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Exploring qualitative regional climate projections: a case study for Nauru

Jaclyn N. Brown[1,*], Josephine R. Brown[2], Clothilde Langlais[1], Rob Colman[2], James S. Risbey[1], Bradley F. Murphy[2], Aurel Moise[2], Alex Sen Gupta[3], Ian Smith[2], Louise Wilson[4], Sugata Narsey[4], Michael Grose[4], Matthew C. Wheeler[2]

[1]Centre for Australian Weather and Climate Research, CSIRO, Hobart, Tasmania 7000, Australia
[2]Centre for Australian Weather and Climate Research, Bureau of Meteorology, Melbourne, Victoria 3001, Australia
[3]Climate Change Research Centre, ARC Centre of Excellence for Climate Systems Science, University of New South Wales, Sydney, New South Wales 2052, Australia
[4]Centre for Australian Weather and Climate Research, CSIRO, Aspendale, Victoria 3195, Australia

ABSTRACT: Coupled General Circulation Models simulate broad-scale climate patterns and are standard tools for understanding potential changes to the climate system. Climate change projection information is required at the local scale for adaptation planning. Model skill can be limited at this scale due to model biases and uncertainties. Pacific Islands are one such example, particularly Nauru which lies at the intersection of the South Pacific Convergence Zone (SPCZ), the Western Pacific Monsoon, the oceanic warm pool and the ENSO zone of influence. In light of such constraints, a qualitative climate projection approach is presented whereby projections are based on expected changes to the broad-scale climate features, drawing on a review of current literature and new research. Nauru sits in the region subject to seasonal and interannual migrations of the SPCZ. Climate models simulate an overly zonal SPCZ with Nauru lying too close to the dry cold tongue zone. This sets an erroneous base state for Nauru by locating it in a very different climate zone. The climate model changes in the SPCZ can be used to argue how the climate of Nauru would change were it and the SPCZ correctly collocated. Similar approaches are applied to the set of climate features influencing Nauru to generate modified climate projections.

KEY WORDS: Climate projections · Tropical Pacific · ENSO · SPCZ · Islands

1. INTRODUCTION

Substantial climatic changes have occurred in the tropical Pacific over the last few decades (ABoM & CSIRO 2011a) and, as concentrations of greenhouse gases increase, impacts from climate change in the Pacific are likely to become more serious (Christensen et al. 2007). Along with many other nations, the Pacific Island Countries and Territories need to develop adaptation strategies for the future in order to reduce any risks associated with these impacts, ensure sustainable development and to guide disaster risk management. An important requirement in the development of such strategies is reliable expert information on how the climate system might respond in the future. At present, this information is primarily obtained from climate model projections but, at the scale of Pacific Islands, these are fraught with uncertainties and biases (J. N. Brown et al. 2013b). Here we conduct a case study of Nauru and explore ways to provide more useful information for this relatively small region.

Nauru is situated in the Western tropical Pacific Ocean (0.5° S, 167° E). It is a raised atoll, ~6 km long (NE–SW) and 4 km wide (NW–SE). On weekly to monthly time scales, rainfall is affected by convec-

*Email: jaci.brown@csiro.au

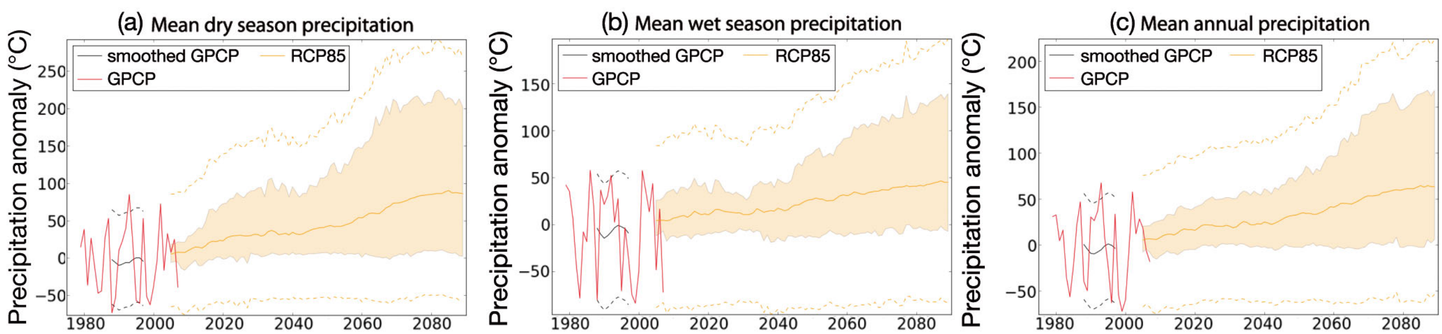
tively-coupled tropical waves including the Madden Julian Oscillation (MJO). On seasonal and interannual time scales, rainfall patterns are modulated by the South Pacific Convergence Zone (SPCZ) and the occasional strong eastward extension of the Western Pacific Monsoon (WPM). Interannual variations in these drivers of Nauru's climate are strongly influenced by El Niño Southern Oscillation (ENSO). Further discussion of these features can be found in the Pacific Climate Change Science Program Report (ABoM & CSIRO 2011a).

Nauru has limited water storage capacity and is reliant on a regular supply of rainfall or costly desalination to meet water needs. It usually experiences severe drought during La Niña years, often receiving as little as 10% of average wet season rainfall. Conversely, it usually receives significantly above average rainfall in El Niño years, often ~150% of average wet season rainfall (ABoM & CSIRO 2011b). However, this typical response to El Niño is reversed in so-called 'zonal SPCZ' events. For example, in 2 recent extreme El Niño years (1982 and 1997), there was ~50% less rainfall than normal (B. F. Murphy et al. unpubl. data). These features of the climate (i.e. extreme rainfall variability, asymmetry about the ENSO phase and non-linearity in the ENSO response) have wide-ranging implications for water supply, flood management, transport infrastructure, agriculture, ecosystems and health (Nauru 1999).

The outputs from Coupled General Circulation Models (GCMs) have been used to provide estimates for projected changes to rainfall and temperature (amongst other variables) at the island scale (Fig. 1). While GCMs are standard tools for better understanding potential changes to the climate system, their utility at the relatively small island scales is limited for various reasons. This is often reflected in the large uncertainties and low confidence statements that accompany many projections. Of particular concern is the large spread in the projections of rainfall changes across different climate models over most Pacific Islands (e.g. Fig. 1a–c).

For small regions, direct model output can be misleading when models fail to adequately simulate the spatial or temporal features of the key climate drivers. For example, in the Pacific region, errors in the representation of the sea surface temperatures (SSTs) can seriously affect the simulations of island surface temperatures, as well as the position of large scale rainfall patterns. If the drivers are broadly well simulated, it is more likely that the models will contain information of relevance to any derived climate projections.

Downscaling approaches may partially correct for such errors that arise in the use of relatively coarse scale grid representations of the surface and sometimes for SST biases (cf. Smith et al. 2013), but they cannot correct any GCM problems associated with e.g. ENSO, or the location of the SPCZ or Intertropical Convergence Zone (ITCZ). Where these are important in determining the climate of a small region such as Nauru, any such problems can seriously affect projected changes, independent of any downscaling approach (i.e. dynamical or statistical).



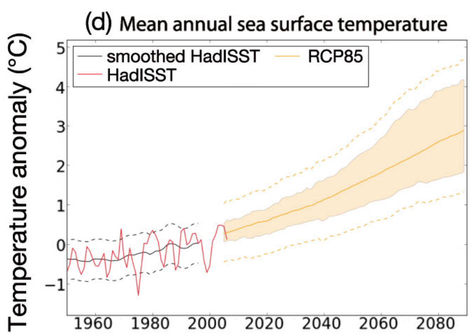


Fig. 1. Historical and simulated mean (a) dry season precipitation, (b) wet season precipitation, (c) annual rainfall, and (d) sea surface temperature (SST) time series for Nauru for the CMIP5 models under the very high emission (RCP8.5). The region analysed is the exclusive economic zone of Nauru evaluated on each model's native grid (see ABoM & CSIRO 2011b for more details). Anomaly (from base period 1986–2005) is shown for the Global Precipitation Climatology Project (GPCP) observation based dataset for rainfall and the HadISST SST (in red). Orange and black lines: smoothed (20 yr running average) multi model mean and observed anomalies respectively. Shading: spread of model values (5th–95th percentile). Dashed lines: 5th–95th percentile of observed inter-annual variability (also added to projections as a visual guide). This indicates that future surface air temperature could be above or below the projected long term averages as expected due to inter-annual variability

The process of evaluation, synthesis, and re-analysis described above can, in principle, produce projections that may differ significantly from those derived from direct (or downscaled) model output. For example, these could involve a complete change in the most likely sign of the projected change due to the sensitivity of small regions to model offset errors. However, in general, where any small scale climate is sensitive to the representation of larger scale features, the model projections tend to reflect this in the wide range of uncertainty that accompanies the projections. The process of deconstructing the large scale features can provide an understanding of why this large uncertainty exists. It is also feasible that a careful deconstruction could actually reduce any such uncertainty by removing any physically unrealistic GCM results. Consequently, qualitative estimates of any future changes may lead to better interpretations of direct model output.

