Global Atmospheric Water Vapor From Satellite Data

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1. GLOBAL ENERGY AND WATER CYCLE EXPERIMENT (GEWEX) OBJECTIVES

GEWEX is a major new project to study global atmospheric and surface processes. The objectives of GEWEX are:

i) To determine the hydrological cycle and energy fluxes by means of global measurements of observable atmospheric and surface properties

ii) To model the global hydrological cycle and its impacts in the atmosphere and the ocean

iii) To develop the ability to predict the variations of global and regional hydrological processes and water resources, and their response to environmental change

iv) To foster the development of observing techniques, data management and assimilation systems suitable for operational application to long-range weather forecasts, hydrology and climate predictions

There are a number of reasons why there should be a concerted effort to obtain a global water vapor climatology using satellite data from the last 10-12 years. These reasons include

i) Water vapor provides a vital link between evaporation, clouds, and precipitation

ii) Water vapor is the largest greenhouse gas and the water vapor feedback mechanism is largely responsible for climate model predictions of global warming

iii) Release of latent heat is critical in tropical climate variability and tropical-extratropical teleconnections

iv) Evaporative cooling of the oceans is in part determined by the amount of water vapor in the lower troposphere

These concerns were acknowledged in a workshop on the role of water vapor in climate held in Easton, MD in the fall of 1990 and have led to a call for the GEWEX Water Vapor Project (GVaP). The goal of GVaP is to improve our understanding of the role of atmospheric water vapor and its variability in global meteorological, hydrological, and climatological processes. Four central scientific objectives of GVaP have been identified. They are:

i) To develop and apply algorithms to derive and validate a global climatology of the horizontal and vertical distribution of atmospheric water vapor focussed on the validation of global climate models.

ii) To develop and improve, through applied and basic research, techniques to provide high vertical resolution global measurements of water vapor from satellites.

iii) To improve climate model parameterizations of hydrological processes, both by establishing a long-term climatology of the vertical distribution of atmospheric water vapor at selected sites with special emphasis on the middle and upper troposphere, and by conducting regional field campaigns in diverse climatological regimes, giving special emphasis to water vapor and its spatial and temporal variability.

iv) To promote basic research contributing to an improved understanding of the role of atmospheric water vapor and its variability in global meteorology, hydrology, and climatology.

These objectives establish a preeminent role for space-based observations of atmospheric water vapor and its variability. In the remainder of this paper, the emphasis is on a preliminary evaluation of our ability to retrieve precipitable water content (PWC) using current and past satellite remote sensors.

2. INSTRUMENTS USEFUL FOR DERIVING A GLOBAL WATER VAPOR CLIMATOLOGY

From a practical standpoint, the only instruments useful for deriving a global water vapor climatology have operated in the microwave and infrared portions of the spectrum. There are advantages and disadvantages to retrieving water vapor in each spectral regions as summarized below. Because of the large temporal gaps in coverage by the microwave instruments and they only can retrieve PWC over the oceans, it is of particular interest to assess the quality and possible improvements that can be made in infrared sensing of atmospheric water vapor.

Microwave

SSMR 1979-1983 22 GHz

SSM/I 1987-present 22 GHz

Advantages - Surface emission versus atmospheric emission large, cloud effects minimized
Disadvantages - Over ocean only, not continuous coverage

Infrared

HIRS/2 1978-present 8.2, 7.3, 6.7 microns
AVHRR/2 1981-present 11.2, 12.2 microns

Advantages - global, continuous coverage
Disadvantages - clouds, partial clouds, surface emission versus atmospheric emission small

3. GLOBAL PRECIPITABLE WATER VAPOR CONTENT: A 5-DAY INTERCOMPARISON

Five days of data is a sufficient length of time to gather a global picture of precipitable water content (PWC) from several different sources without overwhelming modest computer resources. It is also appropriate time span to apply subjective knowledge of synoptic weather conditions. For this study, three sources of satellite retrievals of PWC have been analyzed. These are SSM/I (courtesy F. Wentz, Remote Sensing Systems; Wentz, 1983), NESDIS operational statistical regression method (courtesy S.J.S. Khalsa, CIRES; Smith and Woolf, 1976) and 3I retrievals from NOAA-10 1b data (3I software provided by A. Chedin and N. Scott, ARA/LMD; Chedin et al., 1985). The 3I retrievals were processed in house and it is important to note that the original TIGR was used but with no forecast information.

