Supporting Information for "How did ocean warming affect Australian rainfall extremes during the 2010/11 La Niña event?"

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Text S1. Australian soil moisture and runoff conditions during 2010/11

The relative soil moisture in the Australian Water Availability Product (AWAP) is defined as a fraction of the saturated water-holding capacity of the soil examined in upper and lower soil layers with spatially-varying thicknesses ranging between 0.08m and 0.7m (upper) and 0.5 and 1.9m (lower). Discharge corresponds to catchment outflow (surface runoff + deep drainage), which compares well with independent stream gauge measurements for unimpaired catchments in our region of interest at monthly and longer timescales [Raupach et al., 2009].

The monthly evolution of hydroclimatic conditions across Australia during the period September 2010 to February 2011 shows co-variation of anomalies in precipitation and upper-level soil moisture, while the lower-level lags surface conditions by 2–3 months (Supplementary Fig. S2), a temporal delay consistent with Ummenhofer et al. [2011]. Only southwestern Australia exhibits dry conditions, most pronounced as lower-layer soil moisture deficit. The record precipitation conditions in the spring and summer 2010/11 also led to significant increases in discharge, especially over the northeast Australian coastal regions (Suppl. Fig. S3a). The discharge anomalies that occurred in 2010/11 lay within
the top 3.5% of all and 6% of La Niña years (Suppl. Fig. S3b).

Text S2. Regional climatic conditions during austral summer 1973/74

During 1973/73, northeast Australia experienced unusual wet conditions. Suppl. Fig. S4 shows the anomaly fields during the 1973/74 event for the September–February period. The 1973/74 event occurred during a strong La Niña, with an average September–February Southern Oscillation Index (SOI) value of 1.83 according to NOAA CPC data (http://www.cpc.ncep.noaa.gov/data/indices/soi.3m.txt) and thus only slightly weaker than the September–February SOI value of 2.15 during 2010/11. However, during January 1974, tropical cyclone (TC) Wanda made landfall north of Brisbane on a south-westerly track, also forcing a strong monsoonal trough towards the city; four days with intense rainfall ensued, making this a record wet January and the second wettest month ever recorded, saturating the catchment, resulting in the most severe example of urban flooding in Australia [van den Honert and McAneney, 2011], and leading to a rare flooding of Lake Eyre in the interior of the continent [Pook et al., 2014]. Rainfall during this previous event thus had a substantial contribution from a TC. Suppl. Fig. S5 provides SST anomalies and TC tracks for the South Pacific sector for the 1973/74 and 2010/11 summer seasons. While the SST anomaly patterns are similar for both years, the TC season was a lot more active over the Southwest Pacific in 1973/74 than in 2010/11. The intense monsoonal trough and associated moisture convergence and precipitation over the north and east of the country in 1973/74 are apparent in Suppl. Fig. S4a–c.
While the large-scale circulation anomalies during 1973/74 are reminiscent of those encountered in 2010/11, SST anomalies over the eastern Indian Ocean during 1973/74 exhibit a strongly enhanced meridional SST gradient (Suppl. Fig. S4e) that is not as well-developed in 2010/11 (Fig. 2e). The stronger meridional SST gradient contributes to enhanced westerly onshore moisture flux over northern Australia; the convergence over northern and eastern Australia in 1973/74 could thus have been amplified over the situation in 2010/11 potentially due to the unusual SST conditions in the eastern Indian Ocean, rather than to the warming north of Australia, which is greater in 2010/11: the SST to the north of Australia (in the box indicated) was 28.8°C in 1973/74 (compared to 29.3°C in 2010/11). As above, the role of TC Wanda in the extreme rainfall and extensive flooding in 1973/74 in the northeast cannot be discounted either. As such, the extreme wet conditions in 1973/74 are not inconsistent with the mechanism proposed here.

Text S3. Robustness of SST trends

The exact spatial pattern and magnitude of observed sea surface temperature (SST) trends is sensitive to the data set used and the analysis period, with less confidence in trends prior to 1950 [e.g., Hartmann et al., 2013, and references therein]. An assessment of the SST trend patterns and magnitude used here for the period 1951–2009 versus the period 1951–2010 to the inclusion of 2010 in the trend analysis indicates that the difference is negligible (figure not shown).

