Nadir measurements from ACE of column amounts of atmospheric gases

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ABSTRACT

The feasibility of using nadir observations to make column measurements of several stratospheric gases will be evaluated for the Atmospheric Chemistry Experiment (ACE) Fourier-transform spectrometer (FTS), which is scheduled for launch in 2002 on the SCISAT-1 platform. The measurement technique is based on using FTIR spectroscopy to measure the atmospheric absorption of cold gases below the satellite against the thermal emission background from the warm Earth. The FASCOD3 and MODTRAN4 transmission codes are used to simulate the background emission spectra above the earth; the measured spectra are processed to yield the column concentration of a particular gas in the atmosphere. The gases that can be successfully measured with this technique include ozone, carbon dioxide, carbon monoxide, methane and nitrous oxide. This technique will be demonstrated for nadir IMG spectra obtained in 1997 at a resolution of 0.1 cm^{-1}. Since ACE points at the sun throughout its orbit, even when the earth is in the way, nadir FTS measurements will automatically be taken in addition to the occultation measurements, if enough power is available. A nadir observation will consist of 100 co-added scans at a resolution of 0.4 cm^{-1}, which will require a total time of 16 seconds and achieve a signal-to-noise ratio of 80:1. Using the spectroscopic structure obtained from nadir IMG spectra at a resolution of 0.1 cm^{-1} over an extended spectral interval, it will be demonstrated that a signal-to-noise ratio of 50:1 gives ozone columns with an error of less than 2%.

Keywords: remote sensing, column amounts, infrared, atmospheric absorption, satellite, radiative trapping, greenhouse fluxes

1. INTRODUCTION

SCISAT-1 is a Canadian satellite scheduled for launch in late 2002 or early 2003. The mission objective is to study stratospheric ozone trends, with a particular focus on the polar regions where significant ozone loss has been observed in the past two decades[1]. Measurements of solar attenuation by ozone and other stratospheric constituents are to be taken during occultation events (sunrises and sunsets) by the two instruments on board SCISAT-1; ACE-MAESTRO (Atmospheric Chemistry Experiment - Measurement of Aerosol Extinction in The Stratosphere and Troposphere Retrieved by Occultation) and the ACE-FTS (ACE - Fourier Transform Spectrometer). These instruments are designed to measure absorption spectra in the visible/near-ultraviolet and infrared regions, respectively. MAESTRO is a dual concave grating spectrometer while the FTS uses a Michelson interferometer with InSb and MCT detectors to cover the 3 – 7 micron and the 6 – 13 micron regions, respectively. Since ACE points at the sun throughout its orbit, even when the earth is in the way, nadir FTS measurements will automatically be taken in addition to the occultation measurements, if enough power is available. A nadir observation will consist of 100 co-added scans at a resolution of 0.4 cm^{-1}, which will require a total time of 16 seconds and achieve a signal-to-noise ratio of 80:1. The thermal emission from the warm Earth, which can be represented approximately by a blackbody at a temperature of 280 K, is the source for absorption lines from the colder atmosphere above.

In 1996 the Japanese space agency launched the Advanced Earth Observing Satellite (ADEOS) to monitor global environmental changes in stratospheric ozone and the gases that promote global warming[2]. Of vital application to global warming, ADEOS carried an Interferometric Monitor for Greenhouse Gases (IMG) which consisted of an FTIR

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Earth Observing Systems VII, William L. Barnes, Editor,
Proceedings of SPIE Vol. 4814 (2002) © 2002 SPIE · 0277-786X/02/$15.00

spectrometer looking down at the Earth's surface. With a spectral resolution of 0.1 cm^{-1} this was one of the highest resolution instruments ever flown on a satellite platform. The IMG measured the full thermal infrared spectrum including absorption features due to atmospheric gases[2]; the absorption features are similar to those which we measure in emission with our ground-based spectrometer[3]. Although ADEOS was expected to operate for several years in orbit, the early loss of the satellite due to a solar panel failure on June 30, 1997 has limited the dataset to the first six months of 1997. We have used some of these nadir measurements to demonstrate the feasibility of obtaining column measurements of several greenhouse gases with the ACE-FTS.