Image and contour plots of these data reveal the following characteristics,

i) Infrared methods underestimate PWC in cloudy and partly cloudy areas of the tropics and subtropics compared to microwave methods

ii) Infrared methods overestimate PWC in subtropical subsidence areas

iii) Infrared estimates show a very zonal global PWC distribution. This implies large differences in moisture transport from the tropics to the mid-latitudes for infrared versus microwave estimates.

Tjemkes and Stephens (1990a) have also compared microwave (Tjemkes and Stephens, 1990b) and infrared (NESDIS operational) observations of monthly averaged PWC and its variance. They found similar results to those using only five days. Comparison of observations of PWC variance between the microwave and infrared methods revealed that temporal variations in PWC were almost absent from the infrared observations. This has important implications for monitoring the transport of water vapor in the atmosphere, since this lack of variability in the infrared observations will lead to very low estimates of water vapor exchange between low and high latitudes.

Based on these characteristics, we explore in the next section why there are these large differences between infrared and microwave retrievals of integrated water vapor.

4. LIMITATIONS OF INFRARED INTEGRATED WATER VAPOR RETRIEVALS

4.1. Infrared Versus Microwave Radiative Transfer

Write the radiative transfer equation as

$$I = \varepsilon B(T_S)\tau_S + (1-\varepsilon)\tau\int B(T(p))dt + \int B(T(p))dt \qquad (1)$$

Where

I	is the upwelling radiance
ε	is the surface emissivity

B	is the Plank radiance
τ	is the atmospheric transmittance
T(p)	is the temperature profile

In the infrared $\varepsilon \approx 1.$ so that

$$I = B_s \tau_s + \int B d\tau \qquad (2)$$

Thus for a channel that peaks low in the atmosphere, the upwelling radiance is highly dependent on the surface temperature and surface temperature variations are difficult to separate from atmospheric temperature and moisture variations.

In the microwave (for 22 GHz vertical polarization) $\varepsilon \approx 0.6$ so all terms are retained and the upwelling radiance is less dependent on the surface term.

A difference map (SSM/I PWC - Infrared PWC, not shown) shows a distribution very similar to that shown in figure 12 of Stephens (1990), with the quantity w replaced with infrared PWC. Since w depends only in sea surface temperature, this illustrates the difficulty that infrared PWC retrievals are having separating the surface signal from the atmospheric signal.

4.2 Limited First Guess Moisture Information

Following Eyre (1987), the linear inversion from satellite radiance measurements is

$$x - x_0 = W \sum (y_m - y\{x_0\}) \qquad (3)$$

where

x	is the vector of retrieved atmospheric parameters
x_0	is the first-guess value of the vector
y_m	is the vector of multi-channel brightness temperature measurements
$y\{x_0\}$	is the corresponding vector appropriate to the first guess
W	is the inverse matrix

A minimum variance solution for the inverse matrix W is

$$W = (K \sum C)^T \sum (K \sum C \sum K^T + E)^{-1} \qquad (4)$$

Where

C	is the error covariance of the first guess, x_0
E	is the error covariance of the measurements, y_m
K	contains the partial derivatives of the measurements with respect to the profile evaluated at x_0
	and ^{T} and $^{-1}$ denote matrix transpose and inverse

Looking at the error characteristics, the linear approximation to the forward RTE is

$$y_m - y\{x_0\} = K \sum (x_T - x_0) + e_m \qquad (5)$$

Where

x_T is the vector of the true atmospheric parameters
e_m is the vector of measurement errors

Substituting this into the first equation and rearranging terms

$$x - x_T = (I - R) \Sigma (x_0 - x_T) + W \Sigma e_m \qquad (6)$$

Where

$R = W \Sigma K$
I is the identity matrix

In the 3I method, an initial air mass classification (tropical, mid-latitude, or polar) is made by using TOVS channels that are insensitive to clouds. Dry subsidence areas at low latitudes are classified as tropical. Without using forecast information (which I was not able to acquire at this time), 3I is not able to find the appropriate TIGR class with very dry moisture conditions, but tropical temperature conditions. The 3I results, however, are only preliminary and the 3I retrievals will be recomputed with two improvements. These improvements are using forecast surface temperature and lower troposphere moisture information and using the advanced TIGR data base.

4.3 Partly Cloudy and Cloudy Atmospheres

A second class of differences between the microwave in infrared PWC retrievals occurs in partly cloudy and cloudy areas. In these regions, only "cloud-cleared" radiances are used to retrieve moisture profiles. Ad hoc methods are needed to improve moisture retrievals in these areas.

