Precipitation and Temperature Variations on the Interannual Time Scale: Assessing the Impact of ENSO and Volcanic Eruptions

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ABSTRACT

The effects of ENSO and two large tropical volcanic eruptions (El Chichón, March 1982; Mt. Pinatubo, June 1991) are examined for the period of 1979–2008 using various satellite- and station-based observations of precipitation, temperature (surface and atmospheric), and tropospheric water vapor content. By focusing on the responses in the time series of tropical and global means over land, ocean, and land and ocean combined, the authors intend to provide an observational comparison of how these two phenomena, represented by Niño-3.4 and the tropical mean stratospheric aerosol optical thickness (τ), respectively, influence precipitation, temperature, and water vapor variations.

As discovered in past studies, strong same-sign ENSO signals appear in tropical and global mean temperature (surface and tropospheric) over both land and ocean. However, ENSO only has very weak impact on tropical and global mean (land + ocean) precipitation, though intense anomalies are readily seen in the time series of precipitation averaged over either land or ocean. In contrast, the two volcanoes decreased not only tropical and global mean surface and tropospheric temperature but also tropical and global mean (land + ocean) precipitation. The differences between the responses to ENSO and volcanic eruptions are thus further examined by means of lag-correlation analyses. The ENSO-related peak responses in oceanic precipitation and sea surface temperature (SST) have the same time lags with Niño-3.4, 2 (4) months for the tropical (global) means. Tropical and global mean tropospheric water vapor over ocean (and land) generally follows surface temperature. However, land precipitation responds to ENSO much faster than temperature, suggesting a certain time needed for surface energy adjustment there following ENSO-related circulation and precipitation anomalies. Weak ENSO signals in the tropical and global mean mid- to lower-tropospheric atmospheric (dry) static instability are further discovered, which tend to be consistent with weak ENSO responses in the tropical and global mean (land + ocean) precipitation. For volcanic eruptions, tropical and global mean precipitation over either ocean or land responds faster than temperature (surface and atmospheric) and tropospheric water vapor averaged over the same areas, suggesting that precipitation tends to be more sensitive to volcanic-related solar forcing. The volcanic-related precipitation variations are further shown to be related to the changes in the mid- to lower-tropospheric atmospheric (dry) instability.

1. Introduction

ENSO and large volcanic eruptions can effectively modulate precipitation (P) and temperature (surface and atmospheric) in the tropics and probably across the globe (e.g., Dai and Wigley 2000; Soden 2000; Trenberth et al. 2002; Curtis and Adler 2003; Su et al. 2003; Robock 2000; Wigley 2000; Gillett et al. 2004; Wigley et al. 2005; Gu et al. 2007). Systematic tropospheric and surface warming (cooling) has been discovered across the entire tropical band following the warm (cold) ENSO events (e.g., Wallace et al. 1998; Angell 2000; Sobel et al. 2002; Hoerling and Kumar 2002; Kumar and Hoerling 2003; Su et al. 2005). However, only weak responses are seen in tropical mean (land + ocean) precipitation (e.g., Su and Neelin 2003; Gu et al. 2007), though ENSO can induce intense, opposite precipitation anomalies over land and ocean, respectively (e.g., Dai and Wigley 2000; Trenberth et al. 2002; Curtis and Adler 2003; Gu et al. 2007). In contrast, the 2 large, tropical volcanic eruptions (El Chichón, March 1982; Mt. Pinatubo, June 1991) during the past three decades [the Global Precipitation Climatology Project (GPCP) period] decreased both surface temperature (Ts) and tropical (and global) mean precipitation (e.g., Robock 2000; Wigley...
2000; Soden et al. 2002; Gillett et al. 2004; Wigley et al. 2005; Gu et al. 2007). Thus, the troposphere, in terms of precipitation and temperature, responds differently to ENSO and volcanic eruptions.

Our objective here is to examine the physical processes and explore possible mechanisms behind these different responses by observationally assessing the effects of ENSO and volcanic eruptions on precipitation, temperature (surface and atmospheric), and tropospheric water vapor content. Specifically, we intend to improve our understanding of how and why tropical and global mean (land + ocean) precipitation responds so differently to ENSO and volcanic eruptions. We focus on the time series of precipitation, temperature (surface and atmospheric), and water vapor anomalies for both the tropics and the globe. Efforts are made to identify and then isolate the ENSO and volcanic signals (temperature, precipitation, and water vapor), and use lag-correlation/ lag-regression analyses with ENSO and volcano indices to gain understanding of physical processes.

