El Niño–Southern Oscillation and Associated Climatic Conditions around the World during the Latter Half of the Twenty-First Century

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ABSTRACT

Increases in greenhouse gas emissions are expected to cause changes both in climatic variability in the Pacific linked to El Niño–Southern Oscillation (ENSO) and in long-term average climate. While mean state and variability changes have been studied separately, much less is known about their combined impact or relative importance. Additionally, studies of projected changes in ENSO have tended to focus on changes in, or adjacent to, the Pacific. Here we examine projected changes in climatic conditions during El Niño years and in ENSO-driven precipitation variability in 36 CMIP5 models. The models are forced according to the RCP8.5 scenario in which there are large, unmitigated increases in greenhouse gas concentrations during the twenty-first century. We examine changes over much of the globe, including 25 widely spread regions defined in the IPCC special report *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX). We confirm that precipitation variability associated with ENSO is projected to increase in the tropical Pacific, consistent with earlier research. We also find that the enhanced tropical Pacific variability drives ENSO-related variability increases in 19 SREX regions during DJF and in 18 during JJA. This externally forced increase in ENSO-driven precipitation variability around the world is on the order of 15%–20%. An increase of this size, although substantial, is easily masked at the regional level by internally generated multidecadal variability in individual runs. The projected changes in El Niño–driven precipitation variability are typically much smaller than projected changes in both mean state and ENSO neutral conditions in nearly all regions.

1. Introduction

El Niño–Southern Oscillation (ENSO) is a naturally occurring phenomenon centered in the equatorial Pacific (Collins et al. 2010) that modulates climatic conditions in many regions around the world (e.g., Ropelewski and Halpert 1989; Power et al. 1999; Diaz and Markgraf 2000; Christensen et al. 2013; Nurse et al. 2014; Murphy et al. 2014; Poveda et al. 2001; Mo 2010; Brönnimann et al. 2007; Zhang et al. 1996, 1999; Shabbar and Khandekar 1996; Nakagawa et al. 2000; Kripalani and Kulkarni 1997; Nurse et al. 2014; Smith et al. 2013;

Lough et al. 2016; Australian Bureau of Meteorology and CSIRO 2011a,b). ENSO is active during two phases, El Niño and La Niña, and inactive during so-called neutral years, when climatic conditions in the equatorial Pacific tend to be near their long-term average. “Business-as-usual” increases in greenhouse gas concentrations are expected to cause future changes to both year-to-year precipitation variability in the Pacific linked to ENSO (Power et al. 2013; Cai et al. 2015; Chung et al. 2014; Chung and Power 2016; Watanabe et al. 2014; Seager et al. 2012; Huang and Xie 2015; Huang 2016), as well as changes in long-term average temperature and precipitation in many locations (e.g., Power et al. 2012; Collins et al. 2010; IPCC 2013, 2014; Lough et al. 2016).

While mean state and variability changes have been studied separately, very little is known about their combined impact or relative importance during future El Niño or La Niña years. Bonfils et al. (2015) recently helped to fill this gap by estimating the contribution of changes to both ENSO-driven variability and mean state changes to December–February (DJF) precipitation in

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the twenty-first century. They concluded that global warming tends to enhance both El Niño– and La Niña–driven precipitation variability in most locations and that twenty-first-century ENSO-driven anomalies, when combined with projected mean state changes, can, in some regions, cause unprecedented precipitation.

Here we extend this work to include examination of changes during June–August (JJA) and in ENSO-related surface temperature variability. We also assess the robustness of their key results for DJF using an alternative approach, and we identify several major features of the results that have not been identified previously. We will, for example, provide a quantitative estimate of the increase in ENSO-driven variability around the world, compare the size of changes in ENSO-driven variability with the size of changes in both mean state and ENSO neutral conditions, and consider the signal-to-noise ratio and the implications it has for future climatic conditions at a regional level.

The framework we use in this investigation is schematically represented in Fig. 1. In this idealized example precipitation in El Niño years during the twentieth century (E_{20}) tends to differ from precipitation experienced during neutral years (N_{20}), and precipitation during the twenty-first century in El Niño years (E_{21}) is different from precipitation experienced during twenty-first-century neutral years (N_{21}). We refer to these differences (i.e., $\delta E_{20} = E_{20} - N_{20}$ and $\delta E_{21} = E_{21} - N_{21}$) as El Niño–driven *deviations* throughout this paper. Note that El Niño–driven deviations differ from El Niño–driven *anomalies* (i.e., differences between E and the average) in places where the average and N differ.

In the schematic, the late twenty-first-century El Niño–driven deviation ($\delta E_{21} = E_{21} - N_{21}$) differs from its twentieth-century counterpart ($\delta E_{20} = E_{20} - N_{20}$), so that $\Delta\delta E = \delta E_{21} - \delta E_{20} \neq 0$, and precipitation during ENSO neutral years during the twenty-first century (N_{21}) is different from its twentieth-century counterpart (N_{20}). In this paper the symbol Δ is used to indicate changes that occur in response to external forcing. Thus $\Delta\delta E$, for example, represents the projected change in El Niño–driven deviations. Under this simple framework precipitation during future El Niño years can be expressed as $E_{21} = N_{20} + \delta E_{20} + \Delta\delta E + \Delta N$, where $\Delta N = N_{21} - N_{20}$. Similarly, precipitation during La Niña years in the twenty-first century can be expressed as $L_{21} = N_{20} + \delta L_{20} + \Delta\delta L + \Delta N = L_{20} + \Delta\delta L + \Delta N$, where $\Delta\delta L = \delta L_{21} - \delta L_{20}$, and where $\delta L_{21} = L_{21} - N_{21}$ and $\delta L_{20} = L_{20} - N_{20}$ refer to precipitation deviations during La Niña years in the twenty-first and twentieth centuries, respectively. These symbols, and the relationships between them, are summarized in Table 1.

