A Comparison of Total Precipitable Water between Reanalyses and NVAP

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

RALPH R. FERRARO
ESSIC, and NOAA/NESDIS, College Park, Maryland

MICHAEL FIORINO
Lawrence Livermore National Laboratory, University of California, Livermore, California

(Manuscript received 22 July 2003, in final form 19 November 2004)

ABSTRACT

This study compares monthly total precipitable water (TPW) from the National Aeronautics and Space Administration (NASA) Water Vapor Project (NVAP) and reanalyses of the National Centers for Environmental Prediction (NCEP) (R-1), NCEP–Department of Energy (DOE) Atmospheric Model Intercomparison Project (AMIP-II) (R-2), and the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) from January 1988 through December 1999. Based on the means, NVAP exhibits systematic wetter land regions relative to the other datasets reflecting differences in their analyses due to paucity in radiosonde observations. ERA-40 is wetter in the atmospheric convergence zones than the U.S. reanalyses and NVAP ranges in between. Differences in the annual cycle between the reanalyses (especially R-2) and NVAP are also noticeable over the tropical oceans. Analyses on the interannual variabilities show that the ENSO-related spatial pattern in ERA-40 follows more coherently that of NVAP than those of the U.S. reanalyses. The 1997/98 El Niño’s effect on TPW is shown to be strongest only in NVAP, R-1, and ERA-40 during the period of study. All the datasets show TPW decreases in the Tropics following the 1991 Mt. Pinatubo eruption. By subtracting SST-estimated TPW from the datasets, only NVAP and ERA-40 can well represent the spatial pattern of convergence and/or moist-air advection zones in the Tropics. Even though all the datasets are viable for water cycle and climate analyses with discrepancies (wetness and dryness) to be aware of, this study has found that NVAP and ERA-40 perform better than the U.S. reanalyses during the 12-yr period.

1. Introduction

The goal of this study is to address a question of which global total precipitable water (TPW) datasets are appropriate for water cycle and climate analyses by comparing the spatiotemporal patterns in several widely used and new TPW datasets. TPW represents the total vertically integrated water vapor of an air column overlaying a unit area of the earth’s surface.

Water vapor plays an important role in the earth’s energy balance, owing to its high latent heat and high thermal capacity (Dingman 1994). The constant cycling of water (i.e., the water cycle) through water vapor, from evaporation to condensation and precipitation, also redistributes the heat from the sun over the earth’s surface through the atmosphere.

Water vapor also affects the earth’s climate (IPCC 2001). As a naturally abundant greenhouse gas, water vapor traps the longwave, infrared radiation from the earth’s surface helping to maintain the livable surface temperature. This behavior of water vapor also poses a positive feedback in the changing climate system. Studies suggest that additional water vapor in the atmosphere due to global warming traps more longwave infrared radiation and, hence, amplifies the temperature (IPCC 2001).
Despite its importance described above, the distribution and variability of water vapor in the atmosphere are not completely understood. Among other things, temporal and spatial discontinuities of observations and the inherent problems related to the observations, for example, the use of different instruments, contribute to the lack of understanding. However, many attempts have been made to address these observational problems.

The most recent global water vapor specific analysis based on ground and satellite retrievals is provided by the National Aeronautics and Space Administration (NASA) Water Vapor Project (NVAP; Randel et al. 1996) by combining retrievals from the Television and Infrared Operational Satellite (TIROS) Operational Vertical Sounder (TOVS), the Special Sensor Microwave Imager (SSM/I), and radiosondes. While SSM/I retrievals dominate the analysis over the ocean, radiosonde retrievals dominate the analysis over the land. NVAP uses a weighting ratio of radiosonde:SSM/I:TOVS = 10:9:1, where 10 means weighting at 100%. This means that radiosonde retrievals are assumed to be correct and are given 100% weighting even at coincident points with satellite retrievals. Over land, radiosonde observations are the primary observational source. Ocean-only SSM/I retrievals are weighted at 90% at coincident points with the TOVS retrievals, which are weighted at 10%. TOVS observations are available over both land and ocean. In general, Randel et al. (1996) claim that NVAP is far better than any of its input datasets.

For the 5-yr period 1988–92, Randel et al. (1996) found a Clausius–Clapeyron relationship between water vapor and temperature in NVAP shown most prominently as a drop in global total column water vapor starting in mid-1991 as a result of the Mt. Pinatubo eruption on 15 June 1991, and the effect of the El Niño–Southern Oscillation (ENSO) phenomenon on the interannual variability of global total column water vapor. A Clausius–Clapeyron relationship between water vapor and temperature has also been reported by Prabhakara et al. (1979) and Stephens (1990). The effect of Mt. Pinatubo eruption on the global total column water vapor and the earth’s climate has also been reported by Soden et al. (2002), and related references therein, with comments by Del Genio (2002). Simpson et al. (2001), by using empirical orthogonal function (EOF) analysis, also revealed that the most important spatiotemporal pattern in the global total column water vapor is related to ENSO. They also reported that NVAP is drier relative to the independent dataset of the TOPEX/Poseidon (T/P) microwave radiometer (TMR) possibly due to dry bias in TOVS data because TOVS is unable to perform retrievals over thick cloud regions. However, Simpson et al. (2001) suggest that the NVAP dryness over the tropical oceans is low relative to overocean TPW values. Despite these caveats, they indicate the sufficiency of NVAP for variability studies.