Tokinaga et al. [2012] compared SST trends for the period 1950–2009 amongst a series of observational products, including ERSSTv3b, HadISST1, and different ICOADS SST data sets. They found that ERSST’s trend patterns were similar to those in HadISST and
ICOADS SST, exhibiting strong warming in the tropical Indian Ocean through the western Pacific, and in the central South Pacific [Tokinaga et al., 2012]. The trend in eastern tropical Pacific SST has been shown to diverge amongst different SST products, with a weak equatorial Pacific cooling observed in HadISST, while ERSST and the ICOADS SST feature a warming in the central and eastern equatorial Pacific [Tokinaga et al., 2012]. Previous studies suggested the blending of satellite SST in HadISST to be the main source of the SST trend difference in the equatorial eastern and central Pacific [Vecchi and Soden, 2007; Deser et al., 2010; Tokinaga et al., 2012]. Similarly, Cravatte et al. [2009] found consistent long-term warming in the western Pacific warm pool area, while trends in the central and eastern Pacific are less consistent. Intercomparison of 20th Century SST trends by Deser et al. [2010] revealed that the ERSSTv3b product used here exhibits realistic SST trends in line with uninterpolated and independent temperature measurements over the Indo-Pacific. Its use in the present study therefore is warranted.

Trends in SST are sometimes difficult to assess in light of natural variability on multi-decadal timescales, such as that associated with the Interdecadal Pacific Oscillation (IPO; or Pacific Decadal Oscillation). The pattern of change in Indo-Pacific SST is sensitive to the time period used to calculate the trend and how it relates to the IPO phase. Short-term SST trends of 20–30 year duration are affected by changes in the sign of the IPO phase [e.g., PCCSP, 2011, and references therein]. However, over the past 60 years – the analysis period in this study – changes in the sign of the IPO occurred in 1976/77 and in the early 2000s. As such, the beginning and end of the analysis period here both occur during a negative phase in the IPO. Natural multi-decadal SST variability in the
Indo-Pacific has contributed (and is likely to do so in future) to the overall SST change over past decades that influenced the 2010/11 background conditions. Given this, the focus here lies on assessing the physical mechanisms how the combined natural and anthropogenic long-term SST trend has contributed to the severity of the 2010/11 extreme hydroclimatic conditions in Australia.

**Text S4. Model skill in representing northeast Australian precipitation**

It is important to ascertain that the model has sufficient skill in representing regional precipitation characteristics and in particular teleconnections to the El Niño-Southern Oscillation (ENSO). Several previous studies [e.g., Taschetto et al., 2009, 2010, and references therein] explored links between equatorial Pacific SST and monsoon precipitation across northern Australia using atmospheric general circulation model (AGCM) experiments with the Community Atmosphere Model version 3 (CAM3) and it was shown to be skillful in representing Australian summer precipitation and links to ENSO. Taschetto et al. [2011] compared Australian precipitation and regional sea level pressure (SLP) in CAM3 to the observations (their Fig. 2). They found that the annual cycle of rainfall over northern Australia is slightly overestimated in CAM3 compared to observations. However, overall, CAM3 captures well the seasonality of precipitation and SLP, with the pressure trough and high rainfall intensities during the active monsoon season in the north, little rainfall in the south, and the high-pressure subtropical ridge over the southern half of Australia during austral winter.
For climate models participating in the Coupled Model Intercomparison Project version 3 (CMIP3), Cai et al. [2009] found a tendency to shift the ENSO-Australian rainfall teleconnections to the west, so Western Australia is erroneously more correlated to ENSO than eastern Australia. This is due to the cold tongue bias in the equatorial Pacific and a warm pool located too far west in coupled climate models [e.g., Taschetto et al., 2014, and references therein]. Therefore, use of an AGCM, as employed here, is an advantage, as the experimental design precludes a cold tongue bias. In a five-member ensemble hindcast with CAM3 for the period 1950–2006 [Taschetto et al., 2011], the spatial pattern and magnitude of rainfall anomalies during La Niña events for composites in the hindcast compare well with observed, with largest anomalies in the north and east of the country (Suppl. Fig. S6).

