# Analysis of the Global ISCCP TOVS Water Vapor Climatology

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(Manuscript received 10 December 1991, in final form 24 June 1993)

## ABSTRACT

A climatological examination of the global water vapor field based on a multiyear period of successful satellite-based observations is presented. Results from the multiyear global ISCCP TOVS water vapor dataset as operationally produced by NESDIS and ISCCP are shown. The methods employed for the retrieval of precipitable water content (PWC) utilize infrared measurements collected by the TOVS instrument package flown aboard the NOAA series of operational polar-orbiting satellites. Strengths of this dataset include the nearly global daily coverage, availability for a multiyear period, operational internal quality checks, and its description of important features in the mean state of the atmosphere. Weaknesses of this PWC dataset include that the infrared sensors are unable to collect data in cloudy regions, the retrievals are strongly biased toward a land-based radiosonde first-guess dataset, and the description of high spatial and temporal variability is inadequate. Primary consequences of these factors are seen in the underestimation of ITCZ water vapor maxima, and underestimation of midlatitude water vapor mean and standard deviation values where transient atmospheric phenomena contribute significantly toward time means. A comparison of TOVS analyses to SSM/I data over ocean for the month of July 1988 shows fair agreement in the magnitude and distribution of the monthly mean values, but the TOVS fields exhibit much less temporal and spatial variability on a daily basis in comparison to the SSM/I analyses. The emphasis of this paper is on the presentation and documentation of an early satellite-based water vapor climatology, and description of factors that prevent a more accurate representation of the global water vapor field.

## 1. Introduction

The study of water vapor on synoptic and global scales in a climatological time frame has proven to be a difficult task due to the demanding requirement of consistently dense global surface and upper-air observations. While this goal is not yet realized, some global water vapor characteristics are discernible using the present global observation capability, which consists primarily of land-based radiosonde data. The earliest large-scale water vapor studies came only after World War II, when use of atmospheric data became crucial to many operational aspects of the military. The development of the first synoptic-scale network of such radiosonde stations allowed for the first characterization studies of water vapor distribution [see Bannon and Steele (1960), Budyko (1963), and Starr et al. (1969)]. While radiosonde observations over the World Ocean were (and still are) quite sparse, land data coverage was adequate enough to roughly describe the mean horizontal and vertical distribution of total column water vapor.

Further water vapor characterization work was done by Rosen et al. (1979), and Peixoto et al. (1981), who investigated interannual and intra-annual variability, respectively. Use of an expanded radiosonde network for a multiyear data period allowed for a more thorough examination of the mean state of the moisture field. Noted in these studies was the need for a greater number of global water vapor observations, which are required for an adequate description of the hydrologic cycle and its role in climate.

Some problems and shortcomings plagued these early studies. The lack of adequate observations over a majority of the earth's surface, that is, ocean areas, still provides the most obvious challenge. We now know that the present land-based upper-air network is not dense enough to resolve important mesoscale variations over land. Many observing stations in third world countries, notably in the data-sparse Southern Hemisphere, do not report frequently due to local and regional political unrest. Furthermore, the use of radiosondes with a variety of manufacture origins introduces additional sources of error.

The obvious requirement of consistent information over the World Ocean was addressed by the inclusion of data from polar-orbiting satellites. These platforms could sense much of the global atmosphere in a consistent manner, and on a daily basis. However, while data collection was now possible over the ocean, a new set of challenges became apparent. Remote sensing of water vapor from space is presently done only in bulk atmospheric layers, therefore not resolving the often highly structured vertical profile of water vapor. The

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use of sounding techniques based primarily on infrared measurements allows for retrievals only in clear to partly cloudy areas, thus omitting perhaps the most interesting data: where there are clouds. Microwave sensors are only effective in sensing atmospheric water vapor over ocean and at the present time have limited vertical resolution. Clearly the need for improved data sources is a central concern if more accurate studies are to be carried out.

At this point, though, it is important to examine and benefit from the climatological information we now have available, while at the same time being aware of the deficiencies and biases that prevent a more complete understanding. This study examines a multiyear global satellite-based water vapor dataset by examining means and variability, and comparing them with those from an independent set of satellite data derived from microwave observations. The following section describes the daily water vapor dataset used in the present examination, while section 3 outlines the usable information therein by comparing infrared and microwave analyses. Conclusions and comments follow in section 4.

## 2. ISCCP TOVS water vapor data

This study uses the total column water vapor parameter precipitable water content (PWC), in the characterization of spatial and temporal means and variability of water vapor on the global scale. PWC is defined as the vertically integrated mean specific humidity, or,

$$\mathrm{PWC} = \int_{p_1}^{p_2} \bar{q}\,\frac{dp}{g}, \qquad (1)$$

where $\bar{q}$ is an individual layer-mean specific humidity in the layer defined by pressures $p_1$ to $p_2$, and $g$ is the acceleration due to gravity. The total column value of PWC is derived by integrating over pressure from zero to the surface value. Space-based instruments designed for the retrieval of PWC vary in design, but all sense an averaged state of a given atmospheric volume via passive observation of atmospheric emissions. While radiosonde measurements are directly determined by a simple integration of in situ observations, space-based estimates depend heavily on the method of interpreting the raw radiance data. A method based on the utilization of infrared emissions, valid over both land and ocean, has been employed for more than a decade within the operational polar-orbiting satellite program of the United States. This method, as described below, was used to produce the dataset used in the present study. Additionally, comparative global analyses of water vapor over ocean from the Special Sensor Microwave Imager (SSM/I) instrument are presented and described in section 3.

