Spatial Patterns of Global Precipitation Change and Variability during 1901–2010

GUOJUN GU AND ROBERT F. ADLER

Earth System Science Interdisciplinary Center, University of Maryland, College Park, College Park, Maryland

(Manuscript received 13 March 2014, in final form 24 February 2015)

ABSTRACT

This study examines global precipitation changes/variations during 1901–2010 by using the long-record GPCC land precipitation analysis, the NOAA/Cooperative Institute for Climate and Satellites (CICS) reconstructed (RECONS) precipitation analysis, and the CMIP5 outputs. In particular, spatial features of long-term precipitation changes and trends and decadal/interdecadal precipitation variations are explored by focusing on the effects of various physical mechanisms such as the anthropogenic greenhouse gas (GHG) and aerosol forcings and certain internal oscillations including the Pacific decadal variability (PDV) and Atlantic multidecadal oscillation (AMO).

Precipitation increases in the Northern Hemisphere (NH) mid- to high-latitude lands observed in GPCC can also be found in RECONS and model simulations. Over tropical/subtropical land areas, precipitation reductions generally appear in all products, but with large discrepancies on regional scales. Over ocean, consistent spatial structures of precipitation change also exist between RECONS and models. It is further found that these long-term changes/trends might be due to both anthropogenic GHG and aerosols. The aerosol effect estimated from CMIP5 historical simulations is then removed from the GPCC, RECONS, and AMIP simulations. These isolated GHG-related changes/trends have many similar spatial features when compared to the CMIP5 GHG-only simulations, especially in the zonal-mean context.

Both PDV and AMO have influence on spatial patterns of precipitation variations during the past century. In the NH middle to high latitudes, PDV and AMO have played an important role on interdecadal/multidecadal time scales. In several tropical/subtropical regions, their impacts may even become dominant for certain time spans including the recent past two decades. Therefore, these two internal mechanisms make the estimations of GHG and aerosol effects on precipitation on decadal/interdecadal time scales very challenging, especially on regional scales.

1. Introduction

Exploring how global precipitation may vary under a warming climate, including both precipitation magnitude and spatial distribution, has been a consistent focus for the climate community during the past decades because of its scientific significance and great societal and economic implications (e.g., Allen and Ingram 2002; Chou and Neelin 2004; Held and Soden 2006; Allan et al. 2010; Trenberth 2011; Scheff and Frierson 2012; Liu and Allan 2013; Chou et al. 2013; Marvel and Bonfils 2013). The outputs from global coupled and atmosphere-only models have been frequently applied to diagnose the impact of the anthropogenic greenhouse gas (GHG) forcing on the global hydrological cycle through simplified theoretical (thermodynamic) considerations (e.g., Held and Soden 2006). It has been suggested that given the surface warming due to the anthropogenic GHG increase, global mean precipitation might increase with temperature at a rate of about 2% K\(^{-1}\), while tropospheric water vapor would increase at a much faster rate of about 6.5%–7% K\(^{-1}\) approximately following the Clausius–Clapeyron (C-C) relation. Limited observations with the relatively short record seem to be in agreement with suggested water vapor increase (e.g., Gu and Adler 2013). However, the precipitation data from the Global Precipitation Climatology Project (GPCP; Adler et al. 2003; Huffman et al. 2009), arguably the best current precipitation product with global coverage for the satellite era (post-1979), in general show a negligible change in the global mean (land+ocean) precipitation (e.g., Gu et al. 2007; Adler et al. 2008; John et al. 2009; Gu and Adler 2013), although a significant

Corresponding author address: Guojun Gu, Earth System Science Interdisciplinary Center, University of Maryland, College Park, 5825 University Research Court, Suite 4001, College Park, MD 20740.
E-mail: ggu@umd.edu.

DOI: 10.1175/JCLI-D-14-00201.1

© 2015 American Meteorological Society
precipitation increase has been reported using the SSM/I-based precipitation retrievals for a shorter time period: 1987–2006 (Wentz et al. 2007). Thus the GPCP global precipitation analysis actually tends to indicate an even weaker change in global mean precipitation during the past three decades than what global model outputs and theoretical (thermodynamic) arguments imply for a global surface warming forced precipitation response (e.g., Hwang et al. 2013; Chen and Tung 2014). On the other hand, aerosols have further been emphasized in Bony et al. (2013), Gu and Adler (2013) also explored this inconsistency of long-term precipitation change during the GPCP record and concluded that the near-zero global mean precipitation change during the past three decades might be caused by a combined effect of the anthropogenic GHG-related global warming and internal decadal/interdecadal variations (e.g., Lu et al. 2014), specifically Pacific decadal variability (PDV). It is further argued that because of this combined effect a unique spatial distribution of precipitation change was shaped in the deep tropics, specifically in the tropical Pacific, unlike the patterns simulated by global models driven by GHG and other “observed’” historical radiative forcings. Decadal/multidecadal (internal) oceanic processes and/or modes have further been suggested as the primary factors accounting for the changes and variation in the global mean temperature (e.g., Z. Wu et al. 2011; Tung and Zhou 2013; Chen and Tung 2014). In particular, several temperature hiatus periods appearing during the past 100 years (e.g., Trenberth and Fasullo 2013) have been ascribed to the phase changes of these internal modes (e.g., Z. Wu et al. 2011; Tung and Zhou 2013; Chen and Tung 2014). On the other hand, aerosols associated with human activities have also been shown as an important factor in affecting surface temperature and precipitation changes. The effects of aerosols had caused decadal/interdecadal-scale global cooling offsetting a certain amount of the temperature warming associated with the anthropogenic GHG forcing (e.g., Wilcox et al. 2013) and could have reduced precipitation through influencing surface temperature, directly reducing surface shortwave radiation, modulating cloud microphysics, etc. (e.g., Hwang et al. 2013; Andrews et al. 2010).

Therefore, in this study we intend to further examine the effects of these mechanisms on spatial patterns of precipitation change during the past over 100 years (1901–2010) based on both observations and model simulations. The monthly gauge analysis product (1901–2010) (over land) from the Global Precipitation Climatology Centre (GPCC) is primarily applied. The outputs from phase 5 of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012) are also used to explore the factors that might be critical in affecting precipitation changes/variations. To form a complete view of spatial structures of global (land+ocean) precipitation change during the past over 100 years in which direct observations of oceanic precipitation are not available prior to 1979, a recently developed reconstructed precipitation product (RECONS; 1900–2008) is used, although cautiously, for its global coverage (Smith et al. 2012).

Our first major objective is to furnish an improved understanding of long-term precipitation changes/trends during 1901–2010 by focusing on their spatial patterns. In particular, we intend to assess whether the long-term precipitation changes/trends estimated by linear fits here during the entire time period (1901–2010) are dominated by the anthropogenic GHG forcing or other factors, including decadal/multidecadal (internal) oscillations and/or the impact of anthropogenic aerosols. Our second major objective is to identify decadal/multidecadal-time-scale internal physical modes occurring in the global oceans using the long-record SST product, and then to investigate and estimate these ocean-based impacts on global precipitation. Spatial features of precipitation changes/variations associated with the modes identified can then be compared globally, which will help diagnose and discern the global precipitation change that has already happened during the past century, and may also provide clues to what kind of change and variability in the global hydrological cycle could be expected in the near future. The comparisons could also provide an evaluation of the capabilities of the state-of-the-art CMIP5 models in simulating and reproducing observed global precipitation changes and trends, which is our third objective here.

