The Amplitude-Duration Relation of Observed El Niño Events

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Abstract The authors demonstrate that the El Niño events in the pre- and post-1976 periods show two amplitude-duration relations. One is that the stronger El Niño events have longer durations, which is robust for the moderate El Niño events; the other is that the stronger El Niño events have shorter durations but for strong El Niño events. By estimating the sign and amplitude of the nonlinear dynamical heating (NDH) anomalies, the authors illustrate that the NDH anomalies are negligible for moderate El Niño events but large for strong El Niño events. In particular, the large NDH anomalies for strong El Niño events are positive during the growth and mature phases, which favor warmer El Niño events. During the decay phase, however, the negative NDH anomalies start to arise and become increasingly significant with the evolution of the El Niño events, in which the negative NDH anomalies dampen the sea surface temperature anomalies (SSTA) and cause the El Niño events to reach the SST normal state earlier. This pattern suggests that the nonlinearity tends to increase the intensities of strong El Niño events and shorten their duration, which, together with the previous results showing a positive correlation between the strength of El Niño events and the significance of the effect of nonlinear advection on the events (especially the suppression of nonlinearity on the SSTA during the decay phase), shows that the strong El Niño events tend to have the amplitude-duration relation of the stronger El Niño events with shorter durations. This result also lends support to the assertion that moderate El Niño events possess the amplitude-duration relation of stronger El Niño events with longer durations.

Keywords: climatic oscillation, El Niño events, amplitude, duration

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1 Introduction

El Niño events occur irregularly at intervals of roughly two to seven years, although the average is approximately three to four years (Quinn et al., 1987). These events typically last 12–18 months and are accompanied by swings in the Southern Oscillation (Bjerknes, 1969), an interannual mass exchange between the Eastern (Asian-Australia monsoon region) and Western (Pacific trade wind region) Hemispheres (Walker, 1924). Mature phases of warm episodes tend to occur in boreal winter (Mitchell and Wallace, 1996). Furthermore, for most ENSO warm events, there occur with a deepening in the east and a shallowing in the west of the thermocline along the equator and a phase leading of the thermocline transition to SST prior to the peak of the ENSO event (Wang and Fang, 1996; Duan et al., 2004). Usually, the persistence of the Southern Oscillation breaks down during boreal spring, while the weakest persistence of ENSO arises in this season (Webster and Yang, 1992; Clarke and Van Gorder, 1999; Mu et al., 2007a, b). Additionally, the transition of ENSO from a cold event to a warm event, or vice versa, occurs mostly in boreal spring (Mitchell and Wallace, 1996). Especially, the ENSO events, after the 1976 climate shift, show a prominent characteristic with an amplitude asymmetry between El Niño and La Niña. Many studies have demonstrated that the ENSO asymmetry is a nonlinear characteristic of ENSO (An and Jin, 2004; Duan and Mu, 2006; Duan et al., 2008). Duan et al. (2004) used the approach of conditional nonlinear optimal perturbation (CNOP) to investigate the nonlinear characteristic of initial anomalies that evolve into an ENSO event most probably and showed that the nonlinearity enhances El Niño during its growth phase and favors much larger amplitudes of El Niño events. Recently, Duan et al. (2009) showed that the nonlinearities suppress the strong El Niño during its decaying phase. These studies indicated that the duration of the El Niño events may be related to their amplitudes. What, then, is the amplitude-duration relation of the observed El Niño events? In this paper, we attempt to study the amplitude-duration relation for the observed El Niño events and explore how the nonlinearities modulate the amplitude and duration of these events.

The paper is organized as follows. The data set used in this paper and the EOF-related SST time series are described in the next section. In section 3, we investigate the amplitude-duration of the observed El Niño events. In section 4, we study the mechanism of the amplitude-duration relation of the El Niño events and explore how the nonlinearities modulate the amplitude and duration of these events. Finally, we summarize the main results and present a discussion in section 5.

