ARM-FIRE Water Vapor Experiment (AFWEX) Science Plan

ARM SGP CART Site, Lamont OK
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(Water Vapor IOP #3)

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1. INTRODUCTION

This document describes the third in a series of Intensive Operating Periods (IOPs) dedicated to the measurement of atmospheric water vapor at the Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site. This IOP, the ARM-FIRE Water Vapor Experiment (AFWEX), is a collaborative effort between DOE's ARM and the NASA's FIRE programs. Contained here is a statement of goals for this effort, background on the previous IOPs, status of absolute accuracy issues, and plans for AFWEX. The AFWEX discussion includes the planned instrumentation, an outline of operational issues, and implementation details important for the execution of the IOP.

2. OVERVIEW

There is a recognized need both within and outside the NASA and ARM communities to improve the state-of-the-art in measuring the water vapor in a vertical column, both range-resolved and column-integrated. The primary incentive inside the ARM Program has come from the Instantaneous Radiative Flux (IRF) group, focusing on improving clear sky radiative transfer. This group determined that the ability to directly model the downwelling longwave radiation at the surface using the Line-by-Line Radiative Transfer Model (LBLRTM), using observations of the downwelling spectra by the Atmospheric Emitted Radiance as truth, was limited by the uncertainty in the atmospheric water vapor distribution. To address this issue, a series of Water Vapor IOPs at the ARM SGP CART Central Facility were initiated, with the first two occurring in 1996 and 1997.

There are 2 main goals for these Water Vapor IOPs. The first is to characterize the accuracy of current water vapor measurements, especially the operational observations made by the ARM program. The second goal is to develop techniques for improving the accuracy of these observations or a fusion of them, to obtain the best possible water vapor measurements under a wide range of conditions (clear/cloudy, day/night, etc.). An unusually powerful array of tools for measuring water vapor are now operated routinely at the SGP Central Facility, including a Raman lidar developed by ARM, a dual channel water vapor microwave radiometer, accurate ground- and tower-based in-situ measurements, GPS, and AERI boundary layer soundings, in addition to traditional balloon-borne soundings. Other special observing capabilities are added to enhance the IOPs.

Success of the Water Vapor IOPs, coupled with the extensive continuous data sets and the special observing capabilities of ARM for water vapor, have a wide range of potential implications. Contributions are likely to be significant for improving (1) radiative transfer models, especially including the water vapor continuum and many weak lines (the original IOP objective), (2) Remote sensing of atmospheric water vapor from satellite, (3) Validation of satellite products, (4) Cloud and aerosol formation parameterizations, (5) Atmospheric state for dynamical model input, and (6) Understanding the energy budget and atmospheric cooling connection with upper level water vapor. These are all strong motivations.

The first water vapor IOP, which was held from 10 – 30 September 1996, concentrated on understanding the variability of radiosondes and the lowest few kilometers of the atmosphere for satisfying the identified needs of the IRF group, as the water vapor in this layer has the largest impact on the downwelling longwave radiation sensed at the surface. The second IOP, which was held from 15 September to 6 October 1997, focussed on the absolute accuracy of the measurements and added a focus on the upper troposphere, where small errors have a large effect on the radiation escaping to space.

The approach for the lower atmosphere has been based on several hypotheses. These are

A. Microwave observations of the 22 GHz water vapor line can accurately constrain the total column water vapor amount (assuming a calibration accuracy of better than 0.5 C or 0.35 mm integrated water vapor), because the necessary absorption line parameters are well know from Stark Effect laboratory measurements
B. Continuous profiling by Raman lidar provides a stable reference for handling sampling problems and observes a fixed column directly above the site, only requiring one altitude-independent calibration factor
C. Chilled mirror hygrometers and capacitive in-situ sensors have the accuracy necessary to provide a solid rock to stand on near the surface (at the ground level, 25 and 60 m levels on the tower, and on tethersondes up to 1 km)

For the upper troposphere, we add

D. Aircraft with continuous profiling capabilities from Differential absorption LIDAR (DIAL), paralleling the Ground-based Raman LIDAR capabilities, will handle sampling problems related to comparisons with sonde observations
E. Coupling the absolute calibration of DIAL with state-of-the-art aircraft in situ sensors is adequate airborne truth
F. Night-time Raman LIDAR has adequate sensitivity and stability to transfer IOP-based aircraft truth to long-term observations and to satellite remote sensing validation

3. Results from the first two Water Vapor IOPs

A. Water Vapor IOP #1

The first water vapor IOP, conducted from 10 - 30 September 1996, was very successful in sampling a wide range of conditions with the SGP instrument complement and quantified essential elements of sonde performance. Dual sonde launches, i.e., launching two sonde packages on the same balloon, identified substantial sonde-to-sonde variability in the Vaisala RS-80H (25-30% peak-to-peak mixing ratio differences), with the profile differences behaving like altitude-independent calibration factor differences in the lower half of the troposphere. Consistent and stable MWR intercomparisons allowed us to demonstrate that scaling the sondes with the microwave integrated water vapor greatly reduces the variability in the radiative transfer comparisons to the AERI. Raman lidar continuous profiling demonstrated its value for interpolating comparisons in space and time, and chilled mirror tethersondes were proven to be a practical tool.