Operational satellite-based PWC retrievals have been made since 1978 by NESDIS (Werbowtzki 1981), using raw data collected from the NOAA series of operational polar-orbiting satellites (Kidwell 1991). Nearly continuous global coverage by up to two satellites has been provided since the 13 October 1978 launch of *TIROS-N*. The NOAA satellites have a near-polar sun-synchronous orbit with a 102-minute period. Carried aboard these platforms is the TIROS Operational Vertical Sounder (TOVS) instrument package for retrieval of atmospheric temperature, ozone, and water content. The TOVS system is made up of the second-generation High Resolution Infrared Radiation Sounder (HIRS/2), the Microwave Sounding Unit (MSU), and the Stratospheric Sounding Unit (SSU). All three instruments are used for retrieval of vertical temperature and moisture profiles. Both the HIRS/2 and the MSU instruments are cross-track scanners, capable of sensing a swath 2250 km wide. The HIRS/2 spectrometer has 19 infrared channels and one visible channel, and are operated simultaneously during each scan [see Wu et al. (1992) for a discussion of related brightness temperature standard errors]. Radiance data from HIRS/2 and MSU channels used primarily for temperature sounding are utilized by the operational NESDIS retrieval scheme for determining water vapor content in three layers. A statistical eigenvector regression method (Smith and Woolf 1976) was used before 16 September 1988, and was succeeded thereafter by a physical scheme (Reale et al. 1989) where temperature and moisture profiles are generated in a single-solution vector (Fleming et al. 1986).

The statistic scheme utilizes single field of view (FOV) raw radiance data grouped into 7 by 9 arrays for which tests for clouds are performed. Clear-column radiances are extracted from partly cloudy scenes using the $N^*$, or adjacent pair, method. These cloud-cleared radiances are used along with clear-sky radiances in a weighted average of each box 275 km on a side (McMillin 1978; Swaroop et al. 1988). If the box is predominantly cloudy and less than four clear or cloud-cleared radiances are retrievable, then the box is said to be cloudy, and a missing data flag is assigned. The raw radiance data, as well as regression coefficients, are then supplied to the retrieval module. Weekly updated regression coefficients are made using quasi-collocated radiosonde data, as well as space-based radiance measurements, and are stratified within five latitude zones (60°–90°N, 30°–60°N, 30°N–30°S, 30°–60°S, 60°–90°S). Approximately 8000 retrievals per day are operationally generated.

The three HIRS/2 channels most sensitive to the effects of water vapor are not used in either scheme since they presently have detrimental effects on the output sounding quality (A. Reale 1992, personal communication). This problem has its roots in the input quasi-collocated radiosonde observations that are used as a first-guess field in both schemes, and may not be representative of the sounding field of view. More specifically, the radiosonde data at a given point may not adequately describe the mean state of the atmospheric volume as sensed from space, especially if significant gradients exist.

The operationally produced soundings are provided to the International Satellite Cloud Climatology Project (ISCCP) (Schiffer and Rossow 1983), primarily as an ancillary dataset to the cloud data collected by geostationary and polar-orbiting satellites (Schiffer and Rossow 1985). The ISCCP-provided water vapor profiles are used in the present study. To conform with the ISCCP cloud data format, the sounding data are fit to a 2.5° equal-angle grid, and interpolated to cloud layers so defined by ISCCP.

One day of ISCCP TOVS data consists of composited measurements from either one or two operating polar orbiting NOAA satellites, depending on availability. Data coverage is somewhat less than total, and adjacent measurements may have been taken up to 12 hours or more apart Rossow et al. (1988). The typical daily field has approximately two-thirds of total areal data coverage while the remaining area of missing data is due to gaps in the individual scans, between scans, and where data retrieval is not possible in cloudy scenes. Daily data can be, and has been, used in regional case study applications, but time averages used here are on a global scale to focus on the longer-term large-scale distribution of PWC. A 6½-year time series beginning July 1983 is examined below.

## 3. Analysis

The climatological mean PWC field for the period July 1983 through June 1989 is shown in Fig. 1. Many of the expected climatological features are shown in this analysis. Overall structure is fairly smooth in nature, with many expected latitudinal deviations over the continents. Higher tropical values reveal the presence of the intertropical convergence zone (ITCZ) over the tropical Atlantic and Pacific, and the South Pacific convergence zone (SPCZ) aligned from the tropical west Pacific to the subtropical south-central Pacific. The mean annual ITCZ axis lies in the Northern Hemisphere (NH), at 5°N. Areas of elevated terrain, such as the Tibetan plateau, the western U.S. plateau, and the South American Andes, all exhibit PWC minima. All these features have been previously reported in studies based on radiosonde data, that is, Starr et al. (1969), who used data from the International Geophysical Year (IGY) 1958.

