Tropical Pacific Sea-Surface Temperatures and Preceding Sea Level Pressure Anomalies in the Subtropical North Pacific

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Abstract. The correspondence of sea-surface temperature anomalies to changes in antecedent large-scale sea-level pressure anomalies is investigated using reanalysis data. By statistically examining linearly coupled precursor sea-level pressure fields and resultant SST fields for different lag periods, it is possible to isolate a precursor mode of sea-level pressure (SLP) variability in the central subtropical North Pacific that precedes variations in the January-March El Niño/Southern Oscillation (ENSO) by approximately 12-15 months. A sea-level pressure index, which captures the important characteristics of this precursor mode of variability, is developed and evaluated. It is shown that both analyzed and observed versions of the index are significantly correlated with the January-March ENSO one year later. The SLP index is then used to examine the evolution of the surface circulation and temperature structures leading up to mature ENSO events. Initially, the January-March subtropical North Pacific SLP anomalies are associated with changes in the intensity of the subtropical trade wind regime over the North Pacific, as well as with SST anomalies over the eastern equatorial Pacific and subtropical central Pacific. In agreement with the correlation statistics associated with the SLP and lagged NINO3.4 indices, both the sea-level pressure field and the SST field subsequently develop ENSO-like structures over the course of the following year. Significant discussion of these results and pertinent areas of future research are provided within the broader context of the ENSO system.
1. Introduction

Previous research has shown that the northern hemisphere wintertime climate is strongly forced by large-scale boundary conditions associated with the concurrent El Niño/Southern Oscillation (ENSO) [e.g. see Kumar and Hoerling, 1998; Rowell, 1998; Zheng et al., 2000; Shukla et al., 2000; Alexander et al. 2002]. The ENSO phenomenon itself represents a coupled ocean-atmosphere mode of variability involving sea surface temperature anomalies over the eastern and central equatorial Pacific and sea level pressures and surface winds over the tropical and subtropical Pacific [Philander, 1985]. Numerical, experimental, and theoretical studies have elucidated the impact that ENSO has upon local, regional and global atmospheric dynamics [e.g. Trenberth et al., 1998; Alexander et al., 2002]. Other studies have examined the influence of ENSO upon various climatological fields and have identified regions that are impacted by changes in ENSO [see for instance Ropelewski and Halpert, 1986 and 1996; Kiladis and Diaz, 1989; Gershunov and Barnett, 1998].

Recognizing ENSO’s important influence upon the large-scale climate system, researchers have investigated in detail possible forcing mechanisms for the El Niño/Southern Oscillation [e.g. see Neelin et al., 1998] as well as the evolution of the atmospheric and oceanic components of the ENSO system [Rasmusson and Carpenter, 1981; van Loon and Shea, 1985; Barnett, 1985; Philander, 1985; van Loon and Shea, 1987; Trenberth and Shea, 1987; B. Wang et al., 1999; Chan and Xu, 2000; Delcroix et al., 2000; Wang, 2001; Larkin and Harrison, 2002]. In so doing, they have found precursor fields in the extra-tropics related to the initiation of ENSO events, suggesting that the ENSO phenomenon may not simply be an oscillation of the equatorial ocean/atmosphere system [Kidson, 1975; Trenberth, 1976; Reiter, 1978; van Loon and Shea, 1985; Barnett, 1985; van Loon and Shea, 1987; Trenberth and Shea, 1987; Lysne et al., 1997; Gu and Philander, 1997; Li, 1997; Barnett et al., 1999; Pierce et al., 2000; Wang, 2001; Vimont et al., 2003b]. On interannual time-scales, it appears that variations in the subtropical trade-
wind regime, forced either by underlying SST anomalies [van Loon and Shea, 1985; Weisberg and Wang, 1997; Wang, 2001], remote SST anomalies [Li, 1997], or internal atmospheric variability [Vimont et al., 2001; Vimont et al., 2003a; Vimont et al., 2003b], can initiate the onset of equatorial SST anomalies over the central and eastern Pacific. On longer time-scales, similar modification of the trade-wind regime by mid-latitude climate shifts can alter the base-state of the equatorial ocean/atmosphere system and precondition it to a particular phase of the ENSO [Reiter, 1978; Barnert et al., 1999; Pierce et al., 2000].

Importantly, the ability of numerical models [Barnett et al., 1999; Pierce et al., 2000; Vimont et al., 2001; Vimont et al., 2003a] to capture precursor fields related to the forcing of tropical and subtropical SSTs suggests that these fields correspond to physical modes of variability in the ocean and/or atmosphere, which may also be found in the observed system. Statistical studies have found precursor modes of variability self-contained within the SST and atmospheric fields [e.g. Trenberth, 1976; Graham et al., 1987a; Penland and Sardeshmukh, 1995; Kim and North, 1999]. Other studies have found statistically-coupled atmospheric modes of variability that serve as predictors for ENSO, although the physical mechanisms for such predictability have not been fully investigated [e.g. Barnston and Ropelewski, 1992; Latif et al., 1998]. More recent studies investigating this coupling (published after the present work had been completed) suggest that northern hemisphere wintertime atmospheric variability can initiate underlying subtropical/tropical SST anomalies, which then persist through until the summer; during the summer period these SSTs can subsequently force the overlying atmosphere, resulting in zonal wind stress anomalies that are conducive to initiating and maintaining ENSO variability in the tropical Pacific [Vimont et al., 2003a; Vimont et al., 2003b]. This mechanism is diagnosed in climate models [Vimont et al., 2001; Vimont et al., 2003a] and appears to be active in the observed system as well [Vimont et al., 2003b]. In general, these results further suggest that there are spatio-temporal modes of variability in the observed atmosphere/ocean system that can serve as initiators for ENSO activity in the equatorial region.
Here, we attempt to build upon this research by first identifying atmospheric anomaly patterns that represent both statistically significant precursors to the onset of ENSO events, as well as large-scale modes of variability in of themselves. The paper will then further investigate the ocean/atmosphere structure associated with one of these modes of variability. The major finding is that there appears to be a mode of large-scale atmospheric variability in the sub-tropical/extra-tropical northern hemisphere that precedes the development of mature JFM ENSO events by approximately 12-15 months. We would like to note from the outset, however, that many of the specific results found in pursuit of this particular research question are in agreement with those from previous, disparate papers. Here, we quote from van Loon and Madden, [1981]: “When one works with such an often-investigated phenomenon [the Southern Oscillation] it is impossible to avoid repeating the work of others; our excuse for doing so is that we may have been able to place already-known details as parts of a comprehensive picture.” Throughout, we highlight for the reader those specific findings that have been elucidated elsewhere. We also provide the reader with our own corroborating research, which coalesces these findings into a more inclusive picture of the possible dynamical forcing of ENSO events by subtropical/extra-tropical processes.

In Section 2, the various datasets used in this study are described. The correlation between seasonal sea-surface temperature anomalies and antecedent atmospheric anomalies are discussed in Section 3. This section also introduces an index designed to capture the salient characteristics of the precursor mode of variability and investigates surface fields related to this index. Findings are summarized and discussed in Section 4.