B. Water Vapor IOP #2

The first IOP raised many questions about our fundamental hypotheses and the absolute calibration of the water vapor observations. Therefore, the second IOP, which was conducted from 15 September - 6 October 1997, began to emphasize absolute calibration issues. The new focus for this IOP was on the upper troposphere, which benefited from five aircraft, each carrying either chilled mirror or frost point hygrometers, that were brought together for coincident IOPs (the other IOPs were cloud, aerosol, shortwave, single column model, and UAV). The Raman lidar was demonstrated to be a key tool for this effort because its continuous observations were used as a transfer standard between the aircraft and sonde observations. Preliminary results suggest a possible dry bias of the RS-80H sondes above 8-10 km.

Progress on the absolute calibration issues was mixed. Excellent agreement of tower-based chilled mirrors with Vaisala capacitive sensors removed doubt about the accuracy of good, well-maintained in-situ sensors (and thus validated hypothesis C). However, with the addition of GPS and solar observations of total precipitable water vapor, there were peak-to-peak differences of the order of 15% (or 4 mm in water vapor). There were even substantial differences between different microwave radiometer observations. Also, while GPS water vapor changes tracked the MWR water vapor reasonably well, in absolute terms GPS was 4-8% drier, depending on the processing.

A highlight of this IOP was that the scaling of the scanning Raman lidar profiles with the high quality tower-based sensors was shown to provide an integrated water vapor standard that has the potential to resolve the absolute calibration issue.

4. Status of Absolute Calibration Issues: Current Perspective

The ARM water vapor working group decided to take time off from making more intensive observations during 1998 and 1999 to provide a chance for our understanding to catch up with the measurements and to better plan activities for a 2000 IOP. People used the time well. Considerable efforts to refine the microwave characterization and calibration by Jim Liljegren and new information on sonde biases have significantly modified the detailed picture Here is our current perspective:

(1) ARM Microwave Radiometer (MWR), a stable reference: The ARM Microwave radiometer (MWR) was again found to be very stable, with consistent results during 1996

and 1997. This supports the promise of using it to provide a reliable standard for integrated water vapor under a wide range of conditions (day & night, clear & cloudy when liquid water is not too high). Of course, this would also make it a good transfer standard to calibrate other profiling instruments like the Raman Lidar, radiosondes, and the AERI-retrieved profiles.

(2) Verification of a key part of Hypothesis A: The sensitivity of the microwave brightness temperature at 22 GHz to changes in integrated water vapor expected from theory and laboratory measurements has been tentatively confirmed by atmospheric observations. This was accomplished by comparisons of integrated water vapor from the MWR to integrated water vapor from scanning Raman lidar profiles scaled to match chilled mirror and Vaisala in situ sensors on the 60 m tower during the 1997 IOP. The slope of the integrated water vapor scatter plot is unity to within 1% ±1.4%. This result implies agreement of the microwave radiation sensitivity standard with the chilled mirror and the equilibrium salt bath (carried by the Vaisala in situ sensors) standards, which showed excellent agreement with each other (chilled mirror wetter by just 1.7%). The comparison does show a well-defined offset, with the MWR wetter by 0.9 mm or 1.3 °C brightness temperature (reduced by almost half by post-IOP microwave analysis refinements).

(3) Outstanding Microwave Radiometer Issues: While the results from the ARM MWR are very promising, agreement among different microwave instruments has not been as good as expected (2 °C differences not uncommon). These differences undermine the use of the microwave as our fundamental absolute reference. We must place high priority on resolving the inconsistency in microwave radiometry that violates the expected observing accuracy of Hypothesis A.

(4) GPS role: GPS has the potential to be a very good, cost-effective total water vapor standard. However, current discrepancies of several percent among the results from different processing approaches suggest uncertainty in its absolute calibration. During IOP #2 the favored Scripps/Gamit processing is dryer than the tower/Raman result by about 4-5%, while the ERL (Bernese) processing is dryer by just 1.5%. We should concentrate on transferring what we learn to GPS calibration.

