Analysis of the Non-Linearity of El Niño Southern Oscillation Teleconnections

Claudia Frauen\textsuperscript{1,2}, Dietmar Dommengget\textsuperscript{1,2}, Michael Rezny\textsuperscript{2,3}, and Scott Wales\textsuperscript{2,4}

Corresponding author:
Claudia Frauen
School of Mathematical Sciences
Monash University, VIC 3800
Australia
[claudia.frauen@monash.edu](mailto:claudia.frauen@monash.edu)

\textsuperscript{1} School of Mathematical Sciences, Monash University, Clayton, VIC, Australia
\textsuperscript{2} ARC Centre of Excellence for Climate System Science
\textsuperscript{3} Met Office, Exeter, UK
\textsuperscript{4} Melbourne University, Melbourne, VIC, Australia
Abstract

The El Niño Southern Oscillation (ENSO) has significant variations and non-linearities in its pattern and strength. ENSO events are shifted along the equator, with some located in the central Pacific (CP) and others in the east Pacific (EP).

To study how these variations are reflected in global ENSO teleconnections we analyze observations and idealized atmospheric general circulation model (AGCM) simulations.

Clear non-linearities exist in observed teleconnections of sea level pressure (SLP) and precipitation. However, it is difficult to distinguish if these are caused by the different signs, strengths or spatial patterns of events (strong El Niño events mostly being EP events and strong La Niña events mostly being CP events) or by combinations of these. Therefore, sensitivity experiments are performed with an AGCM forced with idealized EP and CP ENSO sea surface temperature (SST) patterns with varying signs and strengths. It can be shown that in general the response is stronger for warm events than for cold events and the teleconnections shift following the SST anomaly patterns. EP events show stronger non-linearities than CP events. The non-linear responses to ENSO events can be explained as a combination of non-linear responses to a linear ENSO (fixed pattern but varying signs and strengths) and a linear response to a non-linear ENSO (varying patterns). Any observed event is a combination of these aspects. While in most tropical regions these add up leading to stronger non-linear responses than expected from the single components, in some regions
they cancel each other resulting in little overall non-linearity. This leads to strong regional differences in ENSO teleconnections.
1. Introduction

The El Niño Southern Oscillation (ENSO) is the most important mode of interannual climate variability. It has its origin in the interaction of the tropical Pacific Ocean and the atmosphere but its teleconnections reach far beyond the tropical Pacific. Especially the tropical Indian and Atlantic Oceans and the adjacent continents are influenced by ENSO (e.g. Latif and Barnett 1995; Enfield and Mayer 1997). One typical feature of ENSO is its amplitude asymmetry. Positive events (El Niño) tend to be stronger than negative events (La Niña) (e.g. Burgers and Stephenson 1999; Kang and Kug 2002; An and Jin 2004; Frauen and Dommenget 2010). However, other studies have shown that ENSO is not only non-linear in its amplitude but also in its spatial pattern (e.g. Hoerling et al. 1997; Takahashi et al. 2011; Yu and Kim 2011; Choi et al. 2012) and time evolution (e.g. Larkin and Harrison 2002; Ohba and Ueda 2009; Okumura and Deser 2010). Dommenget et al. (2013) showed that significant differences exist in the patterns between positive and negative events and between strong and weak events, which mostly describes the differences between central and eastern Pacific events. Several studies also pointed out that differences exist in the global teleconnections of central and eastern Pacific events. Ashok et al. (2007) show that, depending on the season, the impacts of the Central Pacific El Niño on specific regions can be opposite to those of the Eastern Pacific El Niño. Also, Hu et al. (2012) show that besides the tropics especially the eastern Pacific, North America and the North Atlantic have robust climate differences between the Eastern and Central Pacific El Niño events. Other studies pointed out
significant differences in the regional impact of Central and Eastern Pacific El Niño events over, for example, East Asia (Yuan and Yang 2012), the North Pacific and Southwestern USA (Zhang et al. 2012), Australia (Taschetto and England 2009), and Europe (Graf and Zanchettin 2012).

