ATMOSPHERIC LONGWAVE INFRARED EMISSION SPECTROSCOPY OF WATER VAPOR AT THE SOUTH POLE

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Abstract

The downward infrared radiance spectrum was measured with a Michelson Long Wave Infrared (LWIR) spectrometer at the Amundsen-Scott South Pole Station. Spectra were collected year-round at the South Pole in 1998. This research focuses on the atmospheric water emission lines between 250 and 800 cm\(^{-1}\) (40 to 12.5 \(\mu\)m) region. The spectral resolution is 1 cm\(^{-1}\). The atmosphere over the South Pole is the driest and coldest on Earth. Winter surface temperatures average approximately -60\(^\circ\)C, while the total column water vapor is about 300 \(\mu\)m of precipitable water. Measured clear sky cases were selected for summer and winter months to represent and investigate water in the seasonal extremes. The LWIR spectra are modeled using the Line-By-Line Radiative Transfer Model (LBLRTM) software, the HITRAN database, and NMC temperature and pressure profiles. These spectra are then fitted as closely as possible to the measured spectra to retrieve water column amounts, and to obtain other important information about the atmosphere.

INTRODUCTION

Radiation is essential for atmospheric motion. Radiation measurements used with (theoretical) atmospheric circulation models allow for the ability to predict weather and climate. Radiative transfer models require atmospheric profiles of molecules participating in the atmospheric chemistry. Atmospheric water emission lines yield an abundance of information about the atmosphere’s net radiation in the long wavelength infrared region (LWIR). This is because much of the LWIR region is comprised of water emission lines (i.e. the main contribution of water to net radiation occurs in the LWIR).

The emission spectra under study yield information regarding total column amounts of water vapor as well as other atmospheric components. The spectra also give information about the temperature and cloud conditions of a given location. Water has a continuum absorption, which distinguishes it from most molecules. The continuum’s effect is difficult to study experimentally since an investigation of this type requires a large number of molecules in a low pressure environment (Clough et al., 1992). Therefore, field data was obtained for this study to establish comparisons with model predictions. Water vapor contributes a significant role in the 250-800 cm\(^{-1}\) region regarding atmospheric cooling rates as seen in Clough’s (1992) extensive calculations.

A small BOMEM MB100 Michelson interferometer and a higher spectral resolution AERI-X interferometer collected year-round atmospheric emission spectra at the South Pole for the study of water emission lines in the 250-800 cm\(^{-1}\) and 865-885 cm\(^{-1}\) regions, respectively. Infrared emission spectroscopy was used in this experiment because it allows the measurement of atmospheric thermal emission, dismissing the need for year-round solar radiation.

The seasons at the South Pole are defined by the annual cycle of surface temperature (Warren, 1996). The South Pole summer spans the months December – January, Autumn spans February – March, Winter spans April – September, and Spring spans October – November. Test cases were chosen for the Austral summer and winter to characterize the extreme atmospheric conditions.

A line-by-line radiative transfer model (LBLRTM) was used in this research to calculate spectra for comparison to the measured data. An LBL model offers a higher resolution method of calculation than a band model, and thus more detailed spectral structure in the comparison spectra (Edwards, 1988).

In the 1980’s, a project on Intercomparison of Radiation Codes used in Climate Models (ICRCCM) was undertaken to compare radiative transfer models. Detailed LBL codes and highly parameterized band models were included in this study (Luther et. Al., 1988; Ellingson and Fouquart, 1991). Ellingson et al. (1991) summarized the long wave model results. The input atmospheres used in this comparison were taken from the five reference Air Force Geophysics Laboratory (AFGL) (McClatchey et al., 1972). One main inference of the
long wave study was that the LBL radiative transfer models agree well with each other, but should not be used as a final measure by which to adjudicate other, less detailed models. Therefore, data from the real atmosphere should be compared with the LBL model’s output. The desired outcome of the experiment is to have an excellent comparison of the molecular line parameters of water vapor lines in the 250-800 cm$^{-1}$ region (see Figure 1) under extreme conditions of temperature and water vapor column amounts.

**Figure 1.** Plot of Radiance vs. Wave numbers for a downwelling atmospheric emission spectrum between 0 and 1100 cm$^{-1}$. The small band at 1100 cm$^{-1}$ is ozone. The band centered around 650 cm$^{-1}$ is CO$_2$. Almost all of the remaining radiance is due to H$_2$O. The spectrum was calculated for July 7, 1992. A reference Planck blackbody curve of 235 K is also shown (Van Allen, 1995).

