**MONITORING THE RESPONSE OF THE
UPPER TROPOSPHERE/LOWER STRATOSPHERE TO A
GREENHOUSE GAS SCENARIO**

FINAL PROGRESS REPORT

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Significant Research Accomplishments

A measurement system for examining the possible linkage between an increased concentration of Greenhouse Gases (GGs) and symptoms of climate change has been designed and evaluated. The system consists of a dual port emission interferometer and supporting data analysis algorithms for the remote sensing the upper troposphere/lower stratosphere from a high elevation ground site deployment. Two blackbody systems were designed and tested to provide necessary calibration targets for the interferometer. The interferometer was deployed during four different periods at climatologically distinct locations to test the capabilities of the system. Over two hundred spectra were collected in a variety of conditions ranging from a clear middle latitude atmosphere viewed from mountain site at 3.0 km ASL to sub-tropical marine stratocumulus cloudiness measured at Porto Santo Island near Madeira. The original plan to deploy the system at the NOAA's MLO (Mauna Loa Observatory) was altered a result of the unexpected high cost of deployment at the observatory. The line by line radiance and transmission codes FASCOD2 and FASCOD3 were acquired to provide theoretical comparisons with the measured data. A state of the art computer work station was acquired in order facilitate the line by line calculations and to perform temperature retrievals. The Path Characterization Algorithm was obtained from the U.S. Air Force, Phillips Laboratory and was adapted to a pre-beta version of FASCOD3. The algorithm has been used successfully to retrieve temperature and moisture profiles from both the mountain and sea level deployments. These initial retrievals indicate that ground based systems may only be effective in sensing the temperature and moisture profiles for the first few kilometers above the instrument. The interferometric data have been used to estimate the size of "equivalent spherical" ice particles in cirrus clouds. The data from the sea level deployment were examined in order to retrieve the absorption coefficients of marine stratocumulus clouds and a double iteration algorithm has been developed to deduce the emittance of cirrus clouds from interferometric spectral measurements.

1. Introduction

This report summarizes the original research goals and the progress made toward those goals over the period of October, 1990 to June, 1994. During this period significant resources have been expended toward developing an instrument system capable of monitoring the atmosphere to detect signals of climate change that may result from the increase in concentration of GGs. The results indicate that while the hardware performed to expectations, and that certainly some significant remote sensing of the atmosphere can be achieved, it is questionable if this system can provide data to from which the linkages between increased concentration of GGs and the main signal of climate change may be confidently detected. It is hoped that this document will provide guidance for possible future uses of ground based remote sensing of atmospheric signals linked to climate change.

2. Summary of research objectives and overall results

The complete statement of the research objectives of this project may be found in Appendix A, which is a copy of the original proposal. Basically, the objective was to develop a hardware/software system capable of monitoring the signals of a climate change scenario that might be caused primarily by an increase in CO_2 . The main goals of the research were:

- to investigate the possibility of detecting temperature changes in the upper troposphere/lower stratosphere associated with an increased concentration of GGs;
- to investigate the feasibility of detecting changes water vapor concentrations;
- to use the system to monitor changes in the amounts of upper tropospheric clouds.

Overall, it may be said that the results of this study cast doubt on the ability of a surface based infrared system in achieving the first goal; to the extent that a moistening of the atmosphere in a climate change scenario occurs in the middle and lower troposphere, the second goal can be achieved, and, that the IR interferometer is likely a superior method for detecting the presence and radiative characteristics of upper tropospheric clouds with the caveat that there are no intervening cloud layers.

2.1 Initial goals of the research

The initial literature search indicated that several modeling efforts qualitatively agreed on the atmosphere's adjustment to a marked increase in the concentration of CO_2 . The original proposal utilized in particular the results (temperature and moisture adjustments to a 2CO_2 atmosphere) in Rind (1987), to model atmospheric spectra in a clear atmosphere as measured from a high altitude tropical site. Using the FASCOD2 model it was determined that the ratios of downwelling radiances measured at 60° zenith to those at 0° zenith were sensitive especially to the concentration of CO_2 and to a lesser extent to the modeled temperature changes in the 2CO_2 atmosphere, and that the ratio of radiances observed at zenith in a 2CO_2 atmosphere to those in a standard atmosphere are sensitive anticipated temperature changes, although to a limited extent. More specifically, using $N(\theta)$ to indicate the spectral downwelling radiance measured at an angle θ from the vertical, initial modeling results indicated that:

- $N(60^\circ) / N(0^\circ)$ increased 2 % for each 10 % increase in concentration of CO_2 .