2 The observed sea surface temperature and the reconstructed El Niño events

To examine which type of amplitude-duration relationship the observed El Niño events show, we choose the version 3b of the National Oceanic and Atmospheric Ad-

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ministration Monthly Extended Reconstructed Sea Surface Temperature Dataset (ERSST.v3b/NOAA) at 2°×2° spatial grid for the period of 1950–2003 (Smith et al., 2008). To reduce the effect of observational noise, we perform an EOF analysis for this SSTA time series and adopt the first four EOF modes to reconstruct the SSTA time series for the period of January 1950–December 2003. We use this reconstructed SSTA to investigate the amplitude-duration relation of the El Niño events.

It is known that the ENSO exhibits a decadal change before and after 1976 (Wang and An, 2001). Therefore, to investigate whether the amplitude-duration relation of interest is common in different decades, we explore the amplitude-duration relation of the El Niño events during the periods of the pre- and post-1976 climate shift. We divide the SSTA time series into two periods: 1950–75 and 1978–2003. It is known that if the Niño 3.4 SSTA (or Niño 3.4 index; the SSTA averaged over the Niño 3.4 region) larger than 0.5°C persists for at least six months, it is regarded as an El Niño event. With this prescribed definition, five typical El Niño events occurred during the 1950–75 period. These El Niño events include the 1951, 1957/58, 1963/64, 1965/66, and 1972/73 El Niño events. During the period 1978–2003, there are seven El Niño events, including 1982/83, 1986/87, 1991/92, 1993, 1994/95, 1997/98, and 2002/03 (Figs. 1a and 1b). All these El Niño events exhibit a growth phase, a mature phase, and a decaying phase, and most of them tend to warm in northern spring and peak at the end of the year. We note that the El Niño events identified in this paper are somewhat different from those in McPhaden and Zhang (2009). In particular, the El Niño events in this paper do not include the 1953/54 and 1968/70 El Niño events. To reduce the effect of observational noises, the reconstructed SSTA is adopted to identify the El Niño events in this paper, which may reduce the amplitude of the observed 1953/54 El Niño and make the reconstructed 1953/54 event fail to be a typical El Niño event. In addition, we notice that the 1968/70 El Niño is an event with double peaks; furthermore, the two peaks are of SSTA values with relatively small differences, which is different from other El Niño events and is regarded as a non-typical El Niño event. In any case, the El Niño events used in this paper include the main typical El Niño events during the periods of investigation and are acceptable for the investigation of the amplitude-duration relation.

3 The amplitude-duration relation of the observed El Niño events

In this section, we investigate the amplitude-duration relation of the ENSO warm events by using the SSTA time series in section 2. We use the period of the Niño 3.4 SSTA greater than 0.5°C to measure the duration of the El Niño events and the values of the Niño 3.4 SSTA in the El Niño's mature phase to define their amplitudes. In Figs. 1a and 1b, we plot the duration of the El Niño events as a function of the amplitudes for the periods of 1950–75 and 1978–2003, respectively. It is shown that there are two categories of El Niño events for either the 1950–75 or the 1978–2003 periods. In one category, the durations of the El Niño events gradually increase with the increasing amplitude of the events. In the other category, the durations of the El Niño events shorten with the increase of the amplitude of the events. That is to say, the former category of El Niño events possesses the amplitude-duration relation where the larger the amplitudes of the El Niño events, the longer their durations; while the latter category shows an amplitude-duration relation where the stronger the El Niño events, the shorter the duration. Furthermore, we notice that the former category of El Niño events is much weaker than the latter. In particular, when the El Niño events have a peak SSTA smaller (larger) than approximately 1.5–1.7°C, they are referred to as relatively weak or moderate (strong) El Niño events and possess the former (latter) amplitude-duration relation. For convenience, we simply use "Category-1" and "Category-2" to denote the former and the latter categories of El Niño events.

In summary, the El Niño events in the 1950–75 or 1978–2003 periods can be identified as belonging to Category-1 or Category-2. Category-1 features the relatively moderate El Niño events, in which the stronger El Niño events will have a longer duration, while Category-2 features the relatively strong events, in which the stronger El Niño events tend to have a shorter duration.

