of the $K(K-1)/2$ interpoint distances between cluster centroids approximate the distances in $D$. This approximation amounts to a least-squares solution such that $\sum_{i \neq j} (d_{ij} - |x_j - x_i|^2$ is minimized, where $x_j$ and $x_i$ correspond to the coordinates of the cluster centers, or representative patterns, along the LUS line. We use the dynamic programming recursion
given in Hubert et al. (2002) to achieve a globally optimal least-squares solution. After determining the one-dimensional coordinates for each representative pattern, we redefine the pattern numbers such that the sequence of patterns \( m_1, m_2, \ldots, m_K \) are represented in ascending order according to the coordinates determined by the LUS procedure. Thus, similar patterns have similar pattern numbers, and distinct patterns have a greater difference between their pattern numbers (see Fig. 1).

The ordering of the patterns through the LUS procedure benefits the analysis in several ways. Firstly, the ordering aids in the visualization of the continuum of similar SLP patterns, as similar patterns are numbered closely together rather than randomly scattered, as in k-means clustering alone. Secondly, the pattern ordering enhances the interpretation of changes in the atmospheric circulation with time: changes in the frequency of occurrence of similarly numbered patterns correspond with subtle changes in the circulation, whereas changes in frequency between more widely separated patterns correspond with more dramatic changes in the atmospheric circulation. Finally, the ordering through LUS provides a framework that allows consistency of interpretation for various choices in the number of clusters. In particular, as long as the representative patterns are organized by the LUS procedure, then we expect the progression of representative patterns to illustrate the same general sequence for all values of \( K \). The choice of \( K \), then, determines the level of detail versus the level of generality retained in the set of representative patterns.

2b. SOM analysis of coupled OLR-SLP variability
In order to examine the relationship between North Pacific SLP variability and convection in the tropical Indo-Pacific region, we perform a SOM analysis of the combined tropical Pacific OLR-North Pacific SLP dataset for the winters of 1974-2005. In this analysis we assume that negative OLR anomalies serve as a suitable proxy for anomalous convection, as demonstrated in many previous studies. We first perform SOM analysis to generate 24 coupled OLR-SLP patterns on an ordered 4 x 6 two-dimensional grid (see Johnson et al. (2008) for a detailed discussion of SOM analysis as applied to atmospheric teleconnection patterns). The results of the SOM analysis are similar to those of combined k-means cluster analysis/LUS except that the resulting patterns in the SOM analysis become organized on a two-dimensional plane instead of a line. We choose the SOM-based approach for this particular examination in order to emphasize the spatial ordering rather than the temporal evolution of the coupled OLR-SLP patterns.

For this analysis, we first generate non-overlapping 10-day means of OLR and SLP anomaly data for the equatorial and North Pacific grids, respectively, for each winter between 1974 and 2005. Both modeling (Hoskins and Karoly 1981; Jin and Hoskins 1995; Matthews et al. 2004) and observational studies (Kiladis and Weickmann 1992; Higgins and Mo 1997) suggest that the strongest extratropical response occurs more than a week after the onset of tropical heating, so we allow the OLR anomalies to lead the North Pacific SLP anomalies by 10 days. Thus, each winter consists of twelve pairs of 10-day mean anomaly fields, where each winter begins on December 1st for the SLP fields and on November 21st for the OLR fields. Before combining the OLR and SLP datasets, we normalize all anomalies by their standard deviation at each grid point. In
addition to the latitude weighting mentioned above, we also weight each standardized OLR anomaly value by multiplying by the square root of the ratio of the domain areas (the North Pacific domain area divided by the equatorial Pacific domain area); this additional weighting ensures that each OLR anomaly field receives the same weight in the analysis as each North Pacific SLP anomaly field despite the larger size of the equatorial Indo-Pacific domain. We present the results of these cluster analyses in section 3.

3. The Continuum of North Pacific SLP Patterns

Figure 1 illustrates the 24 SLP anomaly patterns obtained by k-means cluster analysis and ordered by the LUS procedure. The first five patterns are dominated by broad, anomalously strong Aleutian lows, characteristic of the positive phase of the PNA, centered over different parts of the domain. Patterns 6-19 feature dipoles of various orientations, wave trains, and patterns with pairs of smaller-scale anomaly centers of the same sign. The last five patterns, which typify the negative phase of the PNA, are dominated by a broad, anomalous high pressure in the vicinity of the Aleutian Islands. Furthermore, the appearance of numerous dipoles and other patterns suggest that a single index, such as the NPI, does not fully capture the variability of the SLP field over the North Pacific.

