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State-dependent atmospheric noise associated with ENSO

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[1] A strong relationship between ENSO (El Nino/Southern Oscillation) and atmospheric short-term variability in the near-surface zonal wind is reported in the present study. On one hand, anomalies in the variance of the short-term atmospheric variability over the western Pacific tend to lead El Nino development. On the other hand, the activity of the fast atmospheric variability over the central Pacific is simultaneously correlated to the NINO3.4 SST. The significant correlation exists over the broad range of atmospheric variability from the synoptic time scale to the inter-seasonal time scale. This finding supports the notion that the ENSO–state dependence of the atmospheric variability serves as a source of stochastic forcing for ENSO. Furthermore, it is demonstrated that there is a significant interdecadal change in this dependence. The state-dependent noise becomes much stronger in the recent period, which possibly explains the recent increase of the ENSO activities, consistent with the recent theory of noise-induced destabilization effect for ENSO. **Citation:** Kug, J.-S., F.-F. Jin, K. P. Sooraj, and I.-S. Kang (2008), State-dependent atmospheric noise associated with ENSO, *Geophys. Res. Lett.*, *35*, L05701, doi:10.1029/2007GL032017.

1. Introduction

[2] Since the largest El Nino and strongest activity of westerly wind events (WWE) were observed during the year 1997/98 ENSO event [*McPhaden*, 1999], a number of studies have suggested the importance of interaction between ENSO and relatively shorter timescale atmospheric variability such as the Madden-Julian Oscillation (MJO), and WWE [*Moore and Kleeman*, 1999; *Kessler and Kleeman*, 2000; *Vecchi and Harrison*, 2000; *Zhang and Gottschalk*, 2002; *Yu et al.*, 2003; *Kirtman et al.*, 2005; *Wu and Kirtman*, 2006]. Some of these studies showed that the enhanced MJO and WWE activities preceded the peak of El Nino by a few months [*McPhaden*, 1999; *Harrison and Vecchi*, 1997; *Fink and Speth*, 1997; *Zhang and Gottschalk*, 2002]. Others indicate that the MJO and WWEs are preceded by a large-scale SST anomaly [*Luther et al.*, 1983; *Gutzler*, 1991; *Hendon et al.*, 1999; *Vecchi and Harrison*, 2000; *Kessler*, 2001].

[3] Recent theoretical and modeling studies have elucidated the importance of this interaction between two different timescale phenomena [*Lengaigne et al.*, 2004; *Eisenman et al.*, 2005; *Perez et al.*, 2005; *Zavala-Garay et al.*, 2005; *Jin et al.*, 2007]. For instance, *Jin et al.* [2007] demonstrated in a conceptual framework that the interaction between ENSO and the fast atmospheric variability, as modeled by the state-dependent noise forcing or multiplicative noise forcing, enhances instability of ENSO, its ensemble spread, and generate ENSO asymmetry. They proposed a theory of noise-induced instability for ENSO through the interaction between ENSO and the fast atmospheric variability. Observational studies regarding the intensity and nature of the interaction between ENSO and the fast atmospheric variability state are needed in order to quantify the potential importance of the so-called state-dependent noise on ENSO. In this study, authors try to examine the interaction between ENSO and fast equatorial wind variability by using the 56-yr NCEP/NCAR reanalysis data and by focusing on the level and decadal variation of dependence of the atmospheric "noise" on the ENSO state.

2. Data and Methodology

[4] The data used in this study are monthly means of SST and daily 925-hPa zonal wind for the period of 1950–2005. The monthly mean SST data are from the improved extended reconstructed sea surface temperature version 2 (ERSST.v2) data set [*Smith and Reynolds*, 2004] created by the National Climate Data Center (NCDC); this data analysis uses monthly and 2° spatial superobservations, which are defined as individual observations averaged onto their 2° grid. The daily wind data are taken from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR [*Kalnay et al.*, 1996]). Further, we verified our results with the daily wind data sets from ERA40. Despite significant differences documented in other studies between aspects of the NCEP and ERA40 tropical Pacific wind stress [e.g., *Wittenberg*, 2004], we found that the results presented here are not sensitive to the reanalysis data sets. Daily anomalies are obtained after removing the climatologic annual cycle, which is obtained by averaging the all the daily data on the same calendar dates. A 2-180 day band pass with the LANCZOS filter (using 45 weights [*Duchon*, 1979]) is applied to the daily wind anomalies, in order to investigate relatively the fast atmospheric variability associated with ENSO. The filtered zonal wind anomaly data are averaged over 5°S–5°N latitudinal width, to only focus on the impact of atmospheric noise on the equatorial wave guide. Hereafter, the variability of the filtered wind is referred to as atmospheric "noise" for simplicity. Noted that our definition on the "noise" is somewhat limited because the noise occurs all space and time scales. In this study, we only focus on high-frequency atmospheric variability associated with