2. Data

The principal dataset used in this investigation is the reanalysis product from the National Centers for Environmental Prediction (NCEP – see acknowledgements). Details about this dataset, including its physics, dynamics and numerical and computational methods, are discussed in Kalnay et al. [1996] and Kistler et al., [2001]. For this paper, we
focus on the seasonal-mean surface fields, in particular sea-level pressures and low-level winds, for the years 1948-2000. These fields are represented at 2.5-degree resolution in both the meridional and zonal direction, encompassing a total of 144x73 grid points. These fields are chosen because of their integral nature in any air-sea coupling and because of previous studies indicating that they are strong candidates for finding precursor information regarding the development of large-scale SST anomalies [Kidson, 1975; Trenberth, 1976; van Loon, 1984; van Loon and Shea, 1985; Barnett, 1985; van Loon and Shea, 1987; Trenberth and Shea, 1987; B. Wang et al., 1999; Chan and Xu, 2000; Wang, 2001; Larkin and Harrison, 2002]. It should be noted that although surface observations are incorporated into the reanalysis procedure, the surface fields also tend to be influenced by the atmospheric model, which adjusts them to dynamically match the overlying atmosphere. Therefore these variables should be considered a blend of both observational and simulated values [Kistler et al., 2001]. In addition, as one moves into the tropical and southern hemisphere, where observational data are sparse, the analyzed values become more model-dependent and less reliable [Marshall and Harangozo, 2000; Connolley and Harangozo, 2001]. Finally, recent comparison with shipboard observations suggest that the magnitude of high and low pressure values are underestimated. In addition there is a negative bias in the sea-level pressures overall [Smith et al., 2001]. However, we choose to use the reanalysis product owing to its fairly long continuous record (50+ years) and its systematic treatment of observational and numerical data over this entire period. In addition, it represents the only long-term dataset available for studying climate change on diurnal to inter-annual time-scales and global to synoptic spatial scales. We will evaluate results with observed values where possible. In addition, we will re-analyze the results based upon known deficiencies in the data product. It should be noted that all data are archived after incorporation of the TOVS data processing correction, which previously had introduced large-scale errors from 1998-2000 (see http://wesley.wwb.noaa.gov/tovs_problem).
In addition to the reanalyzed atmospheric fields, this study will also examine the time-evolution of the seasonal-mean sea-surface temperature fields taken from the reanalysis product; a description and evaluation of the reanalysis SST dataset can be found in *Hurrell and Trenberth* [1999]. In general, the NCEP Reanalysis SST data are based upon an EOF reconstruction of near-global SST fields using monthly mean observed SST anomalies taken from the Comprehensive Ocean-Atmosphere Dataset (COADS). For this procedure, 20 years (1982-1993) of SST data, incorporating both remotely-sensed and in-situ SST observations, are analyzed to 1-degree resolution using an optimal interpolation scheme. The analyzed field is separated into six geographical sub-regions and an EOF decomposition is performed on the SST anomalies in each region. Analyzed SST fields derived from the COADS dataset are projected upon the spatial patterns for each region to determine the temporal weight for each mode. The weighted modes are then linearly summed to produce estimates for missing grid points. In this manner, the SST dataset provides near-global coverage for the 50-year span under consideration. The data product used here is at Triangular-62 resolution (approximately 2 degrees in latitude and longitude), encompassing a total of 192x94 grid points. The climatology, variance, and errors for this dataset have been considered elsewhere [*Hurrell and Trenberth*, 1999]. In general, although there are known errors and discrepancies in the dataset (particularly in the regions of sea-ice boundaries and with regard to long-term trends), it appears to be one of the more stable and representative products available for studying interannual variability of large-scale sea-surface temperature structures [*Hurrell and Trenberth*, 1999].

Additional datasets and indices will be used throughout the manuscript in order to further investigate the results derived from the reanalyzed data described above. In particular, the primary observational index used throughout this paper is the NINO3.4 index (see acknowledgments for data availability). This index is defined as the area-average SST anomalies between 5N-5S and 170-120W. It is designed to capture variability in the SST field over the equatorial Pacific. Two versions of this index are used. The predominant
version, used for comparison with the reanalysis results, is provided by NOAA’s Climate Diagnostics Center (CDC). It is derived from the same reanalyzed SST field described above and is therefore consistent in its treatment of observed and analyzed values. The second version, for use with the longer observational record, is the monthly-mean Kaplan SST NINO3.4 index. This version of the index is estimated using the reduced-space optimal analysis of the MOHSST5 global sea surface temperature anomalies [Kaplan et al., 1998; see acknowledgments for data availability] and spans the period 1856-1991.

Additional datasets include the monthly mean sea level pressure data from the 2-degree Comprehensive Ocean-Atmosphere Dataset (COADS - see acknowledgments for data availability). This monthly mean dataset spans from January 1854-December 1992 and is derived from marine data observed by ships-of-opportunity, binned to 2x2-degree boxes. Documentation for the dataset itself can be found in Woodruff et al. [1987]. In addition, the suitability of this global SLP product for use in ENSO studies has been examined in Harrison and Larkin [1996]. Here, we will use the data simply to evaluate more extensive results derived from the reanalysis product. We will also use monthly mean station pressure measurements taken from NCAR’s World Monthly Surface Station Climatology [Shea and Spangler, 1985]. These data are evaluated and analyzed extensively in Trenberth and Shea [1987]. As with the COADS SLP data, these are used to further evaluate the results derived from the reanalysis product.

It should be noted here that all data are detrended prior to analysis. It is recognized that by detrending the data, results presented here may not be capturing longer time-scale phenomena and interactions. However, for this particular research effort, we are interested in looking at inter-annual variations, principally related to changes in large-scale fields from one year to the next. By removing the trends in the data, it reduces the low-frequency variance within the various datasets (for instance as quantified in Trenberth and Paolino, [1981]) and ensures that the algorithms and statistics are not simply capturing modes of long-term variability and co-variability. It should also be noted that throughout this paper,
most results will be based upon statistical relationships between various variables. For these statistics, confidence is inferred from a simple two-tailed t-test based upon a Gaussian distribution. In addition, it is presumed that each yearly value (whether based upon a monthly mean or a three-month mean) is an independent event, hence the degrees of freedom (N) for most of the analysis is simply the number of years, minus 2. Throughout this paper, confidence levels greater than 99% (or 95% for some fields) are indicated on all figures; correlations coefficients that exceed the 1% threshold will be termed “statistically significant” or simply “significant”, although it is recognized that this designation is accurate only if the above assumptions are satisfied.

3. Results

3.1. Statistically-coupled Modes of Variability

Previous research has shown that northern hemisphere modes of climate variability are particularly responsive to SST forcing during the wintertime season [Kumar and Hoerling, 1998; Rowell, 1998; Zheng et al., 2000; Shukla et al., 2000]. In order to detect and isolate modes of variability associated with January-March (JFM) sea-surface temperature anomalies, data from the reanalysis product are first used to compute empirical orthogonal functions (EOFs) of the area-weighted, near-global SST field (55S-55N) using the full anomalies (i.e. the EOF is based upon the covariance matrix of SSTs). We have limited our consideration to values between 55N-55S due to spurious values seen in the far northern Atlantic and Pacific related to significant errors in the regions of sea-ice boundaries [Hurrell and Trenberth, 1999]. The area-weighting is achieved by multiplying the grid-point anomalies by the square root of the cosine of the respective latitude, such that the covariance matrix elements are weighted appropriately. To characterize the integrated atmospheric structure, EOFs are also calculated for the 3-month average near-global sea-level pressure field (65S-65N). For this field, however, the EOF procedure is performed on the standardized anomalies, in which each grid-point anomaly is divided by the grid-point
standard deviation over the entire time-period. This standardization is done because SLP anomalies in the high latitudes tend to be much larger than those found in the tropics and subtropics [Kutzbach, 1970; Kidson, 1975]. As with the SST fields, the grid-point anomalies are then area-weighted. For the sea-level pressure fields, EOFs are calculated separately for each 3-month period starting with the January-March period and proceeding through the December-February period.

One of the main foci of this manuscript is to identify precursor modes of SLP variability that precede large-scale changes in the January-March SST structure. In order to identify both the precursor SLP fields and the resultant SST fields, a canonical correlation analysis (CCA) is performed using the JFM SST EOFs and the SLP EOFs for each 3-month period separately, starting with the January-March period two years prior to the SST anomalies. In general, the CCA technique attempts to produce a set of canonical factor (CF) time-series that isolate the highest correlated modes of variability within a subset of the SLP and SST EOF time-series (see the Appendix for details). In order to examine only the large-scale modes of variability, the subset of EOFs used for the CCA is limited to the first nine (9) for the SSTs and the first twelve (12) for the sea-level pressure fields. Although this number is somewhat arbitrary, it is advisable to include enough EOFs so that a large fraction of the total variability is incorporated into the algorithm. In this case, the subset of nine SST EOFs captures 67% of the total JFM SST variance while the subset of twelve sea-level pressure EOFs explains from 70-76% of the three-month mean variance for the respective time-periods. At the same time, the number of retained EOFs should be limited so that the weighting of the covariance matrices does not simply isolate single extreme events within the time-series [Feddersen et al., 1999].

In general, canonical correlation analysis is found to be most appropriate when the behavior of the statistical fields is governed by only a few multifaceted patterns such as is the case with the El Niño/Southern Oscillation [Barnston, 1994]. Importantly, the methodology allows us to identify well-correlated SST and SLP modes of variability.
without explicitly dictating their spatial and/or temporal structures [Pierce et al., 2000]. Overall, CCA analysis indicates that the predominant canonical factor sea-surface temperature pattern that arises from correlation with preceding SLP anomalies involves large SST anomalies in the central and eastern equatorial Pacific (not shown). This correspondence is particularly true for the SLP anomalies beginning in the October-December period 15 months before the SST anomalies. Prior to that period the principal CF SST patterns appear to be related to the Pacific Decadal Oscillation [as described in Mantua et al. 1997]. However, even for these periods, an ENSO-like SST pattern is consistently captured within the first three to four canonical factors. As such, we have decided to focus our research upon the correlation between the JFM ENSO and the state of the preceding SLP fields.