Other features shown in this analysis do not confirm the earlier estimates. Specifically, the magnitude of PWC over the northern half of South America is much lower than previously reported, by as much as 10 mm (Starr et al. 1969). Similar discrepancies are found in other regions, such as equatorial west Africa, India, and the tropical east Pacific. While previous studies investigated datasets from a different time period, it is apparent that the differences are primarily due to method and not natural variability. In fact, the analysis appears to be dominated by underestimates when compared to the early in situ studies. This is reflected in a comparison of hemispheric and global means (see Table 1).

Effects of the inherent biases are seen in large-scale time averages. Estimates of annual hemispheric and

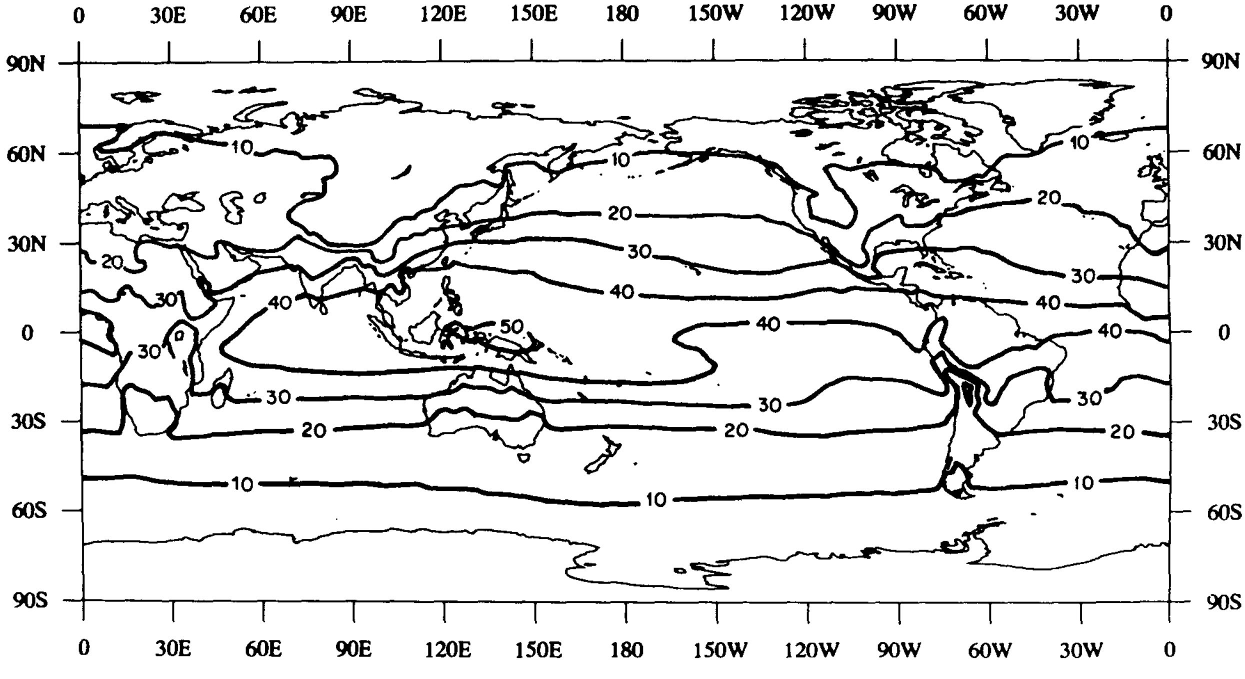

FIG. 1. Mean ISCCP TOVS precipitable water content (mm) for the six-year period of 1 July 1983 through 30 June 1989.

TABLE 1. Estimates of hemispheric and globally averaged PWC (mm).

| Investigator | Data | Time period | NH | SH | GL |
|---|---|---|---|---|---|
| Present study | TOVS | 1983–89 | 24.3 | 22.5 | 23.4 |
| Wittmeyer (1990) | ECMWF | 1983–88 | 28.7 | 26.1 | 27.4 |
| Rosen et al. (1979) | MIT | 1958–63, 1968 | 25.7 | | |
| Starr et al. (1969) | IGY | 1958 | | | 26.0 |
| Trenberth (1981) | Six sources | 1957–78 | | | 25.3 |
| Trenberth (1987) | ECMWF | 1978–85 | | | 28.6 |

globally averaged PWC are given in Table 1. Five independent sets of estimates are added for comparison and are primarily based on analyses of radiosonde measurements, which have relatively little ocean data coverage. The climatological mean value for the NH reported here is 24.3 mm. The NH estimate made by Rosen et al. (1979) is somewhat greater (25.7 mm), and an estimate made using ECMWF analyses (Wittmeyer 1990) is even higher (28.7 mm). ECMWF moisture levels are generally reported to be overestimated, while the TOVS data tends to underestimate the actual conditions due, in part, to the lack of any contribution in cloudy areas, which are often regions of relative maxima. A mean of the globally averaged ECMWF and TOVS datasets coincidentally corresponds very well with the climatological global mean reported by Trenberth (1981) who used specific humidities reported by Oort and Rasmusson (1971) along with a number of surface pressure and geopotential height datasets in a calculation of total atmospheric water vapor mass. Even the early study by Starr et al. (1969) is very close to this value (between 25.0 and 26.0 mm). A consensus estimate of mean SH total column PWC based upon data from Table 1 is near 24.5 mm. It is interesting to note the large difference in Northern versus Southern Hemisphere values for the annual mean. Northern Hemisphere values are substantially larger than those of the SH due to the asymmetry of landmass distribution forcing a mean position of the ITCZ in the Northern Hemisphere. This can be seen in climatological annual and seasonal zonal means shown in Fig. 2. A secondary maximum in aus-