- $N(60^\circ) / N(0^\circ)$ increased only 2 % for changes in temperature profiles associated with a CO_2 doubling scenario.
- $N_{2\text{CO}_2}(0^\circ) / N_{\text{STD}}(0^\circ) \approx 1.4$ when both CO_2 concentration and temperature effects of the doubling scenario were taken into account.
- $N(0^\circ)_{2\text{CO}_2} / N_{\text{STD}}(0^\circ) \leq 1.04$ when only temperatures associated with the doubling scenario were included.

These simple techniques were to be evaluated by deploying the dual-port emission interferometer at a high elevation site over an extended period of time¹. As noted below the goal of a long term, high elevation deployment was never met, but the results from short term deployments are discussed below.

3.0 Progress toward research objectives

The preceding section outlined briefly the major research goals for the project. The following is a rather detailed account of the activity toward accomplishing these goals.

3.1 Interferometer design and original calibration procedures

A Bomem MB100 Michelson interferometer was obtained in October, 1990. The instrument was configured with the dual port emission option which is schematically represented in Fig. 1. This configuration allows the instrument to measure difference interferograms which result from the subtraction of a black body interferogram at near ambient temperature from that of the atmosphere, thus subtracting much of the contribution from the instrument itself. The optics allow a spectral response in the range from 350 to 6000 cm^{-1} range, but the measurements are limited by the spectral response of the middle infrared MCT detector to from 500 to 2000 cm^{-1} . The detector is cooled cryogenically by expanding nitrogen gas into a small dewar behind the detector.

¹The second aspect of this deployment was never achieved do to logistical factors. First, our local deployment at the CSU mountain campus at Pingree Park was limited to summer periods since the campus was not accessible during periods when snow closed the access road. The original intent of deploying at Mauna Loa Observatory did not come to fruition when a change in the directorship of the observatory and a somewhat more restrictive fiscal philosophy required significant support for non-NOAA funded efforts.

Figure 1. Schematic diagram of the optical path of the Bomem MB 100 dual port emission interferometer.

The calibration of the spectra followed the methodology of Revercomb et al (1988). Phase correction of individual spectra was accomplished by the commercial software used to process the spectra according to the Mertz method; see Griffiths and de Haseth, (1986). In this method individual spectra are converted from interferograms by first applying a phase correction, triangularly apodizing the phase corrected interferogram and finally smoothing the data by zero filling before applying the Fast Fourier Transform that transforms the interferogram into a spectrum. For calibration it was necessary to provide two black body sources which radiate at temperatures bracketing the highest and lowest effective temperatures of the measured spectral signal. The easiest way to obtain a cold

temperature black body was to use a dewar filled with liquid nitrogen (ln2). However, for purposes of the initial deployment, it was thought that using a thermoelectrically cooled emitting disk would be logistically simpler as it was hoped that the system could be operated in a quasi-automatic mode by a technician visiting the MLO site. The first calibration platform was thus comprised of two thermoelectrically controlled disks, each of which were housed in foam insulated containers. In order to dissipate the heat generated by the thermoelectric coolers heat sinks were designed which carried the heat away from the bases of the coolers. The heat was ultimately dissipated by a circulating glycol bath cooler. Although cumbersome, this calibration system did not require ln2 and was suitable for eventual nearly automatic operation.

