Atmospheric H_2O, Aerosol and the Unexplained Solar Absorption: A Test with Data from the Atmospheric Radiation Measurement Enhanced Shortwave Experiment

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Introduction

The Atmospheric Radiation Measurement (ARM) Enhanced Shortwave Experiment (ARESE) was designed to resolve a discrepancy between the atmospheric absorption predicted by models and the 10 - 30 W m^{-2} larger value estimated from cloudy-sky measurements. Many recent studies have focused on a significant model-observation difference in clear skies (Arking 1996; Charlock and Alberta 1996; Kato et al. 1997). Arking (1996) attributes a 25-35 W m^{-2} (global average) model observation discrepancy to clear skies because he finds that the unexplained atmospheric absorption is correlated to column H_2O, but is uncorrelated to International Satellite Cloud Climatology Project (ISCCP) cloudiness. The H_2O absorption in current models would have to be increased by more than 50% to explain a discrepancy of this magnitude. However, Arking's analysis uses monthly-mean data from which it is difficult to separate absorption occurring in clear versus cloudy skies (Zhang et al., in press). In this study, we directly test Arking's conclusion using solar radiation data that have been screened for clear skies.

The data used here are a combination of 0.94 µm direct solar radiation measurements from ARESE and broadband solar fluxes measured during the Central Equatorial Pacific Experiment (CEPEX). We test whether the following three mechanisms can be used to explain an excess clear-sky absorption correlated to H_2O: 1) uncertainties in H_2O's near-infrared vibration-rotation line parameters; 2) uncertainties in H_2O continuum absorption; and 3) uncertainties in an absorption by aerosols (which may be indirectly affected by H_2O).

Details of the data and analysis presented here can be found in Conant et al. (submitted) and Vogelmann et al. (in press).

0.94 µm - ARESE

The 0.94-µm H_2O band is a typical near-infrared vibration-rotation band containing over 1000 lines responsible for about 20% of the total H_2O absorption in the atmosphere. By first focusing on the 0.94-µm band, we avoid the introduction of errors from other wavelengths and, thus, more effectively isolate the physics of H_2O line absorption.

We compare direct solar radiation at 0.94 µm measured by two Multi-Filter Rotating Shadowband Radiometers (MFRSRs) with correlated-k atmospheric transmittance calculations. The MFRSRs are from the Solar and Infrared Observing System (SIROS) and the Baseline Surface Radiation Network (BSRN). Eleven cloud-free days during ARESE are identified after requiring that the Belfort laser ceilometer showed no clouds and that the observed direct beam radiance varied smoothly with the top-of-atmosphere (TOA) insolation for the entire sunlit day. The correlated-k model takes as input eight daily H_2O profiles from the Balloon Borne Sounding System (BBSS) and 20-second resolution column H_2O from the Microwave Radiometer (MWR). These H_2O measurements agree for the selected ARESE days with a bias of 1% and rms of 5%.

An observed estimate of H_2O transmission is obtained after removing the effects of Rayleigh scattering and aerosol extinction. Rayleigh scattering is obtained from well-known formulae. Aerosol extinction at 0.94 µm is initially taken from the empirically calibrated MFRSR 0.862−µm window channel. The sensitivity of our conclusions to this aerosol treatment will be tested below.

Figure 1 shows a comparison between the model-derived transmission $<T_{H_2O}>_{CK}$ and the observed $<T_{H_2O}>_{MFRSR}$. A simple linear regression is used to understand the accuracy of the model

