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Spatial and temporal features of ENSO meridional scales

Wenjun Zhang,[1,2] Jianping Li,[2] and Fei-Fei Jin[3]

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[1] The spatial and temporal features of the El Niño/Southern Oscillation (ENSO) meridional scales are investigated using the Hadley Center Global Sea Ice and Sea Surface Temperature (HadISST) data for the period of 1950–2007. The results show that the meridional scales of the ENSO warm and cold events are asymmetric and exhibit interdecadal changes. The meridional extent of the sea surface temperature anomalies (SSTA) during La Niña years is wider than that during El Niño years. This is because strengthened trades and thus strengthened upwelling and meridional currents during La Niña events more effectively spread SSTA away from the equator. With the Walker Circulation weakening in recent decades, which tends to reduce upwelling and meridional currents over the central and eastern equatorial Pacific, the meridional scales of both El Niño and La Niña events also decrease. **Citation:** Zhang, W., J. Li, and F.-F. Jin (2009), Spatial and temporal features of ENSO meridional scales, *Geophys. Res. Lett.*, *36*, L15605, doi:10.1029/2009GL038672.

1. Introduction

[2] The El Niño/Southern Oscillation (ENSO) is the most prominent interannual climate phenomenon owing to tropical ocean-atmosphere interaction and its basic dynamics are now largely understood [e.g., *Bjerknes*, 1969; *Wyrtki*, 1975; *Cane and Zebiak*, 1985; *Battisti and Hirst*, 1989; *Jin*, 1997a, 1997b; *Neelin et al.*, 1998]. Recently, there have been increased interests in decadal variability of ENSO. A number of studies have demonstrated that ENSO displays significant changes in its amplitude, period and onset time [*Wang*, 1995; *Trenberth and Hoar*, 1996; *Gu and Philander*, 1997; *Latif et al.*, 1997; *Zhang et al.*, 1997; *Knutson and Manabe*, 1998; *Zhang et al.*, 1998; *An and Wang*, 2000; *Wang and An*, 2002].

[3] Although many studies have been carried out regarding the various characteristics of ENSO, little attention has been paid to its meridional scales. During ENSO years, sea surface temperature anomalies (SSTA) at the equator, mainly associated with subsurface upwelling over the eastern equatorial Pacific, are spread away from the equator. The ENSO SSTA patterns in the meridional direction show a parabolic shape, with SSTA centered at the equator and decreasing poleward. Figure 1 presents meridional patterns of ENSO SSTA in 1950–2007 composites. The SSTA meridional scales of warm and cold episodes are different, and the meridional scales in La Niña events are obviously wider than those in El Niño events are.

[4] The ENSO meridional scales deserve attention for their possible climatic and dynamic implications. On the one hand, differences in ENSO SSTA meridional patterns may have impact on atmospheric responses. On the other hand, the meridional width of ENSO SSTA, particularly, that of zonal wind stress has significant influence on ENSO periods [*Schopf and Suarez*, 1990; *Kirtman*, 1997]. In this study, we examine the characteristics of the ENSO meridional scales and their decadal changes. We also provide a simple dynamical model to explain a possible mechanism for the asymmetry and interdecadal changes of the ENSO meridional scales.

2. Data and Methods

[5] The main data sets employed in this study are the Hadley Center Global Sea Ice and Sea Surface Temperature (HadISST) Analysis data set (1870–2007) [*Rayner et al.*, 2003], zonal wind stress from the European Centre for Medium Range Weather Forecasting (ECMWF) 40-year (ERA40) reanalysis data set (1958–2001) [*Simmons and Gibson*, 2000] and Simple Ocean Data Assimilation (SODA) data set (1958–2004) [*Carton et al.*, 2000]. The present analyses use the oceanic and atmospheric data sets from 1950 to 2007 and wind stress and SODA data sets for the periods of 1958–2001 and 1958–2004, respectively. For testing the accuracy of the sea surface temperature (SST) data in resolving the meridional scales of ENSO, we have also examined the features of the ENSO meridional scales in extended reconstruction SST (ERSST) [*Smith and Reynolds*, 2004] and results from different data sets are consistent (not shown).