(5) Sonde status: We must assess further the implications of the recently quantified bias associated with past Vaisala RS80 radiosondes. The bias was identified during TOGA COARE (NCAR) and found to be caused by contamination of the capacitive sensor associated with sonde packaging. Preliminary results give much better agreement between average sonde and MWR precipitable water vapor observations, but sonde calibration batch dependencies are not greatly improved.

Resolving these open absolute calibration issues are important, since they significantly affect (1) the water vapor self-broadened continuum, (2) water vapor line strengths for weak lines important for some key remote sensing applications, especially land surface temperature and emissivity, (3) assessment of aerosol impacts in the longwave window regions.

5. ARM-FIRE Water Vapor Experiment (AFWEX) Approach

Resolution of the absolute calibration issue is one of the primary goals during the ARM-FIRE Water Vapor Experiment (AFWEX). The new capabilities desired to help address the outstanding absolute calibration issues, in addition to the suite of instrumentation already at the CART site, are:

1. JPL J-model microwave radiometer, plus a calibration reference (i.e., LN2 blackbody targets) from ETL and Radiometrics, to address the microwave radiometry problem
2. Ground-based DIAL lidar to provide an absolute profiling reference from approximately 100 m to 7 km
3. Chilled mirror radiosondes to help evaluate radiosonde performance directly and to provide integrated water vapor for comparison to other sensors

Accurate measurement of upper tropospheric water vapor is the second primary goal of AFWEX. The conclusions drawn about the measurement capabilities in the lower troposphere are difficult to apply with sufficient accuracy to upper tropospheric water vapor, because small amounts of water vapor in the upper troposphere have such a strong influence on the outgoing longwave flux and the atmospheric cooling rates. The coordination with NASA to make use of the extensive capabilities of the DC-8 will provide airborne ground truth observations to complement the CART site's ground based capabilities. The specific high priority instrumentation on the DC-8 includes:

1. LASE, the NASA/LaRC water vapor DIAL lidar, to provide absolutely calibrated profiles above and below the aircraft flight altitude
2. Accurate in-situ sensors, using both a tunable diode laser hygrometer and a chilled mirror/frostpoint hygrometer
3. Scanning HIS, an airborne version of the AERI, to provide direct observations of the effect of atmospheric water vapor on infrared emission

Other instrumentation that proved invaluable during the previous water vapor IOPs that will also be included, are:

1. Dual sonde and 3-hour sonde launches, including the new Vaisala RS-90 if available.
2. Scanning Raman lidar from NASA/GSFC to provide sensitivity at tower altitudes, to corroborate long dwell upper level observations by the CART Raman lidar, and possibly to explore homogeneity issues by scanning in coordination with microwave TIP calibrations.
3. GPS from either the Central Facility and/or Lamont
4. Chilled mirror in-situ sensor for ground comparisons with sondes

Tower-based chilled mirror in-situ sensors are not planned, because of the good agreement with the current tower in situ sensors demonstrated 1997 and the presence of redundant sensors to detect problems.

A secondary goal of the AFWEX, which meshes well with the primary goals of this IOP, is a careful characterization of both the CART Raman lidar in both the near and far fields, and to evaluate methods of calibration that are independent of radiosondes. The availability of the NASA scanning Raman lidar, LASE airborne DIAL, and MPI ground-based DIAL are major assets for the IOP. Comparing the various lidars is an important step in its own right, and the scanning capability of the NASA Raman lidar extends the lowest altitude sensed downward to altitudes sensed by tower-based instruments while the airborne DIAL will extend these measurements high into the upper troposphere.

6. SCHEDULE

The AFWEX IOP will be conducted at the SGP CART central facility near Lamont, Oklahoma during September-October 2000. This time of year has proven to offer a high probability of clear skies and water vapor amounts ranging from 1-5 precipitable centimeters in the column. Due to a desire to obtain some periods of high water vapor burden (column amounts greater than 3.5 cm), climatology suggests that the IOP should start no later than mid-September. However, conflicts in schedule with the NASA DC-8 aircraft prohibit its availability until at least 1 October. Therefore, the IOP will be broken into two pieces, overlapping them as much as possible. The ground-based portion of the IOP, whose emphasis will be on tackling hypotheses A and B, will run from 18 September – 13 October. The upper tropospheric portion of the IOP will run from 1 October until at least 15 October to tackle hypotheses D, E, and F.