Alternative sources for global water vapor are the reanalyses of the National Centers for Environmental Prediction (NCEP) (R-1; Kalnay et al. 1996), the NCEP–Department of Energy (DOE) Atmospheric Model Intercomparison Project (AMIP-II) (R-2; Kanamitsu et al. 2002), the 15-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-15; Gibson et al. 1997), and the 40-yr ECMWF Re-Analysis (ERA-40; Uppala 2001). Despite the influence of the model used during the assimilation, the reanalyses lend further insight into the vertical distribution and variability of water vapor globally. Furthermore, reanalysis considers all observations together so that the moisture analysis must not only be consistent with moisture-related observations, but with the entire circulation. Hence, the reanalyses have the potential to more accurately resolve the true signal from notoriously noisy moisture observations if the global model physical parameterization accurately simulate the hydrologic cycle.

By comparing R-1 and NVAP, Trenberth and Guillemot (1998) found that R-1 underestimates TPW over the tropical atmospheric convergence zones. [The dryness problem has been addressed in R-2 by changing the assimilation model parameterizations (Kanamitsu et al. 2002)]. Moreover, the variability of R-1 is smaller relative to NVAP over the tropical Pacific Ocean, especially in the central and western regions. Boyle (2000) also reports discrepancies between observational datasets (radiosonde, NVAP, ERA-15, R-1, and R-2) and suggests that they should be used with caution. Nevertheless, Allan et al. (2002) suggest that R-1 has sufficient quality for variability studies.

Although ERA-40 is supposed to be an improvement over ERA-15, based on Fig. 2 of Allan et al. (2002), ERA-40 still exhibits a discrepancy (wetter) if compared to NVAP over the tropical oceans (30°S–30°N) during a period between June 1991 and June 1993.

This investigation will extend the previous studies by performing a more comprehensive comparison and including TPW analyses from NVAP, R-1, R-2, and ERA-40 covering a 12-yr period, from January 1988 to December 1999, with NVAP serving as the basis in the comparison. This study relies on the previous studies on NVAP in its analysis. All detected spatiotemporal patterns in the datasets will be analyzed and compared.
2. Data and methods

This study focuses on the NVAP period (January 1988–December 1999). The datasets are global monthly TPW from NVAP (Randel et al. 1996), R-1 (Kalnay et al. 1996), R-2 (Kanamitsu et al. 2002), and ERA-40 (Uppala 2001), and the monthly sea surface temperature (SST) analysis of Reynolds et al. (2002). The SST data are used for comparing spatiotemporal patterns of the TPW datasets and their ability to resolve patterns of convergence and/or wet air advection zones.

Before doing the comparison, it is important to describe the major differences in the datasets as they affect the TPW field for background (see Table 1). It is generally known that the clear-sky sampling in TOVS tends to underestimate TPW in deep convection regions (over which thick clouds exist; the clear-sky sampling reduces the number of observations used over the regions) if compared to SSM/I (Stephens et al. 1994). However, Stephens et al. (1994) also show that TOVS underpredicts the large-scale subsidence drying and, hence, overestimates TPW if compared to SSM/I. The variability in SSM/I TPW is larger than TOVS and increases with SST (Stephens et al. 1994).

The assimilation of the radiances in the reanalyses is also important in analyzing TPW. In the one-dimensional variational data assimilation (1DVAR), the observational radiances are used to adjust colocated temperature and humidity profiles from a numerical weather prediction (NWP) model’s short-term forecast. The resulting adjusted temperature and moisture profiles are then assimilated as conventional observations in the existing data assimilation scheme. In contrast, all information, including the radiances, are simultaneously used in the three-dimensional variational data assimilation (3DVAR), that is, a direct versus indirect assimilation of the radiances to produce the final three-dimensional analysis (Baker et al. 2003). Thus, the 3DVAR technique uses the observational radiances more optimally than the 1DVAR. An important feature of the 3DVAR technique is that one observation can influence the analysis of more than one variable (Andersson et al. 1995).

While there are no differences in the data sources and assimilation technique, there are changes in the assimilation model from R-1 to R-2. One important change affecting the TPW field is from the simplified Arakawa–Schubert (SAS; Pan and Wu 1995) to the Pan–Grell (COMET Program 2003) scheme in convective parameterization. Even though it affects the vertical distribution of TPW in convective regions (see Norquist and Chang 1994) and meso- and larger-scale circulations (see Donner et al. 1982; Tiedtke 1984; Sud et al. 1992; Zhang 1994), convective parameterization is not the only component in a forecast model affecting the horizontal and vertical distributions of TPW and the related moisture transport (see Roads 2003). It is also important to note that the environment used in predicting convection is strongly influenced by other physical parameterizations in the model (see Soden and Bretherton 1994; Bony et al. 1997; COMET Program 2003). The next paragraph describes generally the overall performance of the models in the reanalyses with regards to TPW.