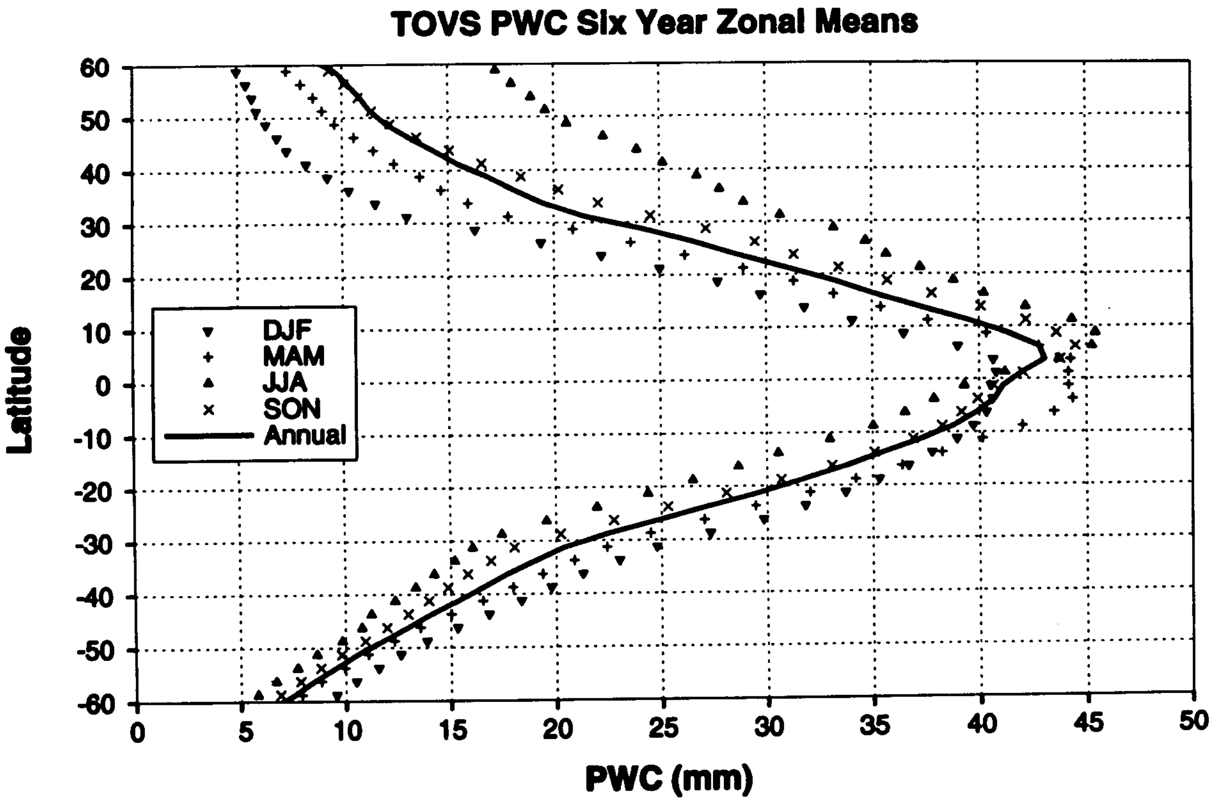

FIG. 2. Climatological seasonal and annual zonal averages of ISCCP TOVS analyzed PWC (mm).

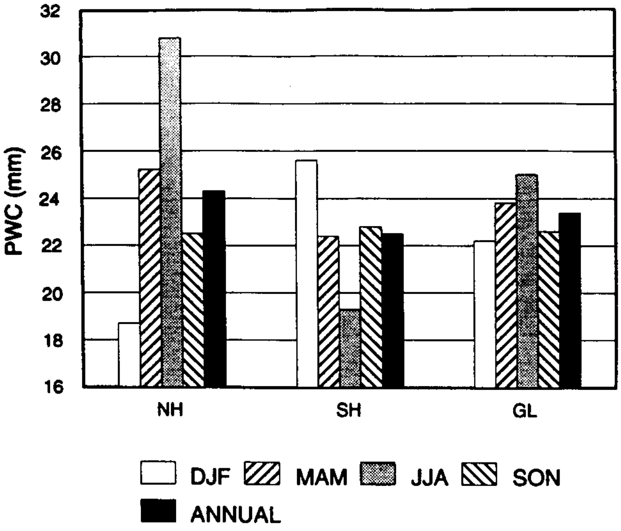

FIG. 3. Climatological hemispheric and globally averaged seasonal and annual PWC (mm).

tral fall near 5°S coincides with annual maximum sea surface temperatures and annual maximum low-level convergence and convection over the Pacific Ocean, which contributes significantly to the zonal mean there during this season. The annual zonal maximum at 5°N represents the influence of zones of convergent trade winds, and agrees well with previous work.

