The Leading Mode of Observed and CMIP5 ENSO-Residual Sea Surface Temperatures and Associated Changes in Indo-Pacific Climate*

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ABSTRACT

SSTs in the western Pacific Ocean have tracked closely with CMIP5 simulations despite recent hiatus cooling in the eastern Pacific. This paper quantifies these similarities and associated circulation and precipitation variations using the first global 1900–2012 ENSO-residual empirical orthogonal functions (EOFs) of 35 variables: observed SSTs; 28 CMIP5 SST simulations; Simple Ocean Data Assimilation (SODA) 25-, 70-, and 171-m ocean temperatures and sea surface heights (SSHs); and Twentieth Century Reanalysis, version 2 (20CRv2), surface winds and precipitation.

While estimated independently, these leading EOFs across all variables fit together in a meaningful way, and the authors refer to them jointly as the west Pacific warming mode (WPWM). WPWM SST EOFs correspond closely in space and time. Their spatial patterns form a “western V” extending from the Maritime Continent into the extratropical Pacific. Their temporal principal components (PCs) have increased rapidly since 1990; this increase has been primarily due to radiative forcing and not natural decadal variability.

WPWM circulation changes appear consistent with a Matsuno–Gill-like atmospheric response associated with an ocean–atmosphere dipole structure contrasting increased (decreased) western (eastern) Pacific precipitation, SSHs, and ocean temperatures. These changes have enhanced the Walker circulation and modulated weather on a global scale. An AGCM experiment and the WPWM of global boreal spring precipitation indicate significant drying across parts of East Africa, the Middle East, the southwestern United States, southern South America, and Asia. Changes in the WPWM have tracked closely with precipitation and the increase in drought frequency over the semiarid and water-insecure areas of East Africa, the Middle East, and southwest Asia.

1. Introduction and background

In this study, we use an ENSO-residual EOF framework to focus on climate variations that are relatively unaffected by hiatus-related cooling in the eastern Pacific (Meehl et al. 2011, 2013). While climate change

ensembles identify a preferential warming in the eastern Pacific and a weakening Walker circulation (Bayr et al. 2014; Chadwick et al. 2013), wind fields associated with the interdecadal Pacific oscillation (IPO) have retarded this anticipated warming since the late 1990s (England et al. 2014; Lyon 2014). Other ocean regions, like the Indo-Pacific warm pool (Williams and Funk 2011) and the tropical western Pacific (Funk 2012), have continued to warm rapidly, in line with global climate change projections. Here, we explore the western Pacific warming and quantify the associated observed climate and precipitation variations using a consistent framework based on the first global ENSO-residual EOFs of 35 observed and coupled climate model simulation variables.

Prior Pacific SST decomposition studies (Dai 2013; Folland et al. 2002; Guan and Nigam 2008; Lyon et al. 2014; Mantua and Hare 2002; Newman 2013; Schubert

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et al. 2009) have identified ENSO variability, a low-frequency “trend” component, and Pacific decadal variability (PDV) or the IPO as the three most important modes of Pacific variability. The trend component typically explains two to three times the variance of the PDV mode (Guan and Nigam 2008). The temporal evolution of the trend mode PC (Compo and Sardeshmukh 2010; Dai 2013; Guan and Nigam 2008; Merrifield 2011; Newman 2013) typically exhibits distinct episodic monotonically increasing low-frequency transitions characterized by mid-twentieth-century stagnation and rapid warming in the 1980s, 1990s, and 2010s.

Other studies have examined centennial SST trends after removing ENSO-related SST variations (Cane et al. 1997; Compo et al. 2011; Solomon and Newman 2012). ENSO-residual SSTs all exhibit “western V”-like warming patterns (cf. Fig. 5 in Solomon and Newman 2012). This V pattern begins near the Maritime Continent and extends into the northern and southern extratropical Pacific. Western V-like warming patterns have also been identified in 1992–2011 SST trends (England et al. 2014) and 1999–2012 versus 1977–98 SST changes (Lyon et al. 2014). England et al. (2014) show that the oceanic response to the observed wind stress field warmed (cooled) the northwestern (eastern equatorial) Pacific. This cooling in the eastern Pacific is characteristic of the ocean response during a negative IPO phase (Dai 2013; Lyon et al. 2014) and may help explain the current hiatus in global warming (Meehl et al. 2011, 2013) and the recent intensification of the Walker circulation (L’Heureux et al. 2013; Li and Ren 2012; Lyon et al. 2014; Meng et al. 2012; Merrifield 2011; Merrifield and Maltrud 2011). The IPO, however, can only account for half of the observed 1992–2011 changes in surface wind stress (England et al. 2014), and neither ENSO nor PDV seems sufficient to fully explain the post-1992 increase in western Pacific SSHs (Merrifield 2011).

Western Pacific SSHs are increasing more rapidly than anywhere else on the planet (Merrifield 2011; Merrifield and Maltrud 2011). These height variations are distinct from ENSO and North Pacific PDV but follow closely the first EOF of 5-yr mean outgoing longwave radiation (OLR) and global SSTs (Merrifield and Maltrud 2011). Merrifield notes Chen et al.’s (2002) early identification of a strengthening tropical circulation based on satellite radiation observations. Following studies identified a Walker circulation trend associated with the first mode of reanalysis data (Minobe 2004) and simulated Indian Ocean precipitation (Quan et al. 2004). More recent observational and atmospheric global climate model (GCM) studies also indicate a strengthening Walker circulation (L’Heureux et al. 2013; Lyon and DeWitt 2012; Lyon et al. 2014; Meng et al. 2012; Minobe 2004; Williams

and Funk 2011), trade winds (Li and Ren 2012), and increases in warm pool salinity (Durack et al. 2012). Recent analyses of reanalysis and phase 5 of the Coupled Model Intercomparison Project (CMIP5) simulations (Sandeep et al. 2014) have suggested that it is the local equatorial Pacific SST gradient, rather than the strength of the global convective mass flux, that is responsible for changes in the strength of the Walker circulation. While Compo et al. (2011) do not find a statistically significant trend in the strength of Twentieth Century Reanalysis Walker strength, Sandeep et al. (2014) show that circulation variations can be decomposed into ENSO and ENSO-residual components. These ENSO (ENSO residual) components indicate significant declines (increases) in Walker circulation intensity. While several studies have documented the CMIP5 models’ tendency toward eastern Pacific warming and more El Niño like (Bayr et al. 2014; Chadwick et al. 2013), we focus here on their ENSO-residual component, finding a strong similarity to ENSO-residual changes in observed SSTs.

While our focus in this study is on large-scale climate variability, our ultimate goal is to better understand recent precipitation changes and droughts in East Africa, the Middle East, the southwestern United States, and southwestern Asia. We conclude, therefore, with a brief analysis of WPWM-related precipitation changes.