We classify each daily SLP field to the best-matching representative pattern on the basis of minimum Euclidean distance. The percentages toward the bottom right of each pattern in Fig. 1 describe the pattern’s frequency of occurrence for the entire 48-year period. The mean pattern correlation (Horel 1985) between each daily SLP field and the
best-matching pattern in Fig. 1 is 0.65, which suggests a rather strong agreement between the daily SLP fields and the cluster centroids in Fig. 1.

The patterns presented in Fig. 1 lend support to the widespread observation that the PNA dominates North Pacific variability. In order to verify this observation, we examine the relationship between the patterns in Fig. 1 and the North Pacific teleconnection patterns, including the PNA, that are monitored by the Climate Prediction Center (CPC). First, we generate monthly time series for each of the 24 North Pacific SLP patterns by projecting the daily SLP field onto each pattern in Fig. 1 and then calculating monthly mean projection values. From the CPC, we obtain monthly mean indices for the PNA pattern, the West Pacific (WP) pattern, the East Pacific/North Pacific (EP/NP) pattern, and the Tropical/Northern Hemisphere (TNH) pattern (the PNA and WP indices are available for all months, but the EP/NP index is not available in December and the TNH index is not available in March). In addition, we obtain monthly mean values of the NPI provided by the Climate Analysis Section at the National Center for Atmospheric Research (NCAR) (Trenberth and Hurrell 1994). All monthly mean time series have been standardized based on the period from 1958-2005. Then, for each of the time series corresponding to the patterns in Fig. 1, we identify all months in which the standardized index exceeds a value of 1.0. Next, we calculate composite teleconnection indices based on the time series obtained from the CPC and from NCAR for each of the months identified in the previous step. We calculate composite indices rather than linear correlations because, in contrast with some other methods, the k-means method does not produce patterns with two opposite phases, so negative indices for the patterns in Fig. 1 may not be physically meaningful. In order to ensure approximate temporal
independence among the indices identified, we establish a minimum separation of two months; if consecutive months exceed the 1 standard deviation threshold, then we keep only the larger of the two values.

Table 1 presents the composite monthly mean teleconnection index values for each of the 24 patterns in Fig. 1. Bold values are statistically significant above the 95% confidence level based on a two-sided t-test, where the number of degrees of freedom ranges from 12 to 30. Inspection of Table 1 confirms the dominance of the PNA, with most of the first and last 10 North Pacific SLP patterns being closely associated with the positive and negative phase, respectively. Thus, the lower-numbered (higher-numbered) patterns in Fig. 1 represent the positive (negative) phase of the PNA continuum. Table 1 also reveals the secondary importance of the WP, EP/NP, and, to a lesser extent, the TNH, with the middle patterns in Fig. 1, particularly 11-15, being dominated by the WP and EP/NP patterns. As expected, the composite NP indices exhibit similar values as the negative of the composite PNA indices. In summary, the continuum of SLP patterns depicted in Fig. 1 exhibit close associations with the canonical North Pacific teleconnection patterns, particularly with the PNA, but almost all patterns in Fig. 1 represent a mix of two or more of these teleconnection patterns.

3a. Intraseasonal variability of the North Pacific continuum

Given the strong association between the patterns in Fig. 1 and the canonical North Pacific teleconnection patterns, we might expect that the patterns in Fig. 1 have short time scales on the order of two weeks, as documented for the continuum of
Northern Hemisphere teleconnection patterns (Franzke and Feldstein 2005). In order to verify that this is the case, we estimate the timescale of each of the 24 patterns by examining the e-folding time of the daily projection time series. For each standardized, daily projection time series, we identify all intervals during which the amplitude exceeds 1 standard deviation for at least 3 consecutive days, and then we define the first day of each interval as the onset day for that event. Next, we average the index amplitudes over all events, generating composite index values beginning with the onset day (lag 0) and ending 20 days after the onset day. We determine the timescale of the pattern as the time required for the maximum amplitude to decay by a factor of 1/e.

The timescales of North Pacific SLP patterns presented in Table 2 indicate that the patterns within the North Pacific continuum decay within short time periods of approximately 5-10 days. The choices for the criteria to determine the timescales are arbitrary, so the precise timescale values exhibit some sensitivity to the criteria we have chosen. For example, if we increase the amplitude threshold to 1.25 standard deviations, the timescale for some patterns changes by approximately 1 day. Thus, the broad conclusion of this analysis remains robust: the SLP patterns within the North Pacific continuum are dominated by short, sub-seasonal characteristic timescales.

