Asymmetry in the response of eastern Australia extreme rainfall to low-frequency Pacific variability

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[1] This study investigates relationships between variability in the Pacific and extreme rainfall in eastern Australia. Using an index of extreme precipitation derived from a daily gridded precipitation data set from 1900 to 2011, we find that a nonlinear relationship between El Niño–Southern Oscillation and extreme rainfall exists. That is, the strength of a La Niña episode has a much greater influence on the intensity and duration of extreme rainfall than the magnitude of an El Niño episode. This relationship is found in both interpolated observations and reanalysis data and may be explained, in part, by shifts in the divergence of moisture flux. There is significant decadal variability in the relationship, such that the asymmetry is enhanced during Interdecadal Pacific Oscillation (IPO)–negative events and is nonexistent during IPO-positive phases. This information has the potential to be of great use in the seasonal prediction of intense rainfall events that lead to flooding. Citation: King, A. D., L. V. Alexander, and M. G. Donat (2013), Asymmetry in the response of eastern Australia extreme rainfall to low-frequency Pacific variability, Geophys. Res. Lett., 40, doi:10.1002/grl.50427.

1. Introduction

[2] Eastern Australia is often subjected to extreme rainfall that can lead to flooding events. In the austral summer of 2010–2011, much of Queensland was affected by severe flooding as a result of unusually large amounts of rainfall. This event, and other flooding episodes in this region, coincided with strong La Niña conditions. Interannual variability in precipitation in eastern Australia is strongly related to the El Niño–Southern Oscillation (ENSO). Put et al. [2012] concluded that ENSO is the major driver of rainfall variability on subdaily time scales in eastern Australia. The Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM) have been also shown to affect rainfall variability in this region. Both IOD and SAM have observed relationships with rainfall in inland areas of eastern Australia [Gallant et al., 2012], and their effects may be part of the cause of noise in the ENSO-rainfall relationship [Gallant and Karoly, 2009]. Spring rainfall is increased in SE Australia in IOD-negative phases, although the negative phase of the IOD is often coincident with La Niña events [Meyers et al., 2007]. Cai et al. [2012] suggested that asymmetry in the ENSO-IOD pathway and its teleconnections causes the positive IOD phase to have a greater impact on Australian climate. The positive IOD phase gives rise to drought conditions in the southeast of the continent [Ummenhofer et al., 2009; Ummenhofer et al., 2011]. SAM influences spring rainfall in eastern Australia [Risbey et al., 2009]. The positive phase of SAM promotes onshore moist flow in New South Wales and Queensland and is associated with an increase in rainfall totals. However, SAM only has a limited effect in modifying the teleconnection pattern between ENSO and Australian climate [Cai and van Rensch, 2012a]. While this study focuses on the effect of ENSO on extreme rainfall variability, the authors acknowledge that IOD and SAM likely have some impact also.

[3] An asymmetric relationship has been observed between ENSO and precipitation in the whole of Australia [Power et al., 2006] and specifically in southeast Queensland [Cai et al., 2010] with changes in the South Pacific Convergence Zone (SPCZ) posed as the cause. The strength of El Niño events has little effect on precipitation across a season, whereas the magnitude of La Niña events seems to play a major role. Extreme rainfall events are those that have the greatest impact on society and the environment; therefore, gaining an understanding of the effect ENSO has on extreme rainfall would be of great use in improving the understanding and predictability of major flood events.

