ATMOSPHERIC CHEMISTRY IN THE ARCTIC AT THE PEARL OBSERVATORY LOCATED AT EUREKA, NUNAVUT

BY JAMES R. DRUMMOND AND THE CANDAC TEAM

The Polar Environment Atmospheric Research Laboratory (PEARL) is located at 80°N, 86°W on Ellesmere Island, near Environment and Climate Change Canada's (ECCC's) Eureka Weather Station. PEARL is a self-contained scientific laboratory operated year-round by the Canadian Network for the Detection of Atmospheric Change (CANDAC) since 2006. Most of the research conducted at PEARL concerns the Arctic atmosphere, but other branches of science are supported including geology and astronomy.

The equipment installed at PEARL comprises a complete monitoring system for looking at the atmosphere from the surface of the earth to a height of about 100 km. More than 20 instruments are currently deployed and there is a "guest instrument" program in place for those who wish to place equipment at PEARL.

Measurements for atmospheric studies at the PEARL are of two types: "in situ" measurements where a sample of the atmosphere is ingested into an apparatus for measurement, and remote sensing measurements which monitor the atmosphere at a distance from the measuring instrument. These remote sensing measurements all rely implicitly or explicitly on spectroscopic and related parameters and use many wavelengths and interactions between the atmosphere and electromagnetic radiation for their success.

INSTRUMENTATION AT PEARL

Remote sensing instruments rely on analyzing incoming electromagnetic radiation to the instrument. At PEARL there are four major sources of radiation:

(1) Sunlight outside of the atmosphere can be nearly described by a Planck function for ~5780K which peaks around 11,000 cm^{-1} (~1 μm). The main advantages of using solar radiation as a source are its directionality which allows for easy localization of the measurement and the strength of the solar beam which results in high(er) signal-to-noise at the detector. However, there is a major disadvantage to solar radiation at PEARL – from mid-October to mid-February there is none and it is dark. We can use moonlight (reflected sunlight) or starlight as substitutes, but these are very much weaker than sunlight and the signal-to-noise of measurements is correspondingly worse. The dark polar night also has profound effects on the atmosphere as we discuss below.

(2) Thermal radiation is ubiquitous for any object above absolute zero temperature and radiation is emitted appropriate to the Planck function which averages below zero degrees centigrade at PEARL. The peak of the radiation is around 500-600 cm^{-1} (16-20 μm). The radiation is omnidirectional and so the instrument receiver defines the field of view and the localization of the measurement. Thermal radiation can be used year-round but the signal-to-noise of measurements tends to be lower than with the solar beam and the radiative transfer calculations are more involved.

(3) Several processes can excite atoms and molecules in the upper atmosphere which then decay emitting radiation at detectable wavelengths. The most usable wavelengths for measurement are in the visible region because the atmosphere is transparent in this region and the interactions that occur at high altitudes are visible from the ground. Measurements are more easily made during the polar night because of the absence of sunlight.

(4) Finally, we can provide our own radiation source by emitting energy and detecting energy transmitted or, more frequently, "backscattered" to the receiver. Some of these measurements are possible in both day and night and this method, through "time of flight" measurements, provides range determination and therefore better localization of the measurement. However, the complexity (and power consumption) of the source also need to be factored into any discussion of usability.

SUMMARY

The remote sensing equipment for atmospheric studies at the Polar Environment Atmospheric Research Laboratory (PEARL) at Eureka, Nunavut is described.

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TABLE 1
Some spectral characteristics of the remote sensing instrumentation at PEARL.