3b. Coupling between the North Pacific SLP patterns and tropical convection

As mentioned in the introduction, numerous studies suggest that anomalous heating associated with tropical convection, particularly in connection with the MJO, may play an important role in initiating extratropical circulation anomalies over the North
Pacific. The emerging picture suggests that the convective outflow from tropical heating anomalies associated with the MJO helps to initiate Rossby waves that propagate poleward into midlatitudes, where these waves can extract energy from the zonally-varying background flow (Simmons et al. 1983; Feldstein 2002; Mori and Watanabe 2008). In order to examine this tropical-extratropical connection, we first present the SOM of coupled OLR-SLP patterns, as described in the previous section.

The SOM in Fig. 2 represents the continuum of coupled OLR-SLP patterns, whereby each 10-day mean OLR anomaly pattern, as discussed in section 2, precedes the corresponding 10-day mean North Pacific SLP anomaly pattern by 10 days. Because of the spatial ordering properties of the SOM algorithm, similar coupled patterns are located close together within the SOM and distinct patterns are more widely separated. The strongest OLR anomaly patterns are located in the top right section of the SOM, particularly the two patterns located in the first two rows and in column 6 (identified hereafter as coupled patterns (1,6) and (2,6)). These two coupled patterns, which only occurred during strong El Niño episodes, feature strong negative OLR anomalies reaching values as low as -80 W/m² that extend from the International Date Line as far east as the South American continent, and positive OLR anomalies as high as 50 W/m² that extend eastward from approximately 90°E to the Date Line. The SLP patterns in Fig. 2 bear an obvious resemblance to those of Fig. 1, whereby the SLP patterns in the top (bottom) two rows of Fig. 2 generally feature low (high) pressure patterns like the lower-numbered (higher-numbered) patterns in Fig. 1.

The coupled patterns in Fig. 2 suggest rather complex relationships between tropical convection and the continuum of North Pacific SLP patterns. Nevertheless, we
can discern a general relationship from this SOM analysis: North Pacific SLP patterns dominated by anomalous low (high) pressure tend to be preceded by anomalous convection east (west) of 120°E. This relationship between the longitude of tropical heating and the sign of the North Pacific SLP anomaly is generally consistent with several previous studies based on numerical modeling (Simmons et al. 1983; Jin and Hoskins 1995; Matthews et al. 2004) and on the analysis of observational data (Weickmann et al. 1985; Ferranti et al. 1990; Kiladis and Weickmann 1992; Hsu 1996; Higgins and Mo 1997).

Although the results in Fig. 2 are generally consistent with this relationship, some coupled patterns suggest that exceptions to this tendency do exist: North Pacific lows (highs) sometimes occur when anomalous convection occurs west (east) of 120°E, and some coupled patterns suggest that strong North Pacific SLP anomalies may occur in the absence of strong, large-scale tropical heating. Thus, tropical heating appears to be an important precursor but not the sole driver of the North Pacific atmospheric circulation.

3c. Relationship between the MJO and the North Pacific continuum

Because the MJO is the dominant form of variability in the tropics on intraseasonal timescales, we next examine more closely the relationship between the North Pacific continuum and the MJO. MJO-related OLR anomalies generally exhibit east-west oriented dipole patterns, like several in Fig. 2, that propagate eastward at approximately 5 ms⁻¹. To examine the link between the continuum of SLP patterns in Fig. 1 and the MJO, we use the MJO time series developed by Wheeler and Hendon
This daily time series consists of both magnitude and a numbered phase (1-8) based on the projection of daily OLR, 200-hPa zonal wind, and 850-hPa zonal wind onto the first two empirical orthogonal functions of the combined OLR and zonal wind fields. Figure 3, which is quite similar to Fig. 8 of Wheeler and Hendon (2004), illustrates the progression of composite OLR anomalies associated with each phase of the MJO. In phase 1, anomalous convection first develops over the western Indian Ocean (first panel of Fig. 3). During the subsequent transitions from phases 1-8, the anomalous convection slowly propagates eastward, amplifying over the Indonesian maritime continent and decaying east of the Date Line. The nominal transition time between each phase is 6 days, though this time may vary from event to event, as one MJO cycle generally takes between 30 and 70 days to complete.