In the infrared

$$I = B_s \tau_s + \int B \, d\tau \qquad (7)$$

where

I is the measured radiance
B_s is the surface Plank radiance
τ_s is the atmospheric transmittance at the surface
B is the atmospheric radiance
τ is the transmittance

In partly cloudy areas

$$I = (1\text{-}Ne)\, I_{clear} + Ne I_{cloudy} \qquad (8)$$

Where

N	is the cloud amount
ε	is the emissivity of the cloud
I_{clear}	is the radiance of the clear area
I_{cloudy}	is the opaque cloudy radiance ($\varepsilon = 1$)

For two adjacent measurements

$$I_1 = (1 - N_1\varepsilon_1)I_{clear} + N_1\varepsilon_1 I_{cloudy} \quad (9a)$$

$$I_2 = (1 - N_2\varepsilon_2)I_{clear} + N_2\varepsilon_2 I_{cloudy} \quad (9b)$$

Assuming that the combined effects of cloud height and emissivity are equal then

$$I_{clear} = (N^*I_1 - I_2)/(N^* - 1) \quad (10)$$

Where

$$N^* = N_1/N_2 = (I_{clear} - I_1)/(I_{clear} - I_2) \quad (11)$$

Iclear is then used to retrieve the clear water vapor profile, but we know that in the presence of clouds that this is a biased estimate.

3I uses ψ-method (single spot infrared + microwave information + initial guess information) to determine the cloud parameters and then evaluate

$$I = NeI_{cloud} + (1-Ne)I_{clear} \quad (12)$$

Where I_{cloud} comes from TIGR

Hayden et al. (1981) suggest an ad-hoc method for accounting for the increase in water vapor content in the fractional cloudy spots. Assume the moisture profile obeys a simple power law

$$q = q_0(p/p_0)^{\lambda} \quad (13)$$

Where $\lambda \cong 3$

The specific humidity at the cloud level q_C is approximated by

$$q_C = N^*q_S + (1-N^*)q_G \quad (14)$$

Where

q_S	is the saturation specific humidity at the cloud top temperature
q_G	is the first-guess specific humidity at the cloud top pressure

Below cloud top, solve for a new λ via

$$\lambda = \ln(q_C/q_0) / \ln(p_c/p_0) \qquad (15)$$

Then solve for the new moisture profile.

3. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. Infrared methods underestimate PWC in cloudy and partly cloudy areas of the tropics and subtropics compared to microwave methods

2. Infrared methods overestimate PWC in subtropical subsidence areas

3. Infrared estimates show a very zonal global PWC distribution. This implies large differences in moisture transport for infrared versus microwave estimates

4. These differences are due to a) differences in the physics of radiative transfer between the infrared and microwave, b) inadequate first guess moisture information in infrared retrieval methods, and c) lack of schemes to account for moisture content in cloudy and partly cloudy regions