2. Data and methods

In this study, we examine the contribution of the west Pacific warming mode (WPWM) to recent Pacific climate variations by examining the first ENSO-residual 1900–2012 EOF in observed and CMIP5 SSTs and in nine other global data fields: near-surface zonal winds and precipitation from the Twentieth Century Reanalysis, version 2 (20CRv2) (Compo and Sardeshmukh 2010); SSHs and ocean depth temperatures at 25, 75, and 171 m using Simple Ocean Data Assimilation (SODA); and precipitation from the Global Precipitation Climatology Project (GPCP).

a. Data

We examine Extended Reconstructed SST, version 3b (ERSST.v3b) SST observations (Smith et al. 2008) and CMIP5 (Table 1) ENSO-residual SST EOFs. Since Solomon and Newman (2012) have recently shown similar ENSO-residual trends and warm pool SST time series in Hadley Centre, ERSST, Centennial Observation-Based Estimates (COBE), and Kaplan SSTs, only ERSST SSTs are used in this study. A subset of CMIP5 models (Table 1) was selected based on the availability of multiple historical, historical–natural, and historical–greenhouse gas and aerosol (GHG) simulations (Taylor et al. 2012). These

TABLE 1. CMIP5 models and WPWM correlations. The correlations were calculated for each ensemble member and then averaged by model. The spatial correlations shown are based on the ERSST and CMIP5 eigenvector correlations over the Pacific (120°E–120°W, 50°S–50°N). The temporal correlations are based on the 1900–2012 ERSST and CMIP5 PC1 time series, smoothed with 10-yr running averages.

Modeling group and model name	Model acronym	Historical simulations	Historical–GHG simulations	Historical–natural simulations	Spatial <i>R</i> with EOF1	Temporal <i>R</i> with EOF1
Canadian Centre for Climate Modelling and Analysis Second Generation Canadian Earth System Model	CanESM2	5	5	5	0.71	0.86
National Center for Atmospheric Research Community Climate System Model, version 4	CCSM4	5	3	3	0.80	0.94
Community Earth System Model Contributors Community Earth System Model, version 1 (Community Atmosphere Model, version 5)	CESM1(CAM5)	2	1	2	0.76	0.93
Centre National de Recherches Météorologiques/Centre Européen de Recherche et Formation Avancée en Calcul Scientifique Centre National de Recherches Météorologiques Coupled Global Climate Model, version 5	CNRM-CM5	5	1	1	0.66	0.90
NOAA/Geophysical Fluid Dynamics Laboratory Geophysical Fluid Dynamics Laboratory Earth System Model with MOM, version 4 component	GFDL-ESM2M	1	1	1	0.58	0.93
Met Office Hadley Centre Hadley Centre Global Environment Model, version 2—Earth System	HadGEM2-ES	2	3	3	0.39	0.54
L’Institut Pierre-Simon Laplace L’Institut Pierre-Simon Laplace Coupled Model, version 5A, low resolution	IPSL-CM5A-LR	2	3	3	0.63	0.88
Atmosphere and Ocean Research Institute (University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine–Earth Science and Technology Model for Interdisciplinary Research on Climate, version 5	MIROC5	3	3	3	0.61	0.90
Max Planck Institut für Meteorologie Max Planck Institute Earth System Model, low resolution	MPI-ESM-LR	3	0	0	0.68	0.92
Total ensemble		28	19	19	0.67	0.88

historical experiments simulate climate based on a combination of internal and external radiative forcing. The natural–historical and GHG–historical experiments isolate the internal and external forcing components associated, respectively, with (i) changes in solar radiation and volcanic aerosols or (ii) changes in anthropogenic GHG. These simulations are initialized using multicentury preindustrial control integrations and then allowed to run through to 2005 (or in some cases 2012), constrained by the observed

atmospheric composition changes that reflect anthropogenic and natural sources. The 2006–12 historical simulation values continue these runs using the assumptions of the 8.5 W m^{-2} “business as usual” representative concentration pathway scenario. This scenario has matched closely the observed 2006–12 emissions (Le Quéré et al. 2013).

Circulation responses are explored using ENSO-residual EOFs from atmospheric (20CRv2) and ocean (SODA) reanalyses. The 20CRv2 assimilates observed

SSTs, surface observations of synoptic pressure, and sea ice distributions (Compo et al. 2011) to generate 6-hourly global atmospheric data from 1871 to 2011. SODA (Carton and Giese 2008) assimilates the 20CRv2 and SSTs to estimate the global ocean state.

Pacific circulation responses (surface winds and precipitation) are confirmed using two additional atmospheric global circulation model (AGCM) ensembles forced by observed SSTs. A 50-member 1950–2010 GFS ensemble was provided by NOAA/ESRL Climate Analysis Branch (CAB), while an 1856–2008 10-member ensemble of Community Atmosphere Model, version 4 (CAM4) simulations was provided by the Lamont-Doherty Earth Observatory, via the International Research Institute's data library. A final check on our analysis extends Merrifield (2011) and Zinke et al. (2014), comparing time series of western Pacific and western Australian tidal gauge observations (Holgate et al. 2013) with the CMIP5 ensemble mean principal component (PC) time series. We conclude with an analysis of GPCP merged satellite–gauge data (Adler et al. 2003) and a WPWM-based AGCM experiment.

b. Methods

This paper examines the first ENSO-residual EOF of SSTs, winds, precipitation, and subsurface ocean temperatures. We refer to this as the west Pacific warming mode. In many datasets, ENSO and the WPWM typically appear as the first or second (or second and first) EOF patterns. Alterations between the ordering of these modes can make comparison across many variables difficult. Here, we explicitly prescribe ENSO as the first principal component (PC) of tropical Pacific SSTs (125°–115°W, 15°S–15°N). Regressing this PC time series against each grid cell's dependent values allows us to consistently estimate and remove first-order ENSO effects from a broad suite of different variables and CMIP5 simulations. While more sophisticated approaches have been developed based on linear inverse models (Compo et al. 2011; Solomon and Newman 2012), the ENSO-residual SST analyses presented here have produced similar results.

Aside from defining ENSO, all EOF analyses are based on latitude-weighted covariance matrices over a quasi-global (70°S–70°N) domain. In the analysis of GPCP precipitation, a correlation matrix was used to emphasize terrestrial precipitation changes with a low variance. A March–May time period is used for all analyses, because of prior research linking Walker circulation changes to declines in the East African boreal spring rains (Lyon and DeWitt 2012; Williams and Funk 2011). A 1900–2012 or 1900–2011 time period is used (depending on data availability), except for the 1979–2012 GPCP precipitation dataset.

Multiple domains, time periods (1900–2012, 1950–2012, and 1970–2012), and ENSO-removal approaches were examined to test the robustness of the WPWM retrieved through the ENSO-residual EOF analysis. Changing the domain to the Indo-Pacific (60°E–90°W, 70°S–70°N) or Pacific (120°E–90°W, 70°S–70°N) produced little change in our results. We also experimented with removing the variability associated with both the first and second ENSO principal component and the Pacific decadal oscillation (PDO). These changes had little impact on our results. In the ENSO and ENSO-residual EOF calculations, the signs of the eigenvectors and principal components were reversed if the first PC (PC1) was inversely correlated with Niño-3.4 SSTs or SSTs in the western Pacific.