We use output from CMIP5 models to estimate climatic conditions during ENSO events (we use the phrases ENSO events or years to refer to El Niño and La Niña events or years collectively) in the latter half of the twenty-first century. We examine changes during future El Niño years relative to neutral conditions during the twentieth century. This is a useful perspective, as it provides information on how future conditions will change relative to what has been experienced in the past. We also quantify the contribution of $\Delta\delta E$ and ΔN to the changes. This enables us to provide a much clearer picture of the role of El Niño in future climate than has been provided to date. We will find, for example, that in some regions δE_{20} , $\Delta\delta E$, and ΔN reinforce each other, producing precipitation extremes that are far greater than those typically experienced during El Niño events in the past.

Much of the discussion above is focused on climatic conditions during future El Niño events, relative to conditions experienced during the twentieth century. It is also useful to know how future climate conditions will vary from year to year in association with ENSO. Previous studies have examined this issue; however, they have tended to focus on changes in (see references above), or adjacent to, the Pacific (e.g., Kug et al. 2010; Meehl and Teng 2007). Here we examine changes to ENSO-driven variability over much of the globe, measured using $\Delta(E - L) = \Delta E - \Delta L = (\Delta\delta E + \Delta N) - (\Delta\delta L + \Delta N) = \Delta\delta E - \Delta\delta L$.

We examine changes between 45°S and 45°N, where most people live, and in 25 regions around the world identified previously in the IPCC special report *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX) (see Fig. 2 and Table 2; IPCC 2012). We consider regions in the Pacific, the Indian Ocean, North America, Central America and Mexico, “small islands” and the Caribbean, South America, Asia, southern Europe and the Mediterranean, Africa, and Australasia.

This paper is organized as follows. The models and methods used are described in section 2. This section also defines the 25 regions in which projected changes are analyzed. Model variability is briefly assessed in section 3. The results are provided in section 4, the reasons why ENSO teleconnections change (together with related issues) are discussed in section 5, and the main conclusions are presented in section 6.

2. Methods

a. Models and forcing scenario

Thirty-six models (see Table S1 in the online supplemental material) from the CMIP5 archive (Taylor et al.

FIG. 1. Schematic representation of climate variables (e.g., precipitation in a particular region) for the twentieth (blue line) and twenty-first (red line) centuries. The terms E_{20} , L_{20} , and N_{20} represent twentieth-century composites of precipitation during El Niño, La Niña, and ENSO-neutral years, respectively; E_{21} , L_{21} , and N_{21} represent their twenty-first century counterparts. The terms $\delta E_{20} = E_{20} - N_{20}$ and $\delta E_{21} = E_{21} - N_{21}$ represent the magnitude of El Niño-driven precipitation deviations in the twentieth and twenty-first centuries, respectively, and $\delta L_{20} = L_{20} - N_{20}$ and $\delta L_{21} = L_{21} - N_{21}$ are their La Niña-year counterparts. Also, $\Delta E = E_{21} - E_{20}$ represents the change in precipitation during El Niño years between the twenty-first and twentieth centuries, and $\Delta L = L_{21} - L_{20}$ represents the change in precipitation during La Niña years between the twenty-first and twentieth centuries. The change in the El Niño- and La Niña-driven precipitation deviations between the twenty-first and twentieth centuries are represented by $\Delta \delta E = \delta E_{21} - \delta E_{20}$ and $\Delta \delta L = \delta L_{21} - \delta L_{20}$, respectively. With this framework $E_{21} = E_{20} + \delta E_{20} + \Delta \delta E + \Delta N$, $L_{21} = L_{20} + \delta L_{20} + \Delta \delta L + \Delta N$, $\Delta E = E_{21} - E_{20} = \Delta \delta E + \Delta N$, $\Delta L = L_{21} - L_{20} = \Delta \delta L + \Delta N$, and the change in ENSO-driven precipitation variability is $\Delta(E - L) = (E_{21} - L_{21}) - (E_{20} - L_{20})$. Finally, $\Delta N = N_{21} - N_{20}$, which is the difference between the twentieth- and twenty-first century composites during ENSO-neutral years.

2012) forced using the RCP8.5 scenario are used. The details of this business-as-usual scenario are provided elsewhere (Moss et al. 2010; van Vuuren et al. 2011). All coupled climate models and the observations were re-gridded to a 1.5° latitude $\times$ 1.5° longitude grid prior to analysis.

b. Motivation for the framework used

Differences between El Niño-driven *deviations* (i.e., $E - N$) and El Niño-driven *anomalies* (i.e., $E - M$, where M is the average), can occur where M and N differ. Differences between M and N can arise in regions where the impact of El Niño on M outweighs the impact of La Niña years (e.g., in the central eastern Pacific; Chung and Power 2016). Consequently $E - M$ underestimates the full impact of El Niño on precipitation in such regions. Similarly, the impact of La Niña on

M outweighs the impact of El Niño in some regions (e.g., over parts of Australia; Power et al. 2006; Chung and Power 2017), and so $L - M$ underestimates the full impact of La Niña on precipitation in such regions. In both cases the impact of El Niño and La Niña on precipitation is therefore more accurately represented by $E - N$ ($=\delta E$) and $L - N$ ($=\delta L$), respectively.