To get a sense of this correlation, we take all of the SLP canonical factor time-series for each of the three-month periods, beginning with the JFM period two calendar years prior to the JFM SST anomalies, and correlate them with the NINO3.4 index for the period concurrent with the SST anomalies. We then select the CF time-series for each 3-month period that shows maximum correlation with the NINO3.4 index. The correlation values for these time-series are shown in Figure 1. It appears that for leads any greater than approximately 15 months (OND two calendar years prior to the target JFM period), modes of sea–level pressure variability show only a moderate correlation with ENSO events (r~0.4). The exception is the 3-month period from June-August (and somewhat from July-September); previous research has highlighted this approximate 18 month lead, which is related to sea-level pressure variability in the western subtropical South Pacific [Trenberth, 1976; Rasmusson and Carpenter, 1981; van Loon and Shea, 1985; van Loon and Shea, 1987]. Sustained correlations, however, rise above r=0.5 approximately 15 month before mature ENSO events (i.e. the OND period two calendar years prior to the JFM target period) and remain well-correlated (r~0.6) with the JFM NINO3.4 index for the next 6 months, suggesting that during the October-March period there are SLP anomaly structures
that may serve as a precursor to ENSO events occurring 9-15 months later. After the MAM period, correlation values jump again, indicating very strong correlations between the isolated SLP structures and the following JFM ENSO events.

To examine the spatial structures associated with these modes of SLP variability, Figure 2 shows the corresponding canonical factor maps for sea-level pressures associated with the CF time-series identified above. For this figure, we start with the canonical factor map for the November-January period 14 months prior to the JFM target date because it represents one of the first three-month periods related to the sustained lead-correlation values. We then show the best-correlated canonical factor maps for alternating three-month periods up through September-November of the year prior to the SST anomalies (similar analysis has been done for the intervening 3-month periods as well, however we show the alternating periods for the sake of brevity). Starting with the initial November-January period, the canonical factor patterns contain a large SLP anomaly situated in the central subtropical Pacific. This pattern persists up through the March-May period, at which point the statistically significant anomalies begin to extend into the southern hemisphere as well as the other ocean basins. From March-May through June-September (not shown), there is a strong tripole feature seen along the equatorial regions, dominated by SLP anomalies over the central and eastern Pacific. By the July-September period preceding the SST fields, a strong dipole in the sea level pressure field appears, which characterizes the Southern Oscillation [see Figure 1 from Trenberth and Shea, 1987]. These results are very similar to those obtained by using CCA to examine the precursor SLP fields associated with just equatorial Pacific SST indices [Barnston and Ropelewski, 1992]; in addition they are similar to results obtained using maximum covariance analysis to examine the wintertime (November-March) subtropical/extra-tropical North Pacific SLP fields associated with equatorial Pacific SST anomalies one year later [Vimont et al., 2003b].

In general, the spatial patterns for the latter periods, beginning with May-July, suggest that the large correlation values seen in Figure 1 are due to the onset of Southern Oscillation
events during this period [Harrison and Larkin, 1998]. However, during the earlier periods, it appears that the SLP anomaly fields that best correlate with JFM ENSO events have a significantly different structure from that associated with the Southern Oscillation itself.

To characterize these earlier periods, the spatial and temporal patterns for the first canonical factor of JFM SST anomalies and JFM sea-level pressure anomalies one year prior to the SST fields are shown in Figure 3. It can be seen that the canonical factor time-series are related to the ENSO phenomena, as represented by the NINO3.4 index (r=0.87 and 0.69 for the SST and SLP modes respectively). However, there are some discrepancies in the time-series. These discrepancies arise because the CCA algorithm is isolating spatio-temporal modes of SLP variability that are most strongly correlated with modes of SST variability one year later, not simply SLP grid-points that show maximum correlation with the modes of SST variability. With regard to the corresponding spatial patterns, the SST map for the first canonical factor (explaining 20% of the field’s total JFM variance) is characterized by strong warming in the equatorial Pacific, particularly in the central portion of the basin, with statistically significant cooling over the western tropical Pacific and central subtropical Pacific. The SST anomalies for each of the respective CF maps have similar structure to that presented here, as well as similar variance explained (not shown). As described earlier, the first SLP pattern (which explains 5% of the total JFM normalized sea-level pressure variance) shows a well-correlated anomaly over the central subtropical Pacific; as mentioned, this SLP pattern is persistent from about October of the previous year through May of the present year. It should be noted, particularly for the SLP fields, that CCA is not designed to isolate modes of variability that explain the most variance but instead is designed to isolate those that have the highest correlation with modes of SST variability. Hence, the low variance explained by the SLP pattern does not indicate a mode of low significance (as it would for an EOF analysis) but instead it indicates a mode of small spatial extent yet high covariability.
Overall, these CCA results suggest that from about November-April there is a spatio-temporal mode of SLP variability in the central subtropical North Pacific that is related to the subsequent evolution of the JFM ENSO. These results are in agreement with previous observational studies investigating antecedent SLP variability [Barnett, 1985; Trenberth and Shea, 1987; Barnston and Ropelewski, 1992; Vimont et al., 2003b]. However, in order to test the patterns’ sensitivity to model error introduced through the reanalysis procedure, we repeat the exact same analysis for the period 1958-2000. It has been documented that the reanalysis fields prior to 1958 are almost completely model dependent due to the lack of upper-air observations [Kistler et al., 2001]. The results using the truncated datasets are quantitatively the same as those using the full datasets with similar time-evolution of the lagged-correlation values, as well as similar structure of the antecedent sea-level pressure fields (not shown). We also test the robustness of these results using only sea-level pressure fields for the northern hemisphere. As discussed above, southern hemisphere sea-level pressure fields are particularly suspect due to lack of observations [Marshall and Harangozo, 2000; Connolley and Harangozo, 2001]. For this analysis, both the lagged correlation values and antecedent sea-level pressure patterns for the preceding October-March period are reproduced using only the northern hemisphere values (not shown). Interestingly, for the later months (May-October), the correlation values decrease, most likely due to the absence of tropical and sub-tropical southern hemisphere sea-level pressure anomalies that are prominent during the Southern Oscillation. Finally, we do a straight lead correlation of the three-month mean SLP anomalies with the JFM NINO3.4 index, starting with the November-January period 14 months prior (Figure 4). From this figure, it can be seen that the subtropical high-pressure anomaly identified earlier is significantly and persistently correlated with the NINO3.4 index from the November-January period through the April-June period (not shown). Starting with the May-July period, the SLP pattern takes on a structure that is more characteristic of the Southern Oscillation, which then persists through the antecedent September-November period. Both the lagged regressions
and lagged CCA have also been performed using the monthly SLP anomalies as opposed to the three-month mean anomalies. Results from these analyses indicate that monthly correlation values are less than the three-month mean values and can vary between months, although the northern hemisphere subtropical SLP anomaly isolated earlier is still above the 95% confidence level from November through May.

Not shown here are the lead-correlation maps for the period 18-20 months prior to the JFM ENSO event. Previous research efforts indicate that there is a significant lead correlation between ENSO and both sea-level pressures and surface wind anomalies over the western subtropical South Pacific during the March-May period 12 (18) months prior to MAM (DJF) ENSO events [Trenberth, 1976; Rasmusson and Carpenter, 1981; van Loon and Shea, 1985; van Loon and Shea, 1987]. CCA maps and lead correlations over the same period, calculated using the NCEP Reanalysis data, indicate very similar features (not shown); in addition, for this 18-month lead period the Reanalysis data indicate there are no significant anomalies in the northern hemisphere, in agreement with van Loon and Shea [1987]. As can be seen in Figure 4, however, the southern hemisphere anomalies become statistically insignificant in the intervening October-March period 12-15 months prior to the mature (JFM) phase of an ENSO event; this insignificance mirrors a weakening of the anomaly field itself, which becomes smaller than the central subtropical North Pacific anomalies during the OND period and remains smaller through the JFM period. The subtropical South Pacific anomaly begins to intensify again in the February-April period with a subsequent decrease in the anomalies over the central subtropical North Pacific. It is still unclear whether the sea-level pressure anomalies in the two hemispheres are related (either directly or indirectly) or whether they represent independent modes of variability, each of which may affect the evolution of the ENSO system over the course of the following 12-18 months. This issue will be dealt with in the Discussion Section.

Overall, however, the results from the CCA and the lead-correlation fields strongly suggest that the three-month mean subtropical North Pacific sea level pressure patterns seen
12-15 months prior to the JFM ENSO are indeed a robust statistical quantity and not simply an artifact of the CCA algorithm. In addition, from both the CCA results and the lead-correlation fields, it appears that during this period these subtropical anomalies are one of the few statistically significant, reanalysis-based SLP precursors to the JFM ENSO. As such, we have decided to investigate further how the atmospheric conditions associated with these anomalies are related to the development of the ENSO over the course of the following year.