Previous studies have also shown that the responses to El Niño and La Niña events are not simply opposite. Significant non-linearities exist in the global precipitation and sea level pressure (SLP) responses. Non-linearities in the tropical Pacific precipitation response are to be expected. The sea surface temperature (SST) threshold for deep convection means that there is a much stronger response to warm SST anomalies than to cold ones. The large zonal climatological SST gradient across the Pacific also results in a spatial shift in the rainfall response between El Niño and La Niña events due to the fact that convection responds to the absolute rather than the anomalous SST (Hoerling et al. 1997). Hoerling et al. (2001) also showed that non-linearities in the tropical precipitation response as well as in the extra-tropical atmospheric response mainly emerge for stronger events. Chung et al. (2013) and Power et al. (2013) demonstrated that global warming can intensify the non-linear tropical precipitation response for El Niño events. Also regional rainfall responses, like for example shown by Cai et al. (2010) for Eastern Australia, show significant non-linear relationships with ENSO. The non-linear response in extra-tropical SLP however, cannot simply be explained by shifts in the deep convection between El Niño and La Niña events (Larkin and Harrison 2002).

This study will systematically show how differences in the sign, amplitude and pattern of tropical Pacific SST anomalies are reflected in global SLP and precipitation responses. This is achieved by analyzing sensitivity experiments, in
which an atmospheric general circulation model (GCM) is forced with idealized ENSO SST patterns of varying sign and strength.

The remainder of this article is organized as follows. In Section 2 we describe the data and model simulations used for this study. The non-linearities in observed ENSO teleconnections are analyzed in Section 3. In Section 4 we study the ENSO teleconnections in an atmospheric GCM forced with idealized ENSO SST patterns. Finally, the main findings and outcomes of this study are summarized in Section 5.

2. Data and Models

For the analyses of observed ENSO teleconnection non-linearities in this study linearly detrended monthly mean SST anomalies for the period 1950-2010 are calculated from the HadISST data set (Rayner et al. 2003). The same is done for SLP data based on the NCEP reanalysis data set (Kalnay et al. 1996) for the same period and for precipitation data based on the GPCP Version 2 monthly Satellite-Gauge data for the period 1979 to 2010 (Adler et al. 2003).

A series of sensitivity experiments with a full complexity atmospheric GCM forced with idealized SSTs in the tropical Pacific (120°E-70°W, 30°S-30°N) were carried out to further support the limited statistics from the relatively short period of observations and to better understand the interactions. The atmospheric model used in this study is a low-resolution version (3.75° x 2.5°) of the UK Meteorological Office Unified Model atmospheric GCM with HadGEM2 physics (Davies et al. 2005; Martin et al. 2010; Martin et al. 2011). Outside the tropical Pacific the atmospheric model is coupled to a simple slab ocean model.
A flux correction scheme is applied here to force the model SSTs to closely follow the prescribed HadISST SST climatology. However, the SSTs are still able to respond to forcings from the tropical Pacific. A 100-year control simulation with prescribed climatological SSTs in the tropical Pacific is performed with this model. Additionally, 12 sensitivity experiments are performed with prescribed ENSO patterns in the tropical Pacific.

The prescribed ENSO patterns (see Fig. 1) are based on the idealized El Niño (PC$_{\text{El-Niño}}$) and La Niña (PC$_{\text{La-Niña}}$) patterns defined in Dommenget et al. (2013). Their PC$_{\text{El-Niño}}$ and PC$_{\text{La-Niña}}$ are an orthogonal rotation of the first and second principal components (PC) of tropical Pacific SST and describe the non-linear spatial structure of ENSO in an optimal way motivated by the scatter plot between PC-1 and PC-2 (see Fig. 2). The scatter points do not form an isotropic cloud, as expected for linear interactions, but appear to have two main orthogonal directions (PC$_{\text{El-Niño}}$ and PC$_{\text{La-Niña}}$), which was also found by Takahashi et al. (2011). It can be seen that strong El Niño events (large positive values of PC-1) are associated with positive values of PC-2. A superposition of PC-1 + PC-2 leads to the typical Eastern Pacific (EP) pattern superimposed in the upper right quadrant. This defines PC$_{\text{El-Niño}}$. The EP pattern is narrower around the equator and has its maximum directly off the coast of South America. Strong La Niña events (large negative values in PC-1) are also associated with positive values of PC-2. Thus, a superposition of –PC-1 + PC-2 leads to the typical central Pacific (CP) pattern (upper left quadrant), which is meridionally wider and has its maximum in the central Pacific. This defines PC$_{\text{La-Niña}}$. Weak El Niño and La Niña events have mostly negative values in PC-2. This means that a weak El Niño (La
Niña) event has the same pattern as a strong La Niña (El Niño) event with opposite sign. The two patterns, EP (PC_El-Niño) and CP (PC_La-Niña), are therefore optimal to study the teleconnections of ENSO. For the sensitivity experiments these two different patterns were normalized to have a NINO3.4 mean SST anomaly of +1K and added to the HadISST climatology in the tropical Pacific with positive and negative signs: Positive Eastern Pacific (EP+), negative Eastern Pacific (EP-), positive Central Pacific (CP+), and negative Central Pacific (CP-). The patterns were added with different strengths: 50%, 100% and 200% corresponding to the normalized patterns multiplied with 0.5, 1 and 2. To get statistically significant results the experiments were run for different periods of time. An overview of the experiments can be seen in Table 1.