Section 2 introduces the precipitation, temperature, and tropospheric columnar water vapor datasets applied in this study. Methodology is briefly described in section 3. Section 4 presents the results with discussions. A summary and the concluding remarks are given in section 5.

2. Datasets

The precipitation product is the monthly GPCP product (version 2.1), a community-based analysis of global precipitation under the auspices of the World Climate Research Program (WCRP). Archived on a global 2.5° × 2.5° grid, the product is combined from a variety of data sources: passive microwave-based rainfall estimates from the Special Sensor Microwave Imager (SSM/I), infrared (IR) rainfall estimates from geostationary and polar-orbiting satellites, and surface rain gauges. The combination procedures are designed to take advantage of particular strengths of the individual input datasets, specifically in terms of bias reduction (Adler et al. 2003; Huffman et al. 2009). The dataset lasts from January 1979 to the present.

Surface temperature anomalies are described using the National Aeronautics and Space Administration (NASA)—Goddard Institute for Space Studies (GISS) monthly surface temperature anomaly field (Hansen et al. 1999). Archived on 1° × 1° grids, the data combine air temperature anomalies from meteorological station measurements over land and sea surface temperature (SST) derived from satellite measurements during the post-1981 period (Reynolds et al. 2002). Detailed information is summarized in Hansen et al. (1999) and the product can be reached through the NASA–GISS data Web site. For consistency, the surface temperature anomaly field is merged onto the GPCP 2.5° × 2.5° grid.

Three atmospheric layered temperature products from the University of Alabama in Huntsville (UAH) are also applied (Christy et al. 2000, 2003), which are derived from the Microwave Sounding Units (MSUs) and the Advanced Microwave Sounding Units (AMSUs). The fields include the deep-layered temperatures for the lower troposphere (TLT), the midtroposphere (TMT), and the lower stratosphere (TLS). Archived on the 2.5° × 2.5° grid, the products cover from 1978 to the present.

The version-6 monthly SSM/I columnar water vapor products from the Remote Sensing Systems (RSS) are used to describe the variations in oceanic precipitable water. The data cover the post-1987 period and are combined from several inter-calibrated satellite retrievals (Wentz 1997). Similar products have been assessed and used in past studies (e.g., Trenberth et al. 2005). Since there is no direct satellite retrieval of water vapor over land, the outputs from the NASA–Modern Era Retrospective-Analysis for Research and Applications (MERRA) are applied. Even though radiosondes are used to constrain the MERRA precipitable water over land and a good agreement is found in oceanic precipitable water between the SSM/I and MERRA, especially on the interannual time scale (not shown), the emphasis is on variations over the ocean, although land and ocean are also presented.

3. Methodology

To examine the ENSO and volcanic effects, the time series of precipitation and temperature anomalies are first constructed for both tropical (25°N–25°S) and global (90°N–90°S) means during the period of 1979–2008. For precipitation and surface temperature, the time series of anomalies are further constructed over land and ocean separately. As introduced above, here SST and air temperature anomalies are used to represent surface temperature variations over ocean and land, respectively. Niño-3.4, a time series of SST anomalies over a domain of 5°N–5°S, 120°–170°W in the tropical Pacific, is used to represent the climatic features associated with ENSO (Fig. 1a). Volcanic signals are denoted by the tropical mean stratospheric aerosol optical thickness (τ). This volcanic index clearly shows the injection of aerosol particles associated with the two large volcanic eruptions during the GPCP record (Fig. 1b; Sato et al. 1993).

Since the two large volcano eruptions overlap in time with two El Niño events (Fig. 1), the resulting responses in the troposphere and the hydrological cycle become complicated, given their possible opposite effects (e.g., Dai and Wigley 2000; Soden 2000; Su et al. 2003; Robock 2000;
Wigley 2000; Gillett et al. 2004; Wigley et al. 2005; Gu et al. 2007). Thus, we must identify and separate the effects of ENSO and volcanic eruptions, if any, in the time series.