Because we are interested in rates of change over time, spatial eigenvector results are scaled by the 1999–2012 or 1999–2011 minus 1978–98 change in the associated PC. These break points are based on IPO–PDO-related shifts in Pacific SSTs (Graham 1994; Lyon et al. 2014). If $\mathbf{p}_1$ is a vector of temporal PC1 values (EOF coefficients) and $\mathbf{e}_1$ is a vector describing the first EOF spatial eigenvector (von Storch and Zwiers 1999), we can estimate the temporal change associated with this eigenvector for years $y_1 \dots y_2$ and $y_3 \dots y_4$ as $[(\mathbf{p}_1)_{y_1,y_2} - (\mathbf{p}_1)_{y_3,y_4}]^T \mathbf{e}_1$, where $(\mathbf{p}_1)_{a,b}$ indicates an average of the PC1 from time a to b . We will often refer to change fields as “WPWM changes.” We test the significance of these change fields using a standard difference of means t test. The EOF procedure and other statistical calculations were first applied to individual simulations and then averaged.

The paper concludes with a brief analysis of observed GPCP precipitation and simulated Community Atmosphere Model, version 5 (CAM5), sea surface temperature forced (AGCM) precipitation responses to WPWM SST patterns. CAM5 is the atmospheric component of the Community Earth System Model, version 1 (Hurrell et al. 2013). The CAM5 model was run using a finite volume scheme on a 0.9×1.25 grid. Shallow convection was simulated using the scheme of Park and Bretherton (2009) and deep convection was simulated using a modified parameterization scheme of Zhang and McFarlane (1995). Ocean SSTs and sea ice were specified in space and time. One set of 10 runs was based on climatological 1983–2012 SSTs. Another set of runs was based on the climatological SSTs modified by the 1999–2012 versus 1983–98 change associated with the western V-like WPWM SST changes. In this experiment, SST variations associated with second ENSO EOF and Pacific decadal variability were also removed before the residual first EOF (EOF1) was calculated. This modification was made to remove as much eastern Pacific

variability as possible. For each simulation, CAM5 was initialized on 1 January and run for 145 days, ending on 1 June of the following year. The March–May season of the second simulation year was analyzed to allow sufficient spinup time of the model.

3. SST EOF results

a. WPWM, ENSO, and residual 1983–2012 SST changes

Figure 1 presents the change (1999–2012 mean minus 1983–98 mean) in the WPWM (Figs. 1a,d), ENSO (Figs. 1b,e), and residual (Figs. 1c,f) SST variability in observations and CMIP5 simulations. The WPWM change map (Fig. 1a) identifies SST increases across the Indo-Pacific warm pool and extratropical Pacific, and along a band stretching across much of the Southern Ocean. These changes resemble centennial trends from the Hadley Centre, Extended Reconstructed SST, COBE, and Kaplan SSTs (Solomon and Newman 2012). The WPWM explains 24% of the global SST variance (Table 2) and experienced 52% of its 1920–2012 change between 1978–98 and 1999–2012 (Table 2). Contours in Fig. 1a show the decadal variance explained by the WPWM. Decadal variance explained is based on local regressions with the WPWM PC using time series smoothed with 10-yr running means. Thick black lines between 145°E, 0° and 170°E, 35°N and 35°S in Figs. 1a,d highlight the western V region. Figure 1a also shows three regions of interest for this study: the western equatorial Pacific (WP; 120°–170°E, 15°S–15°N), the northern subtropical Pacific (NP; 150°E–170°W, 15°–35°N), and the central equatorial Pacific (CP; 170°–120°W, 10°S–10°N). These regions lie along historical shipping routes and have comparably good observational records from the 1920s onward (see Fig. S1 in the supplementary material). We will refer to the area average of the WP and NP region as WP–NP. WP and NP SSTs are positively correlated ($r = 0.82$; $n = 113$; $p = 0.0001$; 1900–2012).

Figure 1d and Table 1 show WPWM changes for the CMIP5 models. Figure 2 shows the WPWM changes, using nine different models, one simulation each. Most of the models [CanESM2, CCSM4, CESM1(CAM5) CNRM-CM5, GFDL-ESM2, MIROC5, and MPI] identify substantial ($> +0.3$ K) WPWM warming in the equatorial western and central extratropical Pacific. The level of correspondence between the CMIP5 ensemble mean WPWM changes and the observed WPWM changes is high (Table 2), with a median spatial correlation of 0.67 and a median temporal correlation of 0.91. In the western V regions, significant warming increases were found across the CMIP5 ensemble, and the WPWM explained more than 50% of the decadal variance. Both the

observed and CMIP5 WPWMs identify a central Pacific cooling, as first identified by Cane et al. (1997) (Compo and Sardeshmukh 2010; Solomon and Newman 2012).

Figures 1b,e show similar estimates of the 1999–2012 versus 1978–98 change in ENSO mode SSTs. The ENSO mode change fields are based on the ENSO regression map multiplied by the change in the ENSO PC time series. Observed eastern Pacific SSTs have cooled, which may be related to a natural hiatus in global warming (England et al. 2014; Meehl et al. 2013). The observed cooling (Fig. 1b) contrasts sharply with the CMIP5 ensembles propensity to predict an increase in El Niño-like SSTs (Figs. 3a,b) and the CMIP5 ensemble mean (Fig. 3c) predicts substantial central Pacific warming between 1999–2012 and 1983–98. Estimates of radiative forcing obtained in this manner show substantial warming almost everywhere and a weakening of the west–east equatorial Pacific SST gradient. The CMIP5 ensemble continues to predict a preferential warming in the Niño-3.4 region (Chadwick et al. 2013), which is also associated with an eastward shift in the Walker circulation (Bayr et al. 2014).

Many of the differences between these fields correspond to recent ENSO variations (Figs. 1b,e). These observed and CMIP5 ENSO responses are explored further in Fig. 3. While smoothed observed and CMIP5 PC time series (Fig. 3a) both indicate long-term warming in the eastern equatorial Pacific, the observed (CMIP5) PC time series decreases (increases) between the mid-1980s and 2012. This produces the opposition of sign evident in Figs. 1b,e. Zonal averages of the ERSST and CMIP5 eigenvectors (Fig. 3b) suggest that the ENSO response is larger in all the CMIP5 models than in the SST observations. This could indicate a tendency to produce too much warming in the cold tongue.

Figures 1c,f show the 1978–2012 changes in residual SSTs (non-ENSO and non-WPWM). The observed residual response is highly significant and resembles patterns identified in several previous studies of decadal variability (Dai 2013; England et al. 2014; Folland et al. 2002; Lyon et al. 2014; Meehl et al. 2011). As expected, averaging across the CMIP5 ensemble removes any PDV signature, and Fig. 1f represents a statistically weak spatially uniform warming tendency.

Overall, these results are consistent with prior studies that consider Pacific SSTs as combinations of a WPWM, ENSO, and internal decadal variability (Dai 2013; Folland et al. 2002; Guan and Nigam 2008; Lyon et al. 2014; Mantua and Hare 2002; Newman 2013; Schubert et al. 2009). Between 1978 and 2012, ENSO and internal decadal variability have acted to cool the eastern Pacific. During the 1980s and 1990s, eastern Pacific SSTs tended to be warm (Graham 1994), and this transitioned into a negative IPO phase in the late 1990s (Dai

FIG. 1. The 1999–2012 minus 1978–98 SST changes associated with (a) the observed ENSO mode, and (c) the WPWM and ENSO residuals, (d)–(f) The same fields based on the CMIP5 ensemble. Slipping indicates statistically significant changes ($\alpha = 0.1$). Contours at 30%, 50%, 70%, and 90% indicate the fraction of decadal variance explained by (a),(d) the WPWM EOF or (b),(e) the ENSO EOF.

