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- Surface ocean warming exacerbated Australian climate extremes in 2010/2011
- Dynamic and thermodynamic atmospheric changes contributed to Australian 2010/2011 extremes
- Ocean warming intensifies rain-producing atmospheric circulation conditions

Supporting Information:
- Texts S1–S4, Figures S1–S7, and Table S1

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How did ocean warming affect Australian rainfall extremes during the 2010/2011 La Niña event?

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Abstract Extreme rainfall conditions in Australia during the 2010/2011 La Niña resulted in devastating floods claiming 35 lives, causing billions of dollars in damages, and far-reaching impacts on global climate, including a significant drop in global sea level and record terrestrial carbon uptake. Northeast Australian 2010/2011 rainfall was 84% above average, unusual even for a strong La Niña, and soil moisture conditions were unprecedented since 1950. Here we demonstrate that the warmer background state increased the likelihood of the extreme rainfall response. Using atmospheric general circulation model experiments with 2010/2011 ocean conditions with and without long-term warming, we identify the mechanisms that increase the likelihood of extreme rainfall: additional ocean warming enhanced onshore moisture transport onto Australia and ascent and precipitation over the northeast. Our results highlight the role of long-term ocean warming for modifying rain-producing atmospheric circulation conditions, increasing the likelihood of extreme precipitation for Australia during future La Niña events.

1. Introduction

Droughts and floods are expected to become more frequent with an intensifying hydrological cycle in a warming world [*Held and Soden*, 2006; *Wentz et al.*, 2007; *Pall et al.*, 2011; *Hartmann et al.*, 2013; *Trenberth et al.*, 2015]. In particular, certain extreme events associated with the El Niño–Southern Oscillation (ENSO) are projected to become more frequent in a warming climate, with widespread consequences for associated Indo-Pacific hydroclimate [*Power et al.*, 2013; *Cai et al.*, 2014, 2015]. The La Niña event of 2010/2011 was exceptionally strong: the record Southern Oscillation Index value averaged for the 2010/2011 December–February months was unprecedented since at least 1876 when records began [*Cai and van Rensch*, 2012]. It was also associated with a series of extreme climatic events around the world, including droughts and heatwaves in Eurasia, especially Russia, extensive flooding in Pakistan [*Trenberth and Fasullo*, 2012], as well as Australia [*Cai and van Rensch*, 2012; *Evans and Boyer-Souchet*, 2012].

In Australia, the flooding in the northeastern state of Queensland in late 2010 and early 2011 followed the wettest austral spring since at least 1900, with spring rainfall averaged over the continent 25% above normal [*Hendon et al.*, 2014]. The precipitation and resultant hydrologic surface mass anomaly persisting in Australia's interior over the following months were so extensive that the global sea-level anomaly in 2011 was lowest since altimeter records began [*Fasullo et al.*, 2013], and record levels of terrestrial CO_2 uptake were driven by enhanced growth in Australia's semiarid vegetation [*Poulter et al.*, 2014].

In addition to the strong La Niña of 2010/2011, several other factors were implicated in the extreme hydroclimatic conditions in northeast Australia. *Cai and van Rensch* [2012] suggested that the recent transition to large-scale climatic conditions associated with the negative phase of the Interdecadal Pacific Oscillation (IPO; or Pacific Decadal Oscillation) led to a strengthening of the teleconnection between ENSO and northeast Australian precipitation, with an increased likelihood of La Niña events being associated with extreme wet conditions [*Power et al.*, 1999]. According to *Hendon et al.* [2014], an extreme positive excursion of the Southern Annular Mode (SAM) contributed 40% to the enhanced precipitation along the east Australian coastline during the record wet spring of 2010: the La Niña conditions induced a weakening of the subtropical jet and subsequent adiabatic warming in midlatitudes promoting development of a positive SAM [*Lim and Hendon*, 2015].

Evaluating the role of anthropogenic forcing for southeast Australian extreme rainfall in 2011/2012 in five climate models participating in the Coupled Model Intercomparison Project, phase 5, *King et al.* [2013] found no significant change in the risk of extreme precipitation over recent decades compared to the reference period at the end of the nineteenth century; instead, they attributed the unusual rainfall conditions to the strong, extended La Niña event. In contrast, for the unusual wet conditions in March 2012 across the eastern half of the Australian continent, *Christidis et al.* [2013] concluded that human influences increased the chances of above-average rainfall by 5–15%. *Lewis and Karoly* [2015] found the strong La Niña to be the dominant factor for wet conditions across eastern Australia in 2010/2011, while during 2011/2012 increasing greenhouse gas concentrations appeared to have contributed more to the probability of extreme seasonal rainfall. They also emphasized the model sensitivity of the results and that attribution statements were sensitive to the specific attribution parameters considered, including thresholds, regions and seasons [*Lewis and Karoly*, 2015]. Figure S1 in the supporting information summarizes the different regions addressed in these previous studies.

