INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **32**: 1782–1791 (2011)
Published online 25 July 2011 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.2393

Large-scale, inter-annual relations among surface temperature, water vapour and precipitation with and without ENSO and volcano forcings

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ABSTRACT: How the global hydrological cycle, generally denoted by precipitation, responds to surface temperature change has been debated for decades. This debate is crucial to correctly assess the global warming-related climate variability/change in the water cycle, but reflects our limited understanding of the relationships that exist among key components of the water cycle on various spatial and temporal scales. Primarily using satellite-based measurements, we find that correlations between precipitation and surface temperature anomalies averaged over large domains (i.e. tropical and global ocean/land areas) during 1988–2008 are very weak once the effects from two large-scale forcings, ENSO and volcanic eruptions, are removed, whereas tropospheric water vapour content varies with surface temperature no matter whether the ENSO and volcanic effects are included or not. We thus conclude that precipitation variability on the inter-annual time scale, once the net large-scale dynamic effects particularly associated with ENSO become weak or limited, does not follow surface temperature and related water vapour variations, even though inter-decadal signals may still exist. This is consistent with the fact that ENSO precipitation signals are usually weak over combined land plus ocean areas for both tropical and global regimes, though ENSO can greatly modulate global precipitation patterns through shifting large-scale circulation systems. These findings are also similar to the weak global-mean precipitation responses under the recent global warming that have been evident in both observations and models, compared to large associated tropospheric water vapour changes, roughly following the Clausius-Clapeyron (CC) relation. Copyright © 2011 Royal Meteorological Society

KEY WORDS precipitation variability; water vapour variability; surface temperature variations

Received 12 June 2011; Revised 26 May 2011; Accepted 9 March 2011

1. Introduction

Global modelling studies indicate that global-mean precipitation might increase with surface warming, but follow a slower pace than tropospheric water vapour content, which should increase roughly with the Clausius-Clapeyron (CC) relation (Allen and Ingram, 2002; Held and Soden, 2006). On the basis of physical constraint that precipitation/latent heat release should be roughly balanced by tropospheric cooling on the scale of global-mean precipitation changes may include two contributions (Allen and Ingram, 2002). One depends on changes of surface temperature, and the other on direct tropospheric energy adjustment not necessarily dependent on surface temperature. Under the global surface warming scenario, these two tend to be oppose each other, thus leaving a warming-related precipitation increase to be relatively weak (Allen and Ingram, 2002; Lambert and Allen, 2009; Andrews *et al*., 2010). Some recent observations seem to agree with this view (Gu *et al*., 2007; Adler *et al*., 2008). The global-mean precipitation change, or trend, during the past three decades is small, although tropical mean precipitation, specifically tropical oceanic precipitation, did show an increase (Gu *et al*., 2007; Adler *et al*., 2008). Estimated global-mean precipitation change rate with surface temperature change is about 2.3%/K during 1979–2006 (Adler *et al*., 2008), within the range of about 1–3%/K derived from climate models (Allen and Ingram, 2002; Held and Soden, 2006; Stephens and Ellis, 2008). During 1988–2008 in which the Special Sensor Microwave/Imager (SSM/I)-based oceanic columnar water vapour content is available, the global-mean precipitation change rate with surface temperature derived from Global Precipitation Climatology Project (GPCP) is about 1.7%/K, compared with the columnar water vapour change rate of about 6.9%/K. However, a larger precipitation increase (over 6%/K) was also reported using the SSM/I-based rainfall retrievals for the post-1988 period (Wentz *et al*., 2007), which is roughly following the CC relation. This 'observed' large precipitation change rate has been followed by intense debates (Stephens and Ellis, 2008; John *et al*., 2009; Liepert and Previdi, 2009; Lambert and Allen, 2009). Varying

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aerosols related forcings in the past decades may offer an explanation (Liepert and Previdi, 2009; Andrews *et al.*, 2010). However, how global precipitation should respond to surface warming is obviously unclear. Furthermore, because of the relatively short record of currently available satellite-based *global* precipitation data sets and the possible existence of inhomogeneities in these data (Adler *et al.*, 2008), it is difficult to derive a solid, observational-based answer at this moment, although most evidence points to a global precipitation trend much lower than the CC relation. In fact, as stated in Adler *et al.* (2008), if we limit our calculation to the same time period (1988–2006) as in Wentz *et al.* (2007), a similar rate of global-mean precipitation change can be obtained from the GPCP monthly product just as claimed in Wentz *et al.* (2007).

Nevertheless, the currently available global observations do allow us to explore the relationships between precipitation and surface temperature on the inter-annual time scale due to the larger signals at that scale and the multiple years available to achieve stable statistics. An examination of the inter-annual correlations among surface temperature, water vapour and precipitation may provide clues to our further understanding of their relationships on the inter-decadal and/or even longer term time scales, although it is anticipated that the variations and associated physical mechanisms at these two time scales will not be identical (Chou and Tu, 2008; Lu *et al.*, 2008). As discovered in the past (Trenberth *et al.*, 1998, 2002; Wallace *et al.*, 1998; Soden, 2000), ENSO is a major player on the inter-annual time scale, which can effectively modulate precipitation and surface temperature patterns in both the tropics and extratropics through shifting large-scale circulation systems. Thus, it can induce coherent patterns of precipitation and surface temperature variations, although not all correlation relations (of either sign) between them across the globe depend on ENSO's modulation (Trenberth and Shea, 2005; Adler *et al.*, 2008). The 1991, Mt. Pinatubo volcanic eruption also induced precipitation and surface temperature anomalies (Robock, 2000; Wigley, 2000; Soden *et al.*, 2002; Gillet *et al.*, 2004; Gu *et al.*, 2007; Trenberth and Dai, 2007), therefore providing another type of forcing to be examined. Global maps of correlations between surface temperature and precipitation have been explored in past studies (Trenberth and Shea, 2005; Adler *et al.*, 2008), which primarily emphasise regional relations. Therefore, the focus of this work is on examining the correlation relations among surface temperature, water vapour and precipitation anomalies averaged over large domains, i.e. tropical (25°N–25°S) and global means, with and without the effects from the two large-scale climatic phenomena: ENSO and volcanic eruptions.

The monthly precipitation data from the GPCP (Adler *et al.*, 2003; Huffman *et al.*, 2009), the vertically integrated SSM/I water vapour product from the Remote Sensing Systems (RSS; Wentz, 1997) and the NASA-GISS monthly surface temperature anomaly field (Hansen *et al.*, 1999) will be the primary data sets examined. Our main statistical focus is on correlations among these variables; however, we understand that a weak correlation does not exclude any internal relations (or sensitivity) between precipitation and surface temperature even on the inter-annual time scale, given related large-scale circulation variations and various complicated feedbacks functioning at a variety of spatial and temporal scales within the coupled global climate system (Held and Soden, 2000; Bony *et al.*, 2006).