Because each phase of the MJO is associated with tropical heating over a particular longitudinal band, the discussion in section 3b suggests that the frequency distribution within the North Pacific continuum may vary based upon the phase of the MJO. To examine this possibility, we first isolate all onset days for each phase in the wintertime MJO time series for the period of 1974-2005. We define an MJO onset day (lag 0) by considering all intervals during which the particular phase is constant for at least two consecutive days and assigning the onset day to the first day of each interval. We choose this threshold of two days for the purpose of simplicity, but the general results are rather insensitive to the number of days that we choose. In addition, we establish a minimum separation of 20 days between onset days; if this separation criterion is not met, then we keep only the onset day with the higher MJO magnitude. Next, we calculate the frequency of occurrence of each pattern in Fig. 1 for five-day intervals centered at
various lags with respect to the onset day. For example, the frequency of occurrence of SLP pattern 1 centered at lag +2 days for a particular MJO phase corresponds with the frequency of pattern 1 during the interval of lag 0 (the MJO onset day) to lag +4 days. We use a five-day interval instead of a single day in order to generate a smoother signal, given that the time required for the extratropical circulation to respond to tropical heating may vary from case to case. Following the convention of Cassou (2008), we express these frequency calculations as anomalous frequency relative to climatology for the period of 1974-2005: a value of 100% means that the pattern occurs twice as frequently as climatology, whereas a value of -100% means no occurrence of that pattern. We calculate the anomalous frequency for lags ranging from +2 days to +28 days at an interval of one day for all 24 patterns and for each of the eight MJO phases.

Figure 4 presents the anomalous frequency of occurrence of each SLP pattern in Fig. 1 relative to the onset of each MJO phase. In each panel, we also present the patterns and lags for which the anomalous frequency is statistically significant above the 95% and 99% confidence levels, based on a Monte Carlo test that we describe as follows. For a given number of onset days, we performed the same anomalous frequency calculations as above but with randomly chosen onset days. We repeated the simulation 10,000 times with different, random onset days to obtain a distribution of anomalous frequencies. We then compared the observed anomalous frequency with this distribution to determine the statistical significance for a two-sided test.

Focusing first on phase 1 (Fig. 4a), we note that the most conspicuous features include the positive frequency anomalies for the higher numbered patterns one to two weeks after the onset of phase 1, particularly for patterns 15, 17, 23, and 24, and the
anomalous frequency of pattern 8 three to four weeks after onset. This observation is consistent with the previous results in Fig. 2, given that phase 1 is associated with emerging convection over the Indian Ocean well west of 120°E and that the higher numbered patterns are associated with anomalous high pressure over the North Pacific (note that pattern 8 also features a high over the Aleutians, which contrasts the other lower numbered patterns). The enhanced occurrence of these higher-numbered patterns, which are members of the continuum of negative PNA-like patterns (Table 1), support the recent results of Mori and Watanabe (2008). That study demonstrated that tropical forcing associated with the MJO is an important initiator of the PNA, with the MJO triggering approximately 30% of the total PNA events.

As expected, these anomalous frequencies shift to smaller lags with increasing phase. By the onset of phase 4 (Fig. 4d), the bright colors for the high numbered patterns and the dark colors for the low numbered patterns at the smallest lags suggest that the onset of phase 4 is characterized by the enhancement of high pressure patterns and suppression of low pressure patterns over the North Pacific. We also note, however, that the lower numbered patterns become anomalously frequent two to four weeks after the onset of phase 4. Again, this observation is consistent with the previous results because the lower numbered patterns generally correspond with anomalous low pressure over the North Pacific, and, consistently, the transition between phases 4 and 5 signal a shift of tropical heating across the longitude of 120°E (Fig. 3). Again, these anomalous frequencies generally shift to smaller lags with increasing phase so that by the onset of phase 7, anomalous low pressure patterns (members of the positive-phase PNA continuum) at the smallest lags dominate (Fig. 4g). Overall, Fig. 4 suggests that the MJO
has a significant impact on the intraseasonal variability of the North Pacific SLP field, with the onset of phases 4 and 5 being dominated by anomalous high pressure patterns, and the onset of phases 7 and 8 being dominated by anomalous low pressure patterns. Based on the lags with the highest anomalous frequencies, this analysis is consistent with the notion that the North Pacific circulation responds one to two weeks after the onset of MJO-related tropical heating, as suggested in the previous modeling and observational studies mentioned above. These results also complement the results of Mori and Watanabe (2008) by illustrating which members of the PNA continuum are most strongly excited by the MJO.

