Title:

Timing of subsurface heat magnitude for the growth of El Niño events

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Abstract

The subsurface heat buildup in the western tropical Pacific and the recharge phase in equatorial heat content are intrinsic elements of El Niño-Southern Oscillation, leading to changes in zonal wind stress, sea surface temperature and thermocline tilt that characterize the growing and mature phases of El Niño (EN) events. Here we use ocean and atmosphere reanalyses and numerical simulations to study the impact on subsequent EN episodes of a sudden discharge or recharge in ocean heat content during these phases. We found that the timing and magnitude of the events are not substantially affected by the phase at which a sudden recharge is prescribed, but instead they largely depend on the phase at which a major discharge is imposed. The different response to the phase of recharges and discharges confirms the non-linear relationship between the intensity of the subsurface heat buildup and the magnitude and timing of subsequent EN episodes.

Introduction

The El Niño-Southern Oscillation (ENSO) phenomenon is the most important mode of variability at interannual timescales (Wang and Picaut 2004), a major source of climate predictability (Chen et al. 2004, Izumo et al. 2010, Barnston et al. 2012, Petrova et al. 2016) and a key factor explaining large-scale teleconnections (Ballester et al. 2011) and having impacts (Ballester et al. 2013, 2016a) worldwide. The dynamics of ENSO arise from a complex interaction between the ocean and the atmosphere in the tropical Pacific (Bjerknes et al. 1969, McPhaden et al. 2006), involving atmospheric winds in the low- and high- troposphere, ocean waves traveling along the equatorial thermocline, the zonal redistribution of surface and subsurface ocean temperatures,

ENSO is typically characterized by its two main opposing phases, El Niño (EN) and La Niña (LN), which define an anomalous warming or cooling of Sea Surface Temperatures (SST) in the central and eastern tropical Pacific, respectively. EN (LN) is always preceded by a meridional recharge (discharge) of basin-wide tropical ocean heat content about 2 to 3 seasons in advance, which deepens (shoals) the whole equatorial thermocline and warms (cools) the ocean subsurface at about 100 to 150 meter depth (Meinen and McPhaden 2000, Ramesh and Murtugudde 2013). This phase is in turn typically led by the tilting mode, a maximum (minimum) in the slope of the equatorial thermocline explained by the strengthening (weakening) of the equatorial trade winds and the subsequent anomalous downwelling (upwelling) of surface warm (subsurface cold) waters in the western Pacific warm pool (Wyrtki et al. 1985, Ballester et al. 2015).

The leading paradigm explaining the oscillatory nature of ENSO, the recharge oscillator, emphasizes the delayed effect of the enhancement (weakening) of the equatorial trade winds that precedes the recharge (discharge) phase. Thus, the off-equatorial wind stress curl is associated with the change rate in equatorward subsurface convergence (divergence) of water masses in the central Pacific, and therefore the tendency towards the deepening (shoaling) of the thermocline (Jin 1997). Once the equatorial trade winds return to their climatological values, westerly (easterly) wind bursts can occur and trigger eastward-traveling downwelling (upwelling) Kelvin waves that deepen (shoal) the thermocline in the eastern Pacific, suppress (enhances) the coastal upwelling there and activate the growth of an EN (LN) event (Ballester et al. 2016b).

This succession of phases is however subject to sources of irregularity, so that it is nowadays widely accepted that ENSO is a slightly damped periodic oscillation modulated by stochastic noise (Kessler 2002). For example, Hu and Fedorov (2016) have recently shown that the 2014/15 EN event was stalled as a result of an unusually strong basin-wide easterly wind burst in June 2014, which partially discharged the basin and affected the growth of the EN episode that was
expected for the end of the year. At that time, basin-wide uniform warm conditions were instead observed in the equatorial Pacific, which were followed by the record-breaking EN episode in boreal winter 2015/16 (Hu and Fedorov 2016, Ballester et al. 2016c).

Ballester et al. (2016c) recently studied the effect of a fast recharge or discharge of ocean heat content by means of an ensemble of numerical experiments, which were used to explore the sensitivity of EN to the magnitude of the heat buildup occurring in the ocean subsurface 21 months earlier. These simulations showed that a large increase in heat content during this phase can lead to basin-wide uniform warm conditions in the equatorial Pacific the winter before the occurrence of a very strong EN event (Figures 1c, 2c, 3c). The experiments also showed that the system compensates any major decrease in heat content and naturally evolves towards a new recharge, resulting in a delay of up to one year in the occurrence of an EN event (Figures 1b, 2b, 3b). In the present study, we extend this analysis with a new set of numerical experiments, in which initial conditions are modified at a later stage of the onset of EN. Here we compare these two families of simulations with the aim of identifying the dynamical mechanisms that explain how differences in the lead time of a sudden recharge or discharge affect the magnitude and timing of subsequent EN episodes.