2. Data sets

The GPCP monthly precipitation product (Version 2.1) is a community-based analysis of global precipitation under the auspices of the World Climate Research Program (WCRP). Designed to take advantage of particular strengths of the individual input data sets, specifically in terms of bias reduction, the product is combined from a variety of data sources including passive microwave-based rainfall estimates from SSM/I, infrared (IR) rainfall estimates from geostationary and polar-orbiting satellites, and surface rain gauges (Adler *et al.*, 2003; Huffman *et al.*, 2009). Archived on $2.5^{\circ} \times 2.5^{\circ}$ grids, the dataset lasts from January 1979 to the present.

The NASA-GISS monthly surface temperature anomaly field combines air temperature anomalies from meteorological station measurements over land and sea surface temperature (SST) derived from satellite measurements during the post-1981 period (Hansen *et al.*, 1999). Detailed information are summarized in Hansen *et al.* (1999) and the data set can be reached through the NASA-GISS data website.

The Version-6 monthly RSS-SSM/I columnar water vapour products are used to describe variations in oceanic precipitable water. The data are combined from several intercalibrated satellite retrievals (Wentz, 1997), and available for the post-1988 period. Similar water vapour products have been assessed and used in past studies (Trenberth *et al.*, 2005; Zveryaev and Allan, 2005). Because of no reliable satellite retrievals of tropospheric water vapour over land, the outputs from the NASA-Modern Era Retrospective-analysis for Research and Applications(MERRA) are applied. Although radiosondes are used to constrain the MERRA precipitable water over land and a good agreement is found for oceanic precipitable water between RSS-SSM/I and MERRA (not shown), we will be cautious in examining the results over land and land + ocean.

3. Identification of ENSO and volcanic signals

To estimate the correlation relations among surface temperature, columnar water vapour and precipitation with and without the ENSO and volcanic effects, the ENSO and volcanic signals in these variables are first identified. We follow the same procedures described in Gu and Adler (2011). Time series of tropical and global-mean

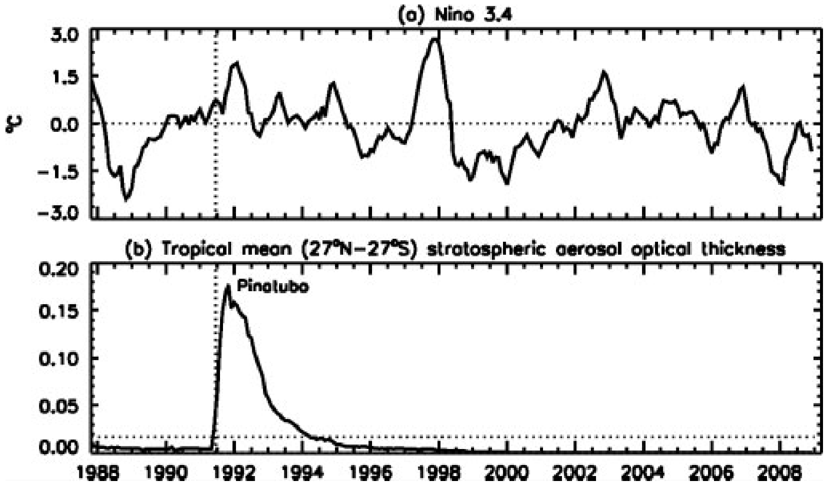

Figure 1. (a) Nino 3.4 (°C) and (b) tropical mean stratospheric aerosol optical thickness (τ).

monthly precipitation, surface temperature and columnar water vapour anomalies are first constructed over land, ocean, and land + ocean. All time series are then de-trended and smoothed by a 3-month-running window. The contributions of linear changes (trends) in the time series are in fact small and thus do not significantly change estimated correlation relations. The time period (January 1988–December 2008) is divided into two periods based on the monthly magnitudes of tropical mean stratospheric aerosol optical thickness (τ) (Figure 1; Sato *et al*., 1993). One period is with volcano impact ($\tau \geq 0.016$), with the other period without volcano impact ($\tau < 0.016$). Relationships of precipitation, surface temperature and water vapour with Nino 3.4 during the non-volcano period are estimated by means of linear lag-regression analysis. These linear relations are then applied to the entire period to estimate the possible projections of ENSO in precipitation, surface temperature and water vapour. To estimate the volcanic effect, the ENSO responses are removed from the time series. The linear relations with τ can thus be estimated by applying linear lag-regression analysis to the volcanic period with the ENSO effect removed. The ENSO and volcanic effects, if any, are therefore identified and separated.

As a detailed assessment of the responses of the tropospheric atmosphere to both ENSO and volcanoes has been provided for the GPCP period (1979–2008) in a recent study (Gu and Adler, 2011), here we only provide a brief summary. Figure 2(a)–(c) depict the time series of tropical SST, columnar water vapour, and precipitation, respectively. Their corresponding ENSO and volcanic responses are shown in Figure 2(d)–(f). As expected, ENSO can effectively modulate area-averaged SST, tropospheric water vapour, and precipitation, with increases associated with positive values of Nino 3.4 and decreases associated with negative values of the index. During the volcanic period (1991–1993), the relationships between these three components and τ in the original time series are weak due to the almost simultaneous occurrence of a warm ENSO event and volcanic eruption and more importantly their opposite effects over oceans (not shown; Gu *et al*., 2007). Once the ENSO effect is removed, however, the volcano-induced changes become prominent (green lines in Figure 2(d)–(f)). The volcanic eruption can effectively reduce oceanic precipitation, and decrease

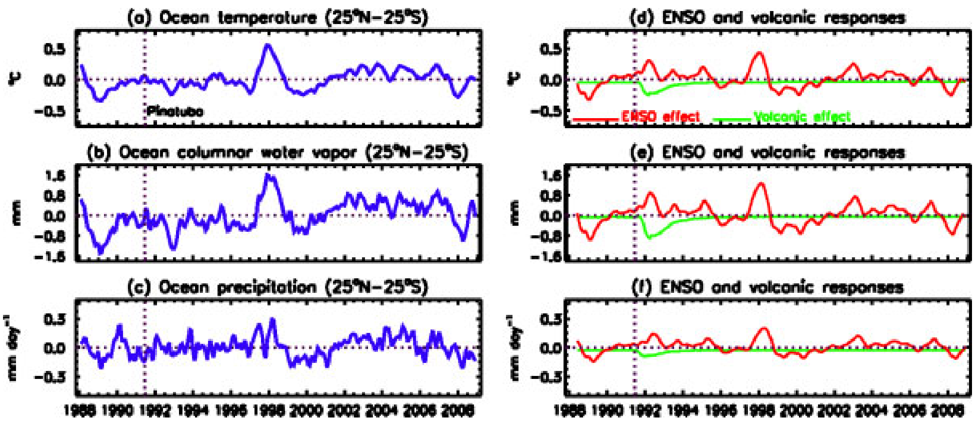

Figure 2. Time series of tropical mean ocean (a) temperature (°C; 3-month running mean), (b) columnar water vapour (mm), and (c) precipitation (mm day^{-1}), and their corresponding linear responses (right panel) to Nino 3.4 (red lines) and τ (green lines). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