[6] According to the definition of the Climate Prediction Center (CPC), ENSO warm and cold episodes are based on a threshold of ±0.5 °C for the Oceanic Niño Index (ONI) [3 month running mean of SSTA in the Niño 3.4 region (5°N–5°S, 120°–170°W)]. Use of the CPC definition identifies 15 El Niño years (1951, 1957, 1963, 1965, 1969, 1972, 1976, 1982, 1987, 1991, 1994, 1997, 2002, 2004, and 2006) and 8 La Niña years (1955, 1964, 1970, 1973, 1984, 1988, 1995, and 1999). A 2–7-year band-pass filter is applied to the SSTA for focusing on the ENSO variability. To investigate the meridional patterns, the zonal average (180°–90°W) is calculated. Each ENSO episode is divided by the maximum SSTA in the region of the central/eastern equatorial Pacific (3°S–3°N, 180°–90°W) in order to remove the influences of ENSO amplitude. We use e-folding meridional scale, namely the meridional distance from the equator such that the ratio between the equatorial and off-equatorial SSTA become 1/e, as the measure for ENSO

[1]College of Atmospheric Sciences, Nanjing University of Information Science and Technology, Nanjing, China.
[2]State Key Laboratory of Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China.
[3]School of Ocean and Earth Science and Technology, University of Hawai'i at Mānoa, Honolulu, Hawaii, USA.

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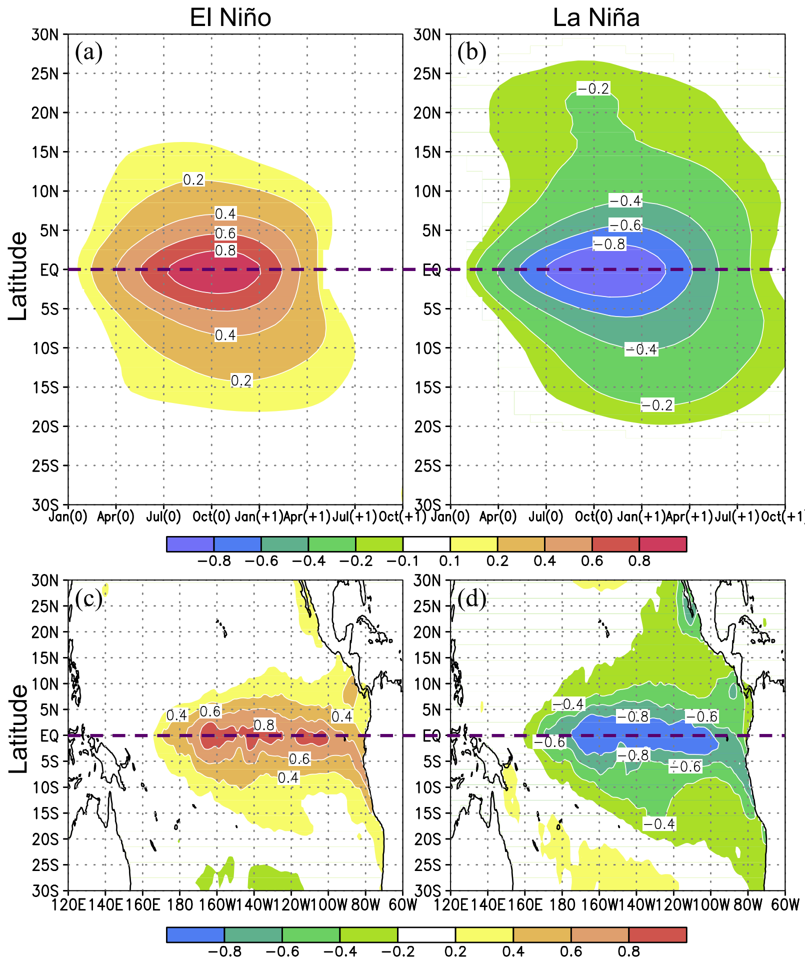

Figure 1. Time-latitude diagram of zonal mean (180°–90°W) 2–7-year band-pass filtered SSTA of 1950–2007 composites for (a) El Niño and (b) La Niña events and composite 2–7-year band-pass filtered SSTA averaged from September (0) to March (+1) in the 1950–2007 period for (c) El Niño and (d) La Niña events. The year 0 refers to the ENSO year in which an anomalously high SST first appeared and was amplified in the tropical Pacific, year +1 refers to the subsequent years.

width. It should be pointed out that this measure is independent of the normalization of SSTA, whereas the normalization allows us to examine composite patterns of ENSO in terms of their meridional scales. We obtain the ENSO composites through a simple average by calendar month, considering the phase-locking nature of ENSO.

