Description of Data and Methodology

The methodology described here closely follows that used in Lewis and Karoly (2013) and King *et al.* (2015).

Data

The Coral Sea region area-average monthly mean sea surface temperature (SST) series for March was obtained from the Bureau of Meteorology. March 2016 was the highest anomaly beating the previous record set in 2015. The Niño-3.4 index representing the state of the El Niño-Southern Oscillation (ENSO) was calculated using SST data for the central equatorial Pacific Ocean from HadISST (Rayner *et al.* 2003).

The record warm March 2016 SST anomalies in the Coral Sea were investigated using an ensemble of state-of-the-art coupled climate model simulations from the fifth phase of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012) archive. Simulations from the "historical" experiment (including natural and anthropogenic influences over 1861-2005), the "historicalNat" experiment (natural-only forcings over 1861-2005) and the RCP8.5 experiment (projected climate over 2006-2100 under a high greenhouse gas emissions scenario) were analysed.

Climate models with at least three historical, one historicalNat and one RCP8.5 simulation available with monthly sea surface temperature "tos" on the data repository at the National Computational Infrastructure in Canberra, were selected (see Table 1).

Methods

Firstly, all model simulations were interpolated to a common regular 2° x 2° latitude-longitude grid. March sea surface temperature anomalies relative to the historical 1961-1990 climatological period were calculated for simulations from each experiment with equivalent historical and RCP8.5 simulations joined in 2005/06. Models were tested on their ability to capture the observed distribution of March SSTs over the 1951-2005 period using a Kolmogorov-Smirnov test. If at least one-third of historical simulations of a particular model failed to reproduce the observed SST distribution ($p< 0.05$) then that model was not used in further analysis. Eleven models passed this test (shown in bold in Table 1).

Investigating the anthropogenic influence on the likelihood of the event

An all-forcings and a natural-forcings ensemble were constructed. The all-forcings ensemble was composed of 28 historical and RCP8.5 simulations for 2000-2030. The natural-forcings ensemble was composed of 28 equivalent historicalNat simulations for 1861-2005. An estimate of the change in likelihood of a record hot March SST was estimated using the Fractional Attributable Risk (FAR) framework. The FAR was calculated as:

$$FAR = 1 - \frac{P_{NAT}}{P_{ALL}}$$

where P_{NAT} is the probability of the event in the natural-forcings ensemble (historicalNat) and P_{ALL} is the probability of a similar event occurring in the all-forcings ensemble (historical and RCP8.5 conjoined). The threshold used to define the extreme event is the previous record, in this case the March 2015 anomaly of +0.86 °C above the 1961-1990 mean. Any extreme event is a March SST anomaly in the Coral Sea exceeding that threshold.

To gain an estimate of the uncertainty in our estimates of FAR statistics, the 28 pairs of simulations were bootstrapped (50% sample size; with resampling) 10 000 times and the FAR recalculated. A conservative 10th percentile estimate of FAR was then calculated and used to estimate the change in likelihood of events like the 2016 SST anomaly due to the anthropogenic influence on the climate through this equation:

$$Change\ in\ likelihood = \frac{1}{1 - FAR}$$

These conservative change in likelihood estimates are the quoted values throughout the article.

Investigating the ENSO influence on the likelihood of the event

The Niño-3.4 index was calculated in each model simulation relative to its own 1961-90 climatology (for the historicalNat simulations this was done relative to itself as opposed to using the equivalent historical simulation). El Niño seasons were defined as October-March periods when the Niño-3.4 index was more than one observed standard deviation above average (+0.91 °C). La Niña seasons were defined as when average SSTs were more than one standard deviation below average and neutral seasons are between one standard deviation above and below average. The FAR was then estimated as:

$$FAR = 1 - \frac{P_{LN,Neutral}}{P_{EN}}$$

where $P_{LN,Neutral}$ is the probability of an event like March 2016 occurring in La Niña or neutral seasons and P_{EN} is the equivalent probability in an El Niño season. Uncertainty estimates of FAR were again estimated through bootstrapping and equivalent changes in likelihood were calculated.

Estimating the anthropogenic influence on the magnitude of the event

The 95th percentile estimates of March average SST in the natural- and all-forcings ensembles were extracted and the difference taken. This was used as an estimate of the anthropogenic influence on extreme warm March SSTs in the Coral Sea region. The 95th percentile was used because there are more data available to estimate this percentile than say the 99th percentile, giving a more reliable estimate.

Estimating when SST anomalies like March 2016 will be near-average events

As anthropogenic forcings are causing warmer SSTs in the Coral Sea we might expect that under increased human influence, SSTs like those in March 2016 will become close to average. To investigate this, 31-year moving windows of the all-forcings ensemble were compiled and the median SST anomaly was extracted. The central year of the 31-year window when the median SST anomaly exceeded +1.09 °C (the March 2016 value) was found.

Table 1: Climate models and simulations used in this analysis. Models in bold passed the validation step described above and simulation numbers in bold were used to estimate the anthropogenic and El Niño influences on the event.