4 How the nonlinearities modulate the amplitude-duration relation for the observed El Niño events

In the last section, we demonstrated that the observed El Niño events can be classified as belonging to Category-1 or Category-2 according to their amplitude-duration relations. The Category-1 El Niño events feature a linear amplitude-duration relation, while the Category-2 events are characterized by a nonlinear amplitude-duration relation. For the linear amplitude-duration relation of the Category-1 El Niño events, with knowledge of the linear dynamical system it is conceivable that the stronger El Niño events will have a longer duration (see Jin, 1997). For the nonlinear amplitude-duration relation of the Category-2 El Niño events, however, we should explore how the nonlinearities modulate the El Niño and lead to the nonlinear amplitude-period relation.

Nonlinear dynamical heating (NDH; Jin et al., 2003) is a measure of ENSO nonlinearity, and it dominates the heat budget of the upper ocean. To quantify this measure and trace its effect on the amplitude-period relation of El Niño events, we calculated the heat budget in the uppermost 50 m of the tropical Pacific. Following Jin et al. (2003), we calculate the heat budget of the ocean surface. The adopted equation is

$$\begin{aligned}\frac{\partial T'}{\partial t} &= -(u'\frac{\partial \overline{T}}{\partial x}+v'\frac{\partial \overline{T}}{\partial y}+w'\frac{\partial \overline{T}}{\partial z}) \\ &\quad -(\overline{u}\frac{\partial T'}{\partial x}+\overline{v}\frac{\partial T'}{\partial y}+\overline{w}\frac{\partial T'}{\partial z}) \\ &\quad -(u'\frac{\partial T'}{\partial x}+v'\frac{\partial T'}{\partial y}+w'\frac{\partial T'}{\partial z})+R'. \end{aligned} \quad (1)$$