Column measurements of greenhouse gases measured in the nadir view will have several beneficial uses, including the provision of acquiring direct measurements of the radiative trapping at the tropopause. The predictions of climate change are simulated by global climate models, based on the amount of outgoing thermal radiation that is absorbed, or trapped, by the troposphere. A recent analysis of 30-year-old IRIS greenhouse flux data compared with IMG measurements has shown the importance of acquiring nadir measurements of upwelling greenhouse fluxes[4].

2. RESULTS AND DISCUSSION

An overview of the thermal emission spectrum as measured by IMG in the nadir from an altitude of 600 km is shown in Figure 1. The relatively noisy spectrum (peak-to-peak SNR = 50:1 @ 1000 cm^{-1}) was measured for a northern latitude winter location. The absorption features associated with the chlorofluorocarbons CFC-11, CFC-12, ozone, nitrous oxide and methane are noted in the figure. The spectrum is too noisy to simply observe carbon monoxide in the atmosphere, although the use of correlation spectroscopy may improve the detection capability. The spectrum in Figure 1 has been expanded in Figures 2 - 6 to show the detailed absorption region denoted for each greenhouse gas. In Figure 2(A) the measured absorption for CFC-11 is shown in the 830-860 cm^{-1} band. Also shown is a representation of a FASCOD3 simulation of the radiance in the nadir view without any CFC-11 present.

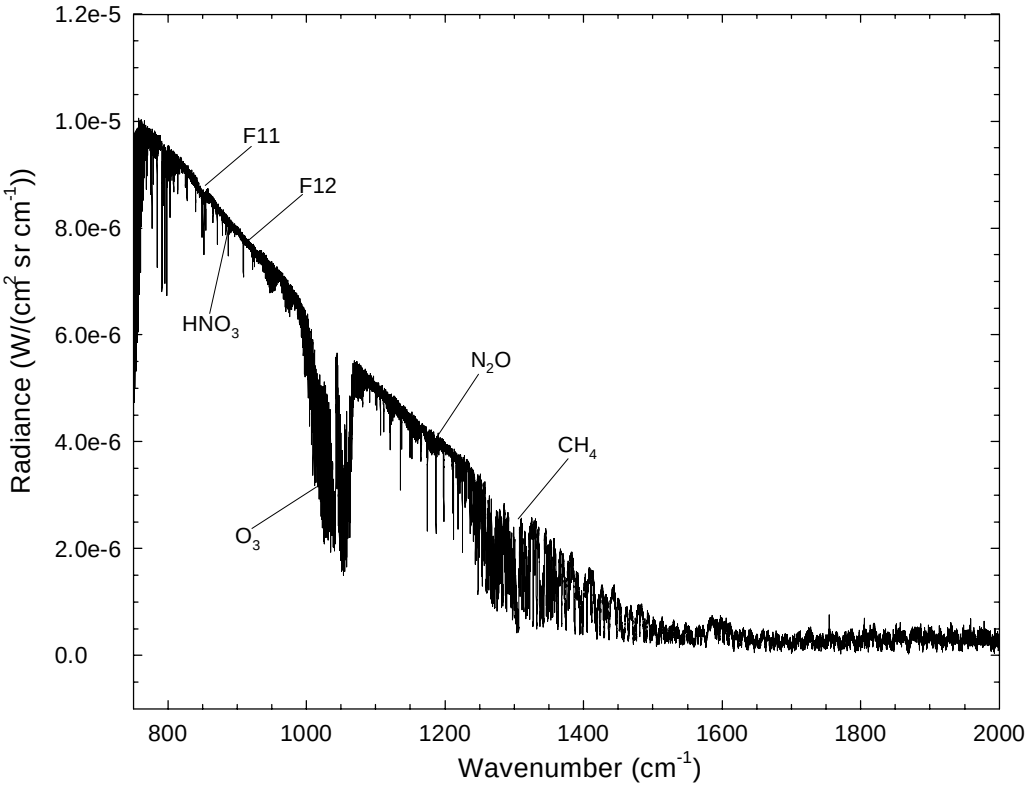

Figure 1: Nadir spectrum obtained with the IMG interferometer onboard the ADEOS satellite at an orbital altitude of 600 km. The spectrum was obtained above a northern latitude at a resolution of 0.1 cm^{-1} for a measurement period of 10 seconds. Some major absorption features are indicated in the figure.