### Table 1. Major differences in the datasets affecting TPW.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Data and assimilation</th>
<th>Convective parameterization</th>
<th>Model resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-1</td>
<td>TOVS sounding products from NOAA/National Environmental Satellite, Data, and Information Service [NESDIS; modified radiance variance retrieval scheme of Reale et al. (1989); HIRS/2 (all except channels 10, 11, and 12) and microwave sounding unit (MSU) channels (Reale et al. 1989)]; 1DVAR</td>
<td>Simplified Arakawa–Schubert</td>
<td>T62L28; sigma coordinate; five levels in PBL</td>
</tr>
<tr>
<td>R-2</td>
<td>TOVS sounding products from NOAA/NESDIS [modified radiance variance retrieval scheme of Reale et al. (1989); HIRS/2 (all except channels 10, 11, and 12) and MSU channels (Reale et al. 1989)]; 1DVAR</td>
<td>Pan–Grell</td>
<td>T62L28; sigma coordinate; five levels in PBL</td>
</tr>
<tr>
<td>ERA-40</td>
<td>TOVS (radiance; all instruments and channels; HIRS channels 10, 11, and 12 contain moisture information); 3DVAR SSM/I (radiance; all channels); 1DVAR</td>
<td>Tiedtke’s mass flux</td>
<td>T159L60; hybrid coordinate; 15 levels in PBL</td>
</tr>
<tr>
<td>NVAP</td>
<td>TOVS sounding products from NOAA/NESDIS [modified radiance variance retrieval scheme of Reale et al. (1989); HIRS/2 (all except channels 10, 11, and 12) and MSU channels (Reale et al. 1989)]; SSM/I [Greenwald et al.’s (1993) retrieval scheme; 19.35- and 37-GHz channels]</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Substantial dryness in TPW should be expected in convective regions in R-1’s model (Derber et al. 1998). Deficiencies in shortwave radiation (Bony et al. 1997) and boundary layer (see Betts et al. 1996) parameterizations have been suggested as likely reasons for the dryness. Kanamitsu et al. (2002) suggest that the improvement in R-2 TPW relative to R-1 is due to changes in the convective and boundary layer parameterizations. There were no changes in convective parameterization in ERA-40 compared to ERA-15 (Källberg 2000). Both used the same mass flux scheme of Tiedtke (1989). The coarse vertical resolution of the ERA-15 model and an underprediction of water vapor transport by the simulated Hadley circulation have been suggested as causing significant wetness in TPW over the dry subtropical ridges off the west coasts of continents and dryness in ITCZ, respectively (Soden and Bretherton 1994).

In this study, all datasets are regressed into a common 2.5° × 2.5° grid by a simple box-averaging method. These regressed datasets are then subjected to statistical analysis. The anomalies, obtained by removing the mean annual cycle (AC) at each grid point, are also subjected to statistical analysis, including EOF.

Significance tests for comparing the mean, standard deviation, and correlation coefficients between the TPW datasets will be based on estimated quasi-independent datasets. These quasi-independent datasets are obtained by first computing the effective time between independent data samples at each grid point using a procedure described in Livezey (1995) and formulated for tests of the mean as

\[ T = 1 + 2 \sum_{\lambda=1}^{N} \left( 1 - \frac{\lambda}{N} \right) \rho_{\lambda}, \]  

where \( T \) is the effective number of months between independent samples, \( \Delta \) is the lag number of the lagged autocorrelation \( \rho \) at a grid point, \( N \) is the total number of lags, and \( n \) is the total number of months. For the 144 months \((n = 144)\) of this study, autocorrelations are computed up to lag 72 \((N = 72)\). Time series of quasi-independent samples are then constructed by thinning the original time series based on the value of \( T \). For example, if \( T \sim 2 \), every other monthly value is discarded. For tests of the standard deviation, \( \rho \) is replaced by \( \rho^2 \) in Eq. (1), and for tests of the correlation of series 1 and 2, \( \rho \) is replaced by \( \rho_1 \cdot \rho_2 \) in Eq. (1).

3. Results

a. Climatology

The 12-yr mean TPW of NVAP and the differences in the mean between the other datasets and NVAP (dataset minus NVAP) are shown in Fig. 1. Only regions with statistically significant (\( t \) test, \( \alpha = 5\% \)) differences in the mean are shaded in Fig. 1. Computed reduced effective degrees of freedom [via Eq. (1)] are used in the \( t \) test. Regions with negative differences are stippled. Also shown in Fig. 1 are Tropics [30°S–30°N; following Allan et al. (2002) in defining the Tropics], Northern Hemisphere (NH; 0°–90°N), Southern Hemisphere (SH; 0°–90°S), and global (90°S–90°N) means of the datasets. Based on Fig. 1, TPW shows a generally decreasing pattern from the Tropics poleward. The large-scale rising motion signature of the tropical convergence zones is shown as high values over the mean positions of the intertropical convergence zone (ITCZ) and South Pacific convergence zone (SPCZ). Although it is not strong over the oceanic regions, the ITCZ signature is also found in high values over the Amazon and equatorial African continent. The mean position of ITCZ over the NH) results in greater TPW in the NH compared to the SH (Wittmeyer and Vonder Haar 1994). The warm pools of the western Pacific and eastern tropical Indian Oceans also have high TPW values related to large-scale rising motions. Anticyclonic regions of sinking motion over the subtropical Pacific and Atlantic Oceans are associated with low-value regions over off the coasts of California, Chile, Morocco, and southwestern Africa. Low TPW values are also shown over the elevated land regions of the western Andes and the Himalayas reflecting dynamical removal of TPW over the regions. The subsidence regions of the Sahel and Arabian Peninsula desert are also shown to have low TPW values. The cold regions of Greenland and Antarctica are also shown to be low in TPW. In general, the spatial patterns show similarities with the patterns reported elsewhere (see Trenberth and Guillemot 1998; Simpson et al. 2001), including studies based on satellite retrievals (see Prabhakara et al. 1985; Wittmeyer and Vonder Haar 1994; Jackson and Stephens 1995).