TABLE 2. Variance explained by the WPWM over the globe and the western Pacific (30°S–30°N, 120°E–160°W), fraction of spectral power at more than 20 yr, and 1999–2011 minus 1978–98 change divided by 1999–2011 minus 1920–39 change. All values are in percent.

	Global	Western Pacific	Fraction of spectral power at >20 yr	Percent change
CMIP SST	17	20	93	47
ERSST SST	24	30	84	52
20CRv2 <i>U</i>	10	22	82	44
20CRv2 <i>P</i>	11	13	77	31
SSH	32	40	86	45
T25m	18	18	86	44
T70m	27	38	81	41
T171m	35	44	83	51

2013; England et al. 2014; Lyon et al. 2014; Meehl et al. 2013).

Figure 4 explores temporal WPWM responses. Between 1900 and 2012 the CMIP5 PC1s covaried strongly with each other and observations (Fig. 4a), with an average (unsmoothed) correlation of 0.88 with the 1900–2012 observed WPWM PC time series (Table 1). This indicates substantial radiative forcing, because the CMIP5 radiative forcing combines both the external forcing associated with anthropogenic greenhouse gas and aerosol emissions and land cover change and internal variations that are primarily due to changes in solar insolation and volcanic eruptions. The combination of these influences, as interpreted by the CMIP5 models, has produced an abrupt acceleration of warming during the 1990s and 2000s. This abrupt warming is associated with radiative forcing and not internal variations associated with PDV. Approximating the warming with a 1900–2012 linear fit underestimates these increases.

Absent a shared radiative forcing, the correlations between CMIP5 PC1 time series are expected to be zero. The results shown in Fig. 4b test this null hypothesis by calculating the running 30-yr correlations between each CMIP5 PC1 and all the 27 other CMIP5 PC1s. The averages of these 27 time series, for each CMIP5 model, are shown with thin red lines. The CMIP5 ensemble average of these average correlations is shown with a thick red line. The thick black line shows the average running 30-yr correlations between the observed PC1 time series and 28 CMIP5 simulations. As the impact of radiative forcing grows in the late twentieth and early twenty-first century, so too does the correlation between the PCs. Figure 4c presents the WP–NP minus CP ENSO-residual SST gradient, based on the boxes shown Fig. 1a. The observed and CMIP5 gradient time series track closely. Both indicate a large gradient increase in the late 1990s and 2000s, with an overall change in the gradient of about +0.8 K since 1920. The level of agreement between the CMIP5 and ERSST SST gradient time series is highly significant ($r = 0.70$; $n = 113$;

$p = 0.0001$; 1900–2012) and the 1978–2012 change in the CMIP5 gradient large ($\sim +0.3$ K). In both the CMIP5 and observations, the gradient changes follow a pattern of increase, stabilization, and increase, rather than decadal (PDV like) oscillatory behavior. The smoothed CMIP5 ensemble mean explains 84% of the variance of the ERSST SST gradient time series.

b. Historical, historical–GHG, and historical–natural western V SST changes

We next examine historical, historical–GHG, and historical–natural simulations in the western V (WP–NP) region in order to contrast internal and external radiative influences. Smoothed area averaged time series of CMIP5 SST anomalies (Fig. 4d) indicate that GHG forcing, acting alone, would have produced a strong linear warming signal and about +0.9 K of warming since 1950. Natural variations in solar insolation and volcanic aerosols, acting alone, would have likely produced modest (~ -0.1 K) cooling during the 1960s and 1970s and during the late 1980s and early 1990s. Between 1950 and 1978, the smoothed historical simulations follow the natural ensemble more closely than the GHG simulations. After about 1978, GHG effects exert greater control (consistent with Fig. 4b) and the historical time series rises more rapidly.

Figure 5a shows the 1999–2005 versus 1978–98 changes in these SST ensembles, expressed as probability distribution functions. For each of the natural–historical, historical, and GHG–historical ensembles, the mean and standard deviation of the SST changes in the WP–NP region were used to derive probability distribution curves. The natural–historical ensemble (black curve) warms by +0.07 K (± 0.12 K), the historical–GHG ensemble warms by +0.23 K (± 0.14 K), and the historical ensemble warms by +0.28 K (± 0.11 K). The historical warming combines a larger GHG warming with a small natural warming tendency. The eruptions of El Chichón and Mount Pinatubo (Fig. S2 in the supplementary material) may have helped suppressed warming during the 1980s and early 1990s. The ensemble mean historical

FIG. 2. The 1999–2012 vs 1978–98 WPWM SST changes for nine CMIP5 twentieth-century climate change simulations. Dots indicate statistical significance at $p = 0.05$. Contours at 30%, 50%, 70%, and 90% show the decadal variance explained by the associated WPWM.

FIG. 3. Comparison of the ERSST and CMIP5 ENSO EOFs: (a) smoothed (10-yr averaged) time series of observed (blue) and CMIP5 (red, thick line shows ensemble average) ENSO PC1 and (b) meridional averages of the CMIP5 (red) and observed (black) ENSO eigenvectors. All PCs and EOFs have been flipped if they exhibited negative correlations with Niño-3.4 SSTs. (c) Multimodel ensemble CMIP5 SST changes between 1999–2012 and 1983–98.

warming rate is essentially the same as the WP–NP warming associated with the observed WPWM (+0.3 K; vertical dashed line). The average of the SST changes shown in the WP and NP boxes in Fig. 1a are almost identical to the average changes shown in Fig. 1d. This is less than the total observed WP–NP warming (+0.42 K; vertical solid line) because of contributions from PDV-related variations (Fig. 1c). Within the natural–historical ensemble, the observed (+0.42 K) 1999–2012 minus 1978–98 warming was extremely unlikely ($p = 0.00005$). Within the historical ensemble, the observed rate of warming was simply unlikely ($p = 0.1$). Natural forcing alone cannot explain the observed WP–NP warming. The observed warming seems likely to be due to a combination of radiative forcing and natural PDV.

c. PDV and ENSO-residual EOF1

Here we further explore the distinct, but spatially overlapping, influences of the WPWM and IPO-related variations. While the spatial and temporal expressions of PDV or IPO vary from study to study, they typically differentiate the northeast and north-central Pacific (cf. Dai 2013) or north-central and eastern equatorial Pacific (Folland et al. 2002). Most standard IPO/PDV indices contain substantial contributions from human-induced global warming (Bonfils and Santer 2011). To isolate and estimate nonradiative PDV variations, we subtracted the full (not WPWM) CMIP5 ensemble means from ENSO-residual SSTs, calculated the first EOF, and scaled the resulting eigenvector by the 1999–2012 minus 1978–98 PC change (Fig. 5b).