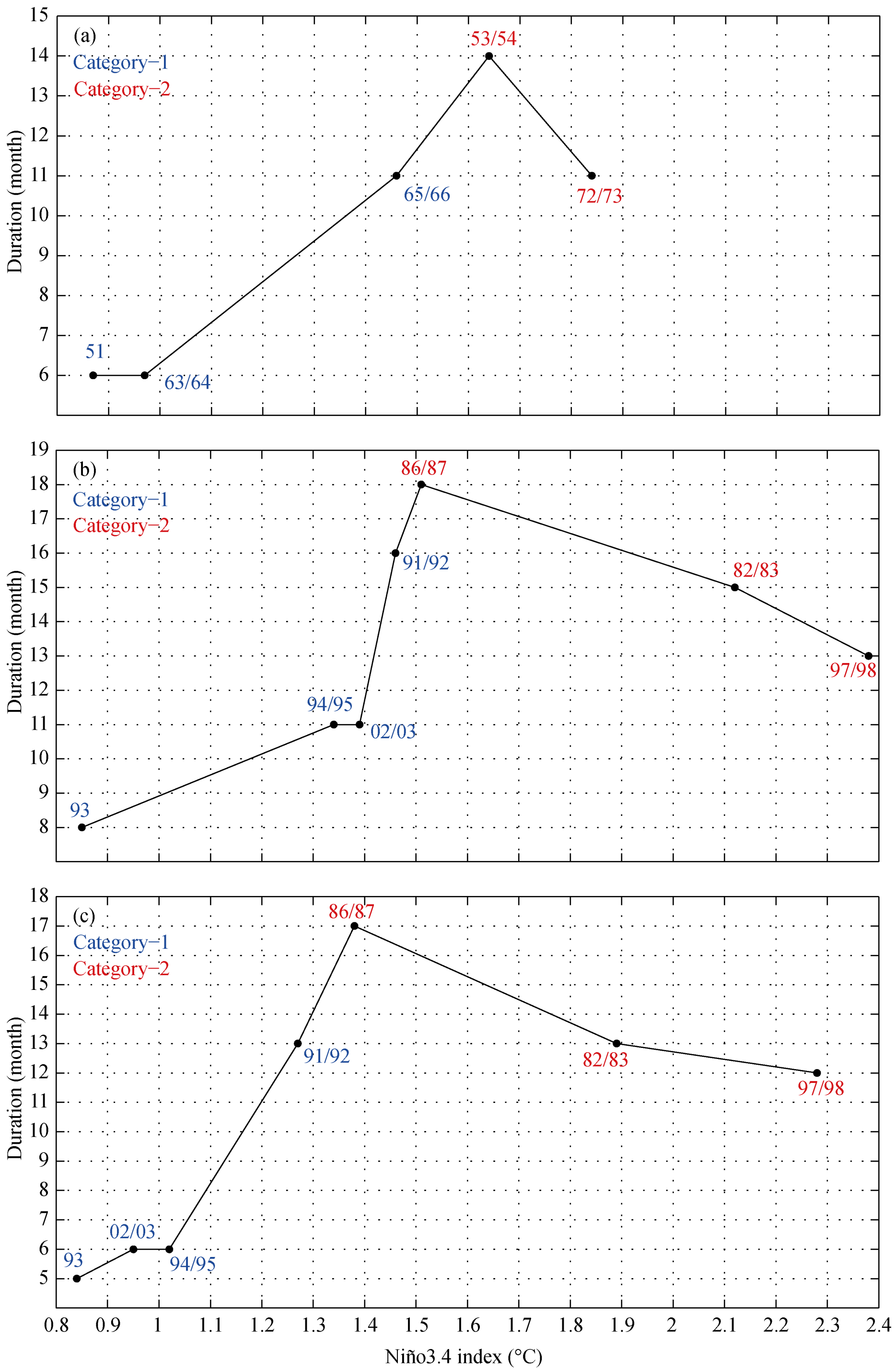

Figure 1 The duration of the El Niño events as a function of their amplitudes. (a) 1950–75 El Niño events; (b) 1978–2003 El Niño events. The data used in (a) and (b) are from the ERSST.v3/NOAA dataset; (c) as in (b), except for the GODAS/NCEP dataset and the period of 1980–2003.

Here, $\overline{T}$, $\overline{u}$, $\overline{v}$, and $\overline{w}$ represent the climatological mean SST, zonal, meridional, and vertical velocities, respectively; T', u', v', and w' denote the anomalous SST, zonal, meridional, and vertical velocities, respectively; and R' describes the contribution from the heat flux and the subgrid scale processes. The term for NDH is in the third bracket of the equation.

We now use the NDH to explain the nonlinear amplitude-duration of the Category-2 El Niño events. In section 2, we use the ERSST.v3b/NOAA SSTA to examine the amplitude-duration relation of the El Niño events. However, this dataset does not include all physical variables (especially the subsurface temperature) related to the NDH. Furthermore, few datasets contain subsurface temperature data of the ocean for the pre-1980 period. It is known that the ocean assimilation data from the Global Ocean Data Assimilation System of National Centers for Environmental Prediction (GODAS/NCEP) consist of all the physical variables associated with the NDH anomalies even though it covers only the post-1980 period. Considering that the amplitude-duration relation of the pre-1976 El Niño events is similar to that of the post-1976 events, it may be reasonable to choose GODAS/ NCEP data to explain the amplitude-duration relation for El Niño events. To guarantee that the NDH anomalies derived from the GOADS/NCEP data are applicable to the amplitude-duration relation of the El Niño events shown in section 2, we first examine whether the El Niño events described by the SSTA in the GOADS/NCEP data possess the amplitude-duration relation shown in section 2. For the SSTA time series in the GOADS/NCEP dataset, we similarly perform an EOF analysis and reconstruct the SSTA time series with the major EOF modes. We then show that the amplitude-duration relation roughly captures the relation demonstrated in section 3 (Fig. 1c). Therefore, it is acceptable to use the NDH derived from the GOADS/NECP data to interpret the amplitude-duration relation for the El Niño events shown in section 3.