The paper is organized as follows. Section 2 provides an introduction of the datasets used in this study. Major results and discussions are presented in section 3. A summary and concluding remarks are given in section 4.

2. Datasets

The monthly land surface precipitation data is from the GPCP Full Data (FD) Reanalysis version 6 (Becker...
et al. 2013; Schneider et al. 2014), which is based on the 67,200 stations worldwide with record durations of at least 10 years. Through a series of procedures for data processing and quality control (Schneider et al. 2014), the GPCC FD product has the quality fit for climate research including trend analysis (Becker et al. 2013), although the temporal inhomogeneity issue may still exist in the product due to its varying data coverage. The GPCC product has also been used in the GPCP satellite-based merged analysis (1979 to near present) by blending the gauge analysis with satellite retrievals over land and using satellite observations over ocean. The GPCC FD product currently extends from January 1901 to December 2010 and is archived on global grid with three spatial resolutions: 0.5°, 1.0°, and 2.5°. Here the dataset with the spatial resolution of 2.5° is used, and there is no data coverage over the Antarctic continent.

The NOAA/Cooperative Institute for Climate and Satellites (CICS) reconstructed monthly precipitation product is used for its quasi-global coverage (Smith et al. 2009, 2012; Ren et al. 2013). The product is constructed by harnessing correlation relations between precipitation and other physical fields specifically the observed global SST and sea level pressure (SLP) data. The historical land surface rain gauges are also merged into the dataset. A canonical correlation analysis (CCA) is applied and the product is further trained using the GPCP monthly data for the satellite era (1979–2008). The product is archived on global grid with spatial resolution of 5°. Currently it lasts from January 1900 to December 2008. It should be noted that the long-term precipitation changes derived from RECONS might primarily manifest the changes in both SST and SLP, but they also reflect the relationships of precipitation with these two components (Smith et al. 2009, 2012). Past studies indicated that the global mean precipitation change rate with surface temperature in RECONS was about 2% K⁻¹ (Arkin et al. 2010; Ren et al. 2013), consistent with modeling results (e.g., Held and Soden 2006). However, Ren et al. (2013) discovered large discrepancies in the spatial features of precipitation changes between RECONS and model results in the equatorial regions, specifically in the Pacific. Hence, the results from RECONS, especially over global oceans, should be interpreted with caution.

The historical simulations from multiple CMIP5 models (Taylor et al. 2012) are used to examine long-term changes/trends in both surface temperature and precipitation due to various natural and anthropogenic radiative forcings (Table 1). Multimodel ensemble means of anomalies are computed to limit internal noises by choosing one realization from each model. Here, 21, 15, and 14 members are used to estimate the ensemble means for the historical (Hist), historical GHG-only (HistGHG), and historical natural forcing-only (HistNat) runs, respectively, which cover the period of 1900–2005.

The five-member ensemble means of the atmosphere-only (AMIP) simulations from the NASA/GISS Model E

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ACCESS1.0</td>
<td>✓</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>ACCESS1.3</td>
<td>✓</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>BCC-CSM1.1</td>
<td>✓</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>BNU-ESM</td>
<td>✓</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>CanESM4</td>
<td>✓</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>CNRM-CM5</td>
<td>✓</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>CSIRO-Mk3.6.0</td>
<td>✓</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>FGOALS-g2</td>
<td>✓</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>GISS-E2-H</td>
<td>✓</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>GISS-E2-R</td>
<td>✓</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>HadGEM2-ES</td>
<td>✓</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>INM-CM4</td>
<td>✓</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>IPSL-CM5A-LR</td>
<td>✓</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>MIROCS</td>
<td>✓</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>MIROC-ESM</td>
<td>✓</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>MIROC-ESM-CHEM</td>
<td>✓</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>MPI-ESM-LR</td>
<td>✓</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>MPI-ESM-MR</td>
<td>✓</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>MRI-CGCM3</td>
<td>✓</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>NCAR/CCSM4</td>
<td>✓</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>NorESM1-M</td>
<td>✓</td>
<td>□</td>
<td>□</td>
</tr>
</tbody>
</table>
(Hansen et al. 2007) are applied to examine simulated trends and internal decadal-multidecadal variations, which are further compared to those derived from the GPCC over land and RECONS over both land and ocean. It is necessary to mention that it is the long record (1880–2010) of these AMIP simulations from this model that make this kind of comparison possible for the entire GPCC period (1901–2010). Furthermore, the comparison with RECONS over global ocean could also be considered as a cross-validation for both the model simulations and RECONS, given possible uncertainties in both. Moreover, the AMIP simulations are forced not only by observed SST and sea ice extent, but also by natural and anthropogenic radiative forcings used in the CMIP5 historical experiments. Hence, the results could be used to assess not only whether the simulations could reproduce the long-term precipitation changes during the past, but also how both surface and atmospheric radiative forcings imposed simultaneously might have impacted these simulated changes given that the observed SST might already be affected by anthropogenic-related forcings. All model outputs have been regridded to match the GPCC’s global 2.5° × 2.5° grids.

The Extended Reconstructed Sea Surface Temperature (ERSST) analysis (v3b) is used here to describe the observed global SST variation patterns and extract decadal-scale signals from its long record (Xue et al. 2003; Smith et al. 2008). Based on the International Comprehensive Ocean–Atmosphere Dataset (ICOADS) release 2.4, ERSST was generated using global spatial correlation patterns/modes developed from the in situ and satellite data (Reynolds et al. 2002). Improved statistical procedures are further taken to make the reconstruction stable.

The NASA GISS surface temperature anomaly (GISS/ts) field is applied to estimate linear changes of global surface temperature because of its coverage over global land (Hansen et al. 1999). Over land, the monthly mean data is from the Global Historical Climatology Network (GHCN) version 3, while over global ocean the Met Office Hadley Centre SST (HadSST1) and the NOAA satellite-based Optimum Interpolation SST (OISST.v2) data are applied for the periods of 1880–1981 and 1982–present, respectively.

3. Results

a. Linear trends/long-term changes of surface temperature and precipitation

Since a main focus here is to explore spatial patterns of precipitation changes/trends during the GPCC period, long-term surface temperature changes/trends are examined first. Global surface temperature has increased during the past over 100 years (Figs. 1a,b).
Temperature increases are larger over land than over oceans, and the most intense warming is seen over the mid- to high-latitude land areas of both hemispheres (Hansen et al. 1999). Weaker and relatively homogeneous warming appears over global oceans in both GISS/ts and ERSST. Nevertheless, it is of note that some discernible differences exist even between these two observation-based datasets, specifically in the Pacific basin.