Model	Historical	HistoricalNat	RCP8.5
ACCESS1.3	**1,2,3**	**1**	**1**
Bcc-csm1.1	**1,2,3**	**1**	**1**
CanESM2	1,2,3,4,5	1,2,3,4,5	1,2,3,4,5
CCSM4	**1,2,**3,**4,**5,**6**	**1,2,4,6**	**1,2,4,6**
CESM1-CAM5	**1,2,3**	**1,2,3**	**1,2,3**

CNRM-CM5	**1,2**,3,**4**,5,6,7,8,9,10	**1,2,4**	**1,2,4**
CSIRO-Mk3.6.0	**1,2,3,4,5**,6,7,8,9,10	**1,2,3,4,5**	**1,2,3,4,5**
GFDL-CM3	1,2,3,4,5	1	1
GISS-E2-H	1,2,3,4,5	1,2	1,2
GISS-E2-R	**1,2**,3	**1,2**	**1,2**
HadGEM2-ES	**1,2,3,4**,5	**1,2,3,4**	**1,2,3,4**
IPSL-CM5A-LR	**1,2,3**,4,5,6	**1,2,3**	**1,2,3**
IPSL-CM5A-MR	**1**,2,3	**1**	**1**
MRI-CGCM3	**1**,2,3	**1**	**1**
NorESM1-M	1,2,3	1	1

Sensitivity Tests

The Coral Sea region (4°S-26°S, 142°E-174°E) is larger than the region of the Great Barrier Reef where the coral bleaching event took place. In the Coral Sea region, March SSTs can be varied through multiple mechanisms including ocean currents (which tend to promote warmer SSTs during La Niña events) and sunshine duration (which tends to be greater and cause increased SSTs in El Niño events). Overall the Coral Sea region SSTs has a positive non-significant correlation (0.19) with the Niño-3.4 index. Tests were performed using SSTs for a much smaller region nearer the Australian coast and the ENSO correlation remains non-significant and positive (0.21). We decided to focus on the larger Coral Sea region as we have greater confidence in climate model representation over the region.

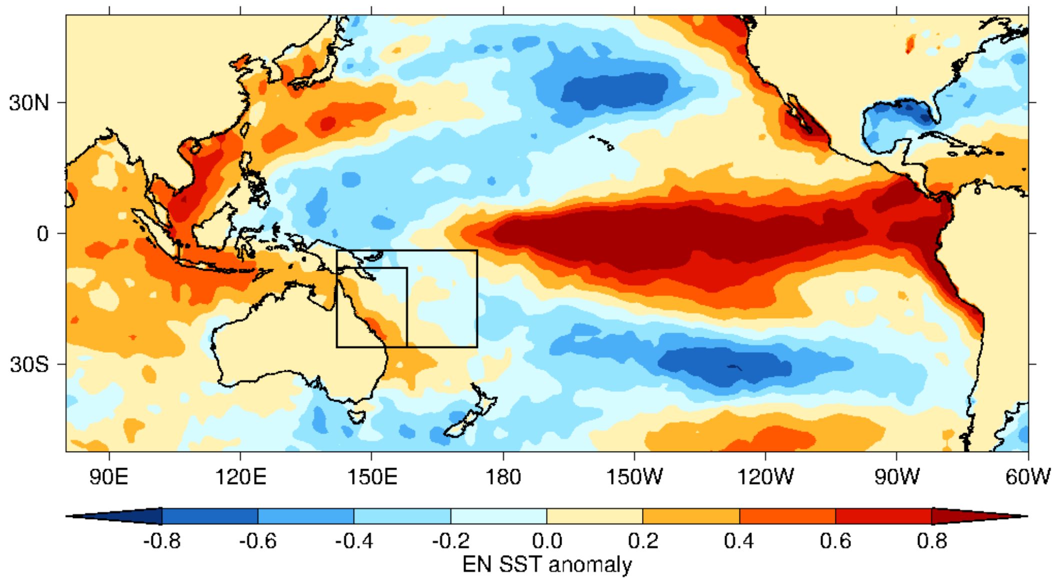

Figure 1: Average March SST anomalies in El Niño seasons. The large box represents the Coral Sea region used in this analysis. Tests were performed on the region covered by the smaller box.

Making the animation of SST anomalies

The animation in the article shows the March 2016 sea surface temperature (SST) anomalies calculated from the UK Met Office Operational Sea Surface Temperature and Sea Ice Analysis dataset (Donlon *et al.* 2012). Anomalies are calculated using the 1985-2015 base period per calendar date. So, for example, the anomaly for 1 March 2016 is calculated by subtracting the observed SSTs for 1 March 2016 from the average for 1 March over the period 1985-2015.

References

Donlon, C. J., Martin, M., Stark, J., Roberts-Jones, J., Fiedler, E., and Wimmer, W. (2012): The Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) system, Remote Sensing of Environment, 116, 140–158, doi:10.1016/j.rse.2010.10.017.

King, A. D., G. J. van Oldenborgh, D. J. Karoly, S. C. Lewis, and H. M. Cullen, 2015: Attribution of the record high Central England Temperature of 2014 to anthropogenic influences. Environ. Res. Lett., 10, 054002, doi: 10.1088/1748-9326/10/5/054002.

Lewis S C and Karoly D J 2013 Anthropogenic contributions to Australia's record summer temperatures of 2013 Geophys. Res. Lett. 40 3705–9

Rayner, N. A.; Parker, D. E.; Horton, E. B.; Folland, C. K.; Alexander, L. V.; Rowell, D. P.; Kent, E. C.; Kaplan, A. (2003) Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century J. Geophys. Res. 108, D14, 4407 10.1029/2002JD002670

Taylor K E, Stouffer R J and Meehl G A 2012 An overview of CMIP5 and the experiment design Bull. Am. Meteorol. Soc. 93 485–98

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