These results identify a substantial PDV shift associated with cooling in the eastern Pacific and warming to the north of Hawaii. This pattern is quite similar to the 1992–2011 SST trends from England et al. (2014), the EOF patterns obtained by Dai (2013) and Lyon et al. (2014), and the residual SST changes shown in Fig. 1c. Figure 5b is also similar to representative concentration pathway 4.5 CCSM4 SST trends during negative IPO global warming hiatus periods (Meehl et al. 2013). The significant trends identified in Meehl et al. (2013) during these negative IPO hiatus periods are primarily constrained to cooling in the eastern Pacific, but some significant warming areas (consistent with Fig. 5b) are also found in the central Pacific near 35°N and 35°S. In the North Pacific, this warming is centered to the north of Hawaii, consistent with PDO impacts (Mantua and Hare 2002), the second EOF of 3-yr moving averaged sea surface temperatures from 1920 to 2011 from the HadISST dataset (Dai 2013), and our PDV estimates shown in Figs. 1c and 4b. IPO/PDV have modulated Pacific SSTs in an important way, but these influences are distinct, spatially and temporally, from WPWM influences. Spatially, WPWM increases have

FIG. 4. SST time series and cross correlations. (a) WPWM PC time series from each CMIP5 simulation (thin red lines), their average (thick red line), and the observations (thick blue line), smoothed with 10-yr running means. The thick black line shows a linear fit to the observed WPWM PC. (b) Thin red lines show the average running 30-yr correlations between a single CMIP5 simulation and the 27 other CMIP5 simulations. The thick red line is the average of the thin red lines. The thick black line shows the average running 30-yr correlations between the observed PC and the 28 CMIP5 PCs. (c) Observed and CMIP5 western vs central Pacific ENSO-residual SST gradient. (d) Spatial averages of western and northern Pacific SST anomalies from the CMIP5 historical-GHG (green), historical (red), and historical-natural (blue) experiments.

followed a characteristic western V (Figs. 1a,d) while temporally following a pattern of episodic but quasi-monotonically increasing warming (Fig. 4a).

Estimating the IPO/PDV SST changes using linearly detrended ENSO-residual SST convolves the WPWM and PDV variations. Figure 5c shows the 1999–2012 versus 1978–98 SST changes associated with the first EOF of 1900–2012 detrended ENSO-residual SSTs. This pattern resembles the observed and CMIP5 WPWM changes (Figs. 1a,d) because the rapid acceleration of WPWM SST increases is not captured and removed by

the 1900–2012 long-term linear trend (Fig. 4a). Recent analyses of hiatus SST changes have examined 1992–2012 SST trends (England et al. 2014). The WPWM has contributed to those changes since the 1992–2012 CMIP5 PC1 (Fig. 4a) trended upward rapidly ($b_1 = 1.8 \text{ yr}^{-1}$; $p = 0.01$). The 1999–2012 SST change associated with this trend (estimated as $14 \text{ yr} \times 1.8 \text{ yr}^{-1} \times$ the CMIP5 ensemble mean WPWM eigenvector) is shown in Fig. 5d. The CMIP5 WPWM indicates that radiative forcing has contributed to substantial 1992–2012 western V warming.

FIG. 5. (a) PDFs of the ensemble WP–NP SST changes between 1999–2005 and 1978–98 from the natural–historical (black), historical (blue), and GHG–historical experiments (red). The observed SST change is shown with a gray solid vertical line. The change associated with the observed WPWM is shown with a dashed gray line. (b) The change between 1999–2012 and 1978–98 associated with the first SST EOF after ENSO and the CMIP5 historical experiment ensemble means have been removed. (c) As in (b), but with ENSO and a linear trend removed. (d) The estimated 1992–2012 SST change associated with a 1992–2012 linear fit to the CMIP5 western V PC time series, as shown in Fig. 4a.

4. ENSO-residual EOFs of 20CRv2 and SODA reanalyses

This section presents the first ENSO-residual EOFs of six variables (Table 2): 20CRv2 surface winds (U); 20CRv2 precipitation (P); SODA SSHs; and subsurface ocean temperatures at 25, 70, and 171 m (T25m, T70m, and T171m, respectively). We focus on the Indo-Pacific, because we are interested in exploring the link between trends in SSTs, increases in western Pacific precipitation, and increases in western Pacific sea surface heights.

a. 20CRv2 surface winds and precipitation

The 1999–2012 versus 1978–98 20CRv2 WPWM precipitation responses (Fig. 6a) exhibit a rainfall dipole that is similar to Williams and Funk (2011), contrasting the central Pacific on one hand with the western Pacific and Indian Ocean on the other. Section 6 briefly examines potential boreal spring terrestrial precipitation changes.

In the 20CRv2, the precipitation changes associated with the WPWM have been about +80 mm in the Indo-Pacific warm pool region and about −80 mm in the central Pacific near the date line. At the center of the warm pool, the first EOF explains more than 70% of the ENSO-residual precipitation variance. In the central Pacific, more than 50% of the variance is explained.

The corresponding WPWM zonal surface wind field changes (Fig. 6b) identify an increase in the magnitude of the trade winds across the central Pacific. The increase in the easterly trade wind velocities across the central Pacific has been about -1 m s^{-1} . This is substantial, in comparison to the 20CRv2 mean in this region, which is about -2.5 m s^{-1} . In the central Pacific, more than 70% of the zonal wind variance is explained by the first EOF. The western Pacific WPWM is linked to equatorial wind changes limited to the tropical Indo-Pacific. One plausible hypothesis to explain this response (Williams and Funk 2011) might be an atmospheric Rossby and Kelvin wave–like response to equatorial and off-equatorial diabatic forcing, as described by the Matsuno–Gill model (Gill 1980). The precipitation WPWM changes (Fig. 6a) locate diabatic forcing over the warm pool. To the west of this, the Rossby wave responses produce enhanced westerly flow across the equatorial Indian Ocean. Across the Pacific, the Kelvin wave response increases the easterly trades. These equatorial easterlies would enhance Ekman pumping and evaporation, cooling the central Pacific, perhaps helping to explain the negative ENSO-residual SST trends first identified by Cane et al. (1997). The warming along the southern extratropics (Fig. 1) also appears to be associated with an increase in westerly wind speeds. The associated PCs of these EOFs (Fig. 6c) show long-term

FIG. 6. The 20CRv2 1999–2011 vs 1978–98 WPWM changes for (a) seasonal precipitation and (b) surface winds. Dots indicate significance at $p = 0.1$. Contours denote that 30%, 50%, 70%, or 90% of the decadal variance is explained by the associated principal component. (c) The smoothed principal components associated with (a),(b). Precipitation is shown in red. Zonal winds are shown in blue.

increases that are similar to the CMIP5 WPWM SST PC1 time series. The level of similarity is quantified in section 5c.

b. SODA sea surface heights and ocean temperatures

We next present the 1999–2012 versus 1978–98 WPWM changes in SODA SSHs and ocean temperatures (Fig. 7). The SODA simulations were driven with the 20CRv2 boundary forcings, so it is not surprising that once again we find a dipole centered between the central and western equatorial Pacific. These results are similar to SODA trends analyzed by Solomon and Newman (2012). Looking at the changes in SSHs (Fig. 7a), we find large ($>+0.1$ m) increases in western Pacific heights, consistent with recent studies (Merrifield 2011; Merrifield and Maltrud 2011), and modest decreases in heights across the northern, central, and eastern Pacific. The WPWM structure indicates a strong preferential warming of the western equatorial Pacific and eastern Indian Ocean. New research, based on 1795–2010 eastern Indian Ocean coral paleoclimate data and 1897–2010 sea level height observations at Fremantle, Australia, provides independent corroboration for the ERSST.v3b SST and SODA SSH estimates: twenty-first-century coral-based SST estimates and Fremantle sea heights are the highest on record (Zinke et al. 2014).