Using regional model simulations, *Evans and Boyer-Souchet* [2012] suggested that anomalously high sea surface temperatures (SSTs) north of Australia—in an area previously linked in observations to increased Australian precipitation during La Niña events since the 1970s [*Nicholls et al.*, 1996]—accounted for 25% of the extreme 10 day rainfall event in northeast Australia in late December 2010. However, the physical mechanisms for how long-term ocean warming can affect regional atmospheric circulation and Australian rainfall extremes during 2010/2011 remain poorly understood. The goal of this study is to explore the processes by which long-term ocean warming might have exacerbated rainfall extremes over northeast Australia during the summer of 2010/2011.

The 2010/2011 La Niña event was characterized by anomalously warm SST in the eastern tropical Indian Ocean and north of Australia. Over the past century, due primarily to anthropogenic climate change, ocean temperatures have warmed globally [*Rhein et al.*, 2013]. Warming has not been spatially uniform, with the Indo-Pacific experiencing robust warming trends at rates exceeding those of other ocean regions due to both natural multidecadal variability and anthropogenic climate change. In 2010/2011, an intense La Niña event contributed to strong warming north of Australia, while long-term ocean warming accounted for approximately 50% of the observed SST anomaly [*Hendon et al.*, 2014]. The question therefore arises as to the physical mechanism behind how long-term ocean warming might have contributed to the hydroclimatic extremes and ensuing flooding across northeast Australia during the 2010/2011 La Niña. This will be estimated using a series of atmospheric general circulation model (AGCM) experiments forced by prescribed SST fields that respectively include, and exclude, the ocean warming signature of the past several decades.

2. Data Sets and Model Experiments

A series of observational and reanalysis products were used, such as from the National Centers for Environmental Prediction/National Center for Atmospheric Research [*Kistler et al.*, 2001], CPC Merged Analysis of Precipitation (CMAP) [*Xie and Arkin*, 1996], Australian precipitation [*Jones et al.*, 2009], Australian Water Availability Project soil moisture and discharge [*Raupach et al.*, 2009], and National Oceanic and Atmospheric Administration Extended Reconstructed SST version 3b (ERSST) [*Smith et al.*, 2008]. La Niña years were determined following the classification method by *Meyers et al.* [2007] and updated by *Ummenhofer et al.* [2011].

The AGCM simulations in this study are based on NCAR's Community Atmosphere Model version 3 (CAM3) [*Hurrell et al.*, 2006]. CAM3 uses a spectral dynamical core, 26 vertical levels, and was run at a T85 horizontal resolution (~1.4° latitude/longitude). Other model-specific aspects relevant to this study are described in relation to the model's simulation of the hydrological cycle [*Hack et al.*, 2006], tropical Pacific variability [*Zelle et al.*, 2005], and specifically the climate of the Australian region [*Taschetto et al.*, 2010; *Ummenhofer et al.*, 2013]. The following AGCM simulations were conducted:

1. Control simulation: A 120 year run with a repeating monthly climatology of global SST [*Hurrell et al.*, 2006] (based on the 1951–2010 period);
2. Hindcast simulation: A simulation forced by global observed SST [*Smith et al.*, 2008] for the period 1951–2010; as such, the SST forcing contains the seasonal cycle, interannual variability, and the long-term trend;
3. Observed 2010/2011 SST experiment: Observed SST during the period January 2010 to March 2011 is used to force the AGCM; 57 ensemble members of 15 months duration each, initialized on 1 January from

different years of the control simulation. Given the atmosphere's chaotic nature and rapid adjustment, initial conditions do not play a role beyond the first 1–2 months (January–February 2010); initialization of the ensemble members therefore does not affect our results for the months September 2010 to February 2011;

4. Detrended 2010/2011 SST experiment: Observed SST during the period January 2010 to March 2011 is used to force the AGCM, only at each grid point the linear SST trend for the period 1951–2009 (containing components due to both anthropogenic factors and low-frequency natural variability) is first removed; 57 ensemble members of 15 months duration each, initialized on 1 January from different years of the control simulation.