Land surface temperature changes in the GISS AMIP runs are in general consistent with GISS/ts except in the regions south of about 60°S (Fig. 1c). Temperature changes simulated in the multimodel ensemble mean Hist and HistGHG are also grossly in agreement with observations (Figs. 1d,e). However, both Hist and HistGHG tend to have a warming maximum in the tropical Pacific usually termed the “enhanced equatorial warming” (e.g., Liu et al. 2005; Xie et al. 2010), which is hardly seen in the observations. HistGHG in general shows much more intense temperature increases than GISS/ts over both global land and ocean, while Hist tends to have comparable temperature changes with GISS/ts except north of about 60°N. Comparison of these temperature changes in Hist and HistGHG suggests that radiative forcings primarily associated with aerosols might have greatly mitigated GHG-related global warming over global land and certain ocean basins (e.g., Dong and Zhou 2014a; Dong et al. 2014a,b), although linear fits estimated here might oversimplify the aerosol impact. To further examine the effects of aerosols, temperature anomalies of multimodel ensemble means for HistNat are computed. Even though linear trends in HistNat during the data record are weak (not shown), anomalies for both HistGHG and HistNat are subtracted from Hist so that linear trends in the residuals (HistResidual) are primarily associated with aerosols (Fig. 1f). Negative temperature trends are seen across the Northern Hemisphere (NH) offsetting the GHG-related warming. Moreover, an interhemispheric temperature gradient appears, which might suggest a greater global impact (e.g., Hwang et al. 2013), even though anthropogenic aerosols are mostly confined in the NH.

1) LAND PRECIPITATION

Linear trends of GPCC annual-mean precipitation during 1901–2010 are depicted in Fig. 2a. Evident precipitation increases appear in the NH mid to high latitudes concurrent with intense surface warming (Fig. 1a). Precipitation reduction occurs in tropical Africa and the northern Indian–Tibetan region, consistent with the changes in monsoon strength denoted by annual ranges of precipitation discovered in Zhang and Zhou (2011). In South America, seesaw structures of precipitation
change are discernible, likely implying shifting of major precipitation zones associated with circulation changes. Australia in general sees a precipitation increase. Positive precipitation changes are also observed in the eastern half of North America.

Land surface precipitation changes are further explored by an EOF analysis of GPCC precipitation anomalies. The leading two EOFs and corresponding PCs are illustrated in Fig. 3. The first EOF/PC is dominated by El Niño–Southern Oscillation (ENSO)-related interannual variations (e.g., Curtis and Adler 2003). However, a wavelet filtering (e.g., Torrence and Compo 1998) of the time sequence of PC1 also indicates the existence of a low-frequency component (red line in Fig. 3c). It is of interest to further note that this mode is in general confined within the latitude band of 40°N–40°S covering the major part of the global monsoon precipitation zones (e.g., Zhou et al. 2008b; Zhang and Zhou 2011), with only a weak effect in higher latitudes (Fig. 3a). The second EOF and PC are depicted in Figs. 3b and 3d, respectively. EOF2 manifests spatial structures of variations similar to the linear trends shown in Fig. 2a, suggesting the dominance of long-term precipitation changes/trends in this mode. Nevertheless,

---

1 Anomalies in this study are estimated using the following procedure. Seasonal cycles are first removed from monthly-time series at each grid. A 13-month running mean is then applied to limit high-frequency noise.
the corresponding principal component (PC2) does not indicate a gradual, steady, long-term increase (Fig. 3d). It shows a consistent increase during the early period (prior to 1940). Between the 1940s to around 1970 changes become weaker, which may partly be related to weak changes in global mean temperature during the same period due to either the effects of anthropogenic aerosols (e.g., Wilcox et al. 2013) or decadal/multidecadal-scale oceanic variations (e.g., Chen and Tung 2014), or both. During the later period (post-mid-1970s), PC2 in general has a weak long-term change. It is also noted that an intense, abrupt increase occurred during the early 1970s. Whether this rapid change is real or due to any data issue warrants further exploration. However, an abrupt drop in NH SST was discovered approximately during the same time span (Thompson et al. 2010). In particular, Zhang and Zhou (2011) indicated that this precipitation increase tends to be in the Southern Hemisphere (SH), which seems to be consistent with an interhemispheric temperature gradient formed by this rapid NH SST drop (e.g., Chiang and Friedman 2012; Hwang et al. 2013).

The results from RECONS are in good agreement with GPCC with the exception of South America (Fig. 2b). Although the reconstruction procedure uses rain gauge information as one source of input (e.g., Smith et al. 2009, 2012), precipitation changes in RECONS are generally weaker, probably because of the smoothing technique in the algorithm and the dataset’s low spatial resolution. However, the linear trend of global mean land precipitation from RECONS is comparable to that for GPCC (Table 2).

The AMIP results show consistency with the observations especially in the NH mid to high latitudes (Fig. 2c). Also, precipitation reduction over tropical Africa is well simulated, and so is precipitation increase over Australia. The consistency shown here suggests the dominant effect of global SST on land surface precipitation changes (e.g., Zhou et al. 2008a) and also demonstrates the fidelity of this model. However, detailed differences can be found over North and South America and along a zonal band ranging from the Mediterranean basin to the southeastern portion of Eurasian continent, which might be related to relatively fewer ensemble members used here for AMIP results that cannot completely limit the effect of internal atmospheric variability. It is also possible that internal variability in GPCC and RECONS might project to the estimated linear trends. In general, the linear trend of global mean land precipitation in AMIP is much weaker than those for both GPCC and RECONS over land (Table 2).

Consistency between the coupled model runs (Hist and HistGHG) and observations is readily seen across the world as well (Figs. 2a,d,e), including precipitation increases in the NH middle and higher latitudes (e.g., Zhang et al. 2007; Noake et al. 2012). Nevertheless, large discrepancies exist even in the linear trends of global mean land precipitation (Table 2). As in AMIP, except over South America and the southwest United States, spatial features of observed precipitation changes are in general well simulated in Hist, although the magnitudes of simulated changes are weaker as shown in past studies (e.g., Zhang et al. 2007; Noake et al. 2012). Comparing HistGHG with Hist and GPCC, we can find some subtle differences appearing in tropical Africa and southeastern Asia, likely implying the effect of aerosols on precipitation, distinct from the GHG effect (e.g., Wu et al. 2013; Song et al. 2014). Also, in the NH mid- to high-latitude precipitation increases in Hist are weaker than in HistGHG. Furthermore, gauged by the sign of precipitation changes over global land, Hist rather than HistGHG tends to manifest more similar features to GPCC. By subtracting precipitation anomalies of HistGHG and HistNat from Hist, linear trends in the precipitation residuals (HistResidual) are estimated (Fig. 2f), which should be dominated by the effect of aerosols. In general, negative trends are seen in the NH lands, partly offsetting precipitation increases related to the anthropogenic GHG.