3.2. Sea-Level Pressure Index

At this point, we could correlate the canonical factor time-series from a given 3-month period with various dynamic and thermodynamic fields in order to further diagnose the relationship between the subtropical SLP anomalies and the evolution of ENSO events 12 months later. However, the CF time-series results tend to be sensitive to variations in the number of retained EOFs and hence we did not feel that they served as an appropriate field for further analysis. Still, given the robustness and persistence of the spatial structures seen in the November-March sea-level pressure fields, the CCA results suggest that an index can be developed which captures the salient features of the canonical factor patterns. The time-series derived from this index can then better serve to analyze the relationship between the SLP and equatorial SST fields.

To construct this index, the NCEP Reanalysis normalized SLP anomalies are area-averaged over 140-175W and 10-25N for each 3-month period beginning with the January-March period and proceeding through December-February. The time-series of the sea-level pressure index (SLPI) for each 3-month period is then correlated with the lagged JFM NINO3.4 index, starting with the January-March period two calendar years prior to the NINO3.4 index (Figure 5). It appears that until about 15 months prior to an ENSO event (i.e. the October-December period two calendar years before the target JFM season), the SLPI does not provide any statistically significant antecedent information regarding the state of the coming SSTs in the equatorial Pacific. However, starting with the October-December
period 15 months before the JFM ENSO event and continuing through the July-September (JAS) period of the year preceding the JFM ENSO event, the SLPI does show significant correlations with the NINO3.4 index. After the JAS period, the SLPI no longer shows a correlation with the following JFM NINO3.4 index. As with the lagged correlation fields and the lagged CCA analysis, if the monthly mean SLP index is computed (as opposed to the three-month mean), the correlation with the following JFM NINO3.4 index is generally less, although still above the 95% confidence level (not shown). For the period November through May, the correlation values generally lie between –0.35 and –0.45, with a maximum correlation in February ($r=–0.61$) and a minimum in January ($r=–0.30$).

A representative time-evolution of the sea-level pressure index can be seen in Figure 6. This figure shows the time-series for the wintertime (JFM) sea-level pressure index and the following JFM NINO3.4 index. The correlation between the two is significant ($r=0.58$), indicating that sea-level pressures over the central subtropical North Pacific are related to the subsequent evolution of the ENSO system. However, there are discrepancies between the two time-series suggesting that this relationship is not one-to-one and may be influenced by other factors unrelated to the sea-level pressure fields described here (see Discussion Section).

In order to further test the results taken from the reanalysis product, two additional indices are estimated. For the first, the monthly mean station pressure measurements from Honolulu are taken from NCAR’s World Monthly Surface Station Climatology. These data span from 1921-1998 and contain no significant inhomogeneties [Trenberth and Shea, 1987]. Next, the monthly climatology is removed, the JFM average surface pressure anomaly is calculated, and the time-series is normalized such that its variance is unity. A second observationally-based index is designed using the monthly mean sea level pressure data from the 2-degree COADS Dataset. As a proxy for the sub-tropical sea-level pressure index, the grid-point data centered at 21N, 159W are selected. The data from this grid-point are chosen because this grid-point is the only one in this region that encompasses
observations over the western portion of the Hawaiian island chain for a large period of the dataset. Data from this grid point are available from January 1922-December 1992. The JFM seasonal average is then calculated, the mean is removed, and the time-series is normalized so that its variance is unity.

For comparison with the equatorial SST data, the monthly-mean Kaplan SST NINO3.4 index is used. For the period of overlap with the SLP measurements, the seasonal average values for JFM are again calculated, the mean is removed, and the resulting time-series is normalized as above. Figure 7 shows the time evolution of the seasonal mean SLP indices with the lagged JFM NINO3.4 index a year later. As can be seen, there are statistically significant correlations between the observed SLP indices and the lagged NINO3.4 index (r=-0.46 and -0.48 for the station-based and ship-based indices respectively). Similar lagged correlations between the Honolulu surface station anomalies and the JFM ENSO have previously been documented by Trenberth and Shea [1987].

Overall, these observed-index results give us confidence that in fact modifications of the subtropical high pressure cell over the central Pacific are related to equatorial SST anomalies the following year. To test the agreement between the various indices themselves, we plot the three SLP indices, normalized over their common time-period of 1948-1992, against one another; in addition, we also plot the two NINO3.4 indices against one another (Figure 8). With regard to the NINO3.4 indices, the agreement is excellent (r=0.99). For the SLP indices, the agreement is still very high, although not as high as with the NINO3.4 indices. The Reanalysis-derived SLP index has a correlation with the WMSSC- and COADS-based indices of r=0.89 and 0.84 respectively; the two extended SLP indices have a correlation of r=0.81. This suggests that the station-based and Reanalysis-based indices show better agreement with one another than they do with the COADS-based index (possibly due to the limited number of observations during the early period of the COADS record, which averaged about 10 per month through 1940).
Another issue to be addressed is whether the statistical relationships between the SLP anomalies over the subtropical North Pacific (as captured by the SLP indices) and the evolution of the ENSO system are stationary. In earlier works, low-frequency changes in ITCZ precipitation are identified and are related to changes in the sub-tropical trade wind activity over the Pacific basin [Reiter, 1978]. It is suggested that these low-frequency changes represent shifts in mid-latitude forcing of ENSO activity. Importantly, an ebb in precipitation (and by extension ENSO) variability is found from 1929-1962 that is hypothesized to be related to a decoupling of trade wind activity from tropical ocean/atmosphere feedback processes [Reiter, 1978]. Other researchers have found similar changes in ENSO-related variance, most indicating a decrease from about 1920-1960, followed by enhanced variance up through the present [Elliott and Angell, 1988; Torrence and Webster, 1999; Urban, 2000]. To test whether the suggested decoupling between ENSO events and the SLP anomalies identified here occurs during periods of low-amplitude ENSO variability, the Reanalysis-based and WMSSC-based indices for the January-March period are correlated with the 1-year lagged JFM NINO3.4 index for overlapping 20-year intervals (Figure 9). The running correlation values show a marked increase in confidence starting around 1954. Prior to this period, the correlation values are below the 95% confidence level from 1920-1954. After this period, significant (above the 99% confidence level) correlation values persist, with the exception of the interval from about 1974-1979. If the correlation values are calculated over 30-year intervals, the period from about 1955 to the present shows significant values (above 99% confidence level) for all years. These results suggest that the subtropical/tropical Pacific coupling identified here may in fact be modulated by longer-term variability within the climate system, particularly as it relates to changes in variance in the ENSO system (see below for comment on the role of “regime shifts” in this coupling).

Because of the dramatic onset of significant correlations between the SLP indices and the lagged NINO3.4 index around 1954, for the rest of the paper we will use the period...
1954-2000 as representative of the period in which we believe subtropical sea-level pressure fields over the central North Pacific play a role in the onset and evolution of the ENSO system over the subsequent year. In addition, we will use the reanalysis-based index time-series as representative of the time-evolution of these sea-level pressure variations, although it is recognized that this index is influenced both by observational and simulated components of the analysis procedure [Kistler et al., 2001]. However, given the agreement between the three indices and the fact that we will be investigating reanalysis-based fields, it seems appropriate to use an index that is consistent with these datasets. We have repeated these analyses using both observational-based SLP indices and results are quantitatively similar. We have also repeated the analysis for the period 1960-2000, which has previously been identified as a period of enhanced ENSO-related variability [Elliott and Angell, 1988; Torrence and Webster, 1999]); again, results are quantitatively similar to those described here.

3.2. Evolution of Related Surface Fields

To see how the evolution of low-level atmospheric fields associated with the SLP index relates to the development of SST anomalies associated with mature ENSO events, we select as a representative time-series the sea-level pressure index for January-March preceding the JFM ENSO. Next, three-month mean sea-level pressure and low-level wind anomalies, starting with the prior November-January (NDJ) period and extending through the following September-November period, are regressed onto the JFM sea-level pressure index (Figure 10). A similar analysis has been done using the monthly mean anomalies and indicates that the patterns presented here are significant at the monthly time-scale as well (not shown). (Because of the sign convention for the index, the evolution shown here is related to the development of mature La Niña events; given the linear nature of the statistics, similar fields but of opposite sign would be expected to precede mature El Niño events.)