3. Observed ENSO teleconnections

Before we go into the analysis of the non-linearity in the ENSO teleconnections it is instructive to first look at the non-linearities in the distribution of the climate variability itself (see Fig. 3). This will give us a first idea of what we should expect for the non-linearities in the ENSO teleconnections. Here, we will focus on the skewness of the distribution as a zero order estimate of non-linearities, but later we will define non-linearities as any deviation from a linear function. The distribution of SST anomalies in the Tropical Pacific is positively skewed in the east and negatively skewed in the west (Fig. 3a), consistent with Burgers and Stephenson (1999). For the tropical Pacific SLP (Fig. 3b) we find roughly the opposite of the SST skewness, as SST and SLP are strongly linked to each other with opposite signs. However, the relative and absolute strength of the SLP
skewness is somewhat different from that of the SST. Overall, the SLP skewness
in the tropical Pacific is weaker than for SST, but stronger for many other regions
outside the tropical Pacific (e.g. Indian Ocean or northern extra-tropics). The SLP
skewness is also more pronounced in the western part of the tropical Pacific
than in the eastern part, which is the opposite for the SST distribution.
Precipitation has positive skewness nearly everywhere, as is well known and
expected from a positive definite variable (Fig. 3c). In particular regions with
relative small mean precipitation near regions of relative strong mean
precipitation (e.g. the boundaries of the inner-tropical convergence zone, ITCZ)
show very large values of skewness. Regions with large mean precipitation (e.g.
ITCZ) show relatively small skewness. In summary, we expect the SLP to
somewhat follow the SST non-linearities, but possibly also show some deviations
from it. The precipitation teleconnections are likely to be positively skewed no
matter what the SST forcing looks like. Thus, non-linearities in precipitation may
not necessarily reflect non-linearities in ENSO teleconnections.
We base the non-linearity of the observed ENSO teleconnections on composites
of El Niño and La Niña events according to the PC_{El-Niño} and PC_{La-Niña} time series.
All months with PC_{El-Niño} ≥ 1.0 are classified as El Niño months and all months
with PC_{La-Niña} ≤ -1.0 are classified as La Niña events. Fig. 4 shows the normalized
SLP response to El Niño and La Niña events and the difference in the response
patterns. The normalization by the mean NINO3.4 SST values allows us to
directly compare the composites of El Niño and La Niña events, as it gives us the
SLP response per NINO3.4 SST anomaly. Note that the La Niña composites have
reversed signs as they are normalized by the mean negative SST anomalies in the
NINO3.4 region. For a linear response model just depending on the NINO3.4 SST anomalies both composites should be identical in this presentation.

First of all, we note that the SLP response patterns (Figs. 4a and 4b) have the well-known structure with the typical pattern of the Southern Oscillation and a negative SLP response over the North Pacific for positive SST anomalies in NINO3.4. However, we can also note that the composites of El Niño and La Niña are not identical, which is quantified by the difference between these in Fig. 4c. The t-values for a Students t-test of the differences as a measure of significance are shown in Fig. 4d. A positive difference means in general that the SLP response is stronger in amplitude per NINO3.4 SST anomaly during El Niño events in regions where the SLP response is positive (e.g. western tropical Pacific) or vise versa: the SLP response is weaker in amplitude per NINO3.4 SST anomaly during El Niño events in regions where the SLP response is negative (e.g. western tropical Pacific). The same holds for negative differences. However, there are also combinations, in which the normalized SLP responses change sign in the composites of El Niño and La Niña (e.g. northeast Asia) and where the SLP response is the same for both El Niño and La Niña events. In these cases the differences do not reflect weaker or stronger responses.