Eventually (during the WISP deployment; see below) it was found that the problem of frost deposition on the cooled disk outweighed the convenience of the thermoelectrically cooled system, and a liquid nitrogen bath was adopted for use as the cold blackbody target. When the liquid nitrogen bath replaced the thermoelectrically cooled disk, a conical copper black body was installed as the warm black body target. Fig. 2 shows the current configuration of the system. The photograph into the gold mirror shows the reflection of a HeNe laser beam used to measure optical displacement within the interferometer.

Figure 2. Photograph of the current configuration of the interferometer system. The interferometer is at the right. In the center from the top to the bottom of the system is the conical copper black body source the opening of which is obscured by the gold reflecting mirror and the In₂ container (below the table top). The interferometer's HeNe laser beam is seen reflecting from the mirror. On the left are the Campbell Scientific data logger system and a DC servo motor for pointing the field of view of the interferometer at the cold black body, the warm black body or at any zenith angle between 0 and 90°.

An example of a test of the system's calibration may be found in Fig. 3, which shows a laboratory measurement of a cavity black body, the associated Planck curve, the difference between the two curves (bottom nearly horizontal line) and a typical clear sky spectrum from the Pingree Park site. This plot indicates that the calibration of the system is adequate to detect the effects of even optically thin clouds or aerosol layers above the "floor" of the clear sky spectrum.

Figure 3. Laboratory calibration of the interferometer system. Planck curve at temperature of blackbody and measured spectrum are shown nearly coincident (top) and their difference, the nearly horizontal line (bottom) are shown in relation to a typical clear sky spectrum measured at Pingree Park.

3.2 Examination of radiance ratios as a signal of climate change.

As noted above, the original signal thought to be a useful signal of climate change was the ratio of radiances observed at various zenith angles. The original analysis

was a simulation of radiances observed from a high elevation tropical ground site, so that much of the lower level water vapor burden would not come into play. But the Mauna Loa deployment was never realized. However, during limited deployment at the Pingree Park Campus (elevation ≈ 3 km) observations were made which led to mixed conclusions about the effectiveness of the ratio methodology. Fig. 4 below is an example of how the measured spectral radiances change as a function of observation zenith angle.

Figure 4. Spectra collected at observation zenith angles of 0, 15, 30, 45, 60 and 75° under clear sky conditions at Pingree Park, September, 1991.

The first question concerned the stability of the ratio $N(60^\circ) / N(0^\circ)$ for a constant concentration of CO_2 . Shown Table 1 below are several ratios taken during the September, 1991 deployment at Pingree Park. The ratios were evaluated at a wavenumber of 746 cm^{-1} , which was determined to be a region where the ratio methods would be most effective. Even though the data set is small, its consistency offered encouragement for the for clear sky cases. The standard deviation of the clear sky value of the ratio is less than 0.5% of its mean. This type of ratioing is, of course, sensitive in part to temperature structure. The range

of surface temperature deviation amongst the clear sky cases represented in the Table was only 3.7 C and the deviations in upper air temperatures were even smaller. Thus, further evaluation of the dependence on temperature structure was indicated. However, this preliminary data indicated that the ratio was extremely sensitive to the presence of even thin clouds. Thus, it would be necessary to ensure that the entire sky was cloud free for the ratio method to reveal any type of sensitivity to changes in temperature regimes. Since the ratio seemed to be sensitive even to near sub-visual cirrus, (in this case the clouds were only visible by looking near the occluded solar disk) it was questionable if the ratios could be used since visual detection of cirrus could not be guaranteed especially for a long term deployment with minimal user attention.

Date	Sky condition	Ratio Value
9/03/91	clear	1.431
9/05/91	near sub-vis cirrus	1.533
9/16/91	cirrus	1.624
9/16/91	clear	1.431
9/16/91	clear	1.435
9/25/91	clear	1.425
9/25/91	clear	1.443
9/25/91	clear	1.435

Table 1. Values of $N(60^\circ) / N(0^\circ)$ at 746 cm^{-1} for clear or nearly clear conditions.