All time series are first detrended and smoothed by a 3-month-running window in that here we are generally focused on the interannual time scale. The GPCP time span (January 1979–December 2008) is then divided into two periods based on the monthly magnitude of $\tau$ (Fig. 1b). One period is that with the volcanic impact (defined as $\tau \geq 0.016$; 67 months), while the other period is the remainder of the time span ($\tau < 0.016$; 293 months). The ENSO effects on precipitation and temperature during the non-volcanic period ($\tau < 0.016$) are then estimated by means of linear lag-correlation–lag-regression analysis between Niño-3.4 and the other variables. These derived linear relations are considered the “normal” ENSO impact and are then applied to the entire GPCP record to estimate the possible ENSO responses, including for the volcano period. To estimate the effect of the two volcanic eruptions, the estimated ENSO effects are removed from the time series. The volcanic effects are then derived by estimating the linear lag correlations–lag regressions of the remaining signals of the various parameters with $\tau$ during the volcanic period ($\tau \geq 0.016$). The ENSO and volcanic effects can thus be identified and separated in the time series. Different from the procedures used in Gu et al. (2007), lag correlation–lag regression, other than simultaneous correlation–regression, analyses are applied here to emphasize–maximize the likely lag responses–adjustments in the surface and tropospheric variables.

4. Results

a. ENSO signals

Time series of precipitation and surface temperature anomalies over tropical and global ocean, land, and land + ocean are shown in Figs. 2 and 3 (blue lines). Linear changes, or trends, exist in some of these time series. Tropical precipitation over either land or ocean has a moderate increase during the GPCP record (e.g., Gu et al. 2007; Huffman et al. 2009). However, there is only a very weak change in global mean precipitation (e.g., Gu et al. 2007; Huffman et al. 2009). In contrast, surface temperature increases not only for the tropical mean but also for the global mean. In reality, intense temperature increases primarily occur in the North Hemisphere mid–high latitudes (e.g., Adler et al. 2008). As stated above, here we will focus on the interannual time scale and these time series are detrended before the lag-correlation relations are estimated.

The lag correlations of precipitation and surface temperature with Niño-3.4 over (tropical and global) land and ocean during the nonvolcanic period ($\tau < 0.016$) are
depicted in Fig. 4. Both tropical oceanic precipitation and temperature positively correlate with Niño-3.4 as expected (solid lines in Figs. 4a, b), with oceanic temperature (or SST) showing a much stronger link with ENSO. It is noted that the maximum correlations occur as Niño-3.4 leads the 2 components by 2 months. Global mean oceanic precipitation and temperature significantly correlate to Niño-3.4 as well, albeit a little bit weaker than their tropical counterparts (dashed lines in Figs. 4a and 4b). Also the same time lag (Niño-3.4 leading by 4 months) is seen for the maximum correlations of both global ocean precipitation and global ocean temperature with Niño-3.4. The same time lags for both the tropical and global oceanic means suggest a coupled response process to ENSO for oceanic mean precipitation and mean SST, though intense precipitation anomalies with both signs occur in the tropics.

Fig. 3. As in Fig. 2, but for surface temperature anomalies.

Fig. 4. Lag correlations of (a) oceanic and (c) land surface precipitation ($P$; mm day$^{-1}$), and (b) ocean and (d) land surface temperature ($T_s$; $^\circ$C) with Niño-3.4 during the nonvolcanic period (tropical mean $r < 0.016$). Positive (negative) lags mean Niño-3.4 lags (leads) $P$ and $T_s$. The 5% significance levels ($\gamma_{5\%}$) are also shown, which are estimated based on the lag-1 autocorrelations of the time series being correlated. Dash-dot lines denote the time lag with maximum correlation.
and across the globe (e.g., Dai and Wigley 2000; Curtis and Adler 2003; Xie et al. 2009), in contrasting to roughly tropical-wide warming or cooling following the ENSO events (e.g., Yulaeva and Wallace 1994; Wallace et al. 1998; Sobel et al. 2002; Su et al. 2005). Understandably, the time lag of maximum correlation for global oceanic mean precipitation and global mean SST is larger than that for tropical oceanic precipitation and tropical SST because more time is necessary for the extension of the ENSO impact to the middle and higher latitudes.