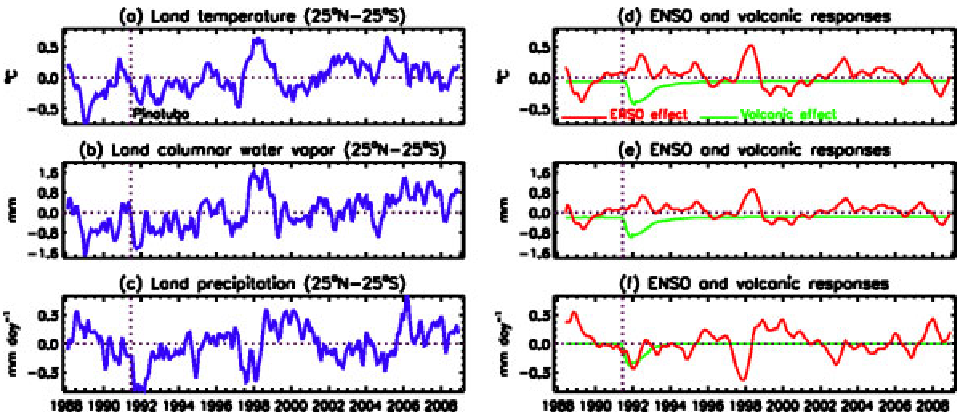

Figure 3. Time series of tropical mean land (a) surface temperature (°C; 3-month running mean), (b) columnar water vapour (mm), and (c) precipitation (mm day^{-1}), and their corresponding linear responses (right panel) to Nino 3.4 (red lines) and τ (green lines). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

both surface temperature and tropospheric water vapour content.

The responses to ENSO and volcano are also estimated over land and land + ocean (Figures 3 and 4). Over land, precipitation has an opposite-sign response to ENSO than over ocean, while surface temperature and tropospheric water vapour in general follow the ENSO-related SST variations. Because of the opposite precipitation responses over land and ocean, the tropical and global-mean (land + ocean) precipitation only weakly responds to ENSO (Figure 4(a) and (d)), whereas the temperature and water vapour responses over ocean and land are of the same sign and reinforce each other. Regarding the volcanic effect, the Pinatubo event decreases precipitation, surface temperature and tropospheric water vapour over land, as it does over ocean, and thus also over land + ocean (green lines in the right panels of Figures 3 and 4). The results suggest that the responses of the global tropospheric atmosphere, including responses associated with the hydrological cycle, are different for ENSO and volcanic eruption events (Gu and Adler, 2011).

The responses of (tropical and global mean) surface temperature, tropospheric water vapour and precipitation to ENSO and volcano have been further examined by estimating their lag-correlations with Nino 3.4 (left panels in Figures 5–7) and τ (not shown), respectively. The results are consistent with Gu and Adler (2011), although the current study is focused on a shorter (1988–2008) period and hence only the effect from Mt. Pinatubo is included.

Also as stated above, we are interested in examining the relationships among temperature, water vapour and precipitation with and without the impact of ENSO and volcano. It is thus necessary to assess whether the method of linear regression applied here has effectively limited the effects of these forcings, in particular that of ENSO. As shown in Figures 5–7 (right panels), there are no coherent, significant ENSO signals left in the residual time series.

4. Correlations among surface temperature, water vapour and precipitation

A significant correlation (0.9) exists as expected between tropical SST and tropospheric water vapour, with a peak occurring when SST leads by about 1 month (red line in Figure 8(a)). This very high correlation partly reflects

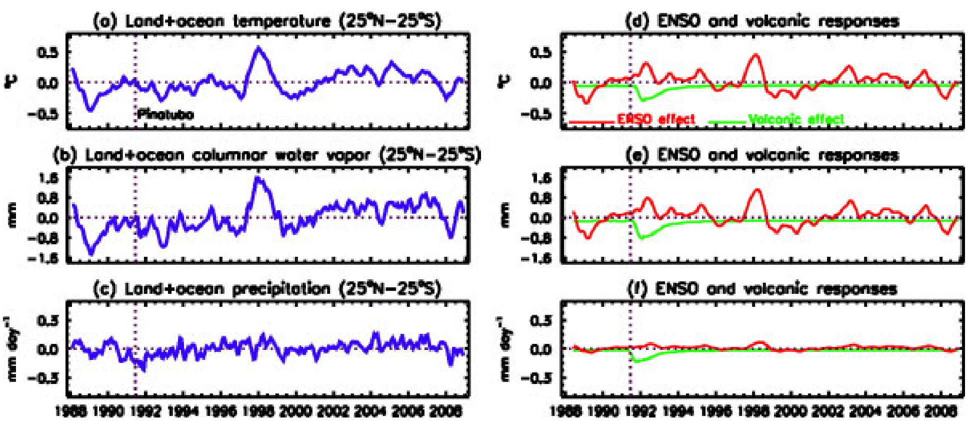

Figure 4. Time series of tropical mean land + ocean (a) temperature (°C; 3-month running mean), (b) columnar water vapour (mm), and (c) precipitation (mm day^{-1}), and their corresponding linear responses (right panel) to Nino 3.4 (red lines) and τ (green lines). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