$$-\ln<T_{H_2O}>_{CK} = A_0 + A_1(-\ln<T_{H_2O}>_{MFRSR}) \quad (1)$$

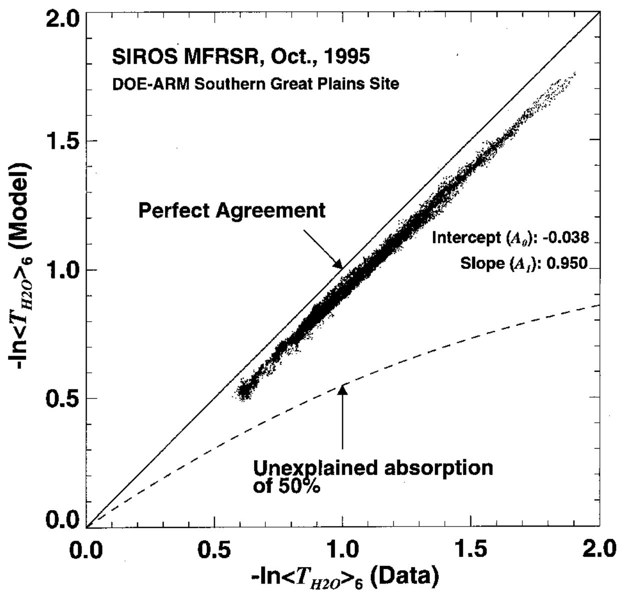

Figure 1. Minus the natural log of the 0.94 µm H_2O transmission - correlated-k model vs. MFRSR observations. Solid and dashed lines represent cases of perfect agreement and an anomalous H_2O absorption of 50%, respectively (Conant et al., submitted).

A_0, the offset term, includes errors not related to H_2O path such as uncertainties in the solar constant or the linear instrument sensitivity. A_1 shows how accurately the model reproduces the decrease in the observed attenuation with an increase in H_2O path. The diagonal ($A_0 = 0.0$; $A_1 = 1.0$) indicates perfect agreement. The dashed curve represents the case where the excess absorption of 50% is due solely to H_2O and is proportionally representative in the 0.94-µm band. Using the SIROS MFRSR, A_0 is -0.38, and A_1 is 0.95.

The value of A_1 is robust to within ±0.03 with respect to instrumental calibration uncertainties, zenith angle dependence, day-to-day variability, and differing instruments (see Table 1). The offset term, A_0, is within the ±0.05 value expected from uncertainties in the instrument calibration. We next test sensitivity to aerosol optical depth by relaxing the constraint that aerosol extinction at 0.94 µm, ($\tau_{0.94}$) is equal to that at 0.86 µm $\tau_{0.86}$. That is, we let $\tau_{0.94} = C\tau_{0.495}$, where C is determined simultaneously with A_0 and A_1 in the least squares fitting. A_1 changes by less than 0.02 for both this case and the case where aerosol extinction is taken from the 0.495-µm channel (i.e.,$\tau_{0.94} = C * \tau_{0.495}$).

We would like to use the above results to test whether a 50% error in H_2O line and/or continuum absorption can be used to explain the 25-35 W m^{-2} excess absorption in the broadband. A strong line absorption error of 50% is not apparent in Figure 2, which shows a percent model error in H_2O absorption at 0.94 µm of 3%-4.5%. This corresponds to only 2 W m^{-2} in the broadband if this were representative of all the strong bands. Second, the model error does not increase with water vapor path, which is a necessary requirement were a continuum absorption to be present at these wavelengths. (If a strong continuum absorption were present across the near-infrared, it would not absorb much energy at 0.94 µm, but would still have a linear or quadratic dependence on H_2O detectable in Figures 1 and 2. See Vogelmann et al. 1997.)

Table 1. Sensitivity of A_0 and A_1 to only 2 W m^{-2} in the broadband if this were representative to sources of uncertainty and changes in the analytical method.