Here, we further assess these features specifically in the context of this study, focusing on northeast Australian precipitation (cf. region indicated in Fig. 1a) for the September–February months over the analysis period 1951–2009. To do this, in addition to the control simulation with repeating monthly climatology of global SST, we also conducted a hindcast simulation with interannually varying SST over the period 1951–2009. Precipitation over northeast Australia in this hindcast simulation that contains both the seasonal cycle and year-to-year variability (e.g., as associated with ENSO) is expected to more closely represent observed rainfall variability (cf. Fig. 1b). More specifically for northeast Australian precipitation, the frequency distribution for this hindcast ranges between 52 mm/month and 151 mm/month, with a mean of 89 mm/month (Suppl. Fig. S7). The simulated values in the hindcast compare to an observed mean of 74 mm/month, as well
as 32 mm/month and 164 mm/month as minimum and maximum (Table S1). As such, the mean simulated September–February precipitation in northeast Australia was higher in the hindcast than observed, while its distribution was somewhat narrower compared to observations, a characteristic often encountered in model simulations.

Given the focus of this study, the relative change in precipitation during La Niña events compared to all years represents a key diagnostic. In observations, northeast Australia experienced a precipitation increase of 21.3% averaged for all the La Niña years, while in the hindcast rainfall was only enhanced by 12.1%. However, when comparing the distribution of percentage changes in precipitation during the 16 La Niña years in observations and the hindcast simulation, no significant difference between the distributions (figure not shown) existed according to a Mann-Whitney test ($p=0.72$). This gives us confidence that the model exhibits sufficient skill in representing La Niña-teleconnections to northeast Australian precipitation, given that we assess relative changes in precipitation between two model experiments and the associated regional circulation anomalies.

References


Figure S1. Australian precipitation anomalies (mm/month) averaged for September 2010 to February 2011 relative to 1951–2009. Boxes delimit the study region in this (black) and previous studies (colored) as indicated.
Figure S2. Monthly observed regional climate anomalies for (a–f) SST (°C), (g–l) precipitation, (m–r) upper level and (s–x) lower level soil moisture anomalies for the period September 2010 to February 2011 relative to the analysis period 1951–2009. Dashed contours indicate anomalies significant at the 90% level.
Figure S3. (a) Australian discharge anomalies averaged for September 2010 to February 2011 relative to 1951–2009 for discharge (mm/month). Only anomalies significant at the 90% level according to a two-tailed student $t$-test are shown. (b) Frequency distribution of discharge over the box indicated in (a) for all years (black), La Niña years (blue), and 2010/11 (red).
Figure S4. Regional climate anomalies averaged for September 1973 to February 1974 relative to 1951–2009 for (a) AWAP precipitation (mm/month), (b) vertical velocity $\Omega$ (Pa/s), (c) 850 hPa moisture transport (kg/ms\(^{-1}\); vectors) and its divergence (s\(^{-1}\); colored), (d) SLP (hPa), and (e) SST ($^\circ$C). Dashed contours indicate anomalies significant at the 90% level according to a two-tailed student $t$-test.
Figure S5. September to February SST anomalies (colored) and TC tracks (black lines) for the 1973/74 and 2010/11 cyclone seasons. TC tracks are based on the IBTrACS database, with stars indicating demise of the TC.
Figure S6. Composite of La Niña September–February precipitation anomalies (mm/day) for (left) AWAP and (right) multi-ensemble mean of 1950–2006 AGCM hindcast simulations with CAM3. La Niña years based on Ummenhofer et al. [2011] and the zero contour is indicated in black.

Figure S7. Frequency distribution of precipitation spatially averaged over northeast Australia (region indicated in Fig. 1a) in (a) observations (AWAP) and (b) hindcast simulation for all years (black) and La Niña years (blue) for the September to February months for the period 1951–2009.
Table S1. Summary of northeast Australian precipitation (in mm/month) in the observations, hindcast simulation with interannually varying SST forcing, and control simulation with climatological SST forcing only. Also indicated is the average precipitation change for La Niña years (relative to all years) as a percentage.

<table>
<thead>
<tr>
<th></th>
<th>Mean (±SD)</th>
<th>Median</th>
<th>Minimum</th>
<th>Maximum</th>
<th>LN % change</th>
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<td>obs</td>
<td>73.7 (±21.9)</td>
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<td>32.4</td>
<td>164.3</td>
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<tr>
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<td>86.0</td>
<td>51.8</td>
<td>150.51</td>
<td>+12.1%</td>
</tr>
<tr>
<td>control</td>
<td>90.4 (±13.1)</td>
<td>89.1</td>
<td>59.0</td>
<td>119.0</td>
<td>–</td>
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