3. Results

We assessed the observed hydroclimatic conditions across Australia during the record wet spring and summer season of 2010/2011. Almost all of Australia experienced anomalously wet conditions during September 2010 to February 2011, with continent-averaged rainfall anomalies in excess of 50–100 mm/month (Figure 1a). Soil moisture during this time—important for natural ecosystems and agriculture—also exhibited anomalous conditions (Figures 1c and 1e). A two-tailed Student's *t* test was used to determine whether the observed composite anomalies differed significantly from long-term mean conditions at the 0.05 level. Precipitation and soil moisture anomalies in September, November, and December 2010 (Figure S2 in the supporting information) made this the wettest spring across Australia since at least 1900, with the seasonal precipitation anomaly in eastern Australia exceeding 3 standard deviations [*Hendon et al.*, 2014].

To quantify the anomalous hydroclimatic conditions over northeast Australia in 2010/2011, average precipitation and soil moisture were examined over the land area boxed in Figure 1a. The September–February long-term mean average precipitation in northeast Australia was 74 (±22) mm/month (±1 standard deviation; Figure 1b). During La Niña events, precipitation in the northeast typically increased to an average of 89 (±27) mm/month. The 136 mm/month September–February average precipitation in 2010/2011 was thus highly anomalous in the long-term context, even for La Niñas, although this event was not unprecedented: 1973/1974 precipitation was 164 mm/month averaged across the region. During January 1974, tropical cyclone (TC) *Wanda* made landfall north of Brisbane (27°S, 153°E) on a southwesterly track. It also forced an intense monsoonal trough toward the region, making this a record wet January and the second wettest month ever recorded, resulting in the most severe example of urban flooding in Australia [*van den Honert and McAneney*, 2011] and a rare flooding of Lake Eyre in the continent's interior [*Pook et al.*, 2014]. Despite this, the 2010/2011 relative soil moisture in the northeast ranked highest since 1951 (Figures 1d and 1f) and discharge was unusually high (Figure S3 in the supporting information). For further detail on the 1973/1974 anomalies, see supporting information and Figure S4.

The anomalous wet conditions of 2010/2011 extended beyond the Australian mainland to the north, affecting Indonesia and western Papua New Guinea (Figure 2a). This was associated with enhanced ascending motion over the Timor Sea, northern and eastern Australia, as well as stronger onshore moisture transport and convergence over these regions (Figures 2b and 2c). The regional circulation anomalies were associated with large-scale changes in sea level pressure (SLP) across the wider Indo-Pacific basin, with anomalously low SLP over the Indian Ocean and western Pacific warm pool, while higher SLP anomalies dominated south of 30°S [*Hendon et al.*, 2014] (Figure 2d). The Indian Ocean, western Pacific warm pool, as well as the subtropical Pacific Ocean, exhibited anomalously warm SST at this time, while the eastern and central tropical Pacific featured cold SST anomalies typical of La Niña events (Figure 2e). Warm anomalies to the north of Australia were 0.5°C warmer than expected during a La Niña event of this size [*Hendon et al.*, 2014]. SST anomalies to the continent's northwest and along the Leeuwin Current along the Western Australian coastline were also exceptionally warm [*Feng et al.*, 2013].

Sustained warming of ocean temperatures has resulted in an overall increase in Indo-Pacific SST over the last 60 years, based on the linear trend over the period 1951–2009 (Figure 3a). In addition, natural and/or forced multidecadal SST variability associated with the IPO has contributed to the overall SST change over the past few decades that influenced the 2010/2011 background conditions. Since the start and end periods of our analysis occur in a negative IPO phase, the contribution of this mode is likely small. While the magnitude and detailed spatial pattern of the trend is sensitive to the observational product and analysis period, broad features across the Indo-Pacific are consistent and insensitive to the end-point year (for details, see supporting information): Enhanced warming at an average rate of >0.02°C/yr over the past 60 years is apparent over the