Wavelength	Instrument	Parameter Measured	Comments
287-363 nm	Brewer ozone spectrophotometer	Ozone	Uses sunlight and differential absorption
Transmit: 308/353 nm Receive: 308/332/353/385/406 nm	Differential Absorption Lidar (DIAL)	Aerosol, temperature, ozone, water vapour	Uses differential absorption to detect ozone profiles
340-1640 nm	CIMEL	Aerosols and optical depth	Measures attenuation of sunlight or moonlight
340-540 nm	Ground-Based Spectrometers (UT and PEARL-GBS)	Ozone and other constituents	Measure direct or scattered sunlight
420-1040 nm	Star photometer	Aerosols and optical depth	Measures attenuation of starlight
Transmit: 532/355 nm Receive: 355-607 nm	CANDAC Rayleigh-Mie-Raman Lidar (CRL)	Clouds, aerosol properties, droplets/ice particles	Uses polarisation to distinguish ice from water
428-910 nm	All-Sky Imager (ASI)	Spatial and temporal fluctuations in airglow and aurora	Several narrow band images at specific airglow wavelengths
558-866 nm	E-Region Wind Interferometer (ERWIN)	Winds in the mesosphere	Interferometric measurement of Doppler shifts of airglow
834-868 nm	Spectral Airglow Temperature Imager (SATI)	Dynamics and temperature of the mesosphere	2-channel spatial scanning Fabry-Perot interferometer
2.4-14 µm	Bruker Fourier Transform Spectrometer (FTS)	minor constituents	Absorption of direct solar beam
3-25 µm	Extended-Range Atmospheric Emitted Radiance Interferometer (E-AERI)	Downwelling radiance and minor constituents	Measures downwards directed radiation throughout the year
Transmit/Receive: 35 GHz	MilliMeter Cloud Radar (MMCR)	Cloud properties	Active radar
23.8 and 31.4 GHz	Microwave Radiometer	Water vapour/liquid	Microwave emission
Transmit/Receive: 52 MHz	VHF radar	Winds and turbulence	Backscatter from atmospheric inhomogeneities
Transmit/Receive: 34.1 MHz	Meteor radar	Winds Temperature around 80-100 km	Measures scatter from ionised meteor trails

Table 1 shows many of the instruments used for remote sensing at PEARL. They include both active sensors, generating their own probe beams and passive instruments relying on natural radiation arriving at the surface. Use is made of the entire spectrum from the ultraviolet to the radio region to elucidate a wide range of atmospheric parameters.

Ultraviolet and Visible Region

In the range 300-600 nm we have a series of lidars. In their simplest form these measure the time of flight of an upward-directed coherent light pulse from the transmitter to a backscattering layer. Scattering can occur from any "particle" from a molecule to a water droplet and the scattering can be elastic or inelastic. Inelastic scattering is particularly interesting because it can reveal details about the composition of the atmosphere as well as its physical state.

Of particular interest is the ozone Differential Absorption Lidar (DIAL) which makes use of the fact that ozone has a very highly structured absorption with wavelength in the ultraviolet whereas most of the other absorbers in the region have relatively unstructured absorption. Thus by choosing two wavelengths close to one another with similar unstructured absorption but with very different ozone absorptions, a unique signature for ozone can be developed as a function of altitude.

This differential absorption technique is exploited in many similar forms by other instruments at PEARL. For example, the Brewer Ozone spectrometer (developed by Dr. Alan Brewer and colleagues at the University of Toronto and further enhanced by the staff at Environment and Climate Change Canada before going into commercial production) uses very similar wavelengths to the DIAL, but it measures the attenuation of sunlight through the atmosphere rather than producing its own radiation. Two other Ultraviolet-Visible spectrometers – the ground-based spectrometers (GBS) – also measure direct and scattered sunlight to produce measurements of atmospheric constituents including ozone.

For measurements in the upper atmosphere, around 100 km altitude, we can use observe the radiation produced by interaction with incoming particles. We can observe the entire sky at particular wavelengths using an All-Sky imager which allows us to observe spatial and temporal fluctuations in the incoming radiation. We can also measure the energy at specific wavelengths to gain information on density and temperature at these levels and by measuring the Doppler shift of the emissions we can deduce winds.

Infrared Region

As wavelengths increase from the visible into the infrared, the interaction with the components of the atmosphere shifts to the vibration-rotation bands. Since oxygen and nitrogen molecules are homopolar and therefore have a negligible vibration-rotation spectrum, the spectra observed are from more minor components of the atmosphere, some with concentrations in the parts-per-billion range. These components including water vapour, ozone, carbon oxides, nitrogen oxides, all play a considerable role in the energy balance of the atmosphere since they interact radiatively with the atmosphere, surface, sun and space. They also chemically interact with each other and incoming sunlight when present. This gives the winter polar atmosphere a distinctly different composition to the summer atmosphere and the transitions at dusk and more importantly at sunrise are extremely interesting. There is always a major observing campaign at PEARL around sunrise in mid-February to study this change-over. The paper by Strong et al in this issue gives some more detail on the infrared spectroscopy of these constituents accomplished at PEARL.

