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RETRIEVALS OF ATMOSPHERIC THERMODYNAMIC STRUCTURE FROM UNIVERSITY OF WISCONSIN SCANNING-HIGH-RESOLUTION INTERFEROMETER SOUNDER (S-HIS) UPWELLING RADIANCE OBSERVATIONS USING A BAYESIAN MAXIMUM A POSTERIORI (MAP) INVERSE METHOD

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1. INTRODUCTION

The University of Wisconsin Space Science and Engineering Center Scanning High-resolution Interferometer Sounder (UW/SSEC S-HIS) is an aircraft-based high spectral resolution infrared spectro-radiometer that has flown on high altitude research aircraft during numerous field experiments. This paper presents a physical retrieval algorithm that was designed specifically for use with the S-HIS instrument. The algorithm uses a Maximum A Posteriori (MAP) approach to the inverse problem, which has an advantage over statistical regression in that it provides error characteristics and an explicit measure of convergence. This methodology requires a priori knowledge of the solution space, and as such, emphasis has been placed on understanding and developing appropriate experiment-specific climatologies. We present case studies showing temperature and moisture retrievals from the S-HIS for several recent field campaigns, including CR-AVE (Costa Rica Aura Validation Experiment) and TC4 (Tropical Composition, Cloud and Climate Coupling experiment). Comparisons will be made with other field experiment data in order to provide preliminary validation for the S-HIS retrievals.

2. S-HIS PHYSICAL RETRIEVAL ALGORITHM

2.1 Bayesian Maximum A Posteriori Retrieval Methodology

The Bayesian MAP is a method for simultaneously retrieving temperature, moisture and ozone profiles from a radiance measurement. This technique, described by Rogers (2000), maps the pdf of the measurement to the pdf of the state, using a priori knowledge of the state, in the form of a climatology. The climatology is critical, in that the covariance matrix of the climatology is used within the retrieval algorithm. Additionally, the mean of the climatology may be used as a first guess. The development of the climatology is discussed in section 3. A line-by-line forward model (AER LBLRTM v10.3) was used to minimize the observed minus calculated radiances, as well as to calculate the analytic jacobians (Clough,1992). The Newton-Gauss method was implemented to find the zero of the derivative of the joint pdf corresponding to the optimal solution. The actual form used is:

$$x = x_a+(K^T S_e^{-1} K+S_a^{-1})^{-1} K^T S_e^{-1} * [R-F(x)+K*(x-x_a)]$$

Where x_a is the first guess, R is the observation, F(x) is the forward model, K is the jacobian (dF/dx), S_a is the covariance matrix of the *a priori* climatology, S_e is the covariance matrix of the measurement error.

2.2 Error Estimation

One advantage of using the Bayesian MAP retrieval method, is that it provides a quantitative assessment of error. The error sources can be split up as:

$$\begin{aligned} x_{hat} - x = &(A - I)(x - x_a) && \textit{smoothing} \\ &+ G_y K_b (b-b_{hat}) && \textit{model parameters} \\ &+ G_y \Delta f(x,b,b') && \textit{modeling error} \\ &+ G_y \varepsilon && \textit{measurement error} \end{aligned}$$

Where G_y is the contribution function ($\partial R/\partial y$), A is the averaging kernel, K is the jacobian, and ε is the random noise of the instrument.

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The measurement error results from the noise of the remote sensing instrument, and is usually random in nature and unbiased/uncorrelated between channels. The two types of modeling error are not currently included in our analysis, but will be in the future. They are systematic, and result from the errors in representation of absorptive gasses within the forward model, as well as the mathematical representation of complicated physical processes. The smoothing error results from the fact that passive infrared remote sensing instruments that measure emitted radiance, like the S-HIS, can not see fine spatial structure in the vertical. For the purposes of this study, we have assumed that the retrieval is an estimate of the true state, with an error contribution due to smoothing, rather than assuming that the retrieval is an estimate of the smoothed state (not the true state). The error contribution due to smoothing is determined by the averaging kernel (A). Figure 1 shows a sample plot of the averaging kernel. Each of the 61 curves represents the averaging inherent in determining a solution for a single level. The vertical width of each curve indicates the degree to which the instrument can resolve temperature, moisture, or ozone in the vertical.