The simulation incorporates line parameters from the 1996 HITRAN database[5] and uses the mid-latitude winter atmosphere of Anderson et al.[6]. The baseline radiance corresponds to a surface temperature of 275.4 K. Figure 2(B) shows the result of subtracting the simulation without CFC-11 present from the measured spectrum. Also shown for comparison is the simulated subtraction of the CFC-11 feature. The comparison shows that the column amount of CFC-11 was 6×10^{15} cm^{-2}. Integrating the spectrum over wavelength and solid angle indicates that CFC-11 absorbs 0.20 W/m^2 in the atmosphere. A similar analysis has been carried out for CFC-12 in Figure 3 where it is observed that the column amount was 1×10^{16} cm^{-2} with a corresponding greenhouse flux of 0.30 W/m^2, trapped by the atmosphere. Figure 4 shows a comparison of the measured and simulated absorption bands of methane. The corresponding column amount was determined to be 3×10^{19} cm^{-2}. The trapped flux was determined to be 0.98 W/m^2. A comparison of the measured and simulated nadir radiances for nitrous oxide in Figure 5 gives a column amount of 6×10^{18} cm^{-2} and a greenhouse flux of 0.68 W/m^2. Figure 6 shows a comparison of the measured and simulated absorption bands of ozone in the nadir view. The ozone column was calculated to be 9×10^{18} cm^{-2} and the trapped flux was determined to be 3.46 W/m^2.