As already mentioned, daylight at PEARL occurs between mid-February and mid-October with much of this time being 24-hour daylight allowing for many measurements of solar attenuation per 24-hour period if the equipment is sufficiently automated. However, there is also the night period when there is no sunlight and in this period instruments that rely on the solar beam make no measurements. Filling in the measurements during the polar night is a major focus of instrument development at PEARL with efforts to exploit different wavelength regions, sighting off of the moon and stars, and active sensing using the lidars and radars.

As the wavelength increases through the infrared, the atmospheric emission (Planck function) also increases and by sensing this signal, measurements can be extended throughout the year.

The annual light/dark cycle at these latitudes is considerably different from the daily cycle further south and combined with the perpetually low solar zenith angles this results in a cold atmosphere. During the polar night there is no sunlight at all and therefore no solar warming of either the atmosphere or the surface and temperatures drop considerably. Surface temperatures in January are on *average* about -20°C. A spectroscopic consequence is that there is very little water vapour in the atmosphere and this has a very noticeable effect on the atmospheric transmission. This can be clearly seen in Fig. 1 which shows spectra measured by the Extended-Range Atmospheric Emitted Radiance Interferometer (E-AERI) which uses a Fourier Transform spectrometer to determine the downwards directed radiation at the surface. The first panel shows spectra taken on November 1, 2008. The “window” region at 800-1200 cm^{-1} (8-13 μm) where the atmosphere is practically transparent except for the ozone feature at 9.6 μm can clearly be seen. Since this this is close to the peak of the surface blackbody spectrum much energy from the surface is emitted directly through the atmosphere to space. A temperature inversion (where the temperature increases with altitude at and near the surface) has the effect of suppressing convection and it is no surprise that the surface becomes extremely cold and this reinforces the temperature inversion which is almost a permanent feature of the near-surface winter polar atmosphere.

As clouds move in they intercept radiation leaving the surface, closing the windows to space (cyan line in Fig. 1), and therefore the surface will warm the atmosphere and the atmosphere the surface.

In addition to the 800-1200 cm^{-1} (8-12 μm) window, at longer wavelengths a “dirty window” appears below 400 cm^{-1} (25 μm). The line structure seen in this region is due to water vapour and in a warmer atmosphere at lower latitudes the water vapour absorption would be more complete thus closing the window for transmission of energy to space. This can be seen in the second panel of Fig. 1 which was taken in the summer when atmospheric temperatures and water vapour content were higher. The presence of this additional window in the polar atmosphere accelerates the energy loss to space from both the atmosphere and the surface, further lowering temperatures.

As has already been noted, there are features for different constituent gases in the downwelling spectrum from the

