Assessing Extratropical Influence on Observed El Niño–Southern Oscillation Events Using Regional Coupled Data Assimilation

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ABSTRACT

The extratropical influence on the observed events of El Niño–Southern Oscillation (ENSO) variability from 1948 to 2015 is assessed by constraining the extratropical atmospheric variability in a coupled general circulation model (CGCM) using the regional coupled data assimilation (RCDA) method. The ensemble-mean ENSO response to extratropical atmospheric forcing, which is systematically and quantitatively studied through a series of RCDA experiments, indicates robust extratropical influence on some observed ENSO events. Furthermore, an event-by-event quantitative analysis shows significant differences of the extratropical influence among the observed ENSO events, both in its own strength and in its relation to tropical precursors such as the equatorial Pacific heat content anomaly. This study provides the first dynamic quantitative assessment of the extratropical influence on observed ENSO variability on an event-by-event basis.

1. Introduction

Although El Niño–Southern Oscillation (ENSO) variability is known to originate from coupled ocean–atmosphere processes in the tropical Pacific (Cane and Zebiak 1985; Jin 1997), some recent studies have recognized that ENSO can also be significantly affected by extratropical climate variability, notably the North Pacific meridional mode (NPMM) and the South Pacific meridional mode (SPMM) (Chang et al. 2007; Vimont et al. 2001, 2003a,b; Alexander et al. 2010; Zhang et al. 2009; Ding et al. 2017; Lu et al. 2017a; Larson and Kirtman 2013, 2014; Pegion and Alexander 2013; Zhang et al. 2014). Nevertheless, extratropical influences on ENSO have been inferred largely from statistical analyses and idealized model experiments, and it remains unclear how the extratropics dynamically impact ENSO variability and predictability in the real world, especially on any specific event. Due to the complexity of ENSO dynamics and the all-inclusive nature of the observations, an event-based assessment of the extratropical influence, as well as its relative importance to tropical dynamics, is still lacking. This paper performs the first quantitative assessment of the extratropical influence on the observed ENSO events from 1948 to 2015 using the recently proposed regional coupled data assimilation (RCDA) method (Lu et al. 2017a,b). The combination of a CGCM, an ensemble approach, and the assimilation of real-world observations in specific regions makes it possible to assess the causal effects of extratropical influences on each ENSO event.

2. Model and methods

The Fast Ocean Atmosphere Model (FOAM) is a fully coupled global atmosphere–ocean general circulation model (Jacob 1997; Jacob et al. 2001). The atmosphere component is a spectral model with a horizontal resolution of R15 (equivalent to $7.5^\circ \times 4.5^\circ$) and an 18-level hybrid vertical coordinate. The ocean component has a horizontal resolution of $2.8^\circ \times 1.4^\circ$ and 24 vertical levels. The land and sea ice components...
are modified based on those of the Community Climate Model 2.

The coupled data assimilation (CDA) system in FOAM is based on the ensemble adjustment Kalman filter (EAKF; Anderson 2001; Zhang et al. 2007), a variant of the ensemble Kalman filter (EnKF; Evensen 1994). The system includes both atmosphere (temperature $T$ and zonal and meridional winds $U$ and $V$) and ocean (temperature) data assimilation, namely ADA and ODA, respectively, and the model components (atmosphere, ocean, land, and sea ice) are fully coupled during forward integration regardless of the assimilation configuration. More details of the CDA system can be found in Lu et al. (2015).

Based on the CDA system in FOAM, the RCDA method limits the assimilation to the desired model variables and domain and then analyzes the ensemble-mean model responses in regions without the assimilation of observations (see Table 1 for a list of the RCDA experiments performed in this study). The RCDA method was first used within a perfect-model framework to study the extratropical control on the El Niño–Southern Oscillation (ENSO) variability in FOAM (Lu et al. 2017a). The main differences and advantages of the RCDA method compared to some previous studies (Lu et al. 2017a,b) and the same ensemble of initial conditions, which are the restart files after a 10-yr ensemble control present-day FOAM simulation that started with the same ocean initial conditions and slightly different atmosphere initial conditions. All RCDA experiments run for 68 years (1948–2015). The experiment setups follow Lu et al. (2017a) except for the use of real-world reanalysis datasets instead of model-generated observations.

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3. Extratropical forced ENSO events

The extratropical influence on observed ENSO variability and events is quantified using a series of RCDA experiments in which the extratropical climate variability is constrained toward real-world observations progressively from the extratropics to the equator. We will focus on the RCDA experiments with only atmosphere data assimilation (ADA), since our experiments, including previous perfect-model study (e.g., Lu et al. 2017a), show little impact of extratropical SST on ENSO variability, a point to be returned to later. Without any assimilation, the Niño-3.4 index [average sea surface temperature (SST) anomaly in the region of $5°S$–$5°N$, $120°W$–$70°W$] in the ensemble control experiment (CTRL in Fig. 1a) is not significantly correlated with the observed Niño-3.4. Given the natural variability of each ensemble member, the ensemble-average Niño-3.4 index stays close to zero and maxes out at around 0.5°C. On the opposite end, in the experiment ADA_ALL (Fig. 1b), the Niño-3.4 index stays close to the observations...
and captures most observed ENSO events, with small remaining deviations caused mostly by model bias.

