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Radiative Heating in Underexplored Bands Campaign (RHUBC) Science Plan

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Radiative Heating in Underexplored Bands Campaign (RHUBC)

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22 February to 14 March 2007
ARM NSA site in Barrow, AK

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Abstract

Radiative cooling and heating in the mid-to-upper troposphere contribute significantly to the dynamical processes and radiative balance that regulate Earth's climate. In the longwave, the dominant agent of this radiative cooling is water vapor. Due to the much greater abundances of this gas at lower levels of the atmosphere, the spectral regions in which the mid-to-upper tropospheric cooling occurs are opaque when viewed from the vast majority of surface locations. The opacity of the lower atmosphere is a formidable obstacle in evaluating radiative processes important in the mid-to-upper troposphere from the surface; however, an even more substantial obstacle has been the lack of radiometric instrumentation in the most critical spectral region for these processes, the far-infrared ($\lambda > 15$ μm). The recent development of a new generation of instruments for the measurement of spectral radiation in the far-infrared has provided the capability to rectify this state of affairs. These instruments will allow the evaluation of radiatively important processes in the mid-to-upper troposphere. This presents ARM with a terrific opportunity to contribute substantially to the improvement of the parameterization of these crucial radiative processes in climate simulations.

We propose to conduct the *Radiative Heating in Underexplored Bands Campaign* (RHUBC, pronounced "roobik") from 22 February to 14 March 2007 at the NSA site in Barrow. This experiment will make detailed observations of the downwelling infrared radiation in the 17-100 μm (100-600 cm^{-1}) rotational and 6.7 μm (1350-1850 cm^{-1}) υ_2 water vapor bands. Both of these spectral bands are underexplored because they are normally opaque at the surface due to strong absorption by water vapor, and hence the radiative heating in these bands is uncertain. High-spectral-resolution observations will be collected by three state-of-the-art Fourier Transform Spectrometers (FTS): the ARM AERI-ER (400 - 3000 cm^{-1}), the NASA/LaRC FIRST (20 - 1600 cm^{-1}), and the Imperial College TAFTS (80 - 650 cm^{-1}). During the proposed IOP period, the precipitable water vapor (PWV) is small (typically less than 3 mm) and thus important parts of the rotational and υ_2 water vapor bands will be semi-transparent, and the incidence of low stratus clouds is at a minimum (~ 40-50%).

Specifically, the primary goals of RHUBC are:

a) To conduct clear-sky radiative closure studies in order to reduce the key uncertainties in the water vapor spectroscopy, including the foreign-broadened water vapor continuum and water vapor absorption line parameters. This campaign would allow a robust set of measurements corresponding to low PWV and cold temperatures to be collected; this is unobtainable in the laboratory.

b) Instrument cross-calibration and validation. FIRST, TAFTS, and the AERI-ER are state-of-the-art instruments that operate in far-IR for the purpose of atmospheric radiative transfer studies. None of these instruments have been validated in an operational environment against a complementary interferometer from a different manufacturer. The inter-comparison will allow a higher confidence in the results from all three instruments.

c) The investigation of the radiative properties of sub-arctic cirrus. The combination of the AERI-ER, FIRST, and TAFTS will allow simultaneous high-resolution measurements of Arctic cirrus emission in the far-IR for the first time. The additional instrumentation (MPL, MMCR) at the ARM site will provide a comprehensive array of auxiliary data, maximizing the scientific value of this data set.

It is anticipated that the ultimate impact of RHUBC will be increased knowledge of mid-to-upper tropospheric radiative processes and, therefore, improved simulations of future climate.

Project Description

1. *Scientific Rationale*

Radiative cooling and heating in the mid-to-upper troposphere contribute significantly to the dynamical processes and radiative balance that regulate Earth's climate. In the longwave, the dominant agent of this radiative cooling is water vapor. Due to the much greater abundances of this gas at lower levels of the atmosphere, the spectral regions in which the mid-to-upper tropospheric cooling occurs are opaque when viewed from the vast majority of surface locations. One of the most critical spectral regions that drives the radiative balance of the Earth is the far-infrared ($\lambda > 15\ \mu m$). As stated in *Harries* [*1996*], "in the radiative cooling of the Earth to space …one very important component is the emission to space from the pure rotation band in the far IR, from water vapor in the upper troposphere." The far-IR is the least observed and least studied part of the Earth's thermal emission spectrum and accounts for up to half of the outgoing longwave radiation [*Collins and Mlynczak*, 2001; *Sinha and Harries*, 1995]. The dominant role of water vapor in upper tropospheric processes can be further seen in Figure 1 (top), which shows the spectral cooling rate profile for a mid-latitude summer (MLS) atmosphere containing water vapor, carbon dioxide, and ozone [*Clough and Iacono, 1995*]. This plot indicates that the major source of mid-to-upper tropospheric cooling in the longwave occurs in the far-infrared.