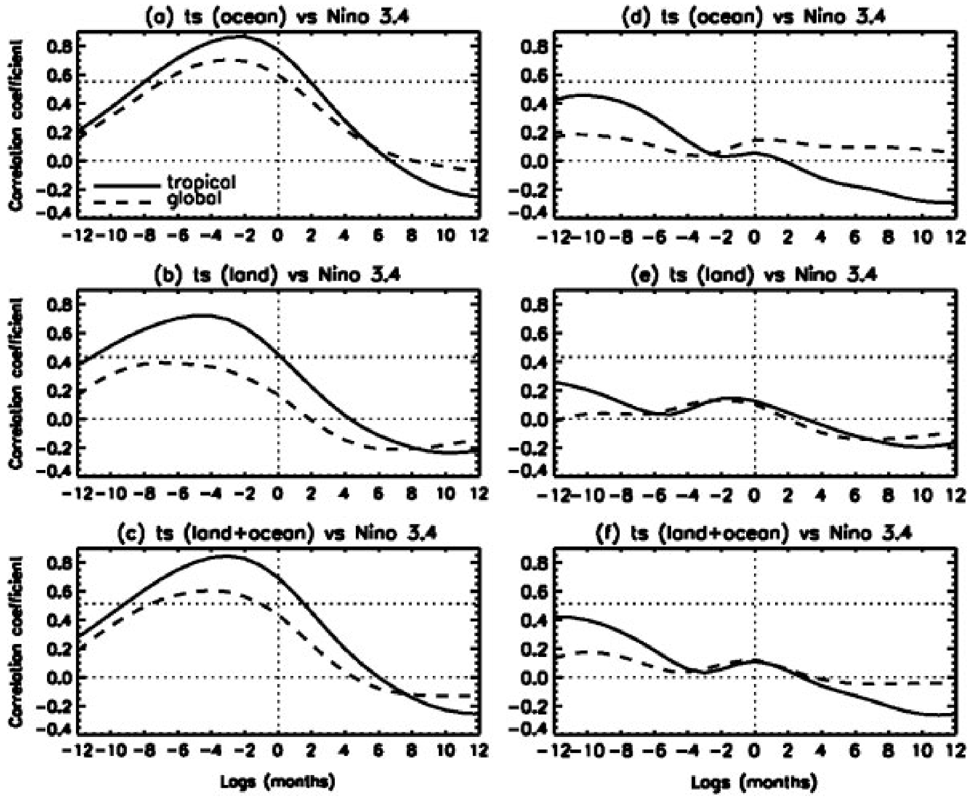

Figure 5. Lag-correlations between surface temperature (Ts) and Nino 3.4. Left panel is for the original time series, and right panel for the time series with the ENSO and volcanic effects removed. The corresponding 5% significance levels ($\gamma_{5\%}$) are also shown (dotted lines), which are estimated based on the lag-1 auto-correlations of the time series being correlated. Positive (negative) lags mean Nino 3.4 lags (leads) Ts.

the strong impact of ENSO on the inter-annual relation between tropical ocean-wide surface temperature and water vapour. A similarly high correlation is seen between these two variables when the area is extended to global oceans (red line in Figure 8(d)). When the effects of ENSO and the volcanic eruption are removed, the peak correlation between temperature and water vapour decreases slightly (blue curve in Figure 8(a) and (d)), but remains easily significant at the 5% significance level, in spite of their weak correlations with Nino 3.4 (Figures 5(d) and 6(d)). The correlation curve, however, changes shape when ENSO/volcano effects are eliminated, with a sharper peak at about the same lag as before. This high correlation without the ENSO and volcano effects confirms intrinsic thermodynamic relations between SST and water vapour. However, other processes may still remain in the residual time series of SST and water vapour. Both time series seem to suggest a decadal shift around 1997/1998, likely related to the Pacific interdecadal variability (not shown), in agreement with other recent studies (Chen *et al*., 2007; Burgman *et al*., 2008). Over land (Figure 8(b) and (e)), the temperature-water vapour correlation is lower in the tropics, showing the negative effect of large-scale dynamics (anomalous descent over land following warm ENSO) being balanced by positive advection from the ocean. When the area is expanded to global land the correlation increases, probably indicative of warmer surface temperatures producing greater local evaporation at latitudes outside the tropics. As over ocean, the over-land correlation drops somewhat when ENSO/volcano effects are eliminated. When the ocean-land combination is examined (Figure 8(c) and (f)), the points already made for the ocean still hold: the peak correlations are high with a small time lag, with a small drop-off in correlation magnitude (still statistically significant) when ENSO/volcano effects are removed. The change in shape of the correlation curve is also retained, indicating these large-area (including global) relations for non-ENSO/volcano processes are very distinct.

The relationship of surface temperature with precipitation is very different from that with water vapour. Figure 9 shows results of parallel calculations with precipitation instead of water vapour. First of all, the correlation between tropospheric water vapour and SST tends to be stronger than that for precipitation, which peaks at 0.58 (compared to 0.9 for water vapour) with a 2-month lag over tropical ocean (red line in Figure 9(a)). After the ENSO and volcanic effects are removed, the correlation between tropical oceanic precipitation and SST becomes weak, below the 5% significance level no matter what time lags are used (blue dashed line in Figure 9(a)). Similar results are obtained for the time series of anomalies averaged over oceans between 80°N–80°S (Figures 8(d) and 9(d)).

Over tropical land, the negative temperature-precipitation correlation associated mainly with ENSO and volcano activity decreases, but still exists when the

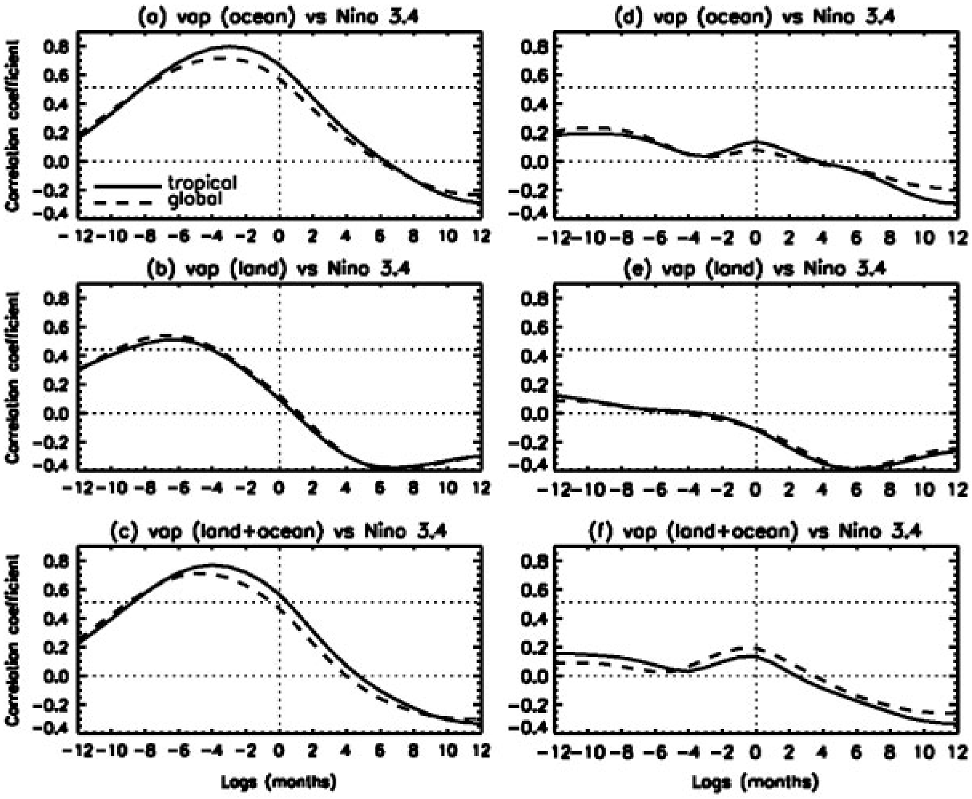

Figure 6. Lag-correlations between columnar water vapor (vap) and Nino 3.4. Left panel is for the original time series, and right panel for the time series with the ENSO and volcanic effects removed. The corresponding 5% significance levels ($\gamma_{5\%}$) are also shown (dotted lines), which are estimated based on the lag-1 auto-correlations of the time series being correlated. Positive (negative) lags mean Nino 3.4 lags (leads) vap.