The extratropical influence on the observed ENSO variability can be seen clearly when ADA is applied only in the extratropics (ADA_20, ADA_24, and ADA_28 in Figs. 1c–e, respectively). In sharp contrast to CTRL, the extratropically forced ADA experiments exhibit significant ENSO variability, and the simulated Niño-3.4 indices are significantly correlated with the observations ($R = 0.421, 0.494,$ and $0.539$ for ADA_28, ADA_24, and ADA_20, respectively). This shows that the assimilation of the observed extratropical atmospheric variability can indeed trigger ENSO events given the available dynamics in this coupled FOAM. [The accuracy of the Niño-3.4 index in the ADA experiments here is, as expected, lower than that in the perfect-model study (Lu et al. 2017a) due to the model bias.] In all of the ADA experiments, the strength of extratropical influence on ENSO increases as the data assimilation boundary moves equatorward. This can be seen in the Niño-3.4 correlations between all ADA experiments and the observations in Fig. 2. The correlations in the ADA experiments increase almost linearly as the data assimilation boundary moves equatorward, becoming significant (99% confidence level) at around 37°. The significant Niño-3.4 correlations in the extratropically forced ADA experiments supplement previous studies

![Graphs showing Niño-3.4 index correlations](https://example.com/graphs)
that found significant correlations between extratropical
precursors and ENSO variability (Vimont et al.
2003a,b; Chang et al. 2007; Anderson 2007); however,
the correlations here are based on fully coupled his-
torical simulations with the extratropical variability
prescribed explicitly and, therefore, represent the
extratropical influence unambiguously.

The impact of the extratropical SST is also studied
in experiments with the observed SST assimilated only [Ocean Data Assimilation (ODA)] and in addition to
the atmospheric assimilation [Coupled Data Assimila-
tion (CDA)] (Table 1). The Niño-3.4 correlations from
ODA and CDA experiments are also shown in Fig. 2.
The ODA experiments could not produce significant
Niño-3.4 correlation until equatorial SST observations
inside 10° are assimilated, agreeing with the perfect-
model study (Lu et al. 2017a). The similarity between
ADA and CDA experiments is expected, considering
that extratropical SST has little impact on ENSO vari-
ability and that atmosphere assimilation enables the
atmosphere component to force rather realistic ocean
variability in the extratropics.

Despite the robustness of significant extratropical
influences in general as shown by Figs. 1 and 2, our
ADA experiments demonstrate that extratropical at-
mospheric forcing has a stronger impact on some El
Niño events (e.g., 1972/73 and 1982/83) than others
(e.g., 1997/98). Figure 3 shows the magnitude and tim-
ing of peak Niño-3.4 indices for the observed El Niño
events in ADA_24 compared to the observations, and
Fig. 4 shows the same for ADA_20 and ADA_28. All
El Niño events in ADA_24 are weaker than in the ob-
servations because they are ensemble averages that
represent only the potential ENSO strength forced by
the extratropics. However, the strength of their relative
extratropical influence clearly varies. Among the four
strongest observed El Niño events (1972/73, 1982/83,
1997/98, and 2015/16), the 1972/73 and 1982/83 El Niño
events show the strongest and most consistent extra-
tropical influences across multiple ADA experiments,
followed by the 2015/16 El Niño, while the 1997/98 El
Niño is the least subject to extratropical forcing. The
strengths of the extratropical influences vary for the
weaker El Niño events, too. For example, the 1986/87 and
1991/92 events are strong in our ADA experiments.
Overall, the average magnitude of the peak Niño-3.4
values in ADA_24 is 44% (standard deviation of 23%) of
those in the observations. In terms of the timing, all the
El Niño events in ADA_24, except the 2002/03 El Niño,
peak simultaneously or slightly earlier than in the ob-
servations (marker colors in Fig. 3) because the annual
cycle of Niño-3.4 variance in FOAM peaks in the fall
instead of winter as in the observations. For further
validation, we performed additional ADA_24 experi-
ments with slightly modified data assimilation parame-
ters (e.g., relaxation factor and localization radius). The
changes to Fig. 3 with the additional experiments are
small and insignificant to the conclusions, especially for
the strongest El Niño events (not shown).