[4] Sea surface temperature (SST) variability in the Pacific on multidecadal time scales is represented by the Interdecadal Pacific Oscillation (IPO), similar to the Pacific Decadal Oscillation (PDO). The SST signatures related with each IPO phase are similar to those seen during ENSO events, although with anomalies extending further into the extratropical Pacific. Previous work has demonstrated the effects of the IPO on Australian rainfall and the teleconnection between ENSO and Australian rainfall [Power et al., 1999]. During IPO-negative (La Niña–like) periods, the asymmetry between ENSO and precipitation is strong, whereas in IPO-positive (El Niño–like) periods, the relationship breaks down and becomes insignificant. Previous studies have found relationships between the IPO and Victorian streamflow [Kiem and Verdon-Kidd, 2009] and flood risk in New South Wales [Kiem et al., 2003; Verdon et al., 2004]. Rainfall variability in Queensland is driven by both ENSO and the IPO [Cai and van Rensch, 2012b; Klingaman et al., 2012]. Whether the IPO has an influence on extreme rainfall events across eastern Australia remains to be seen. If such a relationship exists, knowledge of the phase of the IPO could provide additional predictability for heavy rain and flood events across Queensland, New South Wales, and Victoria.
[5] Atmospheric reanalysis is often useful in examining the physical mechanisms behind observed relationships, as it provides physically consistent assimilated fields of a range of atmospheric variables. However, assessing whether a reanalysis product captures any observed ENSO-extreme rainfall relationship is key to determining whether such mechanisms are well captured. Therefore, we examine whether the Twentieth Century Reanalysis (20CR) [Compo et al., 2011] resembles the observed relationships before applying it to investigating mechanisms to explain our findings.

[6] The data and methods used in this study are described in section 2. In section 3, the ENSO-extreme rainfall relationship in eastern Australia and the effect of the IPO are examined. The results found with the reanalysis data are discussed in section 4. Discussion and conclusions are presented in section 5.

2. Data and Methods

[7] We use the Australian Water Availability Project (AWAP) gridded data set of daily rainfall observations [Jones et al., 2009], regridded to 0.5° resolution, to investigate extreme precipitation. AWAP contains data from 1900 to present, and we use data up to 2011 for our analyses. The focus of this study is on a broad area of eastern Australia shown as the boxed region in Figure 1a. Analysis was also conducted over a smaller area covering southeast Queensland and northeast New South Wales; however, the results were largely similar and less significant. Previous validation of AWAP against high-quality station observations has shown that the gridded data set captures the typical characteristics of extreme rainfall in eastern Australia [King et al., 2012]. AWAP tends to underestimate the intensity of extreme rain events; however, it does capture the variability in extremes, allowing it to be used in climate variability studies such as this one.

[8] Extreme rainfall may be defined in a number of different ways depending on the application being considered. In this study, we examine extreme rainfall in AWAP using the maximum consecutive 5 day rainfall (Rx5day). This is one of the indices recommended by the Commission for Climatology (CCl)/Climate Variability and Predictability/Joint Technical Commission for Oceanography and Marine Meteorology Expert Team on Climate Change Detection and Indices (see http://www.clivar.org组织/etccdi/etccdi.php for more details) [Zhang et al., 2011]. Rx5day values are averaged across eastern Australia to generate values shown on scatterplots.

[9] Indices representing Pacific interannual and multidecadal variability were required. The Southern Oscillation Index (SOI) is used to represent ENSO and is calculated as the difference in standardized pressure between Tahiti and Darwin. Results with SST-based indices, such as the Niño-3.4 index, were also analyzed (not shown) and produced similar, but weaker, results. For the purposes of this study, we define seasons where the SOI is positive as La Niña- and SOI-negative seasons as El Niño. The IPO index [Parker et al., 2007] is derived from the HadSST2 data set [Rayner et al., 2006] with an 11 year Chebyshev filter applied. Due to the 11 year averaging, no IPO values for the most recent years are available, and the later years in the data set are subject to change. For the purposes of this study, only the sign of the IPO is of importance. From 2000 to 2008, the index has negative values. Also, Cai and van Rensch [2012b] found evidence that the wet 2010–2011 summer in Queensland confirms a transition toward the negative phase of the PDO-IPO (similar to the IPO). For these reasons, the IPO is assumed to remain in a negative phase from 2008 to 2011.

[10] Analysis is conducted for the period 1900–2011. The SOI is detrended in all cases. Detrending the extreme rainfall indices had little effect on the results. For the purposes of this study, the results are shown without removing the trend from Rx5day. Rx5day was compared with SOI over different seasons; here results are shown for October–March with the corresponding October–March SOI and IPO index also used. Lag correlations tended to be less significant than concurrent correlations, so these are not shown.