The purpose of this study to explore how we can provide a more meaningful and reliable climate projection for Nauru using a qualitative method based on expected changes to large scale drivers (for which we have greater confidence) rather than direct model output at the local scale (which may be subject to large biases). We are not attempting to provide new model projections, but rather to re-interpret existing results found in the literature while taking into account limitations and biases in the climate models. We begin by determining the key climate features that affect Nauru. We then use the output from climate models as well as surveying results from the literature to establish expected changes to these large scale drivers. The results are then interpreted for their relationship to what might happen locally at Nauru (similar to the method applied by Risbey et al. 2002), and the level of certainty in such a projection is discussed.

2. DATA AND METHODS

Climate model data was obtained from the World Climate Research Program (WCRP) Coupled Model Intercomparison Project Phase 5 (CMIP5) database (Taylor et al. 2012). The 'historical' climate simulations were examined from up to 29 CMIP5 models. For each model, a single realisation (denoted by ensemble number r1i1p1) was analysed. Simulations performed with the CMIP5 models show some improvement in the simulation of current climate features of the Western tropical Pacific compared to earlier CMIP3 models (e.g. Jourdain et al. 2013); however, many of the biases in the Western Pacific remain.

The 'historical' climate simulations are compared with observations and are used to evaluate how well the main climate features are simulated. The future changes in the features and implications for climate projection of Nauru are discussed using current theory and results based on CMIP5 projections (mainly using the Representative Concentration Pathway 8.5 [RCP8.5] scenario).

Observed data products used in this study include merged multi-satellite/gauged products and latest generation reanalyses, including (1) CMAP: precipitation data from 1979 to 2008 (Xie & Arkin 1997); (2) Global Precipitation Climatology Project (GPCP) (Adler et al. 2003); (3) HadISST: sea surface temperature data from 1950 to 2000 (Rayner et al. 2003); and (4) ERA-I: ERA Interim (Simmons et al. 2006).

They were chosen as they provided the most comprehensive data sources available that matched the 1950–2000 period studied.

Local Nauru rainfall data from 1927 to present were provided by the Australian Bureau of Meteorology (ABoM), merging observations from a number of rain gauges in the Yaren province: 'Nauru1' (until April 1950), Nauru coastal station (to September 1977), Nauru Airport (1982 to January 1986), Nauru Automatic Weather Station (AWS) 'Nauru Arc-2' (July 2003 to December 2008) and a manual rain gauge within the AWS enclosure (January 2009 to present).

La Niña and El Niño years are defined here when NINO3.4 monthly anomalies exceed 60% of their standard deviation. An extreme El Niño is defined here as one when the NINO3.4 anomaly exceeds 150% of the standard deviation, with all other El Niño events being classified as 'moderate'. These standard deviation thresholds were chosen to correspond to NINO3.4 anomalies of >+0.5 and +1.2°C in the observations (for moderate and extreme El Niño respectively). This definition is easily applied to model values which can be both biased and liable to exhibit larger or smaller ENSO variability. The present-day period used for assessment is 1979 to 2008, a period when observational products are deemed more reliable than previously due to the inclusion of satellite data. The following events were identified:

(1) La Niña: 1984/1985, 1988/1989, 1995/1996, 1998/1999, 1999/2000, 2000/2001, 2005/2006 and 2007/2008;

(2) Moderate El Niño: 1986/1987, 1991/1992, 1994/1995, 2002/2003 and 2006/2007;

(3) Extreme El Niño/ zonal SPCZ: 1982/1983 and 1997/1998.

Note that 1991/1992 is classified as a moderate El Niño, although this year was a zonal SPCZ event (Vincent et al. 2011).

Here and in our following analysis it is not statistically valid to compare the small number of La Niña and El Niño events from the observational record with a large array of climate models run over long time periods. Nevertheless the biases in the model simulations of the events are clear.

3. RESULTS

The 4 climate features relevant to Nauru are the Western Pacific Warm Pool (WPWP), the Western Pacific Monsoon (WPM), the South Pacific Convergence Zone (SPCZ) and Intertropical Convergence Zone (ITCZ). Changes to El Niño Southern Oscillation (ENSO) modulate these features on interannual time scales. Here we discuss each climate feature, how well it is simulated in the GCMs, the expected changes from both the GCMs and current theory and, finally, the implications for Nauru.

3.1. Western Pacific Warm Pool

3.1.1. Historical period

Nauru lies at the edge of the WPWP (Fig. 2a). In La Niña years the warm pool contracts westward leaving slightly cooler water surrounding Nauru (Fig. 2c). In El Niño years, the warm pool expands eastward (Fig. 2e,g). However, there is relatively little change to the temperature of the water surrounding Nauru during these events. Seasonally there is also little variation in surface temperature (<0.5°C; see Fig. 3c, red line; Fig. 3d, black line). The low seasonal variability is a feature of the warm pool, in contrast to the cold tongue (east of the warm pool edge) where seasonal variability in SST is higher (Fig. 3d).

As was found in an assessment of the earlier CMIP3 models (J. N. Brown et al. 2013b), many CMIP5 models continue to simulate an equatorial warm pool edge situated further west than observed (Fig. 2b compared to Fig. 2a). An overly westward extension of the cold tongue means that, in many models, Nauru is effectively situated within the cold tongue instead of the WPWP. On interannual timescales the simulated SST variations at Nauru are therefore too strong (Fig. 2d,f,h). In effect, in some models Nauru is simulated to lie in the wrong 'climate zone' for the present-day climate.

Finding the 'corresponding climate location' for Nauru in each of the models is one method for accounting for this bias. Using the method of J. N. Brown et al. (2013a), we locate the edge of the warm pool in each model by finding the location where the salinity gradient is a maximum. We align these warm pool edges at 0° in Fig. 3d. J. N. Brown et al. (2013a) also determined a set of better performing models based on how well they simulate the mean longitude of the warm pool edge. For the models that do perform well at simulating the WPWP edge (filled lines) the seasonal variability is generally weaker in the west of the edge than in the east. For the poorer performing models (those with a warm pool edge too far west: dashed lines) the seasonal variability is generally too strong.

3.1.2. Projections

Around Nauru, there has been a warming trend in SST since the 1950s, with a rate of warming of ~0.12°C per decade since the 1970s (ABoM & CSIRO 2011a; Fig. 1d). Physical arguments and modelling studies suggest that mean temperature will continue warming throughout the tropical Pacific (e.g. Ganachaud et al. 2013). Climate model projections of the SST warming around Nauru (Fig. 1d) are dependent on the warming scenario studied, the climate sensitivity of the model used, but are also influenced by individual climate biases. Dynamically, the processes that cause warming within the warm pool are thought to be different to the processes in the cold tongue (DiNezio et al. 2010). Therefore it is useful to look at the warming structure at the edge of the WPWP when interpreting possible changes for Nauru.

A recent analysis by J. N. Brown et al. (unpubl.) determined the location of the dynamical warm pool edge at the equator as simulated in each model and displayed the projected changes in its properties over time. They estimated that the mean edge of the warm pool, for later this century (2050 to 2100) under a high emissions scenario (RCP8.5), would remain (on average) within 10° (east or west) of its present longitude and would warm by about +2 to +3°C (see their Fig. 5). They also found that the mean SST east of the warm pool edge warms significantly more than to the west. The warming patterns were also found to be a function of how well the model could simulate the WPWP—with better models warming less in the Western Pacific. A direct projection of SST change at the location of Nauru was up to 2.8°C different to that projected by this method that adjusts for the errors in the simulation of the edge of the warm pool.