Overall, in the preceding NDJ and coincident JFM periods (Figures 10a,b), there are statistically significant sea-level pressure anomalies extending over most of the subtropical
North Pacific basin, which persist through April of the concurrent year (not shown). Associated with this sea-level pressure signal is a strong, anticyclonic circulation pattern over the central subtropical North Pacific; there are also equatorial westerlies over the central and eastern portion of the Pacific. During the following March-May and May-July period (Figures 10c,d) the subtropical sea-level pressure anomaly weakens considerably while statistically significant anomalies develop in the southern portion of the subtropical Pacific and over the Indonesian region. Importantly, easterly wind anomalies over the western equatorial Pacific, initially associated with anticyclonic circulations around the high pressure anomaly, intensify and persist through the rest of the year; Vimont et al [2003a; 2003b] attributes this intensification to forcing by the underlying SST field during this time (as seen in Figure 11c,d). As time progresses (Figure 10e), these pressure patterns, and the associated wind anomalies, continue to strengthen, resulting in characteristic La Niña-like features [Larkin and Harrison, 2002] by December (Figure 10f). Comparing the evolution of the SLP field associated with the preceding SLP index (Figure 10) to the evolution associated with the following ENSO index (Figure 4), it is evident that during the November-March period, the SLP index-based map shows a much more extensive SLP pattern while the ENSO-based map (Figures 4a,b) shows a more limited domain; the SLP index-based pattern is more comparable to the patterns derived from CCA (Figures 2a,b), suggesting that the CCA- and SLP index-related fields better capture the full structure of the mode of SLP variability, which may differ from the more limited statistical structure associated with the lagged ENSO index.

Figure 11 shows the contemporaneous evolution of the sea-surface temperature field from the prior November-January period through the following September-November period, again regressed onto the JFM sea-level pressure index; as with the SLP fields, all of these SST anomalies are statistically significant when derived using the observational-based indices and are also found in the monthly-mean regression maps. Interestingly, in the coincident November-January and January-March periods (Figures 11a,b) there is a
statistically significant warming of the eastern equatorial Pacific, which persists until March (not shown). Similar to an ENSO event, the equatorial SST field during these months is consistent with the anomalous equatorial westerlies seen in the previous surface fields (Figures 10a,b). However, the correlation between the JFM NINO3.4 index and the concurrent JFM sea-level pressure index is r=0.19, while the correlation of the JFM NINO3.4 index with the SLP index the following winter is r=0.22, indicating that the sea-level pressure index is not significantly related to either the current state of the ENSO system, nor its decaying state (the concurrent/antecedent correlation between the NINO3.4 index and the WMSSC index is r=0.20/0.23; for the COADS index, r=0.22/0.13). In addition, the one-year lagged correlation of the seasonal mean (JFM) NINO3.4 index with itself (for this 53-year period) is 0.03, indicating that information about the equatorial SSTs in this region alone does not provide any predictive information about its state for the coming year [Chan and Xu, 2000].

In addition to the warm-water anomalies over the eastern equatorial Pacific, during the NDJ and JFM periods there are also western subtropical North Pacific warm anomalies and the development of central subtropical North Pacific cool anomalies. The cool anomalies over the central subtropical Pacific persist through the July-September period. By the March-May period (Figure 11c), however, the equatorial warming disappears. In the May-July period (Figure 11d) the first statistically significant sign of cooler SSTs in the central equatorial Pacific appears. The SST maps (of opposite sign) for March-May, April-June (not shown) and May-July all show similarity to a multi-modal, optimal initial SST structure that precedes ENSO events by 7-9 months [Penland and Sardeshmukh, 1995; Penland, 1996], including cold water anomalies over the western subtropical Pacific, warm water anomalies extending from the central/eastern subtropical Pacific to the western equatorial Pacific, and the onset of warm water anomalies over the eastern equatorial Pacific. The largest discrepancy between the SSTs shown here and those found in Penland [1996] is the lack of SLP index-related anomalies over the subtropical south Pacific, suggesting that the
SLP index may only by capturing that part of the multi-modal precursor pattern related to SST anomalies found in the northern hemisphere (see Discussion Section). Importantly, though, the SST signature associated with the SLP index captures the subtropical anomalies that *Vimont et al.* [2003a; 2003b] suggest are necessary for maintaining the tropical/subtropical zonal wind anomalies seen in Figures 10c,d.

By the July-September period (August in the monthly-mean fields), negative equatorial SST anomalies extend fully across the central and eastern Pacific. These anomalies continue to strengthen and expand northward and southward over the central tropical Pacific over the rest of the year, resulting in strong La Niña-like conditions in December (not shown).

Taken together, these two figures suggest that boreal winter subtropical SLP anomalies found over the central North Pacific may influence the evolution of the ESNO system by inducing tropical wind anomalies over the western and central portions of the Pacific basin. These wind anomalies can subsequently modify the underlying surface and subsurface temperature field, resulting in the onset and development of an ENSO event, as described in numerous other studies (see Discussion section). In addition, these results are similar to those found in modeling studies [Vimont *et al.*, 2001; *Vimont et al.*, 2003a], indicating that mid-latitude atmospheric variability can induce SLP changes, which subsequently influence equatorial wind anomalies and the evolution of the simulated ESNO system. Here we are seeing a very similar relationship within the evolution of the analyzed fields, supporting the contention that such a mechanism may be operating within the actual ocean/atmosphere system as well [Vimont *et al.*, 2003b].

Previously, it has been shown that there is a change in the evolution of the ENSO-related SST anomalies after 1978 [*Trenberth et al.*, 2002]. Statistical evidence shows that prior to that date cold water anomalies over the central and eastern Pacific tend to originate at the South American coast and propagate westward; after about 1978, the cold water anomalies develop west of the central Pacific and propagate eastward. In the results
presented here (Figure 11), there is a strong indication that the SST anomalies associated with the preceding SLP index first develop in the western/central equatorial Pacific and then propagate eastward, similar to those associated with the ENSO system after 1979, suggesting that the relationship between SLP anomalies in the subtropical North Pacific and the onset of an ENSO state a year later may only be applicable after 1978. To test this hypothesis, we divide the SLP index time-series and NINO3.4 time-series into two sub-periods, one covering 1954-1978 and the other covering 1979-2000. For the period 1954-1978, the correlation between the JFM SLP index and the JFM NINO3.4 index the following year is -0.71; for the period 1979-2000, the correlation between the SLP index and the lagged NINO3.4 index is -0.59, both of which are above the 99% confidence level for 23 years (|r|=0.53) (for the observed SLP indices the lead-correlation from 1954-1978 is –0.71/~0.62 for the COADS- and WMSSC-based indices respectively). These correlations suggest that the SLP index identified here does have a statistically significant relation with the onset of ENSO events a year later, both before and after the change in ENSO-related SST evolution identified by Trenberth et al. [2002].

4. Summary and Discussion

4.1. Summary

The relationship between changes in antecedent sea-level pressure patterns and interannual variability in JFM sea-surface temperature anomalies is investigated using output from 50-plus years of NCEP Reanalysis data. It is shown that, in general, the main mode of lagged SST variability is related to anomalies in the equatorial Pacific (i.e. ENSO). It is also shown that equatorial Pacific SST anomalies appear to be partly related to a mode of variability in the subtropical North Pacific sea-level pressure field 12-15 months prior to the maturation of the JFM ENSO.

Based upon this finding a new index is introduced, nominally termed the Hawaiian sea level pressure index, which is designed to capture this mode of variability. It is found that
both observed and analyzed versions of the index show significant correlation with equatorial SSTs the following year. Using the wintertime (JFM) evolution of this index, the linkages between the precursor SLP field and variability in the equatorial SST field the following year are examined. Results indicate that for years with positive SLP anomalies over the subtropical North Pacific, there is a subsequent intensification in the subtropical trade wind regime, along with an intensification of tropical easterlies over the central North Pacific. This intensification of the tropical easterlies, in turn, is conducive to initiating La Niña events, which are found to develop over the subsequent year [Rasmusson and Carpenter, 1981; Harrison, 1984; van Loon and Shea, 1985; Philander, 1985; van Loon and Shea, 1987; Li, 1997; Weisberg and Wang, 1997; C. Wang et al., 1999; Chan and Xu, 2000]. Examining the evolution of the associated oceanic fields, it appears that the index is related to concurrent equatorial SST anomalies in the eastern Pacific as well as the tropical and subtropical western North Pacific, suggesting that interannual variability within the tropical Pacific region may affect the subsequent evolution of the ENSO state by remotely influencing the subtropical high-pressure patterns found over the central subtropical North Pacific. However, the sea-level pressure index identified here is not significantly related to either the concurrent state of the ENSO system, or the antecedent state one year prior, indicating that the variations seen in the large-scale circulation fields over the central subtropical/tropical Pacific may represent a separate mode of forcing for the ENSO system (see Discussion Section). It should be emphasized that many other mechanisms are also capable of initiating ENSO events [e.g. see Neelin et al., 1998], which are then maintained by dynamics internal to the equatorial atmosphere/ocean system.