While this study found similarities over regions of spatially dense radiosonde observations (e.g., Europe, China, and North America), Fig. 1 also shows discrepancies in mean climatology. One notable difference is that NVAP is systematically wetter over the Sahel, the Arabian Peninsula desert, the Himalayas, Australia, the western side of the Rockies and Andes, and the cold regions of Greenland and Antarctica relative to the other datasets. The paucity of radiosonde observations and differences in the data assimilation schemes (e.g., the use of TOVS data) are the likely cause of the discrepancies. Some TOVS observations (the majority tended to be in dry or desert regions) had to be removed when producing NVAP because of a wet bias.
compared to nearby radiosondes and SSM/I data (Randel et al. 1996).

Although Kanamitsu et al. (2002) have suggested that the changes in the boundary layer and convective parameterizations (see Table 1) brought the R-2 zonally averaged TPW closer to NVAP over the Tropics compared to R-1, wetness and dryness problems between R-2 and NVAP remain in the Tropics, including the oceans and Southern Hemisphere land (Fig. 1; see Trenberth and Guillemot 1998). Changes in the R-2 parameterizations only affected the spatial pattern of the discrepancies. The zonal averaging done by Kanamitsu et al. (2002) tends to mask the pattern.

Figure 1 shows that the parameterization changes from R-1 to R-2 slightly reduce the dryness of R-2 over atmospheric convergence zones. The pattern of discrepancies (wetness) over the oceans, however, covers a larger area, including the descending branch of the Hadley circulation and the large-scale atmospheric subsidence (sinking) regions associated with anticyclones off the west coasts of North and South Americas, Europe, and Africa. These regions coincide with the cold oceanic upwelling regions.

Other than the clear-sky underestimation of TOVS (Wu et al. 1993), the underprediction of TPW over the ITCZ may be related also to an underprediction of the strength of Hadley circulation in the reanalyses (see Soden and Bretherton 1994). Hence, less moisture is transported to the ITCZ and higher moisture would be observed over the circulation’s descending branch.

The assimilation of TOVS data may also contribute to an overprediction of TPW over oceanic subsidence regions. It is interesting also to see if the overprediction is related to the vertical resolution of the model of U.S.
reanalyses and their ability to resolve the vertical structure of water vapor, especially in the boundary layer. The U.S. reanalyses (5 levels) have lower vertical resolutions than ERA-40 (15 levels; see Table 1 and Soden and Bretherton 1994). Because the systematic overprediction of TPW over the Southern Hemisphere oceans in the U.S. reanalyses cannot be associated with the known problems with TOVS and with the Australian Surface Pressure Bogus Data for the Southern Hemisphere (PAOBS) that were fixed in R-2 (Kanamitsu et al. 2002), it is likely that they represent deficiencies in the U.S. reanalysis models. Differences in horizontal resolution between the U.S. (T62) and European (T159) reanalyses may affect TPW on local scales especially in the vicinity of steep orography (Trenberth and Guillemot 1998).

Despite the relatively wetter land regions of NVAP mentioned above, the hemispheric and global mean values of ERA-40 tend to be higher relative to the other datasets (Fig. 1). These higher mean values are predominantly over the Tropics. Because NVAP is drier relative to the TMR retrievals (Simpson et al. 2001), it is interesting to see if improvements in ERA-40 would make it closer to these retrieval values. NVAP uses an SSM/I algorithm originally developed by Tjemkes et al. (1991) and modified by Greenwald et al. (1993; see Table 1). This scheme does not utilize the SSM/I 22.235-GHz channel (which has saturation problems since it is at the center of the water vapor absorption band); rather, it uses dual-polarization measurements at 19.35 and 37 GHz (along with ancillary input of SST and ocean surface wind speed) to simultaneously retrieve precipitable water and cloud water. Results from these studies do not indicate any sort of saturation issue in moist air masses. In fact, other studies (e.g., Allan et al. 2002) even suspect that SSM/I might be too moist if compared to other satellite-derived climatologies. Thus, the cause of the dryness over the wet regions of the Tropics is not due to the underestimation of NVAP SSM/I algorithm. It is most likely that the dryness of NVAP relative to ERA-40 over the thick cloud regions of the Tropics (i.e., the convergence zones) may reflect the TOVS underestimations over the regions (Wu et al. 1993; see also Wittmeyer and Vonder Haar 1994) as has been suggested by Simpson et al. (2001).

The dryness of NVAP relative to ERA-40 may also be related to the fact that, unlike in the reanalyses, NVAP values are observationally less constrained to other variables, for example, surface pressure. Unlike ERA-15, which used a 1DVAR scheme in assimilating TOVS radiances, ERA-40 uses 3DVAR to directly assimilate TOVS radiances and 1DVAR of total column water content (see Table 1 and Uppala 2001) using SSM/I radiances. Because all channels of SSM/I are used in ERA-40, it is also possible that the saturation issue of channel 22.235 GHz contributes to the higher tropical oceanic values.