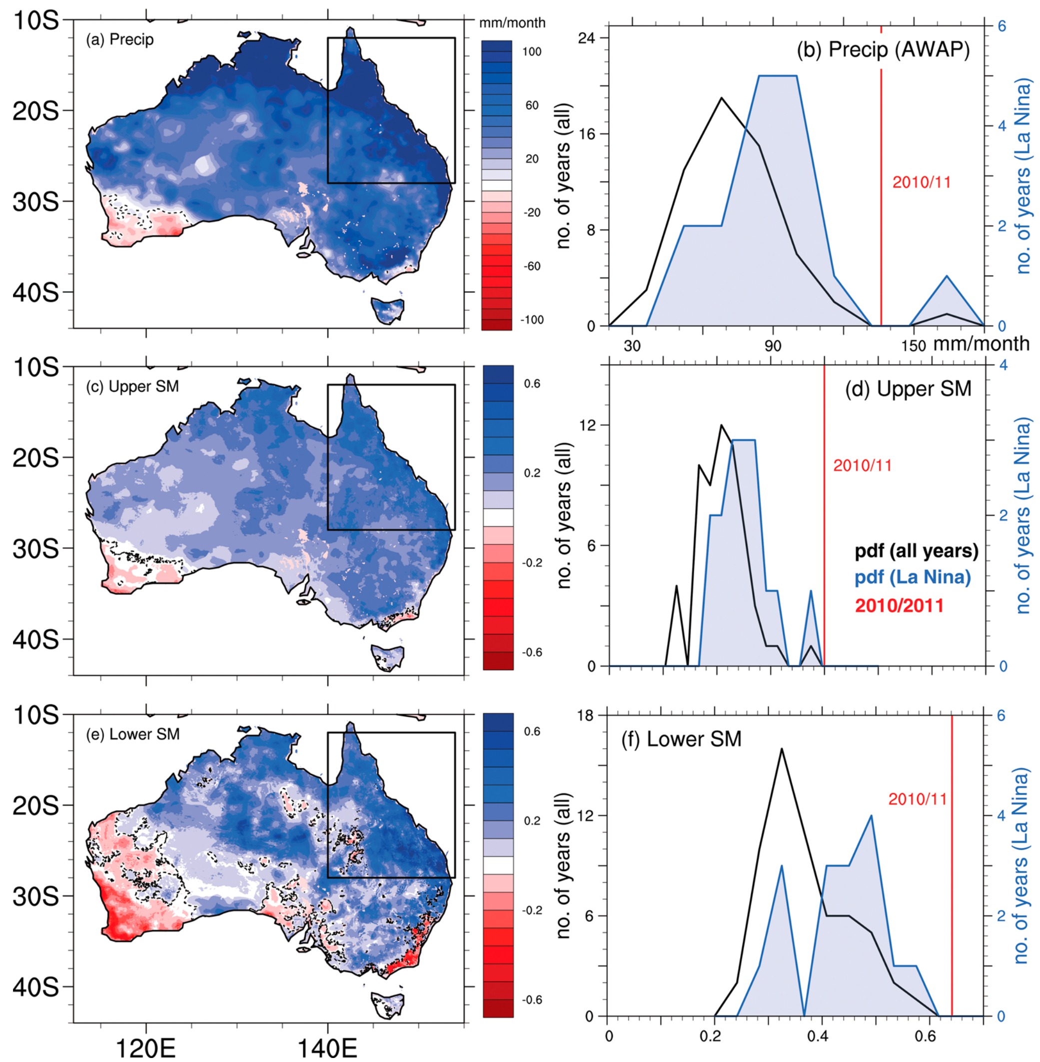

Figure 1. (left column) Australian precipitation and soil moisture anomalies averaged for September 2010 to February 2011 relative to 1951–2009 for (a) precipitation (mm/month) and (c, e) upper and lower level soil moisture. Dashed contours indicate anomalies significant at the 90% level according to a two-tailed Student's *t* test. (right column) Frequency distribution of (b) precipitation and (d, f) soil moisture over the box indicated on the left for all years (black), La Niña years (blue), and 2010/2011 (red).

central and southern Indian Ocean and parts of the Pacific (Figure 3a). Less warming occurred around the Maritime Continent region. However, the 2010/2011 area-averaged 29.3°C SST to the north of Australia (cf. box in Figure 2e) lies in the top 6% of all La Niña events (top 2% of all years; Figure 2f). Given the recent large-scale upper ocean warming in the Indo-Pacific, it is important to understand whether the regional climate response observed during the record La Niña of 2010/2011 was affected by the presence of this warming trend.

A series of AGCM simulations were used to explore this question. The skill of the model in representing regional precipitation and ENSO teleconnections was assessed using a control simulation with climatological SST and a hindcast simulation with observed SST: the model has reasonable skill in reproducing the observed northeast Australian rainfall in regard to seasonality, interannual variability, and in particular ENSO teleconnections (for details see supporting information, Figures S6, S7, and Table S1). Two sets of ensemble AGCM experiments of the 2010/2011 La Niña event were conducted: one forced by observed 2010/2011 SST and the other forced by observed 2010/2011 SST with the long-term (1951–2009) SST trend removed. These were compared to each other and to a 120 year control simulation forced by climatological SST. The frequency distribution of September–February averaged northeast Australian precipitation is shown in Figure 3b for the experiments. The control simulation provides information on the internal variability of the atmosphere in the