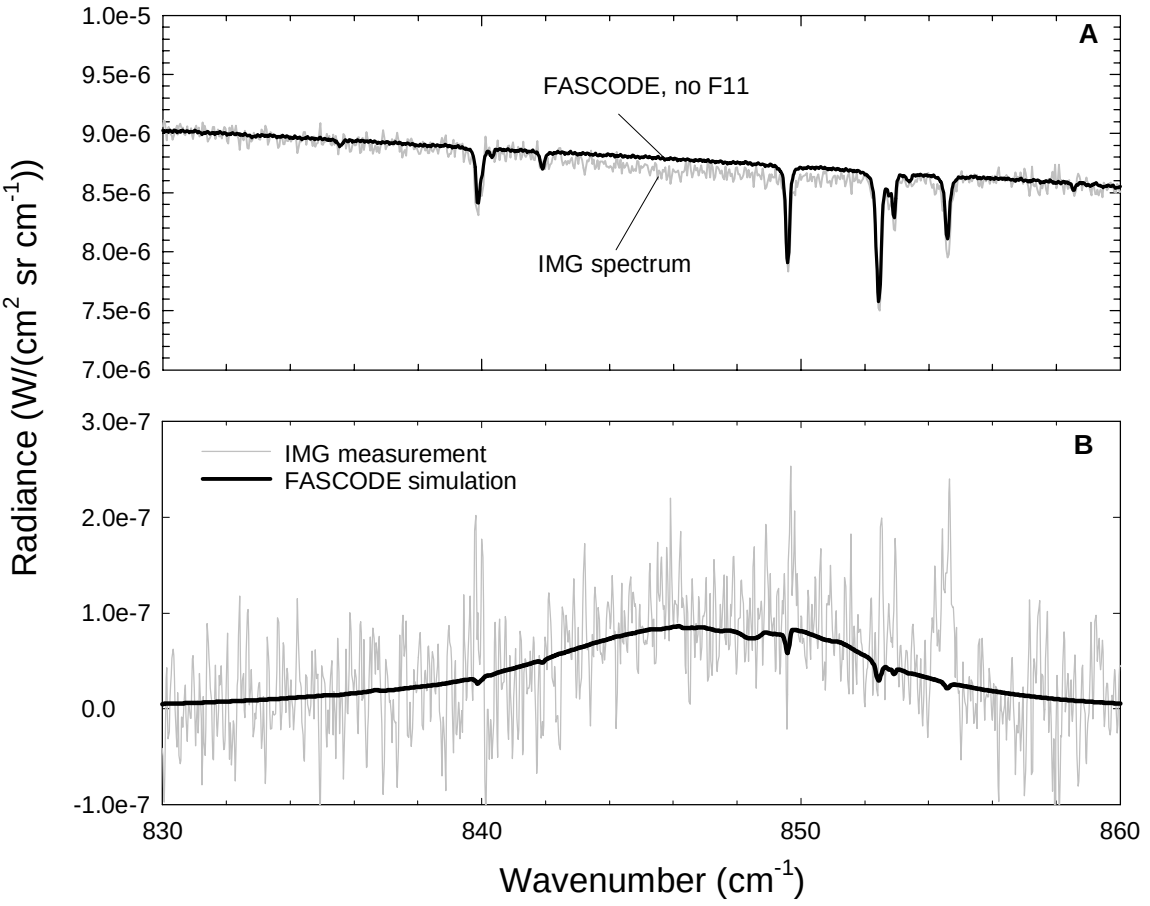

Figure 2: The nadir spectrum obtained with the IMG instrument in the region where F11 absorbs thermal radiation. (A) shows the IMG spectrum and a simulation without any F11 present. (B) shows the result of subtracting the simulated spectrum from the IMG observation. This extracted F11 band also is compared to the simulated extraction. The F11 column amount was 6×10^{15} cm^{-2} and the trapped flux was determined to be 0.20 W/m^2.

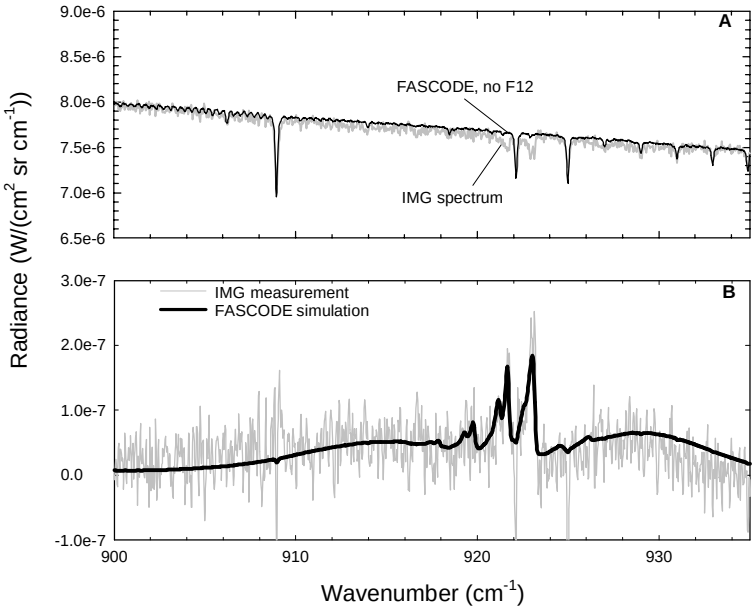

Figure 3: The nadir spectrum obtained with the IMG instrument in the region where F12 absorbs thermal radiation. (A) shows the IMG spectrum and a simulation without any F12 present. (B) shows the result of subtracting the simulated spectrum from the IMG observation. This extracted F12 band also is compared to the simulated extraction. The F12 column amount was 1×10^{16} cm^{-2} and the trapped flux was determined to be 0.30 W/m^2.