7. OPERATIONAL PLANS FOR THE IOP

7.1 Strategy

The operational strategy for the ground-based portion of the IOP is to tackle the microwave radiometry problem head-on, with detailed attention applied to the calibration of the instruments. Thus, all of the radiometers are expected to collect numerous TIP calibration datasets during the clear-sky portions of the IOP, especially when different water vapor burdens are present. Additionally, two types of liquid nitrogen blackbody targets will be present at the IOP to provide another mechanism to validate the calibration derived from TIP curves. All of these instruments will be arranged such that they scan in the same principal plane.,

The flights of the DC-8 for the upper tropospheric portion of the IOP will be conducted under clear skies, predominantly at night. Nighttime operation allows 30-minute averages of the Raman Lidar observations to achieve useful accuracies at these altitudes. Both the CART and the Scanning Raman Lidars will be operated exclusively in zenith mode during aircraft flights. The LASE instrument can profile both below and above the aircraft simultaneously, with the nearest applicable range to the aircraft being about 500 m (i.e., the region from about 500 m below to 500 m above the aircraft cannot be measured well by the LASE). Accurate in-situ probes on the aircraft will be used to provide a data point in this region. To utilize these accurate in-situ probes to the maximum extent, preliminary flight profiles will have the DC-8 changing levels such that a profile can be determined from the in-situ probes, which can then be also compared to the LASE and Raman lidar profiles. As the scanning HIS will be used to test radiometric closure and only will point downward, the DC-8 will tend to fly near its ceiling to get above the majority of the water vapor. A probable flight pattern is a basic clover-leaf pattern, with the primary axes being oriented parallel and normal to the wind. In situ altitude sampling will be accomplished with spirals around the central facility at the beginning and ending of the flight and with some adjustment of level flight leg altitudes. There are approximately 40 hours available for scientific flights on the DC-8, with each flight being about 4 hours in length.

Those instruments that require little or no operator supervision will be operated continuously during the IOP. Instruments that do require operator supervision are expected to operate for at least 8 hours each day in a coordinated effort to maximize the amount of coincident data recorded. In order to meet the measurement objectives, the daily 8-hour period may be shifted across the diurnal cycle as deemed appropriate during the IOP. The initial period of special operations will likely be 21:00 UT - 05:00 UT (4 PM to midnight local time). This schedule will be re-evaluated during the daily meetings of the IOP participants. The IOP chief scientist or his representative will be responsible for informing the site manager of changes in the period of special operations.

7.2 Operational Systems

BBSS	Continuous 3-hour interval schedule, including dual sensor launches (including RS-90's and RS-80's). It is hoped that some of these dual launches would involve a chilled mirror sonde as well.
Raman Lidar	Normal operation (continuous)
TOWER/SMOS	Normal operation
THWAPS	Normal operation
MWR	Normal operation with continuous TIP calibrations in clear sky conditions
AERI	Normal operation
MPL	Normal operation for cloud detection
MFRSR	Normal operation with special intercomparisons

7.3 Additional Instrumentation

NASA/LaRC LASE (aircraft-based DIAL lidar) -- flown on the DC-8
NASA/LaRC or JPL In-situ tunable diode laser water vapor sensor -- flown on the DC-8
NASA/LaRC Frostpoint hygrometer -- flown on the DC-8
U Wisconsin Scanning HIS -- flown on the DC-8
Max-Planck Institute (Germany) ground-based water vapor DIAL lidar
NASA/GSFC scanning Raman lidar. During the clear sky periods, the instrument will scan in a plane coincident with the other microwave radiometers to study homogeneity issues associated with the TIP calibration procedure. This will also enable the derivation of the calibration factor from the in-situ sensors on the tower.
NASA/JPL microwave radiometer (in particular, the J model). Continuous TIP calibration curves will be collected during clear sky periods.
NOAA/ETL microwave radiometer (in particular, the new CSR). Continuous TIP calibration curves will be collected during clear sky periods.
Dual sonde launches (CF only)
Chilled mirrors launched on radiosondes (by Frank Schmedlin, NASA/Wallops).
NCAR and/or JPL GPS water vapor at CF
Chilled mirror for ground-based operation

NASA/Ames 6 channel sunphotometer on the ground (optional)

7.4 Data availability and archival

The ability to compare measurements from different instruments in near real-time (i.e., within 24 h) was deemed critical during the previous IOPs. Therefore, we hope investigators will be prepared to do this again. These initial “quicklook” datasets are not for general consumption, but are only available for the participants at the IOP. The deadline for calibrated datasets useful for intercomparison/analysis by the participants is due 6 months after the conclusion of the IOP. Final datasets, including documentation, are due 1 year after the IOP and will be stored in the ARM data archive.