In addition, the impact of global warming on precipitation depends upon the phase of ENSO in some regions (Chung and Power 2017). We therefore adopt a framework using N as the reference value rather than the average M , as this allows us to unambiguously quantify the impact of ENSO during the three phases of ENSO (i.e., neutral years, El Niño, and La Niña), and it avoids the ambiguity that can arise from asymmetric contributions to M from El Niño and La Niña. This framework differs from that used by Bonfils et al. (2015),

TABLE 1. Symbols used and the interrelationships.

Symbol	Definition	Relationship with other variables
E_{20}	Precipitation or temperature averaged over El Niño events during the twentieth century (i.e., 1950–99)	$E_{20} = N_{20} + \delta E_{20}$
E_{21}	Precipitation or temperature averaged over El Niño events during the twenty-first century (i.e., 2050–99)	$E_{21} = N_{20} + \delta E_{20} + \Delta \delta E + \Delta N$
L_{20}	Precipitation or temperature averaged over La Niña events during the twentieth century	$L_{20} = N_{20} + \delta L_{20}$
L_{21}	Precipitation or temperature averaged over La Niña events during the twenty-first century	$L_{21} = N_{20} + \delta L_{20} + \Delta \delta L + \Delta N$
N_{20}	Precipitation or temperature averaged over neutral years during the twentieth century	
N_{21}	Precipitation or temperature averaged over neutral years during the twenty-first century	$N_{21} = N_{20} + \Delta N$
δE_{20}	Difference between precipitation during El Niño years and neutral years, twentieth century	$\delta E_{20} = E_{20} - N_{20}$
δE_{21}	Difference between precipitation during El Niño years and neutral years, twenty-first century	$\delta E_{21} = E_{21} - N_{21}$
δL_{20}	Difference between precipitation during La Niña years and neutral years, twentieth century	$\delta L_{20} = L_{20} - N_{20}$
δL_{21}	Difference between precipitation during La Niña years and neutral years, twenty-first century	$\delta L_{21} = L_{21} - N_{21}$
$\Delta \delta E$	Change in δE between the twentieth and twenty-first centuries	$\Delta \delta E = \delta E_{21} - \delta E_{20}$
$\Delta \delta L$	Change in δL between the twentieth and twenty-first centuries	$\Delta \delta L = \delta L_{21} - \delta L_{20}$
ΔN	Difference between precipitation in the twentieth and twenty-first century neutral years	$\Delta N = N_{21} - N_{20}$
$(E - L)_{20}$	Difference between precipitation during El Niño and La Niña years, twentieth century	$(E - L)_{20} = E_{20} - L_{20}$
$(E - L)_{21}$	Difference between precipitation during El Niño and La Niña years, twenty-first century	$(E - L)_{21} = E_{21} - L_{21}$
$\Delta(E - L)$	Change in $E - L$ between the twentieth and twenty-first centuries	$\Delta(E - L) = (E - L)_{21} - (E - L)_{20}$

as they use the long-term average as their primary reference. We will examine differences that arise between the two methods in [section 4](#).

[Bonfils et al. \(2015\)](#) also employ an analysis method that is different from ours in several ways. For example, they project model precipitation variability onto the observed pattern of precipitation variability, whereas we use modeled patterns without projecting them onto observed variability. They also use a different method to isolate the ENSO variability. They remove the global average temperature and detrend, whereas we use spectral filtering. As it is important to know if these choices have a significant impact on the results, we will compare key results we obtain with the results obtained by [Bonfils et al. \(2015\)](#) for the period they focused on (i.e., DJF).

c. Classification of El Niño, neutral, and La Niña years

The method used to define El Niño, neutral, and La Niña years is the same as that used by [Power et al. \(2017a\)](#). A spectral filter was first used to eliminate climate variability and changes with periods longer than 13 years. Empirical orthogonal function (EOF) analysis ([Lorenz 1956](#)) was used to extract the first ENSO pattern in the

resulting interannual surface temperature of the observations and every model. The influence of the first EOF on interannual variability in area-averaged averaged sea surface temperature (SST) in the Niño-3.4 region (5°N–5°S, 170°–120°W) was then calculated for the observations and each model. The magnitude and sign of the resulting time series in each model, $N3.4^*(t)$ say, was then used to classify years as El Niño, La Niña, or neutral years using $N3.4^* > 0.8\sigma_{20}$, $N3.4^* < -0.8\sigma_{20}$ or $-0.8\sigma_{20} \leq N3.4^* \leq +0.8\sigma_{20}$, respectively. Here σ_{20} is the twentieth-century value of the standard deviation of $N3.4^*(t)$ in each model and t is time. The EOF analysis was performed on June–December averages of surface air temperature.

The results presented in this paper are based on the periods 1950–99 and 2050–99, after removing the first and last seven years from each period. These years were removed to avoid possible near-end issues associated with the spectral filtering used to calculate the EOFs. Spectral filtering was only used to define ENSO years. The composites presented are based on unfiltered data.

d. Regions

As mentioned in the introduction, special attention is given to changes in the 25 regions, comprising 21

FIG. 2. The 21 land-based regions used in this investigation (see Table 2 for abbreviations): North America (western North America, central North America, eastern North America), Central America/Mexico, small islands/Caribbean, South America (the Amazon, western South America, Northeast Brazil, southeastern South America), Asia (western Asia, Tibetan Plateau, East Asia, Southeast Asia), southern Europe/Mediterranean, Africa (Sahara, West Africa, East Africa, southern Africa), and Australasia (North Australia, southern Australia/New Zealand). The four oceanic regions (not shown) are the equatorial Pacific (180° – 220° E, 5° S– 5° N), the southern tropical Pacific (180° – 220° E, 15° S– 5° S), the northern tropical Pacific (180° – 220° E, 5° – 15° N), and the Indian Ocean (55° – 95° E, 25° S– 0°).