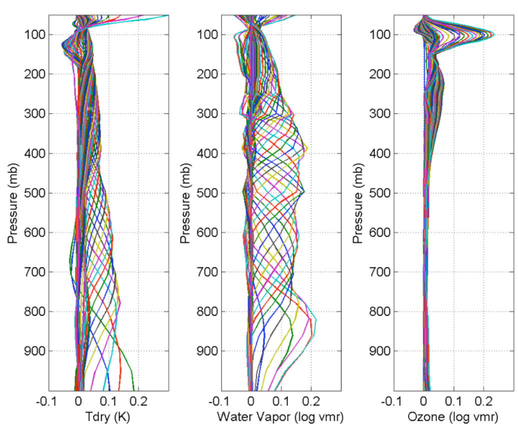

Figure 1. Sample plot of the averaging kernel.

3. S-HIS INSTRUMENT AND FIELD EXPERIMENT DETAILS

The S-HIS is a scanning interferometer which measures emitted thermal radiation at high spectral resolution between 3.3 and 18 μm (specifications). The measured emitted radiance is used to obtain temperature and water vapor profiles of the Earth's atmosphere. The S-HIS produces sounding data with 2 kilometer resolution (at nadir) across a 40 kilometer ground swath from a nominal altitude of 20 kilometers (such as onboard a NASA ER-2 aircraft).

For this study, we will consider S-HIS retrievals from two field experiments: the Costa Rica Aura Validation Experiment (CR-AVE), and the Tropical Composition, Cloud, and Climate Coupling experiment (TC4). Both experiments were based in Costa Rica, with flights to the western Caribbean, the Gulf of Panama, and the Galapagos Islands. CR-AVE took place between 14-27 January 2006. During this experiment, the S-HIS traveled on 6 science flights on the NASA WB-57. In-situ data for profile validation is available from the JPL Laser Hygrometer (also on the NASA WB-57), and from 7 Frostpoint Hygrometer (FH) sonde launches (6 from Heredia, Costa Rica, and one from San Cristobal in the Galapagos Islands). TC4 took place between 14 July and 9 August 2007, and the S-HIS traveled on 11 science flights on the NASA ER-2. In-situ water vapor data are available from 4 WB-57 flights (JPL Laser Hygrometer), as well as 12 FH sonde profiles (6 from Alajuela, Costa Rica, and 6 from San Cristobal in the Galapagos Islands).

4. A PRIORI CLIMATOLOGY DETAILS

The Bayesian MAP method of retrieving temperature and moisture profiles from S-HIS radiances requires the input of a realistic climatology of temperature, water vapor, and ozone. Not only may the climatological mean be used as a first guess, but the climatological covariance matrix is also used within the physical retrieval algorithm. For this study, we have compiled a climatology of WMO standard rawinsondes from within the experiment domain, over the season of interest. Since rawinsonde moisture profiles of upper tropospheric water vapor have documented inaccuracies (Turner et al, 2003), profiles are filled in above 300 mb using an inverse cubic power law.

4.1 CR-AVE Climatology Details

A climatology was compiled for use with the S-HIS retrievals during the CR-AVE experiment. The climatology consists of standard WMO rawinsondes (0 and 12 UTC) that were launched from within the CR-AVE domain (Lat: -4.5^o to 25^o, Lon: -65.5^o to -100^o) between 31 Dec and 14 Feb, 1995 - 2005. 5069 of the 6918 sondes passed preliminary clear-sky criteria and are included in our analysis (RH <= 95% for altitudes below 850 mb, RH <= 90% for altitudes above 850 mb).