For the El Niño events during the period 1980–2003, we estimate the corresponding NDH anomalies for their growth, mature, and decay phases. Here, the so-called growth phase is the period from May to October preceding the El Niño peak, the mature phase covers the period from November to the next February with the peak SSTA in this period, and the decay phase is the period from March to August in the post-El Niño peak period. To illustrate the behavior of the NDH anomalies in each phase, we plot in Fig. 2 the ensemble mean of the time-dependent NDH for the Category-1 and Category-2 El Niño events in the period 1980–2003. We find that for the Category-1 El Niño events, the NDH anomalies are always negligible with the evolution of the El Niño events from the growth phase through the mature phase to the decay phase (left column of Fig. 2). From Eq. (1), it is easily known that the negligible NDH anomalies will have a trivial effect on the SSTA. In this case, the dynamical behavior of the El Niño events may be mainly controlled by a linear system, and it will present the linear amplitude-duration relation in which the stronger El Niño events have a longer duration.

For the Category-2 El Niño events, the NDH shows a different behavior. From Fig. 2 (right column), it is seen that the NDH anomalies have small positive values in the Niño 3 and Niño 4 regions at the beginning of the growth phase (Fig. 2f). However, with the evolution of the El Niño events, the positive NDH anomalies become gradually larger (Fig. 2g). When the El Niño events reach their mature phases, the large positive NDH anomalies nearly cover the entire equatorial Pacific (Fig. 2h). From Eq. (1), we know that the positive NDH anomalies will enhance the SSTA and increase the amplitudes of the El Niño events, which is favorable for much stronger El Niño events. Nevertheless, when these strong El Niño events decay, the negative NDH anomalies gradually start to arise along the equator (see Figs. 2i–j). During July, August, and September of the decay phase, the negative NDH anomalies become large and cover much broader regions near the equator even though there are still positive anomalies in the regions in the eastern Pacific. The negative NDH anomalies during the decay phase will