Hemispheric and globally averaged estimates of seasonal PWC are given in Fig. 3. The global seasonal cycle is far from constant, in fact, it shows the influence of the high-amplitude cycle in the NH. Intraannual variability in the Southern Hemisphere is less due to greater ocean coverage, which moderates the seasonal cycle of atmospheric PWC. Seasonal values for fall in the two hemispheres are most closely matched, and can be seen by comparing the NH mean for SON with the SH mean for MAM in Fig. 3. All other means are significantly different when comparing similar seasons in both hemispheres.

Figure 4 shows a time series of 6½ annual cycles of NH, SH, and global (GL) monthly averages. The larger NH annual cycle is apparent, with much higher warm season values that peak during August and September. Minima in both hemispheres have similar magnitude, showing the similarity of mean moisture in the two cold season atmospheres. The slightly less moist NH minima show the strong influence of cold and dry interior land areas during winter months.

Analyses such as those presented above focus on the long-term mean state of atmospheric water vapor. It is apparent that the information provided therein simply complements the knowledge already put forth in

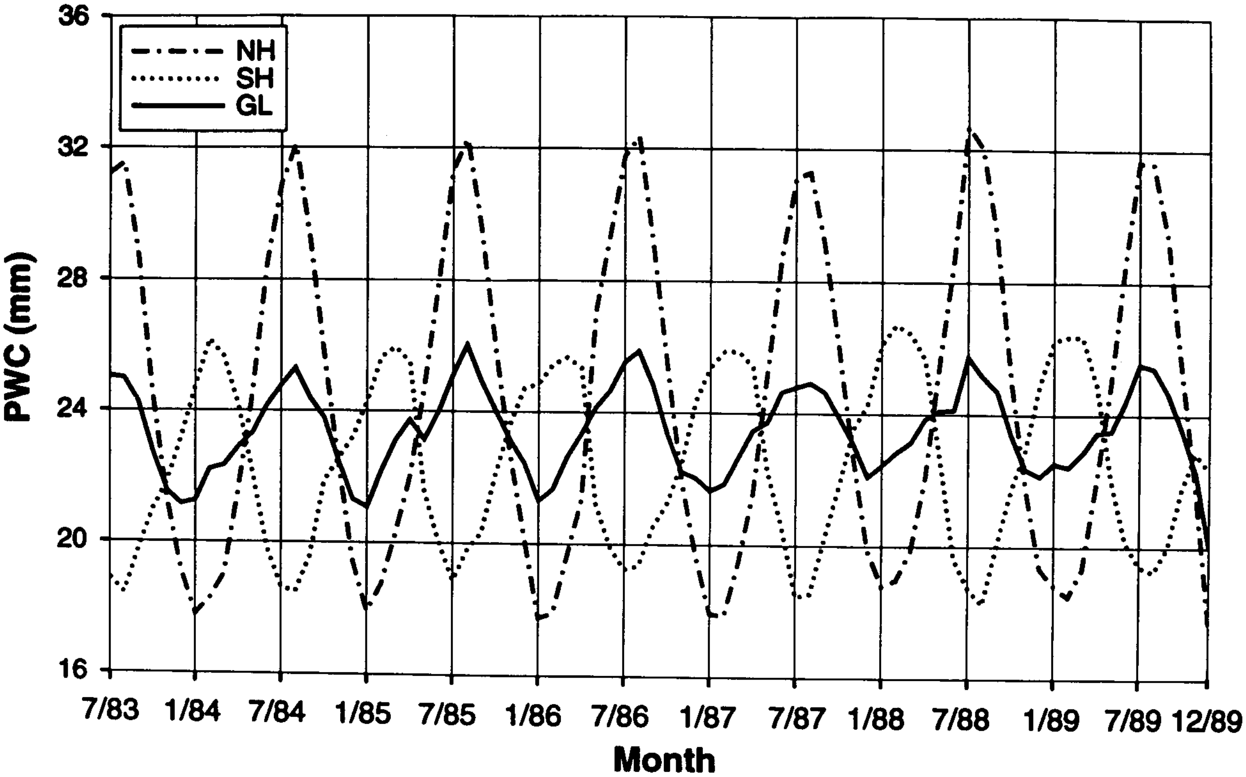

FIG. 4. Time series of hemispheric and globally averaged ISCCP TOVS PWC during the 6½-year study period beginning 1 July 1983.

