Spatial and temporal variability of atmospheric water plays a significant role in the energetics of the global climate. This variability is explored using the NVAP and NCEP–NCAR reanalysis-2 datasets.

Water vapor is one of the most important components of greenhouse gases influencing the Earth’s climate system. It plays a crucial role in the transport of water and energy, and, consequently, in the global biogeochemical cycle. Datasets on global water vapor have recently become available that promise to facilitate fundamental research in the energetics of the climate systems. Here we perform a comparative study of two such datasets, namely, the National Aeronautics and Space Administration (NASA) Water Vapor Project (NVAP) data (Randel et al. 1996), and data extracted from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis-2 project (Kanamitsu et al. 2002), to examine their relative performance in describing the global spatial and temporal variability. The comparison is done for the time span that the two datasets overlap, which covers 12 yr between 1988 and 1999.

The NVAP dataset is a global water vapor dataset, available from 1988 to 1999, at a spatial resolution of 1° latitude × 1° longitude and temporal resolutions of daily, pentad, monthly, and yearly scales (Randel et al. 1996; Simpson et al. 2001; Vonder Haar et al. 2003). This global dataset is produced by blending water vapor observations from three independent sources: surface-based radiosonde observations, satellite-based retrievals from the Special Sensor Microwave Imager (SSM/I), and retrievals from the Television and Infrared Observation Satellites (TIROS) Operational Vertical Sounder (TOVS) (see Randel et al. 1996 and Simpson et al. 2001 for details). The data consist of two global products: total column water vapor and layered column water vapor for four atmospheric layers (> 700,
The layered water vapor is created by slicing through the total column water dataset using the layer information that is available from the radiosonde and TOVS observations (Randel et al. 1996). The NVAP dataset is available from NASA’s Langley Distributed Active Archive Center (DAAC) (online at http://eosweb.larc.nasa.gov/PRODOCS/nvap/table_nvap.html). For this particular study, we used the total column water vapor dataset.

The NCEP–NCAR reanalysis water vapor product (Kalnay et al. 1996; Kistler et al. 2001) is a result of a project aimed at producing consistent and long-term atmospheric variables for the needs of climate studies. It provides global total precipitable water (TPW) data at a spatial resolution of 2.5° latitude × 2.5° longitude and temporal resolution of 6-hourly, daily, and monthly scales. The NCEP–NCAR reanalysis project uses the state-of-the-art global data assimilation technique (i.e., an analysis system that remains unchanged...
except for changes in the observing systems) and a database that is as complete as possible to generate a long-term data product (Kalnay et al. 1996; Kanamitsu et al. 2002), and provides the opportunity to explicitly describe both short- and long-term climate variability (Zveryaev and Chu 2003) within the uncertainties in the input data. The data used in the assimilation come from numerous databases, including radiosondes, ships, buoys, aircrafts, satellites (SSM/I, TOVS), and other sources (Kalnay et al. 1996). The NCEP–NCAR reanalysis is conducted in two phases. The first phase, often called reanalysis–1 (R-1), covers the time period from 1948 to the present. The second phase, referred to as reanalysis–2 (R-2) (Kanamitsu et al. 2002), extends from 1979 to the present. The R-2 project aims to overcome several data and model errors in the first phase of R-1. In this particular study, the R-2 water vapor dataset is used for cross comparison with the NVAP dataset. The R-2 data are available online at http://wesley.wwb.noaa.gov/reanalysis2/index.html.

This study uses simple statistical techniques, such as spatial and temporal averaging, regressions, root-mean-square differences, standard deviations, anomalies, etc., to investigate i) the differences between the two water vapor datasets and ii) the space–time variability of the global water vapor. Monthly mean data are used throughout the analysis.

INTERCOMPARISON AND VARIABILITY STUDIES. Figure 1 shows the spatial distribution, and zonal and meridional mean profiles of the 12-yr-(1988–99) averaged TPW for the NVAP and R-2 datasets. Both datasets portray similar spatial features over much of the globe. Most of the global atmospheric moisture is concentrated around the equatorial regions of the east Indian Ocean, Indonesian Maritime Continent, and west Pacific Ocean (Figs. 1a and 1b). There are also significant areas of maximum water vapor in the equatorial regions of the east and central Pacific, South America, and Atlantic Ocean. Both datasets signify maximum atmospheric moisture for the tropical regions (warm climates) and minimum moisture for the polar regions (cold climates), giving an equator-to-pole moisture gradient. From Fig. 1d we notice that TPW in the north polar area is greater than that of the south polar area, with a difference of about 5 mm for both datasets.

