Observing Atmospheric Water Vapor for Weather and Climate Applications

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Current/Recent Water Vapor Research at CIRA

- Atmospheric rivers
- Scientific data stewardship pilot study
- Passive microwave remote sensing over land
- Indirectly related research (e.g. data assimilation…)
- Creators of NASA Water Vapor (NVAP) dataset in past
Outline

1. New Results / Techniques
2. Measuring Water Vapor from Space
3. Water Vapor Climate Data Record
4. Multisensor / Retrieval Work at CIRA
5. IPCC AR4 Findings
6. Scientific Data Stewardship
New Results & Techniques
Mars TPW can be higher than that over Antarctica!

Uses 1.38 micron channel (same channel is on MODIS)
New measurements from the Tropospheric Emission Spectrometer (TES) onboard Aura allows retrieval of isotopic composition of water vapor from 7.5 – 8.3 μm measurements. Allows exploration of interesting questions like how much moisture is from evaporated cloud? What is the history/source of the moisture?

COSMIC could be a revolutionary satellite system!

COSMIC Soundings in 1 Day
Occultation Locations for COSMIC, 6 S/C, 6 Planes, 24 Hrs
GPS occultation sounding is a spatially weighted average

Courtesy Rick Anthes
A Variety of Intercalibration Techniques are Available

Simultaneous Nadir Overpasses

Zou et al. Recalibration of microwave sounding unit for climate studies using simultaneous nadir overpasses
JGR 2006

Calm, clear cold oceans provide the minimum Tb at < 90 GHz. A natural vicarious calibration reference.

Vicarious Calibration

Topex Microwave Radiometer (TMR) – upwards calibration drift detected at 18 GHz.

Monitoring Water Vapor from Space
## Total Column (TPW)

- Passive microwave 22 GHz + other channels (SSM/I; TMI)
- MODIS TPW (near IR)
- GPS surface-based receiver with accurate barometer
- Split window technique (e.g. 10.5 + 12.5 μm channels); GOES Sounder
- Integration of profiling retrievals

## Profiling

- Passive microwave 183 GHz + other channels (AMSU; SSMIS; SSM/T-2)
- Aqua AIRS instrument (IR - hyperspectral)
- MSG IASI instrument (IR - hyperspectral)
- NOAA HIRS (IR broadband)
- COSMIC GPS occultation (+ predecessors (SAC-C, GPS MET); GRAS, GRACE…
- CrIMSS Future (NPP / NPOESS)
- Limb sounding (upper trop, stratosphere (e.g. MLS)
Advanced Microwave Sounding Unit (AMSU): An Operational Moisture Sounder

- Two modules: AMSU – A and AMSU – B (MHS on NOAA-18)
- 20 channels: 23.8 to 183 GHz
- Spatial resolution from 16 – 48 km at nadir
- NEDT values ranging from 0.11 to 1.06 K (very low)
- On NOAA satellites and Aqua

Note: SSMIS instrument on DMSP has similar features except conical scanning

Microwave Transmittance Spectrum

183 GHz used for moisture sounding
The Challenge of Water Vapor Over Land (MW)

Atmospheric Moisture is Less Pronounced Over Land Versus Ocean in Passive Microwave Sounding Channels (AMSU-B & MHS) / SSMIS

Notice how the moisture features fade out over land.

In the microwave, land is radiatively warm due to high emissivity, while oceans are cool.

And land emissivity is variable and difficult to model...

\[ \varepsilon \text{(ocean)} \approx 0.5 \]
\[ \varepsilon \text{(land)} \approx 0.95 \]

AMSU 23 GHz radiances

4th NOAA/NESDIS CoRP Science Symposium

June 19-20 2007 College Park
Currently, Microwave Atmospheric Moisture Products are Typically Produced Over Ocean But Not Over Land

Global, Blended 6-satellite AMSU / SSM/I TPW Over Oceans

(Kidder and Jones; J. Atmos. Oceanic Tech., Jan. 2007)
Water Vapor Climate Data Record
Water Vapor In the Climate Record: Still a Challenge to Characterize

Challenges:

Intersatellite calibration.
Validation, especially in upper trop. / stratosphere.
Retrieval algorithm errors / model reliance.
Land vs. ocean retrievals.
Cloud clearing (IR-techniques; dry bias).
TPW versus profiling retrievals.
Future merged datasets beyond NVAP (ala ISCCP, GPCP). Beyond ocean-only (e.g. Wentz SSM/I).
Multiple satellite products are blended to create the NVAP dataset.