**INSTRUMENTATION**

**LWIR**

An LWIR interferometer was installed for 1998 year-round data collection. The spectral radiance data was measured at a zenith angle of 0° every 30 minutes. The spectrometer used to measure the LWIR spectra at the South Pole is based upon a commercial BOMEM 160MB interferometer system. This unit was used to obtain calibrated atmospheric emission spectra between 800 cm$^{-1}$ and 250 cm$^{-1}$ and is equipped with a computer controlled scene mirror. The mirror is programmed to alternate between a hot blackbody (40°C), an ambient blackbody, and one sky elevation angle. The blackbodies and scene mirror were integrated into an instrument housing located outside the new Clean Air building. The mirror is viewed by the interferometer through a hole in the wall. In this way, the instrument and the computer that controlled the instrument and recorded data was operated inside a thermally controlled building so that it was kept warm, yet had optical access to the atmosphere.

The unit has a CsI beam splitter and a window that is very hygroscopic. The window must be heated above ambient to avoid fog. This instrument is the same as what was used in Van Allen’s (1995) research, with the exception of some modifications. The earlier experiment collected spectra in the region from 550 to 1650 cm$^{-1}$.

The interferometer has a maximum optical path difference of 1 cm. The interferograms are apodized with a cosine-squared function to reduce the side lobes in the final spectra. The final apodized resolution of the spectra is 1 cm$^{-1}$. A scheduling program running on a personal computer controlled measurements.

**AERI-X**

The Extra-high resolution Atmospheric Emission Radiometric Interferometer (AERI-X) was installed during 1998 in the ASTRO building. It collected data at zenith angles of 30° and 7.5° every 30 minutes. This ground-based spectrometer is also used in comparison to LWIR data. The higher resolution, Atmospheric Emission Radiometric Interferometer has a band pass extending between approximately 650 to 1250 cm$^{-1}$, with a resolution of 0.1 cm$^{-1}$. This range includes the atmospheric window region where cloud information can be retrieved, and O$_3$, HNO$_3$, and chlorofluorocarbons can be found. Some CO$_2$ bands in this region are used to retrieve the temperature profile of the atmosphere. Water lines also exist in this region (Olson et al., 1996). The water lines of interest to this research are those that are fairly insensitive to temperature changes. These lines are useful indicators to the research because they can be used to roughly verify the total water column amounts retrieved from the LWIR spectra.

The AERI-X is also a Michelson-type emission interferometer. The beam splitter is KBr with a Ge coating. The basic interferometer was purchased from Idealab, Inc. The electronics were built and designed at the University of Denver.

The rotatable beam-directing mirror is gold-plated, and the entry window for the sealed case is Ge. The detector is a 1mm$^2$ HgCdTe (MCT) (Olson et al., 1996).

**OPERATION AT THE SOUTH POLE**
The South Pole is an ideal location for acquiring spectral radiance data for testing radiative transfer models. Its atmosphere is among the coldest and driest ($\leq 1$ mm of precipitable water vs. 8 cm in the tropics). This means that the overlap of the emission spectrum of water vapor with that of other gases is greatly reduced. As a result, spectral characteristics of other major infrared emitters such as CO$_2$, O$_3$, CH$_4$, and N$_2$O are very distinct.

The unusually harsh environment of the South Pole hinders efforts to collect ground-based measurements on the Antarctic continent. The South Pole’s high altitude and year-round snow and ice cover insure the low temperatures and water column amounts that are ideal for studying water emission lines. The low atmospheric temperatures provide an extreme test case for assessing radiative transfer models. Water vapor lines are so strong that the 250-800 cm$^{-1}$ region is almost opaque at locations where temperatures, and thus water column amounts are much higher (i.e. lower latitudes).

The South Pole’s summers provide almost complete sunlight while the winters supply almost complete darkness. This region receives more summer sunshine than any other place on earth due to the high altitude and lack of moisture of the continent, and because the perihelion of earth’s orbit around the sun occurs in the austral summer (Rusin, 1964). Winter conditions are characterized as being clear and cold with a prominent temperature inversion.

Routine operations at the South Pole Station provide good ancillary data for characterizing the atmosphere throughout the year. The South Pole Weather Office (SPWO) launches radiosondes once or twice per day and makes surface weather observations at least every 6 hours (more frequently during the summer months). It has been stated that the conditions at the South Pole in the winter are similar to those of the tropopause at lower latitudes (Walden et al., 1998).