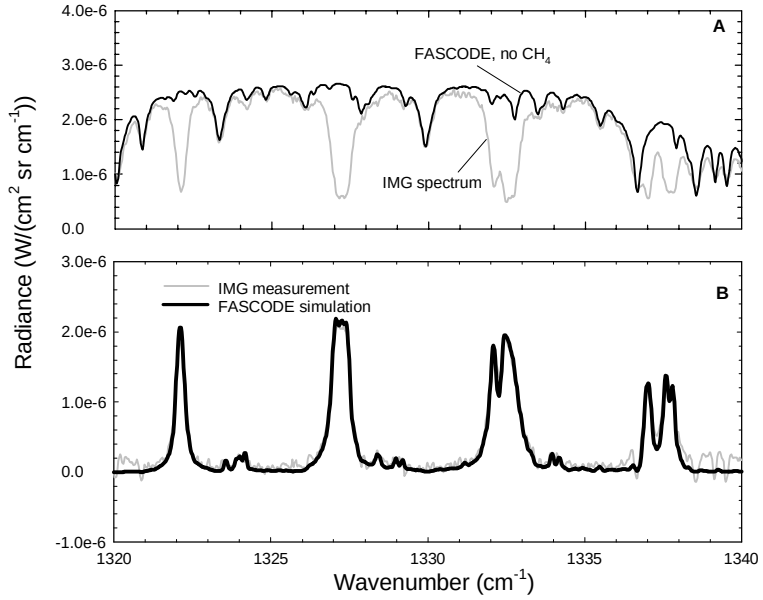

Figure 4: The nadir spectrum obtained with the IMG instrument in the region where methane absorbs thermal radiation. (A) shows the IMG spectrum and a simulation without any methane present. (B) shows the result of subtracting the simulated spectrum from the IMG observation. This extracted methane band also is compared to the simulated extraction. The column amount was 3×10^{19} cm^{-2} and the trapped greenhouse flux was 0.98 W/m^2.

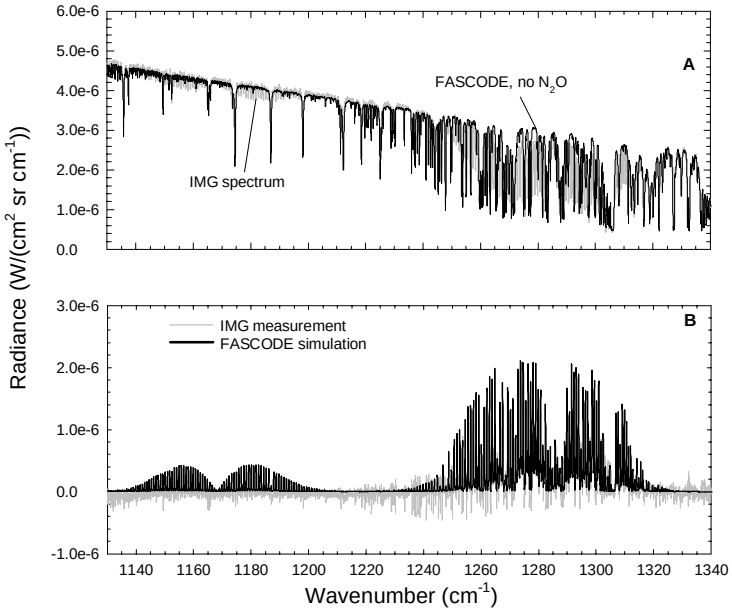

Figure 5: The nadir spectrum obtained with the IMG instrument in the region where nitrous oxide absorbs thermal radiation. (A) shows the IMG spectrum and a simulation without any nitrous oxide present. (B) shows the result of subtracting the simulated spectrum from the IMG observation. This extracted nitrous oxide band also is compared to the simulated extraction. The nitrous oxide column amount was 6×10^{18} cm^{-2} and the trapped flux was determined to be 0.68 W/m^2.