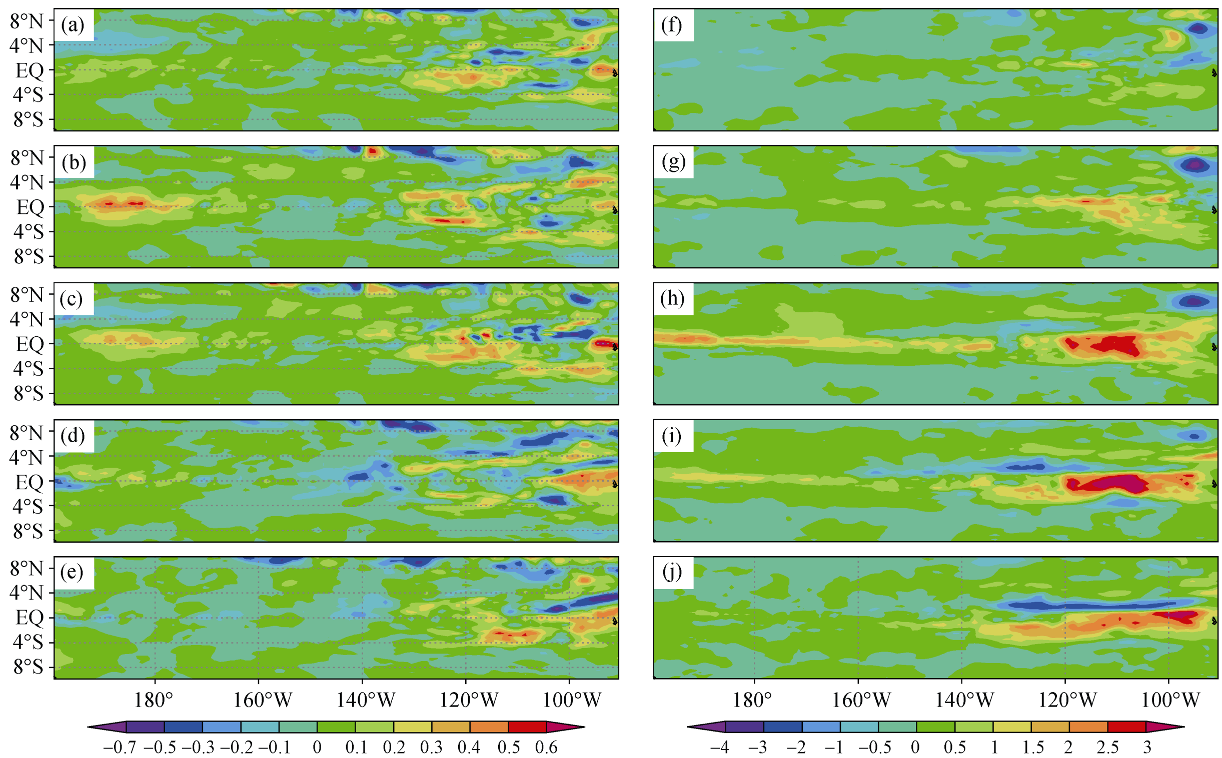

Figure 2 The ensemble mean of the NDH anomalies of moderate El Niño events (left column) and strong El Nino events (right column). A composite for (a) and (f) May–July preceding the El Niño peak, (b) and (g) the continuous August–October, (c) and (h) November–next February with the El Niño peak in this period, and the continuous (d) and (i) March–May and (e) and (j) June–August. The periods as in (a) and (f), and (b) and (g) are in the growth phase of the El Niño events, while those in (c) and (h) are in the mature phase and those in (d) and (i), and (e) and (j) in the decay phase.

suppress the SSTA, which may finally induce the El Niño events reach the SST normal state earlier. In this case, the NDH anomalies tend to shorten the duration of the Category-2 El Niño events. That is to say, the nonlinearities tend to shorten the duration of the strong El Niño events. In the Category-2 El Niño events, then, why do the stronger El Niño events have a shorter duration? Is the answer related to whether the stronger El Niño events are much more easily perturbed by the nonlinearities?

The above analysis uses the NDH anomalies to illustrate that the nonlinearities tend to increase the intensities of strong El Niño events but shorten their durations. That is to say, the nonlinearities associated with NDH favor the stronger El Niño events having shorter duration. Nevertheless, we should note that although we can estimate the tendency of the SSTA evolution according to the sign (positive or negative) and amplitude of the NDH anomalies, the effect of the NDH anomalies on the SSTA will be taken to the linear heating terms (the terms in the first and second brackets in Eq. (1)) by the variables T', u', v', and w' when the El Niño evolves to a long period even to the decay phase. Therefore, if we fully quantify the effect of nonlinearities on the El Niño events, we should evaluate the combined effect of the NDH anomalies and their resultant nonlinear effect in the linear heating terms of Eq. (1). It is obvious that this combined nonlinear effect originates from the effect of the nonlinear advection of heating. Duan et al. (2009) used the combined effect of the nonlinear heating advection derived from a conceptual model to interpret why the observed strong El Niño events have a shorter decay phase. They demonstrated that the stronger the El Niño events, the more significant the suppression of the nonlinear heating advection on these El Niño events during the decay phase, resulting in the stronger El Niño events having a shorter decay phase. We may lend support to their results by demonstrating the nonlinear amplitude-duration of the strong El Niño events in Category-2. In fact, most of the El Niño events tend to begin warming in spring and to peak at the end of the year, and the duration of their growth phases may be trivially different. Consequently, the duration of the warm phase for the El Niño events may be finally determined by the duration of the decay phase. Following Duan et al. (2009), we demonstrate that the combined effect of the nonlinear advection of the heating causes the stronger El Niño events to have a shorter duration.