Global and tropical land precipitation variations are negatively correlated to Niño-3.4 (Fig. 4c). If the estimation is applied to the entire record, the correlations can be slightly stronger because the near simultaneously occurring warm ENSO events and volcanic eruptions both tend to decrease land precipitation (not shown; e.g., Gu et al. 2007). The maximum correlation occurs at the 0 time lag for the tropical land precipitation, showing a fast response of land precipitation to ENSO. Interestingly, the maximum correlation between global land precipitation and Niño-3.4 appears as the latter lags by about 2 months, though the difference between this maximum and the correlation at the 0 time lag is small. This slight lead of precipitation ahead of the ENSO index may imply that land surface precipitation could be very sensitive to Niño-3.4 especially during the developing stage of ENSO because of ENSO-associated circulation anomalies, although significant correlations can be seen with time lags from −4 to +6 months (Fig. 4c). Su et al. (2005) found a similar lead–lag relation, even though they focused on the correlations between precipitation anomalies averaged over the entire tropical region outside of the ENSO forcing zone and Niño-3.4. Tropical land surface (air) temperature is highly but positively correlated to Niño-3.4, and the correlation coefficient attains its peak when Niño-3.4 leads by 5 months (Fig. 4d). This five-month time lag suggests a rough time scale needed for land surface air temperature to adjust because of the variations of surface energy budget caused by ENSO-associated circulation and precipitation anomalies. The correlation between global mean land surface temperature and Niño-3.4 is weak and below the 5% significance level (dashed line Fig. 4d), probably because the more intense surface temperature variations usually occur in the middle and higher latitudes, specifically in the Northern Hemisphere (e.g., Adler et al. 2008), which are not directly related to ENSO.

Consistent with past studies (e.g., Su and Neelin 2003; Gu et al. 2007), tropical mean (land + ocean) precipitation has no significant correlation with Niño-3.4 (solid line in Fig. 5a). The correlation between global mean (land + ocean) precipitation and Niño-3.4 becomes stronger (dashed line in Fig. 5a), with its peak appearing as Niño-3.4 leads by 7 months, despite barely reaching the 5% significance level. This slightly stronger global correlation may result from the ENSO modulations of midlatitude storm tracks and associated precipitation (e.g., Seager et al. 2005) but certainly warrants further exploration.

Tropical mean surface temperature (SST over ocean and air temperature over land) shows a strong, positive correlation with Niño-3.4, and the peak correlation appears as Niño-3.4 leads by 3 months (solid line in Fig. 5b). The correlation between global mean surface temperature and Niño-3.4 is weaker (dashed line in Fig. 5b); however, it is still above the 5% significance level, with Niño-3.4 leading by about 4–8 months, a larger time lag than in the tropics.

Based on derived lag correlations (Figs. 4 and 5), ENSO associated precipitation anomalies are estimated using lag regressions (red lines in Figs. 2 and 3). ENSO signals can be readily seen in both tropical oceanic and land precipitation (Figs. 2a and 2b), though their signs are always opposite (e.g., Dai and Wigley 2000; Curtis and Adler 2003; Gu et al. 2007). However, the ENSO signal in the tropical mean (land + ocean) precipitation is weak (Figs. 2c), reflecting their weak correlations shown in Fig. 5. Global oceanic and land precipitation also responds to ENSO (Figs. 2d and 2e), though weaker than their tropical counterparts. Nevertheless, the global mean (land + ocean) precipitation has a very weak ENSO response, even though the correlation is marginally significant when Niño-3.4 leads by 7 months (dashed line in Fig. 5a).

Tropical SST closely follows the variations of Niño-3.4 (Fig. 3a), manifesting ENSO’s remote impact in the other tropical ocean basins (e.g., Wallace et al. 1998; Sobel et al. 2002; Su et al. 2005). Unlike tropical land precipitation, tropical land surface temperature responds positively to Niño-3.4 (Fig. 3b). Thus, tropical mean surface temperature is seen to vary strongly with Niño-3.4 (Fig. 3c). Intense tropical-wide warming–cooling following the ENSO (warm–cold) events is very different from that for tropical mean (land + ocean) precipitation (Figs. 2c and 3c). Same-sign responses are also seen in the global ocean and land surface (air) temperature (Figs. 3d and 3e). Hence, global mean surface temperature has strong responses to ENSO (Fig. 3f), in contrast to very weak ENSO signals in global mean (land + ocean) precipitation (Fig. 2f).

To further explore why tropical and global mean (land + ocean) precipitation and surface temperature respond so differently to ENSO, the relationships between tropical and global mean atmospheric temperature and Niño-3.4 are examined using the MSU/AMSU layered temperature products. Time series of tropical and global mean TLT, TMT, and TLS are shown in Fig. 6 (blue lines). The TLT − TMT is also computed to represent the possible changes in atmospheric (dry) static instability due to temperature changes in the mid-
lower troposphere. High correlations with Niño-3.4 are observed for both TLT and TMT with peaks occurring when Niño-3.4 leads them by 4 and 6 months for tropical and global means, respectively (Figs. 5c and 5d; Yulaeva and Wallace 1994). It is interesting to further note that the global mean TLT and TMT tend to have much higher correlations with Niño-3.4 than the global mean surface temperature, likely confirming ENSO’s remote modulations through the tropospheric atmosphere (e.g., Wallace et al. 1998; Sobel et al. 2002; Hoerling and Kumar 2002; Kumar and Hoerling 2003). The ENSO signals in TLT and TMT are also estimated using lag regressions and shown in Figs. 6a, 6b, 6e, and 6f (red lines).