Significant non-linearities can be found over the eastern and western tropical Pacific, the tropical to subtropical North Pacific and the South Pacific around 30°S due to the La Niña SLP response being shifted further to the west. Also, south of Australia a significant non-linearity is found due to the positive La Niña SLP response here extending all the way into the Indian Ocean. Over northeast Asia we find a negative SLP response to both El Niño and La Niña, which makes it highly non-linear. Over North Africa, South America and the central South Pacific
strong non-linearities are found as well. However, they are not statistically
significant. It is interesting to note that the NINO3 region more or less marks the
transition zone between positive and negative deviations from a linear response.
The differences in the composites of El Niño and La Niña events have strong
similarities with the composite of El Niño events. This suggests that the non-
linearities are, to zero or first order, reflecting a stronger response to El Niño
events than to La Niña events. But, as pointed out above, some regions also show
significant shifts in the response.

Figure 5 shows the mean precipitation response in percentage of the
climatological precipitation. The strongest response in precipitation during an El
Niño event is found over the equatorial Pacific east of the dateline. During a La
Niña event the response in the equatorial Pacific is weaker and the maximum is
shifted further to the west while in the far eastern equatorial Pacific only a very
small response is found. In the case of an El Niño event one can also find
responses in the central to western Pacific north and south of the equator and
over the maritime continent. In the La Niña case the response south of the
equator extends further to the West over the whole of Australia and into the
Indian Ocean. Other regions, which show an indication of a non-linear response,
are North Africa and Brazil. Again, outside the tropical Pacific the differences
between the El Niño and La Niña responses are rarely statistically significant.
Similar to the SLP response, the differences in the precipitation response look
similar to the composite of El Niño events again suggesting that the non-
linearities are to first order reflecting a stronger response to El Niño events than
to La Niña events. Here, only the annual mean precipitation response is shown
although precipitation has strong seasonal variations and therefore also the
ENSO responses vary with seasons. However, for a seasonal analysis of the non-linearities too little data is available.

Based on the observed ENSO response composites we highlight the following findings:

- Significant non-linearities are found in the SLP response in the far eastern and western tropical Pacific, in the northern tropical to subtropical Pacific, south of Australia, and over Northeast Asia.

- Most of the non-linearities suggest a stronger response to El Niño events than to La Niña events, but some significant shifts in the response pattern also exist.

- For the precipitation significant non-linearities are almost exclusively found in the tropical Pacific.

- The SLP response shows almost no non-linearity over the NINO3 and NINO4 regions, where the strongest ENSO SST anomalies occur.

The observed differences between strong El Niño and strong La Niña events may result from several different factors: The differences in the sign of the events, the differences in the strength of the events and the differences in the pattern of the events. In order to separate the responses according to these different factors the database of observed events is just too small to get statistically significant results. It also needs to be noted that most observed events may be a combination of different patterns, strengths or signs. Therefore, an analysis of idealized model simulations is necessary, in which we can separate the different aspects.
4. Sensitivity experiments

A good way to study the impacts of the different factors (sign, strength and pattern of the events) on ENSO teleconnections is to perform sensitivity experiments with an atmospheric GCM forced by standardized ENSO patterns. An overview of the experiments performed for this study was given in Section 2 and in Table 1. In the following, we will analyze how well the model performs in simulating the ENSO teleconnections in SLP and rainfall and what influence different patterns, signs and strengths of the ENSO events have on the non-linearities in the responses in SLP and precipitation. For precipitation we have to keep in mind that firstly, we only have a very limited amount of reliable observational data. Secondly, it is well known that most of the state-of-the-art coupled climate models have strong biases in the simulated tropical precipitation (Lin 2007). However, since ENSO-related precipitation has very strong socio-economic impacts, it is worth also analyzing the non-linearities in ENSO teleconnections regarding precipitation.

4.1 Comparison with observations

The observed ENSO events are in general a combination of different patterns, signs and strengths. In the set of the idealized sensitivity experiments the 100% EP+ and CP- are the ones that are closest to the composite of the observed ENSO events (Figs. 4 and 5) although the composite threshold of $PC_{\text{El-Niño}} \geq 1.0$ or $PC_{\text{La-Niña}} \leq -1.0$ does not necessarily exclude EP- and CP+ events. If we compare the
EP+ and CP- SLP and precipitation responses (Figs. 6 and 7) with the observed, we see that the model is able to simulate comparable response patterns, especially in the tropical Pacific. Positive forcings result in a negative SLP anomaly in the eastern tropical Pacific and a positive anomaly over the western tropical Pacific and the maritime continent, which represent the Southern Oscillation (Fig. 6a and 6d). Also, the model reproduces the observed negative anomalies in the North and South Pacific in case of an El Niño event as well as the negative anomalies over South America and the positive anomalies over Australia. The negative CP- forcing (Fig. 6e) again reproduces the Southern Oscillation with a positive anomaly over the eastern Pacific and a negative anomaly over the western Pacific and again the response is shifted further to the west (note again, that the responses for negative forcings in Fig. 6 are shown with reversed signs due to the normalization). The strongest anomalies are found off the coast of Australia as in observations. Also, the observed positive anomalies in the North and South Pacific are simulated in the model. What the model does not capture are the responses over Africa, where the experiments either show no response (CP-) or a response with the wrong sign (EP+).