continental regions (see Fig. 2) and four oceanic regions. The regions are listed in Table 2. The four oceanic regions are the equatorial Pacific (180° – 220° E, 5° S– 5° N), the southern tropical Pacific (180° – 220° E, 15° S– 5° S), the northern tropical Pacific (180° – 220° E, 5° – 15° N), and the Indian Ocean (55° – 95° E, 25° S– 0°).

e. Stippling and stars in plots

Stippling in the maps and stars in the bar plots depicting model results indicate that two-thirds or more of the models agree on the sign of the change. We will refer to this as a robust result.

f. Observational data

We use three observational datasets, two for precipitation [GPCC (Schneider et al. 2015) for land regions and CMAP (Xie and Arkin 1997) for ocean regions] and one for sea surface temperature (HadISST; Rayner et al. 2003).

g. Significance test used in Fig. 3

The assessment of statistical significance of the ENSO signal in each region in Fig. 3 begins by identifying all of

TABLE 2. Regions examined (see Fig. 2).

Region	Region
Equatorial Pacific	EP
Southern Pacific	STP
Northern Pacific	NTP
Indian Ocean	IND
West North America	WNA2
Central North America	CNA2
East North America	ENA2
Central America/Mexico	CAM
Small islands region/Caribbean	CAR
Amazon	AMZ
West Coast South America	WSA
Northeast Brazil	NEB
Southeastern South America	SSA
West Asia	WAS
Tibetan Plateau	TIB
East Asia	EAS
South Asia	SAS
Southeast Asia	SEA
North Australia	NAU
South Australia/New Zealand	SAU
Southern Europe/Mediterranean	MED
Sahara	SAH
West Africa	WAF
East Africa	EAF
Southern Africa	SAF

the El Niño and La Niña years in the observational surface temperature record using the method outlined above. The observed precipitation that occurs during the El Niño and La Niña years is then identified and ranked in each region. The average rank of the precipitation during El Niño years is then calculated. For the regions over land, the data extend from 1950 to 2012, during which time there are a total of 13 El Niño years and 17 La Niña years. This gives a total of 30 ENSO years and corresponding ranks from 1 to 30. For the regions over ocean the data extend from 1979 to 2012, giving 6 El Niño years and 9 La Niña years and ranks from 1 to 15.

Monte Carlo simulations are then used to produce time series of artificial data of length 30 for land regions and 15 for ocean regions. The simulated time series are then ranked. The average rank of the first 13 years of the artificial time series (for land regions) or 6 years (for ocean regions) is then calculated and compared with the average rank of the observational data in each region. A total of 100 000 simulations are conducted. The percentage given in each subplot indicates the proportion of Monte Carlo simulations with average ranks that are less extreme than the corresponding observational value for El Niño years. The higher the percentage, the less likely it is that the observed rank can be achieved by chance, and the higher the statistical significance of the observed ENSO signal.

FIG. 3. Observed time series of JJA precipitation in the 25 regions. El Niño years are indicated with red circles and La Niña years with blue circles. Precipitation was averaged over each region. EOF analysis (as described in the text) was used to identify both El Niño and La Niña years. The percentages represent the proportion of Monte Carlo simulations (time series based on randomly selecting the data) that did not exhibit the ENSO signals as large as that present in the observations. The higher the percentage, the more robust the signal. See section 2 for further details. Data: GPCC (Schneider et al. 2015) for land regions, CMAP (Xie and Arkin 1997) for ocean regions, and Rayner et al. (2003) for SST data used to calculate the EOFs employed to categorize El Niño and La Niña years.

El Niño - La Niña precipitation composites (JJA)

FIG. 4. Histograms representing the difference between composites of JJA precipitation during El Niño and La Niña years (i.e., $E - L$), for observations (solid) and MMM (striped). Observational data used as in Fig. 3. Observational and modeled composites have the same sign in 23 of the 25 regions. A star above observational composites indicates that the five or more of the six El Niño events that occur during the period analyzed have precipitation deviations of the same sign. A star above modeled composites indicates that the sign of $E - L$ is the same in two-thirds or more of the 36 models used (i.e., 24 or more models). This corresponds to a statistical significance level of approximately 95% under the assumption of model independence. Because models exhibit codependencies, the corresponding statistical level is likely overestimated. See Power et al. (2012) for further details.

3. Model assessment

ENSO modulates precipitation in many of the 25 regions in both the observations and models (Figs. 3 and 4). While the ability of climate models to simulate ENSO has improved (Flato et al. 2013; Power et al. 2013; Bellenger et al. 2014), the simulation of ENSO in the latest generation of climate models is still not perfect (Flato et al. 2013; Power et al. 2013; Bellenger et al. 2014), and this is true for the difference between El Niño and La Niña precipitation deviations (i.e., $E_{20} - L_{20}$; Fig. 4). It is reassuring to note, however, that the models do have a degree of skill in simulating ENSO. This is reflected in the fact that the sign of $E_{20} - L_{20}$ is the same in the observations and the multimodel mean (MMM;

Fig. 4) in 23 of the 25 regions during JJA. The equivalent figure for DJF (not shown) is 20. The equivalent figures for El Niño deviations (not shown) alone are 21 out of 25 for both JJA and DJF.