4.2. Discussion

As part of the research presented here, we have used a well-established data reduction algorithm to isolate spatio-temporal modes of sea level pressure variability that have significant correlations with the establishment of mature JFM ENSO events over the following months. We then designed an index to capture the salient features of these
spatio-temporal modes of variability and used it to examine the subsequent evolution of the ocean/atmosphere system. Overall, these results suggest that there is a large-scale mode of atmospheric variability, associated with lower-level circulation features (Figure 10) over the tropical and subtropical North Pacific that precedes the development of mature JFM ENSO events by approximately 12-15 months (Figures 6,11). Figure 10 indicates that these subtropical sea-level pressure anomalies (as well as the large-scale upper-air circulation features – not shown) persist through the entire winter and into the early spring and are related to variations in trade-wind activity over the subtropical North Pacific. It is hypothesized that the off-equatorial wind anomalies associated with the modulation of the trade-winds can serve as a partial driver for the development of ENSO events over the following year, as has been documented in Kidson [1975], Rasmusson and Carpenter [1981], Pazan and Meyers [1982], Harrison, [1984], van Loon and Shea [1985], Philander [1985]; Li [1997], Weisberg and Wang [1997], C. Wang et al. [1999], B. Wang et al. [1999], Chan and Xu [2000] and Wang [2001].

It should be mentioned, however, that much about the specific mechanisms involved in this development are still unclear. For instance, we have not investigated the dynamic/thermodynamic role the trade winds play in initiating the onset of an ENSO event. Various hypotheses have been proposed for this initiation. In one scenario, during El Niño events high sea level pressures and anticyclonic circulations over the subtropical western Pacific, forced either by underlying SST anomalies [C. Wang et al., 1999] or changes in the regional Hadley cell circulation [Li, 1997], initiate easterly flow over the western equatorial Pacific similar to that associated with the wintertime sea-level pressure index. This easterly wind anomaly then leads to a decrease in the thermocline depth in the western equatorial Pacific, which can propagate eastward as an equatorial Kelvin wave [Wang, 2001] or a coupled ocean-atmosphere anomaly [Li, 1997], initiating a La Niña event in the central Pacific. Alternatively, the introduction of easterly wind anomalies over the western Pacific during the course of an El Niño event can weaken the westerly-wind induced Kelvin wave.
forcing that remotely sustains warm-water conditions over the eastern Pacific, allowing easterly anomalies found over the far eastern Pacific to initiate enhanced upwelling and La Niña-like conditions in this region [Philander, 1985]. Another possibility is that anomalous pressure patterns over the central and eastern subtropical Pacific, and the associated JFM surface easterlies, may initiate sub-surface temperature anomalies that propagate westward as Rossby waves [Chan and Xu, 2000]. These anomalies can then reflect at the westward boundary, propagate eastward within the thermocline, and shoal in the central and eastern Pacific approximately 6 months later, initiating the onset of an ENSO event. Finally, it is possible that the heat-flux anomalies associated with the anomalous winds establish (either directly or indirectly) a boreal spring basin-scale SST structure (similar to that seen in Figures 11c,d), which is optimal for anomaly growth over the following 7-9 months [Penland, 1996; Vimont et al. 2001; Vimont et al., 2003a].

Needless to say, it is beyond the scope of this paper to investigate the oceanic/atmospheric dynamics associated with these initiation processes. We simply suggest that the surface circulation characteristics, related to anomalous sea-level pressure fields captured by the SLP index, may influence the evolution of the ENSO system via one of these mechanisms. However, in many of the cases mentioned above [e.g., Li, 1997; C. Wang et al., 1999; Chan and Xu, 2000; Wang, 2001], the initiation of ENSO events is attributed to dynamics associated with the present state of the ENSO system and hence is part of a negative feedback within its evolution. For the SLP index, the correlation between the wintertime index and the concurrent, as well as the preceding, JFM NINO3.4 index is insignificant, suggesting that the mode of SLP variability identified by the CCA algorithm may represent a separate mechanism of ENSO forcing; Philander [1985] and Vimont et al. [2003a] highlighted the role such forcing can play in initiating the transition from El Niño to La Niña conditions.

Another uncertainty involves the specific processes that initiate and/or sustain the large-scale changes in the wintertime (JFM) atmospheric dynamics associated with this mode of
SLP variability. It is possible that the low-level atmospheric circulations are forced by remote boundary conditions (i.e. SST anomalies in the eastern or western equatorial Pacific), local boundary conditions (i.e. subtropical negative sea-surface temperature anomalies seen in Figure 11b), or possibly mid-latitude atmospheric processes associated with internal variability and changes in the eddy/mean interactions in this region.

To begin to address this question, we regress the seasonal mean (JFM) zonally-averaged meridional divergent winds (derived from the velocity potential on fixed pressure levels) and omega values against the concurrent seasonal mean values of the SLP index (Figure 12) in order to examine whether the circulation patterns associated with changes in the SLP index are confined to the lower atmosphere or extend to upper levels as well. The zonal average for the wind fields is taken over the central Pacific region from 180W-120W in order to encompass the subtropical SLP variations seen in Figure 10. Overall, there is significant modification of the circulation structure throughout the atmospheric column, including the tropical, subtropical, and extra-tropical regions of the North Pacific. In the low latitudes, vertical circulations are linked by low-level and upper-level divergent meridional winds, indicating that the subtropical sea-level pressure anomalies associated with the SLP index may be related in part to modifications of the regional Hadley cell circulation over the central Pacific basin. In addition, there is anomalous ascent in the mid-latitudes, possibly related to variations in mid-latitude wintertime atmospheric processes and subsequent changes in the indirect Ferrell cell-like circulations. Previous research has identified a boreal-winter, mid-latitude, upper-atmosphere (250mb) zonal wind pattern that has similar lead correlation with the following JFM ENSO signal (r=-0.50) and concurrent JFM SLP index (r=0.70) [Anderson, 2003]. In the previous work, it was found that the upper-atmosphere zonal wind field was related to enhanced stationary wave activity and transient wave activity, both of which may have an influence on the enhancement of the subtropical/mid-latitude circulation anomalies seen here [Peixoto and Oort, 1992]. In addition, though, the zonal wind field was also related to enhanced upper-air divergence and
precipitation over the central and eastern tropical Pacific, which may have an impact on the enhanced regional Hadley-cell circulation seen in Figure 12; alternatively, these low-latitude features may simply be responses to changes in the mid-latitude transient forcing of the subtropical subsidence [e.g. see Trenberth and Stepaniak, 2003]. Presently, research is being conducted to investigate how both tropical and mid-latitude dynamics may be influencing the positioning and evolution of the SLP anomalies found over the central subtropical North Pacific.

Still another uncertainty involves the relation between the SLP index identified here and SLP anomalies in the western subtropical and extra-tropical South Pacific, which have been shown to lead JFM ENSO events by 18-20 months [Trenberth, 1976; Rasmusson and Carpenter, 1981; van Loon and Shea, 1985; van Loon and Shea, 1987]. Although these southern hemisphere SLP anomalies do not seem to persist through the Northern Hemisphere winter period, it is possible the subtropical North Pacific SLP anomalies described here may be related to the antecedent southern hemisphere SLP anomalies identified in earlier works. To get a qualitative sense of how the two pressure centers are related, a second index is developed in which normalized SLP anomalies for June-August are area-averaged over 20-42.5S, 129.5-160E, which represents the core of maximum correlations in the CCA maps for this period as well as the correlation maps of SLP regressed against the JFM NINO3.4 index 18 months later; it also corresponds to the region of maximum correlations seen in Figure 1b of van Loon and Shea [1987]. The correlation coefficient between this Southern Hemisphere index and the JFM NINO3.4 index is $r=-0.56$ (compared with $r=-0.58$ for the Northern Hemisphere index derived from SLP anomalies over Hawaii), indicating that both are statistically related to the evolution and onset of mature ENSO events. However, when the two indices are correlated against one another, the correlation coefficient is only $r=0.35$. This is statistically significant for 52 years of data, suggesting the two are related, but not on a purely one-to-one basis. Because the two indices do not contain considerable amounts of mutual information, the multivariate
regression of the two indices taken against the JFM NINO3.4 index results in higher correlations than either by itself (r=-0.70). Although speculative, we would argue that the two indices represent separate, but possibly related, modes of subtropical variability that, when occurring in succession, have a strong forcing influence upon the tropical Pacific ocean-atmosphere system.

One final qualification to note is that previous authors, using a similar CCA analysis to identify SLP modes for use in long-term (7-16 months) forecasts of ENSO events, have shown that the modes provide only limited predictability [e.g. Graham et al., 1987b; Barnston and Ropelewski, 1992]. In addition, previous work has shown that the occurrence, timing of onset, and intensity of ENSO events associated with subtropical SLP anomalies can also be affected by concurrent activity in the southern hemisphere as well [Chan and Xu, 2000]. Here we introduce the SLP index not necessarily for predictive purposes but to elucidate physical mechanisms that may influence the evolution of the ENSO system. It is recognized that the onset of SLP anomalies over the subtropical North Pacific does not always lead to the development of a mature ENSO event (as mentioned, the correlation between the JFM sea-level pressure index and the lagged NINO3.4 index is not close to unity). However, it does appear that the hypothesized mechanism described here may be capable of initiating the onset of an ENSO event, after which the internal equatorial ocean-atmosphere dynamics can amplify the initial anomaly into a fully-coupled ENSO pattern.