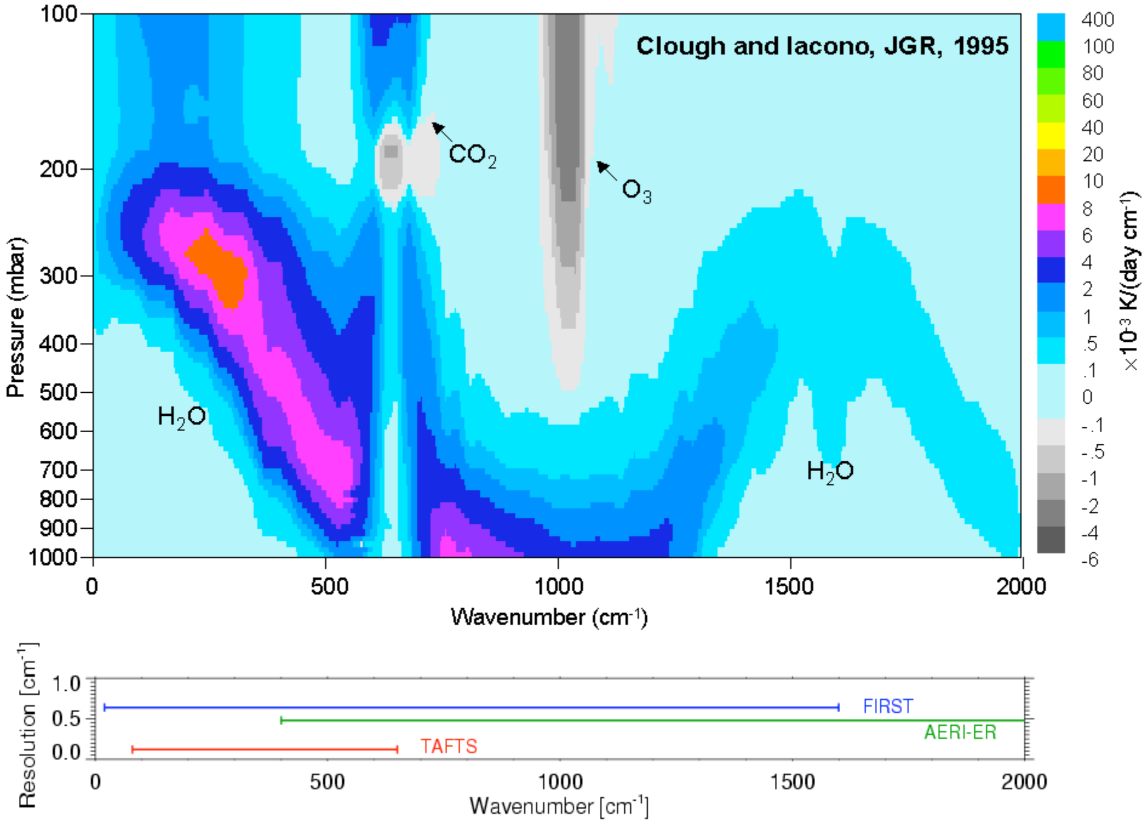

Fig 1: (Top) Spectral cooling rates computed from the mid-latitude summer profile, where the calculation includes the contributions from water vapor, carbon dioxide, and ozone. After *Clough and Iacono* [*1995*]. (Bottom) The spectral range (x-axis) and spectral resolution (y-axis) of the AERI-ER, FIRST, and TAFTS.

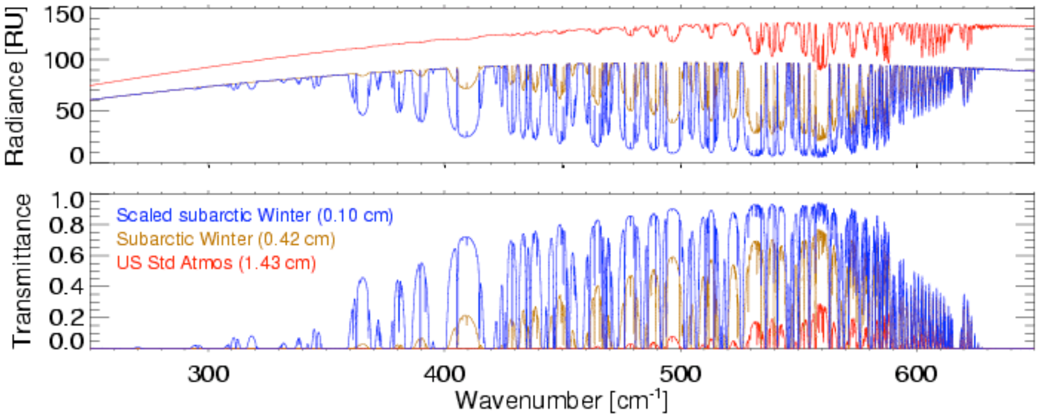

Fig 2: The sensitivity of the downwelling far-IR radiance (top) and the atmospheric transmissivity (bottom) for three different atmospheres with different PWV amounts (indicated in parentheses). A radiance unit (RU) is 1 mW / (m^2 sr cm^{-1}).

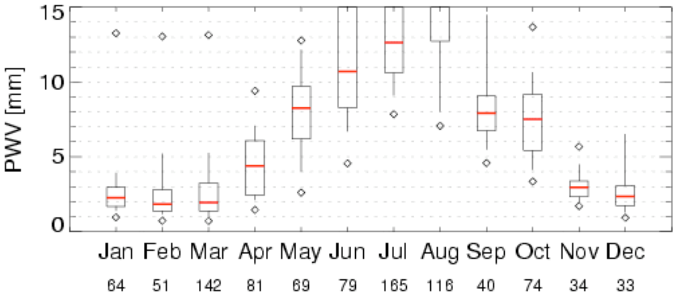

Fig 3: A box-and-whisker plot showing the distribution of PWV at the NSA site computed from radiosonde data collected in 2004-2005. The thick red lines are the median values for the month, the box boundaries denote the 25th and 75th percentiles, and the ends of the whiskers are the 10th and 90th percentiles. Climatologically, the driest period at the NSA site occurs in February and March.

The opacity of the lower atmosphere is a formidable obstacle in evaluating radiative processes important in the mid-to-upper troposphere. Figure 2 shows the downwelling clear sky radiance and atmospheric transmittance for three different atmospheres. The far-IR spectrum is largely opaque at wavenumbers smaller than 530 cm^{-1} for the US Standard Atmosphere, but the transmission increases significantly in the microwindows between absorption lines as the PWV decreases. The minimum PWV observed at the NSA site is approximately 1 mm (Fig 3), and thus the spectrum computed from the scaled subarctic winter profile provides an illustration of the transparency of the atmosphere in the far-IR under ideal clear sky conditions.