Figure 6i shows the differences between the EP+ and the CP- forcing and thus shows the differences between typical strong El Niño and La Niña events (Fig. 4c). Again the model is very similar to the observed differences. Most of the tropical and subtropical response differences are well simulated. Even some of the extra-tropical SLP response differences are similar to those observed. However, the non-linearity over North-East Asia, North Africa and the strength of the non-linearity south of Australia are not captured.
For precipitation we find a strong increase along the equatorial Pacific and reduced precipitation over the maritime continent and the western to central Pacific north and south of the equator in response to positive forcings (Fig. 7a and 7d). In case of the EP+ forcing the negative precipitation response north of the equator extends all the way to the eastern Pacific. This is in good agreement with observations although the positive precipitation response extends too far to the west. In response to negative forcings (Fig. 7b and 7e) we find a reduction in rainfall along the equatorial Pacific, which is weaker than the response to positive forcings. In the CP- case we find a strong increase in precipitation over the maritime continent, northeast Australia, and the western to central Pacific north and south of the equator. Again, this is in good agreement with observations. The model also simulates realistic responses along the coast of California and Mexico. However, the model mostly fails to reproduce a realistic response over Australia. In the CP- case, which represents a typical La Niña event, the negative response is only found over the North-East of Australia and in the EP+ case an unrealistically strong positive response is found over Western Australia. The differences between El Niño and La Niña events (Fig. 5c) are again represented by the differences between the EP+ and the CP- forcing (Fig. 7i). In the tropical Pacific region the model is very similar to the observed differences. However, over Africa the model simulates significant non-linearities, which are not observed.

Overall, the model simulates the responses in SLP and precipitation fairly well, especially over the Pacific Ocean. Therefore, it appears to be a good tool to study the non-linearities in these responses.
4.2 Differences due to EP and CP forcing patterns

The influence of the different forcing patterns, EP and CP, can be estimated by analyzing the differences in the response for the sensitivity experiments with the same sign of forcing and the same strength in the forcing. This is shown in Figs. 6g and 6h for SLP and 7g and 7h for precipitation. The results show that the patterns of the forcings in the tropical Pacific have strong influences on the SLP response over most of the globe. The CP forcing has a much stronger influence over the North and South Pacific for both positive and negative forcings. Also, a small positive response is found over the Indian Ocean only for the CP forcings, especially with positive sign. The main structure may largely be characterized as a westward shift in the tropics for a CP forcing relative to the EP forcing. Thus, the CP forcing has stronger influence on the western tropical Pacific and the Indian Ocean and the EP forcing has a stronger impact on the eastern Pacific and the American Continents. The extra-tropical responses seem to somewhat follow this westward shift characteristics, but the structure is not as clear.

Even stronger differences in the responses to EP and CP forcings are found for precipitation (Fig. 7). Especially for positive forcings a much stronger response is found in the Pacific along the equator and north of the equator for EP forcings. For the CP+ forcing no rainfall response is found over the far eastern equatorial Pacific. On the other hand CP events have a much stronger influence on the Pacific south of the equator. A band of enhanced (reduced) precipitation extends from the central equatorial Pacific to the South-East Pacific for positive (negative) events. The strength of the differences between EP and CP forcings, however, also depends strongly on the sign of the forcings. Again, the main large-
scale structure is a westward shift in the tropics for a CP forcing relative to the EP forcing. The extra-tropical response, however, does not appear to have a simple westward shift following the change in forcing pattern.

4.3 Differences due to the forcing strengths and signs

Figures 6c and 6f show the differences between the SLP responses to positive and negative forcings. In both cases the difference pattern is similar to the positive (El Niño) forcing responses, which suggests stronger responses to positive forcings than to negative forcings over most regions. The differences are mostly stronger for the EP pattern than for the CP pattern. For precipitation (Figs. 7c and 7f) the response to positive forcing is much stronger than the response to negative forcing over the equatorial Pacific, as was expected. Again, the difference is stronger for EP forcings.