Along a given latitudinal belt, mountainous regions, such as the Himalayas, Andes, and Rocky Mountains, and east African highlands, experience relatively lower TPW. This is in agreement with the strong relation between the surface elevation and amount of precipitable water—the higher the surface elevation, the lower the precipitable water. The equator-to-pole moisture gradient is generally observed to be high for areas where there is a transition from lowlands to mountainous ranges.

The two datasets also exhibit significant differences in certain regions of the globe. Figures 1e–1h show the zonal and meridional mean differences between the two datasets. On average, NVAP shows higher moisture for equatorial regions of the Eastern Hemisphere (EH), and lower moisture for midlatitudes of the Southern Hemisphere (SH) and northwestern part of the globe. The main discrepancy (in spatial distribution) between the two datasets lies around the central and western Pacific, central Asia, and west-central and north-central parts of Africa. For the west Pacific region, the NVAP dataset indicates a wetter atmosphere, whereas around the central Pacific, the atmosphere tends to get drier for NVAP than for R-2. Over central Asia (particularly areas of the Tibetan Plateau), the R-2
data indicate lower moisture, and for west equatorial Africa NVAP gives lower moisture.

A linear regression between global monthly mean TPW values of NVAP and R-2 (Fig. 2a) indicates a strong correlation between the two datasets, with a correlation coefficient of 0.95. The best-fit line lies mostly above the diagonal (dotted line), indicating that R-2 moisture is higher. This is also seen from the differences between the global mean monthly values of the two datasets (Fig. 2b), which shows lower values of NVAP than R-2 for most of the time spanning the study period, with the exception of 1988 and 1989. The root-mean-square (rms) of the monthly mean discrepancies between the two datasets is on the order of 0.32 mm.

Time series plots of global and hemispheric averages of annual TPW are shown in Fig. 3. Both datasets attain annual maxima in 1998 and minima in 1992. The decrease of TPW in 1992 is possibly due to the Mt. Pinatubo volcanic eruption, which is believed to have caused a decrease in global temperature of about 0.5°C (Soden et al. 2002). However, the years corresponding to the minima and maxima are somewhat different for the two hemi-
TABLE 1. Constants in Eq. (1), plus root-mean-square-errors (RMSE) and correlation coefficients ($R^2$) between the actual data and the sinusoidal fit for both datasets.

<table>
<thead>
<tr>
<th>Constants</th>
<th>NVAP</th>
<th>NCEP–NCAR reanalysis-2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GL</td>
<td>NH</td>
</tr>
<tr>
<td>a</td>
<td>23.3</td>
<td>19.4</td>
</tr>
<tr>
<td>b</td>
<td>3.3</td>
<td>14.8</td>
</tr>
<tr>
<td>c</td>
<td>1.3</td>
<td>1.5</td>
</tr>
<tr>
<td>d</td>
<td>5.5</td>
<td>3.0</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.26</td>
<td>0.28</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.945</td>
<td>0.996</td>
</tr>
</tbody>
</table>

TABLE 2. The 12-yr global and hemispheric average TPW (mm) for NVAP and R-2 datasets.

<table>
<thead>
<tr>
<th></th>
<th>NVAP</th>
<th>R2</th>
<th>NVAP – R2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>24.51</td>
<td>24.68</td>
<td>-0.17</td>
</tr>
<tr>
<td>NH</td>
<td>25.75</td>
<td>25.13</td>
<td>0.62</td>
</tr>
<tr>
<td>SH</td>
<td>23.27</td>
<td>24.23</td>
<td>-0.96</td>
</tr>
<tr>
<td>NH–SH</td>
<td>2.48</td>
<td>0.90</td>
<td>1.58</td>
</tr>
</tbody>
</table>