3d. Interannual variability of the North Pacific continuum

As stated in the introduction and in numerous previous studies, the anomalous convection associated with ENSO has a significant impact on North Pacific SLP variability. Because ENSO is the dominant form of interannual variability in the tropics, in this section, we assess the impact of ENSO events on the frequency distribution of the SLP patterns in Fig. 1. First, we obtain the three-month running mean values of the Niño 3.4 sea surface temperature (SST) index from the CPC for the period of 1958-2005. This index is defined by the SST averaged over the region extending from 5°N - 5°S and from 120°W - 170°W. Then we assign each month to one of three categories: warm ENSO (El Niño), neutral ENSO, and cold ENSO (La Niña) months, where we have adopted the CPC’s definition for an El Niño (La Niña) episode as any time period for which the monthly Niño 3.4 index is greater than (less than) or equal to 0.5°C (-0.5°C) for at least 5
consecutive months. Table 3 presents the frequency of occurrence of the patterns in Fig. 1 for all winter months (the same values are also shown for each pattern in Fig. 1), La Niña months, neutral ENSO months, and El Niño months. Values in bold indicate frequencies that are significantly different from climatology above the 95% confidence level. We again assess statistical significance with a 10,000-simulation Monte Carlo test for each ENSO category, where we have randomly chosen onset days in each simulation but have maintained identical numbers of events and event durations to those of the real warm, cold, and neutral ENSO events. Approximately one-quarter of all days falls into each of the La Niña and El Niño categories (1456 and 1665 days, respectively).

Inspection of Table 3 and Fig. 1 indicates that El Niño (La Niña) events result in an increased frequency of anomalous low (high) pressure patterns and a corresponding decreased frequency of anomalous high (low) pressure patterns. Most patterns with enhanced frequencies during El Niño and La Niña episodes are associated with the PNA. Thus, the results of this analysis support the previously reported relationship that El Niño (La Niña) events project onto the positive (negative) phase of the PNA (e.g. Horel and Wallace 1981) (except in the case of pattern 8), but that the extratropical atmospheric response is nonlinear (Hoerling et al. 1997). In particular, El Niño (La Niña) episodes correspond to patterns with enhanced frequency at the eastern (southern) part of the domain. Consistent with Mo and Livezey (1986), Tables 1 and 3 indicate that this eastward shifted Aleutian low also projects strongly onto the TNH pattern. The results presented here, however, imply that all patterns within the North Pacific continuum occur during each phase of ENSO, including both phases of the PNA. Careful inspection of Fig. 4 also suggests that the members of the continuum most strongly affected by the
MJO (e.g., patterns 2 and 24) are distinct from the members of the continuum most strongly influenced by ENSO.

The results of Table 3 imply that even though ENSO fluctuates on interannual timescales, its impact on the North Pacific is to change the frequencies of occurrence of patterns with a much shorter timescale. Moreover, these results offer a unique interpretation to the debate about the impact of ENSO on the PNA (Horel and Wallace 1981; Livezey and Mo 1987; Straus and Shukla 2002; van den Dool 2007): ENSO alters the frequency of occurrence of patterns in only one part of the PNA continuum. This argument is consistent with both ideas that ENSO excites the PNA (Horel and Wallace 1981; Feldstein 2000; Molteni et al. 2006) but that these PNA-like patterns may be distinct from the canonical PNA (Straus and Shukla 2002; Straus et al. 2007; van den Dool 2007). The nature of this debate hinges on the notion that the PNA is a single mode, or fixed pattern, that is excited by ENSO, but the contrasting continuum perspective adopted in this study allows both perspectives to have merit.

3e. Interdecadal variability of the North Pacific continuum

In this section, we investigate the interdecadal variability of the North Pacific continuum from the perspective of changes in the frequency distribution of the patterns in Fig. 1 over the period of 1958-2005. In order to describe these changes in frequency distribution, we have calculated the frequency of occurrence of each pattern for each year, and then smoothed each frequency time series with a five-year moving average. The general conclusions are insensitive to this choice of filter, but we choose a five-year
moving average to capture details of both the interannual and interdecadal variability. Figure 5 illustrates the smoothed frequency time series for each pattern. Inspection of Fig. 5 reveals that all patterns occurred throughout the entire period, though the frequencies of occurrence varied throughout the period. In particular, we observe a dominance of the higher-numbered (high pressure) patterns until the late 1970s and then a dominance of lower-numbered (low pressure) patterns throughout most of the rest of the period. This observation agrees with the known regime shift of 1976/77 discussed in the introduction.