Figures 2, 3, and 4 help to assess the overall accuracy and representativeness of the climatology being used, in terms of water vapor. Figure 2 shows that the average over the CR-AVE time period (2006) is within a standard deviation of the 6-year WMO mean. Figure 3 shows that the climatology being used (“Mean WMO Woolf extrap1”) is in line with the measurements being taken during CR-AVE, such as the WB-57 insitu measurements (from the JPL laser hygrometer), and the cryogenic frostpoint hygrometer (FH) sondes (Voeml et al, 2006a), until about 300 mb. Above 300 mb, the climatology shows a slight moist bias compared to these other measurement systems. The Vaisala RS-92 profiles, 7 out of 15 of which were co-located on the same balloons as the FH sensors, show a very strong dry bias above about 250 mb. Figure 4 shows co-located profiles for a single day (22 January, 2006). Despite the time difference between the WMO sonde launch time and the times of the other observations, it does not show a clear bias. The Vaisala RS-92 sonde, which was located on the same balloon as the FH sonde, shows a very clear dry bias above about 300 mb.

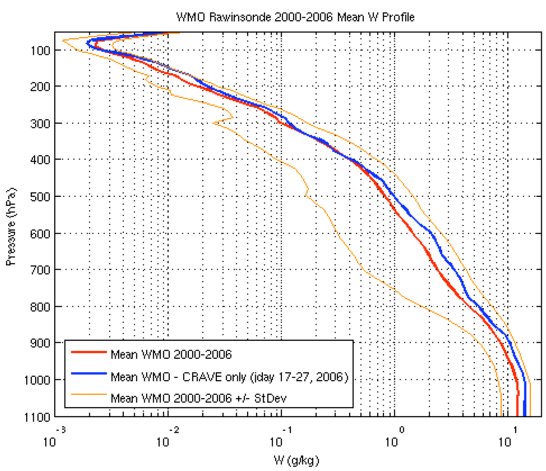

Figure 2. Mean WMO W for CR-AVE, compared to the 6 year mean WMO W.

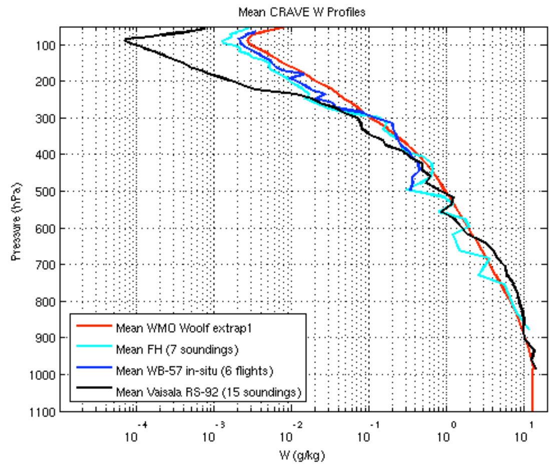

Figure 3. CR-AVE W climatology (“Mean WMO Woolf extrap1”) compared with W measurements made during the CR-AVE experiment.

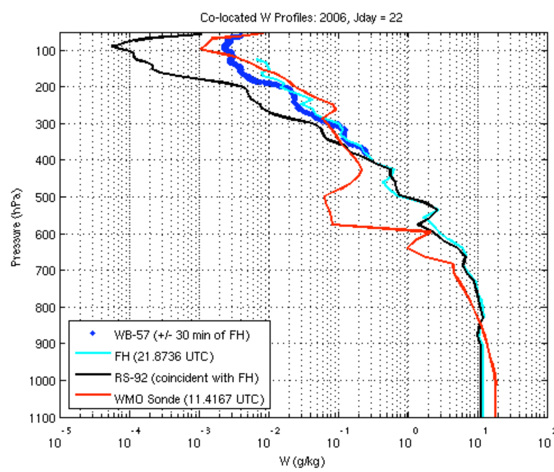

Figure 4. Co-located W profiles from January 22, 2006.