Figure 2 shows the standard deviations of NVAP during the 12-yr period and the differences in the standard deviation between the other datasets and NVAP (dataset minus NVAP). Only regions with statistically significant ($F$ test; $\alpha = 5\%$) differences in the standard deviation are shaded in Fig. 2. As before, the effective (reduced) degrees of freedom are calculated using Eq. (1) in the significance test. The standard deviations (SDs) represent the total temporal (mainly interannual and the AC) variability of TPW. Higher SDs are found over the convergence zones, the western Pacific warm pool, the eastern tropical Indian Ocean, and monsoon regions. It is interesting to note the collocations of negative SD discrepancies (Fig. 2) and dryness in the mean (Fig. 1) in R-1 and R-2 compared to NVAP over major convective regions. The collocations suggest problems in the R-1 and R-2 models, especially in convective parameterizations (Table 1). In this regard, the assimilation of SSM/I in ERA-40 (Table 1) results in a moisture field with similar variability as NVAP over the oceans.

This study next examines areal hemispheric averages of the 12-yr mean annual cycle (the 12-yr means of January–December) in Fig. 3 to highlight differences between the datasets over the tropical oceans. ERA-40 is consistently wetter than NVAP by a nearly fixed amount (~1.5 mm) in both hemispheres. The offset decreases/increases slightly in the dry/wet part of the AC but is otherwise remarkably consistent. Thus, ERA-40 captures the amplitude and phase of the AC in NVAP, and it is noteworthy that both ERA-40 and NVAP use SSM/I observations over the oceans.

The U.S. reanalyses, in contrast, have considerably smaller amplitudes, particularly in the moist (NH summer) part of the mean annual cycle (Fig. 3). This study also sees a slight phase shift in the Southern Hemisphere with R-1 and R-2 peaking in February, whereas NVAP and ERA-40 peak in March. Over the Northern Hemisphere tropical ocean, there is a distinct drop from August through October in R-2 that is not shown in the other datasets.

The differences shown in Fig. 3 are important to note in global TPW studies. Because the tropical oceans cover a large surface area and their role in the global water and energy balance, they play a major role in the global TPW climatology through evaporation. There-
fore, differences between the TPW estimates and true values may affect results of global TPW studies.

b. Interannual variability

Figure 4 shows the correlation coefficient between NVAP interannual anomalies and the other datasets. Only regions with statistically significant ($t$ test; $\alpha = 5\%$; $\nu = 142$) correlation are shaded using reduced degrees of freedom [again via Eq. (1)]. These monthly anomalies are the departure of the monthly TPW value from its annual cycle. The $T$ values from Eq. (1) are used in computing means and anomalies for Fig. 4.

Figure 4 shows that the assimilation of SSM/I in ERA-40 (Table 1) results in higher correlations with NVAP over the tropical oceans compared to the U.S. reanalyses. With its greater surface area, the Southern Hemisphere tropical ocean may play a more important role in global TPW variability than its Northern Hemisphere counterpart or other oceanic regions. Moreover, the most important global spatiotemporal pattern in NVAP (Simpson et al. 2001) is associated with ENSO events with greater spatial extent over the tropical South Pacific Ocean. Therefore, higher correlation coefficients with NVAP in the Southern Hemisphere tropical ocean may be a good measure of the applicability of the dataset to global TPW variability studies. Such a measure may also be the reason why R-1 is sufficient for TPW variability studies as suggested by Allan et al. (2002).

Given the similarity of the R-2 correlation coefficient spatial pattern with R-1, it is likely that R-2 is sufficient for TPW variability studies. However, R-2 has more area with low correlations over the tropical oceans than R-1. The higher correlation coefficients between NVAP and ERA-40 over the Southern Hemisphere tropical ocean and other oceans suggests better applicability of ERA-40 to TPW variability studies.

Fig. 2. The std dev of monthly TPW (mm) over the 12-yr period. Shaded regions are regions where the variances are significantly ($F$ test; $\alpha = 5\%$; reduced degrees of freedom) different from NVAP. Shadings represent the absolute differences between the datasets to NVAP (dataset − NVAP, mm). Regions with negative differences are stippled.
1) THE EFFECTS OF ENSO AND Mt. PINATUBO ERUPTION

The different effects of El Niño on the 12-yr TPW interannual variability are apparent in Figs. 5 and 6 where this study shows the mean anomalies over the Southern and Northern Hemisphere tropical oceans. These means are calculated over the tropical bands of 30°S–0° and 0°–30°N as suggested by Allan et al. (2002) and Robock and Mao (1995).

The TPW interannual variability in the reanalyses generally follows NVAP over the Southern Hemisphere tropical ocean (Fig. 5), mainly because of the relationship between TPW and SST over the ocean following the Clausius–Clapeyron relationship (Prabhakara et al. 1979; Stephens 1990; Soden and Bretherton 1994; Stephens et al. 1994; Jackson and Stephens 1995). Figure 5 shows that the highest peaks over the 12-yr study period occurred around January 1998 coinciding with the peak of the 1997/98 El Niño. This warming event is by far the strongest on record (McPhaden 1999). However, even though the anomalies around this ENSO event are the highest, relative to the U.S. reanalyses, ERA-40 follows NVAP except for three periods of substantial departure that are episodic in nature. From 198801 to 198907 (YYYYMM format for time), ERA-40 is drier by a nearly fixed offset ~2 mm, but in 199201–199301 and 199503–199607, the jump is positive and ~1 mmA likely explanation is variation in the TOVS observations—specifically for 198801–198907: the transition from the National Oceanic and Atmospheric Administration (NOAA)-9 to NOAA-11; for 199201–199301: the loss of NOAA-10 in 199109; and for 199503–199607: the dropout of NOAA-11 data (see Hernandez et al. 2004). The response of the ERA-40 over-ocean moisture analysis to changes in the satellite (TOVS) observing system is symptomatic of the “bias correction” procedure (e.g., Harris and Kelly 2001) in which the raw radiances are adjusted before assimilation to account for global-scale differences between observed and modeled radiances. This explanation is supported by similar jumps in the Northern Hemisphere time series in Fig. 6, implying a global impact of the bias correction.