Closer inspection of Fig. 5 reveals several time intervals on the order of 10 years where particular groups of patterns tended to dominate. Based on visual inspection, we have identified and labeled five separate periods characterized by the dominance of particular groups of patterns: 1958-1971 (P1), 1972-1978 (P2), 1979-1985 (P3), 1986-1997 (P4), and 1998-2005 (P5) (notice that the first two and last two years do not appear in Fig. 5 due to the five-year moving average). We also illustrate the aforementioned regime shift of 1976/77 in Fig. 5 by a dashed white line. We summarize the main features of each period as follows.

The period P1 was dominated by patterns 16-22, though patterns 11-13 were anomalously frequent as well during the first part of the period. As mentioned above, the higher-numbered patterns generally feature broad, anomalous high pressure in the vicinity of the Aleutian Islands, whereas patterns 11-13 feature smaller-scale, negative SLP anomalies centered near the Aleutians. The following period, P2, is characterized by the emergence of patterns 9 and 11, both of which exhibit anomalous low pressure over Alaska and the Aleutians, though the center of the Aleutian anomaly in pattern 11 is
flanked by two broader, stronger high-pressure anomaly centers. The Pacific regime shift occurred during P2, though the onset of P3 two years later appears more striking. The period P3 is characterized by the sudden dominance of patterns with a broad, anomalously strong Aleutian low (patterns 1-3, 5, and 7) and by the near absence of the higher-numbered patterns so prevalent during P1 and P2. The extreme El Niño of 1982/83 likely contributed significantly to the emergence of patterns 1 and 7 during this period. During P4, the broad, strong Aleutian lows in patterns 1-3 become much less prevalent, whereas patterns with anomalous high pressure over the North Pacific (patterns 20-22) make a brief return to prominence. During the final period, P5, the frequency of patterns 20-22 diminishes greatly, whereas patterns 12 and 13 become more prevalent, and patterns 4 and 5 remain common. The anomalously frequent SLP patterns of P5 generally feature low pressure over the North Pacific, though patterns 4 and 12 feature anomalously high pressure over the southern part of the domain.

Next we provide a more quantitative evaluation of the effectiveness of this analysis in capturing the interdecadal variability in the North Pacific SLP field. Specifically, we calculate the composite North Pacific SLP anomalies for P1 through P5 obtained with the actual daily SLP fields and compare those fields with those obtained with

$$\overline{z}_i(x,y) = \sum_{c=1}^{24} m_c(x,y)f_i(m_c), \quad i = 1, 2, \ldots, 5,$$

where $\overline{z}_i(x,y)$ denotes the North Pacific SLP anomaly pattern for period $i$, based on $m_c(x,y)$, pattern $c$ in Fig. 1, and $f_i(m_c)$, the frequency of occurrence of pattern $m_c$ for period $i$. Figure 6 presents both the true SLP anomaly composites and those approximated through the application of (2) for each of P1 through P5. Firstly, we note

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the use of a smaller contour interval for those composites obtained by (2), as those composites tend to underestimate the magnitude of some of the anomaly centers, particularly the smaller-scale centers. As demonstrated in Johnson et al. (2008), the agreement in magnitude tends to increase with $K$, but even with 24 patterns we see rather strong agreement between the true North Pacific SLP anomaly composites and those obtained through (2); the pattern correlations between the true composites and the corresponding analysis-derived composites range from 0.77 to 0.92. Thus, we conclude that interdecadal variability of the North Pacific SLP field can be described rather well by the changes in the frequency distribution of the patterns presented in Fig. 1 that fluctuate on intraseasonal timescales.

4. Discussion and Conclusions

In this study, we examine the intraseasonal, interannual, and interdecadal variability of the North Pacific SLP field in the context of the variability in the frequency of the cluster patterns that comprise the North Pacific continuum. On intraseasonal and interannual timescales, convection in the equatorial Pacific exerts a significant influence on this frequency distribution, particularly in association with the MJO and with ENSO. Given the statistically significant relationships between MJO phase and SLP pattern frequency of occurrence, particularly those associated with the PNA, these results lend promise to enhancing weather predictability over the North Pacific and regions downstream for lead times of one to three weeks.