Radiative closure experiments performed in the ARM program (e.g. Turner et al., 2004a; Mlawer et al., 2000; Tobin et al. 1999) have provided a great value to the program and to the atmospheric community. These studies have focused on the critical examination of the three components on which these studies are based: radiative measurements, the calculations of radiative transfer models, and the specification of the properties of the radiating atmospheric column (i.e., the atmospheric state). The lack of radiative closure experiments in the far-IR has precluded lowering the uncertainty of mid-to-upper troposphere radiative calculations in climate models, and the subsequent improvement in our ability to simulate the behavior of this important region and the planet's radiative balance. One of the radiative mechanisms blocked from evaluation by the opacity of the lower troposphere is emission by the water vapor continuum. One of ARM's greatest improvements to the treatment of radiation in climate models is the 300% adjustment of the strength of the foreign-broadened water vapor continuum absorption in the 400-600 cm^{-1} region of the spectrum (Tobin et al., 1999). Although any adjustment needed to be made to continuum absorption at lower wavenumbers is likely to be less dramatic (Green et al., 2005), no quantitative statements can be made about the accuracy of radiative transfer models in the important 100-400 cm^{-1} spectral region due to the lack of measurements collected in very dry conditions. Another source of uncertainty in far-infrared radiative transfer models is due to the water vapor line parameters in this region. Recent analysis of ARM NSA ACRF data [*Delamere et al., 2004*] has indicated that the water vapor line widths provided by the HITRAN line parameter database for the region 420-500 cm^{-1} have substantial errors. It is expected that line parameter inaccuracies also occur at lower wavenumbers, but so far it has been impossible to verify this due to the atmospheric opacity and the lack of observations. In the far-IR, the uncertainties due to the water vapor continuum, water vapor line widths, and water vapor line intensities result in an uncertainty in the calculation of net flux in the mid-to-upper troposphere of nearly 3 $\mathrm{W/m}^2$, comparable to the effect of doubling carbon dioxide.

Accurate water vapor measurements are critical in longwave radiative closure experiments [*Revercomb et al. 2003*]. Vaisala radiosondes, while being arguably better than the radiosondes from other manufacturers, still exhibit significant sonde-to-sonde variability in the calibration of their water vapor sensors as well as calibration batch dependencies and day/night biases [*Turner et al. 2003*]. A series of water vapor IOPs at the ARM Southern Great Plains site has determined that scaling the radiosonde water vapor profile by a height independent factor derived from the microwave radiometer (MWR) provides, to first order, an accurate water vapor profile for infrared radiative transfer [*Turner et al. 2003, Revercomb et al. 2003, Turner et al. 2004*]. However, the uncertainty of the PWV retrieved from the 23.8 and 31.4 GHz channels of the MWR is approximately 0.4 mm, which is significant for cases where the PWV is less than 8 mm [*Cadeddu et al. 2006*], and thus scaling radiosonde profiles to agree with the MWR's PWV actually increases the random error and uncertainty in the longwave model vs. observation analysis [*Tobin et al. 2000*]. Therefore, a more accurate reference standard is needed to scale the radiosonde water vapor observations in the dry Arctic.

The 183.31 GHz water vapor line is significantly stronger than the 22.2 GHz water vapor absorption feature (Fig 4), and thus microwave radiometers that observe near the former frequency are approximately 70 times more sensitive to PWV than the MWR [*Cimini et al. 2006a*]. The ARM program has recently benefited from a DOE SBIR effort, which resulted in an automated 183-GHz radiometer being permanently deployed at the NSA site [*Cadeddu et al. 2006*]. The ARM program also has deployed the NOAA multi-frequency radiometer, which has a set of channels near 183 GHz, at the NSA site during past IOPs. Both of these instruments are able to provide the observations needed to accurately retrieve the PWV used in the line-by-line radiative transfer calculations, and thus are critical components of this IOP.

The opacity of the atmosphere at most locations near sea level also prevents evaluation of other critical radiative effects, such as those of cirrus ice clouds. The refractive index of ice changes significantly between 100 cm^{-1} and 1000 cm^{-1} (Fig 5, left); in spectral regions where the imaginary refractive index becomes small scattering becomes more important (e.g., near 400 cm^{-1}). Thus the scattering and absorption properties of ice clouds may not be represented properly in radiative transfer models used in climate models, resulting in errors in computed outgoing longwave radiation.

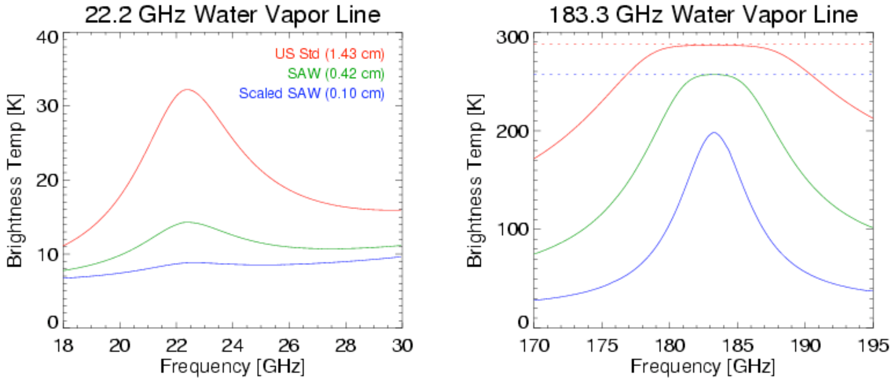

Fig 4: Calculations showing the surface-observed sky brightness temperature near the 22.2 and 183.3 GHz water vapor absorption lines for three different atmospheres (PWV for each atmosphere is given in the parentheses). The dotted lines denote the surface air temperature.