ENSO and volcanic effects are removed (Figure 9(b)). On the other hand, the correlation between precipitation and surface temperature is weak over global land (80°N–80°S) even including the ENSO and volcanic effects. This is likely due to intense land temperature fluctuations that are usually observed in the mid-higher latitudes specifically in the Northern Hemisphere (Adler *et al.*, 2008). However, high correlations between tropospheric water vapour and surface temperature are still seen over global land with and without the ENSO and volcanic effects (Figure 8(b) and (e)).

Over land and ocean combined, precipitation weakly correlates to surface temperature for both tropical and global means (red lines in Figure 9(c) and (f)). With the ENSO and volcanic impact removed, the correlations become statistically insignificant (blue dashed lines in Figure 9(c) and (f)). In contrast, high correlations between tropospheric water vapour and surface temperature appear no matter whether the ENSO and volcanic effects are included or not (Figure 8(c) and (f)). To summarize, on the largest scale, i.e. the global scale, inter-annual variations in global surface temperature lead distinct changes of the same sign in global water vapour by about a month, whether or not ENSO/volcano effects are included. However, global precipitation variations on the inter-annual time scale also follow surface temperature variations of the same sign, here by about 2 months, but only weakly if ENSO is included, and not at all if the ENSO/volcano effects are removed.

To make a further comparison, the correlation relations between precipitation and water vapour are also estimated (Figure 10). Similar relations as between precipitation and surface temperature are found over tropical and global ocean (Figure 10(a) and (d)). Over land (Figure 10(b) and (e)) precipitation tends to be positively correlated with tropospheric water vapour with the ENSO and volcano effects included, and the peak correlation between global land precipitation and water vapour can even reach the 5% significance level. It is interesting to further note that once the ENSO and volcano effects are removed, the correlations between precipitation and water vapour become stronger and their peaks occurring near the zero-time lag are well above the 5% significance level (blue lines in Figure 10(b) and (e)). This indicates that after the ENSO and volcano effects are removed, in particular after the ENSO-related water vapour anomalies (and the associated large-scale circulation anomalies) are removed, land surface precipitation changes may primarily be related to local evaporation and moisture convergence/divergence processes. Over land and ocean combined, precipitation shows a similar correlation relation with water vapour as with surface temperature. However, the correlations between precipitation and water vapour are much stronger, well above the 5% significance level (red lines in Figure 10(c) and (f)). After the ENSO and volcano effects are eliminated, the correlations between precipitation and water vapour become weaker (blue lines in Figure 10(c) and (f)), similar as

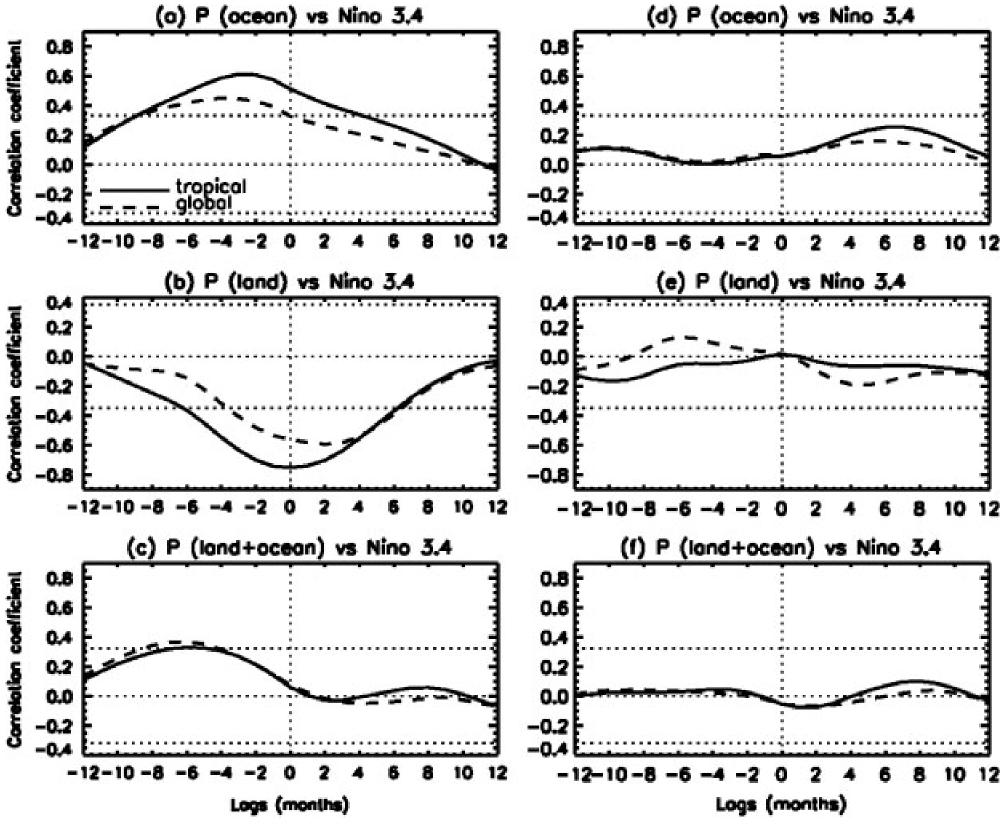

Figure 7. Lag-correlations between precipitation (P) and Nino 3.4. Left panel is for the original time series, and right panel for the time series with the ENSO and volcanic effects removed. The corresponding 5% significance levels ($\gamma_{5\%}$) are also shown (dotted lines), which are estimated based on the lag-1 auto-correlations of the time series being correlated. Positive (negative) lags mean Nino 3.4 lags (leads) P.