3.3 Traditional remote sensing of temperature and moisture profiles

If the inhomogeneity of an apparent clear sky could cause uncertainty in detecting the signals of climate change, it was thought that a more traditional approach to remotely sensing the temperature and moisture profiles in the atmosphere might be productive. To be useful it would be necessary to obtain temperature profiles throughout a significant portion of the atmosphere, from the measurement altitude to as high as 10 or 15 km. Traditional temperature retrieval algorithms have been applied for a few decades as a tool to remotely sense temperatures from satellite platforms and development of an algorithm was not part of the goals of this research. Rather, because of its availability and its compatibility with the FASCOD family of algorithms, we acquired the Path Characterization Algorithm from the US Air Force Phillips Laboratory. Even so, considerable resources were

expended adapting the algorithm to our purposes. First, the algorithm had to be modified to execute on the HP Apollo series 700 workstation acquired for these calculations. Second, a routine needed to be incorporated into the FASCOD3P code to match the model calculations to instrument characteristics. Without going into great detail, this involved smoothing and apodizing the FASCOD3P radiances to match the manner of spectral signal processing from the interferometer software. Since the retrieval problem is inherently unstable, it is imperative that discrepancies between calculated and measured spectra due to signal processing be eliminated to the fullest extent possible leaving only the actual radiative differences as the signal of interest.

The Path Characterization Algorithm may be described as a physical least squares approach since it relies on a physically comprehensive forward calculation, rather than on a statistical database, for example or on a neural network approach. Using the FASCOD3P model to provide a modeled spectra, $F_i(x)$ where x is the desired state parameter (temperature, H_2O concentration, O_3 concentration, etc.), the algorithm seeks to minimize a variance, $\sigma^2 = \sum_i W_i [R_i - F_i(x)]^2$,

where R_i is the measured spectral radiance vector and W_i is the weight for the i th observed radiance. The algorithm uses an iterative approach solving the system which is consistent with the approaches described by Rodgers (1976, 1990) and Eyre (1989). It is customary to add a penalty function Γ to the above so that quantity to minimize becomes;

$\sigma^2 = [R - F(x)]^T W [R - F(x)] + x^T \Gamma x$, where T indicates the transpose of the matrix. For the maximum likelihood method the penalty function is $\Gamma = S_x^{-1}$, where S_x is the error covariance matrix of the first guess for x and $W = S_R^{-1}$ where S_R is the covariance of the measurements. For the ridge regression approach, Γ is given by $\Gamma = \delta_j \gamma_j$, where γ_j is a damping factor. To date we have only used this last approach which is similar to that described in Twomey (1977). In either approach the iteration proceeds by finding;

$$x^{n+1} = x^n + (K^T W K + \Gamma)^{-1} K^T W r^n,$$

where n is the order of the iteration and the residuals are found as; $r^n = R - F(x^n)$. The matrix K represents the Jacobian of the forward model with respect to the state parameter x . For example, if x represents the temperature T_j at the j th level in the atmosphere, then;

$$K_{ij} = \frac{F_i(T_j^0 + \delta T) - F_i(T_j^0)}{\delta T},$$

where T_j^0 is the initial temperature guess and F_i is the forward calculation at the i th spectral interval.

We have applied this algorithm to spectra collected at Pingree Park. Fig. 5 shows an example of the method applied to both the temperature and moisture variables.

Figure 5. Retrieval of temperature (top) and water vapor (bottom) from Pingree Park data using the US Air Force Phillips Laboratory Path Characterization Algorithm

In each of the examples the results of the retrieval are shown along with the reference used to start the retrieval (mid-latitude summer atmosphere) and the profile measured with a sounding. The profiles begin from the bottom at the elevation of the Pingree Park site, nearly 3 km. In the lower plot the irregular behavior of the profile is an artifact of the choice of units for the concentration of water vapor (molecules / cm²) and atmospheric layers of unequal thickness. Inspection of these results indicated that the retrieval was not able to track the actual sounding for more than a few kilometers above the surface, although in this case the sounding is close to the mid-latitude summer sounding used as a first guess. In utilizing the ridge regression mode choosing an acceptable magnitude of γ parameter is only gained after a little experience. Choosing a value too small will cause an unstable result, while choosing a value too large forces the retrieval toward the reference or, in other words, ignores the measured radiance data. In Fig. 6 the results for clear sky spectra at Porto Santo Madeira are shown. In this case it is seen that the retrieval is following the inversion but at approximately 3.3 km the retrieval favors the reference over the sounding. Above that level it is difficult to evaluate if the retrieval is actually capturing the information from the measured radiances, or if it is following the reference, which may be considered as a virtual measurement as explained in Rodgers (1970).