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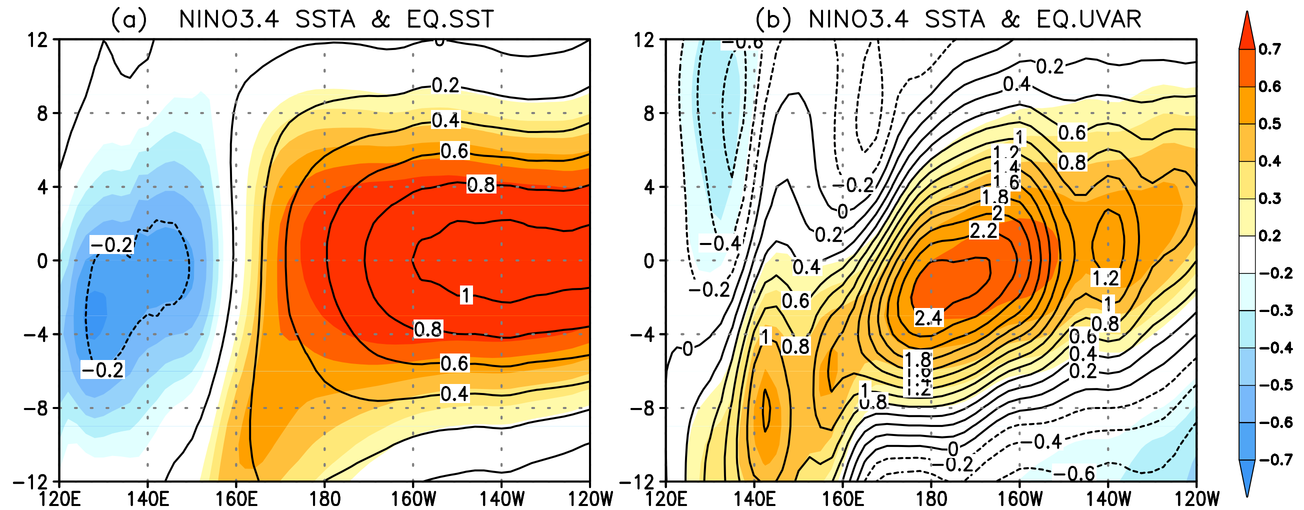

Figure 1. Lag-regression (contour) and correlation (shading) coefficients of (a) SST (averaged over 5°S–5°N) with respect to NINO3.4 SST, and (b) atmospheric noise variability (averaged over 5°S–5°N). Lag (months) is indicated on the vertical axes, with negative values representing SST or atmospheric noise leading NINO3.4 SST. The unit of regression coefficients is dimensionless and $m^2\ s^{-2}\ K^{-1}$, respectively.

ENSO. The variance of the filtered wind is calculated in 5-month moving window.

3. Results

[5] To examine the relation between ENSO and atmospheric noise variability, lag-regression coefficients are calculated with respect to the NINO3.4 SST, which is anomalous SST averaged over 170–120°W, 5°S–5°N. Noted that the statistical relation between ENSO and atmospheric variability is not sensitive to a choice of other ENSO indices such as NINO3 and NINO4 SSTs. Figure 1 shows the lag-regression coefficients for the recent 26-year period of 1980–2005. The SST anomalies are also displayed for comparison. In overall view, the enhanced noise variance seems to propagate eastward from the western Pacific at the El Nino onset phase to the eastern Pacific at the El Nino decaying period. In particular, stronger (weaker) activities for the atmospheric noise are observed over the western Pacific 7–10 months prior to the mature stage of El Nino (La Nina). The correlation coefficients are more than 0.5 with 99% confidence level. Note that the large tropical Pacific SST anomaly is not yet established by that time. The strong variance at El Nino onset phase is possibly linked to the eastward extension of warm pool [*Kessler et al.*, 2005; *Eisenman et al.*, 2005] and anomalous westerlies over the western Pacific [*Seiki and Takayabu*, 2007a, 2007b]. This indicates that the strong MJO and WWE activities play a role in triggering the development of El Nino, as previous studies have argued [*McPhaden*, 1999; *Kessler and Kleeman*, 2000; *Boulanger et al.*, 2001; *Lengaigne et al.*, 2004]. Therefore, the activity of the fast atmospheric variability can be used as a precursor for El Nino onset, one of the challenging problems in current El Nino prediction.