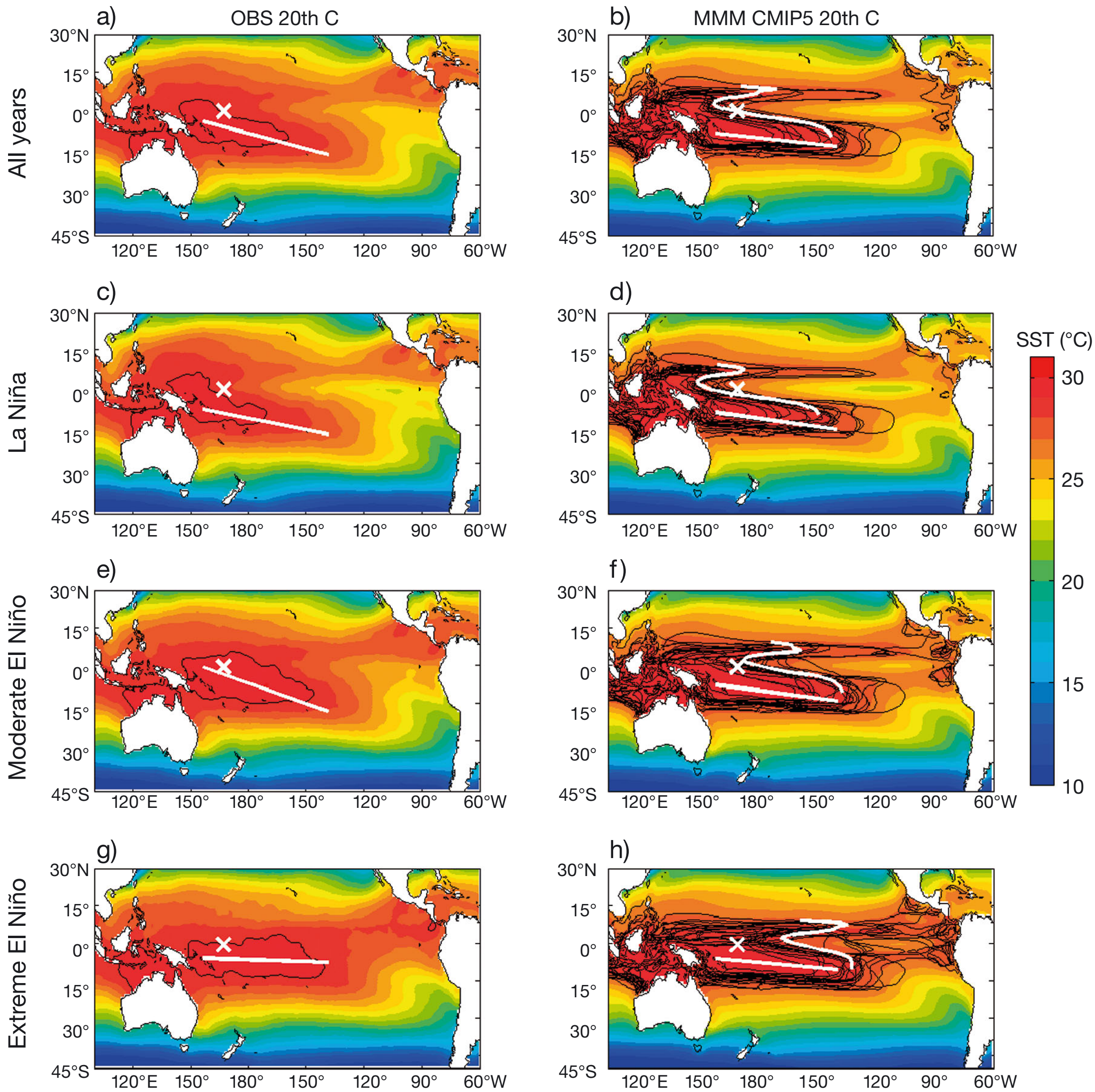


Fig. 2. Observed (OBS) sea surface temperature (SST) contrasted with the CMIP5 multi-model mean (MMM) over the 1950–2000 period for (a) HadISST all years, (b) CMIP5 MMM all years, (c) HadISST La Niña years, (d) CMIP5 MMM La Niña years, (e) HadISST moderate El Niño years, (f) CMIP5 MMM moderate El Niño years, (g) HadISST extreme El Niño years and (h) CMIP5 extreme El Niño years. Historical simulations: HadISST data and CMIP5 model data for years 1950–2000. X: location of Nauru. Black line: edge of the dynamic warm pool for the observations and each CMIP5 model; curved white line: multi-model mean position of warm pool; straight white line: South Pacific Convergence Zone (SPCZ) position as determined by linear fit method in Brown et al. (2011)

Projections of changes to the position of the WPWP edge are crucial for estimating changes in other features of the system. Near the edge, strong atmospheric convection occurs once the water warms above the convection threshold, currently estimated at close to 28.5°C (Sud et al. 1999). In the future, this isotherm is projected to move eastward with an expected equatorial warming. Theory and models, however, show that the threshold for convection should increase at a similar rate to the SST (Johnson & Xie 2010). The net result of the projected warming is that the zone of strong convection actually does not move far from its present day location, but just occurs at higher temperatures. This is most likely to have been the case during the Last Glacial Maximum (Hoyos & Webster 2011). Knowing that the models indicate little change in the location of the WPWP edge is also important for more complex projection studies involving ecosystems and fisheries where ocean convergence is important (e.g. Bell et al. 2013), not just changes in local temperature.

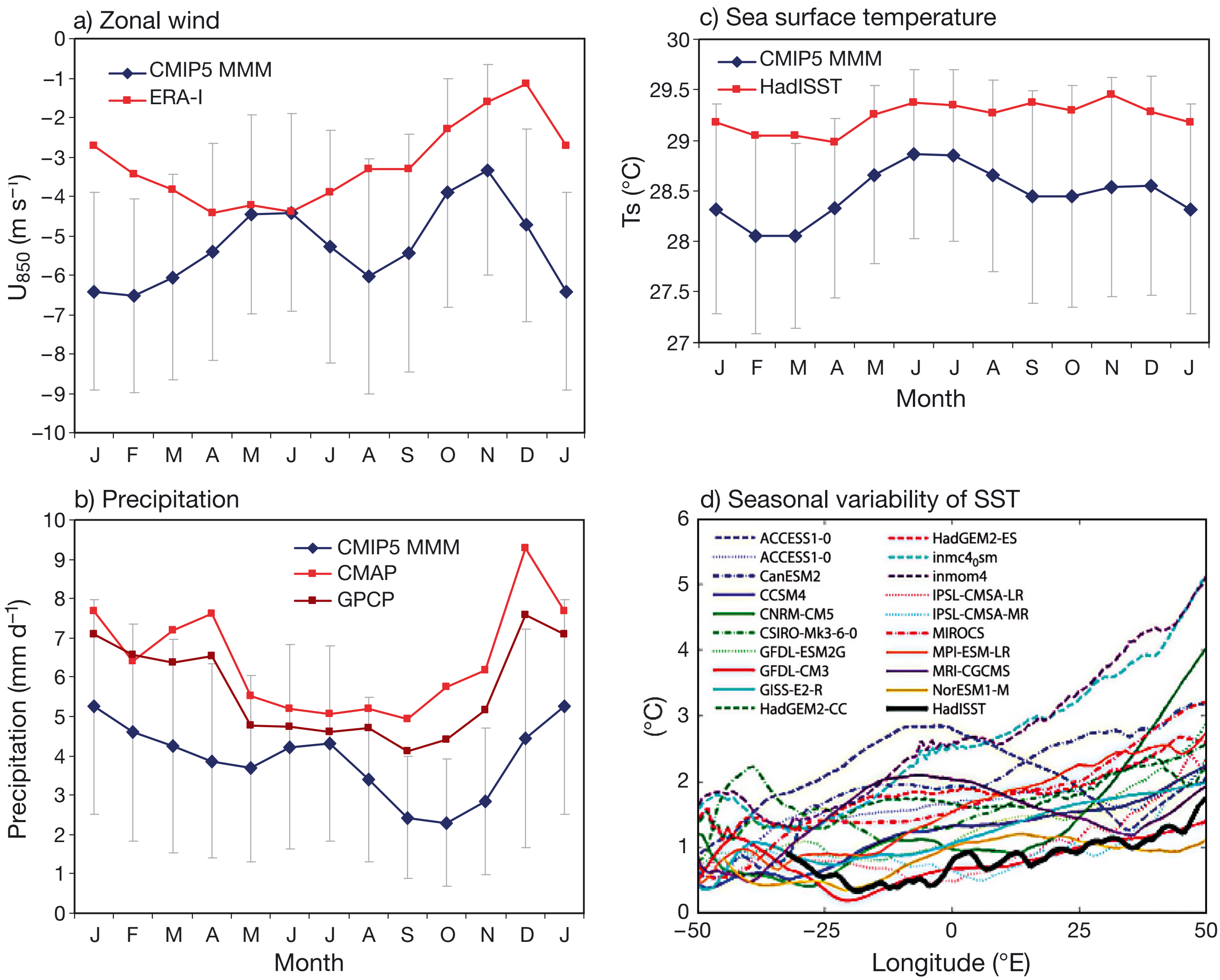


Fig. 3. Seasonal cycle of (a) zonal winds (u_{850}), (b) precipitation and (c) surface ('skin') temperature (Ts). Observed or reanalysis values in red and brown, CMIP5 MMM in blue. Error bars: 1 SD of model spread. All values are calculated over the region 165°–170°E, 2°S–2°N, for 1986–2005. (d) Magnitude of seasonal variation in equatorial sea surface temperature (SST) (max. to min. temperature) for HadISST and CMIP5 models. Results are plotted with respect to each model's Western Pacific Warm Pool (WPWP) edge (centred at 0°), and models with a 'better' simulated mean WPWP are plotted as filled lines, as defined by J. N. Brown et al. (2013a)

3.1.3. Implications for Nauru

Nauru presently lies on the WPWP edge and in a region of active convection in the present day. Based on GCM the projections for the Warm Pool, it seems likely that Nauru will remain within this warm SST, highly convective regime, and in a similar position relative to the edge of the dynamic warm pool. The surrounding waters are expected to warm by ~2 to 3°C over the 21st Century under the RCP8.5 emissions scenario.

3.2. Western Pacific Monsoon and seasonal cycle of winds and rainfall

3.2.1. Historical period

The region affected by the WPM undergoes a seasonal reversal of low level winds from dry season easterlies to wet season westerlies (Wang & Ding 2008). Nauru lies on the equatorial edge of the summer WPM region (Fig. 4a, red line). As such, Nauru's climate is not monsoonal, but is best described as lying within a continuously convective regime with a relatively weak seasonal cycle in climatological zonal wind. The climatological low-level mean winds have an easterly component all year round which weakens slightly during December to February (DJF) when rainfall also peaks (~50% stronger than the dry season; Fig. 3a,b).