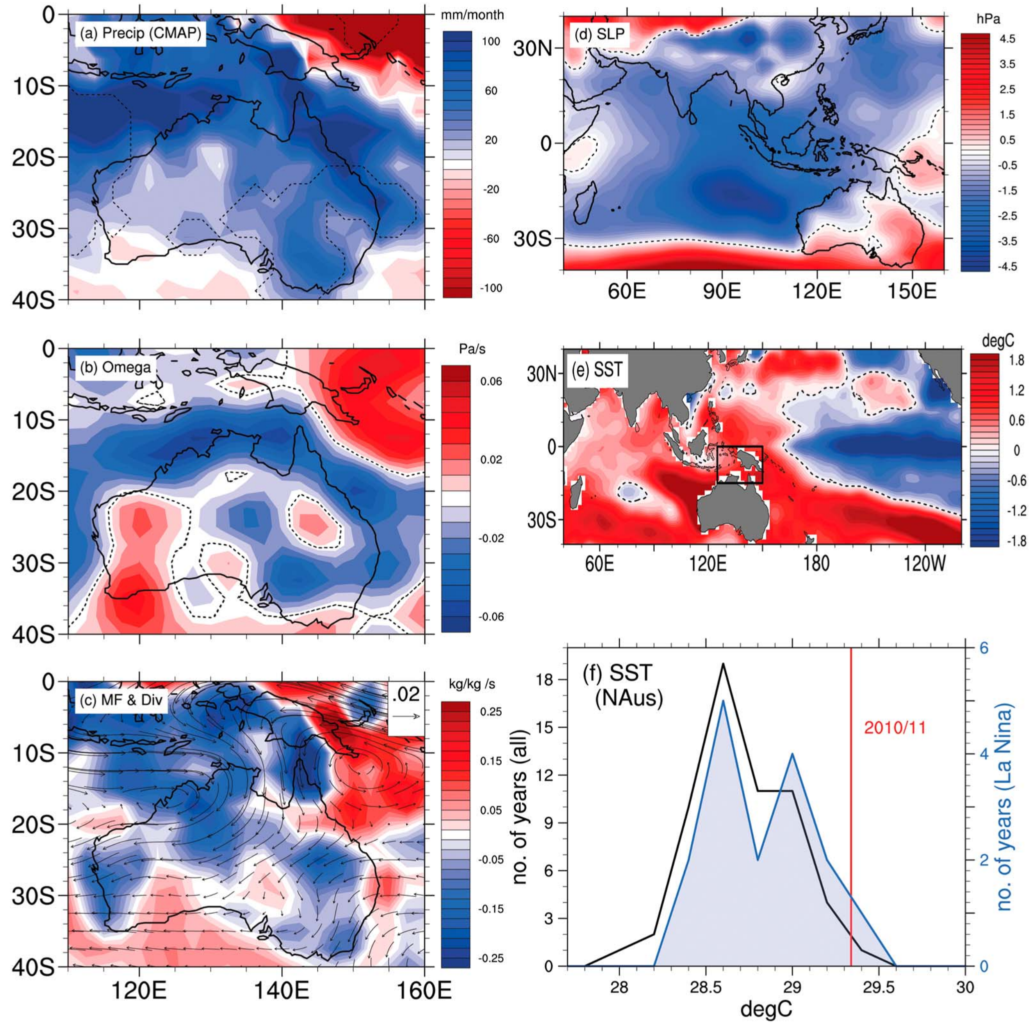

Figure 2. Regional climate anomalies averaged for September 2010 to February 2011 relative to 1951–2009 for (a) CMAP precipitation (mm/month), (b) vertical velocity Ω (Pa/s), (c) 850 hPa moisture transport (kg/m s^{-1}; vectors) and its divergence (s^{-1}; colored), (d) SLP (hPa), and (e) SST (°C). Dashed contours in Figures 2b, 2d, and 2e) indicate anomalies significant at the 90% level according to a two-tailed Student's *t* test. (f) Frequency distribution of SST over the box indicated in Figure 2e for all years (black), La Niña years (blue), and 2010/2011 (red). The 2010/2011 CMAP precipitation anomaly in Figure 2a is relative to 1979–2009, and dashed contours indicate anomalies significant at the 80% level.

model that is independent of SST anomalies. This simulation indicates that in the absence of ENSO-related variability the regional precipitation varies from 59 to 119 mm/month with a mean of 90 mm/month. In the ensemble simulations forced by actual observed 2010/2011 SST, precipitation ranges between 86 and 154 mm/month with a mean of 122 mm/month. This suggests that the SST conditions in 2010/2011 increase rainfall across northeast Australia compared to years with average climatological SST.