Methods

The model used here is the Community Earth System Model (CESM) v1.2 (Hurrell et al. 2013). The atmospheric component has a resolution of 2.5° in longitude and 1.875° in latitude, with 30 vertical levels. The ocean model uses a displaced pole grid with approximately 1° resolution in longitude and 0.5° in latitude, which is refined within the tropical band up to 0.25° at the equator. There are 60 vertical levels with the highest resolution (10 m) in the upper 150 m, and the lowest (250 m) in the deep ocean.
An EN episode with the same magnitude as the recent 2015/16 event (i.e. Niño3.4 Index = +2.8 °C) was chosen from a reference (REF) 100 year spin-up simulation, which is validated against the composite of the 1972/73 (+2.5 °C), 1982/83 (+2.6 °C) and 1997/98 (+2.7 °C) EN events in the ORAS4 (Balmaseda et al. 2013) and NCEP/NCAR (Kalnay et al. 1996) reanalyses (here referred to as OBS). We compare two families of ensemble experiments, with initial conditions corresponding to a lead time of 21 (i.e. March 1st of year -1, see Ballester et al. 2016c) and 11 (i.e. January 1st of year 0) months before the December peak of this event. We note that these stages of the episode correspond to the maximum in the slope of the equatorial thermocline (here labeled with the TM prefix standing for Tilting Mode, Figure S1b) and to an early phase of the basin-wide deepening of the thermocline (label RP for Recharge Phase, Figure S1e), respectively.

In each of these families, the intensity of the initial subsurface warm anomaly was decreased (negative sign representing a discharge in heat content) or increased (positive sign or recharge). The warm temperature anomalies were fully modified only in the inner three-dimensional box [120E-80W] x [10S-10N] x [50-200m], and this modification was linearly decreased to zero from the border of this box to the frontier of the outer box [100E-60W] x [15S-15N] x [20-300m]. For example, Figures S1a,d (Figures S1c,f) show the initial equatorial temperature conditions in the TM-80% and RP-80% (TM+80% and RP+80%) experiments, in which the subsurface warm anomaly was reduced (amplified) by 80%. Each set of experiments in turn consists of 10 simulations with slightly perturbed initial conditions.

Results

The comparison with the observation composites (Figures 1a, 2a, 3a) shows that the model correctly reproduces the main dynamical processes preceding the peak of the major EN events on
record and the subsequent transition towards LN, including the main subsurface ocean features and
the interaction between the atmosphere and the ocean surface (Figures 1d, 2d, 3d). The model for
example simulates the slow but steady accumulation of subsurface warm waters in the western
Pacific near and above the thermocline, due to stronger-than-normal easterly trade winds in the
central Pacific during year -1, and the associated downward heat advection in the warm pool
(Figures 1g, 2g, 3g). Some differences are however found, e.g. the westerly wind anomalies are
stronger in the model than in the observation composites during the growing and decaying phases of
EN, which in turn explains the warm SST bias of the model in the central Pacific (Figure 2g). But
still, the observation composites correspond to the average of 3 EN events, and therefore only the
sign and not the magnitude of the anomalies can be directly compared with the REF simulation,
which represents one single very big EN event.

The transition from the initial tilting mode to the recharge phase is seen to be associated
with anomalies in the wind stress curl, which according to the recharge theory generates
equatorward subsurface convergence of water masses in the central Pacific, and therefore the
tendency towards the deepening of the thermocline (Jin 1997). Thus, Figure 4 shows that the
interhemispheric difference (northern minus southern hemisphere) of the tropical wind stress curl is
negative throughout year -1 in the whole basin, as well as in the central and eastern Pacific during
the stages of largest warming rate in year 0. Ballester et al. (2016b) showed that a fraction of this
subsurface warming is additionally explained by zonal and vertical advection of heat along the
subsurface currents near the tilted thermocline. We note that positive anomalies in interhemispheric
wind stress curl difference also coincide with the eastward-propagating subsurface cooling tendency
and the associated transition towards LN conditions (McGregor et al. 2012).

In agreement with the observed composites, the initial conditions in the RP experiments
were prescribed at the beginning of the last month in which the ocean surface and the atmosphere
are in a neutral phase in the REF simulation (e.g. last month with slightly negative values of the
Niño3.4 Index; Figures 5b,e). Just a few months later, in late winter and early spring of year 0, the
first strong westerly wind anomalies are found in the warm pool (dashed green line in Figure 2d), and as a result, the upwelling Kelvin waves start to cross the basin (Figure 3d) and the accumulated subsurface heat reaches the eastern Pacific (Figure 1d). The timely prescription of subsurface heat content anomalies in the RP experiment just before the activation of the Bjerknes feedback is therefore designed to give some insight into the irreversibility of the EN event at this advanced stage of the oscillation.