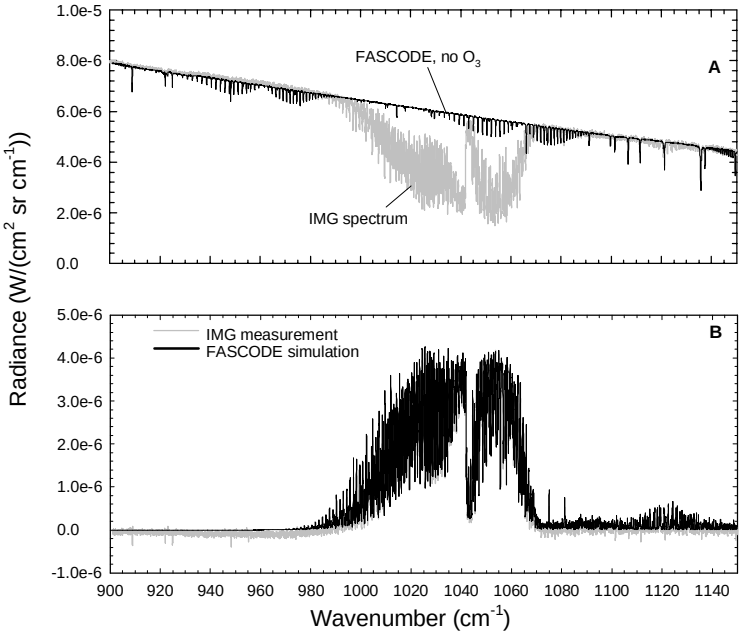

Figure 6: The nadir spectrum obtained with the IMG instrument in the region where ozone absorbs thermal radiation. (A) shows the IMG spectrum and a simulation without any ozone present. (B) shows the result of subtracting the simulated spectrum from the IMG observation. This extracted ozone band also is compared to the simulated extraction. The ozone column was calculated to be 9×10^{18} cm^{-2} and the trapped greenhouse flux was determined to be 3.46 W/m^2.

The comparison of radiative spectral measurements made at the surface and at the top-of-the-atmosphere enables an important investigation to be made of the interference effect of water vapour bands on other gases in the atmosphere[7]. For example, the contrast between the effect that the water vapour overlap has on the surface forcing and radiative trapping of methane is illustrated in Figure 7. The surface forcing radiation and the radiative trapping, as calculated at the 12 km high tropopause, were simulated with the FASCOD3 line-by-line radiation model[8] using the 1976 U.S. Standard atmosphere to represent average global conditions of temperature and water vapour[6]. Also shown in Figure 7 is the absorption spectrum associated with atmospheric water vapour (top most spectrum). The line transition parameters for these gases were taken from the 1996 HITRAN database[5]. We have shown in the past, through measurements of thermal emission spectra, that FASCOD3 reliably predicts the forcing radiation of greenhouse gases[3]. In Figure 7, the surface forcing of methane in the 1300 cm^{-1} band, where the water vapour absorption is nearly unity, is reduced significantly compared to the radiative trapping component.

From the comparison of the trapping and surface forcing radiation fluxes in the absence of water vapour in Figure 7, it is clearly evident that the radiative trapping is less affected by the presence of the strong absorption bands of water vapour. By comparing the radiative trapping of methane in Figure 7 with and without water vapour present, a discrepancy of between 30 – 50% exists for the methane bands. On the other hand, for the surface forcing scenario the entire R-branch beyond 1310 cm^{-1} is nearly absorbed out, and many additional lines are missing in the Q-branch of the methane band, due to the presence of water vapour in the lower troposphere. Furthermore, the comparison of the surface forcing with the radiative trapping in the absence of water vapour shows that the former is larger due to the thermal and pressure gradient of the atmosphere; however, this excess emission is more than compensated with the addition of water vapour, resulting in a reduction of the surface forcing band relative to the trapped radiation band.

It will be important to verify experimentally the interference effect of water vapour on all of the greenhouse gases, since this has an impact on the global warming potential (GWP) of the gases. The concept of a global warming potential for each greenhouse gas was introduced about ten years ago[9] to help determine the relative ability that a particular gas may have towards forcing the Earth's climate. Specifically, the GWP of a greenhouse gas is the product of the radiative forcing of the gas, as determined at the tropopause, and its concentration, integrated over some time frame. The GWPs are usually referenced to the radiative impact of carbon dioxide. One of the main problems with this formulation is the dependence of the forcing radiation on overlapping absorption bands of other gases. The impact of the overlapping bands, particularly those of water vapour, on the GWP depends on whether one considers the radiative forcing at the tropopause, as currently accepted by IPCC, or whether one considers the surface forcing radiation, which is responsible for the actual warming of the Earth's surface. In general, these two quantities are only identical for an isothermal atmosphere containing well-mixed gases, a scenario that never occurs in nature. The interference effect of water vapour is particularly important since it has many absorption bands throughout the entire thermal infrared region that overlap to some extent with every other greenhouse gas. In addition, its relatively high concentration close to the Earth's surface results in a blanket of protection that effectively absorbs the downward greenhouse radiation from other gases higher in the atmosphere and reduces their warming impact on the Earth. The radiative trapping parameter is relatively unaffected by the presence of a low-lying water vapour layer, as was discussed above. Hence, the true GWP of gases that have a strong overlap with water vapour is expected to be less than the value that is currently reported by IPCC[10], which is based on the radiative forcing determined at the tropopause.