The 25-m SODA temperature EOF response (Fig. 7b) is very similar to the ERSST SSTs but exhibits a more pronounced cooling at the equator to the east of the date line. This response is centered between 5°S and 5°N. Over the 1990–2009 time period, this region has been associated with strong increases in easterly wind stress and Ekman pumping velocities (Merrifield 2011). Deeper in the ocean (Figs. 7c,d), the equatorial warming and cooling changes are larger, while the extratropical Southern Hemisphere signal weakens. Warming in the western tropical Pacific Ocean response extends hundreds of meters into the ocean. All of the associated time series (Figs. 7e–g) indicate a strong 1990–2012 increase, in line with increases in the CMIP5 ensemble mean PC1. The level of temporal covariance is quantified in the next subsection.

c. Principal component cross correlations

So far, we have examined WPWM EOFs from (i) 28 historical CMIP5 SST simulations from nine models, (ii) observed SSTs, (iii) 20CRv2 zonal winds and precipitation, and (iv) SODA SSHs and ocean temperatures. Table 2 shows the amount of variance explained by these fields across the globe (70°S–70°N) and within the western and central equatorial Pacific (120°E–120°W, 15°S–15°N). The ensemble mean CMIP5 SST WPWM response explains 30% of the ENSO-residual

western Pacific SST variability. The observed SST WPWM response explains 20%. The other values range from 10% for global winds and precipitation to 44% for the 171-m SODA ocean temperatures in the western Pacific. In the western and central Pacific Ocean, a large portion of the SST, SSH, and subsurface temperature variability is explained by the WPWM. This table also shows the fraction of each PC's spectral power (based on a Fourier transform), occurring at frequencies of greater than 20 yr. The spectral power at more than 20-yr periodicities ranges from 77% to 93%. Table 2 also shows the fraction of the 1920–2012 change in each PC that occurred between 1978 and 2012. For most of these variables, about half of the 93-yr change occurred over the past 30 yr.

The 1900–2012 cross-correlations between the unsmoothed PCs are displayed in Table 3. These EOF calculations were all done independently. The wind PC exhibits the weakest cross-correlations (~ 0.8), the SST and precipitation cross correlations of the unsmoothed PCs are about 0.9 between most variables, while the SSH and subsurface temperature components covary almost perfectly. The temporal responses of all the components have a characteristic structure: increases during the early century contrast with slowing or stabilization during the mid-twentieth century, followed by increases during the late twentieth and early twenty-first century. Strongly covarying WPWM variations dominate ENSO-residual global SSTs, winds, precipitation, SSHs, and ocean temperatures.

d. Tropical Pacific zonal circulation patterns

The spatial pattern of the precipitation change (Fig. 5a) suggests that western Pacific diabatic forcing is associated with something resembling an atmospheric Kelvin wave response (Fig. 5b) over the central equatorial Pacific. Regressions (Fig. S3 in the supplementary material) between precipitation and surface winds from a 50-member 1950–2010 GFS ensemble and a 10-member 1900–2008 CAM4 ensemble produce similar results. The GFS and CAM4 simulations were provided by the Earth System Research Laboratory and the Lamont-Doherty Earth Observatory Climate Group, respectively. The respective slope values have been multiplied by the corresponding component change between 1999–2012 and 1978–98 to provide changes in millimeters and meters per second. While the patterns vary, all three sources of information show precipitation changes on the order of ± 150 mm and zonal wind velocity changes of up to -3.6 m s^{-1} . Again, the strongest zonal wind response lies along the equator, reminiscent of an equatorially trapped Kelvin wave. Similar regressions with 5-, 70-, and 171-m SODA zonal and meridional currents (Fig. S4 in the supplementary material)

FIG. 7. SODA 1999–2011 vs 1978–98 WPWM changes for (a) SSH, (b) 25-, (c) 70-, and (d) 171-m ocean temperatures. (e)–(h) Standardized WPWM principal component time series smoothed with 10-yr running means. The red lines show the WPWM PC1 from the SODA (e) SSH, (f) T25m, (g) T70m, and (h) T171m. The thick red line in (e)–(h) is the observed ERSST WPWM PC1.

TABLE 3. WPWM PC1 correlations, based on interannual 1900–2012 or 1900–2011 time series. All values were significant at $p = 0.001$.

	CMIP5 SST PC1	ERSST SST PC1	20CRv2 U	20CRv2 P	SSH	T25m	T70m
ERSST SST	0.88						
20CRv2 U	0.86	0.86					
20CRv2 P	0.81	0.81	0.91				
SSH	0.86	0.86	0.91	0.88			
T25m	0.95	0.95	0.90	0.89	0.94		
T70m	0.83	0.83	0.88	0.88	0.98	0.94	
T171m	0.83	0.83	0.89	0.88	0.99	0.93	0.98

indicate increased easterly velocities in the upper ocean, centered on the equator, between 120°E and 120°W . The western V WPWM SST changes (Fig. 1), as interpreted by the 20CRv2 and SODA reanalyses, produce a zonal equatorial response across the central and eastern Pacific.

Figure 8 explores this equatorial response using longitude-by-height regressions with atmospheric (20CRv2) geopotential heights, zonal winds, and pressure vertical velocity (ω) and by using longitude-by-depth regressions with SODA temperatures (T), zonal velocities, and vertical velocities (w). These results are based on reanalysis fields sampled along the equator. We contrast the WPWM and ENSO responses. The WPWM temporal response is characterized by the PC1 of ENSO-residual ERSST SSTs. ENSO is characterized

by the PC1 of equatorial Pacific SSTs. Since ENSO and the WPWM PCs are, by construction, independent, bivariate ENSO PC and WPWM PC, regressions were used to estimate the response fields. The responses shown are for a one standard deviation variation. The WPWM atmospheric response (Fig. 8a) is characterized by a low-level easterly response near the date line. The ENSO atmospheric response (Fig. 8b), on the other hand, is higher in the troposphere and east of the date line. In the ocean (Fig. 8c), WPWM regressions indicate confluent easterlies, current anomalies, and downwelling. These circulation changes are associated with warming that increases with depth. This warming lies beneath the rising sea surface heights shown in Fig. 6. In the eastern Pacific, the WPWM circulation changes

FIG. 8. (a) Longitude vs pressure level regressions between 20CRv2 geopotential heights, zonal winds, and ω and the standardized observed WPWM PC. (b) As in (a), but for ENSO PC1. (c) Longitude vs depth regressions between SODA T , zonal velocities, and w and the standardized WPWM PC. (d) As in (c), but for ENSO PC1. In (a),(b), the maximum zonal wind speeds and pressure vertical velocities are 2.5 m s^{-1} and 0.014 Pa s^{-1} , respectively. In (c),(d), the maximum zonal and vertical velocities are 0.08 and $9.3 \times 10^{-6} \text{ m s}^{-1}$, respectively. The shading and arrows show, respectively, the slope coefficients when heights, u , and ω are estimated based on the WPWM PC1.