4. Results

Projected changes in climatic conditions during future El Niño years

1) COMPARISONS BETWEEN $\Delta\delta E$ AND $E_{20} - N_{20}$ ($=\delta E_{20}$)

During JJA (Fig. 5; see also Table S2) the magnitude of ΔN exceeds the magnitude of $\Delta\delta E$, (i.e., $|\Delta N| > |\Delta\delta E|$),

El Niño precipitation composites (JJA)

FIG. 5. Histograms representing regional averages of JJA MMM precipitation (mm day^{-1}). From left to right in the histograms (see Table 1 for variable descriptions): $\Delta N = N_{21} - N_{20}$, (light gray bars); $\Delta\delta E = \delta E_{21} - \delta E_{20}$ (dark gray bars); $\delta E_{20} = E_{20} - N_{20}$ (blue bars); and $E_{21} - N_{20} = \delta E_{20} + \Delta\delta E + \Delta N$ (red bars). Black stars indicate that two-thirds or more of the models agree on the sign of the bar. Red stars indicate that two-thirds or more of the models agree on the sign of the difference between the values represented by the red and blue bars ($= E_{21} - E_{20} = \Delta\delta E + \Delta N$).

in 24 out of 25 regions. In fact in nearly all regions $|\Delta N| \gg |\Delta\delta E|$. The exceptions are southeastern South America, the southern tropical Pacific, and western North America.

Twentieth-century El Niño-driven precipitation deviations (δE_{20}) during JJA (Fig. 5; see Table S2) are reinforced robustly (i.e., in two-thirds or more of models) by $\Delta\delta E$ (i.e., δE_{20} and $\Delta\delta E$ have the same sign) in the equatorial Pacific. As variability in this region has a major impact on variability via teleconnections to many other regions, we might expect to see widespread robust changes elsewhere. However, reinforcement during JJA is only evident in 14 other regions. Furthermore changes in δE are only robust in four regions outside the equatorial Pacific.

El Niño-driven precipitation deviations during DJF (Fig. 6; Table S3) are reinforced by $\Delta\delta E$ in 16 regions, although the intensification is only robust in three regions.

2) COMPARISONS BETWEEN $E_{21} - N_{20}$ AND $E_{20} - N_{20}$ ($=\delta E_{20}$)

Precipitation during twenty-first-century El Niño events differs more from twentieth-century neutral conditions than does precipitation during twentieth-century El Niño events (Fig. 5; Table S2) in 20 regions. That is, $|E_{21} - N_{20}| > |\delta E_{20}|$ in 20 regions. However, the El Niño-driven deviations are only reinforced by $\Delta N + \Delta\delta E$ in 13 of these regions (i.e., the sign of $E_{21} - N_{20}$ is the same as the sign of δE_{20} in 13 regions). In the other seven regions there is a change of sign between δE_{20} and $E_{21} - N_{20}$. The regions exhibiting robust changes are identified in Fig. 5 using red stars.

Figure 6 and Table S3 indicate that DJF precipitation during El Niño years becomes more extreme (i.e., $|E_{21} - N_{20}| > |\delta E_{20}|$) in 18 of the 25 regions, although the

El Niño precipitation composites (DJF)

FIG. 6. As in Fig. 5, but for DJF.

El Niño-driven deviations are reinforced by $\Delta N + \Delta \delta E$ in only 14 of these regions. In other words, the sign of $E_{21} - N_{20}$ is the same as δE_{20} in only 14 of these 18 regions. The most robust changes occur in the equatorial Pacific, the southern tropical Pacific, western North America, eastern North America, Central America/Mexico, the West Coast of South America, southeastern South America, western Asia, the Tibetan Plateau, East Asia, Southeast Asia, southern Europe/Mediterranean, West Africa, and East Africa.

3) MAPS

Maps of δE_{20} , $E_{21} - N_{20}$, and other key quantities during JJA are presented in Fig. 7. The spatial structure of the simulated $E_{21} - N_{20}$ (Fig. 7c) is similar in many respects to the simulated δE_{20} (Fig. 7b) but is much larger in magnitude in many regions. This includes much more intense precipitation in the equatorial Pacific and much greater drying over equatorial Southeast Asia, the eastern equatorial Indian Ocean, and Mexico and Central

America. The reinforcement of δE_{20} in much of the equatorial Indo-Pacific arises because both ΔN (Fig. 7d) and $\Delta \delta E$ (Fig. 7e) tend to reinforce the twentieth-century El Niño-driven deviations (δE_{20} ; Fig. 7b).

The changes evident in $\Delta \delta E$ —which measure change in El Niño’s contribution to variability about a changing mean state (i.e., the “volatility”)—are consistent with previous research that focused on changes in ENSO-driven precipitation anomalies relative to a changed background state (Power et al. 2013, 2017a; Chung et al. 2014; Chung and Power 2015, 2016). These studies showed that the intensification of El Niño-driven anomalies primarily arises in the Indo-Pacific from a nonlinear interaction between background warming and largely unchanged El Niño-driven SST anomalies.

During JJA in the twentieth century, El Niño increases precipitation over the central and eastern Pacific (Figs. 7a,b, which show δE_{20} in the observations and models, respectively). Both the projected changes to both the ENSO-neutral state (ΔN) and El Niño deviations

FIG. 7. Precipitation (mm day⁻¹) maps for JJA showing (a) observational and (b) MMM values of δE_{20} , and MMM values of (c) $E_{21} - N_{20}$ ($= \delta E_{20} + \Delta \delta E + \Delta N$), (d) ΔN , and (e) $\Delta \delta E$. Stippling in (a) indicates that five or more of the six El Niño events that occur during the period analyzed have precipitation deviations of the same sign. Stippling in the remaining panels indicates that the sign of the change is the same in two-thirds or more of the 36 models used (i.e., 24 or more models). Observational data are from CMAP.