At the time of this writing, it cannot be reported that the myriad of possible scenarios of applying this algorithm to the data have been explored. As mentioned above, to date, the algorithm has only been applied in the ridge regression mode. A complete analysis of this problem would make an interesting topic of its own and would focus on a complete error analysis of the retrieval. The framework for the analysis is outlined in the documentation of the algorithm, but covariance information on the influence of the first guess has not been obtained. However, even without a complete error analysis, it does not appear, from our limited experience, that temperature retrieval is applicable to only the first few kilometers above the instrument. Also, since the possible impact of undetected cirrus cloudiness was mentioned regarding the ratio method, it should be pointed out here that cirrus clouds will degrade the retrieval from the more traditional means although it is not clear in which case the effects would be more detrimental. This may also be a topic for a more complete error analysis.

Figure 6. Temperature retrieval using the US Air Force Phillips Laboratory Path Characterization Algorithm for a clear sky case in Porto Santo, Madeira. Retrieval (1) and Retrieval (3) refer to the order of the iterations used in the retrieval.

Lastly, before leaving the subject of temperature retrieval (for the purposes of examining linkages between increased concentrations of GGs and climate change) it is noted that the ratio method and the physical least squares method are of course somewhat related. In one of the earliest discussions of temperature retrieval, King (1964) showed that lapse rates of individual layers could be retrieved in theory by measuring the radiances at different zenith angles. The methods are compared to some extent by Twomey (1977), in which it is shown that

the zenith angle scanning is no more stable than constrained least squares approaches, and that smoothness of the kernels in the retrieval problem is the cause of the instability in either approach. It is intriguing to note however, that King's analysis is applied monochromatically to radiances viewed at different zenith angles, while the physical least squares algorithm uses hundreds of spectral measurements from a single viewing angle. To the knowledge of the authors of this report, an investigation of the benefits of combining these approaches has not been explored.

Similar remarks may be made concerning the retrieval of water vapor from the ground based system. A careful inspection of the lower portion of Fig. 5 reveals that a typical retrieval of the concentration of water vapor follows the measured profile up to an altitude of about 5.5 km. The sounding and retrieved values are nearly identical at 3.5 km (approximately 0.5 km above the instrument) but by 5.5 km it is evident that the retrieval is favoring the reference. By 6.5 km the retrieval and reference are nearly equal and above that altitude all three profiles are essentially the same. Thus, the results for temperature retrieval and water vapor retrieval are essentially the same; little information is available beyond a few kilometers above the ground. However, as far as an indication of climate change, a detection of moistening of the lower and middle troposphere may be more significant. In the article of Rind (1987), it was shown that the increase in water vapor would be realized throughout the troposphere, with the 2CO_2 , average annual, specific humidity being increased by 2 to 3 g/kg at the levels detectable by the interferometric system. Thus, from our initial results, a long term retrieval of mid-tropospheric water vapor is detectable from the high elevation site and to the extent that the climate models are accurately predicting this scenario in the 2CO_2 atmosphere, the system could reliably be used. Again, it must be noted, that the retrieval is limited to times of clear sky condition. While it is obvious that middle level cloud would completely invalidate retrieval of water vapor, the effects of cirrus clouds on the water vapor retrieval process have not been investigated.