On interannual timescales, ENSO episodes generally correspond with the enhanced frequencies of occurrence of particular members within the PNA continuum.
Although we have considered the relationship between ENSO and the PNA for the period of 1958-2005, we should exercise caution in this interpretation, as suggested in DeWeaver and Nigam (2002), given the short time record and the existence of substantial interdecadal variability. For example, the mean CPC PNA index for the La Niña episodes during the period of 1958-1976 (before the North Pacific regime shift) is -0.44; for La Niña episodes from 1977-2005, the mean PNA index is only -0.13. For El Niño episodes, the mean PNA index is actually slightly negative before 1977 (-0.07), and it rises to 0.52 during the 1977-2005 period. These results suggest the existence of substantial interdecadal variability in the relationship between the North Pacific continuum and ENSO. The reasons for this non-stationary ENSO/PNA relationship are unclear but worthy of further investigation.

In this study, we also demonstrate that the interdecadal variability in the North Pacific SLP field can be understood as a change in the frequency distribution within a continuum of intraseasonally-varying SLP patterns. Within this framework, however, we do not describe the interdecadal variability as a secular, step-like regime shift, as many previous studies have done. With regard to the well-known shift in North Pacific climate during the mid-1970s, we describe the shift as a transition from the dominance of various patterns with anomalous high pressure over the North Pacific (the higher-numbered patterns in Fig. 1) to the dominance of patterns with anomalous low pressure over the same region (the lower-numbered patterns). Figure 5 demonstrates that on interannual and interdecadal time scales we also observe more subtle changes in the frequency distribution, such as the changes that occur from P1 - P5 described in the previous section. This observation along with the results presented in Fig. 6 suggest that
interdecadal variability over the North Pacific involves not only changes in the strength of the Aleutian low but also changes in the spatial structure of the Aleutian low and surrounding anomaly centers.

As in Bond et al. (2003), the analysis presented in this study suggests that conditions over the North Pacific cannot be characterized by a single index, such as that of the PNA or NPI. Indeed, the results of Dettinger and Cayan (1995) suggest that the climate impacts downstream of the North Pacific may be sensitive to the details in the changes of the atmospheric spatial patterns, which cannot be captured by the trend in the PNA index alone. In this study, we present a method that illustrates the complex distribution of synoptic states over the North Pacific yet retains enough simplicity that the temporal and spatial variability over a range of time scales can be captured in just a few figures.

Acknowledgments.
The authors offer their gratitude for support through the Office of Science (BER), U.S. Department of Energy, Grant No. DE-FG02-05ER64058 and through the National Science Foundation, Grant No. ATM-0649512. We also thank the Climate Analysis Branch of the NOAA Earth System Research Laboratory/Physical Sciences Division for providing us with the NCEP/NCAR Reanalysis data. In addition, we acknowledge the NOAA Climate Prediction Center and the Climate Analysis Center of NCAR for providing us with the climate indices. Finally, we thank the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, for the interpolated OLR data provided at their website at http://www.cdc.noaa.gov.
References


List of Figures

FIG 1. The SLP anomaly patterns obtained by k-means cluster analysis, contoured at intervals of 2 hPa. Solid (dashed) lines depict positive (negative) values, with the zero contour omitted. The pattern number is displayed in bold below each pattern, and the percentages at the bottom right of each map describe the pattern frequency for the period of 1958-2005.

FIG 2. The 4 x 6 SOM of coupled OLR-SLP anomaly patterns, where the OLR anomaly pattern lies below the associated SLP anomaly pattern. The contouring convention is the same as in Fig. 1, but the contour interval is 1 hPa for the SLP anomaly plots and 5 Wm\(^{-2}\) for the OLR anomaly plots. In addition, OLR anomalies below -10, -25, and -50 Wm\(^{-2}\) are shaded in light, medium and dark blue, respectively, and OLR anomalies above 10, 25, and 50 Wm\(^{-2}\) are shaded in yellow, orange, and red. In the SLP anomaly plots, land is shaded in gray. (Note that the longitude ranges are 120\(^{\circ}\)E to 120\(^{\circ}\)W for the SLP plots and 20\(^{\circ}\)E to 60\(^{\circ}\)W for the OLR plots). The percentage at the bottom right of each OLR pattern describes the frequency of occurrence of the coupled pattern for the period of 1974-2005.