However, the region is subject to very large interannual variability relative to the climatological annual cycle (Fig. 4b, red line compared to blue). In particular, during DJF, the easterly component frequently weakens and reverses due to ENSO-dominated variability as evidenced by the strong relationship between the zonal wind component and Nino3.4 (Fig. 4b, green line). In strong El Niño events (such as 1997/98 and 1982/83) westerly winds typically extend across Nauru and far to the east (Fig. 4a, pink lines), contiguous with the WPM region to the south.

Smith et al. (2012) found that relatively few CMIP3 models were able to reproduce the cycle of both winds and rainfall for regions located within the Western Pacific monsoon region. In the vicinity of

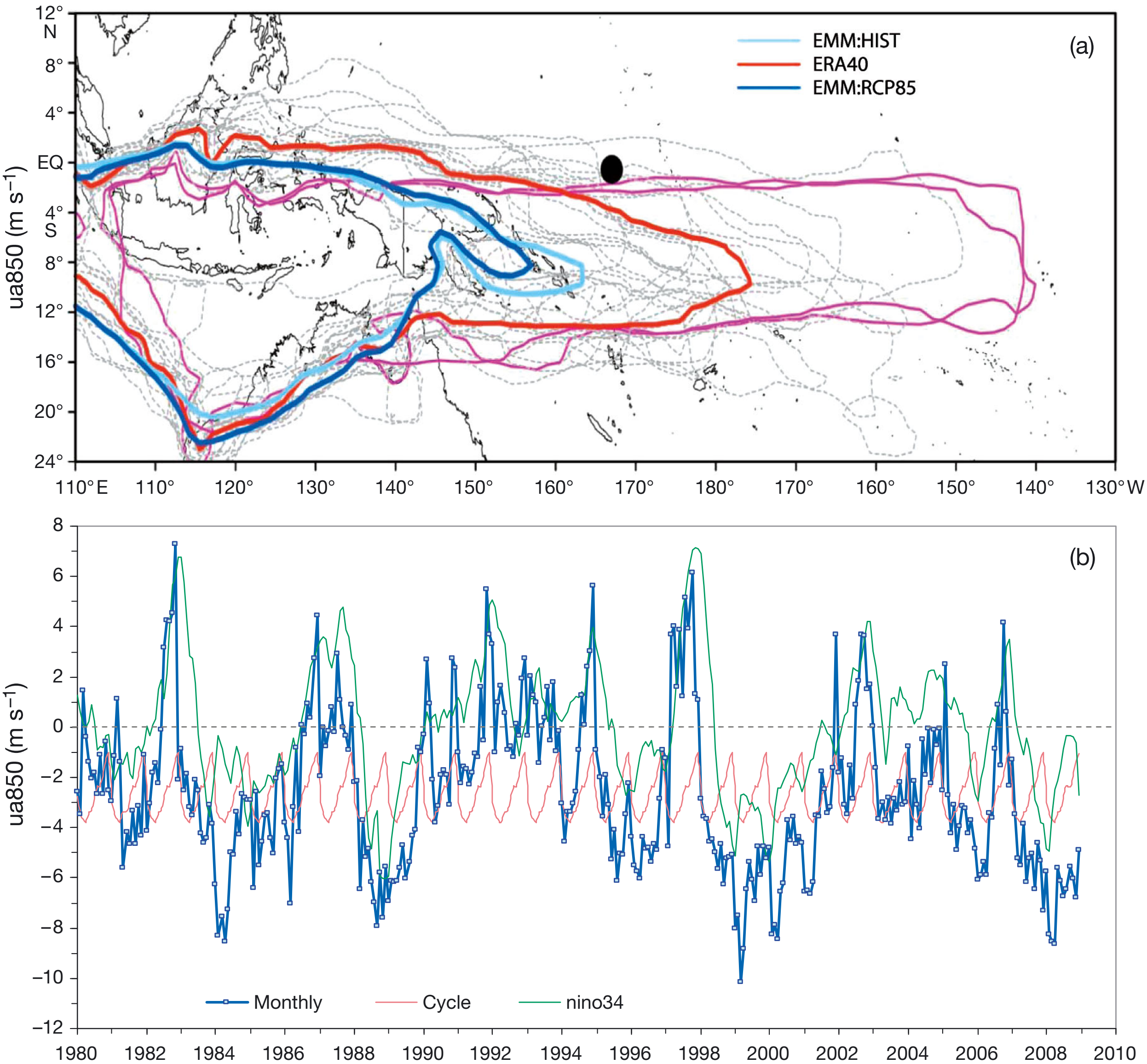


Fig. 4. (a) Representation of the Western Pacific Monsoon (WPM) edge in January in each year (1980–1999) according to low level circulation (ua850 winds) from ERA40 (grey dotted lines), 2 strong ENSO years (purple lines) and the 20-yr average position and extent (solid red line). Ensemble mean model (EMM) from CMIP5 Historical simulations (light blue) and RCP8.5 (dark blue line) future projected simulations are also shown. Black dot: location of Nauru. (b) Interannual variability of low level winds for Nauru (blue line, from ERA-I, 1980–2008), its annual cycle (red) and nino34 SST variability (green line, scaled by factor of 3 for comparison)

Nauru, the low-level winds are not well simulated. The multi-model mean winds have an overly strong easterly component, with a double peak in magnitude during DJF and June to August (JJA) (Fig. 3a). While the models appear to capture the gross features of rainfall seasonality (i.e. the maximum in DJF; Fig. 3b), they tend to underestimate the total annual rainfall, and fail to reproduce the peak of rainfall in March to April. Instead, they display a spurious additional JJA peak, the source of which is not yet understood.

The mean position of the monsoon edge is simulated to be too far west (January mean position is shown in Fig. 4a, cyan line). This is tied to the cold tongue bias discussed above which affects most models and shifts climatological features too far west. The strong bias in the easterly wind component, together with the bias in WPWP, also indicates that the models effectively place Nauru too far from the region of mean convection associated with the upward branch of the Walker Circulation.

3.2.2. Projections

There is little change to the simulated location of the edge of the WPM in the CMIP5 models (Fig. 4a, blue lines). Consequently, the projections suggest that it is likely that the monsoon will play a similar role in Nauru's climate as it does today (despite the fact that in the climate models the biased extent of the WPM means that it plays essentially no role on Nauru's climate in present day simulations).

Conversely, we have shown that the seasonal cycle of winds and rainfall over Nauru do contain some biases (Fig. 3b,c) and any future changes to these cycles should be carefully interpreted given that the models tend to simulate the monsoon edge too far from Nauru.

3.2.3. Implications for Nauru

Although the models locate the monsoon region too far west and south, the projections suggest that changes to the WPM and associated impacts on Nauru are likely to be modest. As Nauru lies on the edge of the WPM, if the WPM was to expand in the future, it may encompass Nauru, making Nauru's climate more monsoonal; however, there is no indication from the models that this is likely to occur.

3.3. South Pacific Convergence Zone and Inter-tropical Convergence Zone

3.3.1. Historical period

Nauru is also located in the region where the SPCZ and ITCZ merge (Fig. 5a). In the wet season (November to April), it is located in a wet, convective regime as the SPCZ intensifies and the ITCZ moves equatorward (not shown). In the dry season (May to October), rainfall decreases as the SPCZ weakens and the ITCZ moves northward.

In general, model representations of the SPCZ tend to be too zonal (Fig. 5b compared to Fig. 5a), as demonstrated by J. R. Brown et al. (2013). The simulated SPCZ and ITCZ also merge further west than observed due to the cold tongue SST bias and associated dry bias in this region. This contributes to the cold and dry bias in climatological rainfall over Nauru (Fig. 3b).

Fig. 5 also demonstrates that the CMIP5 models are able to realistically simulate meridional excursions of the SPCZ in response to ENSO events, consistent with previous studies (J. R. Brown et al. 2011, 2013). However, because the SPCZ tends to be simulated in the wrong location to begin with, the actual position of the SPCZ during ENSO events tends to be different to what is observed. In addition, only a subset of CMIP3 and CMIP5 models are able to realistically simulate the rarer 'zonal SPCZ' events (cf. Cai et al. 2012) that occur when eastern equatorial SSTs are significantly warmer than what is typically found in an El Niño event.

3.3.2. Projections

In response to the greater warming near the equator, the equatorward side of the SPCZ, at the longitude of Nauru, is projected to become wetter in both seasons. This is a robust response in the majority of CMIP5 models (J. R. Brown et al. 2013) as well as in model results where SST biases have been reduced (Widlansky et al. 2013). Widlansky et al. (2013) note that a moderate warming of only 1 to 2°C has a weak decrease in SPCZ intensity, while a warming of >3°C leads to a wetter SPCZ.