3.4 Detection of cirrus clouds and radiative properties

One of the possible effects of an increase in CO_2 and other green house gases is an indirect influence on the amount of global cloudiness. Indeed, the role of cloud systems in a changing climate scenario has prompted much research in the last decade, supplying the motivation for major research efforts including the Atmospheric Radiation Measurement (ARM) Program, the First (International Satellite Cloud Climatology Program) Regional Experiment (FIRE), and the Atlantic Stratocumulus Transition EXperiment (ASTEX). Of all the different cloud categories, cirrus clouds may be the least understood as to their role in a climate change scenario. Knowledge of the aspects of their formation, maintenance and usually slow dissipation, as well as their effects on the earth-

atmosphere radiation budget, is elusive due to their position in the atmosphere and the small optical thicknesses they usually achieve. Of the goals listed at the outset of the research, the detection of cirrus clouds and their optical properties is the one which has been identified as being best accomplished by the high elevation deployment of the interferometer system. Below, three aspects of this problem are summarized; detection of cirrus clouds, inferring the emissivity of the clouds and to a less certain extent, monitoring of the cloud's mean particle size.

3.4.1 Cirrus cloud detection

As was noted above, even near sub-visual cirrus clouds were detected in the ratios which were being examined for stability. Another instance where the system could be quantitatively checked for cirrus detection presented itself in Parsons, KS in November, 1991. As part of our participation in the FIRE Cirrus II effort, there was an opportunity to compare the detection capabilities with those of a LIDAR system deployed by NASA Langley. Fig. 7 below shows pre and post-onset spectra taken about one hour apart. Fig. 8 shows the corresponding LIDAR record of the volume backscatter coefficient for the same period. The LIDAR and interferometer were positioned within 20 meters of each other.

Figure 7. Pre and post cirrus onset spectra from Parsons, KS on November 26, 1991 for a portion of the atmospheric window region.

Figure 8. NASA Langley LIDAR on November 26, 1991. Plot shows the time height cross section of the volume backscatter coefficient during the onset of an approaching cirrus layer.

Another interesting opportunity to observe the effect of upper level clouds on the window spectra presented itself September 5, 1991 at the Pingree Park Campus on a day which began with moderately thick cirrocumulus overcast. By late morning the clouds had thinned considerably to what could be termed thin cirrus. Early in the afternoon the clouds could almost be termed sub-visual cirrus, and it was only by looking near the occluded solar disk that some cloud was evident. Fig. 9 depicts the spectra at 0° observation angle for each of these cases. The downward slope of the spectra from low to higher wavenumbers is evident in the figure. The two bottom curves are portions of the spectra from which the ratios

Figure 9. Downwelling spectral radiance in the atmospheric window during conditions of dissipating cirrus overcast at Pingree Park on September 5, 1991.

for the two cloudy cases of Table 1 were extracted.

A close examination of the bottom trace, for the near sub-visual cirrus, indicates that some slight slope remains. Even this small sloping spectra could be contrasted with that of a clear atmosphere in which this portion of the spectra would be more nearly horizontal, especially in the 800 to 1000 cm^{-1} portion of the spectrum.

Of course, in addition to the mere presence of clouds, their physical characteristics are subject to change as well in any climate change scenario. The primary cloud

parameter of interest is the cloud optical depth. Also important is the microphysical makeup of the cloud. The sensitivity in the infrared window to presence of cirrus assumes there are no intervening middle level clouds. The detection of middle level clouds would of course be a simple task and to the extent that the change in frequency of occurrence or spatial coverage may be used as an indication of climate change, the interferometer system could provide information in this area as well. In any case, it is noted that this simple task of detection would be best accomplished in a relative sense after a database of clear sky spectra had been established for the site. The signal will also have some sensitivity to temperature changes and variations in upper level atmospheric moisture; however, these are thought secondary effects. It is also noted that in our experience, simple threshold detection of cirrus could not be reliably performed from a low elevation installation. The deployment of the interferometer during ASTEX especially, indicated that there is sufficient natural variation in low level aerosol loading such that a higher order detection scheme would be required. Further research might indicate if the "slope" method presented in Ackerman et al. (1990), would resolve the signals of cirrus at a low elevation site.