We also use the Simple Ocean Data Assimilation Reanalysis data (SODA; Cartoon and Giese, 2008) to calculate the NDH. These reanalysis data cover not only the period of 1978–2003 but also the period of 1950–75; furthermore, they include all physical variables related to NDH. Our results demonstrate that for either the 1950–75 or 1978–2003 periods, the El Niño events can also be identified as belonging to Category-1 or Category-2 according to the amplitude-duration relation, whose results are very similar to those derived from the GOADS/ NCEP data. Moreover, we also show that the NDH anomalies for the Category-1 El Niño events are always negligible with the evolution of the events from the growth phase through the mature phase to the decay phase. For the Category-2 El Niño events, the large positive NDH anomalies nearly cover the entire equatorial Pacific during the mature phase, and the negative NDH anomalies gradually begin to arise with the decay of the El Nino events and then become large along the equator. It is inferred that the strong El Niño events of Category-2 possess much stronger nonlinearities, which enhance the El Niño events during the mature phase and suppress them during their decay phase, shortening the duration of the El Niño events. Nevertheless, it should be noted that the NDH anomalies associated with the Category-2 El Niño events for the pre-1980 period are not as significant as those of the post-1980 period. This result may indicate that the Category-2 El Niño events of the post-1980 period are much more significantly affected by the nonlinearities compared with the Category-2 El Niño events of the pre-1980 period.

In summary, the NDH anomalies for the moderate El Niño events are negligible, resulting in the linear amplitude-duration relation. However, the NDH anomalies for the strong El Niño events are significant; furthermore, they enhance the El Niño events during the growth phase, but dampen them during the decay phase, and shortening their durations. Due to the overall effect of the nonlinear advections from both the linear heating terms and the NDH terms, there is a nonlinear amplitude-duration relation for the strong El Niño events, that is, the stronger El Niño events have shorter durations.

5 Summary and discussion

In this paper, we use the observed SST of the period 1950–2003 and investigate the amplitude-duration relation of the El Niño events. It is shown that the El Niño events in the 1950–75 and 1978–2003 periods exhibit two amplitude-duration relations. One is that the stronger El Niño events have longer durations and the other is that the stronger El Niño events have shorter durations. The former features the moderate El Niño events, but the latter is related to the relatively strong El Niño events. To explain the amplitude-duration relation of the El Niño events, we evaluate the NDH anomalies, which is a measure of ENSO nonlinearities. By investigating the sign and amplitude of the NDH anomalies, we demonstrate that the NDH anomalies are negligible for moderate El Niño events but large for strong El Niño events. Furthermore, the large NDH anomalies for strong El Niño events are positive along the equator during the growth and mature phases but tend to be negative during the decay phase. The behavior of the NDH anomalies favors the SSTA being larger in the El Niño peak but dampens the SSTA during the decay phase and shortens the duration of the strong El Niño events. Duan et al. (2009) demonstrated that the stronger the El Niño events, the more significant the effect of nonlinear advection of heating on the events (especially the suppression of nonlinearity on the SSTA during the decay phase), which, combined with the results that the nonlin-earities shorten the duration of the strong El Niño events shows that the strong El Niño events tend to have the amplitude-duration relation of the stronger El Niño events having a shorter duration. This result also lends support to the assertion that the moderate El Niño events possess the amplitude-duration relation of the stronger El Niño events having longer durations.

We also investigate the amplitude-duration relation of the growth and decay phases of the El Niño events. We demonstrate that the amplitude-duration relation of the growth phase has the same tendency as that of the whole El Niño event shown in section 3, while the amplitude-duration relation of the decay phase presents a relatively small change with the increase of the amplitude of El Niño events, which indicates that the amplitude-duration relation of the El Niño events may be mainly determined by the property of the amplitude and duration in the growth phase. Due to the limitation of the paper length requested by the journal, we simply report here the results and not the details.

Eccles and Tziperman (2003) used a toy ENSO model to argue that, on the one hand, if the ENSO is governed by a linear system, the larger the amplitude of the ENSO, the longer the period of the ENSO; on the other hand, if the ENSO is described by a nonlinear system, the larger the amplitude of the ENSO, the shorter the period of the ENSO. However, all these results were derived from a toy model, and they did not show whether such amplitude-duration relations exist in the observed El Niño events. In this paper, we demonstrate that the observed El Niño events possess the amplitude-durations, as suggested in Eccles and Tziperman (2003). Furthermore, we demonstrate how the nonlinearities modulate the El Niño's amplitude and duration by tracing the behavior of the NDH anomalies during the El Niño period, and we provide a possible mechanism for this modulation.

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