3. Some Characteristics of ENSO Meridional Scales

[7] From the ENSO meridional patterns shown in Figures 1a and 1b, positive anomalies in the El Niño composite extend to about 10°N and near 15°S, based on a 0.2 contour. In the La Niña composite, negative anomalies extend to above 15°N and 15°S. The meridional extent of negative anomalies in the cold events is wider than that of positive anomalies in the warm events. The results are similar based on 0.4 or 0.6 contour. In spatial patterns of ENSO composites from September of year 0 to March of year +1 (Figures 1c and 1d), the SSTA less than −0.8 reaches 4°S and 4°N in the La Niña composite and the SSTA larger than 0.8 is within 2° away from the equator in the El Niño composite. Based on the 0.2 contour, the La Niña SSTA reaches above 20°N and 20°S over the eastern Pacific, and the El Niño SSTA only extends to around 11°N and 18°S. Therefore, the meiridional scales are asymmetric for the El Niño and La Niña events.

[8] Associated with positive (negative) SSTA in the eastern tropical Pacific, the Walker Circulation weakens (strengthens) with westerly (easterly) wind anomalies. Recently, many observed investigations indicated that the mean state displays significant interdecadal variability over the tropical Pacific [*Gu and Philander*, 1997; *Zhang et al.*, 1997; *Latif et al.*, 1997; *Zhang et al.*, 1998]. For example, the mean trade winds have decreased after the late of 1970s in both ENSO warm and cold events (Figure 2). To relate this changes in mean trade wind stress with ENSO meridional scale, we plotted in Figure 2 the zonal wind stress averaged over the region of 5°S–5°N, 180°–90°W as a function of the ENSO widths. From the monthly scatter diagram, there is a weak negative correlation (−0.34) between ENSO widths and zonal wind stress, which is statistically significant at the 0.01 confidence level. This correlation indicates that stronger zonal wind stress tends to favor the occurrence of wider meridional scales.

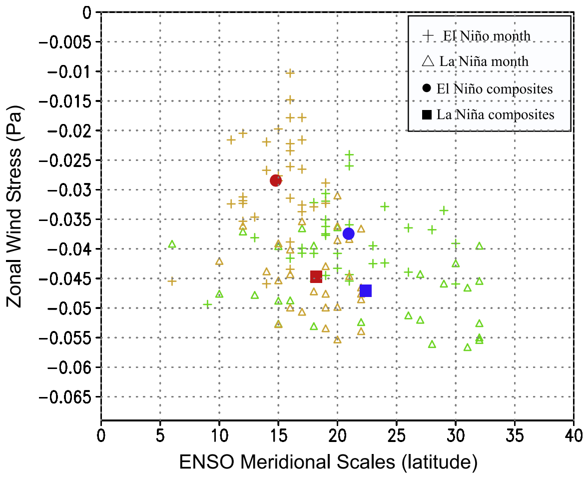

Figure 2. Scatter plot of mean zonal wind stress in the central and eastern Pacific (5°S–5°N, 180°–90°W) and the widths of ENSO events. Pluses and triangles denote monthly El Niño and La Niña events, respectively. Circles and squares are averaged from September (0) to March (+1) of El Niño and La Niña composites, respectively. The cool colors (green and blue) and warm colors (yellow and red) denote the periods 1958–1976 and 1977–2001, respectively.

[9] We further compare mean ENSO widths for the 27-year period of 1950–1976 with the recent 31-year period of 1977–2007, as shown in Figure 3. For the pre-1976 El Niño composite, the anomalous center above 0.2 extends to above 10°N and 15°S. In the post-1976 El Niño composite, the center only reaches 10°N and 11°S. Thus, the meridional scales are smaller for the 1977–2007 than the 1950–1976 composite, which are 13 and 17 degrees of latitude for the Sep(0)–Feb(+1) mean, respectively. Similar changes appear during La Niña years, with widths being 16 and 21 degrees of latitude in the 1977–2007 and the 1950–1976 composites, respectively. The meridional scales of El Niño and La Niña both decrease after the late 1970s.

[10] Consistent with the results in Figure 1, Figure 3 also shows the asymmetry of the meridional scales between the El Niño and La Niña composites in both 1950–1976 and 1977–2007 periods, that is, the meridional scales during La Niña years are wider than those during El Niño years.