Large differences between simulated (in AMIP, Hist, and HistGHG) and observed precipitation changes appear over South America and in the southwest United States as mentioned above. The larger than observed warming in the central-eastern equatorial Pacific in both Hist and HistGHG may partly explain the appearance of precipitation decreases over these regions (Figs. 1d,e and 2d,e). Land surface temperature responses in AMIP different from the observed could be a reason for the differences in precipitation change over the same

---

**Table 2. Linear trends (mm day$^{-1}$ century$^{-1}$) of annual mean precipitation for GPCC, RECONS, GISS/AMIP, and multimodel-mean Hist, HistGHG, HistNat, and HistResidual.**

<table>
<thead>
<tr>
<th></th>
<th>GPCC</th>
<th>RECONS</th>
<th>AMIP</th>
<th>Hist</th>
<th>HistGHG</th>
<th>HistNat</th>
<th>HistResidual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land</td>
<td>0.026</td>
<td>0.023</td>
<td>0.004</td>
<td>-0.013</td>
<td>0.050</td>
<td>-0.008</td>
<td>-0.055</td>
</tr>
<tr>
<td>Ocean</td>
<td>0.041</td>
<td>0.014</td>
<td>0.008</td>
<td>0.014</td>
<td>0.062</td>
<td>0</td>
<td>-0.049</td>
</tr>
<tr>
<td>Land+Ocean</td>
<td>0.035</td>
<td>0.010</td>
<td>0.006</td>
<td>0.058</td>
<td>-0.002</td>
<td>-0.051</td>
<td></td>
</tr>
</tbody>
</table>
regions (Figs. 1c and 2c). These inconsistencies emphasize the difficulties of current global models in reproducing past climate, in particular variations/changes on regional scales in the hydrological cycle. Furthermore, as mentioned above, the AMIP runs are forced not only by observed SST and sea ice extent but also by historical radiative forcings applied in the historical runs (e.g., Hansen et al. 2007; Taylor et al. 2012). It is likely that SST observations might already include signals from these radiative forcings. Hence, this kind of forcing configuration in AMIP could be another reason. However, it is also possible that data quality issues might still exist in both surface temperature and precipitation observations, for instance over the Amazon region in South America.

2) OCEANIC PRECIPITATION

RECONS and the CMIP/AMIP simulations provide an opportunity to investigate precipitation variations over global oceans for the past over 100 years. However, as we emphasized above, because of the lack of any direct observations of oceanic precipitation prior to 1979, interpretations should be treated with caution.

As for long-term land precipitation changes discussed above, similarities between RECONS and both Hist and HistGHG can be found as well in the tropical oceans, although detailed agreements tend to be poorer than over global land areas (e.g., Ren et al. 2013). A large band of precipitation increase appears in the equatorial Pacific with precipitation reduction north or south of it extending to the subtropics of either hemispheres. In the tropical Indian Ocean, precipitation increase also appears in RECONS, Hist, and HistGHG. These consistencies tend to confirm the role of external radiative forcings, specifically GHG, in forming the centennial time scale trends in the major oceanic precipitation zones, and furthermore provide certain confidence in RECONS especially for the large-scale change patterns. Nevertheless, not surprisingly, detailed discrepancies in regional patterns can be found in many regions between RECONS and both Hist and HistGHG, for instance, in the tropical Atlantic. Also, comparing Hist and HistGHG indicates many regional differences. Since precipitation changes/trends related to the natural forcings (HistNat) are weak (Table 2), these differences primarily suggest the effect of aerosols. Precipitation changes associated with aerosols are clearly shown in various ocean basins (Fig. 2f). In particular, there is a systematic, interhemispheric, southward shift of precipitation in the tropics, corresponding to the temperature gradient depicted in Fig. 1f, roughly consistent with Hwang et al. (2013).

The AMIP results show large discrepancies from RECONS over global oceans (Figs. 2b,c). In the tropical Pacific, spatial distributions of precipitation changes are different and precipitation reduction tends to be dominant in AMIP, specifically in the equatorial region, in sharp contrast to those derived from RECONS, and from both Hist and HistGHG. In the tropical Indian Ocean, a precipitation increase appears in the tropical zone, but a band of precipitation decrease occurs south of it. Precipitation increase also appears in AMIP in the tropical Atlantic, which is not discernible in RECONS and both Hist and HistGHG. These discrepancies tend to put certain doubts on the AMIP results, although linear fits used here might be oversimplifying for describing long-term changes. The differences between the AMIP results and those from the Hist HistGHG runs are perhaps not surprising, since the trend patterns of SST for them are dissimilar (Fig. 1) and regional features of precipitation change may primarily be forced by SST (e.g., Xie, et al. 2010; Li et al. 2010). However, these differences seem to not fully account for these differences. More discussion is given in section 3c(1) where precipitation changes primarily associated with the SST-based long-term-change index are estimated. Also, it needs to be mentioned that an inspection of the time series of global mean oceanic precipitation from AMIP and RECONS indicates that they follow each other well (not shown). However, the linear trends of global mean oceanic precipitation in both AMIP and Hist are much weaker than that for RECONS (Table 2), as are their global land + ocean mean values. Using the global mean rain rate of 2.67 mm day$^{-1}$ estimated from GPCP (1979–2010), the global mean precipitation change rate with surface temperature in RECONS is about 1.9% K$^{-1}$, similar to that estimated for HistGHG (1.9% K$^{-1}$) using simulated global mean rain rate (2.83 mm day$^{-1}$) and surface temperature trend (0.11 K decade$^{-1}$). Nevertheless, the global mean precipitation change rate is much weaker in both AMIP and Hist, less than 1% K$^{-1}$. This confirms the difficulties in reproducing long-term precipitation changes/trends in the current model simulations, although the simulated surface temperature trend in Hist approaches the observed one: 0.07 K decade$^{-1}$. For AMIP runs, no energetic constraint at the surface could also be a reason.

b. Decomposition of global SST variability/change

Past studies have shown the existence of internal decadal/multidecadal oscillations in the atmosphere–ocean coupled system (e.g., Zhang et al. 1997; Deser et al. 2004). They might be an intrinsic component of climate change and significantly affect spatial structures of global precipitation variability/change in addition to the global long-term surface warming–related changes. To investigate the impact of interdecadal variations on
precipitation changes during the 100-yr period and to put the satellite-era (1979–2012) precipitation changes into a longer-term context, we next decompose SST fields and then use those results to decompose the precipitation fields.

In terms of SST, distinctly different spatial patterns of linear changes can be seen specifically in the Pacific basin during two time periods: 1900–2012 and 1979–2012 (cf. Figs. 1 and 4). Figure 5 further illustrates the linear changes of land precipitation during the recent past three decades. Compared to Fig. 2 (for 1901–2010), large differences are found in the tropical and subtropical lands, implying the effects of decadal-scale internal variability on precipitation. For instance, an evident precipitation increase is seen over West Africa during 1979–2010, confirmed by the AMIP simulations, in contrast to precipitation reduction during the entire data record (1901–2010); over the southwest United States, precipitation decreases occurred during 1979–2010, also confirmed by the AMIP results. Thus, to improve our understanding of global precipitation changes, especially their spatial structures during the past over 100 years and the more recent period, it is necessary to identify and examine the effects of decadal/multidecadal-time-scale internal physical modes.