When the AGCM is forced by 2010/2011 SST with the long-term warming trend removed, a shift in the northeast Australian precipitation distribution is seen with fewer ensemble members recording very high rainfall amounts compared to the standard 2010/2011 forced experiment (Figure 3b). Overall, a significant ($P = 0.039$) difference in the rainfall distribution between the two cases is apparent: a Kolmogorov-Smirnov two-sample test indicates that the northeast Australian rainfall amounts in the two experiments, i.e., 2010/2011 with and without SST trend included, are not drawn from the same distribution. In particular, the likelihood of very high rainfall is significantly enhanced when the SST forcing includes the underlying warming trend inherent in the 2010/2011 observations. In contrast, there is little difference between the simulated rainfall at the lower end of the distributions.

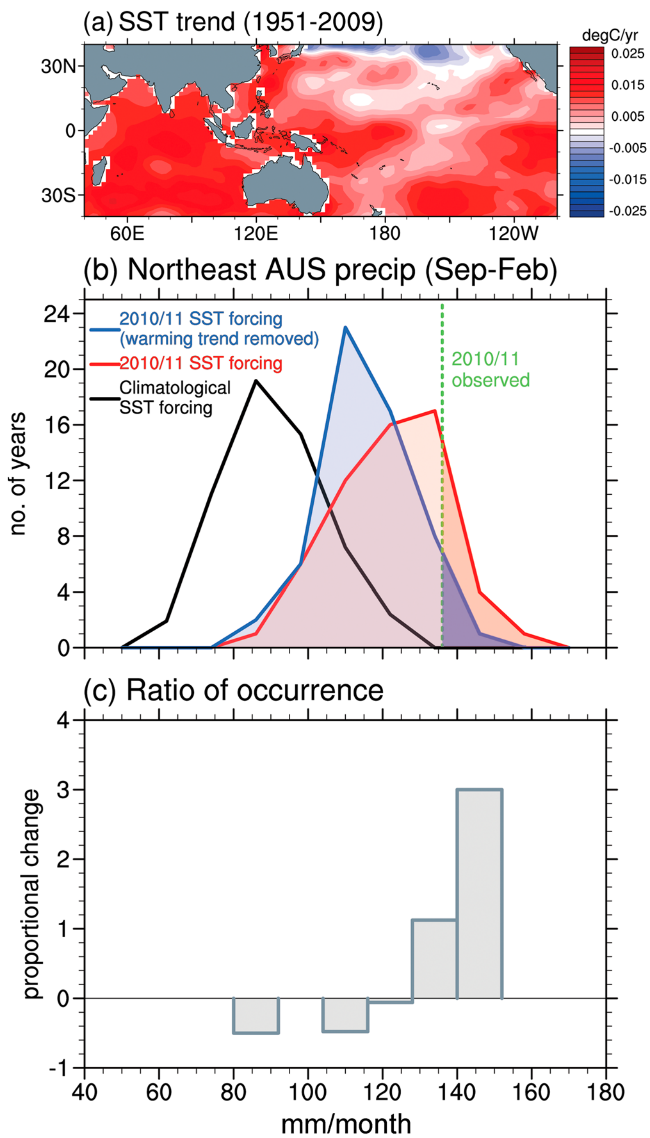

Figure 3. (a) Indo-Pacific SST trend (1951–2009; °C/yr). (b) Frequency distribution of simulated northeast Australian precipitation across the ensemble members for the different experiments. Analyses are averaged for the period September 2010 to February 2011. The rainfall distributions between the two 2010/2011 experiments differ significantly at the 95% level according to a Kolmogorov-Smirnov two-sample test. (c) Simulated change in the relative likelihood of 2010/2011 northeast Australian rainfall amounts due to ocean warming (relative to the likelihood that no warming had occurred).

The ratio of occurrence across the ensemble members in the two experiments provides an estimate of the relative likelihood of receiving a certain amount of rainfall from the two experiments (Figure 3c). Rainfall at the observed level of 136 mm/month (i.e., corresponding to years whose rainfall lies within the top 3.3% of years for the past 60 years) is three times as likely in the case with ocean warming. In fact, in the model, the warming drives rainfall totals that are not possible in the simulation without ocean warming. This demonstrates how the underlying change in the background SST field skewed the chances of a spring/summer of extremely high rainfall for northeast Australia, compared to what would be the case without multidecadal ocean warming.