4.2 TC4 Climatology Details

A similar climatology was compiled for use with the S-HIS retrievals during TC4. Similar to the CR-AVE climatology, this climatology consists of standard WMO rawinsondes that were launched from within the TC4 domain (same as the CR-AVE domain). The range of dates included was 1 Jul to 1 Sep, 1997 – 2006. 6234 of the 8559 sondes were determined to be clear.

5. RETRIEVAL RESULTS

5.1 January 25, 2006 Case from CR-AVE

The flight track for 25 January, 2006 is shown in Figure 5. Two FH sonde profiles were available for validation, one from San Cristobal at 2006 UTC and one from Heredia at 2135 UTC. Comparisons with the San Cristobal sonde, however, are complicated by persistent cloud cover.

Figure 6 shows the Observed minus Calculated radiances (blue) from the S-HIS and from the retrieval, for a single converged profile, as well as the S-HIS noise (red). The residuals are generally small (less than 1.5 $mW/m^2*str*cm^{-1}$), indicating good agreement between the observations and the retrieval.

Figure 7 shows the retrieved T and W profiles, compared with a nearby FH sonde profile, as well as the climatological mean profile (also used as a first guess for this case). The time difference between the retrieval and the sonde launch is 49 minutes, and the distance between them is 11.77 km. The retrieval error bars are also shown, with the total error shown in red, and the measurement error shown in green. For this case, the smoothing error exceeds the measurement error, which is exemplified by figure 8. In general, the agreement between the FH sonde and the retrieval is good, from the surface to about 300 mb, considering that the S-HIS is an emitted radiance sensor and therefore can not resolve the fine vertical structure that the sonde can measure. Above 300 mb, the retrieval exhibits a substantial moist bias, most likely due to the fact that the climatology is also biased, and there is a limited amount of information provided by the measurement.

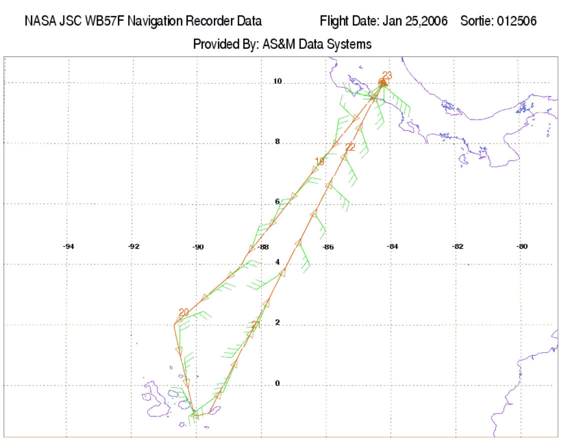

Figure 5. Flight track for the WB-57 for 25 January 2006.

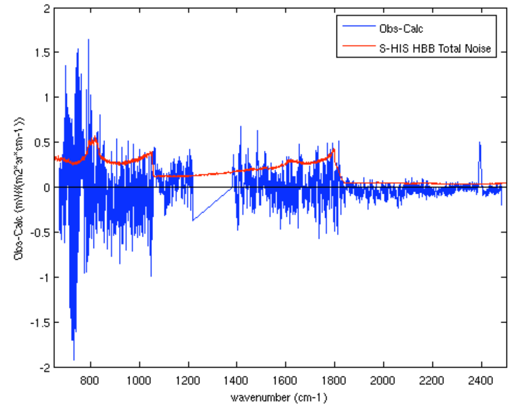

Figure 6. Observed minus calculated radiances (blue), with S-HIS noise (red), for a single converged profile (2224 UTC, 25 January 2006).

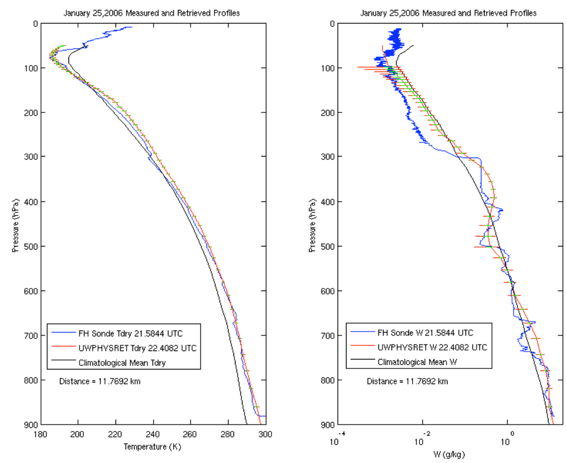

Figure 7. Retrieved T,W profiles vs. climatological mean and FH sonde measured profiles.