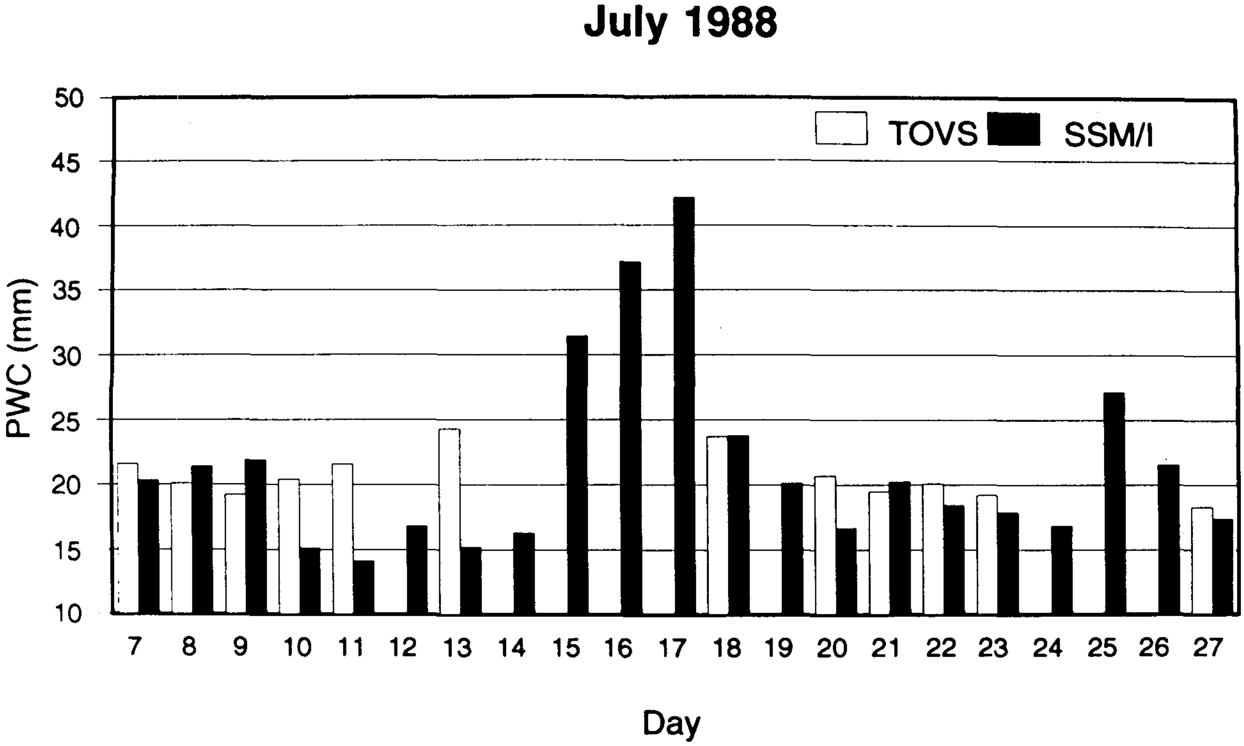

FIG. 5. Daily observations of PWC (mm) from SSM/I and TOVS for the 2.5 degree grid box centered at (48.75°N, 178.75°W).

previous studies based on in situ data, and fails to make a significant step forward in our understanding of important issues such as interannual variability and climate change. It is therefore necessary to examine how smaller-scale variations of water vapor, in both time and space, affect the long-term means. This is possible by comparing satellite and in situ measurements, but the inherently variable nature of this important parameter makes it difficult to compare radiosonde data at specific points with the averages of atmospheric volumes retrieved from space. Perhaps a more appropriate comparison is between two independent methods of space-based retrievals. The ISCCP TOVS infrared method is therefore compared with analyses of microwave observations of water vapor from the Special Sensor Microwave Imager (SSM/I) flown aboard the Defense Meteorological Satellite Program (DMSP) polar orbiters (Hollinger et al. 1987), and the physical retrieval scheme of Greenwald et al. (1993). The retrieval of microwave observations exploits the extent of depolarization by atmospheric water vapor of the surface emission. This method simultaneously determines columnar water vapor and liquid water using both horizontal and vertical polarization measurements at 19.35 and 37 GHz.

The month of July 1988 was chosen for the comparison. Data from both the ISCCP TOVS and SSM/I datasets at a representative midlatitude grid box near 50°N and the date line are first examined. Transient synoptic systems in the north central Pacific Ocean forced relatively high water vapor values (exceeding 40 mm) north from lower latitudes to this grid box two times during this month. Southwesterly flow was established across 25 degrees of latitude to transport anomalously moist conditions into the grid box of interest during these two episodes. The rest of the month showed no signs of such a subtropical "connection." Daily observations of water vapor from both datasets are presented in Fig. 5. Missing data during 12 July, 14–17 July, 19 July, and 24–26 July represent days when no TOVS retrieval was possible due to cloud cover. During the days when information from both datasets was available, the TOVS values were higher 8 days out of 12. The values from SSM/I during 15–17 July and 25 July are significantly higher than the monthly mean from either dataset and correspond with missing TOVS data, thereby illustrating a negative bias toward TOVS retrievals made in clear conditions. More specifically, the mean and standard deviation for the TOVS observations in Fig. 5 are 20.7 mm and 1.81 mm, respectively, while those for the SSM/I data are 21.5 mm and 7.33 mm. While this example only shows a very limited number of observations, we believe it is symptomatic of periods when significant poleward transport of water vapor occurs. Monthly means would be affected to a lesser degree than would standard deviations (by missing data during anomalously moist periods) since most of the variability occurs in a few