Unlike the anomalies for the Southern Hemisphere tropical ocean, the anomalies for the Northern Hemisphere tropical ocean decrease during warm ENSO events (Fig. 6). This non-SST-related change is likely due to shifts in the distribution of convection (see Rasimusson and Carpenter 1982; Weare 1987; Deser and Wallace 1990). However, it is interesting to note that R-1 does not go negative like the others during the 1997/98 El Niño and that the drop in ERA-40 anomalies associated with the event occurs 1 month after the others. Differences relative to NVAP are also shown in Fig. 6 for R-2 and ERA-40.
Another interesting depiction from Fig. 5 is the TPW interannual variability associated with the 1991/92, 1993, and 1994/95 El Niño events with peaks in February 1992, May 1993, and December 1994 [based on the Niño-3.4 region (5°S–5°N and 120°–170°W) index of Trenberth and Stepaniak (2001)]. Figure 5 shows that the 1991/92 El Niño (March 1991–August 1992) is accompanied by a normal positive jump of anomalies from March to August 1991 that is followed by generally decreasing anomalies up to around December 1992. This response of TPW does not show the positive peak in February 1992 related to the warming event as in the 1997/98 El Niño. It is most likely that the drop from August 1991 to around December 1992 corresponds to the cooling effect of the Mt. Pinatubo eruption. The 1994/95 El Niño is well represented in the anomalies, signifying the dissipating of the eruption’s effect.

The cooling effect of the Mt. Pinatubo eruption on the Northern Hemisphere tropical ocean TPW variability is also apparent Fig. 6, especially in the variability related to the 1991/92, 1993, and 1994/95 El Niño events. However, the drop reaches its lowest around February 1992, months earlier than that of the Southern Hemisphere, following the peak of the 1991/92 El Niño event. The delayed effect over the Southern Hemisphere is consistent with the fact that the eruption cloud covered more of the Northern Hemisphere than the Southern Hemisphere (McCormick and Veiga 1992; Stowe et al. 1992).

Figures 5 and 6 show other deviations of ERA-40 from the other datasets. ERA-40 tends to be considerably higher than the other datasets between 1992 and 1999. The most likely explanation is the aerosol effects related to the Mt. Pinatubo eruption in June 1991 on
the High Resolution Infrared Radiation Sounder (HIRS) radiances especially from the NOAA-12 satellite that became operational in June 1991. A silicate absorption feature of the channel 10’s (NOAA-12 satellite) 1220 cm\(^{-1}\) central frequency results in low surface emissivities leading to an overestimation of lower-tropospheric water vapor (Susskind et al. 1997). There is no direct bias correction due to aerosol effects lead-

Fig. 5. TPW monthly anomalies time series (mm) over the SH tropical ocean. An anomaly is the departure from the interannual mean over the 12-yr study period of the respective month. Positive and negative shadings indicate the periods of El Niño and La Niña events, respectively. The confidence interval of NVAP is computed from the anomalies field by assuming a normal distribution of the field and by using ±1.96(\text{SD}/\sqrt{n})

Fig. 6. Same as in Fig. 5, but for the NH tropical ocean.
The moistening brings ERA-40 more in line with NVAP during the 1992–99 period. Figure 7 shows the different responses of TPW to the ENSO events and the Mt. Pinatubo eruption over the Southern Hemisphere tropical land. The TPW variability in Fig. 7 shows a general temporal pattern of positive jumps of anomalies accompanying the peaks of El Niño events with peaks occurring in the same month or later. In contrast, the peaks of TPW anomalies for the Northern Hemisphere tropical land occur in the same month of the peaks of El Niño events or before (Fig. 8). Figures 7 and 8 also show many mismatches between NVAP and the other datasets.

Another interesting feature of TPW variability in Figs. 7 and 8 is the sharp drop following the Mt. Pinatubo eruption in NVAP, which reflects the aerosol impact on the satellite observations. The cooling effect of the eruption also affects TPW variability associated with the 1991/92 and 1993 El Niño events by pushing them into negative values.

2) EOF ANALYSIS

EOF analysis of the datasets, including SST (Reynolds et al. 2002), reveals two important spatiotemporal patterns associated with the ENSO events. Figure 9 gives the first EOF (EOF-1) and associated explained variance (EV) of the TPW and SST datasets. The EV value signifies how much spatiotemporal variations are explained by the EOF and its time series. The spatial patterns of the EOF-1 in Fig. 9 show the contrasting regions over the tropical Pacific Ocean as a response to the ENSO-related SST variability over the ocean. It is interesting that the ERA-40 spatial pattern better approximates NVAP, as also indicated by their spatial correlation coefficient of 0.95, than the other datasets to NVAP. The spatial pattern of cooling and warming regions over the tropical Pacific Ocean during ENSO events in ERA-40 are more coherent in following that of NVAP than those of the U.S. reanalyses. The coherency in the spatial pattern will be reflected in the time series of EOF-1.