4. Role of Eastern Tropical Pacific Upwelling on ENSO Meridional Scales: A Simple Dynamical Model

[11] Following the approach taken by *Saravanan and McWilliams* [1998], we consider the simplest form of oceanic advection in the meridional direction and assume that the slab ocean moves with a steady meridional velocity $V(y)$ in each ENSO episode. Since SSTA meridional advection originates at the central/eastern equatorial Pacific, we may write an equation without external forcing for SSTA T' over the central/eastern tropical Pacific as follows:

$$\frac{\partial T'}{\partial t} + V(y)\frac{\partial T'}{\partial y} + \alpha T' = 0, \qquad (1)$$

where α is an intrinsic damping coefficient. This equation is applicable in the off-equatorial regions of a few degrees away form the equator because upwelling there can be negligible. However, neglecting the SSTA zonal and vertical advection is a severe approximation and is made primarily for reasons of simplicity. The SSTA T' can be approximately expressed as:

$$T' = \hat{T}(y)e^{i\omega t}, \qquad (2)$$

where ω is the frequency, and $\hat{T}(y)$ denotes the SSTA meridional pattern. The boundary condition is:

$$T|_{y=0} = Ae^{i\omega t}, \qquad (3)$$

where A is a constant denoting the SSTA amplitude at the equator and $y = 0$ indicates the region within about 3° of the equator. After substituting equations (2) and (3) into equation (1), we obtain

$$\frac{\hat{T}(y)}{A} = e^{-\int_0^y \frac{i\omega+\alpha}{V(y)}dy}. \qquad (4)$$

For simplicity, we consider a steady SSTA ($\omega = 0$) and a constant damping coefficient, such that the meridional pattern $\hat{T}(y)/A$ is only a function of the meridional currents $V(y)$. Over the eastern equatorial Pacific, meridional currents $V(y)$ are closely related to the equatorial upwelling. Therefore, strong (weak) upwelling and meridional currents correspond to large (small) SSTA meridional scales.

[12] The mechanism can be used to understand the meridional scale asymmetry for El Niño and La Niña phases of ENSO cycle. During El Niño (La Niña) phase, weakened (strengthened) trade winds can lead to weak (strong) upwelling and meridional currents. As shown in Figure 4a, the meridional currents in La Niña events are stronger than those in El Niño events over the equatorial Pacific, especially at the region south of the equator. Following equation (4), the meridional scales during La Niña events would be wider than those during El Niño events, as shown in Figures 1 and 2. Furthermore, the anomalous meridional heat transport in La Niña events is stronger than that in El Niño events. In southern equatorial Pacific (Figure 4b), the anomalous meridional heat transport during La Niña years is more than twice as much during El Niño years. In comparison with El Niño events, the meridional spread of La Niña SSTA away from the eastern equatorial belt is larger.

[13] The Walker Circulation has been weakening since the late half of the 20th century in the tropical Pacific [*Tanaka et al.*, 2004; *Vecchi et al.*, 2006; *Power and Smith*, 2007]. Concurrently, the upwelling decreased by about 25% in an equatorial strip between 9°N and 9°S in the period 1950–1999 [*McPhaden and Zhang*, 2002]. As a result, the meridional scales of ENSO warm and cold events are both getting narrower (Figures 2 and 3).

5. Concluding Remarks

[14] The meridional structure of El Niño events differ from that of La Niña events. Over the central and eastern equatorial Pacific, the meridional currents increase (de-