[11] The Twentieth Century Reanalysis (20CR) for 1900–2008 is used to complement the AWAP (i.e., interpolated observations) study to investigate mechanisms behind the observed relationships as it provides physically consistent fields of meteorological parameters. The reanalysis has been formed by assimilating observed surface pressure, SSTs, and sea ice into an atmospheric model at T62 (roughly 1.9°) resolution. The 20CR ensemble contains 56 individual members created using an ensemble Kalman filter data-assimilation technique. The SOI was calculated for each ensemble member using the same method as for the observed SOI. The sea level pressure values in each of the gridboxes in which Tahiti and Darwin are located are used for this calculation. Rx5day was also calculated from the 20CR for all 56 individual ensemble members for the gridboxes that most closely match the domain used previously for the observation-based data. Scatterplots of the SOI against Rx5day were produced for each of the 56 ensemble members separately and for all members together. An analysis of the ENSO-extreme rainfall relationship was also conducted for IPO-positive and IPO-negative periods separately. For studying the mechanisms involved in the ENSO-extreme rainfall relationship, several monthly ensemble mean fields from the 20CR were analyzed. The outgoing longwave radiation (OLR) field was examined, and fields of specific humidity, zonal, and meridional winds were used to calculate fields of moisture flux and moisture flux divergence. These fields were examined for different ENSO and IPO phases and correlated with the SOI and IPO indices.

[12] Similar to Cai et al. [2010] and Cai and van Rensch [2012b], scatterplots are produced with statistical tests on El Niño and La Niña values of SOI performed separately. Lines of best fit, using ordinary least squares regression, are plotted on all scatterplots for El Niño and La Niña values of SOI separately with the gradient given. The Spearman’s rank correlation coefficients and p values for statistical significance of linear fits are also calculated. Only very small differences were found in correlation coefficients through the use of different methods. A significance level of 5% was chosen for deciding whether a given relationship was significant or not.

3. Extreme Rainfall in Relation to Pacific Variability

[13] Correlation coefficients between SOI and Rx5day during October–March (Figure 1a) are positive across most of eastern Australia and significant across large areas. In La Niña seasons, there is greater extreme rainfall than in El Niño seasons. Stronger La Niña events are usually
associated with larger values of Rx5day (Figure 1b), with positive, statistically significant correlations. Correlations in El Niño seasons are comparatively small and nonsignificant. These results agree well with Cai and van Rensch [2012b], who assessed summer season total rainfall anomalies in SE Queensland. We have extended this to show that the relationship holds for a much larger area and specifically for extreme rainfall events.

The 2009–2010 season stands out as having the greatest Rx5day value for a strong El Niño season. The three strongest La Niña seasons (1973–1974, 1975–1976, and 2010–2011) also have the largest values of 5 day precipitation accumulations. The 1973–1974 season has the highest Rx5day value in the October–March period over the 111 year series. While the 2010–2011 season was the strongest La Niña in the series (measured by SOI), the Rx5day value was lower than those of 1973–1974 and 1975–1976, suggesting that the recent heavy rainfalls were not without precedent when averaged over the whole of eastern Australia. Conducting the same analysis over a smaller area (southeast Queensland and northeast New South Wales) showed that the 2010–2011 values of this index were lower than those seen during many other seasons also. Although the extreme rainfall of 2010–2011 led to disastrous flooding, this analysis suggests that other strong La Niña seasons have led to similarly intense rainfall previously.

[15] Extreme rainfall in eastern Australia may also be influenced by variability in the Pacific Ocean on longer time scales. To determine whether the IPO has an effect on the asymmetric ENSO-extreme rainfall teleconnection, the relationship between SOI and Rx5day was determined separately for IPO-positive and IPO-negative seasons (Figures 1c and 1d). During the IPO-negative (La Niña–like) phases (Figure 1c), the magnitude of La Niña events is observed to strongly influence extreme rainfall with large slope values and a correlation of 0.65. In El Niño seasons, there appears to be a weaker relationship where stronger El Niño events have smaller values of maximum 5 day rainfall totals. This relationship is significant (p value < 0.05) if 2009–2010 is removed from the analysis. In IPO-positive (El Niño–like) seasons (Figure 1d), there are no statistically significant relationships between ENSO and Rx5day. The results presented here provide further evidence of the IPO influence on the
climate of eastern Australia. Cai and van Rensch [2012b] observed a PDO-IPO effect on the ENSO-rainfall relationship in SE Queensland but with a much smaller data sample.