The time series of EOF-1 is shown in Fig. 10. The Niño-3.4 index (Trenberth and Stepaniak 2001; Fig. 10) and EOF-1 of SST (not shown) have a correlation coefficient of 0.90, signifying that the index represents the ENSO-related SST variability over the tropical Pacific Ocean. The index shows that the 1997/98 El Niño indeed has the highest magnitude compared to the other warm ENSO events during the 12-yr period. Only NVAP, R-1, and ERA-40 are able to show this relative magnitude of the event in their EOF-1 time series, although R-1 is relatively weak in this regard. The correlation coefficients between the Niño-3.4 index and NVAP, R-1, and ERA-40 EOF-1 time series are 0.92 (consistent with Simpson et al. 2001), 0.88, and 0.91, respectively.

The spatial patterns of the second EOF (EOF-2; Fig. 11) show TPW response to the contrasting SST pattern
over the Niño-1 + 2 (0°–10°S, 90°–80°W) and Niño-4 (5°N–5°S, 160°E–150°W) regions. The trans-Niño index (TNI; Trenberth and Stepaniak 2001) describes the variability of the SST contrasting pattern. Trenberth and Stepaniak (2001) suggest that the TNI is useful in describing the “flavor” of ENSO. None of the time series of the datasets’ EOF-2 (Fig. 12) have a high correlation coefficient with TNI. However, all the datasets

![Image](http://journals.ametsoc.org/jcli/article-pdf/18/11/1790/3787939/jcli3379_1.pdf)

**Fig. 8.** Same as in Fig. 5, but for the NH tropical land.

**Fig. 9.** EOF-1 and the associated EV. Monthly anomalies are used in EOF analysis. Also shown is EOF-1 from SST analysis of Reynolds et al. (2002) and spatial correlation coefficients between EOF-1 of the reanalyses and NVAP. Shading signifies the loadings of the eigenvector.
are generally able to show the flavor of the 1997/98 El Niño and the interdecadal variation of ENSO events captured by TNI (see Fig. 1 of Trenberth and Stepaniak 2001) during the 12-yr period.

c. Resolving spatial patterns of convergence and/or wet-air advection zones

The datasets are further analyzed for their ability in resolving patterns of convergence and/or moist-air advection zones, by predicting over-ocean tropical TPW (TPW) using an approach reported by Stephens (1990) and monthly SST (Reynolds et al. 2002). The differences in the mean annual value between the datasets and TPW during the 12-yr period show TPW changes due to changes in circulation versus changes in air temperature due to SST. Positive differences show regions of enhanced upward moisture flux due to convergence and/or moist-air advection (see Prabhakara et al. 1979). Conversely, subsidence and/or dry-air advection would appear as negative differences (see Prabhakara et al. 1979). Figure 13 shows that the patterns of ITCZ and SPCZ, the western Pacific warm pool, and the convergence zones over the Indian Ocean are well represented by NVAP and ERA-40. The convergence and/or wet-air advection zones are not well resolved in R-1 and R-2, although R-2 performs better than R-1. This may indicate weaknesses in moisture advection and/or convective parameterization of the U.S. reanalyses. Likewise, the subsidence regions off the west coasts of the African continent and South America are better delineated in NVAP and ERA-40, although R-1 and R-2 also indicate these.

Figure 14 shows the mean annual distribution of the Global Precipitation Climatology Project (GPCP; Huffman et al. 1997) over the ocean during the 12-yr period. The high precipitation values in Fig. 14 suggest the location of convergence zones, for example, the ITCZ, SPCZ, and the western Pacific warm pool. The spatial patterns of convergence and/or moist-air advection zones in NVAP and ERA-40 closely match the patterns in GPCP. This suggests the superiority of NVAP and ERA-40 in resolving patterns of convergence and/or moist-air advection zones relative to the U.S. reanalyses. This also suggests a better precipitation field in ERA-40 relative to the U.S. reanalyses.

Further investigation on the ability of the datasets in resolving the spatial patterns of convergence and/or moist-air advection zones is also done. The same analysis described above is done for different temporal bases. The results (not shown) still show the superiority of NVAP and ERA-40 relative to the U.S. reanalyses in resolving the spatial patterns of the zones.

4. Summary and conclusions

This study has analyzed and compared spatiotemporal patterns in the global monthly total precipitable wa-
Fig. 11. Same as in Fig. 9, but for EOF-2.

Fig. 12. The time series of EOF-2. Also shown is the TNI of Trenberth and Stepaniak (2001). Positive and negative shadings indicate the periods of El Niño and La Niña events, respectively.
ter of NVAP to that from the NCEP R-1, R-2, and ERA-40 reanalyses during a period from January 1988 through December 1999. The datasets and their anomalies were subjected to statistical analysis. The anomalies were obtained by removing the 12-month mean annual cycle from each monthly value over the 12-yr study period.

By comparing the datasets, this study revealed that

**Fig. 13.** The mean annual distribution of \( \frac{\text{TPW} - \text{TPW}}{\text{TPW}} \) (in %) over the tropical ocean. Regions with negative values are stippled. Positive regions represent convergence and/or wet-air advection zones.

**Fig. 14.** The mean annual distribution of precipitation over the tropical ocean.
NVAP is systematically wetter over the Sahel, the Arabian Peninsula desert, the Himalayas, Australia, the western side of the Rockies and Andes, and the cold regions of the Greenland and Antarctica relative to the other datasets. Compared to the reanalyses, NVAP has a higher-amplitude annual cycle. It is most likely that the discrepancies reflect the impact of differing models and assimilation techniques for the satellite data, particularly in regions of sparse radiosonde coverage.