In contrast to strong ENSO modulations of TLT and TMT, no coherent ENSO signals can be found in tropical and global mean TLT – TMT (Figs. 6c and 6g). Correlations between TLT – TMT and Niño-3.4 are weak and well below the 5% significance level (Fig. 5e). This indicates that the ENSO events have small net influence on atmospheric dry instability for the tropical and global means, which might be a contributing factor for weak ENSO responses in tropical and global mean precipitation (Figs. 2c, 2f, and 5a). However, because of ENSO-related tropical water vapor variations, changes in moist instability may still appear. In fact, ENSO-associated changes in dry instability can be seen regionally. A narrow zone of increase (decrease) in TLT – TMT occurs right over the tropical central-eastern Pacific following the occurrence of warm (cold) ENSO events, sandwiched by two zones of opposite changes north and south of it (not shown). This is consistent with the fact that even though the ENSO-related tropical and global (land + ocean) mean precipitation is weak, intense precipitation anomalies of either sign appear in the tropics and across the globe due to the large-scale atmospheric circulation anomalies initiated in the tropical central-eastern Pacific. It is further found that in the lower stratosphere, the effect of ENSO is also weak and a coherent ENSO signal can hardly be found in TLS (Figs. 6d and 6h), resulting in very weak correlations between TLS and Niño-3.4 (Fig. 5f).
b. Volcanic signals

We now focus on identifying volcanic signals in various components during the volcanic period ($\tau \geq 0.016$). After the ENSO effect is removed, the estimated impact of the 2 volcanic eruptions can be discerned in the time series of both precipitation and surface temperature anomalies over land, ocean, and land + ocean (blue lines in Figs. 7 and 8) and are also clearly shown in tropical and global mean TLT and TMT (Figs. 9a, 9b, 9e, and 9f). Furthermore, even though ENSO has very limited impacts on TLT – TMT and TLS (Figs. 5e and 5f), volcanic signals can easily be found in both (Figs. 9c, 9g, 9d, and 9h).

Lag correlations with $\tau$ during the volcanic period ($\tau \geq 0.016$) are estimated (Figs. 10 and 11). Linear responses are also computed using lag regressions (red lines in Figs. 7–9). In the tropics, volcanic eruptions can effectively reduce precipitation and decrease surface temperature over both land and ocean (Figs. 7 and 8). Maximum correlations between (ocean, land, and land + ocean) surface temperature and $\tau$ are found as the latter leads by 3 months, suggesting a lagged response–adjustment at the surface (solid lines in Figs. 10d, 10e, and 10f). However, maximum correlations between (ocean, land, and land + ocean) precipitation and $\tau$ occur surprisingly when the latter lags by 0–2 months with a shallow slope (solid lines in Figs. 10a, 10b, and 10c). This implies an immediate response of precipitation following eruptions and associated solar radiative forcing and also suggests that the volcanic effect on precipitation may be very effective during the early stage of eruptions.

Volcanic eruptions also reduce global mean precipitation and decrease global mean surface temperature over both land and ocean (Figs. 7f, 8f, and 10). Similar as in the tropics, global precipitation tends to respond faster to volcanic-related forcings than surface temperature does. In particular, the global mean (land + ocean) precipitation strongly correlates to $\tau$ with the maximum correlation appearing when $\tau$ leads by 1 month (Fig. 10c), while the maximum correlation between the global mean surface temperature and $\tau$ appears as the latter leads by about 10 months (dashed line in Fig. 10f), qualitatively consistent with past modeling results (e.g., Figs. 1 and 2 in Soden et al. 2002). Thus, the responses of global mean precipitation and surface temperature to volcanic eruptions are different as well.