January 1, 2000

Total Precipitable Water (TPW) shown here.

NVAP covers 1988 - 2001

Blended satellite products are often used to measure climate variables:
(e.g. ISCCP, GPCP)
Each sensor has strengths and weaknesses.
Time series of NVAP Global Mean TPW, 1988 - 1999

Annual Cycle ~ 10 % of Global Mean
NVAP – The NASA Water Vapor Project Dataset

- Daily or twice daily
- 1 degree or ½ degree grid
- Up to 10 polar orbiter inputs (SSM/I, AMSU, TOVS, ATOVS, TMI, SSM/T-2)
- 1988 – 2001
- Mostly Model Independent!

Mean total column water vapor, 1988 - 1999
Interannual Variability – 1988 – 1999

The annual cycle has been removed. This reveals phenomena operating on timescales longer than a year, such as El Nino / La Nina.

With the annual cycle included. The monsoon and storm track regions are well delineated by their impact on the annual cycle.
Comparison of the Total Column Water Vapor, Sea Surface Temperature, and Lower Tropospheric Temperature Anomalies - Global Means

Three Independent Satellite Measurements – Highly Coupled

Mt. Pinatubo Eruption March 1991

Major El Nino begins May 1997

Multiple, unrelated CDR’s can reinforce each other

-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8

0.00
0.30
0.60
0.90
1.20
1.50


Total Column Water Vapor Anomalies - NVAP
Lower Tropospheric Temperature Anomalies - MSU
Sea Surface Temperature Anomalies - Reynolds

Mt. Pinatubo Eruption March 1991
Major El Nino begins May 1997

Three Independent Satellite Measurements – Highly Coupled

Multiple, unrelated CDR’s can reinforce each other
NVAP SSM/I Instruments Usage

1993, 1994  All months - F10, F11
1995  All months - F10, F11, F13 starts 5/95,  except: Jul - F10, F11 only
1996  All months - F10, F11, F13
1997  F10 ends 11/15, F11, F13, F14 starts May, except: Feb - F10, F11 only,  Dec - F11, F14 only
1998  All months - F11, F13, F14,  except: Apr - F11, F14 only,  Aug - F11, F14 only
1999  F11 ends Apr, F13, F14
2000  F11 Jan and Feb, F13, F14, F15 starts March
2001  All months – F13, F14, F15

Every transition in this record represents a challenge for climate monitoring
Multisensor and Retrieval Work at CIRA
Blended SSMI-AMSU (ocean) and GPS (overland) TPW AM of Jun 25

Climate meets weather

Experimental TPW Anomaly from NVAP weekly mean 1988-1999

200% of normal

Rainfall totals from Silver Spring, Montgomery County, Maryland

8.56” - 24 hour totals thru AM Jun 26
11.65” - 48 hour totals thru AM Jun 27
12.71” - 84 hour totals thru AM Jun 28

Courtesy Sheldon Kusselson, NESDIS SAB

CIRA Experimental Blended TPW Products
http://amsu.cira.colostate.edu/gpstpw
OR… in the words of Stan Kidder at CIRA:

“You do climate research to first find out what’s wrong with your instrument and algorithm.”
November 15, 2006 18 UTC “Atmospheric River”: Example of how the GOES/POES products are complementary.

Blended AMSU / SSM/I Total Precipitable Water Product (above) shows atmospheric river clearly.