Using direct output, >80% of CMIP5 models project an increase in Nauru rainfall during the dry season (Figs. 6a & 1a), and the majority (>67%) of models project an increase in rainfall during the wet season (Figs. 6b & 1b). These increases are consistent with both 'thermodynamic' (i.e. increased water va-

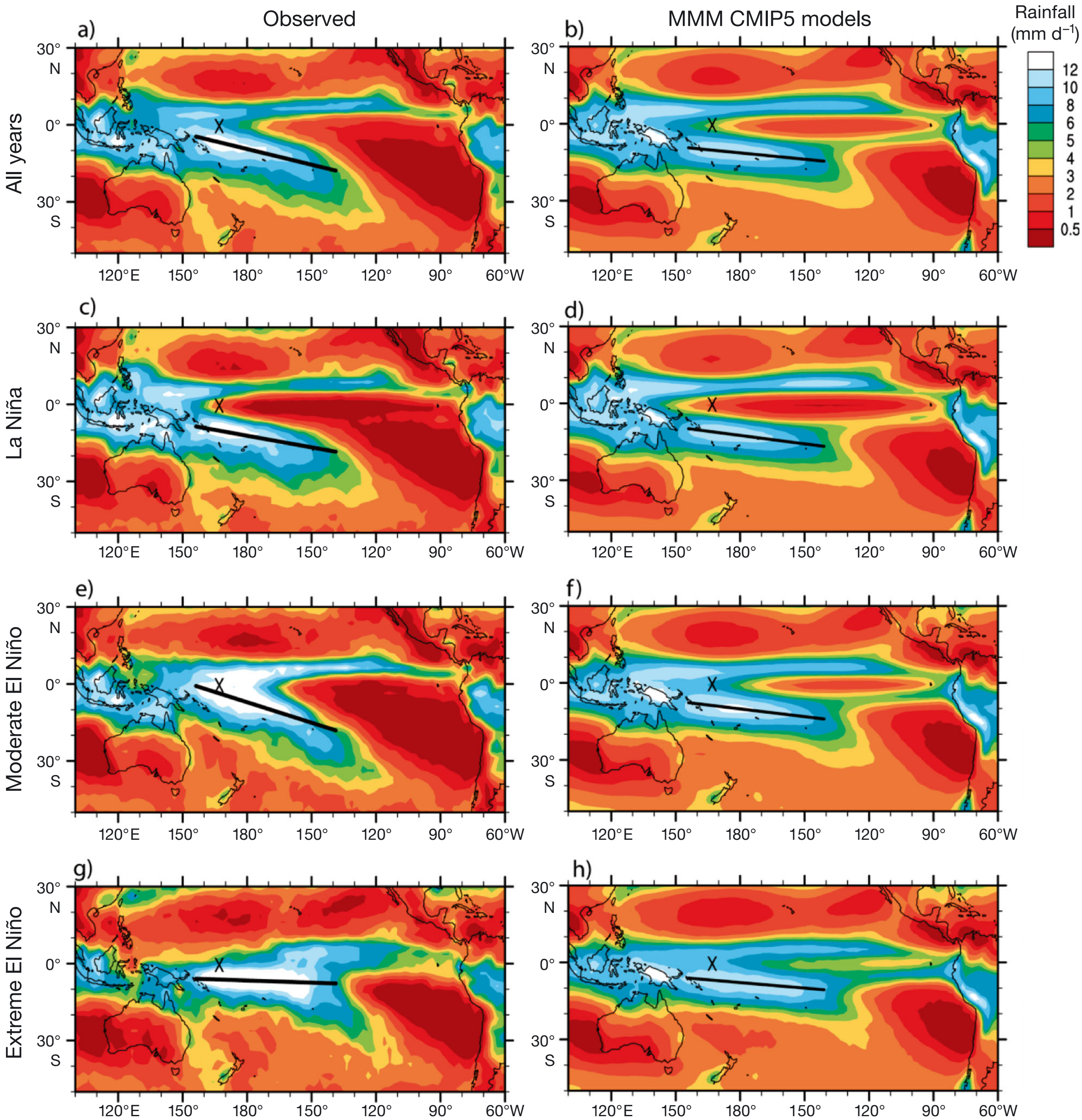


Fig. 5. December–February (DJF) rainfall: (a) CMAP all years, (b) CMIP5 Multi-Model Mean (MMM) all years, (c) CMAP La Niña years, (d) CMIP5 MMM La Niña years, (e) CMAP moderate El Niño years, (f) CMIP5 MMM moderate El Niño years, (g) CMAP extreme El Niño years and (h) CMIP5 extreme El Niño years. CMAP data for years 1979–2008 and CMIP5 model data for years 1970–1999 from historical simulations. Black line: South Pacific Convergence Zone (SPCZ) position fitted using linear fit method (Brown et al. 2011). X: location of Nauru

pour carrying capacity of the warmer atmosphere) and 'dynamic' (i.e. circulation change) effects (e.g. Held & Soden 2006, Seager et al. 2010, J. R. Brown et al. 2013). Even though models do not correctly simulate the position of the SPCZ and ITCZ relative to Nauru, the projection of increased rainfall is consistent with these physical arguments. The spatial uniformity of the projected increases along the equator (Fig. 6) suggests a high level of consensus amongst the models or, alternatively, a systematic bias affecting all models.

If we focus on just those models which have been assessed as 'better performers' in terms of their simulation of the warm pool edge and equatorial SST

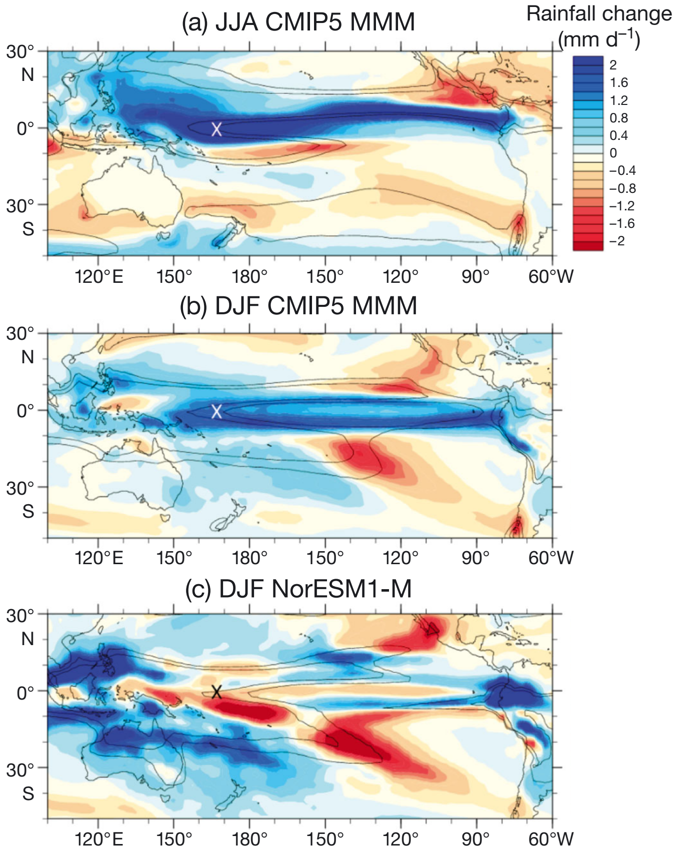


Fig. 6. Projected rainfall changes: RCP8.5 (2070–2099) minus Historical (1970–1999). CMIP5 multi-model mean for (a) June–August (JJA) and (b) December–February (DJF), and (c) single model projection for DJF from NorESM1-M. Black lines: 4 and 6 mm d^{-1} contours for Historical (1970–1999) seasonal mean rainfall. X: location of Nauru

structure (Brown et al. 2013a, Grose et al. in press) we can nominate the NorESM1-M, ACCESS1.0 and CNRM-CM5 models. These simulate weak decreases in rainfall for Nauru which are not statistically significant ($p > 0.05$). The output from the NorESM1-M model is shown in Fig. 6c to demonstrate how one model can differ from the multi-model mean. Limiting projections to the results of just a few models is not desirable as this would increase the uncertainty and may unfairly weight other biases that may not have been detected. If anything, these results suggest that projections of very large increases from the poorer performing models should be treated with caution.

3.3.3. Implications for Nauru

The task of simulating the present-day climate and generating rainfall projections for a region such as Nauru is a highly difficult and complex problem. Different models and projection methods lead to differing conclusions. Projections of the northern edge of the respective SPCZ in each model suggest an intensification of rainfall. However caution should be taken as the models with better SST representations project little or no change. This is one area that requires further research.

3.4. El Niño Southern Oscillation

3.4.1. Historical

El Niño Southern Oscillation (ENSO) is responsible for most of the interannual climate variability in the tropical Pacific by altering the position and magnitude of many climate features including the WPWP, WPM and SPCZ. Nauru rainfall fluctuations provide a perfect illustration of this and can be understood in terms of movements of the SPCZ. During El Niño events, the ITCZ and SPCZ tend to both move toward the equator in the wet season (Fig. 5c) bringing above average rainfall to Nauru. During La Niña events, the ITCZ and SPCZ tend to retract from the equator compared to their average wet season location, and so Nauru experiences relatively dry conditions.

However, during 2 recent extreme El Niño events (1982/1983 and 1997/1998), the SPCZ became more zonal, and the centre of convection associated with the SPCZ moved to the east of Nauru (Vincent et al. 2011, Cai et al. 2012) (Fig. 5g). Consequently, during these zonal SPCZ events, Nauru failed to experience the wet conditions normally associated with El Niño events (B. F. Murphy et al. unpubl. data), as shown in Fig. 7.