The spatial pattern of the precipitation differences between the two simulations indicates that the high rainfall conditions in the case that includes ocean warming extended beyond northeast Australia into the Coral Sea and toward Papua New Guinea (Figure 4a). This is due to enhanced ascending motion and anomalous moisture convergence over eastern Australia and Papua New Guinea (Figures 4b and 4c). The ocean warming

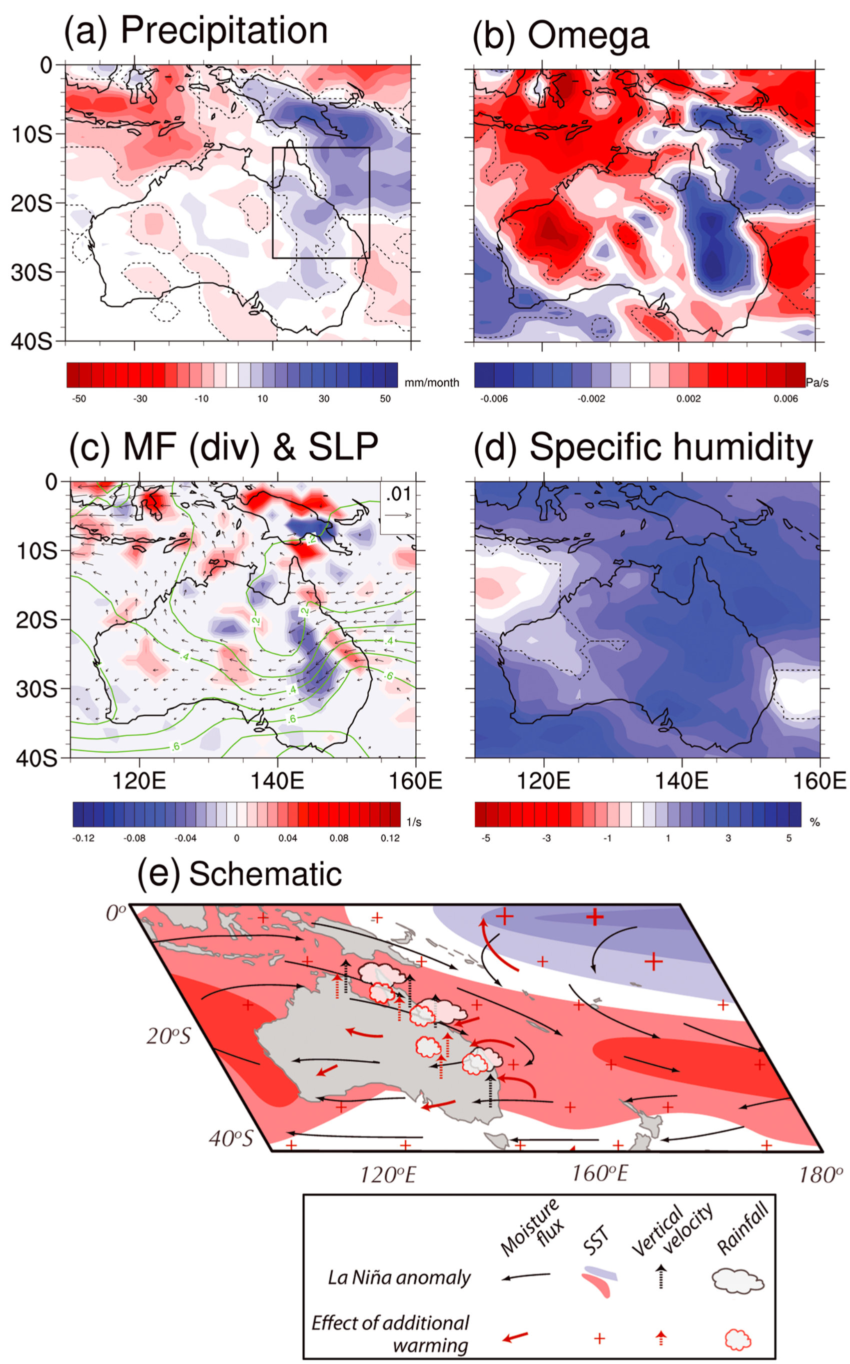

Figure 4. Differences in simulated climate fields between the two 2010/2011 SST forced experiments averaged for the period September 2010 to February 2011 for (a) precipitation (mm/month), (b) vertical velocity Ω (Pa/s), (c) moisture transport (kg/m s^{-1}; vectors) and its divergence (s^{-1}; colored) at 850 hPa and SLP (green contours), and (d) specific humidity as percentage change. Dashed contours in Figures 4a, 4b, and 4d indicate differences significant at 90% according to a two-tailed Student's *t* test, while Figure 4c only contains significant differences. The box in Figure 4a indicates the northeast Australian region used in the analyses. (e) Schematic of regional climate anomalies due to the La Niña conditions (black symbols), with red symbols indicating the additional contribution from long-term ocean warming.