spheres. For the Northern Hemisphere (NH) (Fig. 3b) maximum TPW is recorded in 1988 for NVAP and in 1990 for R-2, while the minimum is recorded in 1992 for both datasets. For SH (Fig. 3c) the maxima is in 1998 for both datasets, while the minima is in 1996 for NVAP and in 1999 for R-2. Both datasets show higher moisture for the NH compared to the SH. The difference between NH and SH (Fig. 3d) is quite significant for NVAP (about 2.5 mm), compared to that of the NCEP–NCAR reanalysis (about 0.9 mm). Randel et al. (1996) attribute the differences between the NH and SH to the geographical dissimilarities between the two hemispheres. One should also notice that throughout 1988–99, NVAP gives higher annual average moisture than R-2 for NH, while R-2 gives higher moisture for the SH. The discrepancy between the two datasets is higher for SH.

Figure 4 shows the global and hemispheric average annual cycles of TPW for both datasets. For both NH (Fig. 4b) and SH (Fig. 4c) the annual cycle takes a sinusoidal shape with the maximum during summer and the minimum during winter of the respective hemispheres. The global average cycle (Fig. 4a) takes a shape similar to that of NH cycle, suggesting that the NH has a more dominant influence. The sinusoidal equation that best fits the annual cycles shown in Fig. 4 takes the following general form:

$$a + b \sin\left(\frac{n - c}{12} \cdot \pi\right),$$  \hspace{2cm} (1)

where $a$, $b$, $c$, and $d$ are constants, with values as given in Table 1, and $n$ is 1 for January, 2 for February, . . . , and 12 for December. We note that the equation is cubic sinusoidal for NH and square sinusoidal for SH for both datasets. As can be seen from the statistical measures given in Table 1 and the curves presented in Fig. 4, the sinusoidal equations well fit the annual cycles. The global cycle is a little bit skewed and does not fit perfectly to the sinusoidal shape.

As explained in Fig. 3, the annual cycle (Fig. 4) also affirms that NVAP is wetter than R-2 for NH, and vice versa for SH. Table 2 presents space–time average TPW differences between the NH and SH for the two datasets.

Figure 5 shows the 12-yr-averaged spatial distribution of seasonal TPW. Both datasets capture a similar seasonal pattern, though there is a significant difference in magnitude. Both datasets indicate a shift of precipitable water toward the south during December–January–February (DJF) (Fig. 5a) and toward the north during June–July–August (JJA) (Fig. 5c). During March–April–May (MAM) (Fig. 5b) and September–October–November (SON) (Fig. 5d), the moisture is more or less concentrated around the equator. The shift toward the south during DJF is not as pronounced as the shift toward the north during JJA.
Figure 6 quantitatively explains the seasonal differences between the two datasets. The difference is significantly high during DJF in which R-2 is consistently higher than NVAP by about 0.44 mm throughout the 12-yr period. The agreement between the two datasets is strong during JJA, with a correlation coefficient of 0.86 and only minor discrepancies between them. Weak correlation is observed for SON with a correlation coefficient of 0.56.

Both datasets indicate a significant difference between DJF and JJA. The spatial distribution of the difference (JJA - DJF) is given in Figs. 5i and 5j, while a time-series plot of the difference is given in Fig. 6e. The difference takes a similar pattern for the two datasets. From Figs. 5i and 5j we see that the difference is more pronounced in regions that experience a monsoon system, reaching up to 40 mm for NH and 25 mm for SH. From Fig. 6e we note that i) the difference (JJA - DJF) is positive throughout the study period, indicating a wetter global average atmosphere during JJA than during DJF, ii) the difference takes a cyclic pattern with maxima and minima at roughly about 3–4-yr intervals, and iii) the difference is higher for NVAP compared to R-2. Table 3 summarizes the seasonal differences between the two datasets.

Figure 7 presents a comparison of spatial distribution of annual TPW anomalies between the two datasets for four selected years (1988, 1992, 1996, and 1998). The years 1988 and 1996 were La Niña years, whereas 1992 and 1998 were El Niño years. For all 4 yr the anomaly patterns are similar between the two datasets, with maximum anomalies mainly concentrated around the equa-
TABLE 3. The 12-yr seasonal global average TPW (mm) for NVAP and R-2 datasets.