A further complication is that El Niño events sometimes involve warm SST anomalies that are more evident over the central equatorial Pacific than in the east. These have occurred more frequently in recent decades (McPhaden et al. 2011). In these situations Nauru tends to receive much more rainfall (ABoM & CSIRO 2011a, (B. F. Murphy et al. unpubl. data).

Simulations of ENSO in climate models are expressed through the drivers we have discussed. Therefore ENSO-related biases are also apparent in the warm pool position, and the position and orientation of the SPCZ. Any changes to ENSO related variability in a climate model are also conditional on how the biases manifest. How well ENSO is simulated in climate models is a much discussed topic. The latest CMIP5 models have improved ENSO simulations

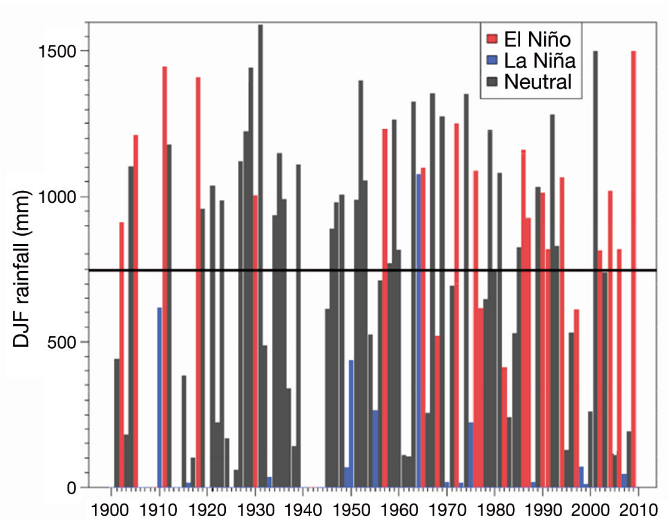


Fig. 7. Total December–February (DJF) rainfall at Nauru for each year for 1900–2009. ENSO phase: El Niño (red), neutral (grey) and La Niña (blue). Observations are from a combined Yaren rainfall site. Data is missing in years 1906–1909 and 1940–1944

compared to CMIP3, but this is partly attributable to the removal of the poorest performing models (Guilyardi et al. 2012). Biases still exist in the ENSO dynamics and SST perturbations (Kim & Yu 2012, Zhang & Jin 2012, J. N. Brown et al. 2013a) and the atmospheric teleconnections (Catto et al. 2012, J. N. Brown et al. 2013b). Further, it is unclear how ENSO will change in the future which is critical to understanding the future climate of Nauru (Vecchi & Wittenberg 2010, Guilyardi et al. 2012, Ganachaud et al. 2013).

3.4.2. Projections

Changes in rainfall in Nauru from ENSO will likely occur through changes in SPCZ intensity and location. All models project that ENSO will continue in the future, implying that the north–south movements of the SPCZ relative to Nauru will continue also. Fig. 8 shows the projected rainfall during both phases of simulated ENSO-like events and can be compared to Fig. 5d,f. During La Niña-like phases, Nauru is simulated to effectively fall into a dry regime as the SPCZ and ITCZ separate (as seen in observations; Fig. 5c,d). However, the same projections indicate that this dry regime does become slightly wetter in the models (compare Fig. 5d with Fig. 8a).

During El Niño phases, the SPCZ is observed to lie over Nauru (Fig. 5e) leading to relatively large rainfall amounts (~12 mm d^{-1}). Model projections suggest that the SPCZ gets wetter with a multi-model mean increase of about +20% (from ~10 to 12 mm d^{-1}), indicating this might be the expected projection for Nauru (compare Fig. 5f with Fig. 8b). If instead the projection is calculated directly from the location of Nauru in the models, the projection is a change from ~8 mm d^{-1} in the present day to 10 mm d^{-1} by the end of the century. Both increases correspond to an increase of 2 mm d^{-1}; however, one is based on changes in the intensity of the SPCZ (which lies over Nauru in reality) while the other is based on changes in the rainfall at the intersection of the SPCZ and ITCZ (which lies over Nauru in models).

It has been suggested (Cai et al. 2012) that zonal SPCZ events may become more common — primarily due to background SST warming, rather than any change to the frequency of extreme El Niños. While only 2 such events have been detected over recent time, an increase in the frequency of these events has the potential to seriously threaten water security for Nauru.

All models project that ENSO will continue to be an important source of variability in the future. By examining long control simulations from the climate models (figures not shown) we find that ENSO changes projected in many models lie within the range of the models' internal ENSO variability. Future projections therefore are really an exercise in sensitivity assessments considering the possibility that ENSO may con-

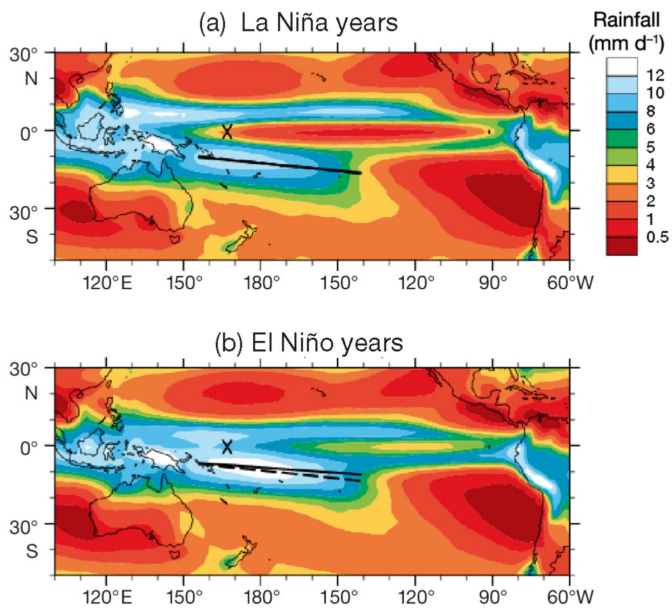


Fig. 8. CMIP5 multi-model mean December–February (DJF) rainfall (mm d^{-1}) for (a) La Niña years and (b) El Niño years for RCP8.5 (2070–2099) simulations. Solid line: South Pacific Convergence Zone (SPCZ) position for RCP8.5; dashed line: SPCZ position for Historical (1970–1999). Lines are fitted using linear fit method (Brown et al. 2011). X: location of Nauru

tinue unchanged, or it may increase or decrease in magnitude or frequency. This is critical information however; an increase (decrease) in the frequency of ENSO would mean dry La Niña and wet El Niño years occurring more (less) often. The spatial SST and surface wind structure of El Niño events may also change, with associated changes in rainfall impacts.

3.4.3. Implications for Nauru

In summary, relatively wet and dry years for Nauru, associated with moderate El Niño and La Niña events, are expected to continue. Zonal SPCZ events due to changes in background temperature may also increase, which may cause more atypical dry conditions during El Niño events. The fact that atmospheric moisture is expected to increase suggests rainfall associated with typical El Niño and La Niña events is likely to increase. Over at least the next 20 to 30 yr, changes to regional climate associated with natural ENSO variability are expected to be as important as any climate change signal.

3.5. Frequency and intensity of rainfall

3.5.1. Historical

Extreme rainfall events tend to be associated with tropical convective cells which are moderated by the MJO, the SPCZ, ENSO and interactions between them. Note that Nauru is not affected by tropical cyclones as it is situated too close to the equator.

The relationship between station rainfall and the MJO in the western Pacific has been analysed by Matthews & Li (2005). They were unable to include Nauru station data in their analysis due to insufficient data; however, they found that nearby stations in Kiribati had a strong MJO signal within their rainfall variability. The MJO must pass over Nauru to reach Kiribati, therefore if the MJO is significant for Kiribati, then it is likely to also be significant for Nauru.

Unfortunately, there are relatively few available long-term observed daily rainfall records for Nauru to allow us to investigate the processes leading to extreme rainfall. However, long-term, monthly rainfall records are available and it is possible to identify extreme events at this time scale (Fig. 7). For example, in December 2009, 880.1 mm fell compared to the December long-term average of ~250 mm. Since 2009 was an El Niño year, this wet anomaly is not surprising. Outgoing longwave radiation (OLR) data during this period indicates that the rain most likely arrived via an MJO event that stalled in the region of Nauru (Fig. 9). Other similar examples can be found where OLR data indicates a relationship between MJO behaviour and the monthly rainfall totals at Nauru.

To determine more robust relationships between the MJO and extreme rainfall, daily data is needed. A useful next step will be to obtain a longer time-series of daily data and link the high rainfall events to local convection patterns. This approach has already been trialled on the available high resolution data at Nauru since 1999 showing the relationships between precipitation and column water vapour (Holloway & Neelin 2010) and atmospheric circulation (Lintner et al. 2011).

Analyses of model outputs suggest that they do a reasonable job of capturing rainfall variability at the monthly timescale, despite the fact that the representation of the MJO in climate models is problematic (Lin et al. 2006, Hung et al. 2013). Studies of possible changes to the MJO suggest an increase in the variance of precipitation in the MJO frequency band (Liu et al. 2012). However the problems in simulating the MJO, as well as many other climate features, limit our ability to place high confidence in these projections, in particular the extent to which we can address possible changes to extreme rainfall events caused by any changes to the MJO (e.g. Dai 2006).