3.4.2 Inferring the radiative properties of cirrus clouds

Up to now this report has focused on signals of climate change that could be detected using the mid-IR interferometer in a stand-alone mode. In the last two sections the discussion is extended to quantities which are of climatic significance and which may be examined from the interferometric data in conjunction with supporting data. The first of these concerns the radiative characteristics of cirrus layers. Of course, just detecting the cirrus is important in examining a linkage to a 2CO_2 scenario, but it is the radiative properties of the cirrus clouds which are most significant and which must be monitored. Examples which have been pursued to date are the retrieval of cirrus cloud emissivity and the retrieval of a bulk cloud ice crystal size parameter, which is initially being examined as an equivalent ice sphere radius.

An opportunity to examine the utility of the interferometer system for retrieving cirrus cloud emissivities was presented during the November, 1991 FIRE experiment at Parsons KS and the June, 1992 ASTEX activity at Porto Santo Madeira. A double iteration scheme which extends the work of Ackerman et al. (1990), was used to interpret ground based interferometric measurements. (The interferometric measurements were supported by LIDAR to locate the cloud layer in an atmospheric sounding which was also required.) The iterations alternately update the radiative properties of the cloud and sub-cloud layers until a convergence is achieved in each layer. A simple spectral reflection algorithm is employed. Fig. 10 displays the results from analysis at both sites. It displays the volume extinction of the mid-latitude and sub-tropical cirrus as the slope of the

natural log of transmission versus cloud layer thickness. These measurements indicate the ability of the system to retrieve trends in the optical properties of the clouds, when the interferometer is part of a more complete observing system.

Figure 10. Volume extinction coefficients derived from interferometric measurements of cirrus clouds at Parsons, KS and Porto Santo, Madeira.

In addition to the inference of cloud emissivity work is in progress on the ability to determine some measure of the size of the cloud particles. Recently, the methods

aimed at estimating the radius of equivalent spherical particles has been demonstrated by examining the slope of the emission in the window region; see Prabhakara (1988), Ackerman et al. (1990), and Parol et al (1991). The theoretical basis for this determination relies on the sensitivity of the ratio of the absorption efficiency factor at two wavelengths to particle size. For example, writing a simplified equation for the radiance below the cloud I_{obs} as;

$$I_{obs} = I_{clr} + B(T_c) [1 - e^{-\tau^*/\mu}] T_{atm},$$

where I_{clr} is the downward radiance emitted by the atmosphere below the cloud which is approximated by measuring the downward radiance in a clear atmosphere, τ^* is the optical thickness of the cloud, μ is the cosine of the viewing angle, and $B(T_c)$ is the Planck function at the cloud temperature T_c and T_{atm} is the transmission of the atmosphere beneath the cloud, where it has been assumed that the cloud is isothermal and scattering has been ignored. Defining

$\Delta I = I_{obs} - I_{clr}$, and solving for τ^* gives;

$$\tau^* = -\ln \left[1 - \frac{\Delta I}{T_{atm} B(T_c)} \right].$$

The optical thickness may be evaluated at two wavenumbers in this manner and the ratio $\gamma = \frac{\tau_1}{\tau_2}$ formed. For a monodispersed cloud composed of spherical

particles of radius a , the optical thickness may be written as, $\tau^* = \pi N_0 a^2 Q_{abs}$, where N_0 is the concentration of the particles and Q_{abs} is the absorption efficiency factor. The ratio of optical depths is then given by, $\gamma = \frac{Q_{abs,1}}{Q_{abs,2}}$. Using single

scattering algorithms, either for Mie scattering for spherical particles or more sophisticated methods such as the Discrete Dipole Approximation for crystals of various shapes, it is then possible to plot the ratio as a function of particle size as was done in Parol et al (1991). This exercise was carried out for a measurements of cirrus on June 6, 1992, at Porto Santo Madeira. The results are shown below in Fig. 11 which indicates the particle size and visible optical thickness derived from solar transmission measurements.

Figure 11. Visible optical depth (top) and equivalent ice sphere particle size (bottom) inferred from the interferometric method and a solar transmittance method.

Various methods are currently being explored to infer some measure of particle size or, ice water content directly. The figure above indicates that there is some promise for using ground based interferometric measurements to infer particle size or ice water content as a significant signal of climate change, although much work remains to be done to more precisely relate the interferometric measurement to cirrus ice water content.