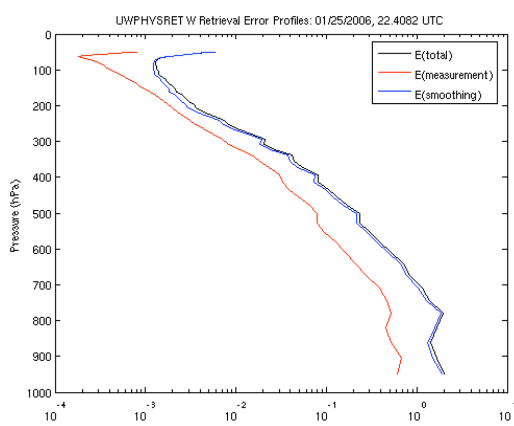

Figure 8. Relative contributions of the measurement error and the smoothing error to the total error, for a single converged retrieval (2224 UTC).

5.2 August 06, 2007 Case from TC4

Retrievals of atmospheric T and W profiles were performed for the ER-2 segment in the vicinity of the Galapagos Islands (1430 to 1448 UTC). A portion of the flight track of the ER-2 from this day is shown in figure 9. A FH sonde was available for comparison (14 UTC), as was a dropsonde (1439 UTC). Careful analysis of retrieval error is underway, with additional validation available from the DC-8 DIAL in stacked formation and the nearby WB-57 in-situ data.

Figure 10 shows the cross section of all of the converged temperature and moisture retrievals from this time period. The white bars represent times which the retrieval did not converge, most likely due to low level cloud cover. The retrieval shows a very uniform temperature structure, with a very moist marine boundary layer extending to between 875 and 900 mb (spanning the lower 7-9 retrieval levels), capped by a very dry layer between about 600 and 800 mb. Figure 11 shows a single physical retrieval profile compared to the climatological mean, a retrieval done using regression, and two sonde profiles (dropsonde and FH sonde). Both the regression and the physical retrieval show skill in retrieving the temperature and moisture profiles below about 200 mb. Above 200 mb, the retrieved temperature profiles are realistic, but the moisture retrievals show a clear moist bias, more in line with the climatology than the FH sonde measurements.

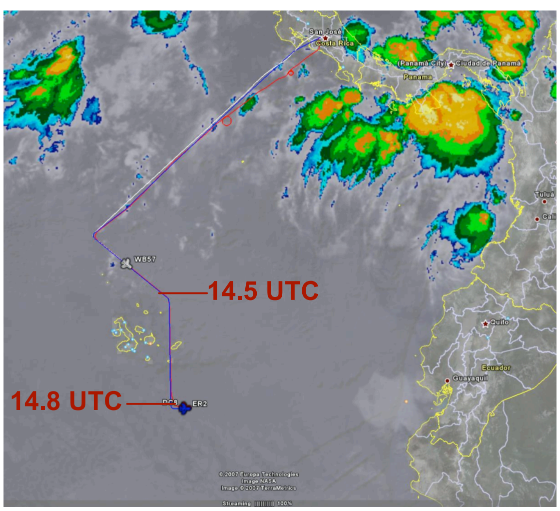

Figure 9. Partial flight track for the ER-2 on 6 August 2007.