When the heat content is reduced by 80% during the recharge phase (experiment RP-80%; Figures 1e, 2e, 3e, 5d-f), the same dynamical mechanisms as in the REF simulation operate during the stages of the oscillation that precede the peak of the episode. Thus, the growth and eastward propagation of the subsurface warm anomaly, as well as the subsequent onset of the EN event, remain very similar in timing and approximately proportional in magnitude to that shown in the REF ensemble, with the anomaly of the Niño3.4 Index reaching +1.15 °C and representing a relative decrease of about 60%. The maximum in westerly wind and SST anomalies is however found to occur earlier, in August of year 0, so that the heat content in the basin is completely discharged by the end of the year and the Niño3.4 Index returns to values close to 0 in March of year +1. The fast and early termination of the event generates very weak cold subsurface temperature anomalies and no reinforcement of the trade winds in the warm pool, which explain the lack of a LN event by the end of year +1.

The dynamics of ENSO in the RP-80% experiment are completely different from those resulting from the ensemble of simulations in which the same fraction of the heat content is removed during the tilting mode 10 months earlier (TM-80%). In these runs, a weak LN event develops at the end of year -1, which re-activates the generation of the subsurface heat buildup in the western Pacific and leads to a strong EN episode that peaks in December of year +1 (Niño3.4 Index = +2 °C; Figures 1b, 2b, 3b, 5a-c; Ballester et al. 2016c). Differences between both cases therefore highlight the importance of the timing of the prescribed discharge (Figures 1h, 2h, 3h). When the discharge occurs during the tilting mode, the system is forced to make a step back and re-
recharge the heat content; but if the discharge instead occurs just before the maximum of the recharge phase, the system reaches a point of no return in which the remaining heat is released leading to a weak EN event. Differences in the timing of the initial discharge and the eventual occurrence of a re-recharge process particularly have a substantial effect on the magnitude of the subsequent EN event, given that the event occurring with one year of delay in TM-80% is almost twice as large than the one in RP-80%.

Instead, no differences between the TM and RP experiments exist if the heat content is amplified by 80%. In the TM+80% experiment, the excess heat in the western Pacific is quickly released and starts to warm the eastern Pacific subsurface, but the surface warming at the end of year -1 is uniformly distributed along the equatorial Pacific and therefore the Bjerknes feedback is not activated, representing a transition step towards a very strong EN episode one year later (Niño3.4 Index = +4 °C; Figures 1c, 2c, 3c, 5a-c; Ballester et al. 2016c). Similarly, in the RP+80% experiment, the heat is immediately released, leading to an event of similar magnitude that peaks at the end of the year (Figures 1f, 2f, 3f, 5d-f). Differences between the two experiments are indeed seen to be negligible in terms of atmospheric winds, heat content and surface and subsurface temperatures and currents (Figures 1i, 2i, 3i). This result indicates that, as expected, the transition from the tilting mode to the recharge phase is a necessary step for the onset of EN events (Meinen and McPhaden 2000), and that it cannot be fastened or bypassed by suddenly increasing the heat content in the western Pacific or in the whole basin.

Discussion and summary

The present study highlights the asymmetry between the impact of a sudden discharge or recharge in ocean heat content on subsequent EN events (cf. Figures 5a-c and 5d-f). We find that the timing and magnitude of the episodes are not substantially affected by the phase at which a
sudden recharge is prescribed. In this regard, EN events are seen to be independent from the timing of a sudden subsurface heat content reinforcement, given that the larger warming rate in the RP+80% experiment quickly transforms the subsurface heat content into surface temperature anomalies. In contrast, the timing and magnitude of EN episodes are substantially affected by the phase at which a large discharge is prescribed, given that a new recharge reinforcing the heat content and delaying the event by one year only takes place when heat is discharged during the tilting mode and not later during the recharge phase.

This result contrasts with the recent evolution of ENSO, in which the basin-wide easterly wind burst observed during the recharge phase in June 2014 stalled the EN event that was expected for the end of the year, and instead a record-breaking episode was observed one year later. This case is not explained by our idealistic numerical experiments because they do not include the prescription of westerly wind bursts during the second half of year 0. These episodes, which were observed in August and autumn of 2014 and were not thermally-driven by local SSTs, triggered two groups of eastward-traveling downwelling Kelvin waves that redistributed the surface warming and led to basin-wide uniform warm conditions in winter 2014/15 (see for example Figure 2a in Hu and Fedorov 2016). This configuration, which is not found in the simulations due to the absence of prescribed westerly wind bursts, did not favor the activation of the Bjerknes feedback during the second half of 2014, and therefore the Walker circulation remained in a neutral phase and the accumulated heat was not discharged towards higher latitudes (Ballester et al. 2016c). The subsequent warm base state in the equatorial Pacific, together with additional westerly wind bursts observed in 2015, became the perfect ingredients for the record-breaking magnitude of the 2015/16 EN episode (Hu et al. 2014, Levine and McPhaden 2016).