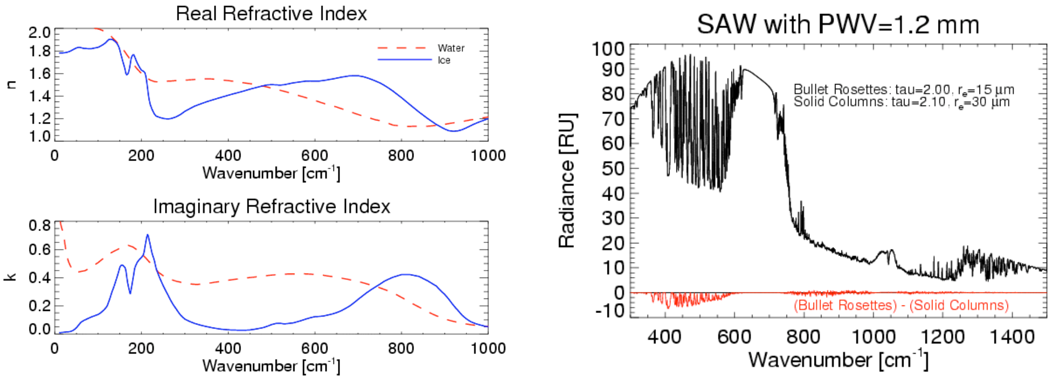

Fig 5: (Left) Real (n) and imaginary (k) refractive indices of water and ice in the infrared. (Right) Comparison of two downwelling infrared radiance calculations, one assuming bullet rosettes and the other assuming solid hexagonal columns. The optical depths and effective radii were chosen to get agreement in the 8-13 µm band. The cloud was placed at 10 km in the subarctic winter profile. A RU is a radiance unit, which is 1 mW / (m^2 sr cm^{-1}).

At present, modeling and analysis of cirrus properties are carried out by observing the properties of clouds in the mid-infrared atmospheric window and then extending those calculations to the far-IR using Mie theory. However, while Mie theory can be used to model the scattering by spheres, realistic ice crystals are far more challenging, as a myriad of cirrus particle shapes and sizes are typically contained in ice clouds [*Baran*, *2004*]. Recently, modeled single-scattering properties of ice particles have been published [*Baum et al*., *2005a, b*]. These have been validated in the mid-IR but not in the far-IR. For example, Fig 5 (right) illustrates that two simulated cirrus clouds, consisting of different habits, effective radii, and optical depths, can have similar spectral radiance signatures in the 8-13 µm band but differ substantially (over 10 %) in the 18-35 µm region. Observations of far-IR radiance in the presence of cirrus clouds, such as those collected during this experiment, can be used to test and validate the modeled optical far-IR properties of ice clouds. This is a critical objective since cirrus clouds are known to cover 30% of the Earth's surface [*Wylie and Menzel*, 1994].

While the transparency of the lower atmosphere has hindered the evaluation of the far-IR and its contribution to the radiative processes in the middle and upper troposphere, an even more substantial obstacle has been the lack of radiometric instrumentation in the far-IR. The recent development of a new generation of instruments for the measurement of spectral radiation in the far-IR has provided the capability to rectify this state of affairs (Fig 1, bottom).

As part of this experiment, we propose to deploy three of these instruments side-by-side at the ARM NSA site to evaluate their calibration and performance, and to address the uncertainties and science questions posed above. This presents ARM with a terrific opportunity to contribute substantially to the evaluation and improvement of the parameterization of these crucial radiative processes in climate simulations, thereby allowing ARM to even more comprehensively attack its primary goal "to improve the treatment of cloud and radiation physics in global climate models in order to improve the climate simulation capabilities of these models."

2. *Instrument Descriptions*

i) AERI-ER

The Atmospheric Emitted Radiance Interferometer (AERI) is an automated ground-based interferometer that measures downwelling infrared radiance at 0.5 cm^{-1} unapodized resolution. Two high-emissivity blackbodies and careful characterization of the instrument result in the absolute calibration of the observed radiance being better than 1% of the ambient radiance [*Knuteson et al*. 2004a, b]. The ARM program has deployed AERIs at all of Climate Research Facilities, and extensive datasets (over a decade at the SGP site, nearly 8 years at the NSA site) have been collected. The AERIs deployed in the Arctic are modified systems that have an extended range, and thus observe downwelling radiance from 3.3 to 25 μm (3000 – 400 cm^{-1}). Comparisons of the observed radiance from two collocated AERI extended-range (ER) systems at Barrow, with each instrument utilizing a different set point for the hot blackbody, agreed within the 1% ambient radiance level thereby demonstrating the calibration consistency between different AERI systems and the accuracy of the non-linearity correction applied to the AERI observations [*Turner et al*. 2004b].

ii) FIRST

The Far-Infrared Spectroscopy of the Troposphere (FIRST) instrument was recently developed at NASA Langley Research Center. The FIRST instrument consists of a scene select mirror, a Fourier transform spectrometer (FTS), aft optics, a detector assembly, and associated electronics [*Mlynczak et al*., 2005]. The FTS and aft optics are cooled to ~180 K by liquid nitrogen, the detectors are cooled to 4.2 K by liquid helium, and the rest of the instrument is at ambient temperature. Thin polypropylene windows isolate the cold FTS optics from the scene select mirror and from the detector dewar. The FTS is a compact plane mirror Michelson interferometer that achieves very high throughput (0.47 cm^2 sr) with a modest 7 cm diameter beam. Broadband response (100-1600 cm^{-1}) is made possible by the bilayer thin-film beamsplitter. FTS scanning and detector sampling are controlled by a separate metrology laser interferometer that monitors the position of the scan mirror. Interferometer alignment (for both the infrared and laser interferometers) can be adjusted if necessary by remotely controlling the tip and tilt of the non-scanning interferometer mirrors. The FTS scans over optical path differences of +/- 0.8 cm for a nominal unapodized resolution of 0.625 cm^{-1}; the scan time varies from 1.4 to 8.5 s, depending on the detector sample interval. Trimming and centering the interferograms reduces the realized unapodized resolution to 0.643 cm^{-1}. The FIRST instrument made a successful high-altitude balloon flight in 2005 from Ft. Sumner, NM, observing the nearly complete thermal emission spectrum of the Earth from a space-like vantage point for the first time [*Mlynczak et al*., 2006]. The FIRST radiance observations between 850-1000 cm^{-1} agree well with the spectrum observed by the AIRS instrument on the AQUA satellite [*Mlynczak et al. 2006*] during the single overpass afforded by this balloon flight.