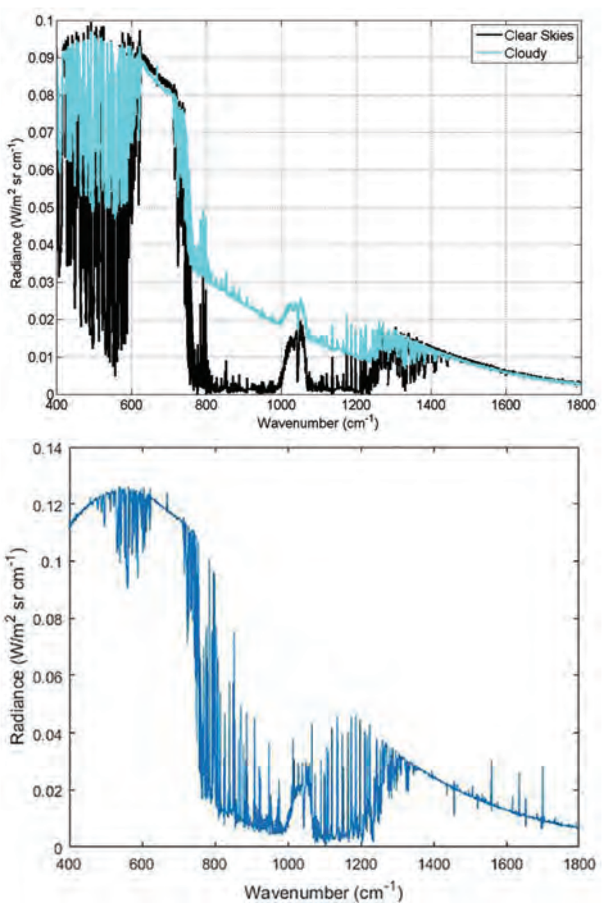

Fig. 1 Spectra of downwelling radiation measured by the Extended Range Atmospheric Emitted Radiance Interferometer (E-AERI) at PEARL. The upper panel compares two times in November 2008. The black line is for clear sky and the cyan line for a cloudy sky. The lower panel is for a summer (warmer) atmosphere with some cloud and shows the closing of the very long wavelength window below 600 cm^{-1} (16 μm) to space due to the increased water vapour in the atmosphere. (Figures courtesy of Zen Mariani)

atmosphere and analysis of these spectra provides a method of determining gaseous composition as well as the radiance spectrum throughout the year limited only by the available signal-to-noise ratio.

The cold, dry atmosphere of the polar regions is of interest to the astronomers who desire very good "seeing" in the atmosphere for good astronomical observations. There is also the attraction of prolonged periods of total darkness. Studies at PEARL have shown that in the winter the seeing can be very good – comparable with that at major telescope locations – and plans are underway to conduct further tests at PEARL as to its suitability as the site of a polar telescope.

Microwave and Radio Region

As we move to longer wavelengths we come to the microwave and radar instrumentation. Even the 4-6 GHz (C-band) satellite communications system at PEARL has to be considered a research problem because of the long pathlengths through the atmosphere on the way to the geostationary satellite. There is some attenuation due to water at these wavelengths especially in summer, but more importantly there are density fluctuations that can cause lensing and dissipation effects of the beam, particularly in the summer. Specific techniques have been developed to overcome these problems and provide a continuous internet connection throughout the year.

The PEARL cloud radar is a vertically-pointing cloud radar operating at 35 GHz. By measuring the characteristics of the echo, especially the magnitude and the Doppler shift, information on the cloud and aerosols directly above PEARL can be obtained and this is complementary to the information from the lidars since the radar information is weighted more towards the larger particles and the lidars to the smaller.

Water vapour and liquid absorption are sensed at frequencies of 20-30 GHz (K-band) and 31.4 GHz (liquid) using a microwave radiometer (MWR). By looking upwards and measuring the brightness temperature at these frequencies and comparing it to the cosmic background and the actual temperature known from climatology or radiosondes, the amounts of water vapor and liquid can be determined.

A radar at 52 MHz measures wind and turbulence in the atmosphere from near the surface and into the stratosphere around 20 km by tracking echoes from small-scale fluctuations in the atmospheric state. It is one of a number of similar radars deployed in Canada and around the world.

Another radar at 34 MHz measures reflections from ionized meteor trails in the upper atmosphere. There are a large number of sub-visible meteors arriving at the Earth daily and these disintegrate in the upper atmosphere leaving trails that are detectable by radar. The resulting echoes can be interpreted in terms of the density and winds in the atmosphere around 85 km altitude.

DATABASES

Data collected at PEARL is analyzed by the PEARL team and then made available to the scientific community. There are very few measurement sites this far North and so the data are very important to developing a Canadian and global view. PEARL data are placed in many international databases including the Aerosol Robotic Network (AERONET), the Network for the Detection of Atmospheric Composition Change (NDACC) and the Total Column Carbon Observing Network (TCCON). In some instances these are the only data available for the Canadian Arctic. Radar data are also regularly ingested by the European Centre for Medium Range Weather

Forecasting (ECMWF). And finally data are also available from our own website at http://www.candac.ca. The PEARL team aims to have as much data as possible publicly available.

CONCLUSIONS

As can be seen from this brief survey, spectroscopy and more generally the physics of the interaction between particles and electromagnetic energy are at the heart of all the remote sensing measurements made at PEARL. The veracity of these measurements depends upon a detailed understanding of these interactions and as understanding increases, so does our ability to interpret the measurements. Also of importance is the ability to quickly make the calculations which are necessary to interpret the measurements. With many atmospheric components and many processes operating simultaneously, the situation can rapidly become extremely complex. The PEARL team is continuously refining and upgrading the measurement interpretation capabilities to provide the best information available.

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