There are stronger La Niña events in the IPO-negative periods, so to ascertain whether the IPO is only influencing ENSO, or if it is affecting the teleconnection itself, further analysis is required. The relationship between ENSO and extreme precipitation was also tested only for IPO-negative La Niña seasons where the SOI was less than the maximum SOI during IPO-positive seasons, so as to remove the effects of strong La Niña events (not shown). The slopes of best fit lines were reduced, but correlations remained significant despite the reduction in sample size. These results provide strong evidence that the IPO influences both ENSO itself and the ENSO-extreme rainfall teleconnection and could aid in the prediction of extreme rainfall events.

4. Asymmetric Relationship in the Twentieth Century Reanalysis

To facilitate investigation of mechanisms related to the extreme rainfall response in eastern Australia to ENSO and the IPO, we examine these relationships using the output from the 56 ensemble members in the 20CR. There is good correspondence between the observed SOI and the SOI in each ensemble member’s reanalysis with correlations in excess of 0.6 for all members for 1900–2008. The correlation between the observed SOI and the ensemble mean SOI is 0.69. As expected, given the increasing density in the observational network assimilated into the 20CR, there is a decrease in spread in the SOI between individual ensemble members through the period (Figure 2a).

The ENSO-extreme rainfall relationship is then examined using Rx5day calculated from the reanalysis for all ensemble members (Figure 2b). The asymmetric ENSO-extreme rainfall relationship is captured by reanalysis despite missing the recent strong El Niño (2009–2010) and La Niña (2010–2011) episodes. All members have statistically significant relationships in La Niña seasons and nonsignificant relationships in El Niño seasons. There is some spread between ensemble members and differences in whether a particular season is classified as El Niño or La Niña. This is demonstrated by crosses that are long in the horizontal and cross the dashed line where SOI is equal to zero. The IPO modulation of this relationship is also seen in the reanalysis (Figures 2c and 2d) although not necessarily in all members. Out of the 56 ensemble members, 44 have significant relationships in IPO-negative La Niña seasons [where the observation-based relationship is strongly significant (Figure 2c)]. Also, in IPO-positive La Niña seasons, the relationship is significant in 16 members, where the observation-based statistical relationship is nonsignificant (Figure 2d).

The ability of the reanalysis to capture the observation-based ENSO-extreme rainfall asymmetry suggests that large-scale mechanisms are the cause of it. Previous discussions...
on the mechanism behind the observed asymmetry between ENSO and seasonal rainfall have focused on the South Pacific Convergence Zone (SPCZ) shifting to enhance convection across eastern Australia in La Niña events and suppress convection during El Niño [Power et al., 2006; Cai et al., 2010]. Cai and van Rensch [2012b] found evidence of a shift in the ENSO-precipitation relationship between the most recent IPO-positive and IPO-negative phases using fields of

Figure 3. (a) Map showing average October–March moisture flux divergence at 1000 hPa in the 20CR. Maps of correlation coefficients between SOI and moisture flux divergence at 1000 hPa in (b) La Niña seasons and (c) El Niño seasons. Stippling shows statistical significance at the 5% level.
OLR and SSTs. In order to investigate further and for a longer period, we examine fields of OLR, moisture flux, and moisture flux divergence for 1900–2008 using the 20CR. Fields of these variables for individual members of the ensemble were not available, so the ensemble mean fields are used here. Common patterns emerge when analyzing composites of these three fields for different ENSO and IPO phases.