<table>
<thead>
<tr>
<th>Season</th>
<th>NVAP</th>
<th>R2</th>
<th>NVAP – R2</th>
</tr>
</thead>
<tbody>
<tr>
<td>DJF</td>
<td>23.37</td>
<td>23.79</td>
<td>-0.42</td>
</tr>
<tr>
<td>MAM</td>
<td>24.36</td>
<td>24.46</td>
<td>-0.10</td>
</tr>
<tr>
<td>JJA</td>
<td>26.18</td>
<td>26.26</td>
<td>-0.08</td>
</tr>
<tr>
<td>SON</td>
<td>24.14</td>
<td>24.21</td>
<td>-0.07</td>
</tr>
<tr>
<td>JJA–DJF</td>
<td>2.81</td>
<td>2.47</td>
<td>0.34</td>
</tr>
</tbody>
</table>

Fig. 6. Time series plots of seasonal global average TPW for both NVAP and reanalysis-2 datasets: (a) DJF, (b) MAM, (c) JJA, (d) SON, and (e) JJA–DJF. The terms “$R^2$” and “RMS” stand for correlation coefficient and root-mean-square difference, respectively, between the two datasets.

Fig. 7. Time series plots of annual TPW anomalies for NVAP and R-2 datasets.

The tropical Pacific Ocean and its environs in both cases. Both datasets have indicated positive maximum anomalies over the central and eastern Pacific and negative maximum anomalies over western Pacific areas for 1992 and 1998 (El Niño years), and vice versa for 1988 and 1996 (La Niña years). This is due to the strong link between the moisture anomaly and ENSO phenomenon. Because El Niño is associated with the warm climate over much of the Pacific Ocean, it leads to a positive moisture anomaly (moist atmosphere) over those areas, and vice versa for a La Niña event.

Although the two datasets show similar anomaly patterns, there are, however, differences in the magnitudes (amplitudes) of the moisture anomalies (Fig. 7). First of all, higher anomalies are observed for NVAP than for R-2. For instance, for the year 1988 NVAP shows a maximum anomaly of about 8 mm in contrast to the 6 mm shown for R-2. Second, in some cases the position of the maximum anomalies are shifted, and the signs of the anomalies are reversed from one dataset to the other. For example, see areas over Africa in 1988 and 1998, and areas over the Tibetan Plateau in 1996 and 1998. These discrepancies, especially for the aforementioned areas, are quite significant and can lead to different interpretations of climate variability.

Time series plots of monthly and annual anomalies of TPW for the two datasets are shown in Figs. 8a and 8b, respectively. Also included in Fig. 8 is the global surface temperature anomaly, computed based on NASA’s Goddard Institute for Space Studies (GISS) global surface temperature data (Hansen et al. 1999). The first 3 yr (1988–90) and part of 1996 show significant discrepancies between the anomalies of the two TPW datasets. There is, however, a good agreement for most parts of the other years. Linear regressions between the two datasets show a correlation coefficient of 0.66 for the monthly anomalies and 0.74 for the annual anomalies. TPW anomalies are closely correlated to surface temperature anomalies. The correlation with surface temperature is higher for R-2 than for NVAP (Fig. 8d). The maximum cross correlation between TPW and surface temperature is reached when the temperature leads the TPW by 2 months and
equals 0.67 for R-2 and 0.50 for NVAP. This suggests that precipitable water anomalies are driven by the temperature anomalies.

Comparison of seasonal average anomalies is shown in Fig. 9. The discrepancy between the anomalies of the two datasets is largely evident for MAM and SON.Spe-
specifically, significant differences are observed for MAM in 1988–89 and 1998. The correlation between the anomalies is much stronger for JJA compared to other seasons.