The above-mentioned asymmetry between the recharge and discharge scenarios is explained by the direct relationship between the wind power (i.e. zonal wind stress acting on the kinetic energy of surface currents) and the buoyancy power (i.e. anomalous tilt of the equatorial thermocline sustained by the kinetic energy of the ocean currents, Brown et al. 2011). Thus, in the
initially-recharged experiments, the additional heat is rapidly released regardless of the phase of the oscillation in which it is prescribed, because the unmodified trade winds cannot sustain the anomalous slope of the thermocline resulting from the superimposed heat content. Instead, in the initially-discharged experiments, the unmodified winds can sustain and eventually reinforce the imposed more stable flatter slope of the thermocline. The response of the coupled ocean-atmosphere system therefore depends on the stage of the oscillation in which the anomalous heat content is prescribed.

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References


Figure 1. Longitude-time Hovmöller diagram of equatorial temperature (shading, in °C) and zonal current (contour, in m/s) anomalies at the level of the thermocline.

Panels correspond to the observation composite of the December 1972, 1982 and 1997 El Niño events (a), the reference simulation (d), and a 80% reduction (b,e) or amplification (c,f) of the subsurface warming during the tilting mode (b,c) and the recharge phase (e,f). Panels in the third column show the differences between the second minus the first column. The minimum contour is ±0.1 m/s and the contour interval is 0.2 m/s, with grey solid (black dashed) lines depicting positive (negative) anomalies. The solid (dashed) green lines indicate the peak of El Niño (the recharge phase) in the reference simulation.

Figure 2. Longitude-time Hovmöller diagram of sea surface temperature (shading, in °C) and surface zonal wind (contour, in m/s) anomalies.

Panels correspond to the observation composite of the December 1972, 1982 and 1997 El Niño events (a), the reference simulation (d), and a 80% reduction (b,e) or amplification (c,f) of the subsurface warming during the tilting mode (b,c) and the recharge phase (e,f). Panels in the third column show the differences between the second minus the first column. The minimum contour is ±0.5 m/s and the contour interval is 1 m/s, with grey solid (black dashed) lines depicting positive (negative) anomalies. The solid (dashed) green lines indicate the peak of El Niño (the recharge phase) in the reference simulation.

Figure 3. Longitude-time Hovmöller diagram of sea surface height (shading, in cm) and surface zonal current (contour, in m/s) anomalies.

Panels correspond to the observation composite of the December 1972, 1982 and 1997 El Niño events (a), the reference simulation (d), and a 80% reduction (b,e) or amplification (c,f) of the subsurface warming during the tilting mode (b,c) and the recharge phase (e,f). Panels in the third
column show the differences between the second minus the first column. The minimum contour is ±0.1 m/s and the contour interval is 0.2 m/s, with grey solid (black dashed) lines depicting positive (negative) anomalies. The solid (dashed) green lines indicate the peak of El Niño (the recharge phase) in the reference simulation.

**Figure 4.** Longitude-time Hovmöller diagram of anomalies in equatorial temperature tendency at the level of the thermocline (shading, in °C/year) and the interhemispheric difference in wind stress curl between [0,20N] and [20S,0] (contour, in N/m$^3$).

The panel corresponds to the observation composite of the December 1972, 1982 and 1997 El Niño events. The minimum contour is ±0.5·10$^{-8}$ N/m$^3$ and the contour interval is 10$^{-8}$ N/m$^3$, with grey solid (black dashed) lines depicting positive (negative) anomalies. The solid green line indicates the peak of El Niño.

**Figure 5.** Evolution of the Tropical Heat Content (10$^{16}$ J) and the Niño3.4 Index (°C).

Lines correspond to the reference simulation (black), and a 80% reduction (cyan), a 40% reduction (magenta), a 40% amplification (red) and a 80% amplification (blue) of the subsurface warming during the tilting mode (a-c) and the recharge phase (d-f). The solid green lines indicate the peak of El Niño in the reference simulation, and the crosses (circles) correspond to the initial (final) month of the model runs. The Tropical Heat Content was computed as the temperature average within 120E-80W, 5S-5N and the upper 300m.
Figure 1.
Figure 2.
Figure 3.
Figure 4.
\frac{\partial \theta}{\partial t} \text{ and } \nabla \times \mathbf{T}_{\text{NH-SH}}
Figure 5.