FIG 3. December-March composite OLR anomalies for each phase of the MJO. The contouring convention is the same as in Fig. 1, but the contour interval is 5 Wm\(^{-2}\). Shading levels denote OLR anomalies less than -5, -15, and -25 Wm\(^{-2}\), respectively, and hatching levels denote OLR anomalies greater than 5 and 15 Wm\(^{-2}\), respectively.
FIG 4. The anomalous frequencies of occurrence for the SLP patterns in Fig. 1 for each of the 8 phases of the MJO. In each panel, the colored plot corresponds with the anomalous frequency of occurrence for each pattern (numbered as in Fig. 1 on the y-axis) as a function of lag (days) with respect to the onset day. The plot on the right depicts the patterns and lags for which the frequency anomalies are statistically significant at the 95% (gray) and 99% (black) significance levels.

FIG 5. The wintertime pattern frequency time series corresponding to each pattern depicted in Fig. 1. The colors describe the frequency of occurrence of each pattern for each winter season between 1958 and 2005, where a five-year moving average has been applied to the frequency time series of each pattern. Five separate periods, P1 – P5, are identified as periods between the thin vertical black lines, and the dashed white line corresponds to the Pacific regime shift at the beginning of 1977.

FIG 6. The analysis-derived SLP anomalies (a, c, e, g, i; see text for details) and the true SLP anomalies (b, d, f, h, j) for the periods P1 (a, b), P2 (c, d), P3 (e, f), P4 (g, h), and P5 (i, j). The contour interval is 0.1 hPa for the analysis-derived composites on the left side and 0.2 hPa for the true composites on the right side. The zero contour has been omitted in each plot.
TABLE 1. Monthly mean composite values of the PNA, WP, EP/NP, TNH, and the NP indices corresponding to the SLP patterns in Fig. 1. Bold values are statistically significant at the 95% confidence level for a two-sided t-test.

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### TABLE 2. Timescale (days) of each of the 24 North Pacific SLP patterns in Fig. 1.

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TABLE 3. Frequencies of occurrence (%) of the North Pacific SLP patterns in Fig. 1 for all winter (DJFM) months, and for La Niña, neutral ENSO, and El Niño months in the winters of 1958-2005. Values in bold are significantly different from climatology at the 95% confidence level.

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FIG 2. The 4 x 6 SOM of coupled OLR-SLP anomaly patterns, where the OLR anomaly pattern lies below the associated SLP anomaly pattern. The contouring convention is the same as in Fig. 1, but the contour interval is 1 hPa for the SLP anomaly plots and 5 Wm$^{-2}$ for the OLR anomaly plots. In addition, OLR anomalies below -10, -25, and -50 Wm$^{-2}$ are shaded in light, medium and dark blue, respectively, and OLR anomalies above 10, 25, and 50 Wm$^{-2}$ are shaded in yellow, orange, and red. In the SLP anomaly plots, land is shaded in gray. (Note that the longitude ranges are $120^\circ$E to $120^\circ$W for the SLP plots and $20^\circ$E to $60^\circ$W for the OLR plots). The percentage at the bottom right of each OLR pattern describes the frequency of occurrence of the coupled pattern for the period of 1974-2005.
FIG 3. December-March composite OLR anomalies for each phase of the MJO. The contouring convention is the same as in Fig. 1, but the contour interval is 5 Wm$^{-2}$. Shading levels denote OLR anomalies less than -5, -15, and -25 Wm$^{-2}$, respectively, and stippling levels denote OLR anomalies greater than 5 and 15 Wm$^{-2}$, respectively.
FIG 4. The anomalous frequencies of occurrence for the SLP patterns in Fig. 1 for each of the 8 phases of the MJO. In each panel, the colored plot corresponds with the anomalous frequency of occurrence (%) for each pattern (numbered as in Fig. 1 on the y-axis) as a function of lag (days) with respect to the onset day. The plot on the right side of each panel depicts the patterns and lags for which the frequency anomalies are statistically significant at the 95% (gray) and 99% (black) significance levels.
Fig 5. The wintertime pattern frequency time series corresponding to each pattern depicted in Fig. 1. The colors describe the frequency of occurrence of each pattern for each winter season between 1958 and 2005, where a five-year moving average has been applied to the frequency time series of each pattern. Five separate periods, P1 – P5, are identified as periods between the thin vertical black lines, and the dashed white line corresponds to the Pacific regime shift at the beginning of 1977.
FIG 6. The analysis-derived SLP anomalies (a, c, e, g, i; see text for details) and the true SLP anomalies (b, d, f, h, j) for the periods P1 (a, b), P2 (c, d), P3 (e, f), P4 (g, h), and P5 (i, j). The contour interval is 0.1 hPa for the analysis-derived composites on the left side and 0.2 hPa for the true composites on the right side. The zero contour has been omitted in each plot.