($\Delta \delta E$) reinforce the existing El Niño–driven deviations (δE_{20}) in the equatorial Pacific at this time of the year (i.e., JJA); however, the reinforcement from ΔN is much stronger.

This analysis reveals for the first time that changes to precipitation in future El Niño years during JJA are, relative to twentieth-century neutral conditions, primarily determined by changes in background climate

FIG. 8. As in Fig. 7, but for DJF.

rather than changes in El Niño–driven variability. This is also true for El Niño years during DJF (Fig. 8). It is also evident from comparing Figs. 7 and 8 that $\Delta\delta E$ tends to be greater over the equatorial Pacific during JJA than during DJF. This contrasts with ΔN (and the change in the mean; not shown) which is much larger during JJA than it is during DJF.

4) COMPARISON WITH BONFILS ET AL. (2015)

It is of interest to compare the results with those of Bonfils et al. (2015), who examined changes during DJF, as we have done in Fig. 8. As noted previously, Bonfils et al. (2015) used different techniques to estimate quantities related to ENSO-driven variability. Despite

FIG. 9. Precipitation (mm day^{-1}) maps showing JJA MMM values of (a) ΔN , (b) ΔM , and (c) $\Delta N - \Delta M$. Here M is the individual model mean, and $\Delta M = M_{21} - M_{20}$. Stippling indicates that the sign of the change is the same in two-thirds or more of the 36 models used (i.e., 24 or more models).

these differences, our results are very similar to those obtained by Bonfils et al. (2015; see their Fig. 4). This indicates that the main results are not sensitive to the details of either analysis method.

The results are similar in part because the projected change in the average [the reference used by Bonfils et al. (2015)] is very similar to the projected change in N (the reference value we use) nearly everywhere (Fig. 9). Given that we also used several different approaches in our analysis to the methods used by Bonfils et al. (2015), we can confirm that the main conclusions of both studies do not depend upon the details of the analysis method. It also indicates that ΔN (i.e., the change in precipitation during ENSO neutral years) can be regarded as a very good approximation to mean state change.

5) PRECIPITATION DURING EL NIÑO YEARS

The reinforcement of some important features of El Niño precipitation anomaly patterns is very marked. For example, the prominent dipole in the equatorial

Indo-Pacific in δE_{20} (Fig. 7) with drying over equatorial southeast Asia and the eastern Indian Ocean and enhanced precipitation over most of the equatorial Pacific, becomes over 200% more intense. Drying during El Niño becomes well over 200% more intense over central America/Mexico (cf. $E_{21} - N_{20}$ and δE_{20} in Fig. 7; i.e., cf. Figs. 7b and 7c).

As illustrated in Table S2, in some other regions ΔN has the opposite sign to δE_{20} , and this can reduce the magnitude or even change the sign of precipitation relative to N_{20} (i.e., of $E_{21} - N_{20}$). In East Asia, for example, precipitation during JJA declines in the twentieth century (i.e., $\delta E_{20} < 0$) are replaced by precipitation increases in the twenty-first century ($E_{21} - N_{20} > 0$; Fig. 5; Table S2).

These results reveal that in many regions, projected changes in precipitation during ENSO neutral years, in mean state precipitation, and in El Niño-driven precipitation deviations can lead to precipitation amounts during El Niño years that are very different from what

El Niño surface temperature composites (JJA)

FIG. 10. As in Fig. 5, but for surface temperature (i.e., histograms representing regional averages of JJA MMM surface temperature).

has typically been experienced in El Niño years to date (see, e.g., Figs. 4, 6–8a,b, and 9a,b).

6) SURFACE TEMPERATURE

The preceding sentence is true for surface temperature *everywhere* (Fig. 10), indicating that climatic conditions during future El Niño events—including both temperature and in many places precipitation—will be very different to what has been experienced in the past over the entire surface of Earth (we have examined 45°S–45°N, but we know that surface temperature also increases at higher latitudes). Figures 5–8 and 10 indicate, however, that this is largely due to ΔN , not $\Delta \delta E$.

Figure 10 also shows that there is a small but robust reduction in the magnitude of El Niño-driven surface temperature deviations in the equatorial Pacific. This will act to partially offset the enhancement of the El Niño-driven precipitation anomalies arising from non-linearity (Power et al. 2017a).

7) PROJECTED CHANGES IN ENSO-DRIVEN VARIABILITY

So far we have examined climatic conditions during future El Niño years relative to N_{20} and changes in the magnitude of El Niño-driven precipitation and temperature deviations. In this subsection we extend the analysis by examining changes in ENSO-driven variability between twenty-first-century El Niño years and twenty-first-century La Niña years. This variability is an important feature of future climate, as the larger this variability is, the greater the impact the variability will tend to have on managed and natural systems.