This event-by-event quantification of extratropical
influence has implications for both the onset mechanism
and the predictability of ENSO. The variation in the
strength of the extratropical influence on ENSO events
suggests that it is an oversimplification to assess the average effects of extratropical precursors across multiple ENSO events. Statistical approaches such as composite analysis or temporal correlation would underestimate the impact of extratropical precursors on some events while overestimate the effect on some others, limiting our understanding of the ENSO onset mechanism through extratropical forcing. The variation in extratropical influence also helps partially explain the varying predictability of different ENSO events. We hypothesize that the El Niño events that endure more extratropical influence (e.g., 1972/73 and 1982/83 El Niño events) may be more difficult to predict at longer lead times because predictability in the extratropical atmospheric variability is lost beyond a few weeks.

The contrast between the 1972/73 and 1982/83 El Niño events and the 1997/98 El Niño does not necessarily mean that the extratropical precursors are stronger for the former than the latter. Strong favorable extratropical precursors are found before all three events by previous studies (Vimont et al. 2003b; Chang et al. 2007; Ding et al. 2017). Instead, this contrast suggests that the extratropical forcing is more important for the onset of the 1972/73 and 1982/83 El Niño events, while other factors such as westerly wind burst (WWB) events and equatorial ocean preconditioning play bigger roles for the 1997/98 El Niño. Previous studies have shown that the recharging of the equatorial thermocline was extremely rapid across the Pacific in early 1997, which was caused by strong MJO and WWB events in late 1996 and early 1997 (McPhaden 1999). In our RCDA experiments, the observed extratropical forcing is assimilated while the WWB events and equatorial ocean preconditioning are missing, so events like the 1972/73 and 1982/83 El Niño events are better reproduced.

4. The 1972/73 El Niño

The 1972/73 El Niño event is consistently reproduced across multiple extratropically forced ADA experiments, and we will detail its extratropical forcing as a case study. From 1972 to 1973, the ensemble-mean Niño-3.4 indices for ADA_20, ADA_24, and ADA_28 all peak in December 1972, the same month as the observed Niño-3.4, with ADA_20 and ADA_24 peaking at 1.3°C while ADA_28 is close to 2°C. Two subtropical wind indices are used to represent the forcing from PMMs, namely the average low-level (900 hPa–surface) wind speed in the southeastern tropical Pacific (SPW; 15°–25°S, 80°–110°W), representing the SPMM, and that in the north-central to eastern tropical Pacific (NPW; 15°–25°N, 120°W–180°W), representing the NPMM. The observed NPW and SPW show negative anomalies (Fig. 5b), indicating reduced trade winds, in the spring and summer of 1972. Similar SPW and NPW anomalies appear in ADA_24, except there is an even larger NPW anomaly during the summer of 1972. These wind speed anomalies could trigger El Niño onset through teleconnection mechanisms such as the wind–evaporation–SST feedback (Liu and Xie 1994) and trade wind charging (Anderson et al. 2013). The timing of the extratropical forcing relative to the Niño-3.4 peak also falls in line with previous studies. An SPW anomaly like that in May 1972 of ADA_24 has been shown to favor El Niño events with a lead time of 4–6 months in FOAM (Lu et al. 2017a), while an NPW anomaly like that during March–July 1972 has been found to lead El Niño peaks by 7–9 months in both observations and climate conditions.

Fig. 4. As in Fig. 3, but for (a) ADA_20 and (b) ADA_28 against observations.

The importance of extratropical forcing for the 1972/73 El Niño in ADA_24 is further demonstrated by short RCDA sensitivity experiments (SE hereafter). All SEs are run for 2 years from the start of 1972, mimicking the 1972/73 period of ADA_24 except for the following modifications. In SE1 and SE2, the ocean initial conditions are changed to those from the start of 1976 and 1997 of ADA_24, respectively, both of which have a discharged equatorial Pacific thermocline. In SE3, the 30-day running-mean anomalies are removed from the atmospheric observations before assimilation.

First, we show the slightly favorable positive heat content precursor in January 1972 (black line in Fig. 6b) is not crucial for the onset of the 1972/73 El Niño in ADA_24. These two experiments, SE1 and SE2, replicate the 1972/73 period of ADA_24 except that the ocean initial conditions are replaced with the ADA_24 ocean state during January 1976 and January 1997, respectively. The equatorial Pacific upper ocean is in a discharged state at the start of both 1976 and 1997 in ADA_24. The initial negative heat content anomaly (blue and red lines in Fig. 6b) does generate a dip in the Niño-3.4 index from January to May 1972, but with the assimilated extratropical atmospheric forcing, the SST cooling is quickly reversed to warming and the Niño-3.4 SST eventually catches up with the original ADA_24 in September 1972. This suggests the extratropical forcing of the 1972/73 El Niño event can overcome a moderately unfavorable oceanic initial state 1 year prior to the Niño-3.4 peak. It also supports the notion that the slight re-charging of the equatorial thermocline in early 1972 is not necessary for the extratropical triggering of the 1972/73 El Niño onset in ADA_24. The time scale of the key extratropical atmospheric variability that is responsible for the triggering of the 1972/73 El Niño is further explored in sensitivity experiments SE3 and SE4. Extratropical atmospheric variability, as indicated by the observed daily series of NPW and SPW (Fig. 7), contains both high- (daily to weekly) and low- (monthly and lower) frequency variability; the former is dominated by midlatitude synoptic weather activity while the latter