Acknowledgments. NCEP Reanalysis data provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their Web site at:

http://www.cdc.noaa.gov

Climate indices provided by NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their Web site at:

http://www.cdc.noaa.gov/ClimateIndices/index.html
COADS sea-level pressure data and Kaplan extended NINO3.4 index taken from the IRI/LDEO Climate Data Library website at:

http://iridl.ldeo.columbia.edu/
Appendix

The canonical correlation analysis (CCA) performed here is similar in nature to a simple EOF analysis, although the field on which the single value decomposition is performed differs in that it contains a cross-correlation matrix relating the predictand field to the predictor field. An excellent resource for CCA is Bretherton et al. [1992]. This work also provides a comparison between CCA and other multivariate analysis techniques. Other descriptions, in various forms, can be found in Barnett and Preisendorfer [1987], Graham et al. [1987a], and Cherry [1996].

For this study, we first select the nine EOFs of near-global January-March sea-surface temperature anomalies and the first twelve EOFs of near-global three-month mean sea-level pressure anomalies, as taken from a 53-year subset of the NCEP Reanalysis product. The next step to performing the CCA is to calculate the cross-covariance matrix between the predictor, in this case the time-series of SLP EOFs, and the predictand, i.e. the time-series of SST EOFs (the same procedure can be performed with the designations reversed and there is no loss of generality). The auto-correlation matrix for each of the fields is also required. Because the time-series of the EOFs are used, this auto-correlation matrix is simply a diagonal matrix that normalizes the values in the cross-covariance matrix.

Given a set of EOF time-series (weighted by the respective eigenvalues) for the sea-level pressures $P$ and the sea-surface temperatures $T$, in which the rows represent the position in time and the columns represent the position in EOF-space, a cross-correlation matrix $[TP]$ can be calculated as the inner product $T^TP$ and auto-correlation matrices $[PP]$ and $[TT]$ calculated as $P^TP$ and $T^TT$ respectively where brackets $[]$ represent the expectation operator and the superscript ‘T’ represents the transpose of the matrix. The matrix equation that needs to be solved is then:

$$(T^TP - l)A = 0$$
where $\mathbf{\Sigma}$ represents the diagonal matrix of eigenvalues (equal to the squared correlation of the reconstructed time-series) and $\mathbf{A}$ represents a transformation matrix, which is used to reconstruct the time-series of the canonical factors from the time-series of the EOFs. The elements of $\mathbf{A}$, whose rows represent the position in EOF-space and whose columns represent position in CF-space, give the weighting of each of the original predictand EOFs that comprise the CF time-series. Hence, to calculate the CF time-series of the predictand, in this case SST patterns $\mathbf{T'}$, the original weighted time-series is multiplied by the transformation matrix, i.e. $\mathbf{T'} = \mathbf{T}^t \mathbf{A}$. To calculate the corresponding spatial patterns, it is assumed that the reconstructed anomaly field should be equal to the anomaly field represented by the original EOFs, i.e. $\mathbf{X'}^t \mathbf{T}=\mathbf{X} \mathbf{T}^t$ where $\mathbf{X'}$ and $\mathbf{X}$ represent the spatial CF and EOF patterns for the sea-surface temperature anomalies respectively. Hence:

$$\mathbf{X'} = (\mathbf{X} \mathbf{T}^t)(\mathbf{T'}^t)^{-1}.$$ 

It should be noted that it would have been equally valid to assume that the reconstructed anomaly field should be equal to the *original* anomaly field but for our datasets most of the variance of the original anomaly field is contained within the first few EOFs and hence the spatial CF patterns do not show much difference between the two methods. The resultant time-series are normalized such that their variance is unity. The spatial patterns are then multiplied by the weighting used to normalize the time-series in order to arrive at spatial maps that represent characteristic anomalies in the respective fields.

To reconstruct the predictor fields, i.e. the sea-level pressure fields, a similar procedure is used but the matrix equation that needs to be solved is now:

$$([\mathbf{T}^t \mathbf{T}][\mathbf{U}][\mathbf{U}^t][\mathbf{T}^t \mathbf{U}^t])^{-1} \mathbf{B}=0$$

Note that the eigenvalues, $\mathbf{\Sigma}$, are the same for each equation.
References


Elliott, W.P., J.K. Angell, Evidence for changes in Southern Oscillation relationships during the last 100 years, *J. Climate*, 1, 729-737.


**Figure Legends**

**Figure 1** Correlation of the canonical factor time-series for sea-level pressure (SLP) with the January-March (JFM) NINO3.4 index. The x-axis is the first month of the three-month average of SLP beginning with January, two calendar years prior to the NINO3.4 index. For each 3-month period, only the canonical factor with maximum correlation is shown. Canonical factor time-series produced by performing a canonical correlation analysis of the three-month average anomaly field with the JFM SST anomaly field concurrent with the NINO3.4 index. See text for details.

**Figure 2** Canonical factor pattern of three-month mean sea level pressure anomalies constructed by performing a canonical correlation analysis against the following JFM sea-surface temperature anomalies (in the case of panel (a) the analysis is performed against the SST anomalies 14 months later). Shown here are correlation coefficients. Contour interval is 0.15; minimum contour is +/-0.35 (approximately 99% confidence limit). Positive values are shaded. Only canonical factor patterns with maximum correlation to the lagged JFM NINO3.4 index are shown. (a) November-January; (b) January-March; (c) March-May; (d) May-July; (e) July-September; (f) September-November.

**Figure 3** (a) Normalized time-series for the first canonical factor of JFM sea-surface temperature anomalies (thick solid line) and the preceding year’s JFM normalized sea level pressure anomalies (thick dashed line) taken from the NCEP Reanalysis, along with the normalized NINO3.4 index (thin solid line). The time-series are normalized such that they have unit variance. Therefore, the associated geographic patterns in Fig.3b represent characteristic anomalies in the SST field. (b) First canonical factor pattern of sea-surface temperature anomalies. Contour interval is 0.2 K; minimum contour is +/-0.2 K. Positive values are shaded. Thick black line represents regions with correlation values greater than
+/- 0.35 (approximately 99% confidence limit). (c) Correlation coefficients of sea level pressure for the first canonical factor. Contour interval is 0.15; minimum contour is +/- 0.35. Positive values are shaded.

**Figure 4** Three-month mean sea level pressure anomalies correlated with the following JFM NINO3.4 index (in the case of panel (a) the analysis is performed using the NINO3.4 anomalies 14 months later). Shown here are correlation coefficients. Contour interval is 0.15; minimum contour is +/-0.35 (approximately 99% confidence limit). Positive values are shaded. (a) November-January; (b) January-March; (c) March-May; (d) May-July; (e) July-September; (f) September-November.

**Figure 5** Correlation of the 3-month mean sea-level pressure index (SLPI) with the January-March (JFM) NINO3.4 index. The x-axis is the first month of the three-month average of SLPI beginning with January, two calendar years prior to the NINO3.4 index. Index constructed by calculating the area-average standardized sea level pressure anomalies from 140-175W, 10-25N, taken from the NCEP Reanalysis. See text for details.

**Figure 6** (a) Normalized time-series of standardized NCEP Reanalysis JFM sea level pressure anomalies averaged from 140-175W, 10-25N, multiplied by -1 (solid line); time-series is shifted forward one year (i.e. the 1948 value is plotted in 1949). Also shown is the normalized time-series of the JFM NINO3.4 index for the current year (dashed line).

**Figure 7** (a) Normalized time-series of Honolulu JFM surface pressure anomalies taken from the WMSSC archives, multiplied by -1 (solid line); time-series is shifted forward one year. Also shown is the normalized time-series of the JFM NINO3.4 index for the current year (dashed line); NINO3.4 index taken from Kaplan optimal analysis indices. (b) Same as (a) except for the normalized time-series of standardized JFM sea level pressure.
anomalies at 21N, 159W, taken from COADS, multiplied by -1 (solid line); time-series is again shifted forward one year. Also shown is the normalized time-series of the JFM NINO3.4 index for the current year (dashed line).

Figure 8 (a) Normalized time-series of the JFM SLP Indices derived from the Reanalysis (thick, solid line), COADS (thin, dashed line) and WMSSC (thin, solid line) archives. All time-series normalized by the standard deviation of the respective time-series for the common period 1948-1992. (b) Normalized time-series of the JFM NINO3.4 indices taken from the CDC (thick, solid line) and Kaplan optimal analysis (thin, dashed line). Both time-series normalized by the standard deviation of the respective time-series for the common period 1950-1991.