A simple and useful measure of ENSO-driven variability is $E - L$ (i.e., the difference between precipitation in El Niño and La Niña years) (see Fig. 1 and Table 1). The projected changes in $E - L$ are depicted in Fig. 11 (JJA) and Fig. 12 (DJF) and Tables S4 and S5. Note that $E - L$ is projected to increase in 18 of the 25 regions during JJA and in 19 regions during DJF. This

El Niño - La Niña precipitation composites (JJA)

FIG. 11. Histograms representing regional averages of JJA MMM El Niño (δE_{20} and δE_{21} ; blue and red bars on the left side of each panel) and La Niña (δL_{20} and δL_{21} ; two middle bars) precipitation deviations (mm day^{-1}) and ENSO-driven precipitation variability (mm day^{-1} ; $E_{20} - L_{20}$ and $E_{21} - L_{21}$; bars on the right side of each panel), in the twentieth and twenty-first centuries.

is consistent with previous studies showing that El Niño-driven (Chung and Power 2015, 2016) and La Niña-driven (Chung and Power 2014, 2016) precipitation anomalies in the Pacific will increase and that precipitation variability generally over the Pacific will tend to increase (e.g., Power et al. 2017a). These results are collectively significant at a high level. It should be noted, however, that the changes in $E - L$ are only robust in four regions during JJA and three regions during DJF. All robust changes during JJA and DJF represent an intensification of the twentieth-century $E - L$ signal.

Of the 15 regions with robust $E - L$ signals during JJA in the twentieth century, 12 regions have signals that intensify during the twenty-first century, although only four of the increases are robust. None exhibits robust weakening. Of the 20 regions with robust $E - L$ signals during DJF in the twentieth century, 17 regions have signals that intensify during the twenty-first century,

although only three of the increases are robust. None of these 20 regions exhibits robust weakening.

If we restrict attention to regions beyond the equatorial Pacific with a robust ENSO signal in the twentieth century (see Tables S4 and S5), then there is a 21% median increase in ENSO-driven precipitation variability in JJA in the 14 regions (with increases in 12 of the 14 regions, a result that is statistically significant at the 99.9% level) and a 16% median increase in DJF across 19 regions (with increases in 14 regions, with statistical significance $> 99\%$ level).

The results suggest that the robust increase in the magnitude of variability in the tropical Pacific appears strong enough to produce a 15%–20% increase in variability in many regions beyond the tropical Pacific. The results for the regions taken collectively are highly robust in the sense that it is extremely unlikely to see such widespread agreement on the sign of change in so many

El Niño - La Niña precipitation composites (DJF)

FIG. 12. As in Fig. 11, but for DJF.

regions by chance. However, when the regions are examined individually, the projected changes are only robust in a very limited number of regions. These last two results (i.e., a collective significance that is very high, but with low statistical significance in individual models at the region level) are consistent with the presence of a pervasive signal (i.e., a widespread increase in ENSO-driven variability) that has a low signal-to-noise ratio at the regional scale. Thus the projected increase in ENSO-driven variability is easily masked in individual models on a regional scale by naturally occurring, internally generated multidecadal variability. Internal variability can occur as random contrasts in ENSO activity on multidecadal time scales, as well as in internal processes not related to ENSO that also influence climate in the regions examined.

8) CHANGES IN $(E - L)/N$

We have seen that N exhibits increases and decreases across the globe, while $E - L$ tends to increase in

magnitude. It is also of interest to know if $E - L$ tends to increase if it is expressed as a fraction of N . The answer is yes. In JJA, 14 of the 15 regions that have a robust twentieth-century $E - L$ signal exhibit an increase in $(E - L)/N$ from the late twentieth century to the late twenty-first century, a result that is statistically significant above the 99.99% level. In DJF $(E - L)/N$ increases in 13 of the 20 regions that have a robust twentieth-century $E - L$ signal (statistically significant above the 94% level). The median percentage increases in $(E - L)/N$ are 36% (JJA) and 10% (DJF).

9) $|\Delta N/N|$ COMPARED WITH $\Delta(E - L)/(E - L)$

As noted above, $|\Delta N|$ tends to be much larger than $|\Delta \delta E|$. However, the size of the fractional changes in N and $E - L$ show the reverse relationship. In other words, $|\Delta N/N|$ tends to be much smaller than $|\Delta(E - L)/(E - L)|$ in regions where there are robust twentieth-century signals in $E - L$. In such regions the median values of $100|\Delta N/N|$ are 7% (JJA) and 6% (DJF), whereas the

median values of $100|\Delta(E - L)/(E - L)|$ are 23% (JJA) and 30% (DJF). These findings are consistent with the magnitude of percent increases in projections of precipitation extremes tending to be greater than the magnitude of percent changes in average precipitation (see, e.g., Whetton et al. 2015).

5. Discussion

The primary driver of ENSO teleconnections is the impact that ENSO has on the intensity or position of convective precipitation in the tropical Pacific. Projected changes in ENSO teleconnections can therefore arise if the impact of ENSO on convective precipitation in the tropical Pacific changes. This is in fact what tends to occur in both CMIP3 and CMIP5 models. These models tend to project an intensification of ENSO-driven precipitation in the central-eastern Pacific (Kug et al. 2010; Power et al. 2013; Chung et al. 2014; Chung and Power 2016; Watanabe et al. 2014; Huang and Xie 2015; Huang 2016), and the center of maximum variability tends to shift east near the equator (Kug et al. 2010; Power et al. 2013; Bayr et al. 2014).

The intensification of ENSO-driven convective precipitation in the equatorial Pacific alone would be expected to increase the intensity of ENSO teleconnections, and the eastward shift in the center of action for ENSO has been shown to drive an eastward shift in teleconnections to North America (Kug et al. 2010; Meehl and Teng 2007).