Figure 8 shows the different SLP responses to different strengths and signs of forcings. The EP and CP -200% experiments represent the cases where the mean SSTs are the coldest and the +200% experiments where they are the warmest. Thus, the experiments in this figure are organized by coldest (bottom) to warmest (top). Again, as all responses are normalized by the NINO3.4 SST anomalies, a linear response should result in all responses being the same. To first order, we can note that for both EP and CP forcing the strength of the response increases with the overall warming of the SST. In particular, the SLP response in the North Pacific in the EP+ case is highly non-linear. This result is in good agreement with Hoerling et al. (2001), who found a stronger winter-time atmospheric circulation response over the North Pacific for El Niño than for La
Niña events, which was only evident for strong events. However, some regions
do not quite follow this simple principle. The tropical Indian Ocean response to
the CP forcing, for instance, is not just increasing with the warming of the SST. In
general, the CP pattern does not show as clear an increase in response as the EP
pattern.

Figure 9 shows the precipitation response to different strengths and signs of
forcings. As expected, the rainfall response in the tropical Pacific is highly non-
linear. For both EP and CP events the relatively weakest response is found for
the negative 200% experiments and the strongest for the positive 200%
experiments. The non-linearities are stronger for positive than for negative
forcings and stronger for EP than for CP events. A remarkable non-linearity is
seen in the precipitation response over Northern Africa and the Arabian
Peninsula for both the EP and CP forcing. Here, it changes sign in the normalized
response pattern from negative to positive, which means that the precipitation
response is the same for El Niño as for La Niña events. There are no indications
of this non-linearity in the observed precipitation response, but the observed
SLP response does show some weak indication of such a non-linearity.

4.4 Combined effects

In the above analysis sections we concluded that different grades of non-linearity
are found in different regions. To get a better understanding of the different
effects of the patterns, strengths and signs of ENSO events we now focus on a
number of different regions: the Tropical East Pacific (TEP) (75-110°W, 20°S-
10°N), the Tropical West Pacific (TWP) (120-170°E, 15°S-15°N), the North
Pacific (NP) (135-180°W, 35-60°N), and the Tropical Indian Ocean (TIO) (60-110°E, 20°S-10°N). Since the non-linearities in the precipitation response in the tropical Pacific are somewhat expected, and the responses outside the tropical Pacific are of limited confidence, we are focusing on the SLP response in the following section and analyze this in more detail. See Figure 10 for the SLP response to the EP, CP and a realistic combined forcing. The realistic combined forcing is a linear combination of the EP and CP forcings and represents what is most closely matching the observed. Dommenget et al. (2013) show that strong positive ENSO events in general have an EP pattern while strong negative events have a CP pattern and vice versa for weak events (see also Section 2 and Figure 2). Therefore, in the response to ‘realistic combined forcings’ we combine the responses for 200% CP-, 50% EP- forcing, 50% CP+ forcing, and 200% EP+ forcing and assume that the 100% events can be either EP or CP forcing and thus take their average responses. To quantify the linearity or non-linearity of the responses, we fitted a linear and a quadratic curve to the data points represented by the mean responses.

In the TEP region the response to either an EP or a CP forcing is linear (Fig. 10a and 10b). In the TWP the response is non-linear for both forcing patterns with a slightly stronger non-linearity for the EP forcing pattern (Fig. 10d and 10e). For the NP strong non-linear responses are found for both forcing patterns (Fig 10g and 10h). However, here the spread is also wider. For the TIO the overall responses are small compared to the other regions, but a slightly non-linear response is found for the CP forcing (Fig. 10j and 10k). If we combine the different forcing patterns to the realistic forcing, we get a very different picture. Over the TEP, where the response to both forcing patterns is linear, we get an
indication of a non-linear response with the realistic forcings (Fig. 10c). This is due to the difference in strength of the responses to EP and CP patterns. The stronger response to the EP pattern gives a stronger than linear response for the +200% and -50% cases and the weaker CP response gives a weaker than linear response for the -200% and +50% cases. Combined this gives a near quadratic response function with larger response for strong positive (El Niño) events and weaker response for strong negative (La Niña) events.

The opposite is true for the NP region. Both the EP and the CP forcings show a strong non-linearity. However, in the realistic forcings the non-linearities cancel each other and lead to a linear response (Fig. 10i). Again, this is due to the difference in strength of the responses to the EP and CP patterns, which, when combined, lead to a linear response. In the TIO region the combined response is a significant non-linear response, which even reverses sign, leading to negative SLP responses for both El Niño and La Niña events (Fig. 10i). Again, this is a combination of a weak response to the EP pattern and a strong response to the CP pattern. In the TWP region all responses are similarly weakly non-linear, no matter whether we consider EP, CP or the combined.