[6] A distinctive strong relationship between ENSO and atmospheric noise over the central Pacific is shown in Figure 1. The noise variance is simultaneously correlated with the NINO3.4 SST. The correlation coefficients are more than 0.6 with 99% confidence level. This significant relationship was reported in previous studies focusing on MJO activity [*Gutzler*, 1991; *Hendon et al.*, 1999; *Kessler*, 2001; *Tam and Lau*, 2005] and WWEs [*Luther et al.*, 1983; *Harrison and Vecchi*, 1997; *Seiki and Takayabu*, 2007a]. The eastward extension of the warm pool [*Kessler et al.*, 1995] and background westerlies flow [*Lau and Lau*, 1992] can accompany the eastward shift of MJO events and WWEs during the El Nino mature phase. This close relationship between ENSO and noise variance supports the theoretical framework and this relation is modeled simply as idealized state-dependent noise [*Jin et al.*, 2007]. The result shown in Figure 1 supports the notion that atmospheric noise depends on the state of ENSO. That is, the El Nino SST anomaly allows favorable conditions for strong activity of the atmospheric transient zonal wind anomalies in the equatorial Pacific. Since there is a significant difference between noise that is independent of the ENSO state and noise that is dependent on ENSO state, as illustrated conceptual by *Jin et al.* [2007], the atmospheric transient variability may not only just trigger some ENSO events, but also impact ENSO growth rate and asymmetry. This argument will be discussed later in this study.

[7] The "atmospheric noise variance" in Figure 1 in fact includes a broad range of timescales from synoptic to the inter-seasonal timescale. To discern which frequency band of the atmospheric variability has a strong relation with ENSO, we first applied a Morlet wavelet analysis basis to a box-averaged unfiltered daily zonal wind anomaly. Then the 5-month moving-averaged wavelet power is linearly correlated with and regressed onto NINO3.4 SST with 12-month lead-lag span, as shown in Figure 2 for the three box-averaged zonal winds. For the wind anomalies averaged over 140–160°E, 5°S–5°N, the wavelet power tends to lead the NINO3.4 SST for every frequency. This is consistent with the results from Figure 1. Significant correlations are found in the broad spectrum from 10 days to 90 days.

[8] For the box in the west of the dateline (160–180°E, 5°S–5°N), the lead-lag relation is significantly different, depending on the frequency of the wind variability. For a