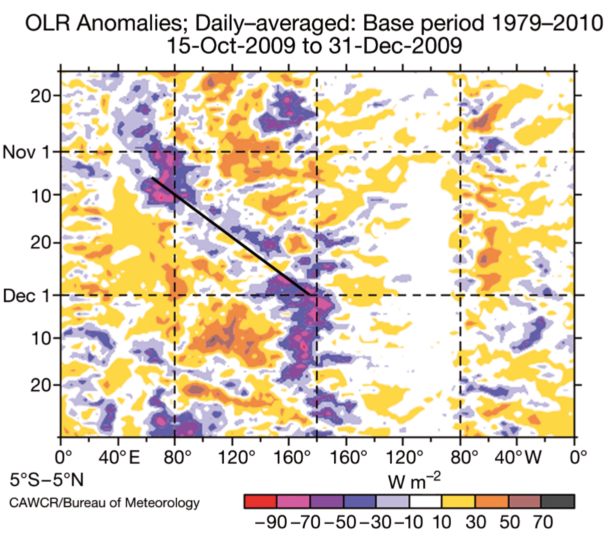


Fig. 9. Outgoing long wave radiation (OLR) anomalies averaged between 5°S and 5°N from mid-October to December 2009. Negative OLR anomalies are indicative of enhanced deep convection and increased rainfall. Thick black line: passage of the Madden Julian Oscillation (MJO) which stalls near the longitude of Nauru (167°E)

3.5.2. Projections

Analyses of extreme rainfall events is commonly assessed by quantifying the daily totals associated with a particular return values (e.g. the 1-in-20 year return events). Analysis of the simulation of these extremes in CMIP3 (Kharin et al. 2007) and CMIP5 (Sillman et al. 2013) have shown that model-based estimates for these measures vary considerably, particularly in the large inter-model disagreements in the Tropics. This is not unexpected given the fact that rainfall at small spatial and time scales is affected by many factors including surface topography (Smith et al. 2013).

In addition, coarse-scale GCMs can differ in their parameterization of important convective systems which contributes further to uncertainty in projections. Examples from 2 CMIP5 models (Nor-ESM-1M and CNRM-CM5) are presented here to demonstrate the diversity of projections (Fig. 10). Both these models are classed as having low biases in the western Pacific (Grose et al. in press). The NorESM1-M model shows a general tendency for increased 1-in-20 year return event values, with increases in the east but decreases in the west. The region surrounding Nauru is characterised by decreases. On the other hand, the CNRM-CM5 model also shows a tendency towards values for wetter 1-in-20 year events

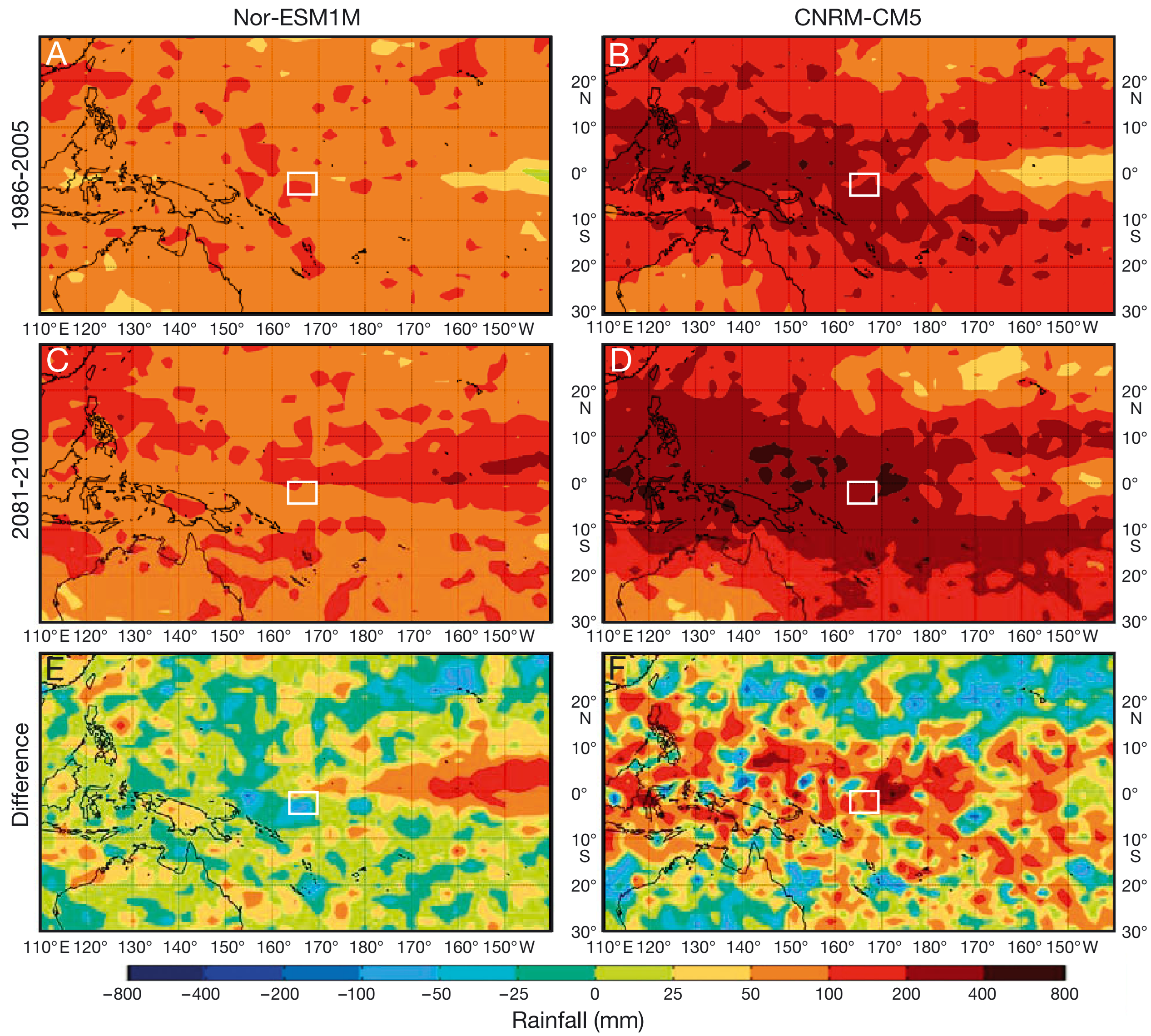


Fig. 10. Extreme rainfall values (mm) for the 1-in-20 yr event in 2 CMIP5 models: Nor-ESM1M (left) and CNRM-CM5 (right), for the period (a,b) 1986–2005 compared to (c,d) 2081–2100 values in the RCP8.5 scenario. (e,f) Difference between the 2 time periods. White rectangle: location of Nauru

over all regions (including Nauru) within the Pacific basin (Fig. 10e,f). The NorESM1-M model shows an increase in the east and decrease in the west for intensity of the 1-in-20 year event, while the CNRM-CM5 model has a noisy response, but is more suggestive of a basin-wide increase (Fig. 10e,f)

Theoretical arguments suggest that, globally, light rainfall events will occur less often and heavy rainfall events will become more common (Sun et al. 2007). Observational studies support this idea demonstrating that global average precipitation intensity is increasing under global mean warming, though observational estimates put this rate at ~23% K^{-1} (Liu et al. 2009), compared to climate model estimates of 2% K^{-1} (Sun et al. 2007, IPCC 2012), suggesting models are severely underestimating the response to climate warming.

A number of studies have explored the changes to some of the mechanisms that bring about projected rainfall changes in the tropical Pacific (Chou et al. 2009, 2012). Using 10 models from CMIP3, projected to 2081–2100 under the A1B scenario, Chen et al. (2012) found that, for the climate features relevant for Nauru, mean precipitation increases in a warmer climate due to an increased frequency and intensity of medium to heavy rain events, and fewer light rain events. Chen et al. (2012) demonstrated that thermodynamic changes to precipitation over the tropics do not show a strong spatial variation, and the magnitude of this contribution is close to that predicted by the Clausius–Clapeyron relationship, i.e. ~7.5% K^{-1}. The dynamic component of rainfall change introduces greater spatial variability in the tropics and largely controls whether there is an increase or decrease in precipitation frequency in the future. As is the case with projections for large scale features such as the SPCZ, small scale extreme rainfall projections are dependent on the spatial structure of the simulation of climate features and gradients in SST.

3.5.3. Implications for Nauru

Process-based studies suggest an increase in the frequency and intensity of extreme rainfall events over Nauru. At this stage there is no strong evidence indicating any dependence on season, phases of interannual variability, or features such as the MJO. Consequently, it is unclear whether coarse-scale model estimates of extreme rainfall are a useful guide for projected change to extreme rainfalls.