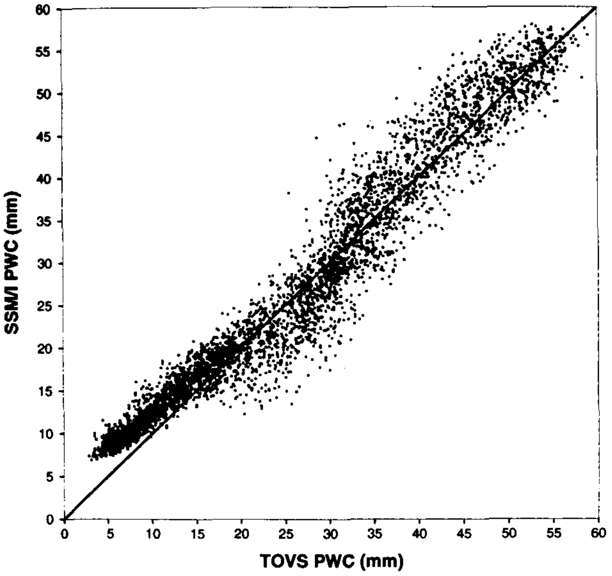

FIG. 6. Scatterplot of the individual grid box monthly mean PWC values of ISCCP TOVS vs SSM/I for July 1988 shown with the line of perfect agreement.

days during a given month, as shown in this example, and below in comparisons of monthly mean and standard deviations for both datasets.

Figure 6 shows a comparison of TOVS and SSM/I monthly mean PWC for each coincident 2.5-degree grid box value in a scatterplot for the month of July 1988, as well as the line of perfect agreement. In order to be as consistent as possible in this comparison, the SSM/I monthly means were computed in areas where total cloud cover was not present, as determined by data from coincident TOVS information. This was accomplished by screening the SSM/I data with a clear/cloudy mask based upon a data quality flag from the TOVS dataset. In this analysis, water vapor values from TOVS are shown to be significantly drier than those from SSM/I in grid boxes where the columnar water vapor is less than 20 mm. This dry bias in the TOVS data exists over colder ocean areas in the mid- and high-latitude storm tracks, and is largely due to an underestimation of water vapor there during the clear and partly cloudy nondisturbed periods between transient baroclinic systems. Significant overestimation within TOVS PWC is found in regions of strong subsidence over ocean areas west of continents in the subtropics. The effect of this is seen in Fig. 6 for TOVS PWC greater than 17 mm and less than 32 mm. For PWC estimates greater than 32 mm the scatter increases but less overall bias is noted. The effect of biases due to cloud cover are omitted from this analysis because only clear-sky SSM/I data were used in the comparison.

The previous comparison of SSM/I and TOVS monthly mean PWC was made for predominantly cloud-free areas over ocean. In order to gauge the impact of cloudiness on TOVS time means, we hereby compare clear versus cloudy monthly means from SSM/I data (see Fig. 7), and therefore infer biases in the TOVS data using the relationship between TOVS clear and SSM/I clear PWC as shown in Fig. 6. The monthly mean clear (cloudy) values in Fig. 7 were obtained by separately computing the means from daily values deemed clear (cloudy) using the TOVS cloud mask as previously described. This analysis shows monthly mean water vapor for cloudy areas is generally higher than in clear areas, especially so where values are greater than 35 mm. It is therefore assumed that a similar relationship exists in the TOVS data, where a substantial negative bias is introduced in areas of predominant cloud cover.

These comparisons of monthly means are supplemented by a comparison of the standard deviations as shown in Fig. 8. The values from each dataset show a high level of disagreement, and the SSM/I data shows a higher degree of variability in this analysis. A map of the global distribution of TOVS standard deviation shows no recognizable features and only apparently random noise (not shown), while a similar analysis from SSM/I data clearly exhibits maxima in storm track regions [see Tjemkes and Stephens (1990) for a similar comparison]. Therefore, while time means of a month or more agree fairly well between the two datasets, their representation of variability is quite different. In fact, the TOVS standard deviations produced by the statistical retrieval scheme exhibit a minimal amount of useful information when considered over any long-term period, while standard deviations of SSM/I water vapor data exhibit a realistic distribution.

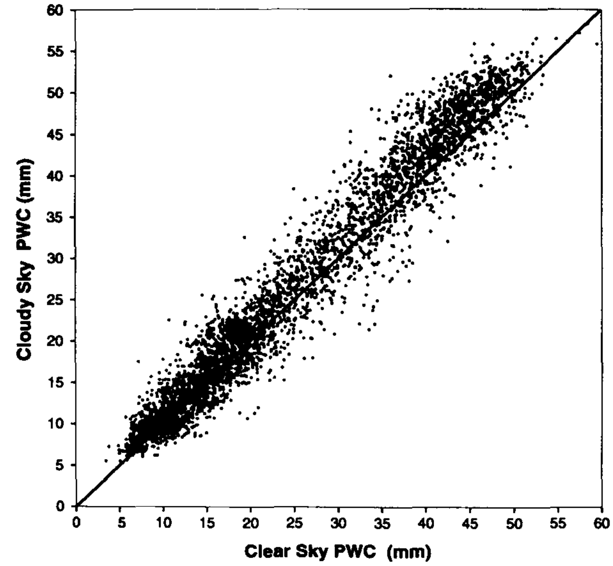

FIG. 7. Scatter of individual grid box monthly mean clear vs cloudy PWC (mm) from SSM/I. TOVS data quality flags were used to determine which SSM/I grid boxes were described as "cloudy." The line of perfect agreement is also shown.