Physical modes on the longer-than-seasonal time scales in global oceans during 1900–2012 are identified by means of an EOF analysis of SST anomalies between 65°N and 65°S. The first three leading EOF/PC couplets are illustrated in Figs. 6a–c and 6f–h. The first EOF depicts consistent global SST warming during the time period, and the corresponding principal component (PC1) in general follows the variations of global mean SST (not shown). PC1 further suggests that even though this mode is in general dominated by a consistent warming trend (Fig. 6f), decadal/multidecadal oscillations are also seen in addition to high-frequency signals.
FIG. 6. (a)–(c) The first three leading EOFs and (f)–(h) corresponding principal components of SST anomalies between 65°N and 65°S during 1900–2012. (g) Also shown are corresponding high-frequency (period < 8 yr, blue; PC2-high) and low-frequency (period > 8 yr, red; PC2-low) components of PC2. (d), (e) Regression maps of ERSST anomalies onto the normalized PC2-high and PC2-low, respectively.
The second EOF/PC couplet represents a mode composed of intense interannual variations (Figs. 6b,g). The spatial pattern of EOF2 illustrates the dominance of ENSO-related variations. However, this mode (PC2) seems to include decadal/interdecadal time scale signals as well, just like the precipitation PC1 shown in Fig. 3c. A wavelet filtering procedure is thus applied to separate these two types of oscillations from each other (e.g., Torrence and Compo 1998). The high-frequency (period $\lesssim 8$ yr; blue line in Fig. 6g) component is highly correlated with Niño-3.4 as expected (Fig. 7a); the correlation coefficient is $-0.83$ (well above the 95% confidence level). The low-frequency component (period $> 8$ yr; red line in Fig. 6g) seems to represent interdecadal variability in the global ocean. In particular, an inspection of this low-frequency time series indicates that its primary phase shifts tend to be consistent with the so-called regime changes related to the Pacific decadal variability (PDV), including two recent swings: 1976/77 and 1998/99 (e.g., Zhang et al. 1997; Burgman et al. 2008; Gu and Adler 2013). Its correlations with the Pacific decadal oscillation (PDO) index from the University of Washington (http://jisao.washington.edu/pdo/PDO. latest) and corresponding low-frequency component (period $> 8$ yr) of the index are $-0.49$ and $-0.63$ (both well above the 95% confidence level), respectively (Fig. 7b). This PDO index is defined as the leading PC of monthly SST anomalies in the North Pacific Ocean poleward of 20°N (Zhang et al. 1997; Mantua and Hare 2002). It is also of interest that the two components of SST PC2 are similar to the corresponding ones of land precipitation PC1 with opposite signs (Figs. 3c and 6g), confirming coherent variations in both fields on their respective time scales.

Regression maps of SST anomalies against these two SST PC2 components (PC2-high and PC2-low) are constructed and further compared with each other (Figs. 6d,e). Differences in regressed SST anomalies can readily be found between PC2-high and PC2-low. Spatial structures of PC2-high related SST anomalies manifest typical La Niña–type variations in the Pacific with the most intense signals in the central-eastern equatorial Pacific and with corresponding strong effects extending into the subtropical Pacific of both hemispheres (e.g., Zhang et al. 1997; Dong and Zhou 2014b). In the tropical Indian Ocean, SST cooling occurs specifically in the central-western basin accompanying the tropical Pacific fluctuations. Responses in
the Atlantic, though weak, can be observed as well. For PC2-low, intense SST variations are also located in the Pacific basin and have spatial structures similar to those with PC2-high. However, the most intense SST anomalies related to PC2-low are in the NH midlatitudes, not in the deep tropics. Also, detailed differences in the spatial structures of SST anomalies can readily be found specifically in the equatorial Pacific. For instance, there are no significant PC2-low related signals in the far eastern equatorial Pacific, in contrast to strong same-sign anomalies covering the entire tropical central-eastern Pacific for PC2-high. In general, the PC2-low related SST changes in the Pacific are consistent with those for PDO discovered in past studies (e.g., Zhang et al. 1997; Deser et al. 2004), confirming its representation of the Pacific decadal/interdecadal time scale oscillations. It is further noted that SST variations related to PC2-low in the other two ocean basins are entirely different from those for PC2-high (e.g., Wu et al. 2009, 2010). In the Indian Ocean, PC2-low corresponds to positive SST anomalies and the most intense responses are in the southern Indian Ocean. Positive SST anomalies are also seen across most of the Atlantic for PC2-low, in contrast to relatively weak responses to PC2-high. Moreover, SST anomalies related to PC2 beyond the 40°N–40°S latitude band are primarily contributed by PC2-low (Figs. 6b,d,e).

The third EOF/PC couplet is primarily composed of multidecadal-scale oscillations (Figs. 6c,h). The third EOF has intense positive signals in North Atlantic and the northeast Pacific, and opposite, negative anomalies in the Southern Hemisphere midlatitudes forming an interhemispheric temperature contrast (e.g., Dong et al. 2006; Hodson et al. 2010). The anomaly patterns in the North Atlantic tend to be similar to what have been discovered for the Atlantic multidecadal oscillation (AMO) (e.g., Enfield et al. 2001; McCabe et al. 2004; Sutton and Hodson 2007). The corresponding PC3 explicitly manifests the AMO-related multidecadal-timescale oscillations including the recent swing around the mid-1990s (e.g., Knight et al. 2006; Zhang and Delworth 2007; Nigam et al. 2011) and its correlation with the AMO index from the NOAA/ERSL/PSD (http://www.esrl.noaa.gov/psd/data/timeseries/AMO/; Enfield et al. 2001) is 0.72 (Fig. 7c), well above the 95% confidence level. Also, the co-occurrence of positive SST anomalies in both the North Atlantic and the northeast Pacific may imply a teleconnection between the two ocean basins (e.g., Zhang and Delworth 2007; S. Wu et al. 2011). Furthermore, the interhemispheric temperature contrast shown in Fig. 6c seems to be consistent with the notion of a global, remote impact of temperature anomalies in the North Atlantic (e.g., Chiang and Friedman 2012).

Therefore, global SST variations on longer-than-seasonal time scales during 1900–2012 can be decomposed into four major mechanisms represented by PC1 (long-term-change), PC2-high (ENSO), PC2-low (PDV), and PC3 (AMO), respectively. Spatial features of precipitation changes during the GPCC period (1901–2010) can thus then be stratified according to these four SST-based indices.

c. Precipitation variations/changes associated with SST indices

Regression maps of precipitation anomalies against these four SST-based indices are first constructed and then compared in this section. We focus on the precipitation anomalies from GPCC, RECONS, and the AMIP runs since it is still difficult to directly compare Hist and HistGHG against time-varying observations.