Another way to visualize the non-linearity is to look at histograms of SLP responses over NINO3.4 SST anomalies using the fitted quadratic response functions shown in Fig. 10. Therefore, we drew normally distributed random NINO3.4 SST anomalies (10^4) with the observed NINO3.4 SST standard deviation and calculated the SLP responses according to the quadratic fits described above. The resulting SLP histograms with the standard deviation, skewness and kurtosis can be seen in Fig. 11.
In all four regions the SLP variability in response to the combined CP and EP forcings is less than the observed variability. However, in the TWP and TEP regions a significant part of the total SLP variability can be attributed to the response to SST variability. Especially in the TWP region this simple model reproduces the observed variability and non-linearity in the SLP distribution quite well. This, first of all, illustrates that the SLP response to the SST anomalies is a significant part of the total SLP variability in this region. In the TEP region, however, the simple model overestimates the skewness. In the NP and TIO regions the ENSO model related SLP distributions are much narrower than the observed, which illustrates that the observed SLP variability is not dominated by the ENSO response.

So far, we only looked at the mean response in four specific regions. However, it is interesting to look at a global distribution of ENSO SLP response non-linearity. Therefore, we calculated the mean response and its spread for each point and performed the same linear and quadratic fits as above for each point. Figure 12 shows the estimated t-values for the CP, EP and the combined SLP response for deviations from a linear response model. For all three forcings the t-values for the quadratic fits are very small (not shown) while the t-values for the linear fit are quite significant in several regions indicating strong non-linearities. For a CP forcing only weak non-linearities are found in most of the Pacific basin. The strongest non-linearity is found over the far western tropical Pacific. Also, in the eastern North and tropical Pacific north of the equator non-linearities are found. Non-linearities are also found over South America and the whole tropical Atlantic. However, there the response itself was very small. For the EP forcing the non-linearity in the Pacific basin is much stronger. Again, the strongest non-
linearity is found over the western tropical Pacific and the maritime continent. Also, the North Pacific, the eastern tropical Pacific north and south of the equator, the tropical continents, and the tropical Atlantic non-linearities are found. If we combine the different forcings to the realistic forcings we find the strongest non-linearities. We find strong non-linearities over the central to western tropical Pacific and the far eastern tropical Pacific. Also, non-linearities are found over central America, the tropical Atlantic, central to south Africa, the Indian Ocean and the South Pacific. Again, we also find that the combined realistic response has a near linear response in the northern North Pacific in contrast to the EP and CP forcing, which are both non-linear.

5. Summary and Discussion

In the study presented here we analyzed the non-linearity in the ENSO teleconnections based on observations and model simulations. We were not only interested in the differences between strong El Niño and La Niña events but also in the influences of the different factors pattern, strength and sign of the SST forcing. Therefore, we performed idealized model experiments, in which we forced a full complexity atmospheric GCM with standardized ENSO patterns of different signs and strengths. Although the observational database for composites of strong El Niño and La Niña events is very small, we can see that there are significant non-linearities in the SLP and precipitation responses. The model simulations reproduce the SLP and precipitation response patterns quite well, especially over the Pacific Ocean.
The SLP response shows strong non-linearities in the tropical Pacific and throughout the whole tropics and subtropics. In most regions the main characteristic of the SLP response per unit SST anomaly is that it is stronger for warmer SST anomalies. This is similar to the non-linearities found in the zonal wind and SST interactions in the tropical Pacific (e.g. Kang and Kug 2002; Philip and van Oldenborgh 2009; Frauen and Dommengen 2010; Dommengen et al. 2013) and the non-linearities found by Bayr et al. (2013) in the Walker Circulation response. In the literature so far there has been no physical explanation given for why we see a stronger atmospheric circulation response for warmer SST anomalies of ENSO. However, it is plausible to assume that this is related to the non-linearities associated with the moist convection intensities. These are to a large part controlled by the Clausius–Clapeyron relationship, which allows for stronger atmospheric circulation responses for warmer SSTs due to non-linear increases in saturated water vapor levels. However, it is beyond this study to support this link in physical processes.

The non-linearities in precipitation are mostly confined to the tropical Pacific and to the largest part follow from the basic non-linearities that we see for the precipitation distributions in general. The shifts that we find in the tropical Pacific are consistent with those found by Chung et al. (2013) and Power et al. (2013).