Linear correlations of tropical and global mean TLT and TMT with $\tau$ are strong when the latter leads by several months (Figs. 11a and 11b), showing the tropospheric adjustments following volcanic eruptions. The time lags for the peak correlations are generally similar as for the tropical and global mean surface temperature (Figs. 10f, 11a, and 11b). It is further found that both the tropical and global mean TLT – TMTs are highly correlated with $\tau$ (Fig. 11c), compared to their weak relation with Niño-3.4 (Fig. 5e). These high negative correlations suggest that volcanic eruptions can effectively influence the atmospheric (dry) stability (or lapse rate) at the mid- to lower troposphere. Strong positive

![Fig. 6. Time series of (left) tropical and (right) global (a),(c) TLT, (b),(f) TMT, (c),(g) TLT – TMT, and (d),(h) TLS (°C; blue lines). (a),(b),(e),(f) Red lines represent corresponding linear responses to Niño-3.4.](unauthenticated)
correlations between TLS and $\tau$ are also observed (Fig. 11d), confirming systematic warming at stratospheric and upper-tropospheric levels following volcanic eruptions noted in past studies (e.g., Stenchikov et al. 1998; Robock 2000). Figure 9 further shows the linear responses of these components to volcanic eruptions.

c. Comparison and discussion

The responses of tropical and global mean precipitation, temperature (surface and atmospheric), and tropospheric water vapor to ENSO and volcanic eruptions are different, including their lag-correlation relations with Niño-3.4 and $\tau$ gauged by the peak correlation coefficient. Oceanic precipitation responds to ENSO with the same time lags as SST for both tropical and global means (Figs. 4a and 4b). Tropical and global mean tropospheric water vapor over ocean is also shown to respond strongly to ENSO and follows SST variations (Fig. 12a). However, the response of oceanic precipitation to volcanic eruptions tends to be faster than that of SST especially for the tropical means (Figs. 10a and 10d), though tropospheric water vapor still follows SST (Figs. 10d and 12c). Over land, precipitation shows a faster response to ENSO than surface (air) temperature specifically for the tropical means (Figs. 4c and 4d). For the responses to volcanic eruptions over land, surface (air) temperature lags $\tau$ by 3 months compared to no time lag between precipitation and $\tau$ (Figs. 10b and 10e). It is of interest to note that for the ENSO effect, tropical (and global mean) land surface temperature shows a larger time lag to Niño-3.4 than tropical (and global mean) SST (Figs. 4b and 4d), though the correlations between global mean land surface temperature and Niño-3.4 are not statistically significant. However, the time lag for the peak correlation between tropical mean land surface temperature and $\tau$ is the same as that between SST and $\tau$ (solid

![Fig. 7. Time series of (left) tropical and (right) global precipitation anomalies (mm day$^{-1}$; blue lines) with the ENSO effect removed over (a),(d) ocean, (b),(e) land, and (c),(f) land + ocean. Also shown are their corresponding linear responses to $\tau$ (red lines).](image1)

![Fig. 8. As in Fig. 7, but for surface temperature anomalies (°C).](image2)
This may imply that the ENSO effect that originated from the tropical central-eastern Pacific goes through large-scale circulation anomalies and tropospheric wave dynamics to spread tropospheric temperature anomalies (e.g., Wallace et al. 1998; Sobel et al. 2002) and furthermore likely through different responses between over ocean and land; however, the responses to volcanic eruptions over both land and ocean are primarily through direct (zonal-mean) solar radiative forcing (e.g., Robock 2000).

The correlations between tropical and global mean (land + ocean) precipitation and Niño-3.4 are weak (Fig. 5a), compared with strong correlations with τ (Fig. 10c). Furthermore, mid- to lower-tropospheric dry instability (TLT − TMT) shows no correlation with Niño-3.4 (Fig. 5e) but is strongly correlated to τ with the latter leading by 1 and 2 months for tropical and global mean TLT − TMTs, respectively (Fig. 11c). Tropical and global mean surface and tropospheric temperatures, that is, Ts, TLT, and TMT, all are highly correlated to both Niño-3.4 and τ (Figs. 5b–d, 10f, 11a, and 11b). However, the time lags for the peak correlations between global mean temperatures and τ are much larger. Global mean tropospheric water vapor shows similar lag-correlation relations with Niño-3.4 and τ as temperature (Figs. 12b and 12d). This may suggest that the ENSO-forced surface temperature variations are dominated by tropical contribution, in contrast to the global surface temperature changes following volcanic eruptions with the involvement of tropospheric water vapor (e.g., Soden et al. 2002). Finally, global and tropical mean lower-stratospheric temperature has no significant correlation with Niño-3.4 (Fig. 5f) but is highly correlated to τ with peak correlation at the 0 time lag (Fig. 11d), a strong reaction to the injection of aerosol particles (e.g., Robock 2000).