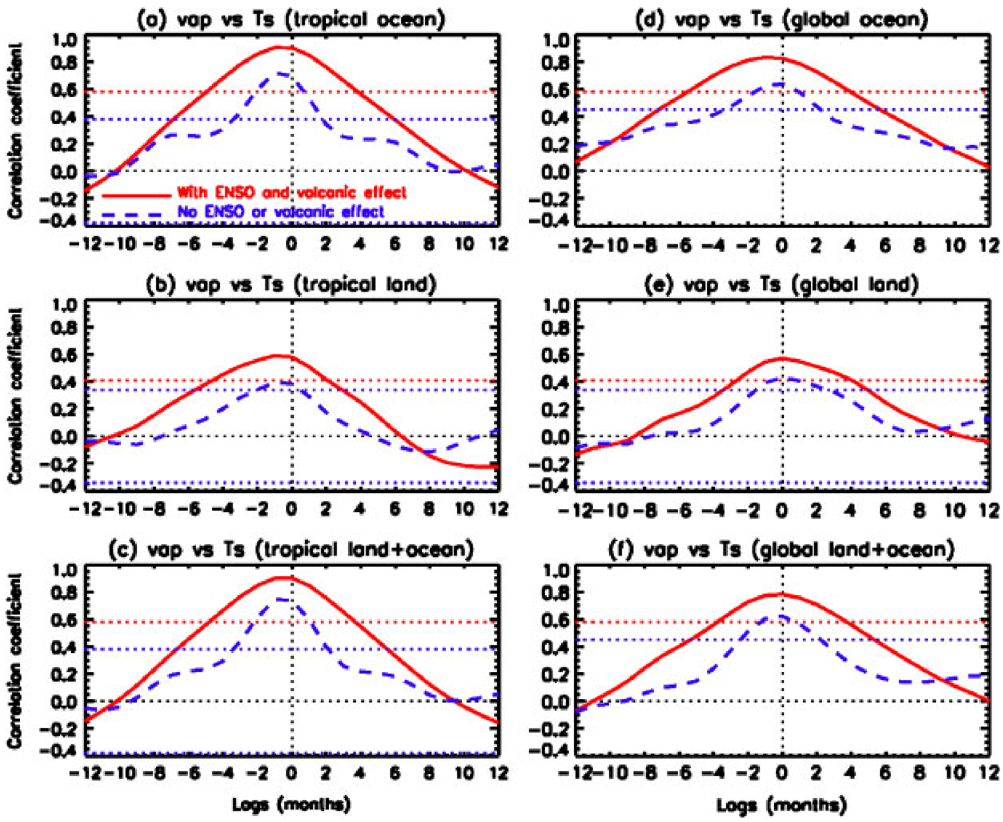

Figure 8. Lag-correlations between columnar water vapour (vap) and surface temperature (Ts) with (red solid lines) and without (blue dashed lines) the ENSO and volcanic effects. The corresponding 5% significance levels ($\gamma_{5\%}$) are also shown (colour dotted lines), which are estimated based on the lag-1 auto-correlations of the time series being correlated. Positive (negative) lags mean Ts lags (leads) vap. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

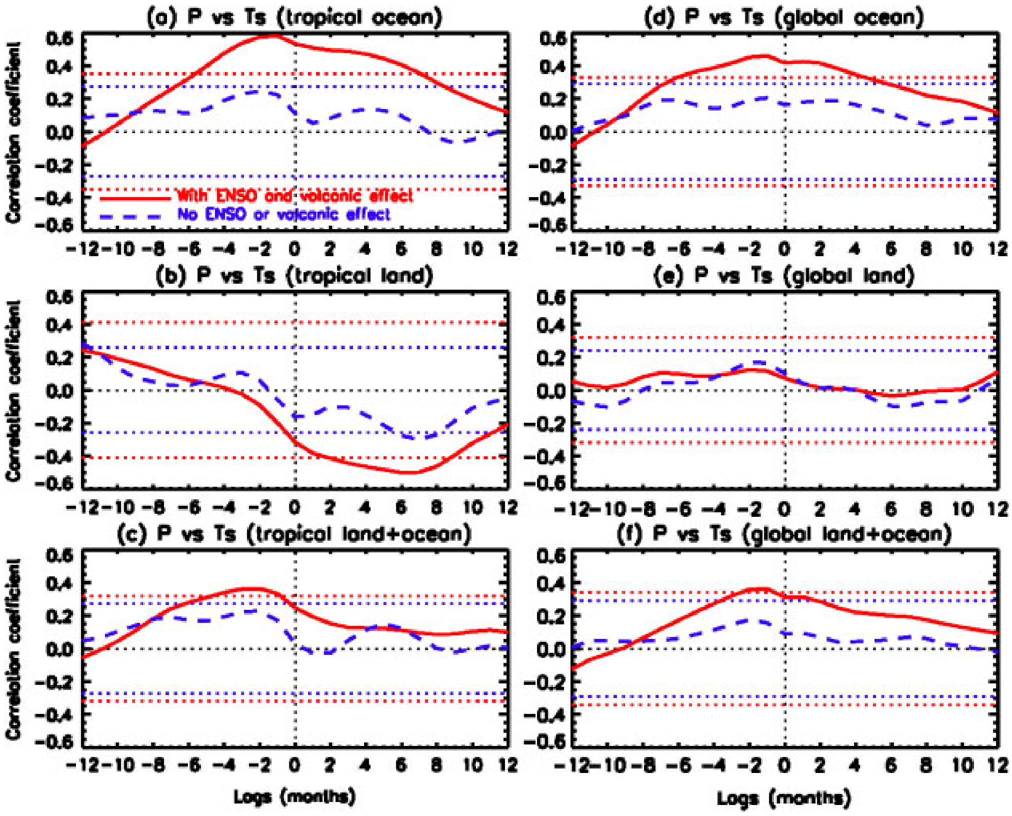

Figure 9. Lag-correlations between precipitation (P) and surface temperature (Ts) with (red solid lines) and without (blue dashed lines) the ENSO and volcanic effects. The corresponding 5% significance levels ($\gamma_{5\%}$) are also shown (colour dotted lines), which are estimated based on the lag-1 auto-correlations of the time series being correlated. Positive (negative) lags mean Ts lags (leads) P. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

those for precipitation and surface temperature (blue lines in Figure 9(c) and (f)).

5. Discussion

On the inter-annual time scale large-area tropospheric water vapour and precipitation amounts respond to changes in surface temperature changes in very different ways. Over ocean and land, and over the tropics and the globe, when surface temperature increases, so does water vapour. However, the link between precipitation and surface temperature changes is complex. Even when ENSO and volcano effects are removed from the relations, water vapour responds directly to surface temperature, but any significant positive (same sign) correlation between surface temperature and precipitation disappears.