FIG. 9. (a) Average tidal gauge observations (black) from Pago Pago (American Samoa), Apra Harbor (Guam), and Kwajalein (Marshall Islands); non-ENSO 20CRv2 zonal winds (red) at the date line (170°E – 170°W , 5°S – 5°N); the observed WPWM PC1 (green); the CMIP5 mean WPWM PC1 (blue); and the difference between equatorial western and central Pacific precipitation (magenta). All data have been smoothed with 5-yr running means. (b) Five-year running averages of tidal gauge data from Walaga (Perth, Australia; black), the observed ERSST WPWM PC1 (green), and the CMIP5 mean WPWM PC1 (blue). The PC, U , and P time series shown are based on regressions with the tidal gauge observations.

appear to be associated with a slowing of the rapid subsurface westerly countercurrent, and cooling temperatures indicate a decrease in the height of the thermocline, especially between 160° and 110°W . The changes are different from the oceanic ENSO response, which contrasts cooling near 200 m in the western Pacific with warming in the upper ocean east of 120°W .

Both the WPWM and ENSO responses appear similar to previous analyses by Solomon and Newman (2012), except that our results suggest more warming at depth in the western Pacific, perhaps because we have used a PC, rather than a linear trend, emphasizing changes during the 1990s and 2000s. Merrifield (2011) and England et al. (2014) also find that this recent era has been associated with very rapid increases in sea surface heights, easterly wind stress, and Ekman pumping velocities across the central Pacific. The WPWM responses appear quite different than the variations associated with ENSO (Fig. 8d), which indicate an eastern Pacific zonal velocity response focused near the surface and a western Pacific zonal velocity response that is strongest near 200 m. ENSO-residual and ENSO atmospheric responses (Figs. 8a,b) can be meaningfully compared with the ENSO-related and ENSO-unrelated Pacific Walker circulation changes shown in Sandeep et al. (2014).

e. Changes in western Pacific and western Australian tidal sea gauge heights

Our next analysis subsection connects WPWM SST variations with changes in western Pacific and Western Australia tidal gauge heights. Following the work of Merrifield (2011), we use the average of three long-running

tide gauges (Guam, Pago Pago, and Kwajalein) to represent sea level heights in the western Pacific. Merrifield shows that the variations of these sea level heights covary closely with zonal wind stress across the equatorial Pacific, the first mode of 5-yr averaged SSTs, and the first mode of global OLR. We can confirm a similar relationship between these western tropical Pacific sea level heights and our observed SST WPWM PC1 (Fig. 9a), the CMIP5 WPWM PC1, 20CRv2 equatorial zonal winds at the date line (170°E – 170°W , 5°S – 5°N), and the gradient between western (140° – 170°E , 5°S – 5°N) and central Pacific (180° – 150°W , 5°S – 5°N) 20CRv2 precipitation. We can add to Merrifield's analysis, however, a deeper historical context, provided by the 1900–2012 and/or 1900–2011 PC1 time series (Figs. 4a, 6, and 7) and the changes in the observed and CMIP5 SST gradient (Fig. 4c). The relatively small changes indicated between 1950 and the mid-1990s, followed by the rapid rise in heights in the 1990s, are quite consistent with the nonlinear secular increases produced by the CMIP5 models (Figs. 4a,c). This figure can be compared with Fig. 1b of England et al. (2014), which shows similar 20CRv2 Pacific wind stress values. Some substantial fraction of the 1983–2012 increase in WP–NP SSTs appears related to a combination of internal and external radiative forcing (Fig. 4a).

Figure 9b displays similar tidal gauge data from Western Australia (Walaga). This site was chosen because a recent coral analysis (Zinke et al. 2014) from the nearby Houtman Abrolhos Islands documented a long-term 1795–2010 warming trend consistent with NOAA SST (Smith et al. 2008) observations and Walaga tidal gauge

observations. The 1900–2012 Walaga gauge observations covary with the observed and CMIP5 WPWM PCs. Both the western Pacific (Fig. 9a) and the Western Australian (Fig. 9b) gauge observations increase rapidly in the 1990s and 2000s. Table 4 shows the correlations between the tidal gauge data and other time series. All correlations are significant at $p = 0.001$.

5. GPCP WPWM changes and CAM5 precipitation simulations

Our analysis concludes with an examination of the global ENSO-residual 1979–2012 GPCP WPWM changes and a set of CAM5 AGCM precipitation simulations, described previously in section 2b. The (unsmoothed) GPCP PC1 (Fig. 10a) is nonstationary, with strong increases in the 2000s. The ENSO-residual GPCP EOF was based on the correlation matrix, to emphasize changes over lower precipitation land areas. The ENSO-residual covariance-based EOF (not shown) exhibited Modoki-like (Ashok and Yamagata 2009) patterns with a strong interannual signature and without any secular trend. Regressing this time series against unsmoothed western Pacific gauge data from Fig. 9a ($r^2 = 0.51$; $n = 34$; $p = 0.0001$) produces the black line in Fig. 10a. Both time series increase substantially in the 2000s and these increases appear consistent with long-term trends in the longer time series shown in Fig. 9.

Scaling the EOF1 eigenvector with the 1999–2012 versus 1983–98 PC1 differences produces the standardized precipitation changes shown in Fig. 10b. Large ($\sim +0.7\sigma$) standardized increases are identified over the western V warming areas and along the subtropical convergence zones. Decreases of similar magnitude are found at the equatorial date line and across the subtropical North Pacific. Over land, the most coherent regions of statistically significant declines are located over eastern Africa, central Africa, the Arabian Peninsula, and central southwestern Asia. Less significant declines are identified across eastern East Asia, southern North America, and southern South America.

The results of the CAM5 WPWM experiment (Fig. 10c) are quite similar, indicating that WPWM SST forcing has contributed substantially to the large observed GPCP changes. While the patterns are not identical, the CAM5 simulations also exhibit significant rainfall increases in the western V warming regions and precipitation declines across the equatorial and subtropical eastern Pacific. Statistically significant declines are found across eastern Africa, the Arabian Peninsula, and central southwestern Asia. The magnitude of these changes is also quite large ($\pm 0.7\sigma$). For eastern East Africa at least, the potential food security implications are

TABLE 4. Correlations between 1950–2011 or 1900–2012 time series. Data have been smoothed with 5-yr running means. All correlations significant at $p = 0.05$.

Time series	Years	R
Western Pacific tidal gauges and date line zonal winds	1950–2011	−0.90
Western Pacific tidal gauges and WP-EP precipitation	1950–2011	+0.89
Date line zonal winds and WP-EP precipitation	1950–2011	−0.89
Western Pacific tidal gauges and observed WPWM PC1	1950–2011	+0.90
Western Pacific tidal gauges and CMIP5 WPWM PC1	1950–2011	+0.94
Western Australia tidal gauges and observed WPWM PC1	1900–2012	+0.83
Western Australia tidal gauges and CMIP5 WPWM PC1	1900–2012	+0.91

substantial. WPWM-like SST patterns (Hoell and Funk 2014; Liebmann et al. 2014; Lyon and DeWitt 2012; Shukla et al. 2014a; Williams and Funk 2011) have been shown to increase the chance of drought substantially in eastern East Africa and may have contributed to increased chances of drought during the boreal fall of 2010 and spring of 2011 (Lott et al. 2013) and the 2003–12 era (Funk et al. 2013). A key driver of recent East African drying appears to be the gradient between the equatorial western Pacific and the Niño-4 region (Funk et al. 2014), and this gradient can be used to provide useful predictions of precipitation (Shukla et al. 2014a) and soil moisture (Shukla et al. 2014b).