1) Long-term change in precipitation

The spatial pattern of the SST PC1-related GPCC precipitation anomalies (Fig. 8a) highly resembles that for the GPCC linear trends (Fig. 2a) and the second EOF mode of GPCC precipitation anomalies (Fig. 3b). For RECONS (Fig. 9a), the spatial structures of the SST PC1-related precipitation anomalies are also consistent with the trend maps of both GPCC and RECONS (Figs. 2a,b). These similarities confirm the evident correspondence/consistency between long-term SST and precipitation changes, although much richer spatial structures appear in precipitation changes stressing evident regional features.

The PC1-related AMIP precipitation anomalies over land show spatial structures resembling the estimated linear changes in AMIP precipitation (Fig. 2c and 10a), which are in good agreement as well with those derived from both GPCC and RECONS (Figs. 8a, 9a, and 10a). Nevertheless, detailed discrepancies are readily seen between AMIP and GPCC, and large differences tend to appear over the regions where their linear trends are also different (Fig. 2), including the Asian monsoon region (e.g., Zhou et al. 2008a,b).

Similarities in PC1-related oceanic precipitation change patterns are also seen between RECONS and AMIP (Figs. 9e and 10e), in particular in the Pacific basin. Along the central-eastern equatorial Pacific a band of positive precipitation anomalies appears, although much weaker in AMIP, with negative anomalies extending from the tropics to the subtropics of both hemispheres. However, in the tropical western Pacific, negative anomalies are generally seen in RECONS, whereas weak or even positive anomalies occur in
AMIP. Moreover, a band of positive anomalies in AMIP extends northeastward from the South China Sea to the NH midlatitudes. In the Indian Ocean, a large area of positive precipitation anomalies appears in the equatorial region in both RECONS and AMIP. However, there is a band of negative anomalies in AMIP roughly along 20°S. Precipitation anomalies are in general weak in the Atlantic in both products, and their spatial structures tend to be different.

It is also noted that large differences exist between AMIP linear trends and PC1-related precipitation anomalies specifically in the tropical Pacific basin (Figs. 2c and 10e), different from those for RECONS (Figs. 2b and 9e). This tends to suggest that the AMIP precipitation trends shown in Fig. 2c are driven by both surface boundary (SST and sea ice extent) and radiative forcings, while precipitation anomalies regressed against PC1 are primarily associated with SST changes likely already including the effects from both the anthropogenic GHG and aerosols. The results hence put doubts on the forcing configuration in the AMIP5 runs applied here. The question for the community is thus “What kind of forcing configurations are really needed to reproduce the past climate, specifically precipitation?”.

It is necessary to note that broad similarities between PC1-related precipitation anomalies and corresponding linear trends for GPCC, RECONS, and AMIP might suggest that SST PC1 could roughly manifest long-term changes/trends in the system, which could include the effects from both the anthropogenic GHG and aerosols.
FIG. 9. Regression maps of reconstructed (RECONS) precipitation (1900–2008) anomalies over (left) land and (right) ocean onto the normalized leading principal components of SST anomalies between 65°N and 65°S. (a),(e) PC1, (b),(f) PC2-high, (c),(g) PC2-low, and (d),(h) PC3.
FIG. 10. Regression maps of GISS AMIP5 precipitation (1900–2010) anomalies over (left) land and (right) ocean onto the normalized leading principal components of SST anomalies between 65°N and 65°S. (a),(e) PC1, (b),(f) PC2-high, (c),(g) PC2-low, and (d),(h) PC3.
Also, as mentioned above, spatial features of precipitation trends over land in Hist rather than in HistGHG tend to be more similar to those in GPCC (Fig. 2). And the time series of multimodel ensemble mean SST differences between Hist and HistNat between 65°N and 65°S (not shown) also tends to resemble the PC1 of observed SST, in particular with a period of weak temperature changes during the 1940s–1960s, implying the impact of aerosols over the global ocean.

2) PDV AND ENSO

Figure 8c depicts the PC2-related GPCC precipitation anomalies. Spatial patterns of precipitation anomalies are in agreement with those induced by ENSO due to the dominance of interannual signals. Compared to PC1-related changes (Fig. 8a), the ENSO effect is in general concentrated within the latitude band of 40°N−40°S and tends to be weak in the higher latitudes. Moreover, precipitation anomalies associated with this mode are in agreement with those directly derived from GPCC precipitation (Figs. 3a and 8c), although their signs are opposite. Precipitation anomalies with PC2’s two components, PC2-high (ENSO) and PC2-low (PDV), are similar over most tropical land areas (Figs. 8d,e). Over North America, negative anomalies appear specifically in the southwest region. Positive (negative) anomalies are seen in the northern (southern) portion of South America, although the PC2-low (PDV)-related negative anomalies south of about 20°S are much weaker. Over the African continent, positive anomalies appear for both PC2-high (ENSO) and PC2-low (PDV). Positive precipitation anomalies are seen in the Maritime Continent and Australia for both indices as well. In East Asia and the Indian subcontinent, similar positive precipitation anomalies are in general observed, but detailed discrepancies appear along the coast of East Asia and over the Tibetan region. The largest differences are seen over the Eurasian continent north of about 40°N. There is a band of negative anomalies related to PC2-high (ENSO) roughly along 40°N covering a large area of the continent, while the PC2-low (PDV)-related responses are weak. On the other hand, positive precipitation anomalies north of about 60°N associated with PC2 are primarily contributed to by PC2-low (PDV) as mentioned above, and the effect of PC2-high (ENSO) tends to be weak. This suggests the relative importance of these two mechanisms in the high latitudes, compared to precipitation anomalies associated with PC2 (Fig. 8c).

The PC2-high (ENSO) signals in RECONS over land are highly consistent with those in GPCC (Figs. 8c and 9b). For PC2-low (PDV), the patterns of precipitation response in RECONS and GPCC are also very similar, although differences in the magnitude of anomalies exist. The magnitudes of precipitation anomalies in RECONS tend to be smaller than the corresponding ones from GPCC, similar to the amplitude differences in their corresponding linear trends (Figs. 2a,b).

Spatial structures of the ENSO and PDV effects represented by PC2-high and PC2-low, respectively, are well simulated over land in AMIP (Figs. 10b,c), specifically in those regions with strong precipitation responses to the Pacific SST fluctuations, even though relatively large differences can be found in the southeastern part of Asia and over Australia. These results indicate the fidelities of this global model, although the magnitudes of simulated regional precipitation variations tend to be weaker as pointed out before.

Oceanic precipitation anomalies associated with PC2-high (ENSO) and PC2-low (PDV) are estimated as well for RECONS and AMIP, respectively. For PC2-high (ENSO) (Figs. 9f and 10f), precipitation anomalies are similar in the Pacific for both products except in the tropical western Pacific including the South China Sea and the regions along the coastline of East Asia. High similarities in spatial distribution of precipitation anomalies can also be seen in the Atlantic. In the Indian Ocean, an east–west dipolar structure of anomalies occurs in RECONS but is not evident in AMIP. These discrepancies may suggest the limitations of the current model in simulating remote responses of precipitation to ENSO.