iii) TAFTS

The Tropospheric Airborne Fourier Transform Spectrometer (TAFTS) instrument was developed at Imperial College, London. The TAFTS is a far-IR Martin-Puplett polarising FTS [*Canas et al., 1997*]. It has liquid helium-cooled detectors that operate in two bands, 80-300 cm^{-1} and 300-650 cm^{-1} and a resolution of 0.12 cm^{-1}. A steerable pointing unit allows TAFTS to operate in a nadir, zenith or direct net radiance mode with a scan duration of about 2 seconds. Four internal blackbodies provide in-flight calibration that occupies about one third of a measurement cycle. The TAFTS instrument is primarily an aircraft instrument and has been in operation since 1999. It has flown on three platforms including the UK Met. Office C-130, ARA Egrett and the FAAM BAe-146. It has taken part in various campaigns in the UK and Australia. Previous successful campaigns have included clear-sky studies in the UK in collaboration with the UK. Met. Office and NASA, and cirrus campaigns with a number of UK universities at mid-latitudes and the tropics.

iv) GSR

The NOAA Earth System Research Laboratory has designed a multi-frequency scanning radiometer operating from 50 to 380 GHz [*Westwater et al. 2004*]. The radiometers are installed into a scanning drum scanhead that is mechanically and electrically compatible with the NOAA Polarimetric Scanning Radiometer (PSR) aircraft instrument. The PSR system has operated in more than 15 experiments and has over 600 flight hours of successful operation observing the Earth's surface and atmospheric parameters. The ground-based scanning radiometer (GSR) instrument has 11-channels in the 50-56 GHz region, a dual-polarization measurement at 89 GHz, 7-channels around the 183.31 GHz water vapor absorption line, dual-polarized channels at 340 GHz, and 3-channels at 380 GHz. All of the radiometers are mounted within a rotating scanhead, use lens antennas, and view two external reference targets during the calibration cycle. New thermally stable calibration targets with high emission coefficients have been designed for the purpose. In addition, each of the radiometers' design includes two internal reference points for more frequent calibration. The beam widths of the GSR channels are 1.8° and can be averaged to given beam-widths consistent with the ARM MWR (4.5 to 5.5°). Further details on this instrument and its calibration are given in Cimini et al. (*2006b*).

v) GVR

The G-band water vapor radiometer (GVR) was developed and built by ProSensing Inc. with a U.S. DOE Small Business Innovation Research (SBIR) grant [*Pazmany, 2006*]. It measures brightness temperatures from four double sideband channels centered at ±1, ±3, ±7, and ±14 GHz from the 183.31 GHz water vapor absorption line. Bandwidths of the 4 channels are 0.5, 1.0, 1.4, and 2.0 GHz, respectively. The radiometer uses a hot (~330K) and warm (~290K) calibration targets, and the calibration accuracy is approximately 1 K. The GVR was deployed at the NSA site from April 2005 – March 2006, and initial results are given in *Cadeddu et al.* [*2006*]. The GVR is currently being hardened and upgraded as a result of this initial deployment and will return to the NSA site in approximately October 2006.

3. Radiative Heating in Underexplored Bands Campaign

Our lack of knowledge of mid-to-upper tropospheric radiative processes is a significant uncertainty in simulations of future climate and, therefore, a barrier to the determination by policy makers of strategies to ensure the future health of our planet. To address the scientific issues discussed above, we propose to conduct the *Radiative Heating in Underexplored*

Bands Campaign (RHUBC, pronounced “roobik”) from 22 February to 14 March 2007 at the NSA site in Barrow. During this time of year, the PWV is typically between 1-3 mm (Fig 3) and the frequency of occurrence of low stratus clouds is at a minimum (approximately 40-50%). This campaign would allow the collection of a robust set of measurements corresponding to low PWV and cold temperatures; this is unobtainable in the laboratory. The primary goals of RHUBC are:

a) The performance of clear-sky radiative closure studies in order to reduce key uncertainties in water vapor spectroscopy, including the foreign-broadened water vapor continuum and water vapor absorption line parameters in the far-infrared spectral region.

b) Instrument cross-calibration and validation. FIRST, TAFTS, and the AERI-ER are state-of-the-art instruments that operate in far-IR for the purpose of atmospheric radiative transfer studies. None of these instruments have been validated in an operational environment against a complementary interferometer. The inter-comparison will allow a higher confidence in the results from all three instruments.

c) The investigation of the radiative properties of sub-arctic cirrus. The combination of the AERI-ER, FIRST, and TAFTS will allow simultaneous high-resolution measurements of Arctic cirrus emission in the far-IR for the first time. The additional instrumentation (MPL, MMCR) at the ARM site will provide a comprehensive array of auxiliary data, maximizing the scientific value of this data set.

In order to accomplish the objectives of this experiment, the FIRST and TAFTS must be deployed to the site. Additionally, since accurate PWV observations are critical, we require that observations by a 183 GHz microwave radiometer be made at the site. It is our understanding that the ProSensing GVR will be returned to the NSA site in Oct 2006 after its refurbishment and will be operational during the proposed IOP period. However, given the GVR is still a relatively new instrument, we highly recommend that the NOAA GSR also be deployed to provide another observation for this critical measurement. Finally, the atmospheric state must be well described for the forward calculations, and thus we require an additional 40 radiosondes (to supplement the twice daily launch schedule currently being used at the NSA site) that can be launched during the IOP.

The data collected in RHUBC will be used to perform a detailed radiative closure analysis, consisting of a simultaneous evaluation of the three fundamental components of such a study: the atmospheric state above the instruments’ location; the measurements of the radiometers; and the spectroscopic underpinnings of the radiative transfer calculations in the relevant spectral regions. A vital step in this procedure will be, for each case analyzed, the determination of the water vapor field present based upon contemporaneous GSR, GVR, and radiosonde measurements.