Warmer surface temperatures tend to force greater evaporation (mainly over oceans, but over some land areas with relative high soil moisture) and, therefore, in general, higher values of vertically-integrated water vapour, which is however governed by the CC relation (Allen and Ingram, 2002; Held and Soden, 2006). The increased water vapour (even if generated mostly over oceans) is transported horizontally for a wider, even global, effect. However, variations in precipitation, although affected by variations in water vapour, are primarily governed by stability and vertical motion. Mass budget constraints limit areas of ascent, so that increases in water vapour do not necessarily result in significant increases in total precipitation. However, large-scale dynamical effects of ENSO may still produce a residual increase of precipitation following increases in surface temperature and water vapour. Nevertheless, inter-annual precipitation variability over a large domain where the net large-scale dynamic adjustments are weak (e.g. ENSO effects removed and/or limited) does not follow the changes of surface temperature and water vapour. If we consider the global troposphere as a roughly horizontally homogeneous column with no net effect of large-scale overturning adjustments, precipitation variability within this column should thus be balanced by tropospheric atmospheric cooling given the small heat storage in the atmosphere (Allen and Ingram, 2002). Various feedbacks can be active to adjust surface and tropospheric temperatures, with water vapour and clouds being jointly involved (Held and Soden, 2000; Bony *et al.*, 2006), but the tropospheric energy budget will remain roughly in balance, restraining any further significant precipitation changes. This tends to lend support to the theoretical argument for accounting for a weak global-mean precipitation response under the global warming scenario in both models and observations. The results shown here seem to be consistent with past studies focusing on tropical convection over various ocean domains and/or climate regimes (Lau *et al.*, 1997; Tompkins and Craig, 1999).

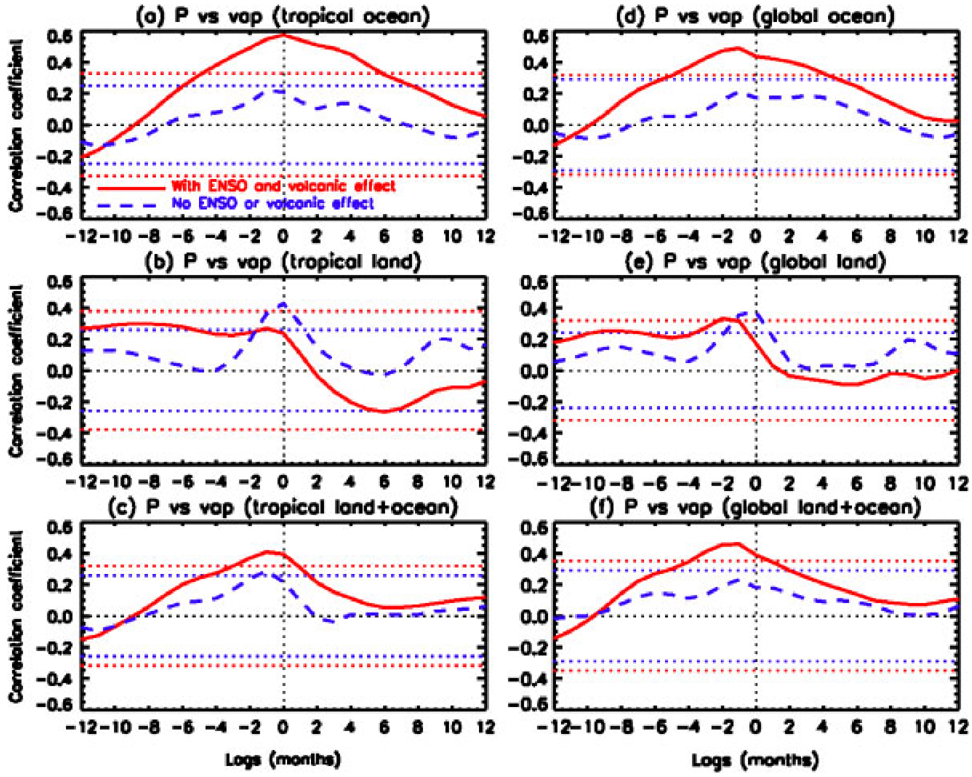

Figure 10. Lag-correlations between precipitation (P) and columnar water vapour (vap) with (red solid lines) and without (blue dashed lines) the ENSO and volcanic effects. The corresponding 5% significance levels ($\gamma_{5\%}$) are also shown (colour dotted lines), which are estimated based on the lag-1 auto-correlations of the time series being correlated. Positive (negative) lags mean vap lags (leads) P. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

Lau *et al*. (1997) showed the importance of large-scale atmospheric circulation in the relations between tropical oceanic convection and SST. Tompkins and Craig (1999) suggested as well that tropical oceanic convection is in general not sensitive to SST if there is no large-scale circulation forcing.

The weak inter-annual correlation between precipitation and surface temperature is also in agreement with the fact that a relatively weak relation is always seen between tropical mean (land + ocean) precipitation and surface temperature (and Nino 3.4) even with the ENSO effect (Figure 9(c) and (f); Su and Neelin, 2003; Gu *et al*., 2007).

However, these results do not mean that surface temperature variations have negligible impact on global precipitation. On the contrary, it indicates the complexity of the precipitation–temperature relations in that various forcings may work on different time scales and thus succeeding, dominant feedback mechanisms could be different on these different time scales. For instance, in contrast to ENSO, volcanic eruptions can effectively decrease surface temperature and reduce global precipitation over both land and ocean (Gu *et al*., 2007). However, our calculations also indicate that when the strong inter-annual effects of ENSO and volcanoes are removed over large areas (e.g. global oceans), the results for the remaining inter-annual variations resemble those for the trend, at least in the relation between water vapour and precipitation. The results here also suggest that we may have to focus more on the regional changes of precipitation, which are closely related to the large-scale circulation variations due to global surface temperature change. Changes in precipitation extremes on the inter-annual time scale and perhaps the interdecadal-to-long-term scales should be further examined as well from this standpoint in the future.

Acknowledgements

The global surface temperature anomaly data and the tropical mean stratospheric aerosol optical thickness were provided by the NASA-GISS from its Web Site at http://data.giss.nasa.gov. The RSS-SSM/I columnar water vapour data were downloaded from http://www.remss.com. This research is supported under the NASA Energy and Water-cycle Study (NEWS) program.

References

Adler RF, Huffman GJ, Chang A, Ferraro R, Xie P, Janowiak J, Rudolf B, Schneider U, Curtis S, Bolvin D, Gruber A, Susskind J, Arkin P. 2003. The version 2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (1979-Present). *Journal of Hydrometeorology* **4**: 1147–1167.

Adler RF, Gu G, Wang J-J, Huffman GJ, Curtis S, Bolvin D. 2008. Exploring relationships between global precipitation and surface temperature on the longer-than-seasonal time scales (1979–2006). *Journal of Geophysical Research-Atmospheres* **113**: D22104, DOI: 10.1029/2008JD010536.