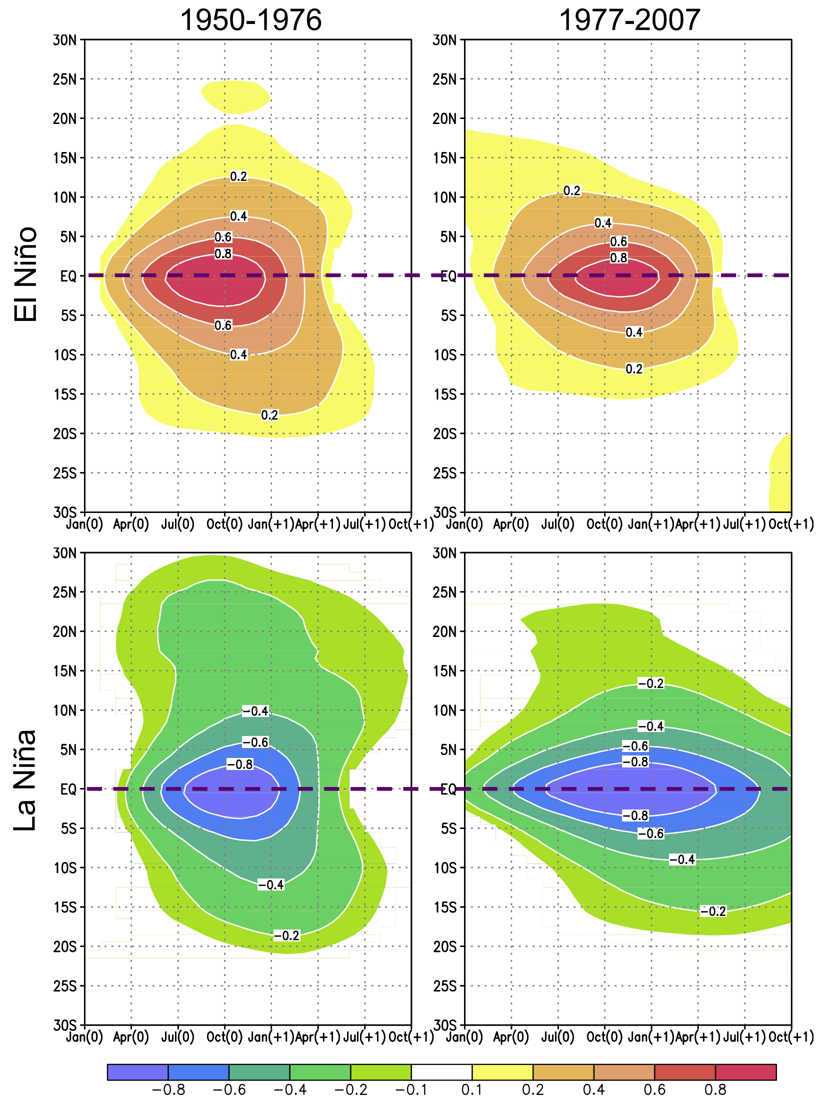

Figure 3. Time-latitude diagram of zonal mean (180°–90°W) 2–7-year band-pass filtered SSTA for (top) El Niño and (bottom) La Niña composites for (left) 1950–1976 and (right) 1977–2007.

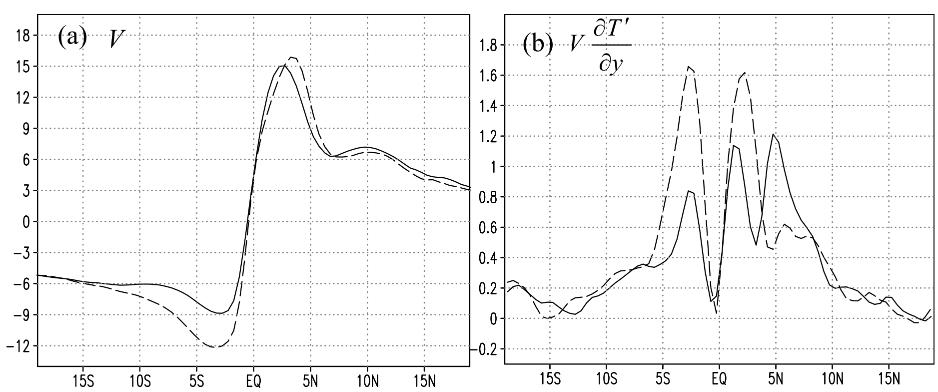

Figure 4. (a) The zonal mean (180°–90°W) surface meridional currents (cm/s) and (b) anomalous surface meridional heat transport ($10^{-2}s^{-1}$) during ENSO years. The surface meridional heat transport of Figure 4b is through the advection of SSTA by mean meridional flows. The solid (dashed) lines denote the average from September (0) to February (+1) of El Nino (La Nina) composites. The La Nina values in Figure 4b are reversed. The data used here is from Simple Ocean Data Assimilation (SODA) reanalysis (1958–2004).

crease) during La Niña (El Niño) years, associated with the strong (weak) upwelling induced by strong (weak) trade winds. Thus, the La Niña meridional scales are significantly wider than El Niño's, because SSTA over the equator can be transported further to the off-equatorial regions during La Niña years than El Niño years. In recent decades, the Walker Circulation has exhibited a weakening tendency, with anomalous westerly winds over the equator. This causes the mean meridional currents to decrease, with weak upwelling over the central/eastern equator. Hence, the SSTA meridional scales of El Niño and La Niña events both are reduced in the post-1976 period.

[15] Different meridional patterns of ENSO SSTA may affect tropical and extratropical atmospheric circulations through air-sea interaction and atmospheric teleconnection. Through observational analyses and modeling, our ongoing work shows that the anomalous atmospheric circulations are different in different ENSO meridional patterns for both ENSO warm and cold events. These results will be reported in a forthcoming paper.

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F.-F. Jin, School of Ocean and Earth Science and Technology, University of Hawai'i at Mānoa, 2525 Correa Road, Honolulu, HI 96822, USA.

J. Li and W. Zhang, State Key Laboratory of Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China. (ljp@lasg.iap.ac.cn)