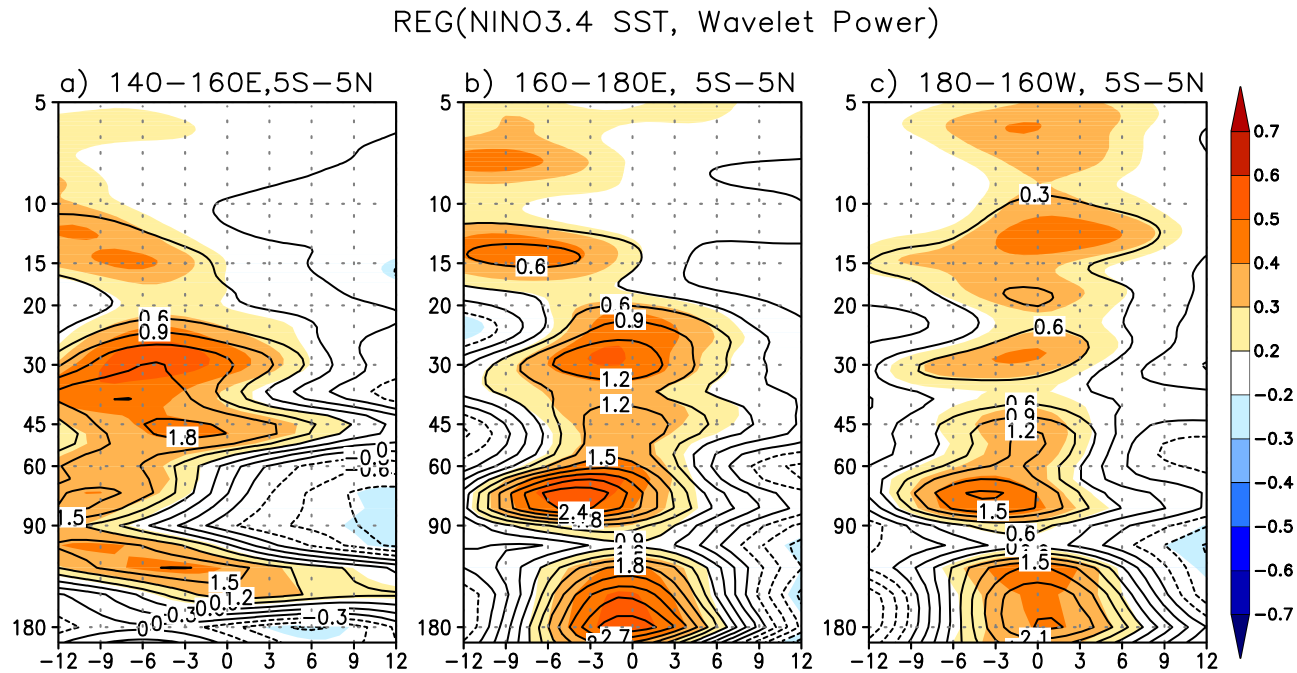

Figure 2. Lag-regression (contour) and correlation (shading) coefficients of wavelet power with respect to NINO3.4 SST. The wavelet power is obtained for the wind anomalies averaged over (a) 140–160°E, 5°S–5°N; (b) 160–180°E, 5°S–5°N; and (c) 160–180°W, 5°S–5°N. Lag (months) is indicated on the horizontal axes and period of wind variability (days) is indicated on the vertical axes. The unit of regression coefficients is $m^2\ s^{-2}\ K^{-1}$.

shorter time scale (less than 20 days), the strong atmospheric noise variance leads El Nino by 3–12 months. Because the correlation is high even when the lag time is 12 months, the high-frequency variability can be a potential precursor of the ENSO prediction. *Kug et al.* [2005] showed that the low-frequency westerlies over the Western Pacific are observed prior to El Nino onset. The strong synoptic activity is possibly linked to the westerlies flow [*Seiki and Takayabu*, 2007a, 2007b]. However, the details of the dynamics behind this statistical relation are still not clear and will be pursued in further studies. Unlike the shorter time scale, the noise variance is simultaneously correlated to the NINO3.4 SST in the relatively longer time scale. The significant correlations are found in three frequency bands, which are the MJO frequency (20–60 days), extended MJO frequency range (60–90 days), and the inter-seasonal time scale (100–180 days). While this relation in MJO frequency is reported from several studies [*Gutzler*, 1991; *Hendon et al.*, 1999; *Kessler*, 2001; *Tam and Lau*, 2005], the relations in the two relatively lower frequency bands are not well documented, though *Marcus et al.* [2001] found that amplitude envelopes of the west equatorial Pacific wind stress in the extended MJO time scales significantly correlate with NINO3 SST at 8- month lag. The correlation in the period of 100–180 days is interesting; the correlation coefficients are robust with various moving windows (5 to 10 months). For the box in the east of the date line (160–180°W, Figure 2c), the correlation pattern is overall similar to that of Figure 2b. However, significant simultaneous correlations are found in the shorter time scales (5–20 days). From Figure 2, the fact that the relation between NINO3.4 SST and wind variance is strong for the variability in the frequency bands on intraseasonal timescale and beyond is noteworthy. The state-dependent atmospheric noises with a longer timescale tend to have a more effective impact on ENSO because the noise-induced destabilization effect on ENSO growth rate is proportional to the lifetime scale of the state-dependent noise [*Jin et al.*, 2007].