Since the GWP of a gas is used to quantify its climate forcing impact, it is also a major parameter on which climate change policy issues are established (e.g. Kyoto accord). Therefore, its determination based upon experimental measurements should be a priority, since legislated polices may have significant consequences on the economy and standard of living conditions.

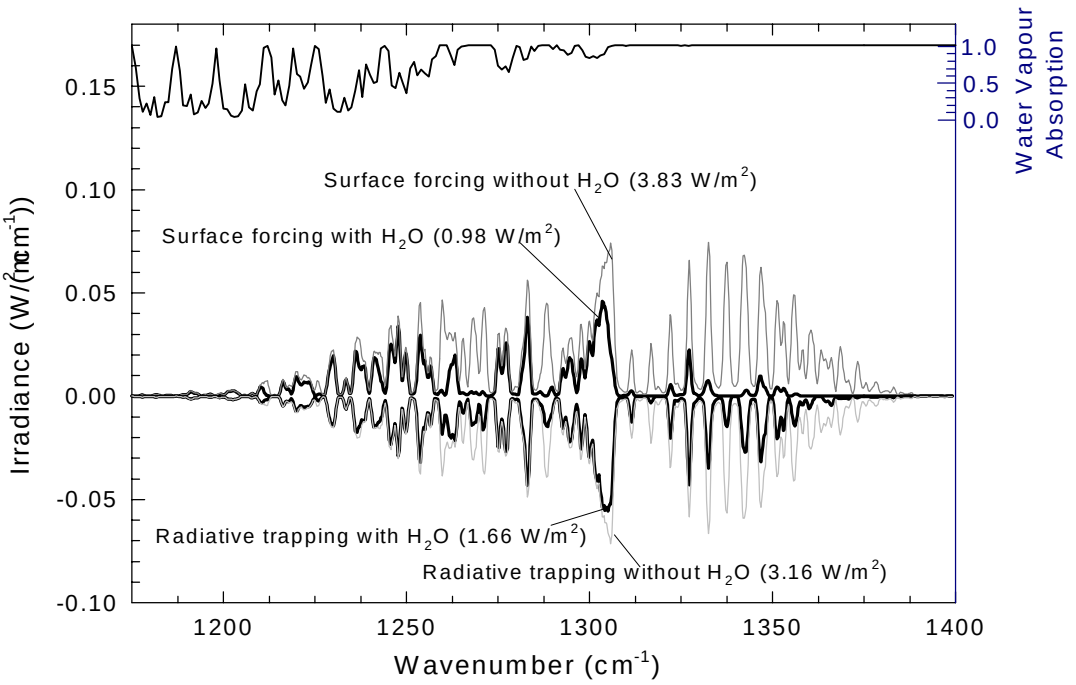

Figure 7: A comparison of the surface forcing and radiative trapping of CH_4 for the 1976 U.S. Standard atmosphere. The comparison shows the impact that overlapping absorption bands of water vapour have in reducing the surface forcing radiation of CH_4, particularly in the 1310 – 1400 cm^{-1} region, compared to the radiative trapping in the same region.

3. CONCLUSIONS

An analysis has been made of several nadir absorption spectra measured from orbit by the IMG spectrometer on the ADEOS satellite. The column amounts of several greenhouse gases, including F11, F12, methane, nitrous oxide and ozone, and their corresponding radiative fluxes have been determined. This work indicates that column amounts of the same gases should be able to be successfully retrieved with the ACE-FTS onboard the SCISAT-1 satellite, which will be launched in late 2002 or early 2003. These column amounts should complement the occultation measurements of ozone profiles which will be made with the FTS and MAESTRO instruments. The nadir acquisitions should be of interest to many fields of atmospheric science including the investigation of global warming and climate change, and air pollution monitoring.

ACKNOWLEDGMENTS

This research was supported by an NSERC collaborative grant led by the ACE Principal Investigator, Peter Bernath. Additional funding was provided generously by Enbridge Consumers Gas, and through an NSERC Industrially Oriented Research grant. The authors would like to thank Jim Chetwynd (AFRL) for the FASCOD3 simulation software and his expert advice in its use.

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