Both R-1 and R-2 underpredict TPW over the ITCZ and overpredict in the large-scale oceanic subsidence zones and the Southern Hemisphere oceans compared to NVAP. In addition, this study found a lower range in the annual cycle over the ITCZ in the two U.S. reanalyses and NVAP vis-à-vis ERA-40. The assimilation of TOVS data and deficiencies in the models used in the U.S. reanalyses may be responsible for the under-/overprediction.

ERA-40 tends to be wetter than NVAP over the lower-tropospheric convergence zones and because NVAP is dryer relative to the TMR retrievals, it would be interesting to see if ERA-40 is closer the retrievals. Other than TOVS dryness over the zones, the dryness of NVAP relative to ERA-40 may be related to the fact that the NVAP observation is observationally less constrained. While NVAP analyzed TPW retrievals, ERA-40 used a 1DVAR scheme to retrieve TPW from SSM/I radiances and a 3DVAR scheme for TOVS radiances and other information. An important feature of the 3DVAR scheme is that one observation can influence the analysis of more than one analysis variable.

Differences in annual cycle between the datasets are also noticeable over the tropical oceans. Even though the values are higher than NVAP, only ERA-40 has a similar pattern.

This study relied on NVAP as the baseline in comparing the interannual variability of the datasets. This comparison revealed different responses of TPW from the datasets to large-scale climate variability, such as ENSO and the Mt. Pinatubo eruption, over the tropical regions. For example, the EOF analysis of NVAP showed a spatial pattern of cooling and warming regions in the tropical Pacific Ocean during ENSO. The EOFs from ERA-40 were more coherent and closer to NVAP than in the U.S. reanalyses.

This study’s analysis of interannual variability over the tropical oceans showed that only NVAP responded strongly to the strongest 1997/98 El Niño relative to other El Niño events during the period of study. All of the datasets showed decreased TPW over tropical land and oceans following the Mt. Pinatubo eruption in June 1991 (in response to the cooling). However, NVAP exhibits a sharp drop over the tropical land due most likely because of aerosol-induced biases in the satellite retrievals.

In terms of the ability to resolve the spatial patterns of convergence and/or moist-air advection zones in the Tropics, NVAP and ERA-40 are superior to the U.S. reanalyses as their spatial patterns more closely match GPCP precipitation. The inability of the U.S. reanalyses to resolve the spatial patterns may indicate deficiencies in moisture advection and/or convective parameterizations of their models.

It has been shown that the number of observations, the spatial and temporal coverage of the datasets, model parameterizations, and assimilation schemes are important in producing the relatively high-quality TPW field in the reanalyses. In addition, this study suspects that the multivariate nature of 3DVAR, in which all observations affect the analysis jointly, is important in producing a better TPW reanalysis field. Although being free from model parameterizations and assumptions is considered a strength of NVAP, the comparison between NVAP and the reanalyses shows discrepancies between the observationally less constrained values of NVAP and the reanalyses.

In conclusion, even though all the total precipitable water datasets are viable for water cycle and climate analyses, this study has found that NVAP and ERA-40 perform better than the U.S. reanalyses during the 12-yr period. However, there are differences (wetness and dryness) that should be considered when using such analyses, particularly with regard to ENSO climate variability and the Mt. Pinatubo eruption. Results from the EOF analysis of spatiotemporal variability also supported this study’s conclusion that the NVAP and ERA-40 TPW respond realistically to ENSO. More significantly, only NVAP and ERA-40 resolved non-SST-related changes in TPW due to changes in the general circulation as seen in the remarkable correspondence to the observed precipitation spatial pattern.

Acknowledgments. This research is supported under NOAA Grant NA17EC1483 to the Cooperative Institute for Climate Studies (CICS), Earth System Science Interdisciplinary Center (ESSIC), University of Maryland, College Park (UMCP). Participation of AS and RRF is supported by the NOAA/Office of Global Programs (OGP) and for MF under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory, University of California, under Contract W-7405-Eng-48. Access to the NCEP, NCEP/DOE, and SST data is supported by NCAR Scientific Computer Division. NVAP is available on CD-ROM from the International GEWEX Project. The au
thors gratefully thank John Forsythe and three anonymous reviewers for their insightful review that were substantially useful in improving this paper.

REFERENCES


Andersson, E., P. Courtier, C. Gaffard, J. Haseler, F. Rabier, P. Undén, and D. Vasijevic, 1995: 3D-Var—The new operational scheme. ECMWF Newsletter, No. 71, ECMWF, Reading, United Kingdom, 2–5.


Boyle, J. S., 2000: Comparison of atmospheric water vapor in observational and model data sets. PCMDI Rep. 54, 40 pp. [Available from PMDI, Lawrence Livermore National Laboratory, P.O. Box 808, L-103, Livermore, CA 94551-0808.]


ECMWF, cited 2003: Some aspects of the quality of the ERA-40 analyses. [Available online at http://www.ecmwf.int/research/era/Data_Services/section3.html#ha.]


Pan, H.-L., and W. Wu, 1995: Implementing a mass flux convective parameterization package for the NMC medium-range forecast model. NMC Office Note 409, 40 pp. [Available from NCEP/EMC, 5200 Auth Road, Camp Springs, MD 20746.]


Roads, J., 2003: The NCEP-NCAR, NCEP-DOE, and TRMM