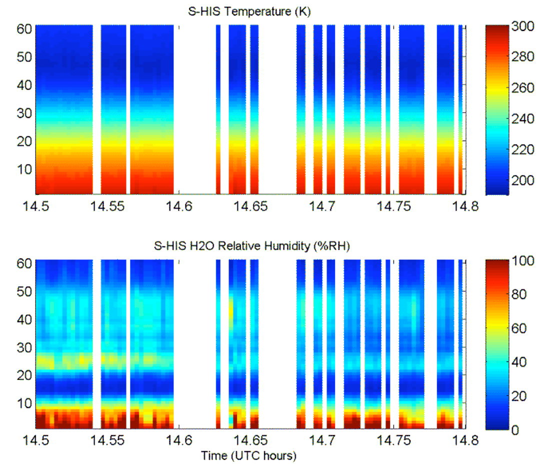

Figure 10. All converged S-HIS retrievals between 14.5 and 14.8 UTC on 6 August 2007

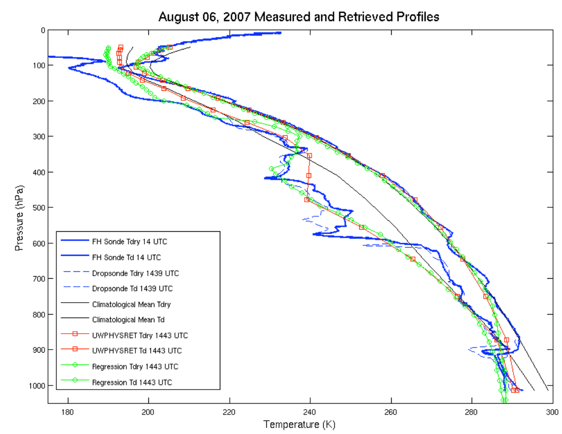

Figure 11. Comparison of 1443 UTC retrieval with FH and dropsonde profiles.

5.3 Impact of Upper Level Water Vapor on TOA Flux

Top of Atmosphere Outgoing Longwave Radiation (TOA OLR) is sensitive to changes in upper level water vapor. Figure 11 shows that for total column integrated water vapor amounts of 1 mm (or about 6 km), water vapor perturbations of only 10% may lead to OLR differences of 1 W/m^2. High spectral resolution satellite instruments that measure OLR, such as AIRS, may be able to contribute to the assessment of upper level water vapor.

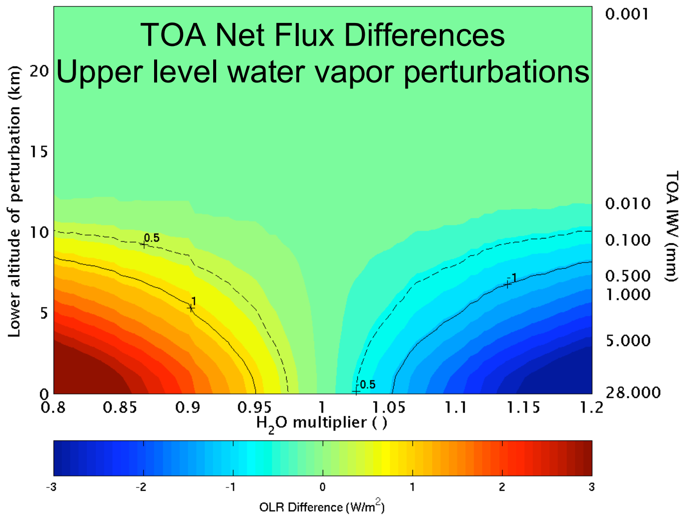

Figure 12. Top of atmosphere flux differences for upper level water vapor perturbations at various heights.

6. FUTURE WORK

The analysis of the S-HIS data collected during CRAVE and TC-4 is ongoing with an emphasis on the validation of the upper level water vapor retrievals from the S-HIS radiances. Future work includes application of the S-HIS averaging kernel to the in situ validation data in order to evaluate the smoothing effect of the infrared sensor on the observed data. Additional retrievals also will be performed using modified climatologies in order to quantify the absolute accuracy of the S-HIS water vapor retrievals above 300 mb. In addition, comparison to coincident Aura (TES) and Aqua (AIRS) retrievals is planned.

7. REFERENCES

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