The differences in the responses of global and tropical mean (land + ocean) precipitation to ENSO, especially the La Niña events that have negative surface temperature anomalies, and to volcanic eruptions surely imply different physical adjustment processes near the surface and in the tropospheric atmosphere. The weak correlations between tropical and global mean (land + ocean) precipitation and Niño-3.4 may be explained by the fact that unlike the same-sign responses of temperature (surface and tropospheric) over both land and ocean, opposite ENSO responses of precipitation over land and ocean, more accurately intense precipitation anomalies following SST anomalies in the tropical central-eastern Pacific and opposite mean precipitation anomalies outside of that region (e.g., Dai and Wigley 2000; Curtis and Adler 2003; Xie et al. 2009), always occur owing to ENSO-related large-scale circulation anomalies, leaving the (tropical and global) mean (land + ocean) precipitation as a residual. This implies that despite a major factor forcing large-scale circulation anomalies on the interannual time scale, ENSO could only have a small net effect on the global (and tropical) mean tropospheric energy budget, thereby resulting in weak responses in global (and tropical) mean (land + ocean) precipitation (e.g., Allen and Ingram 2002). In contrast, volcanic
eruptions can induce immediate solar energy perturbation at surface and within the atmosphere. Past modeling studies have shown that global precipitation may be more sensitive to shortwave forcing than longwave forcing (e.g., Allen and Ingram 2002; Gillett et al. 2004). Evident precipitation decreases over both land and ocean following volcanic eruptions tend to confirm this.

Different responses in the mid- to lower-tropospheric (dry) atmospheric stability seem to be another reason for the discrepancies in the responses of tropical and global mean (land + ocean) precipitation to ENSO and volcanic eruptions. ENSO can induce intense surface and tropospheric atmospheric temperature changes. However, there is no associated change in the (tropical and global mean) mid- to lower-tropospheric atmospheric temperature instability (Fig. 5e), although tropospheric water vapor is also a factor for convection and precipitation variations, which closely follows surface temperature fluctuations. Nevertheless, coherent variations exist in the mid- to lower-tropospheric (dry) instability during the volcanic period, and volcanic signals can even be seen in the original time series of tropical and global mean TL T–TMT (Figs. 6c and 6g). For the responses of global precipitation to volcanic eruptions, the changes in microphysical properties of precipitating clouds due to increased aerosols could also play a role as suggested by Spencer et al. (1998). Immediate lower-stratospheric warming following volcanic eruptions indicates the appearance of volcanic-related aerosols (Figs. 9d, 9h, and 11d) in both the lower stratosphere and troposphere. The increased aerosol content may partly account for immediate decreases in precipitation for these particles’ microphysical effects on clouds and precipitation (e.g., Spencer et al. 1998; Berg et al. 2006), though further evidence is required to establish this relation.

5. Summary and concluding remarks

The effects of ENSO and volcanic eruptions on global and tropical mean precipitation and temperature (surface and atmospheric) are examined using the 30-yr (1979–2008) GPCP monthly precipitation dataset, the NASA–GISS surface temperature analysis, and the satellite-based

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**Fig. 10.** Lag correlations of (left) precipitation (mm day$^{-1}$) and (right) surface temperature (°C) with $\tau$ during the volcanic period (tropical mean $\tau = 0.016$) with the ENSO effect removed: (a),(e) ocean, (b),(f) land, and (c),(f) land + ocean. Also shown are the 5% significance levels ($\gamma_{5\%}$) estimated based on the lag-1 autocorrelations of the time series being correlated.
atmospheric layered temperature data. Lag-regression–lag-correlation analyses are applied to discriminate among the anomalies in these fields resulting from ENSO and volcanic eruptions. The physical mechanisms behind the differences between the responses of precipitation and temperature to the ENSO and volcanic-related forcings are explored and further compared.

Precipitation and temperature (surface and atmospheric) are shown to respond differently to ENSO and volcanic eruptions. ENSO events induce strong same-sign surface...

![Fig. 11. Lag correlations of (a) tropical and (b) global TLT and TMT, (c) TLT – TMT, and (d) TLS (all °C) with τ during the volcanic period (tropical mean τ  0.016) with the ENSO effect removed. Also shown are the 5% significance levels (γ5%) estimated based on the lag-1 autocorrelations of the time series being correlated.]

![Fig. 12. Lag correlations of column water vapor (mm) over (a),(c) ocean and (b),(d) land + ocean with (a),(b) Niño-3.4 during the nonvolcanic period (tropical mean τ  0.016), and (c),(d) with τ during the volcanic period (tropical mean τ  0.016) with the ENSO effect removed. The data used here are the RSS-SSM/I product over ocean and the NASA–MERRA reanalysis output over land. Also shown are the 5% significance levels (γ5%) estimated based on the lag-1 autocorrelations of the time series being correlated.]