For PC2-low (PDV) (Figs. 9g and 10g), high consistencies in precipitation anomalies are seen in the Pacific between RECONS and AMIP. As for PC1 and PC2-high (ENSO), large differences appear in the western Pacific where precipitation anomalies in AMIP are weak, in contrast to intense positive anomalies in RECONS. In the tropical Atlantic, precipitation anomalies are similar. However, in the Indian Ocean relatively strong precipitation anomalies appear in AMIP, whereas precipitation anomalies are only seen in the east basin close to the Maritime Continent.

3) AMO

Following intense positive SST anomalies in the North Atlantic (Fig. 6c), PC3-related GPCC precipitation anomalies shown in Fig. 8b are generally in agreement with what have been discovered for the AMO impact in the past studies (e.g., Enfield et al. 2001; McCabe et al. 2004; 2 Also, comparing Figs. 8e and 9c, a large strip of negative GPCC precipitation anomalies over West Africa may imply some data quality issues in GPCC and warrant a further examination of the dataset itself.)
Positive precipitation anomalies are observed over tropical African continent, roughly consistent with past studies (e.g., Zhang and Delworth 2006). Over South America, positive anomalies appear in the northeastern part of the continent, while negative ones are seen covering most of the southern part. It is also interesting to note that likely following PC3 (AMO)-related SST anomalies in the Pacific, precipitation anomalies can be seen over the Maritime Continent in the western Pacific and Australia as well. In particular, compared to positive precipitation anomalies associated with PC2-low (PDV), negative precipitation anomalies appear over Australia for PC3 (AMO) (Figs. 8b,e).

The PC3 (AMO)-related precipitation anomaly patterns over land in RECONS are very similar globally to those from GPCC (Figs. 8b and 9d), in spite of some discrepancies occurring in the Maritime Continent and over part of South America.

AMIP provides a roughly consistent description of AMO associated precipitation changes over land as GPCC (Figs. 8b and 10d). In particular, precipitation variations are in general well simulated over several major areas that are strongly influenced by AMO, including West Africa, North and South America, although detailed discrepancies are still seen.

For oceanic precipitation, large differences can be found in precipitation anomalies related to PC3 (AMO) between RECONS and AMIP (Figs. 8b and 10d). As shown above, PC3 is in general dominated by the AMO (Fig. 8c). Thus its impact should be strong in the pan-Atlantic basin. Intense positive precipitation anomalies occur in AMIP likely following AMO-related warming. However, PC3-related RECONS precipitation anomalies in the Atlantic are weak. In the Pacific and Indian Oceans, obvious discrepancies are seen in both products. These discrepancies not only may suggest the difficulties of the model in simulating the AMO’s global impact mentioned above, but also may imply the possible limitations of RECONS specifically over global oceans where direct observational constraints are lacking.

d. Composite of GHG-related, long-term precipitation trend patterns

As shown in Figs. 1 and 2, the effect of anthropogenic aerosols might have directly projected onto long-term changes/trends in both temperature and precipitation. Also, the PCI derived from global SST might include the effects from both the anthropogenic GHG and aerosols. Hence, the aerosol effect should certainly appear in GPCC, RECONS, and the AMIP ensemble means as well. Thus, to isolate the effect of anthropogenic GHG in long-term precipitation changes/trends, the aerosol effect should be removed or limited. All products are then regressed to the RECONS and RECONS over ocean [GPCC(L)+RECONS(O)] is used as an approximation of observations. Precipitation anomalies associated with aerosols (HistResidual) are estimated by subtracting HistGHG and HistNat from Hist; then anomalies in both HistResidual and HistNat are subtracted from GPCC(L)+RECONS(O) and AMIP. Linear trends in the residuals of GPCC(L)+RECONS(O) and AMIP are then estimated, which should be primarily associated with the anthropogenic GHG effect (Figs. 11a,b).

Compared to simulated precipitation changes/trends related to GHG (Fig. 11c), common features can readily be seen globally in both GPCC(L)+RECONS(O) (Fig. 11a) and AMIP (Fig. 11b), although large detailed discrepancies still appear, especially in the Pacific basin. This strongly emphasizes the difficulties in assessing the GHG effect on regional scale. A composite of the GHG effect is further constructed by averaging these three (Fig. 11d). Furthermore, the number of products with the same sign of precipitation trend among these three is counted at each grid over land and ocean, as a rough gauge of consistency for the composite (Fig. 11e). Consistency of GHG-related precipitation changes can generally be seen in the mid to high latitudes of both hemispheres and in various tropical and subtropical regions, including the tropical Indian Ocean, the southeastern Pacific, part of tropical Atlantic, and Australia, among others. However, large differences appear specifically in the tropical Pacific mostly due to the discrepancies of AMIP from both HistGHG and GPCC(L)+RECONS(O).

Area-integrated values of linear trends are further computed (Table 3). They all show positive values over land, ocean, and land+ocean, confirming the possible precipitation increases following the GHG increase during the time period. Most intense increases are found in GPCC(L)+RECONS(O), and HistGHG shows relatively weak precipitation increase. Using the global mean rain rate (2.83 mm day$^{-1}$) and surface temperature trend (0.11 K decade$^{-1}$) from HistGHG, the global mean precipitation change rates are estimated as 3.0% and 2.0% K$^{-1}$ for the GHG components of GPCC(L)+RECONS(O) and AMIP, respectively, compared to 1.9% K$^{-1}$ for HistGHG. For the composite, the number is 2.3% K$^{-1}$. Although these numbers
are within the range derived in past studies (e.g., Held and Soden 2006; Ren et al. 2013), they indicate the existence of large uncertainties.

Meridional profiles of zonal-mean precipitation changes/trends are also estimated (Fig. 12). Similar methods are used to estimate the GHG effect in both GPCC(L) + RECONS(O) and AMIP. The zonal averaging of each estimate produces a strong commonality among the products, especially over ocean. The composite means of these three are also computed. Over ocean, tropical precipitation increase is seen along with reductions in the subtropics and increases in the mid to high latitudes in both hemispheres. Over land, weak precipitation changes are seen between 0° and 40°N, with increases in the NH mid to high latitudes and south of the equator (0°–40°S). Precipitation decreases are

![Image of Figure 11](https://example.com/image.png)

**Fig. 11.** Linear trends of precipitation (mm day$^{-1}$ decade$^{-1}$) associated with anthropogenic GHG for (a) GPCC over land and RECONS over ocean [GPCC(L) + RECONS(O)], and (b) GISS/AMIP, which are estimated by removing the estimated effects of natural (HistNat) and aerosol (HistResidual) forcings. (c) Linear trends of precipitation (mm day$^{-1}$ decade$^{-1}$) in HistGHG. (d) Composite map of linear trends using HistGHG and estimated GHG effects in GPCC(L) + RECONS(O) and AMIP. (e) Number of same sign for the composite at grids in which GPCC (over land) and RECONS (over ocean) are available.
also seen south of 40°S, basically over the southern tip of South America. Consistency in the zonal features of GHG-related land+ocean precipitation trends from these three can readily be found (Fig. 12f), and the composite is in general similar to that for oceanic precipitation (Fig. 12d).