Source/Change	A_0	A_1
Use of BSRN MFRSR	-0.02	-0.02
5% uncertainty in solar constant	±0.05	0
5% uncertainty in inst. calibration	±0.05	0
Day-by-day fitting variability (rms)	±0.02	±0.02
Zenith angle binning (rms)	±0.01	±0.01
Fitting aerosol extinction to 0.862	0	0.01
Fitting aerosol extinction to 0.495	0.01	0
±5% bias in H_2O column	0	±0.03

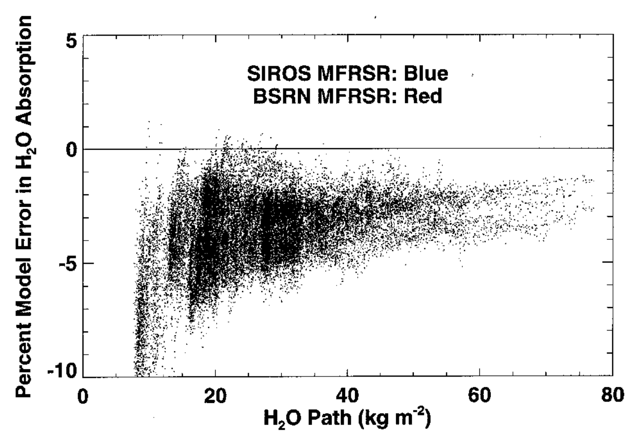

Figure 2. Percent model-observations discrepancy in atmospheric absorption at 0.94 µm. The mean error is 3% using the SIROS MFRSR and 4.5% for the BSRN (Conant et al., submitted).

Broadband - CEPEX

The 0.94−µm H_2O band has been useful in demonstrating that there is no large, systematic error in H_2O strong-line or continuum absorption. However, broadband pyranometer (0.28 - 2.8 µm) data are necessary to confirm our conclusions for the atmospheric clear-sky solar radiation budget. CEPEX provides an ideal location for testing Arking's hypothesis because the column H_2O is 35 - 50 kg m^{-2}, where Arking finds large model errors, and it is thousands of kilometers away from any continental or urban aerosol sources.

A combination of surface, tropopause and TOA data are used to determine the absorption in the atmosphere. Calibrated pyranometers accurate to 10 W m^{-2} aboard two surface platforms, the R/V *Vickers* and the NOAA P-3 aircraft, independently measured the clear-sky net surface solar radiation during March 1993. Net solar radiation at the tropopause was determined by bolometric radiometers accurate to within 1% aboard the ER-2 aircraft. The clear-sky TOA net solar radiation extrapolated from the tropopause measurements agrees with the TOA net solar radiation observed during the Earth Radiation Budget Experiment (ERBE), a 5-year satellite experiment, which provides the variability of the clear-sky flux used in this study. Atmospheric absorption is obtained by subtracting the clear-sky net solar radiation observed at the TOA from that at the surface. Likewise, the experimental uncertainty in the atmospheric absorption is determined from a sum-of-squares combination of the sampling and instrumental uncertainties at the TOA and the surface.

Two broadband models are used for comparison with the data. The first is the Li et al. (1993) transfer function, which determines surface solar radiation from the TOA albedo and column H_2O. This algorithm has been slightly altered to represent a tropical atmospheric profile instead of the sub-arctic summer profile for which the model was designed. The Li et al. algorithm specifies aerosol as an absorptive arctic haze. The second model is a 38-band 4-stream discrete ordinates radiative transfer code, which uses an exponential sum fitting technique for H_2O, CO_2, and O_3 gas absorption. H_2O and O_3 profiles are obtained from balloon sondes launched from the ship during CEPEX. Surface albedo is specified based on the P-3 measurements. A conservative maritime aerosol is tuned so the TOA albedo matches the observations. Thus, each model predicts the atmospheric absorption based on the observed range in TOA albedos and the measured column H_2O. The difference in aerosol absorption specified by the two models is used to bound the model uncertainties.

Figure 3 shows that the models predict the same range of atmospheric absorption as do the observations. The experimental uncertainty of 7 W m^{-2} is not sufficient to allow for a significant excess H_2O absorption in this moist tropical region. We next test Arking's hypothesis that clear-sky model-observation errors should increase with increasing H_2O. Figure 4 shows that no significant trend exists in the CEPEX comparison for column H_2O amounts between 35 and 50 kg m^{-2}.