See presentation Wednesday by Jack Dostalek and poster by Brant Dodson for more CIRA research on Atmospheric Rivers.
Retrieval Algorithm Development

CIRA 1-Dimensional Variational Optimal Estimator (C1DOE) Retrieval

-- Focused on moisture profiles over land and ocean from microwave radiances

Scientific Cousin of NOAA MIRS System
Ocean Validation of C1DOE Promising

- **1000 hPa (g/kg)**
  - Bias = 1.76
  - RMS = 2.23
  - R = 0.90

- **850 hPa (g/kg)**
  - Bias = 1.19
  - RMS = 1.91
  - R = 0.92

- **700 hPa (g/kg)**
  - Bias = 0.83
  - RMS = 1.46
  - R = 0.92

- **500 hPa (g/kg)**
  - Bias = -0.15
  - RMS = 0.68
  - R = 0.88

Constant 50% RH first guess
November 6, 2006 “Atmospheric River” (Pacific NW Floods)

Different techniques, similar results…
…but C1DOE provides vertical information

Note different scales

1000 – 850 hPa Layer TPW

500 – 300 hPa Layer TPW

Moist boundary layer, dry aloft
C1DOE Improves Moisture Over Forecast Model Initialization

C1DOE (integration of profile)

GDAS (a priori)

NOAA MSPPS “TRUTH” (column-only technique)

C1DOE captures spatial gradients well in the stratus region

GDAS: 3.67 mm bias
C1DOE: 1.5 mm bias

vs. NOAA
GDAS computed forward model brightness temperatures (Delta Tb) versus measured AMSU brightness temperatures in the stratus region.

Scatter indicates forecast model initialization does not have correct moisture / clouds.

June 8, 2006
Emissivity Must Be Constrained to Retrieve Atmosphere Over Land

Emissivity Variance = 0.5 (very large!)

Expect increased convergence with:
• Dynamic land emissivity background
• Infrared cloud detection
• Observation / RTM bias reduction

GDAS TPW, 18 UTC June 8, 2006

No emissivity constraint:
Little atmospheric change

Tight emissivity constraint:
white areas nonconvergent

Extreme constraints: 0.01 $\varepsilon$ variance, 2 K AMSU noise; Land temperature $\sigma$ 2 K
IPCC AR4 Findings
TPW (lower trop)

1988-2004:
+ 1.2% / decade (0.40 mm / decade)

“A significant upward trend is observed over the global oceans and some NH land areas, although the calculated trend is likely influenced by the large interannual variability in the record.”
Upper Trop:
“The available data do not indicate a detectable trend in upper-trop RH. However, there is now evidence for global increases in upper-tropospheric specific humidity over the past two decades, which is consistent with the observed increases in tropospheric temperatures and the absence of any change in relative humidity.”
By Clausius-Clapeyron equation, expect 7 % TPW / 1 K increase: A strong signal to seek. Results here indicate 1.3 % +/- 0.3 % / decade (ocean-only)

_Trenberth et al. 2005_
Scientific Data Stewardship
Ten GCOS Satellite Climate Monitoring Principles
(from Tom Karl, NCDC)

1. Minimize orbit drift
2. Ensure sufficient overlap
3. Replace prior to failure
4. Rigorous pre-launch calibration
5. Adequate on-board calibration
6. Continue baseline instrument observations on decommissioned satellites
7. Operational production of priority climate products
8. Facilitate access to products, metadata, and raw data
9. Need in situ baseline observations
10. Real-time monitoring of observing system performance

The Unwritten Principle

Use of multiple observing systems and multiple analysis teams (for the same variable)
“Science Stewardship of Thematic Climate Data Records- A Pilot Study with Global Water Vapor”

Scientific stewardship of the water vapor CDR has been demonstrated by CIRA by extending a historical dataset forward in time to overlap more capable instruments.

NVAP in archive exists 1988-2001; AIRS exists 2002+

NVAP partially created in 2003-2004 to compare with the new AIRS results
AIRS vs ATOVS

AIRS vs SSM/I

TPW differences from AIRS and NVAP components January 2003

Journal paper in progress

RED = AIRS MOISER

TMI – AIRS

NVAP merged - AIRS

ATOVS - AIRS
Stewardship Pilot Study Conclusions

A recreation of the NVAP total precipitable water (TPW) data from 2003-2004 shows that AIRS, SSM/I and TMI agree well.