20 During La Niña seasons, there is evidence of enhanced convection in eastern Australia and vice versa for El Niño seasons based on OLR (not shown). Also, there is multidecadal modulation of convection in eastern Australia associated with the IPO (not shown). The cause of the asymmetry in the ENSO-extreme rainfall relationship is less clear. However, there is some evidence for a local change in convective activity. On average, there is near-surface moisture flux convergence across most of Queensland and weak divergence in southeast Australia (Figure 3a). The correlation between moisture flux divergence and SOI in La Niña seasons only (Figure 3b) tends to be significantly negative in inland eastern Australia. This means that in stronger La Niña seasons, more moisture is transported into the region as opposed to in weaker La Niña seasons. In El Niño seasons only (Figure 3c), correlation coefficients between SOI and moisture flux divergence are generally positive and significant in southeast Australia. Given that the occurrence of rainfall is more strongly related to convergence than divergence, and that, on average, there is divergence in the southeast of Australia, the relationship in La Niña seasons is likely to be of greater importance than that observed in El Niño seasons. We suggest that this result may provide some physical basis for the ENSO-extreme rainfall asymmetry. We stress that further investigation into the physical mechanisms at work is required before firmer conclusions may be drawn. However, from analyzing 20CR fields, it seems that local changes in convective activity may be the primary cause of the asymmetry. These local changes may be as a result of the teleconnections to the SPCZ and its movements.

5. Discussion and Conclusions

21 This study has shown that the previously known asymmetry in the ENSO-rainfall teleconnection in eastern Australia can be extended to extreme rainfall also. While this result might not be surprising, as rainfall and extreme rainfall are not necessarily independent of each other, it nonetheless adds an important extra dimension to our knowledge of the influence of ENSO on Australian climate. The magnitude of La Niña events has an influence on extreme rainfall intensity, while the strength of an El Niño event has no significant effect. This extends to other extreme rainfall indices representing different aspects of extreme rainfall, such as frequency and duration (not shown). However, the maximum number of consecutive dry days in a year has a more linear relationship with annual SOI, and the strengths of El Niño and La Niña events are both of importance.

22 Given that the 20CR captures the observed asymmetry in the ENSO-Rx5day relationship, a large-scale mechanism is likely to be the cause. This suggests that the 20CR may be used to examine potential mechanisms to explain the asymmetric relationship. There is strong evidence for enhanced convective activity in eastern Australia during La Niña seasons as opposed to El Niño seasons, and this may be related to movements in the SPCZ. The ENSO-extreme rainfall asymmetry, however, seems to be most closely related to local enhancements of near-surface moisture flux convergence in stronger La Niña seasons as opposed to in weaker La Niña seasons. Cai et al. [2012] suggested that in La Niña seasons, the Pacific-South America pattern, an equivalent barotropic Rossby wave train emanating from the tropical Pacific, impacts upon the eastern seaboard of Australia. However, this does not explain the strong observed relationships that extend into the inland areas of SE Australia. Further investigation into the cause of the ENSO-extreme rainfall teleconnection is required.

23 Our results also indicate strong interdecadal modulation of the ENSO-extreme rainfall teleconnection related to the IPO. IPO-negative phases accompany significant relationships between the strength of La Niña events and extreme rainfall in eastern Australia. In El Niño seasons, there is some indication of a similar relationship during IPO-negative years; however, further investigation is required to establish the validity of this relationship. During IPO-positive phases, these relationships break down during both El Niño and La Niña seasons. Again, this interdecadal modulation is captured in the reanalysis to some degree.

24 The IPO plays a large role in the frequency of major flood events in eastern Australia with those during the 1950s, 1970s, and 2010–2011 all occurring while the IPO has been in its negative (more La Niña–like) phase. Very intense rainfalls in eastern Australia that lead to severe flood events are often associated with strong La Niña seasons. Given that the IPO is likely to be in its negative phase, it is possible that there will be further strong La Niña events in the coming years. Therefore, there is an increased likelihood of major flood events occurring in this region while the IPO remains in its negative phase. It is worth noting, however, that the IPO has limited predictability, and its state at any present time is unknown due to the way it is calculated. This work has shown that the states of ENSO and, to a lesser degree, the IPO provide predictability of extreme rainfall events that lead to the most devastating floods.

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References