6. Summary and discussion

a. Summary

The primary results of this study are as follows:

- 1) Observation-based and historical CMIP5 SST WPWM eigenvectors and PCs match closely; hence, the observed western V-like warming over the past few decades has been largely produced by radiative forcing (Figs. 1, 2, and 4) and not internal Pacific decadal variability (Fig. 5).
- 2) The ENSO mode of the observed and historical CMIP5 SST track fairly closely, but the CMIP5 eigenvectors are about twice as large across the eastern Pacific. A combination of hiatus-related PDV and a weaker than observed ENSO eigenvector has resulted in cooler than predicted eastern Pacific SSTs (Figs. 1 and 3).
- 3) The interaction of internal and external radiative forcing produced rapid WP–NP warming in the 1990s and 2000s, with a concomitant jump in the western

FIG. 10. (a) PC1 time series of ENSO-residual global GPCP precipitation (red) and western Pacific tidal gauge data (black). The gauge data have been regressed against the GPCP PC1. (b) GPCP 1999–2012 vs 1983–98 EOF1 changes in standardized precipitation. Dots indicate significance at $p = 0.1$. Changes are shown as standardized precipitation index (SPI) deviations. Areas with climatological precipitation standard deviations < 10 mm have been masked. The yellow rectangle denotes eastern East Africa (32°–50°E, 0°–13°N). (c) CAM5 1999–2012 vs 1983–98 ensemble average changes in standardized precipitation when forced with changes in the WPWM SSTs; dots and yellow rectangle as in (b).

Pacific SST gradient. Running 30-yr PC cross correlations also rise steeply, indicating increasing radiative control. The observed 1978–2005 warming of the WP–NP was very unlikely without GHG forcing (Fig. 4).

- 4) Western V-like warming is not strongly influenced by nonradiative internal PDO variability (Fig. 5).
- 5) The pattern of the WPWM circulation responses in global zonal surface winds and precipitation is consistent with a Matsuno–Gill-like response to diabatic forcing over the Maritime Continent (Fig. 6). An

equatorial acceleration of central Pacific trade winds appears associated with an east–west dipole in Pacific basin ocean temperatures and SSHs (Figs. 7 and 8).

- 6) Correlations between the WPWM PCs themselves and between the WPWM PCs and WP tidal gauge heights, WP–EP precipitation, and date line zonal winds are all strong ($> |0.81|$) and significant (Tables 3 and 4 and Fig. 9). Low-frequency variations in these fields and the recent rise in western Pacific SSHs appear to be strongly influenced by radiative forcing.

The recent increase in the Walker circulation is related to the WPWM and radiative warming in the western Pacific.

- 7) The western Pacific SST gradient, date line zonal surface winds, and WP-EP precipitation gradient modulate weather on global scales. The WPWM of boreal spring GPGP precipitation indicates significant drying across parts of East Africa, the Middle East, western Asia, southern North America, and southern South America. Increases are identified in northern Australia, southern Africa, Southeast Asia, and northern South America. An AGCM experiment recreates many of these changes. The associated precipitation changes can be substantial, more than half a standardized deviation (Fig. 10).
- 8) The combination of summarized results 1–7 imply that radiative forcing in the western V region has contributed to SST variations associated with substantial changes in precipitation.

b. Discussion

While coupled ocean–atmosphere climate models robustly predict a slowing of the Walker circulation (Held and Soden 2006; Vecchi and Soden 2007; Vecchi et al. 2006), new research suggests that strength of the Walker circulation is largely determined by the strength of the local equatorial Pacific SST gradient, as opposed to the global convective mass flux (Sandeep et al. 2014). Sandeep et al. (2014) furthermore show how variations in the SST gradient and Walker circulation intensity can be divided into ENSO and ENSO-residual components, each with opposing tendencies over time. Such decompositions may provide important new ways of thinking about climate change. ENSO and ENSO-residual variations are likely to vary in different ways, at different times, and on different time scales. In this study, like Sandeep et al. (2014), we found opposing ENSO and the WPWM influences on the equatorial Pacific SST gradient. While ENSO and the IPO strongly influence the eastern Pacific, the WPWM followed closely the CMIP5 ensemble mean, indicating strong radiative forcing in the western V.

It should be noted, however, that we also find substantial evidence linking radiative forcing to increased ENSO warming (Fig. 3). The CMIP5 and observed ENSO PCs track closely, with PDV-related excursions leading to ENSO cooling in the 1940s–50s and 1990s–2010s. While radiative forcing is warming the eastern Pacific, internal variability has dominated the signal over the past few decades (Kosaka and Xie 2013; Meehl et al. 2013), leading to an overall cooling (Fig. 1b). It is interesting to note, in fact, that both the WPWM and ENSO PCs indicate hiatus conditions, in the sense that

their most recent values fall very near the bottom of the CMIP5 ensemble distributions shown in Figs. 3a and 4a. For the WPWM, this has resulted in slower warming between the 1990s and 2010s. For the ENSO region, this has resulted in cooling SSTs as the observed ENSO PC transitioned from a value near the peak of the CMIP5 ENSO PC distribution in 1990 to near the bottom in 2010. Thus, while hiatus-related cooling appears to be affecting both the WPWM and ENSO variability modes, the influence on the latter has been much greater.

As increasing warm pool temperatures increase precipitation and diabatic forcing, we have hypothesized (Funk et al. 2008; Williams and Funk 2011) that the associated low-frequency (decadal) atmospheric response to radiative forcing in the Indo-Pacific warm pool may be similar to the Matsuno–Gill model (Gill 1980). This may be relevant to the EOF results presented here, which identified a Kelvin wave–like equatorial zonal wind response over the central Pacific and an associated precipitation dipole as the first ENSO-residual mode of variability (Figs. 6 and 10). Upwelling associated with this response might help explain the central Pacific cooling identified in ENSO-residual trend analyses (Cane et al. 1997; Compo and Sardeshmukh 2010; Solomon and Newman 2012).

When combined with hiatus-related cooling in the central Pacific, the WPWM changes presented here have contributed (Figs. 4 and 9) to a stronger western Pacific SST gradient (Hoell and Funk 2013), which can interact with La Niña to intensify the Walker circulation and modulate Northern Hemisphere upper circulation patterns, producing droughts in East Africa, the Middle East, southwestern Asia, and southern North America (Hoell et al. 2014). These same regions appear associated with WPWM precipitation declines in our EOF and AGCM analyses (Fig. 10). Thus, radiative forcing in the western V region appears associated with substantial precipitation changes.

Focusing on East Africa boreal spring rains have exhibited substantial declines since 1998, primarily because of changes in tropical Pacific SST variations (Lyon and DeWitt 2012) that resemble the equatorial Pacific dipole identified in Williams and Funk (2011) and the WPWM variations described here. Similar patterns have been associated with Pacific (Lyon et al. 2014) and East African (Yang et al. 2014) decadal variability. These papers and other recent studies (Funk et al. 2013; Liebmann et al. 2014; Tierney et al. 2013) all relate western V–like SST warming patterns to increasing East African aridity during boreal spring, consistent with the Walker circulation intensification of Williams and Funk (2011). The WPWM analysis presented here suggest that the key

components forcing this drying tendency: warming western V SSTs, increased date line trade winds, and the WP–EP precipitation gradient have all been strongly influenced by radiative forcing.

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