It is important to note that this determination will involve a second radiative closure study, this one in the microwave region, which will simultaneously evaluate the water vapor profile, the microwave measurements, and the spectroscopy of the radiative transfer model, MonoRTM [*Clough et al., 2004*]; in this context, the presence of both the GSR and GVR instruments is critical to the success of the campaign. The water vapor profiles determined by this approach will be used as input to the LBLRTM radiative transfer model [*Clough and Iacono, 1995; Turner et al. 2004*], which will be utilized to compute radiances for comparison with corresponding measurements of the AERI, FIRST, and TAFTS. Any discrepancies between the calculations and measurements, or between measurements of the different instruments, will be carefully assessed to determine which of the three components is responsible for the discrepancy. Given the lack of experimental validation of spectroscopic parameters in the far-infrared and ν_2 bands of water vapor, it is likely that one of the causes of measurement-model discrepancies that are found in RHUBC will be these parameters, most notably the water vapor continuum, line strengths and widths.

Whatever spectroscopic parameters are found to need adjustment, the RHUBC team is well-positioned to pass these improvements onto the rest of the community and have them affect future GCM simulations. In particular, the water vapor continuum parameterization used by almost all radiative transfer models, the MT_CKD model, has been developed and is maintained by one of the RHUBC PIs. If the RHUBC analysis leads to the conclusion that the MT_CKD needs revision, within a short time period after the analysis is complete a revised version will be created and an announcement will go out to the community. Additionally, the research group at AER has long-standing and deep connections with the developers of the HITRAN spectroscopic database. As was the case when the work of Delamere et al. (2004) indicated issues with the water vapor line widths between 420-500 cm^{-1}, any issues with the far-infrared line parameters discovered as a result of RHUBC will be communicated to HITRAN, and a revision will likely result. As for the effect of any spectroscopic changes from RHUBC affecting GCM simulations, one of the PIs is the lead developer of RRTM [*Mlawer et al., 1997*], a fast radiation code used in a number of GCMs. Changes to the MT_CKD continuum or HITRAN line parameters will be incorporated into more accurate absorption coefficients in RRTM, and the subsequently revised version of RRTM will be distributed to modeling centers with which it is associated.

RHUBC also provides an opportunity to intercompare several state-of-the-art far-IR interferometers. The AERI-ER, which participated in SHEBA and has been deployed at the ARM NSA site since 1998, has compared well with other AERI-ER instruments [e.g., *Turner et al. 2004b*]. However, the TAFTS and FIRST utilize different approaches (e.g., liquid helium cooled detectors) to make similar measurements, and thus are complementary measurements that can be used to further evaluate the accuracy of the AERI-ER and vice versa. The investigators for this proposal have extensive experience with infrared interferometer data and their evaluation, and thus intercomparisons will lead to improved observations and increased confidence in these observations.

Similarly, RHUBC will also provide an opportunity to evaluate ARM's new 183 GHz millimeter wave radiometer (the GVR) against a complementary system (the GSR) that has been deployed at the NSA site during two previous IOPs (spring 1999 and spring 2004). The complementary observations, both of which using different instrumental and calibration approaches, will be used to characterize the GVR's accuracy. The PWV retrievals from these two radiometers will be used to scale the radiosondes water vapor profiles and to drive infrared radiation calculations which are then compared against the infrared observations; comparisons such as these have also been used to characterize the accuracy of the PWV retrievals [e.g., *Turner et al. 2003*].

Cirrus clouds cover a substantial fraction of the globe at any given time, and thus their radiative properties must be understood in order to capture them correctly in climate models. Several groups have proposed theoretical treatments of the ice crystal radiative properties in the far-IR [e.g., Baran, 2004, Baum et al., 2005a,b, Yang et al. 2003]; however, due to the lack of observations in this spectral region, these models have not been validated. RHUBC provides an opportunity to investigate the ability of these single scattering property models under low PWV conditions to provide closure in the far-IR as well as in other spectral regions (e.g., 8-13 μm and 3-4 μm). Additionally, the co-located observations by the ARM micropulse lidar (MPL) can be used to provide another estimate of the cirrus optical depth to constrain and/or evaluate the optical depths retrieved from the ground-based IR observations, and the combined MPL and millimeter-wave cloud radar (MMCR) observations provide an estimate of the ice particle size (e.g., Donovan and van Lammeren, 2001) that can be used in a similar manner. This dataset will also be used to examine the sensitivity of the far-IR radiance, in a relative sense to the radiance in the 8-13 μm and 3-4 μm bands, to the assumption of the ice particle size distribution.

The ARM Instantaneous Radiative Flux (IRF) working group has enthusiastically endorsed this experiment. The proposed RHUBC observations at the NSA site will also contribute to the objectives of the International Polar Year.

4. *Project Management*

Principal Investigators (PIs) Dr. David Turner and Dr. Eli Mlawer will actively manage this field experiment. Each of the investigators brings a set of unique skills and experience to the team. Dr. Turner has extensive experience analyzing AERI data, and will be the AERI instrument mentor starting October 2006. He has performed spectral radiative closure studies similar to the ones planned for RHUBC, and as such has worked with microwave radiometer and radiosonde data. In addition, Dr. Turner has had previous experience conducting experiments in the Arctic. Dr. Mlawer has extensive experience with line-by-line radiative transfer modeling and validating these models with high-spectral resolution radiance observations. He is the lead developer of the MT_CKD water vapor continuum, used by virtually all modeling centers, which will be a beneficiary of improvements in knowledge resulting from RHUBC. Drs. Turner and Mlawer have worked together on many collaborative projects for more than a decade, including a number of efforts related to the objectives of RHUBC.

The responsibilities of the RHUBC PIs will be wide-ranging and extensive in the execution of the campaign. Prior to mid-February 2007, the PIs will interact with the NSA site scientist team to ensure that all preparations necessary for the campaign's success are being undertaken, including the construction of a shelter for the far-IR instruments, the purchase and delivery of cryogens, the preparation of standard ARM instrumentation needed for RHUBC, etc. During this period, the PIs will interact with the Co-Investigators who are bringing their own instruments to NSA to make sure that all necessary efforts are being expended to prepare these instruments for RHUBC and that these collaborators are kept informed of general developments concerning the campaign. It is expected that the instruments being brought to NSA especially for RHUBC will arrive one week before the commencement of the campaign in order to have sufficient time to be set up and evaluated. Either Dr. Turner or Dr. Mlawer will be present for the entire set-up time period to supervise and troubleshoot any issues that arise.