The intensification of ENSO teleconnections in both DJF (Bonfils et al. 2015; section 4) and JJA (section 4) is consistent with the intensification of ENSO-driven variability in the tropical Pacific. However, we saw that while the intensification is collectively significant in the sense that it is evident in, for example, 19 regions of the 25 regions we examined, the intensification was only robust (i.e., evident in two-thirds or more of models) in a small number of regions. The simplest explanation for these results is that the intensification of ENSO teleconnections occurs in response to the enhanced ENSO-driven variability in the tropical Pacific, but the remote enhancement is generally small relative to the magnitude of internal multidecadal variability and is therefore easily swamped by internal multidecadal variability in individual model runs.

Our results are also consistent with those of Perry et al. (2017), who showed that the spatial extent of statistically significant ENSO-driven precipitation and temperature variability is projected to increase in CMIP5 models. This too is expected in response to enhanced ENSO-driven variability in convective precipitation in the tropical Pacific.

ENSO teleconnections might also be modified to some extent because the mean state through which ENSO signals are communicated is also projected to change (see, e.g., IPCC 2014). However, we are not aware of any study that has examined the impact of mean state changes on ENSO teleconnections. This would be a useful topic for further investigation.

6. Conclusions

Precipitation during future El Niño events is a function of 1) current levels of El Niño-driven precipitation variability and projected changes in both 2) El Niño-driven precipitation variability and 3) precipitation in neutral years, as illustrated in Fig. 1. Here we examined the combined impact of these three factors on precipitation during El Niño years around the world during June–August (JJA) and December–February (DJF) under the RCP8.5 scenario in 36 CMIP5 models. We found that projected changes in precipitation during El Niño years are, in general, primarily determined by a balance between factors 1 and 3, with factor 2 typically making only a relatively small contribution.

Precipitation experienced during El Niño events in the latter half of the twenty-first century, relative to twentieth-century neutral conditions, varies markedly from place to place. For example, over the Mediterranean, Northeast Brazil, Central America, parts of Southeast Asia, and southern Australia, twenty-first-century El Niño events tend to be drier than twentieth-century El Niño events. Over East Asia and the Tibetan Plateau, on the other hand, precipitation during El Niño years tends to be higher. Over southern Africa and the Caribbean islands precipitation during El Niño years tends to be lower.

We also found the following:

- ENSO-driven precipitation variability is projected to increase in 18 of the 25 regions examined during JJA and in 19 of the regions during DJF.
- Regions with a robust ENSO signal in the twentieth century (i.e., statistically significant correlations between ENSO and regional precipitation) exhibit a median 21% increase in ENSO-driven precipitation variability (with increases in 13 out of 15 regions) in JJA and a median 16% increase in DJF (20 regions, with increases in 15 regions).
- The multimodel results for the regions, taken collectively, are highly robust, and the DJF result is consistent with the findings of Bonfils et al. (2015).
- When the regions are examined individually, however, the projected changes in $E - L$ (i.e., the difference between precipitation composites in El Niño and La

Niña years; see Fig. 1 and Table 1 for definitions of variables used and the relationships between them) are only robust in a very limited number of regions.

- The last four results are consistent with there being an externally forced increase in ENSO-driven precipitation around the world on the order of 15%–20%. This represents an increase that, although substantial, is small enough to be easily masked at the regional level in individual runs by sampling error arising from internal variability on multidecadal time scales. This internal variability can take the form of random multidecadal changes in the magnitude of ENSO-driven convective precipitation in the tropical Pacific, as well as internal multidecadal variability unrelated to ENSO that influences the regions.
- As the real world is analogous to an individual model “realization,” it too could exhibit internal multidecadal variability in the late twenty-first century that masks (or reinforces) this externally forced signal. We can say, however, that the external forcing increases the likelihood that the variability in the real world will be intensified under high-emissions scenarios.
- The magnitude of ENSO-driven precipitation variability, expressed as a fraction of neutral precipitation [i.e., $\Delta[(E - L)/N]$], tends to increase in regions with robust twentieth-century ENSO signals. The increases are on the order of 36% (JJA) and 10% (DJF).
- In regions that have robust twentieth-century signals in ENSO variability, fractional changes in ENSO-driven variability tend to be much larger than fractional changes in ENSO neutral precipitation in the same regions [i.e., $|\Delta(E - L)/(E - L)| \gg |\Delta N/N|$].
- Projected changes in mean state and neutral precipitation are very similar over the globe. This helps to explain the agreement between the results we obtained for DJF and the results presented by Bonfils et al. (2015) for the same season. This agreement arises despite the fact that the methods used are different. This increases confidence in both the results that Bonfils et al. (2015) present and those presented here.
- Projected mean state changes in surface temperature are everywhere much larger than corresponding projected changes in El Niño–driven surface temperature variability.

Together, these results indicate that the latter half of the twenty-first century under the RCP8.5 scenario is (conservatively) more likely than not to see enhanced ENSO precipitation variability in many locations about mean state and ENSO neutral conditions that are generally very different from those experienced during the twentieth century.

Caveats and further research

Note that CMIP5 models still exhibit shortcomings in their ability to simulate ENSO and recent multidecadal changes in Pacific climate (e.g., England et al. 2014; Kociuba and Power 2015; Power et al. 2017a). This lowers confidence in the results, even if there is a high degree of agreement among models. It will therefore be useful to examine the key issues raised in this paper in the next generation of climate models, especially if they are better able to simulate ENSO and recent climate change in the Pacific (e.g., Kociuba and Power 2015; Power et al. 2017b). Additional useful areas for future research include

- explaining why $|\Delta N|$ tends to be much larger than $|\Delta \delta E|$, and why $|\Delta N/N|$ tends to be much smaller than $|\Delta(E - L)/(E - L)|$, and
- clarifying the role of mean state changes in causing changes to teleconnections.

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