5. DISCUSSION AND CONCLUSION

Global climate models are important tools for understanding the global climate system and provide useful information for adapting to climate change. For some variables and regions, the present day climate is well simulated providing greater confidence in projections taken directly from the model output (Fig. 11). In other cases, particularly in regions of large model biases and for variables with spatially heterogeneous projected changes, a process based understanding can *complement* model output and assist in determining the confidence and rationale of a climate projection. In cases where there is no clear indication of future change, then the full range of possible changes should be explored. Where model uncertainty is large, or where critical biases exist, raw model output is unlikely to produce useful guidance. In such cases, a process-based study, such as the one presented here, can provide an *alternative*

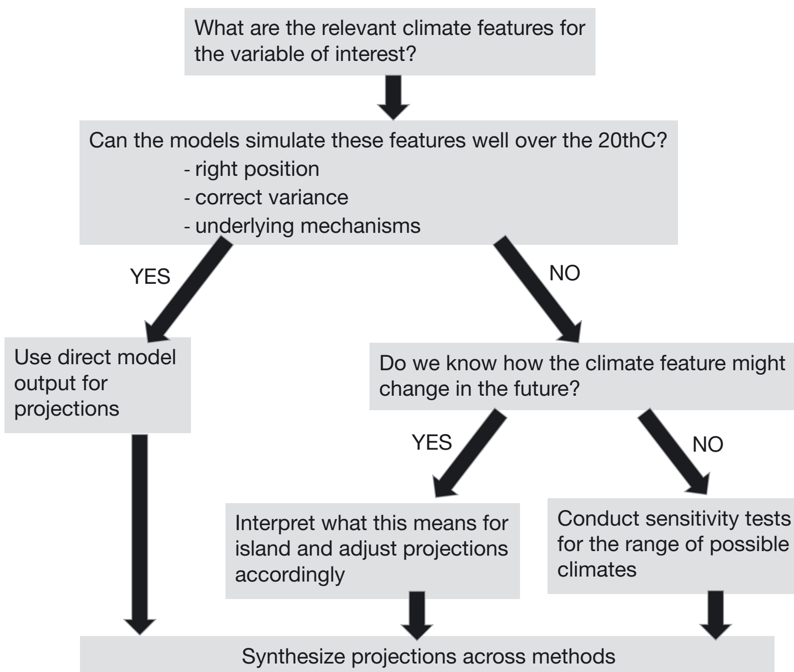


Fig. 11. Decision tree around methods for developing climate projections. When a climate model is able to simulate the relevant climate features well, then the use of direct model output is appropriate. If not, then either the biases in the climate features can be corrected or physically plausible future scenarios can be discussed. In any case, the outputs from each method should be synthesized in generating the final result

approach that can (1) explain why the model results are uncertain, (2) identify why some model results are less likely than others, and (3) better convey to end-users how their climate may change in the future. This approach is in line with the advice given in the IPCC Guidelines (Mastrandrea et al. 2010) for determining confidence ratings.

In the specific case of Nauru, raw model outputs indicate:

- An increasing trend for SST (Fig. 1d). While the direction of change is consistent across models, the magnitudes vary considerably.
- A very large diversity in rainfall projections (Fig. 1a–c). Reports that use this output (e.g. ABoM & CSIRO 2011b) often give accompanying confidence ratings to account for model biases and ranges of disagreement between model projections. In the case of Nauru's rainfall, this confidence is low. The interpretation of these results can only be that direct model output provides little guidance for Nauru's future rainfall, though there is a suggestion that an increase in rainfall is more likely than a decrease.

One of the goals of using a more qualitative process-based approach, based on more robust changes to climate features, is to draw out additional information and provide a more solid foundation for confidence ratings. By analysing the mechanisms driving rainfall variability we can assess which of these mechanisms has a more robust response and why, thus allowing us to say more about expected changes to the mean, extremes and variability. It also allows for confidence in the climate change signal to be increased in some cases. From reviewing the literature of projected changes to climate features, our study has led us to the following conclusions:

(1) Surface waters around Nauru will almost certainly continue to warm over the next 100 yr for global warming under the range of RCP emission scenarios. The range is likely to be 2 to 4°C by 2100 under the RCP8.5 scenario.

In accordance with global warming, the surrounding waters of Nauru are expected to warm, and consequently so will temperatures over Nauru. Nauru lies at the edge of the WPWP. Studies that explore changes to the region at the edge of the warm pool (rather than at the location of Nauru) in climate models suggest a warming of ~2 to 4°C through the 21st Century under RCP8.5. Determining the warming rate from this adjustment to the edge of the warm pool leads to a lower projection on average. This is because many models place Nauru in the cold tongue instead of the warm pool, which is warming at a faster rate. While a warming trend is consistent with the CMIP5 model direct outputs, it can be seen with higher confidence due to the process-based understanding shown.

(2) It is likely that dry season rainfall totals will increase on average. Wet season rainfall totals may increase, or have little change, but a large decrease is unlikely.

Nauru lies in a region of convective rainfall in the current climate. It is projected to stay in such a regime, with a warming of the surrounding SST, leading to increased atmospheric moisture and hence increased rainfall (via thermodynamic processes) in all seasons. Most climate models project increased rainfall via dynamic processes in the equatorial region, particularly in the dry season (May to October). In the wet season (November to April), shifts in the position and intensity of the SPCZ are more important for Nauru. As the position and intensity of the SPCZ is strongly influenced by underlying SST gradients, it is difficult to provide confident projections of future change based on the current generation of models. Further research is needed into the dynamics of the SPCZ and how it is affected by changing SST patterns.

(3) Heavy and extreme rainfall events are expected to increase in frequency and intensity.

In addition to changes in seasonal and annual mean rainfall, recent studies suggest that there will be an increase in the frequency and intensity of heavy precipitation, and a decrease in the frequency and intensity of light precipitation. Such changes may have adverse impacts, for example producing flooding or damaging crops. Changes to MJO could influence the incidence of extreme rainfalls, but there is insufficient physical understanding on the projected trend in MJO to infer changes to extremes through this mechanism.

Similarly the extreme rainfall events are expected to intensify. Models vary in their simulation of extreme events, and are not always spatially coherent in their projections over the western equatorial Pacific. However, extreme events have some of the greatest impacts, and improved simulation of such events is of great importance for Pacific Island nations (Nauru 1999).

(4) Strong interannual variability in rainfall will continue; however, both La Niña and El Niño are projected to be wetter than in the past. Zonal SPCZ events may become more frequent resulting in lower rainfall than what is normally expected in an El Niño.

Future changes (if any) to ENSO behaviour will strongly affect water security for Nauru. At this stage there is no consensus on how ENSO will alter in magnitude, frequency or even type. It is expected that this mode of variability will continue and will affect the climate features in similar ways to the present.

The ENSO signal in Nauru's rainfall occurs due to the north–south movements of the SPCZ, ITCZ and changes in the eastern edge of the WP monsoon. During La Niña, the SPCZ moves away from Nauru; however, models show that the rainfall will still increase in these events. The bias in the position of the SPCZ in models however may impact this finding.

During El Niño, the SPCZ is projected to intensify (J. R. Brown et al. 2013). As the SPCZ lies over Nauru during ENSO events, it is expect that the typical amount of rain in this phase may increase. An exception is the zonal-SPCZ events, such as occurred in 1997/1998 and 1982/1983. In these cases the SPCZ moved away from Nauru, meaning rainfall was below average. Zonal SPCZ events are projected to become more common in the future, though irrespective of how the characteristics of El Niño are projected to change.

Some of Nauru's main concerns around climate change are related to drought and extreme rainfall. Our study shows that these issues will remain significant, and may become more problematic in the future. Despite indications of increased rainfall over Nauru on average, the dry La Niña years will continue, and the possible increase in zonal-SPCZ, El Niño will not always return the rainfall in the 'good' years. By contrast, extreme wet events damage infrastructure, and cause contamination of ground water with consequences for human health. It is very likely that these extreme rainfall events will continue in the future and they are projected to become heavier and more frequent.

This research highlights some key areas of uncertainty that require further exploration:

(1) How ENSO will change in the future.

(2) How the SPCZ will respond to changing SST patterns.

(3) Changing structure of the western Pacific warm pool.

(4) Understanding the MJO and how its impacts will change in the future.

(5) Relationship between changes to extreme rainfall and longer modes of variability.

(6) Closely monitor and compare current trends with model projections.

Our qualitative method of constructing a climate projection offers an alternative way to extract additional projection information from climate models at the island scale when direct model output is not appropriate (Fig. 11). In some cases our findings are consistent with the direct model output, but this is often fortuitous, as the processes responsible for change may be different. A process based analysis provides reasoning for the climate change. Physically plausible projections, where values of change are underpinned by a physical understanding of the likely changes driving them, can be used with more confidence than projections given without context. Down-scaling and regional models provide another approach to overcoming limitations related to low resolution of climate models (something that our qualitative approach does not tackle). However, downscaling does not remove the inherent biases in the externally forcing from climate models (see Risbey & O'Kane 2011, J. N. Brown et al. 2013b for further discussion around these issues)

An additional value of this qualitative approach is that the rationale for the projections and their limitations or confidence ratings is made explicit. We argue that there is higher confidence in our conclusions, given that they have, to the extent possible, accounted for model biases. This discussion may provide further guidance for both users of climate scenarios and in targeting critical uncertainties for further research.

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