The standard deviation computed for monthly mean TPW is shown in Fig. 10. We computed the standard deviation separately for interseasonal (Figs. 10a and 10b) and interannual (Figs. 10c and 10d) variability, because they show very different characteristics. The interseasonal variability attains a maximum around the midlatitudes and a minimum around equatorial and polar areas. Areas of maximum standard deviation for interseasonal variability coincide well with areas that
experience monsoon rainfall. Generally, there is higher interseasonal variability for the NH than for the SH. Contrary to the interseasonal variability, the standard deviation for the interannual variability attains its maximum in the equatorial region and decreases poleward. As should be expected, the interannual variability is typically larger for areas associated with ENSO, such as the Pacific Ocean. The discrepancy between the standard deviation of the two datasets is evident particularly around the Tibetan Plateau and Andes Mountain ranges for the interannual variability. These findings are consistent with that of Simpson et al. (2001), who found regions of large TPW variability in the Tropics and midlatitudes (though they did not distinguish between interseasonal and interannual variability) and patterns indicative of ENSO-related variability.

From the time series plots of standard deviations (Figs. 10e and 10f), we make two important observations. First, there is higher variability for NVAP than for R-2 and, second, there is larger interseasonal than interannual variability. The space–time average of the standard deviation for the interseasonal variability is found to be 5.4 mm for NVAP and 4.8 mm for R-2, whereas that of interannual variability is 2.4 and 2.2 mm for NVAP and R-2, respectively. Maximum interseasonal variability is observed in 1998 for both datasets, and maximum interannual variability is observed in February for NVAP and in April for R-2.

**CONCLUSIONS.** Precipitable water is an important climate variable that shows significant variability in space and time. The spatial variability is highly related to latitude and surface altitude. The latitudinal profile shows a bell-shaped distribution with tropical maxima and polar minima. High-elevation surfaces (such as mountainous regions) experience lower moisture than lowland surfaces (such as over the ocean). The temporal variability is closely related to atmospheric circulation events, such as monsoons and ENSO events. Variability within a year is primarily due to the monsoon events, while year-to-year (interannual) variability is attributable to ENSO. Interannual variability is less pronounced compared to interseasonal variability. Total precipitable water anomalies are closely related to global surface temperature anomalies, with the temperature driving the precipitable water. It is also interesting to note that the NH has a more moist atmosphere than the SH. The annual cycle takes a sinusoidal shape for both hemispheres with maxima during summer and minima during winter of the respective hemispheres. The global annual cycle follows the signatures of the NH cycle.

Comparison of NVAP and reanalysis-2 total precipitable water products show that qualitatively both datasets show similar patterns. However, quantitatively there are considerable differences (both spatially and temporally) between them. The discrepancies between the two datasets can be summarized through two important observations. First, on average, R-2 shows a wetter atmosphere than NVAP does. This discrepancy is especially high during DJF. Second, the variability analysis indicates that NVAP shows higher variability than R-2, both spatially and temporally.

**ACKNOWLEDGMENTS.** Data used in this study were obtained from NASA’s Langley Distributed Active Archive Center and NOAA’s Climate Diagnostics Center. Partial support for the research was provided by NSF Grant EAR 02-
Fig. 10. Average standard deviation of TPW for interseasonal variability for (a) NVAP and (b) NCEP–NCAR reanalysis-2; average standard deviation of TPW for interannual variability for (c) NVAP and (d) NCEP–NCAR reanalysis-2; time series plot of global average standard deviation for (e) interseasonal and (f) interannual variability. The term $R^2$ indicates correlation coefficient and RMS indicates root-mean-square value for the difference between the two datasets.

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REFERENCES


THE LIFE CYCLES OF EXTRATROPICAL CYCLONES

Edited by Melvyn A. Shapiro and Sigbjørn Grønås

Containing expanded versions of the invited papers presented at the International Symposium on the Life Cycles of Extratropical Cyclones, held in Bergen, Norway, 27 June–1 July 1994, this monograph will be of interest to historians of meteorology, researchers, and forecasters. The symposium coincided with the 75th anniversary of the introduction of Jack Bjerknes’s frontal-cyclone model presented in his seminal article, “On the Structure of Moving Cyclones.” The monograph’s content ranges from a historical overview of extratropical cyclone research and forecasting from the early eighteenth century into the mid-twentieth century, to presentations and reviews of contemporary research on the theory, observations, analysis, diagnosis, and prediction of extratropical cyclones. The material is appropriate for teaching courses in advanced undergraduate and graduate meteorology.

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