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and mid- to lower-tropospheric temperature anomalies averaged over both land and ocean. However, the tropical and global mean (land + ocean) precipitation is weakly correlated with Niño-3.4 and thus has only weak ENSO responses, though intense opposite-sign ENSO-associated precipitation anomalies appear over land and ocean. The two volcanic eruptions, on the other hand, effectively decrease surface temperature and reduce precipitation over both global land and ocean.

Lag-correlation analyses provide further details of these distinct responses. The ENSO-related peak responses in oceanic precipitation and sea surface temperature (SST) have the same time lags with Niño-3.4 for both tropical and global means. Tropical and global mean tropospheric water vapor over ocean (and land) generally follows surface temperature. Land precipitation responds to ENSO much faster than surface temperature averaged over the same area. Weak ENSO impact on tropical and global mean mid- to lower-tropospheric atmospheric (dry) static instability is also discovered, seemingly consistent with weak ENSO responses in the tropical and global (land + ocean) mean precipitation. To volcanic eruptions, tropical and global mean precipitation over either ocean or land responds faster than (surface and atmospheric) temperature and tropospheric water vapor averaged over the same areas, suggesting that precipitation tends to be very sensitive to volcanic-related solar radiative forcing. Furthermore, the volcanic-related precipitation variations tend to be related to the changes in the mid- to lower-tropospheric atmospheric (dry) instability.

In summary, during the ENSO events, intense precipitation anomalies first appear in the tropical central-eastern Pacific forced by the ENSO-related SST fluctuations, which then induce the large-scale circulation anomalies and simultaneously spread temperature anomalies through the tropospheric atmosphere (e.g., Wallace et al. 1998; Sobel et al. 2002). These circulation anomalies, by default, cannot induce the same-sign precipitation anomalies over both land and ocean (e.g., Dai and Wigley 2000; Xie et al. 2009), while tropospheric temperature anomalies can propagate the ENSO signals to the tropical (and global) surface through wave dynamics (e.g., Yulaeva and Wallace 1994; Sobel et al. 2002; Su et al. 2005). Thus, the mean (tropical and global) precipitation is not expected to vary significantly with surface (and tropospheric) mean temperature. The insensitivity of mean (tropical and global) lower-tropospheric temperature instability to ENSO tends to further suggest that there is no effective mechanism to force tropical and global mean (land + ocean) precipitation variations during the ENSO events, even though both surface and tropospheric temperatures strongly respond to Niño-3.4. On the other hand, the volcano-related precipitation anomalies are likely associated with the changes of lower-tropospheric atmospheric instability and also possibly related to aerosol effects on microphysical properties of precipitating clouds (e.g., Spencer et al. 1998). Different from relatively fast precipitation responses, temperature (surface and tropospheric) and tropospheric water vapor variations show a lagged response particularly for the global means (e.g., Soden et al. 2002).

Weak responses of tropical and global mean (land + ocean) precipitation to ENSO may provide some clues for our understanding of global long-term precipitation changes intensively discussed recently (e.g., Allen and Ingram 2002; Wentz et al. 2007; Gu et al. 2007). Even though physical forcing mechanisms for surface and tropospheric atmospheric temperature changes are different during (warm) ENSO and the global warming scenario (e.g., Lau et al. 1996), it is of interest to further examine how increased tropospheric water vapor impacts surface precipitation averaged over very large domains of small net dynamic effect, for instance, tropical and global means (land + ocean) and in various regions across the globe. A simple energy argument suggests that precipitation over large domains with minor net dynamic effects should be roughly balanced by tropospheric radiative cooling (e.g., Allen and Ingram 2002). Thus, further radiative budget analyses at both the surface and the top-of-atmosphere (TOA) are necessary based on the availability of long-record global-covered observations, especially for further exploring the insensitivity (or weak sensitivity) of global (and tropical) mean (land + ocean) precipitation occurring during both ENSO and global warming scenario.

Finally, it has to be mentioned that the arguments made here are primarily based on linear correlation/regression analyses. The responses of the tropospheric atmosphere and the hydrological cycle are certainly a complicated nonlinear process, and linear relationships are only one of the measures of assessing their sensitivity to various climatic forcings. Thus, further quantitative explorations are necessary and may depend on the availability of long-record global measurements and detailed modeling experiments.

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