[9] So far, we described the relationship between ENSO and atmospheric noise variances using the recent 26 years data (1980–2005). The characteristics of ENSO changed significantly in the late 1970s [*Wang*, 1995; *An and Wang*, 2000; *An*, 2004]. The amplitude and asymmetry of ENSO are enhanced in recent periods. It is possible that these changes of ENSO characteristics have been accompanied by change of the ENSO-noise relationship. To address this issue, the 15-years sliding regression and correlation between NINO3.4 SST and the noise variance are calculated as shown in Figure 3a. There is clearly a decadal modulation of the state-dependent noise. In general, the regression coefficients are gradually increasing over the central and eastern Pacific, even though relatively larger regression coefficients appeared at the early 1960s. On the other hand, the negative correlation is weakened over the 120–140°E during the recent period. As a result, the interaction between ENSO and the atmospheric noise is stronger in the recent period. Figure 3b shows the sliding regression and correlation between NINO3.4 SST and the wavelet power of the western box of the dateline (160–180°E) shown in Figure 2. These results indicate that the relation between ENSO and atmospheric noise is getting stronger.

[10] *Jin et al.* [2007] demonstrated that the state-dependent noise causes enhancing growth rate of El Nino and generates ENSO asymmetry. In their conceptual model, they assumed an ad hoc stochastic forcing as the form of $(1 + BT)\xi$ in the SST equation of the simple recharge-oscillator model [*Jin*, 1996, 1997; *Burgers et al.*, 2005]. Here, T represents normalized ENSO SST anomalies, such

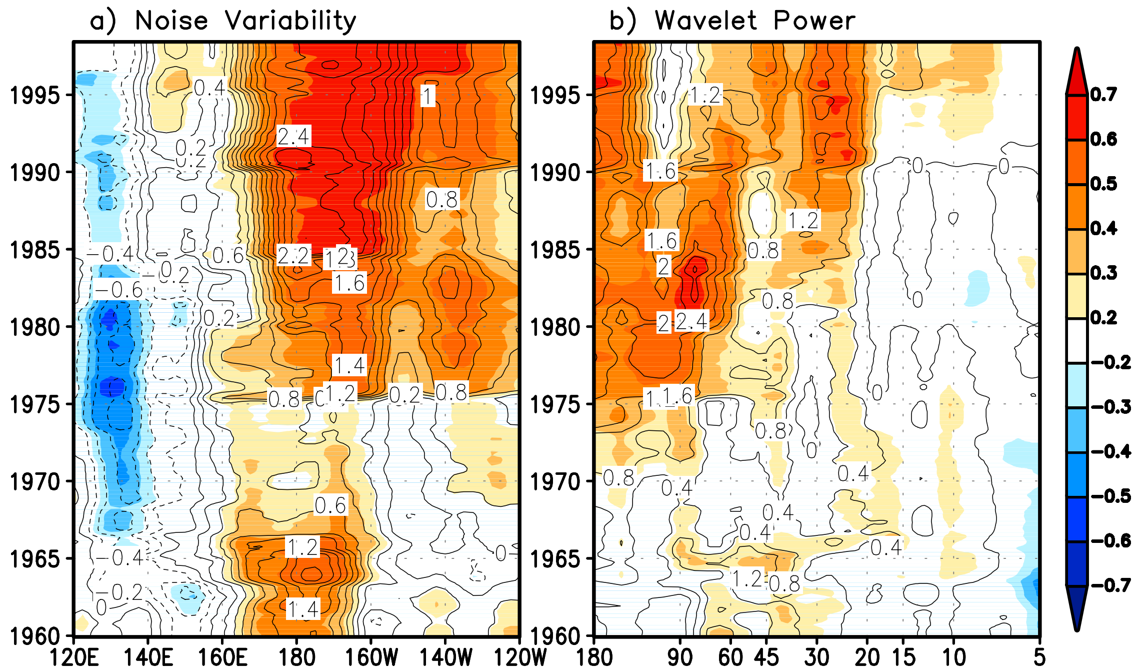

Figure 3. 15-years sliding regression (contour) and correlation (shading) coefficients of (a) the noise variance and (b) the wavelet power of the western box of dateline (160–180°W, 5°S–5°N) with respect to the NINO3.4 SST. The period of wind variability (days) is indicated on the horizontal axis of Figure 3b. The unit of regression coefficients is $m^2 s^{-2} K^{-1}$.