4.0 Summary of findings

Even though the long term, high elevation deployment of an interferometric system was not accomplished, the following list summarizes the findings that establish the system as a valuable tool for examining the linkages between the increase in GGs and signals of climate change:

- Neither the ratio nor traditional retrieval methods appear to offer a sound solution for remotely sensing temperature of the upper troposphere/ lower stratosphere from a high elevation ground based deployment. Both methods are subject to degradation from unreported cirrus cloudiness and the smoothness of the weighting function kernel.
- To the extent that climate models are correct in predicting a moistening of the entire troposphere, the high elevation ground based system can detect the increased humidity using traditional retrieval methods provided cloud filtering algorithms are developed.
- The presence of clouds of almost any thickness is detectable by the system. The infrared emittance and a first order estimate of the equivalent ice sphere radius appear to be achievable with the system.

5.0 Summary of instrument deployments

In the sections above results have been presented which were derived from data collected at different locations. Here a summary of the system deployments in addition to the system work at the Department of Atmospheric Science at Colorado State University are noted:

- March to April, 1991, deployed at Platteville, CO during the Winter Storms Project (WISP), frost deposition on the cold blackbody disk dictated that the its thermoelectrical design was not practical.
- August and September, 1991 at Pingree Park, CO, first examples of

excellent agreement with the FASCOD models obtained, ratio methods initially checked, sensitivity to cirrus established. Spectra were used for initial temperature and moisture retrievals.

- November , 1991 at Parsons KS, during FIRE II Cirrus IFO, intensive data collection at fully instrumented site, additional sensitivity to cirrus onset documented. Cirrus emissivity and particle radii subsequently inferred.
- June, 1992 at Porto Santo, Madeira, during ASTEX IFO, intensive data collection at fully instrumented site. Cirrus emissivity and particle radii subsequently inferred.

6.0 Suggestions for future research

As discussed above, the ground based interferometric system has been shown to be an effective tool in most respects for detecting signals of climate change which have been predicted as part of the CO₂ doubling scenario. However, it is apparent to the authors most of the results presented above are, to varying degrees preliminary in nature. In this section several suggestions are made which the authors believe to be valid areas of future research.

- a) Although the ratio method was believed to be extremely sensitive to the presence of unreported cirrus cloudiness, a long term deployment at a high elevation site may allow sufficient confidence in the behavior of the ratios to filter the cloudy cases from the data.
- b) Traditional temperature retrievals did not appear to be productive for remotely sensing the upper tropospheric temperatures; however, some combination of the ratio signal and traditional spectral signals might lead to improved results. Also, the analysis presented here was limited to the spectral region near the 15 μm CO₂ emission band. Retrievals using multiple frequency regions might be more successful. A larger database from a high elevation site may provide confidence on retrieval height limits.
- c) Related to the temperature and moisture retrieval problem is the prospect of retrieving the concentrations and/or profiles of other GGs. The US Air Force Path Characterization Algorithm may be used in theory to retrieve the concentration of any of the gaseous constituents of the atmosphere which are treated in the FASCOD algorithm. And, although it was not the intent of the proposal to make this a principal goal, retrieval of GGs in conjunction with detection of climate change signals using a single system would be desirable, even if only from a logistical standpoint.

d) Detection of cirrus layers appears to be an simple task for the interferometric system; however, the role of changes in upper tropospheric temperature should be established. This is another task which may only be achievable from the data gathered during a long term deployment.

e) Retrieval of cirrus cloud optical properties was demonstrated when supporting LIDAR and sounding data are available. The inference of these properties is dependent on the treatment of multiple scattering in the cirrus layer and the type of phase function used in the analysis. Currently, work is ongoing in this area and the sensitivity of retrieved cirrus emissivity to assumed particle shape and distribution will be investigated.

f) Retrieval of particle size and/or ice water content has only been investigated in a more or less cursory manner. Several questions remain on the role of small particles in complicating analysis and the use of multi-spectral data for improving the retrieval.

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