At least one of the PIs will be present at NSA during the entire three-week duration of RHUBC so that there is always someone present to make necessary judgments. It is anticipated that each PI will be at NSA for 2+ weeks, overlapping with each other for a few days in the middle of the four-week time period (one week set-up + three-week campaign). One key decision that the on-site PI will make is the timing of the launches of the additional radiosondes requested for the campaign. The successful accomplishment of RHUBC's objectives is dependent on the presence of low water vapor column amounts and the absence of liquid clouds. A RHUBC radiosonde will be launched only if these conditions are present, which will require a judgment call to be made by the on-site PI. When a day with optimal conditions occurs (i.e. clear skies with PWV near 1 mm), a number of radiosondes launches are likely to occur. The PIs will work with site scientist team to do evaluate local weather forecasts, which will have to be taken into account in order to make appropriate preparations. In addition, the PI will work with the mentors of the special RHUBC instruments to plan, implement, and troubleshoot day-to-day activities related to the campaign.

After RHUBC is over, the PI present will coordinate all necessary efforts to return the instruments and site to their normal state of affairs. The PIs will lead the efforts to analyze the data collected, interface with ARM infrastructure to enable access via the ARM archive to RHUBC data within the field, and communicate the results of the campaign to the ARM IRF working group, ARM management, and to the broader ARM and radiation science communities.

This experiment will utilize radiometric instruments brought to the NSA ACRF specifically for this campaign. The PI from each instrument will be a RHUBC Co-Investigator, ensuring that measurements from all essential instruments will be of the highest quality possible. Dr. Cadeddu has collaborated directly with the vendor in the initial analysis of the first year of data from the GVR and is extremely well suited for her planned critical role in RHUBC. Drs. Mlynzcak and Green are the PIs of the FIRST and TAFTS instruments, respectively, while Dr. Westwater is the PI of the GSR. Each of these Co-Investigators will be responsible for the transport of their instrument to the site, its set-up during the week before the commencement of the campaign, the operation of the instrument during the three weeks of RHUBC, and its transport from NSA after the campaign. During the campaign, they will interact with the PIs and the other instrument Co-Investigators to begin the analysis of the measurements that their instrument has made. In this regard, Drs. Westwater and Cadeddu will work with the PIs to use the measurements of the these two microwave radiometers in concert with the radiosonde data to determine the best estimate of the water vapor field emitting the radiation that is the focus of RHUBC. The extensive experience of these two scientists, along with the complementary radiative transfer modeling skills of Drs. Turner and Mlawer, will be critical to making this essential determination. In addition, Dr. Westwater has had previous experience conducting experiments in the Arctic.

Relevancy to the long-term goals of the DOE Office of Science

This proposed field campaign has clear and direct relevance to the long-term goals of the DOE Office of Biological and Environmental Research. Policy makers, in order to determine safe levels of greenhouse gases, must depend on computer simulations of future climate. The accuracy of these simulations is limited by uncertainties in the parameterizations of key physical processes. One significant uncertainty is associated with the radiative heating of the mid-to-upper troposphere, an important contributor to the dynamical processes and radiative balance that affect our climate. This primary objective of the *Radiative Heating in Underexplored Bands Campaign* (RHUBC) is a major reduction of this key limiting uncertainty, which will be accomplished by the simultaneous removal of the two obstacles that have heretofore prevented substantial progress in this quest: the high opacity of the lower atmosphere due to water vapor has obstructed the observation of the relevant radiative processes from the surface; and the lack of well-calibrated spectral instruments that measure radiation in the associated spectral region, the far-infrared, has eliminated the possibility of obtaining data to improve our knowledge of these processes. The resulting improvement of our knowledge of atmospheric radiative processes will lead to better climate simulations of all latitudes, including a reduction in the differences between observations and simulations of many key climate-related physical quantities such as temperature and moisture.

References

Baran A. J., 2004: On the scattering and absorption properties of cirrus cloud. *J. Quant. Spectrosc. Rad. Trans.*, **89**, 17-36.

Baum, B. A., Andrew J. Heymsfield, Ping Yang and Sarah T. Bedka, 2005a: Bulk Scattering Properties for the Remote Sensing of Ice Clouds. Part I: Microphysical Data and Models. *J. Appl. Meteor.*, **44**, 1885–1895.

Baum, B. A., Ping Yang, Andrew J. Heymsfield, Steven Platnick, Michael D. King, Y.-X. Hu and Sarah T. Bedka, 2005b: Bulk Scattering Properties for the Remote Sensing of Ice Clouds. Part II: Narrowband Models. *J. Appl. Meteor.*, **44**, 1896–1911.

Cadeddu, M., J.C. Liljegren, and A. Pazmany, 2006: Measurements and retrievals from a new 183-GHz water-vapor radiometer in the Arctic. *IEEE Trans. Geosci. Remote Sens.*, submitted.

Canas AA, JE Murray JE, and JE Harries, 1997: The Tropospheric Airborne Fourier Transform Spectrometer, SPIE, **3220**, 91-102.

Cimini, D., E.R. Westwater, A.J. Gasiewski, M. Klein, and J.C. Liljegren, 2006a: Millimeter- and submillimeter-wave observations of low vapor and liquid water amounts in the Arctic winter. *Proc. 16th ARM Science Team Meeting*, March 23-31, Albuquerque, NM.

Cimini, D., E.R. Westwater, A.J. Gasiewski, M. Klein, and J.C. Liljegren, 2006b: The ground-based scanning radiometer (GSR): a powerful tool for the study of the Arctic atmosphere. *IEEE Trans. Geosci. Remote Sens.*, submitted.