as NINO3 SST, ξ is a red-noise process with constant variance and B is a non-dimensional parameter to represent simply the ENSO state-dependence of the noise forcing. Using the result in Figure 3, we may qualitatively estimate this parameter B by assuming a linear relationship between the variations in the noise variance and the NINO3.4 SST. The parameter B is thus proportional to $\frac{R}{\sigma_w^2 \sigma_N}$. Here, R is the regression coefficient (Figure 3) averaged in the central Pacific (160°E–140°W) and σ_W^2 is the mean variance of the atmospheric transient wind variability and σ_N is the standard deviation of NINO3.4 SST anomalies. As shown in Figure 4, B is of relatively small value before the 1980s and increased significantly to a moderate value afterward.

[11] As it is noted by *Jin et al.* [2007], the impact of the state-dependent noise forcing on the stability of ENSO is proportional to B^2. Because the value of B is nearly doubled before and after the middle 70s, the effect of the so-called noise-induced destabilization on the ENSO has quadrupled during this period. Thus the noise-induced destabilization effect could have played an important role in the enhancement of ENSO activity in the past few decades. This provides an alternative view to the observed

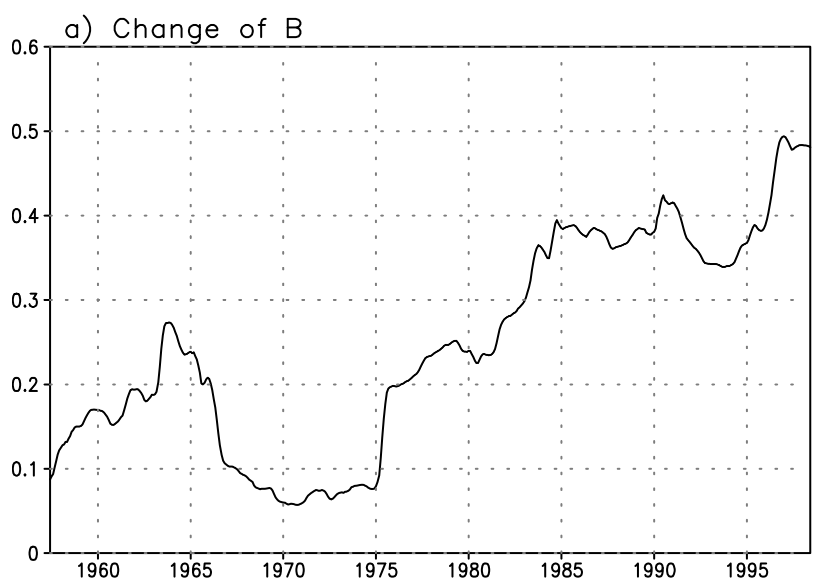

Figure 4. Changes of relative B value ($\frac{R}{\sigma_w^2 \sigma_N}$) with 15-year moving window. The detailed definition for relative B value is referred to in the text.

ENSO change, namely, the observed ENSO changes are generated by the slow background change [*An and Jin*, 2000; *Fedorov and Philander*, 2000], and internal ENSO dynamics [*Timmermann and Jin*, 2002].

4. Summary and Discussion

[12] The relationship between ENSO and atmospheric noise is examined using NCEP reanalysis data. We found that atmospheric noise variance over the central Pacific is simultaneously correlated to the NINO3.4 SST. That is, the atmospheric noise becomes significantly energetic during warm ENSO events. The significant relationship exists over most frequencies from the synoptic time scale to the interseasonal time scale. This observational study lends support to the notion that the atmospheric noise variability is modulated by the ENSO state. The extension of the warm pool and the low level westerlies give a favorable condition for the fast atmospheric variability during El Nino state [*Seiki and Takayabu*, 2007b]. When NINO3.4 SST is one degree above normal for moderate El Nino, the noise variance is changed by about 30–40 percent of the climatological noise variance over the central Pacific. In the case of strong El Nino, the change of the noise variance will be even larger than the climatological value. Recent theoretical work [*Jin et al.*, 2007] proposed a new destabilization mechanism for ENSO through the so-called noise-induced instability due to state-dependent noise forcing. Our analysis suggests that this state-dependent noise has become stronger in the past few decades, which may contribute to the increases in the ENSO activity.

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