**TEMPERATURE**

Altitudes between 2.8 and 60 km were accounted for in a profile of 27 layers. The altitude at the South Pole station is approximately 2.8 km above sea level. The layering grid was adjusted to its finest (approximately .1 km) between 2.8 and 4.0 km. It is here that a strong temperature inversion exists. The strength of the inversion is greatest in the winter months and weakest in the summer months.

**WATER VAPOR**

Water vapor is an extremely important atmospheric constituent. It is present in a very large portion of the atmospheric spectrum, however it is the least known of the gases measured at the South Pole. The accuracy in measuring water vapor at the South Pole is poor due to the inhospitable conditions. Thermistors in the different apparatus (frost-point hygrometers, carbon hygristors, Vaisala Humicaps) freeze at the extremely low tropospheric temperatures. The carbon hygristors and Humicaps are calibrated only down to -40°C, and the frost-point hygrometers are designed to measure stratospheric humidity (Walden et al., 1998). The current upper air system radiosondes consistently read lower than normal relative humidity values. Corrections to this problem are being made, mostly by using a Global Positioning System to track the upper air system. Current testing reveals that the new radiosondes used with this system have yielded higher, more realistic relative humidity readings (Phano, personal communication).

Relative humidity profiles are used as input for LBLRTM calculations. Data suggests that the relative humidity over ice is close to saturation in the near-surface layer. To support this suggestion and finding, Schwerdtfeger (1970; 1984) interpreted the frequent occurrence of ice crystals in the atmosphere as evidence that the lower atmosphere must be at least saturated with respect to ice. Best fits to summer spectra included near-surface relative humidity between 90 and 110%.

**WATER VAPOR CONTINUUM**

Continuum absorption due to water vapor has posed a complex problem for researchers concerned with atmospheric radiative problems. Because of this, a universal definition of continuum absorption has not been established. The LWIR region of the atmosphere is strongly dependent on the water vapor continuum. Laboratory measurements of the continuum are difficult in part due to the long path lengths required with current spectroscopic techniques. Great difficulty exists for obtaining atmospheric measurements due to factors such as accurate characterization of the path, turbulence, instrument calibration, and aerosols. From a theoretical view, the continuum is a fairly complex problem that currently lacks a complete and satisfactory explanation (Clough et al., 1989). With regard to the difficulty in obtaining measured data to validate the continuum model, it is hoped that the LBLRTM-calculated data fitted to the measured data.
will match well, so as to provide a method to validate the continuum calculations.

**LBLRTM**

The basic aim of a radiative transfer model is to solve the equation (Edwards, 1988)

\[
I(\nu)_2 = I(\nu)_1 \tau (\nu, z_1, z_2) + \int [B\{\nu, T(z)\} k(\nu, z) p_\alpha(z) dz] \tau(\nu, z, z_2) \tag{1}
\]

where \(I(\nu)_1\) and \(I(\nu)_2\) are the radiances in units of \(W/(m^2 \text{ sr cm}^{-1})\) at points \(z_1\) and \(z_2\) respectively where \(z\) is an arbitrary measure of distance. The first term is the transmitted component, and the second term is the emission component. The emission term is integrated from \(z_1\) to \(z_2\).

The line-by-line radiative transfer model (LBLRTM) used in this research is a product of Atmospheric and Environmental Research, Inc. (AER). The LBLRTM is based on the FASCODE line-by-line model. A radiance algorithm has been used to treat the vertically inhomogeneous atmospheres resulting in substantially improved accuracy, and the model is directly applicable to long wave cooling rate calculations. A layered atmosphere is used with each layer assumed to be in local thermodynamic equilibrium with respect to absorption in the layer. A CKD continuum calculation (Clough et al., 1989) and the HITRAN96 database are used. The HITRAN database is a comprehensive molecular line data compilation. It supplies parameters necessary for LBLRTM’s calculations such as line strengths, locations, and widths.

**DATA RESULTS**

This research has yielded some interesting anomalies. It is being investigated as to whether an apparent excess of radiance is caused due to the line parameters in this region, continuum calculation errors, or user-inputted errors in temperature and relative humidity profiles (see Figure 2). The same atmospheric profiles inputted into LBLRTM for the AERI-X data in the region 865–885 cm\(^{-1}\), seem to yield a roughly accurate total water column amount, and temperature agreement.

**Figure 2.** Clear sky South Pole spectra for February 2, 1998. Dotted spectrum calculated by LBLRTM. Solid spectrum was measured by the LWIR interferometer. Units of radiance are microwatts/(cm\(^2\) sr cm\(^{-1}\)). Units of wave numbers are cm\(^{-1}\).

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