Hence, these composite map and zonal profiles might be considered as a “good estimate” of the GHG effect on global precipitation during the last century using both observations and models.

4. Summary and concluding remarks

Spatial features of precipitation variations/changes during 1901–2010 are explored by means of the long-record GPCC land precipitation product, the NOAA/CICS reconstructed (RECONS) precipitation (land+ocean) analyses, and the CMIP5 multimodel outputs. Specifically, precipitation changes/variabilities over global land are examined using GPCC, RECONS, GISS AMIP, and Hist/HistGHG, while RECONS, GISS AMIP, and Hist/HistGHG are used to investigate global oceanic precipitation changes/variabilities.

a. Long-term precipitation changes/trends

Long-term precipitation changes/trends are examined two different ways: 1) to calculate linear trends of annual-mean precipitation at each grid and 2) to estimate linear regressions of precipitation anomalies with the first leading PC of global SST anomalies (60°N–65°S). These two methods provide consistent results in particular on the spatial patterns of long-term precipitation changes.

Over global land, consistent features are found among these data and model products in the NH mid to high latitudes where precipitation increases are generally seen during the period. Over subtropical and tropical land areas, precipitation reductions are generally shown. In spite of detailed discrepancies on the regional scales, consistent spatial patterns of precipitation changes can still be found among these products specifically in the tropical African continent, the eastern portion of North America, the southeast part of South America, and the west half of Australia. However, large discrepancies appear in the Amazon region of South America, the southwestern corner of North America, and the northern Indian–Tibetan region. Over global ocean, consistencies in spatial distributions of precipitation changes/trends between RECONS and Hist/HistGHG can be seen in the Pacific and Indian Oceans. The AMIP results show different spatial features of linear trends in the Pacific possibly because of simultaneously applying surface boundary (SST and sea ice extent) and radiative forcings, which are partly confirmed by regressing precipitation anomalies onto the first leading PC of global SST anomalies.

The long-term changes/trends in surface temperature and precipitation, especially on regional scales, are also likely influenced by aerosols. Precipitation trends in Hist other than in HistGHG are more similar to the GPCC linear trends over land. And spatial patterns of the SST PC1 related precipitation changes generally resemble those of GPCC linear trends over land. This implies that the SST PC1 itself might manifest the effects from both the anthropogenic GHG forcing and aerosols. The aerosol effect is then estimated by subtracting precipitation anomalies in HistGHG and HistNat from Hist. Precipitation changes/trends associated with GHG in observations [GPCC(L)+RECONS(O)] and AMIP are then estimated. Composite structures of GHG-related precipitation changes/trends are further estimated using the linear trends in HistGHG and the GHG-related trends in GPCC(L)+RECONS(O) and AMIP. This may be a good gauge of our understanding of regional features of GHG-related precipitation changes, although discrepancies exist among these three, especially in the Pacific basin. Greater consistency can be found in the zonal-mean profiles for the GHG-related precipitation trends for these three. The composite zonal profiles over ocean, land, and land+ocean thus appear to provide good estimates of the anthropogenic GHG effect on precipitation.

b. Precipitation variations related to PDV and AMO

The second and third SST EOF/PC couplets in general correspond to interannual variation and decadal/multidecadal oscillations in global oceans. In particular, the second EOF/PC can be further decomposed into corresponding high-frequency (PC2-high) and low-frequency (PC2-low) components, which correspond to ENSO and PDV related variations.

<table>
<thead>
<tr>
<th>Composite</th>
<th>GPCC(L)+RECONS(O)</th>
<th>AMIP</th>
<th>HistGHG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land</td>
<td>0.069</td>
<td>0.094</td>
<td>0.066</td>
</tr>
<tr>
<td>Ocean</td>
<td>0.072</td>
<td>0.091</td>
<td>0.062</td>
</tr>
<tr>
<td>Land+Ocean</td>
<td>0.071</td>
<td>0.092</td>
<td>0.062</td>
</tr>
</tbody>
</table>
respectively. In general, PC2-low (PDV)-related GPCC precipitation anomalies have similar spatial distributions in the tropics as PC2-high (ENSO). However, in the NH mid to high latitudes, the effect of PC2-low (PDV) on precipitation can be seen as well, in contrast to weak influence from PC2-high (ENSO) there. The third leading mode (EOF3/PC3) is primarily associated with AMO (e.g., Enfield et al. 2001; Sutton and Hodson 2007). The effect of PC3 (AMO) on GPCC precipitation can readily be found in the pan-Atlantic basin (e.g., Zhang and Delworth 2006; Nigam et al. 2011). For instance, negative precipitation anomalies, albeit weak, appear in the eastern portion of North America, and positive (negative) anomalies appear in the northern (southern) part of South America; also, positive precipitation anomalies occur in the tropical African continent. The effects of PDV, ENSO, and AMO are further examined using RECONS and the AMIP5 simulations, and the results are in general in agreement with those from the GPCC data over land.

Using RECONS and the AMIP5 outputs, oceanic precipitation anomalies associated with these three
modes are examined as well. PC2-high (ENSO)- and PC2-low (PDV)-related precipitation anomalies are similar in AMIP and RECONS. Large discrepancies exist in the PC3 (AMO)-related precipitation anomalies between AMIP and RECONS.

In summary, even though long-term precipitation changes/trends in the NH mid to high latitudes are likely affected by both the anthropogenic GHG and aerosols, PDV (PC2-low) and AMO (PC3) may have influences as well on decadal and multidecadal time scales. In the tropical/subtropical regions, ENSO (PC2-high), PDV (PC2-low), and AMO (PC3) all play roles in precipitation variations/changes including both magnitude and spatial distribution. Therefore, the combined impact from these factors makes the estimation of regional precipitation changes extremely difficult, in particular when the length of time period considered is relatively short compared to (or comparable to) the periods of these internal modes. Also, to make reasonable projections of global precipitation variability/change in the future, the capabilities of climate models in simulating/forecasting these internal decadal/multidecadal-time-scale modes are crucial, in addition to their fidelities of simulating forced responses to a variety of radiative forcings. It should also be noted that these internal modes might be modulated by external forcings through the changes in the mean state (e.g., Dong et al. 2014a).

Acknowledgments. We thank the editor, Dr. Aiguo Dai and three anonymous reviewers for their comments and suggestions. The ERSSST dataset (v3b) was downloaded from the NOAA-NCDC website at http://www.ncdc.noaa.gov/erstt/. The NASA-GISS global surface temperature anomaly product was downloaded from its website at http://data.giss.nasa.gov/. The CMIP5 outputs were downloaded from CMIP website (http://cmip-pcmdi.llnl.gov/index.html). We acknowledge the World Climate Research Programme’s Working Group on Coupled Modelling, which is responsible for CMIP. Also for CMIP, the U.S. Department of Energy’s Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. This research is supported under the NASA Modeling, Analysis, and Prediction (MAP) and the NASA Energy and Water-cycle Study (NEWS).

REFERENCES


Deser, C., A. S. Phillips, and J. W. Hurrell, 2004: Pacific interdecadal climate variability: Linkage between the tropics and