Clough, S.A. and M.J. Iacono, Line-by-line calculations of atmospheric fluxes and cooling rates II: Application to carbon dioxide, ozone, methane, nitrous oxide, and the halocarbons*, J. Geophys. Res., 100*, 16,519-16,535, 1995.

Clough, M.J. Iacono, and J.-L. Moncet, 1992: Line-by-line calculations of atmospheric fluxes and cooling rates: application to water vapor. *J. Geophys. Res.*, **97**, 15761-15785.

Clough, S. A., M. W. Shephard, E. J. Mlawer, J. S. Delamere, M. J. Iacono, K. Cady-Pereira, S. Boukabara, and P. D. Brown, Atmospheric radiative transfer modeling: a summary of the AER codes, Short Communication, *J. Quant. Spectrosc. Radiat. Transfer*, *91*, 233-244, 2005.

Delamere, J.S., S.A. Clough, and E.J. Mlawer, 2004: An investigation of atmospheric water vapor and its radiative effects at the ARM North Slope of Alaska CART site. Presented at the 14th ARM Science Team meeting, Albuquerque, NM.

Donovan, D.P., and A.C.A.P. van Lammeren, 2001: Cloud effective particle size and water content profile retrievals using combined lidar and radar observations - 1. Theory and examples. J. Geophys. Res., **106,** D21, 27425-27448.

Green, PD., JE Murray, C. Cox, JE Harries, JC Pickering, and JP Taylor, 2005: High resolution far-IR spectra from the TAFTS instrument during EAQUATE 2004. *Fourier Transform Spectroscopy/Hyperspectral Imaging and Sounding of the Environment Topical Meeting on the CD-ROM*, The Optical Society of America, Washington DC.

Knuteson, R.O., and coauthors, 2004a: The Atmospheric Emitted Radiance Interferometer (AERI) Part I: Instrument Design. *J. Atmos. Oceanic Technol.*, **21**, 1763-1776.

Knuteson, R.O., and coauthors, 2004b: The Atmospheric Emitted Radiance Interferometer (AERI) Part II: Instrument Performance. *J. Atmos. Oceanic Technol.*, **21**, 1777-1789.

Mlawer, E.J., .J. Taubman, P.D. Brown, M.J. Iacono and S.A. Clough, 1997: RRTM, a validated correlated-k model for the longwave. *J. Geophys. Res.*, **102**, 16,663-16,682.

Mlawer, E.J., P.D. Brown, S.A. Clough, L.C. Harrison, J.J. Michalsky, P.W. Kiedron, and T. Shippert, 2000: Comparison of spectral direct and diffuse solar irradiance measurements and calculations for cloud-free conditions, *Geophys. Res. Lett., 27*, 2653-2656.

Mlynczak, M. G., et al., 2005: The far-infrared spectroscopy of the troposphere project, in *Enabling Sensor and Platform Technologies for Spaceborne Remote Sensing*, George J. Komar, Jinxue Wang, and Toshiyoshi Kimura, Editors, Proceedings of SPIE, Vol. **5659**, 81-87.

Mlynczak, M. G., D. G. Johnson, H. Latvakoski, K. Jucks, M. Watson, G. Bingham, D. P. Kratz, W. A. Traub, S. J. Wellard, and C. R. Hyde, 2006: First light from the far-infrared spectroscopy of the troposphere (FIRST) instrument, *Geophys. Res. Lett.*, **33**, L07704, doi:10.1029/2005GL025114.

Pazmany, A.L., 2006: Compact 183-GHz radiometer for airborne and ground-based water vapor and liquid water. *IEEE Trans. Geosci. Remote Sens.*, submitted.

Revercomb, H.E., and coauthors, 2003: The Arm Program's Water Vapor Intensive Observation Periods**.** *Bull. Amer. Meteor. Soc.*, **84**, 217–236.

Tobin, D.C., and coauthors, 1999: Downwelling spectral radiance observations at the SHEBA ice station: Water vapor continuum measurements from 17-26 micrometer, *J. Geophys. Res.,* **104**, 2081-2092.

Tobin, D.C., R.O. Knuteson, and H.E. Revercomb, 2000: Observed and calculated downwelling longwave spectral radiances at the SHEBA ice station: Prelude to an arctic AERI/LBLRTM QME. *Proc. 10th ARM Science Team Meeting*, March 13-17, San Antonio, TX.

Turner, D.D., D.C. Tobin, S.A. Clough, P.D. Brown, R.G. Ellingson, E.J. Mlawer, R.O. Knuteson, H.E. Revercomb, T.R. Shippert, W.L. Smith, and M. Shepard, 2004a: The QME AERI LBLRTM: A closure experiment for downwelling high spectral resolution infrared radiance, *J. Atmos. Sci.,* **61**, 2657-2675.

Turner, D.D., H.E. Revercomb, R.O. Knuteson, R.G. Dedecker, and W.F. Feltz, 2004b: An evaluation of the nonlinearity correction applied to Atmospheric Emitted Radiance Interferometer (AERI) data collected by the Atmospheric Radiation Measurement Program. ARM Tech. Report TR-013, 9 pp. Available at http://www.arm.gov/publications/tech_reports/arm-tr-013.pdf.

Westwater, E.R., and coauthors, 2004: The 2004 North Slope of Alaska Arctic Winter Radiometric Experiment. *Proceedings of the 14th ARM Science Team Meeting*, March 22-26, 2004, Albuquerque, NM.

Wylie D. P., and W. P. Menzel, 1994: Four years of global cirrus cloud statistics using HIRS*,* *J. Climate*, **7**, 1972-1986.

Yang, P., M.G. Mlynczak, H.-L. Wei, D.P. Kratz, B.A. Baum, Y.X. Hu, W.J. Wiscombe, A. Heidinger, and M.I. Mishchenko, 2003: Spectral signature of ice clouds in the far-infrared region: Single-scattering calculation and radiative sensitivity study. *J. Geophys. Res.*, **108**, doi: 10.1029/2002JD003291.