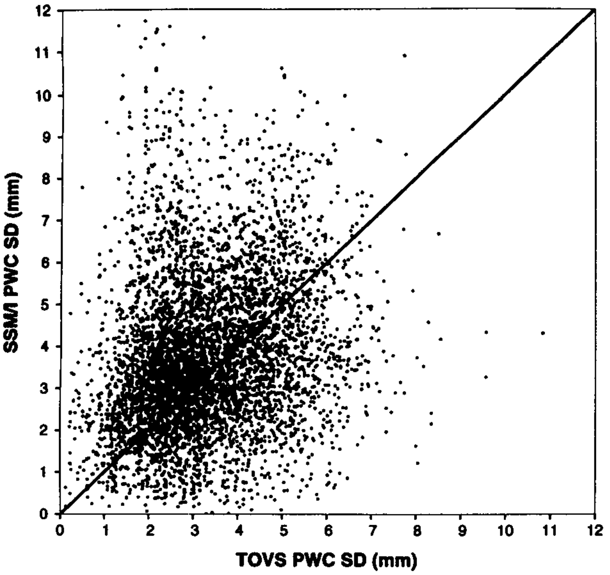

FIG. 8. Scatter of TOVS vs SSM/I PWC standard deviations (mm) from monthly mean PWC for July 1988 under clear or partly cloudy conditions. Also shown is the line of perfect agreement.

A significant improvement in TOVS standard deviations is noted since the operational switch to a physical scheme [see Stephens and Jackson (1993) for comparative analyses of physically retrieved TOVS with SSM/I and radiosonde data].

The consequences of missing data in large-scale analyses of water vapor are especially significant when compared to those of other atmospheric variables. The highly transient nature of water vapor demands accurate and contiguous measurements, especially since atmospheric transport processes play a crucial role in the hydrologic cycle, ocean–atmosphere interaction, and in the general circulation. Since a significant amount of moisture is moved poleward in mesoscale to synoptic-scale systems that may have predominant cloud cover, a negative bias can be introduced due to the difficulty of retrieval in predominantly cloudy conditions, and due to the lack of high-quality input statistics provided by the retrieval first-guess field. These regions are often characterized by moisture values that are significantly greater than the zonal average. Virtually no TOVS water vapor information is available in precipitating regions, except where gaps are filled by some other means. Phenomena such as "moisture bursts," as studied by McGuirk et al. (1987), are known to play an important role in transporting moisture poleward from the tropics, forcing cirrus shields, and therefore strongly affecting the synoptic-scale radiation budget. In addition, relative changes in water vapor in the upper troposphere have disproportionately large effects on greenhouse warming [Stephens and Greenwald (1991)]. It is now obvious that better measurements of water vapor near the tropopause are needed to improve our knowledge of not only the moisture distribution and variability, but its interaction with other parameters, such as clouds and radiation. Relatively narrow streams of moisture must be adequately characterized also to fully understand the contribution of moist transient systems to the global mean state of the moist atmosphere. It is important, however, to supplement estimates of time means with calculations of spatial and temporal variability of water vapor over long periods of time.

## 4. Summary and conclusions

Analyzed ISCCP TOVS precipitable water content fields show many expected mean features that are climatologically consistent with previous studies based on radiosonde observations. The mean positions of ITCZ and SPCZ features are well shown. Gradients across coastlines are seen, as are variations across gross land surface features. A dramatic asymmetry exists in Northern versus Southern Hemisphere PWC time series amplitudes. While cold season PWC minima are comparable for both hemispheres, the Northern Hemisphere maxima is much larger than in its counterpart in the SH.

While generalized patterns correspond with earlier work, some features exhibit significantly different maximum or minimum values, and long-term hemispheric and globally averaged PWC values are lower than other independent estimates. PWC is overestimated under dry subtropical high pressure cells, underestimated in the midlatitude storm tracks, and underestimated in the tropics. In addition, the TOVS dataset fails to adequately represent the spatial and temporal variability of water vapor, which is a critical component in a proper description of the general circulation. Standard deviation analyses of SSM/I data and fields derived from the newer TOVS physical scheme are much more realistic.

Some uncertainty exists in the outlook for future improved observations of atmospheric water vapor. Our network of ground-based upper-air systems is not likely to improve in the near future, so we must look to satellite systems for additional improved measurements. Clearly there is much room for improvement in space-based instruments used to sense atmospheric water vapor. Significant advances in our understanding of this variable are likely to be realized using advanced sensors of the future, provided that careful planning and successful funding efforts continue forward. Some hope lies in the use of instruments such as advanced microwave sounders (AMSU, SSM/T-2) as well as planned systems with enhanced observational potential, such as sensors planned to fly on Earth Observing System (EOS) missions within the next decade. Additional insight will be gained from microwave sounders, which will yield improved vertical profiles of water vapor, which will in turn provide a better understanding of the role of water vapor and its variability in weather and climate.

*Acknowledgments.* This research has been supported by NASA Grant NAG 1-865. We wish to thank Lola Olson at GSFC for supplying the ISCCP TOVS data, and the reviewers for their very helpful comments and suggestions. SSM/I data was provided by Tom Greenwald and Graeme Stephens here at Colorado State University. Judy Sorbie Dunn is acknowledged for her figure drafting work.

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