Studying the combined influence of the pattern, strength, and the sign of the event shows that each component plays a role for the non-linearities. For SLP it can be seen that the non-linearity is stronger for an EP forcing pattern than for a CP forcing pattern. If we take into account that strong positive events generally have an EP pattern and strong negative events a CP pattern (and vice versa for
weak events), and combine the responses accordingly, we find overall the
strongest non-linearities. However, this has different effects over different
regions. Over regions like the far eastern tropical Pacific the response to each
forcing pattern separately is mostly linear. When we combine the forcings
realistically, we find a strong non-linearity. The opposite is true for the North
Pacific, where the response to each pattern separately is non-linear. In the
realistic combination of the responses, however, the non-linearities cancel each
other and the response is linear.

The main conclusion of our work, therefore, is that the linearity or non-linearity
of ENSO teleconnections results from a combination of a linear response to a
spatially non-linear ENSO (varying ENSO patterns) and a non-linear response to
a linear ENSO (fixed patterns but varying signs and strengths). For the analysis
of ENSO teleconnections, especially also in fully coupled GCMs and future climate
projections, it is not sufficient to build composites based on the sign of events.
Also, for models to realistically simulate ENSO teleconnections it is important to
realistically simulate not only the amplitude of events but also the different
patterns of events.

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Computational Infrastructure in Canberra.
References


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**Table 1:** Overview of simulations performed: NINO3.4 SST anomaly of the prescribed patterns and lengths of the simulations.
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Figure 2: Scatter plot of observed tropical Pacific SST anomalies PC-1 and PC-2 data pairs (black dots) with a quadratic fit (red line) after Dommenget et al. (2013). Superimposed are the typical SST anomaly patterns relating to the different regimes. Next to the axes are the EOF patterns associated with the respective PCs.

Figure 3: Skewness of observed monthly mean a) SST anomalies [K], b) SLP anomalies [hPa], and c) precipitation anomalies [mm/day]. Note the different color bar for precipitation.

Figure 4: Composites of observed mean SLP anomalies during a) El Niño events and b) La Niña events normalized by the NINO3.4 SST anomalies. El Niño (La Niña) events are defined as months with PC_{El-Niño} ≥ 1.0 (PC_{La-Niña} ≤ -1.0). In c) the difference between the response patterns a)-b) is shown. Units are [hPa/K]. d) shows the Students t-values for the difference in c) scaled by the factor 1/3.

Figure 5: Same as Fig. 4 but for observed mean precipitation anomalies per climatological precipitation (value of 0.5 means the precipitation anomaly is 50% of the climatological precipitation) normalized by the NINO3.4 SST anomalies. Please note the non-linear color bar for a)-c). Units are [%/K].
**Figure 6:** SLP response patterns from a) the EP+ 100% experiment, b) the EP-100% experiment, d) the CP+ 100% experiment, and e) the CP- 100% experiment normalized by the NINO3.4 SST anomalies. Further, the differences between c) EP+ - EP-, f) CP+ - CP-, g) EP+ - CP+, h) EP- - CP-, and i) EP+ - CP-. All differences are statistically significant at 90% level following a Students t-test.

Units are [hPa/K].

**Figure 7:** Same as Fig. 6 but for mean precipitation anomalies per climatological precipitation. Again the responses are normalized by the NINO3.4 SST anomalies. Units are [%/K].

**Figure 8:** SLP response patterns for the a) CP+ 200%, b) EP+ 200%, c) CP+100%, d) EP+ 100%, e) CP+ 50%, f) EP+ 50%, g) CP- 50%, h) EP- 50%, i) CP-100%, j) EP- 100%, k) CP- 200%, and l) EP- 200% experiments normalized by the NINO3.4 SST anomalies. Units are [hPa/K].

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**Figure 10:** Summarized SLP responses to CP forcings (blue), EP forcings (red) and combined forcings (black) for a)-c) Tropical East Pacific, d)-f) Tropical West Pacific, g)-i) North Pacific, and j)-l) Tropical Indian Ocean. The crosses indicate the mean SLP response, the error bars indicate one standard error, the dashed lines represent a linear fit, and the solid lines a quadratic fit. For the combined forcings the color of the crosses indicates the type of forcing (blue = CP forcing, red = EP forcing, magenta = CP and EP forcing).
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**Figure 12:** Estimated t-values for the deviations of the SLP responses from a linear fit (dashed lines in Fig. 10) for a) CP forcings, b) EP forcings and c) combined forcings.
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