The ATOVS operational TPW product behaves as an outlier compared to AIRS, SSM/I and TMI.

Useful information for a needed reanalysis.

The recovery and rescue of over 100 8mm tapes containing SSM/I antenna temperature data from 1987-1992 was successful. The data has been delivered on DVD to Fuzhong Weng at NESDIS for eventual inclusion into CLASS.
Conclusions

- Exciting new satellite measurements of water vapor continue to become available.
- Climate research feeds back to weather applications.
- The global water vapor CDR needs reanalysis/improvement.
- IPCC AR4 beginning to find upwards trends in TPW from SSM/I over ocean only from a reanalyzed dataset.
- Great NWP needs for improved moisture initialization. Multisensor products have proven useful for forecasters. Satellite moisture metrics for NWP are possible.
Some indicators of a warming climate

- Increase in temperature, decrease in the diurnal temperature range
- More intense precipitation events
- Increase of atmospheric water vapor
- Increase of summer droughts
- Increase in tropical cyclone intensities
- Intensified droughts and floods associated with El Nino
- Increase of sea level
<table>
<thead>
<tr>
<th>Time Dependent Bias</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TOVS:</strong></td>
<td></td>
</tr>
<tr>
<td>2 Changes in NOAA operational TOVS algorithm</td>
<td>Use a consistent climate-oriented retrieval such as NASA Pathfinder Path A (Susskind et al. 1997).</td>
</tr>
<tr>
<td>3 Values before 1996 &lt; 1 mm truncated</td>
<td>Do not use NOAA operational TOVS</td>
</tr>
<tr>
<td>4 NOAA operational ATOVS product used in 2000 – 2001, found to be an outlier.</td>
<td></td>
</tr>
<tr>
<td><strong>SSM/I:</strong></td>
<td></td>
</tr>
<tr>
<td>• 22 GHz channel not used 1988-1992</td>
<td>Apply a fixed algorithm through time Use consistent techniques outlined in Vonder Haar (2003)</td>
</tr>
<tr>
<td>• Precipitation and sea ice detection methods vary</td>
<td>Use results of Colton and Poe (1999)</td>
</tr>
<tr>
<td>• Updated antenna pattern correction needed for each instrument</td>
<td></td>
</tr>
<tr>
<td><strong>Radiosonde:</strong></td>
<td></td>
</tr>
<tr>
<td>• Varying quality control methods</td>
<td>Use climate-oriented data such as CARDS (Eskridge et al. 1999)</td>
</tr>
<tr>
<td>• 2000 – 2001 did not use radiosonde</td>
<td></td>
</tr>
<tr>
<td><strong>Miscellaneous:</strong></td>
<td></td>
</tr>
<tr>
<td>1. Topography masking causes TPW too high over high terrain (1988 – 1992)</td>
<td>Use single high resolution (&lt; 10 km) global topography mask such as GTOPO30</td>
</tr>
<tr>
<td>2. Land mask adjustments</td>
<td></td>
</tr>
</tbody>
</table>
1.9 % / decade

2.1 % / decade

1.0 % / decade

Figure 1 Anomaly time series of three climate variables. a, b, c, Water vapour $W$ (green), sea surface temperature $T_s$ (black), and air temperature $T_a$ (red) are shown for the northern extratropics (20°N–60°N; a), tropics (20°S–20°N; b), and southern extratropics (20°S–60°S; c). Air temperature is divided by 1.6.
A similar trend analysis of NVAP is in progress at CIRA

Figure 2.26: Trends in annual mean surface water vapour pressure, 1975 to 1995, expressed as a percentage of the 1975 to 1995 mean. Areas without dots have no data. Blue shaded areas have nominally significant increasing trends and brown shaded areas have significant decreasing trends, both at the 5% significance level. Biases in these data have been little studied so the level of significance may be overstated. From New et al. (2000). [IPCC 2001].
The velocity of GPS relative to LEO must be estimated to \( \sim 0.2 \text{ mm/sec}! \) (velocity of GPS is \( \sim 3 \text{ km/sec} \) and velocity of LEO is \( \sim 7 \text{ km/sec} \)) to determine precise temperature profiles.
NVAP Mode (Most Common) Data Source Changes Through Time