Figure 9 Correlation of the January-March (JFM) SLP Indices with the JFM NINO3.4 Index the following year. Correlations have been evaluated for overlapping 20-year intervals and are plotted every year at the beginning of the interval. Thick line represents the 95% confidence limit (r=-0.44); Thin line represents the 99% confidence limit (r=-0.56). For the Reanalysis-based SLP index (o), correlation values are calculated using the CDC NINO3.4 index; for the WMSSC-based SLP index (x), correlation values are calculated by combining the Kaplan NINO3.4 index from 1922-1949 with the CDC Nino3.4 index from 1950-1999.

Figure 10 Regression maps of 3-month mean sea-level pressures and low-level (s=0.995) wind vectors, calculated against the normalized JFM sea-level pressure index for the period 1954-2000. Contour interval for sea-level pressures is 0.25 mbar; minimum contour is +/-0.25 mbar. Positive values are shaded. Thick black line represents regions with correlation values greater than +/-0.37 (approximately 99% confidence limit). Unit wind-vector of 3 m/s shown in lower right of the respective panels. (a) November-January (prior to SLP
Index); (b) January-March; (c) March-May; (d) May-July; (e) July-September; (f) September-November.

**Figure 11** Regression maps of 3-month mean sea surface temperature anomalies calculated against the JFM sea-level pressure index for the period 1954-2000. Contour interval is 0.2 K; minimum contour is +/-0.2 K. Positive values are shaded. Thick black line represents regions with correlation values greater than +/- 0.37 (approximately 99% confidence limit). (a) November-January (prior to SLP Index); (b) January-March; (c) March-May; (d) May-July; (e) July-September; (f) September-November.

**Figure 12** Zonally-averaged JFM meridional-vertical circulation anomalies derived by regressing the meridional divergent winds and omega values onto the concurrent JFM sea-level pressure index for the period 1954-2000. Zonal-average done for values between 180W-120W. Divergent meridional wind values calculated from the divergence of the velocity potential at each pressure level. Omega values are equal to vertical motion in pressure coordinates at the given level. Thick line represents the 95% confidence limit (r= +/- 0.29) for the vertical wind component. Unit wind-vector of 2 m s\(^{-1}\) (2x10\(^{-4}\) mbar s\(^{-1}\)) shown in upper right of the panel.
Figure 1  Correlation of the canonical factor time-series for sea-level pressure (SLP) with the January-March (JFM) NINO3.4 index. The x-axis is the first month of the three-month average of SLP beginning with January, two calendar years prior to the NINO3.4 index. For each 3-month period, only the canonical factor with maximum correlation is shown. Canonical factor time-series produced by performing a canonical correlation analysis of the three-month average anomaly field with the JFM SST anomaly field concurrent with the NINO3.4 index. See text for details.
Figure 2 Canonical factor pattern of three-month mean sea level pressure anomalies constructed by performing a canonical correlation analysis against the following JFM sea-surface temperature anomalies (in the case of panel (a) the analysis is performed against the SST anomalies 14 months later). Shown here are correlation coefficients. Contour interval is 0.15; minimum contour is +/-0.35 (approximately 99% confidence limit). Positive values are shaded. Only canonical factor patterns with maximum correlation to the lagged JFM NINO3.4 index are shown. (a) November-January; (b) January-March; (c) March-May; (d) May-July; (e) July-September; (f) September-November.
Figure 3 (a) Normalized time-series for the first canonical factor of JFM sea-surface temperature anomalies (thick solid line) and the preceding year’s JFM normalized sea level pressure anomalies (thick dashed line) taken from the NCEP Reanalysis, along with the normalized NINO3.4 index (thin solid line). The time-series are normalized such that they have unit variance. Therefore, the associated geographic patterns in Fig.3b represent characteristic anomalies in the SST field. (b) First canonical factor pattern of sea-surface temperature anomalies. Contour interval is 0.2 K; minimum contour is +/-0.2 K. Positive values are shaded. Thick black line represents regions with correlation values greater than +/- 0.35 (approximately 99% confidence limit). (c) Correlation coefficients of sea level pressure for the first canonical factor. Contour interval is 0.15; minimum contour is +/-0.35. Positive values are shaded.
Figure 4 Three-month mean sea level pressure anomalies correlated with the following JFM NINO3.4 index (in the case of panel (a) the analysis is performed using the NINO3.4 anomalies 14 months later). Shown here are correlation coefficients. Contour interval is 0.15; minimum contour is +/-0.35 (approximately 99% confidence limit). Positive values are shaded. (a) November-January; (b) January-March; (c) March-May; (d) May-July; (e) July-September; (f) September-November.
Figure 5  Correlation of the 3-month mean sea-level pressure index (SLPI) with the January-March (JFM) NINO3.4 index. The x-axis is the first month of the three-month average of SLPI beginning with January, two calendar years prior to the NINO3.4 index. Index constructed by calculating the area-average standardized sea level pressure anomalies from 140-175W, 10-25N, taken from the NCEP Reanalysis. See text for details.
Figure 6 (a) Normalized time-series of standardized NCEP Reanalysis JFM sea level pressure anomalies averaged from 140-175W, 10-25N, multiplied by -1 (solid line); time-series is shifted forward one year (i.e. the 1948 value is plotted in 1949). Also shown is the normalized time-series of the JFM NINO3.4 index for the current year (dashed line).
Figure 7 (a) Normalized time-series of Honolulu JFM surface pressure anomalies taken from the WMSSC archives, multiplied by -1 (solid line); time-series is shifted forward one year. Also shown is the normalized time-series of the JFM NINO3.4 index for the current year (dashed line); NINO3.4 index taken from Kaplan optimal analysis indices. (b) Same as (a) except for the normalized time-series of standardized JFM sea level pressure anomalies at 21N, 159W, taken from COADS, multiplied by -1 (solid line); time-series is again shifted forward one year. Also shown is the normalized time-series of the JFM NINO3.4 index for the current year (dashed line).
Figure 8 (a) Normalized time-series of the JFM SLP Indices derived from the Reanalysis (thick, solid line), COADS (thin, dashed line) and WMSSC (thin, solid line) archives. All time-series normalized by the standard deviation of the respective time-series for the common period 1948-1992.  (b) Normalized time-series of the JFM NINO3.4 indices taken from the CDC (thick, solid line) and Kaplan optimal analysis (thin, dashed line).  Both time-series normalized by the standard deviation of the respective time-series for the common period 1950-1991.
Figure 9  Correlation of the January-March (JFM) SLP Indices with the JFM NINO3.4 Index the following year. Correlations have been evaluated for overlapping 20-year intervals and are plotted every year at the beginning of the interval. Thick line represents the 95% confidence limit ($r=-0.44$); Thin line represents the 99% confidence limit ($r=-0.56$). For the Reanalysis-based SLP index (o), correlation values are calculated using the CDC NINO3.4 index; for the WMSSC-based SLP index (x), correlation values are calculated by combining the Kaplan NINO3.4 index from 1922-1949 with the CDC Nino3.4 index from 1950-1999.
Figure 10 Regression maps of 3-month mean sea-level pressures and low-level ($\sigma=0.995$) wind vectors, calculated against the normalized JFM sea-level pressure index for the period 1954-2000. Contour interval for sea-level pressures is 0.25 mbar; minimum contour is +/-0.25 mbar. Positive values are shaded. Thick black line represents regions with correlation values greater than +/- 0.37 (approximately 99% confidence limit). Unit wind-vector of 3 m/s shown in lower right of the respective panels. (a) November-January (prior to SLP Index); (b) January-March; (c) March-May; (d) May-July; (e) July-September; (f) September-November.
Figure 11 Regression maps of 3-month mean sea surface temperature anomalies calculated against the JFM sea-level pressure index for the period 1954-2000. Contour interval is 0.2 K; minimum contour is +/-0.2 K. Positive values are shaded. Thick black line represents regions with correlation values greater than +/- 0.37 (approximately 99% confidence limit). (a) November-January (prior to SLP Index); (b) January-March; (c) March-May; (d) May-July; (e) July-September; (f) September-November.
Figure 12 Zonally-averaged JFM meridional-vertical circulation anomalies derived by regressing the meridional divergent winds and omega values onto the concurrent JFM sea-level pressure index for the period 1954-2000. Zonal-average done for values between 180W-120W. Divergent meridional wind values calculated from the divergence of the velocity potential at each pressure level. Omega values are equal to vertical motion in pressure coordinates at the given level. Thick line represents the 95% confidence limit (r=±/− 0.29) for the vertical wind component. Unit wind-vector of 2 m s⁻¹ (2x10⁻⁴ mbar s⁻¹) shown in upper right of the panel.