![Figure 5](https://example.com/fig5.png)

**Fig. 5.** During the 1971–73 period, the (a) Niño-3.4 index is shown for observations, CTRL, ADA_20, ADA_24, and ADA_28. Light-colored dashed lines are the corresponding ensemble members for each ADA experiment. (b) Wind speed indices for NPW (orange) and SPW (purple) from observations (dashed) and ADA_24 (solid).

![Figure 6](https://example.com/fig6.png)

**Fig. 6.** (a) Niño-3.4 index and (b) zonal-average Pacific heat content ($t_{300}$) during 1971–73 from observations ADA_24, and sensitivity experiments (SE) 1–3.
involves low-frequency atmospheric and coupled ocean–atmosphere variability such as the North Pacific Oscillation (NPO). When the 30-day running-mean anomalies, representing the low-frequency variability, are removed from the atmosphere observation before assimilation, the resulting SE3 shows no apparent Niño-3.4 warming throughout 1972 and 1973. Therefore, the low-frequency component of the extratropical atmosphere variability is critical for triggering the 1972/73 El Niño. This conclusion has been assumed implicitly in most previous studies of extratropical influences on ENSO, because only monthly or seasonal observations are usually considered (Vimont et al. 2003b; Chang et al. 2007). However, our study supports this argument explicitly with dynamic experiments in a CGCM. This could benefit ENSO prediction, because it suggests the possibility of an extratropical impact from low-frequency atmospheric variability beyond a few days of lead time.

5. Conclusions and discussion

This paper provides the first quantitative event-by-event assessment of the extratropical influence on the ENSO events during the 1948–2015 period using the RCDA method. Robust responses in ENSO variability are found when only the extratropical atmospheric variability is constrained toward real-world reanalysis data. In the meantime, there is considerable event-by-event variation in the strength of extratropical control. Among the strongest observed El Niño events, the 1972/73 and 1982/83 events exhibit greater extratropical influence than the 1997/98 and 2015/16 events across multiple extratropically forced RCDA experiments. For example, the 1972/73 El Niño, which is preceded by favorable extratropical precursors from both hemispheres, can be triggered even with a discharged equatorial Pacific thermocline 1 year prior. Furthermore, the low-frequency atmospheric variability from the extratropics contributes the most to the triggering of the 1972/73 El Niño.

Our study indicates that for the quantification of the extratropical influence on ENSO, a generalization across all ENSO events may be insufficient since the strength of the extratropical influence could vary greatly from event to event. This varying strength of extratropical influence on different observed ENSO events.
cycle (Levine and McPhaden 2015) and mean climatology (Lübbecke and McPhaden 2014), or the ENSO diversity (Capotondi and Sardeshmukh 2015). Recognition of ENSO events with strong extratropical influence, in either observations or climate models, is a critical step toward helping us better understand and improve the predictability of ENSO events in the future.

Compared with previous perfect-model studies of the same topic, the introduction of model biases brings many complications to the work presented in this paper. First of all, the real-world implications of this study are still limited by the ability of the CGCM to resolve related processes. The real-world extratropical impact on ENSO could be either underestimated here due to the lack of certain teleconnection mechanisms, or overestimated due to, for example, weak stochasticity in ENSO dynamics. Second, the assimilation of real-world observations also alters the climatology of the model’s tropical climate (Lu et al. 2017b), which could cause the ENSO behavior to change from the perfect-model framework. One other complication from model biases is its effect on the performance of the data assimilation system (Zhang and Rosati 2010).

Besides model biases, which have been and will continue to be a key issue for modeling studies, there are some other limitations in this pilot study for the new RCDA approach. Using data assimilation in the study of climate dynamics is still an emerging area, so its experimental design and analysis methods remain to be defined and improved. Assimilating reanalysis datasets brings additional biases from the reanalysis system; however, its impact on the results seems small (Liu et al. 2016). The datasets we are assimilating have evolving observational networks over time, which could affect our comparisons of ENSO predictability between different events over time. The changes in observational networks should always be considered when comparing predictability or prediction skills over time.

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REFERENCES

Larson, S. M., and B. P. Kirtman, 2013: The Pacific Meridional Mode as a trigger for ENSO in a high-resolution coupled