Recommendations

1. Continue to improve first guess moisture information

2. Evaluate ad hoc schemes for adjusting moisture profiles in cloudy and partly cloudy regions

3. Explore methods to combine infrared and microwave observations of atmospheric water vapor

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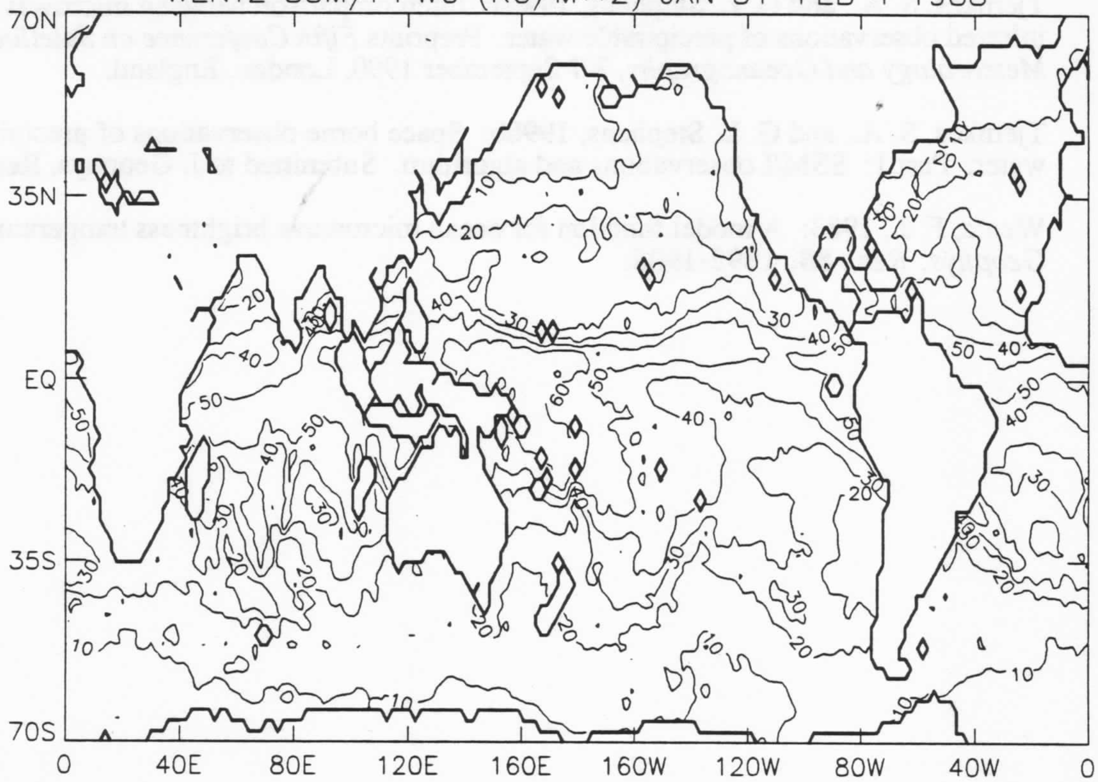
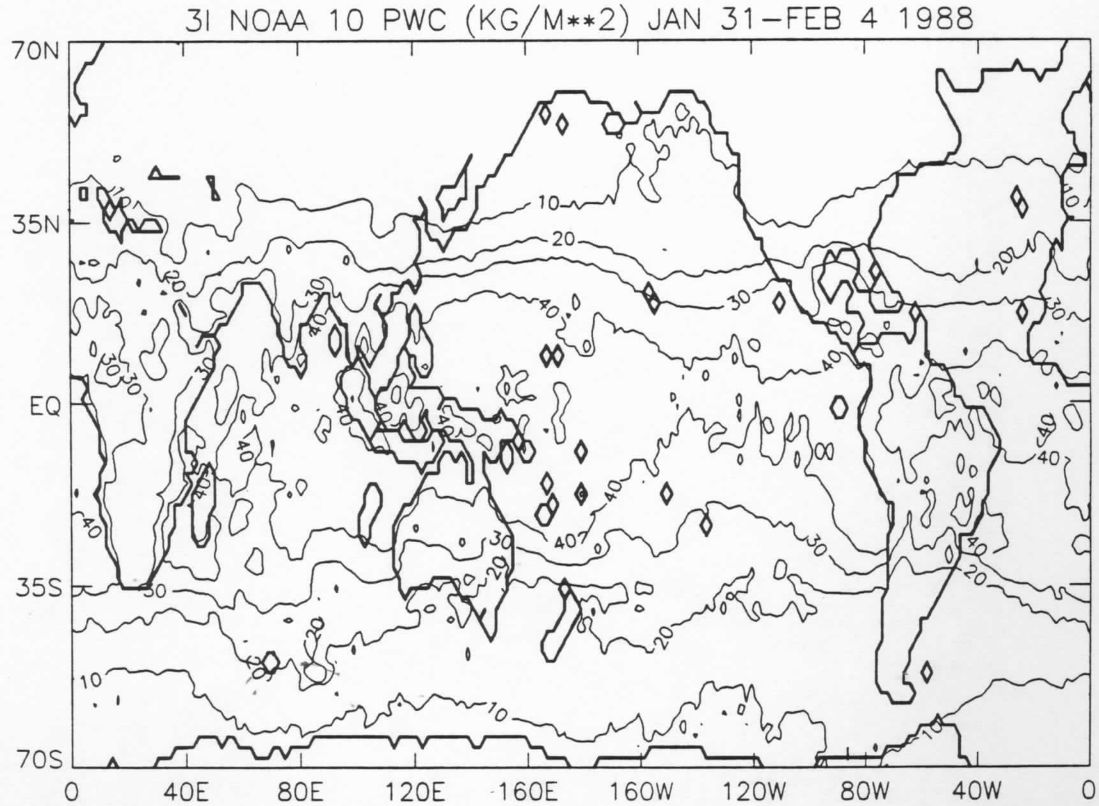
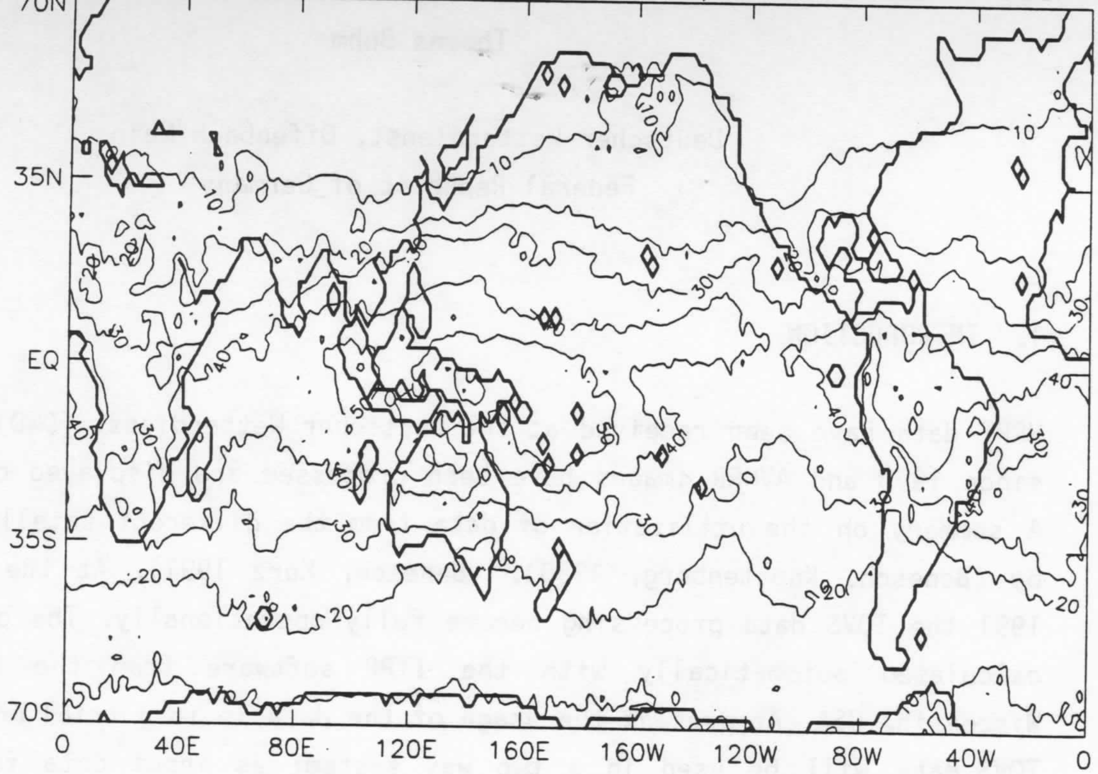
WENTZ SSM/I PWC (KG/M**2) JAN 31–FEB 4 1988