Allen MR, Ingram WJ. 2002. Constraints on future changes in climate and the hydrologic cycle. *Nature* **419**: 224–232.

Andrews T, Forster PM, Boucher O, Bellouin N, Jones A. 2010. Precipitation, radiative forcing and global temperature change. *Geophysics Research Letters* **37**: L14701, DOI: 10.1029/2010GL043991.

Bony S, Colman R, Kattsov VM, Allan RP, Bretherton CS, Dufresne J-L, Hall A, Hallegatte S, Holland MM, Ingram W, Randall DA, Soden BJ, Tselioudis G, Webb MJ. 2006. How well do we understand and evaluate climate change feedback processes?. *Journal of Climate* **19**: 3445–3482.

Burgman RJ, Clement AC, Mitas CM, Chen J, Esslinger K. 2008. Evidence for atmospheric variability over the Pacific on decadal timescales. *Geophysics Research Letters* **35**: L01704, DOI: 10.1029/2007GL031830.

Chen J, Del Genio AD, Carlson BE, Bosilovich MG. 2007. The spatiotemporal structure of 20th century climate variations in observation and reanalyses. Part II: Pacific pan-decadal variability. *Journal of Climate* **21**: 2634–2650.

Chou C, Tu J-Y. 2008. Hemispherical asymmetry of tropical precipitation in ECHAM5/MPI-OM during El Niño and under global warming. *Journal of Climate* **21**: 1309–1332.

Gillet NP, Weaver AJ, Zwiers FW, Wehner MF. 2004. Detection of volcanic influence on global precipitation. *Geophysics Research Letters* **31**: L12217, DOI: 10.1029/2004GL020044.

Gu G, Adler RF. 2011. Precipitation and temperature variations on the inter-annual time scale: assessing the impact of ENSO and volcanic eruptions. *Journal of Climate* **24**: 2258–2270.

Gu G, Adler RF, Huffman G, Curtis S. 2007. Tropical rainfall variability on interannual-to-interdecadal/longer-time scales derived from the GPCP monthly product. *Journal of Climate* **20**: 4033–4046.

Hansen J, Ruedy R, Glascoe J, Sato M. 1999. GISS analysis of surface temperature change. *Journal of Geophysics Research* **104**: 30997–31022.

Held IM, Soden BJ. 2000. Water vapor feedback and global warming. *Annual Review of Energy and the Environment* **25**: 441–475.

Held IM, Soden BJ. 2006. Robust responses of the hydrological cycle to global warming. *Journal of Climate* **19**: 5686–5699.

Huffman GJ, Adler RF, Bolvin DT, Gu G. 2009. Improvements in the GPCP global precipitation record: GPCP version 2.1. *Geophysics Research Letters* **36**: L17808, DOI: 10.1029/2009GL040000.

John VO, Allan RP, Soden BJ. 2009. How robust are observed and simulated precipitation responses to tropical ocean warming? *Geophysics Research Letters* **36**: L14702, DOI: 1029/2009GL038276.

Lambert FH, Allen MR. 2009. Are changes in global precipitation constrained by the tropospheric energy budget?. *Journal of Climate* **22**: 499–517.

Lau K-M, Wu H-T, Bony S. 1997. The role of large-scale atmospheric circulation in the relationship between tropical convection and sea surface temperature. *Journal of Climate* **10**: 381–392.

Liepert BG, Previdi M. 2009. Do models and observations disagree on the rainfall response to global warming? *Journal of Climate* **22**: 3156–3166.

Lu J, Chen G, Frierson DMW. 2008. Response of the zonal mean atmospheric circulation to El Niño versus global warming. *Journal of Climate* **21**: 5835–5851.

Robock A. 2000. Volcanic eruptions and climate. *Reviews of Geophysics* **38**: 191–219.

Sato M, Hansen JE, McCormick MP, Pollack JB. 1993. Stratospheric aerosol optical depths, 1850–1990. *Journal of Geophysical Research* **98**: 22987–22994.

Soden BJ. 2000. The sensitivity of the tropical hydrological cycle to ENSO. *Journal of Climate* **13**: 538–549.

Soden BJ, Wetherald RT, Stenchikov GL, Robock A. 2002. Global cooling after the eruption of Mount Pinatubo: a test of climate feedback by water vapor. *Science* **296**: 727–730.

Stephens GL, Ellis TD. 2008. Controls of global-mean precipitation increases in global warming GCM experiments. *Journal of Climate* **21**: 6141–6155.

Su H, Neelin JD. 2003. The scatter in tropical average precipitation anomalies. *Journal of Climate,* **16**: 3966–3977.

Tompkins AM, Craig GC. 1999. Sensitivity of tropical convection to sea surface temperature in the absence of large-scale flow. *Journal of Climate* **12**: 462–476.

Trenberth KE, Shea DJ. 2005. Relationships between precipitation and surface temperature. *Geophysics Research Letters* **32**: L14703, DOI: 10.1029/2005GL022760.

Trenberth KE, Dai A. 2007. Effect of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering. *Geophysics Research Letters* **34**: L15702, DOI: 10.1029/2007GL 030524.

Trenberth KE, Branstator GW, Karoly D, Kumar A, Lau N-C, Ropelewski C. 1998. Progress during TOGA in understanding and modeling global teleconnections associated with tropical sea surface temperatures. *Journal of Geophysical Research* **103**(C7): 14291–14324.

Trenberth KE, Caron JM, Stephaniak DP, Woeley S. 2002. The evolution of ENSO and global atmospheric surface temperatures. *Journal of Geophysical Research* **107**: D8, DOI: 10.1029/ 2000JD000298.

Trenberth KE, Fasullo J, Smith L. 2005. Trends and variability in column-integrated atmospheric water vapor. *Climate Dynamics* **24**: 741–758.

Wallace JM, Rasmusson EM, Mitchell TP, Kousky VE, Sarachik ES, von Storch H. 1998. On the structure and evolution of ENSO-related climate variability in the tropical pacific: Lessons from TOGA. *Journal of Geophysical Research* **103**(C7): 14241–14259.

Wentz FJ. 1997. A well-calibrated ocean algorithm for special sensor microwave/imager. *Journal of Geophysical Research* **102**(C4): 8703–8718.

Wentz FJ, Ricciardulli L, Hilburn K, Mears C. 2007. How much more rain will global warming being? *Science* **317**: 233–235.

Wigley TML. 2000. ENSO, volcanoes and record-breaking temperatures. *Geophysics Research Letters* **27**: 4101–4104.

Zveryaev II, Allan RP. 2005. Water vapor variability in the tropics and its links to dynamics and precipitation. *Journal of Geophysical Research* **110**: D21112, DOI: 10.1029/2005JD006033.