1988 - 1999

- 8 = Radiosonde data only
- 7 = TOVS and SSM/I combination
- 6 = SSM/I only
- 5 = SSM/I interpolated / TOVS combination
- 4 = SSM/I interpolated
- 3 = TOVS only
- 2 = Space interpolated-filled
- 1 = Time interpolated-filled
- 0 = Missing data

Dominated by SSM/I over ocean

More TOVS soundings produced by NESDIS after 1992

1992

A reanalysis of NVAP is needed to reduce time-dependent biases

1996
Calm, clear cold oceans provide the minimum Tb at < 90 GHz. A natural vicarious calibration reference.

Modeled Tb’s

Topex Microwave Radiometer (TMR) – upwards calibration drift detected at 18 GHz.
RED = AIRS MOISTER

TMI - AIRS

SSM/I - AIRS

AIRS vs TMI

AIRS vs SSMI
Introduction

A major update to the SSM/I and TMI datasets has been implemented.
SSM/I Version 5 (V05) has been updated to Version 6 (V06).
TMI Version 3 (V03) has been updated to Version 4 (V04).
The major objectives of the updates were to:

1. Remove spurious trends in the wind speed retrievals.
2. Implement a much-improved rain rate algorithm.
3. Achieve better consistency for all retrievals over the 8 satellite platforms (i.e., 6 SSM/I, TMI, and AMSR-E).
4. Make minor improvements in other retrievals, namely SST and vapor.

In addition to the SSM/I and TMI updates, a minor update to the AMSR-E rain rates has also been implemented. There was a small bug in the calculation of the composite maps (3-day, weekly, and monthly) that mostly affected the monthly maps. As a result, the monthly rain rates were biased low by about 0.03 mm/hr relative to the daily maps. Also, in the daily maps, extremely light rain (<0.025 mm/h) is now set to zero. This change has little effect on the mean rain rates, but does affect the aerial coverage. Since this is a minor update, we denote it as V05a, as compared to the preceding V05 dataset.

Two scientific papers (wind and rain) are in preparations that describe in detail the new wind and rain products. Drafts of the papers will be available at www.remss.com by the end of November 2006.

For all of these updates, the satellite datasets have been completely reprocessed and the new versions, in their entirety, are now available for downloading. Any users doing climate work with our wind speeds or rain rates should definitely replace their earlier versions with SSM/I V06 and TMI V04. We also suggest that the AMSR-E V05a datasets be downloaded to ensure complete consistency among the various datasets. There are no changes to the file format, so read routines do not need to be changed.

RSS considers the September 2006 Update to be a very important milestone in our production of Climate Data Records (CDR). Investigators can confidently use these new satellite datasets for detailed interannual and decadal trend studies. As always, continued funding for production and dissemination of these CDR is dependant upon you, the users, to let us know how you have used these data and their value to your research. Please make sure you provide us with information about your work, send results and/or papers to our office, and always provide your correct email when accessing the data by ftp.

Thank you
Algorithm Improvements for SSMI

1. The intersatellite calibration of the 6 SSMIs at the antenna-temperature ($T_A$) level has been completely redone. There were problems with the V05 calibration procedure that was introducing spurious trends into the wind speed retrievals. Fortunately these problems had only a small effect on the vapor retrievals. The new SSM/I wind retrievals are now consistent with buoys and scatterometers over the 19-year SSM/I period (1987-2006). The intersatellite agreement in the water vapor retrievals is also improved for V06.

2. A much improved rain algorithm has been implemented. More realistic freezing level heights and beam-filling corrections are used. We rederived the relationship between rain column height and sea surface temperature (Reynold's SST) using NCEP freezing level heights in raining conditions. The new relationship produces freezing level heights that are more realistic and spatially representative. In addition, we have made two major changes to the beamfilling correction. 1) Previously, we allowed the correction to "max-out" when the radiometer saturated. The new correction produces more realistic corrections when saturation occurs. 2) We now incorporate footprint size into the beamfilling correction in order to bring SSM/I, AMSR-E and TMI rain rates into better agreement. As a result, the cloud water and rain rate retrievals are very consistent across all 8 satellite platforms (i.e, 6 SSM/I, TMI, and AMSR-E). This consistency is also a result of using the same method of $T_A$ resampling for all satellites (see next item).