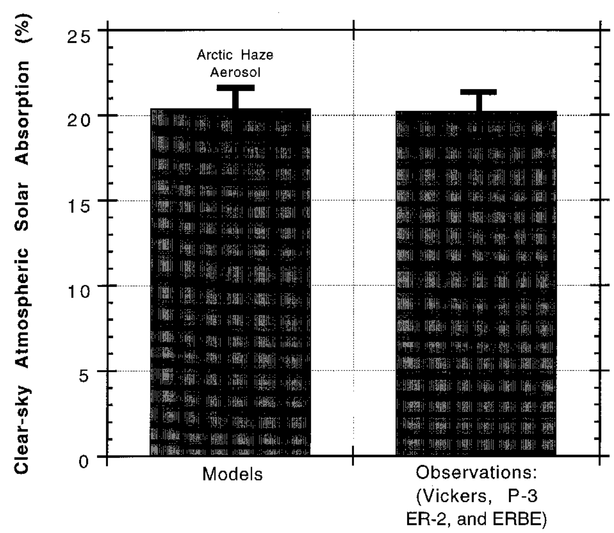

Figure 3. Mean clear-sky atmospheric solar absorption (expressed as a fraction of the TOA insolation of 451 m^{-2}) from CEPEX. The range bars in the models arise primarily from differences in aerosol absorption. The range bars in the data arise from the experimental uncertainties. (Conant et al., submitted).

Conclusions

We conclude that there is no evidence for a 25-35 W m^{-2} excess clear-sky absorption that is related to uncertainties in H_2O line parameters or a continuum effect. Likewise, there is no evidence for a strong aerosol absorption in the tropical Pacific. We do not rule out the possibility that small (< 7 W m^{-2}) uncertainties still exist, but our search for the source of the (all-sky) excess absorption is now limited to continental aerosols or clouds.

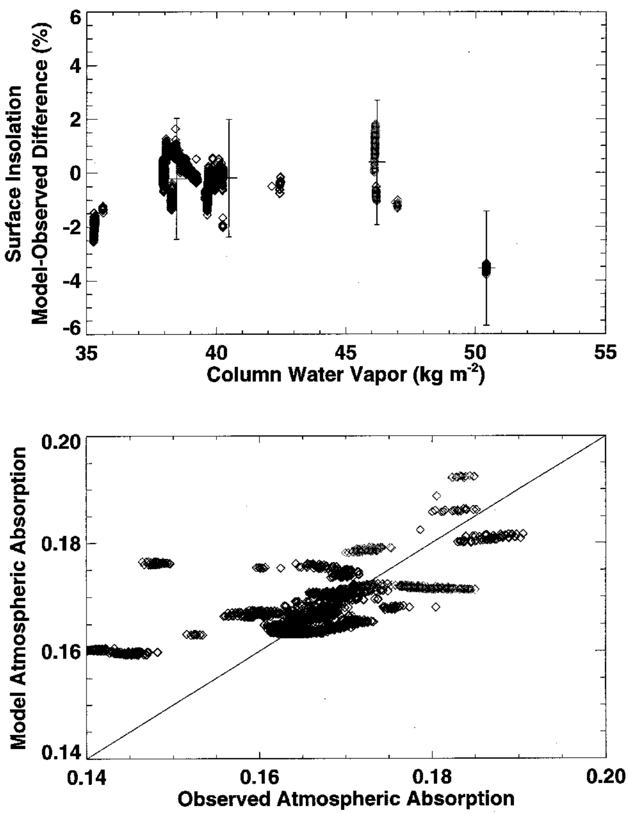

Figure 4. A) Error in model-observed surface insolation from the CEPEX broadband fluxes plotted as a function of H_2O. Bars show the experimental uncertainty for each 5 kg m^{-2} H_2O bin average. A positive trend would indicate an underestimate in H_2O absorption by the model. B) Model atmospheric absorption plotted vs. observed. The lower right side of the diagonal would indicate an excess absorption in clear-skies. (Conant et al., submitted).

Acknowledgments

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