in the tropics alters the large-scale atmospheric circulation due to changes in the SLP pattern. An anomalous pressure gradient across eastern Australia is simulated in the model (Figure 4c), which leads to enhanced advection of moisture from the Coral Sea into Queensland. Anomalous moisture convergence occurs inland and is transferred from the surface to upper tropospheric levels as indicated by anomalous (upward) vertical velocity over eastern Australia (Figure 4b). This ascending motion intensifies convection and thus generates anomalous precipitation over Queensland (Figure 4a). Percentage changes in specific humidity in the atmosphere indicate that the additional SST warming of ∼0.5°C results in a percentage change of +2–4% in specific humidity across the study region (Figure 4d), consistent with the Clausius-Clapeyron relation that the water-holding capacity of the atmosphere increases by about 7% for every 1°C rise in temperature [*Hartmann et al.*, 2013].

4. Discussion and Conclusions

In summary, we have shown how long-term Indo-Pacific oceanic warming can act to increase the likelihood of a summer of extremely high rainfall over northeast Australia. Extreme warm SST occurred in 2010/2011, surrounding the Australian continent, in particular, in the eastern Indian Ocean, western Pacific warm pool region, and Coral Sea. While these regions typically experience anomalous warm SST during La Niñas, significant warming over the past few decades has contributed an additional ∼0.5°C to the extreme SST anomalies [*Hendon et al.*, 2014]. This change is associated with both thermodynamical changes (with increased moisture availability in a warmer atmosphere) and dynamical changes (associated with regional differences in warming rate). A summary of the main dynamical processes involved is shown in Figure 4e. During a strong La Niña event, there is enhanced onshore moisture transport onto eastern Australia and anomalous ascent, resulting in increased precipitation over the East. The background warming trend further modifies this circulation, resulting in even greater onshore moisture transport, stronger ascent over eastern Australia, and additional precipitation.

An important caveat with our study is that the model used is unable to resolve the effect of TCs. On synoptic timescales, torrential rainfall and flooding in northeast Australia has often occurred in conjunction with TCs, such as TC *Yasi* in 2010/2011 and TC *Wanda* in 1974 [*van den Honert and McAneney*, 2011]. However, for the November–April period 1969–2010, the contribution of TCs to total summertime rainfall for our study area in northeast Australia averaged 11% along the coast and 4% further inland [*Dare et al.*, 2012]. While TCs contribute to northeast Australian summer rainfall, the contribution in 2010/2011 was confined to the coast and is unlikely to have had a major influence on the regional total. The 2010/2011 TC season was near normal in the Australian region, in contrast to the unusually active 1973/1974 season (see TC tracks in Figure S5). Thus, while our simulations are unable to capture these small-scale phenomena, this is unlikely to affect our conclusion that the warming trend acted to enhance large-scale La Niña rainfall, making the extreme rainfall in 2010/2011 more likely. Thus, our results provide a mechanistic understanding of how large-scale circulation anomalies give rise to enhanced moisture transport in the region.

While changes in extreme precipitation are expected in a warming world [*Held and Soden*, 2006; *Wentz et al.*, 2007; *Pall et al.*, 2011; *Hartmann et al.*, 2013; *Lehmann et al.*, 2015], it is not possible to attribute any single event to anthropogenic climate change. However, ocean warming has been found to play a role in certain extreme precipitation events [*Meredith et al.*, 2015; *Trenberth et al.*, 2015]. Here ensemble model experiments have allowed us to elucidate the physical mechanisms explaining how long-term SST trends might have contributed to extreme precipitation conditions in northeast Australia during the exceptionally strong La Niña event of 2010/2011. It should be noted that the response described here is likely to be sensitive to both the (atmospheric) model used and the SST trend pattern applied [*Lewis and Karoly*, 2015]. However, using a different model, the POAMA seasonal forecasting model, initialized with 2010/2011 SST with and without long-term ocean warming included, *Lim et al.* [2015] also found wetter conditions across Australia when long-term ocean warming is included, linking this to a positive SAM response. In the simulations performed here, we have shown how recent SST trends significantly increase the likelihood of extreme hydroclimatic conditions over northeast Australia during the 2010/2011 La Niña via enhanced onshore moisture advection and convergence over the northeast. This has implications for future extreme rainfall events as 21st Century ocean warming progresses, with more frequent extreme La Niña events [*Cai et al.*, 2015] likely to bring a stronger chance of damaging high rainfall to the north of Australia as a consequence of global warming.

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