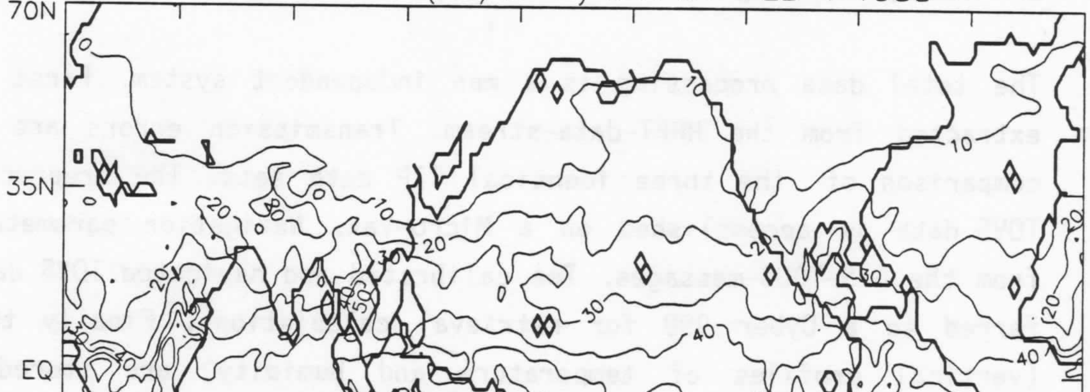
3I NOAA 10 PWC (KG/M**2) JAN 31–FEB 4 1988



NESDIS NOAA 9 & 10 PWC (KG/M**2) JAN 31-FEB 4 1988



ECMWF PWC (KG/M**2) JAN 31-FEB 4 1988



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