3. The geophysical retrieval algorithms required that the $T_A$ measurements from different frequencies all be resampled to a common spatial resolution. For SSM/I, we had been using a very simple averaging technique to accomplish the resampling. In the V06 algorithm, a more precise $T_A$ resampling method is used to optimally interpolate the $T_A$ observations to a common footprint. This technique is now the same as used for TMI and AMSR-E. Use of the new technique had little impact on surface wind speed or columnar water vapor, but it did have a substantial impact on the rain retrievals. It increased the cloud water and rain rates making them more consistent with AMSR-E and TMI.

4. The geophysical retrieval algorithms and data processing systems have been modified and restructured to bring a higher degree of commonality to the SSM/I, TMI, and AMSR-E. Essentially the same set of algorithms is now used to process all three types of satellite microwave radiometers. This will help to ensure greater consistency among the extended suite of satellite microwave radiometers.
Algorithm Improvements for TMI

1. The generation of a CDR for TMI is particularly challenging due to the following:
   a. The vapor-deposited aluminum (VDA) on the TMI antenna oxidized and/or cracked. As a result the antenna has an emissivity of graphite, which is 3 to 4%.
   b. The solar environment for TMI is constantly changing due to its near-equatorial orbit drifting through the diurnal cycle. Furthermore, the solar environment changes radically every month or so when a 180° yaw maneuver is completed.
   c. In September 2001, the TMI orbit was boosted from an altitude of 350 km to 400 km.
   d. There are small errors in the knowledge of the satellite roll and pitch, particularly right after the 2001 orbit boost.

Our new calibration algorithms attempt to correct for all these effects. We found that the algorithm used to correct roll and pitch errors was introducing a small along-scan error in the SST and wind retrievals. This problem has been fixed in V04. We also found small systematic biases in the SST, wind, and vapor retrievals that were correlated with the yaw state (either 0° or 180°). Finally, we found small systematic biases in wind and vapor for the time period before the boost as compared to the time period after the boost. Both these biases have been removed in V04 products.

2. The new rain rate algorithm was implemented, as described in Item 2 above for SSM/I. As a result, the cloud water and rain rate retrievals are now very consistent across all 8 satellite platforms (i.e., 6 SSM/I, TMI, and AMSR-E).

3. TMI had been using the same type of $T_A$ resampling as we use for AMSR-E (see Item 3 above in the SSM/I description). However, the resampling was not correctly taking into account the change in geometry that occurs when TMI goes through a 180° yaw maneuver. The resampling weights were correct for 180° yaw orientation but were incorrect for the 0° yaw orientation. This error led to a distortion near the swath edges and produced a positive bias in cloud water and rain rate at the swath edges. We have corrected this problem and now use 4 separate sets of resampling weights: yaw 0°-preboost, yaw 180°-preboost, yaw 0°-postboost, yaw 180°-postboost. Use of the new weights makes little impact on SST, wind speed, or columnar water vapor, but does significantly affect cloud water and rain rate.

4. The geophysical retrieval algorithm and data processing system was updated as described in item 4 above for SSM/I.
Motivation

- Water vapor in the atmosphere is expected to increase with warming (~ 7 % / K; Trenberth et al). Water vapor is a key greenhouse gas.

- Trends have been reported in surface and radiosonde observations (IPCC, 2001) and SSM/I over oceans (Wentz et al, 2000).

- What is the error in our water vapor CDR’s? Can we detect trends? How can new sensors (Aqua, GPS) be used to refine the water vapor CDR?

Wentz and Schabel (2000): + 2.1 % (~0.5 mm) / decade in Tropical Oceans (SSM/I)

Ross and Elliott (2001) (radiosondes): ~3 % / decade over N. America

The NVAP (1988 – 1999) global average of TPW is 24.5 mm, with no significant trend