HUMIDITY EFFECTS ON THERMAL ATMOSPHERIC TRANSMISSIONS: STUDY OF POTENTIAL EFFECTS OF SMALL HYGROSCOPIC AEROSOL PARTICLES IN THE LONGWAVE INFRARED REGION

R. Raqueño, R. Kremens, C. Salvaggio, M. Montanaro

Rochester Institute of Technology

R. Gelein

University of Rochester
Medical Center

ABSTRACT

This study investigates small aerosol particles as a source of an imaging phenomenon observed in thermal remote sensing data. The phenomenon is characterized by degraded atmospheric transmissions in the thermal infrared while high transmissions (clear conditions) are observed in the visible wavelength region. This atmospheric anomaly has been linked to conditions of high environmental humidity. A hypothesis attributes the cause of this phenomenon to small hygroscopic particles (under the 200 nm diameter) which weakly scatter in the visible region, but may have (for high particle concentrations) sufficient absorption effects in the Longwave Infrared (LWIR).

We describe an experiment to test this hypothesis. The method takes a simple, but novel approach of using a suite of cameras to image an aerosol stream from a Harvard Ultrafine Concentrated Ambient Particle System (HUCAPS). Used primarily for toxicology studies of environmental aerosols, the HUCAPS has the ability to control and vary properties of humidity, temperature, particle size distribution, and number density of aerosol particle stream concentrated by this system. This gives a unique opportunity to image a controlled and well characterized plume of very fine aerosol particles and determine if any significant optical effects can be observed in the LWIR region.

***Index Terms*—** Aerosol, LWIR , Humidity, MODTRAN, HUCAPS, Mie, Atmospheric Transmission

1. INTRODUCTION AND HYPOTHESIS

The experiment described in this paper addresses a small part of a larger remote sensing problem related to degraded atmospheric transmissions in the LWIR. The overall objective of this research is to understand a phenomenon that has been observed with high altitude (6,000-16,000 meters) oblique-viewing airborne spectral imaging systems in the LWIR. It is a condition where a seemingly clear atmosphere with little extinction in the VNIR-SWIR region is associated with a dramatic decrease of atmospheric transmission in the LWIR. These situations are especially problematic because decisions to collect thermal data based on visible observations have resulted in thermal imagery of degraded quality affecting its exploitation value. The goal is to identify the meteorological conditions under which this phenomenon is likely to occur in order to task collections appropriately. Observations of this phenomenon have been correlated to the onset of high humidity conditions indicating that the phenomenon probably occurs during a transitional phase in the atmospheric aerosol constituency. The characteristics of the particles are such that their sizes small enough that they do not scatter visible light to produce the familiar hazy conditions often associated with high humidity. The increased humidity conditions likely induces a water vapor to liquid vapor phase change with these aerosols as nucleation sites. The hypothesis behind this LWIR attenuation suggests that the atmospheric attenuation is caused by high concentrations of liquid water coated aerosol particles with diameters in the order of 0.1-0.2 microns. While these particles impart an attenuation due to absorption in the thermal region, their particle size has very little impact in the reflective regime. The aerosol particles at the root of the phenomenon is likely due to solution droplets in a haze state [1] in which very small droplets that have nucleated on particles (e.g., ammonium sulfate) are in stable equilibrium with the surrounding air. They have not reached an activated state where they rapidly form into cloud droplets. Mechanisms describing these different phase interactions described in detail by [2] for various aerosol constituency of chemical as well as physical aggregation with different materials. Much of the literature is focused on the cloud microphysics and particles that reached the activated state and are therefore observable in the visible regime (>400 nm). The conditions described in this problem occur before this observable regime and a laboratory experiment was designed and conducted to understand the detectability of this phenomenon in a controlled setting.

2. EXPERIMENT

In order to test the hypothesis behind the anomalous transmission phenomenon, a source of high concentration aerosols in the nano-particle regime is needed to image a plume in the thermal and visible region to qualitatively detect their optical effects. In addition, a means of monitoring the particle size distribution and number density is necessary to correlate against these optical observations. Such an instrument called the HUCAPS was identified (*cf.* Figure 1) in the field of environmental medicine research where it is used as a source of well defined aerosols for animal and human studies in inhalation toxicology. The HUCAPS system and the principles

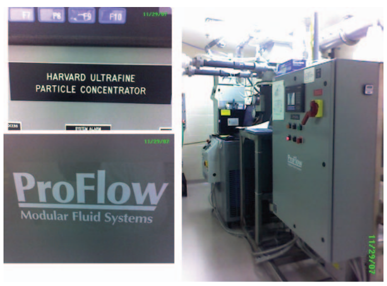

Fig. 1. Image of HUCAPS instrument used to generate hygroscopic aerosols below 200 [nm] from ambient environment. It supplies a well characterized aerosol stream in terms of particle size distribution and number density.

of its operation are described in great detail in [3] [4]. The input aerosol particles comes from an outdoor intake source. The instrument processes this input air stream and subjects it to several stages of heating, condensation, and aerosol size discrimination to produce the desired nano-particle aerosol stream for the inhalation studies. The output is an aerosol stream that is comfortable for inhalation through a face mask by the subject (between 70-75 degrees Fahrenheit and a relative humidity of about 85 percent). The human subject study is conducted for approximately two hour blocks in the chamber (*cf.* Figure 2). The camera package is introduced into the chamber for the imaging experiments after these session to take advantage of existing setup and optimal operating state of the system. Depending on the environmental conditions at the intake of the HUCAPS system, the resulting aerosol stream can have final concentrations over a million particles per cubic centimeter. These aerosols have size ranges in the nano-particle regime (5-200 nm diameter).

Because of the dynamic nature of the aerosol plume, a compact imaging package using an LWIR bolometer camera and a visible video camera was assembled to simultaneously record any detectable plume activity (*cf.* Figure 3) inside the chamber (*cf.* Figure 4). The two cameras as well as video input monitoring settings and environmental data were recorded to a 4-channel DVR to produce a time-synchronized

Fig. 2. The HUCAPS aerosol output is introduced into this chamber designed for human subject studies.

video stream. A blackbody resolution target was arranged as a background for the aerosol plume as it is imaged by the camera package (*cf.* Figure 5). Because of space constraints in the chamber, the blackbody background was devised from a cell culture flask containing water at a monitored temperature. To provide a regulated contrast pattern to the blackbody background, a resolution plate was placed over the cell culture flask to help in the detection of the plume. Without the contrast provided by the resolution plate, it would be difficult to discern the plume if its radiance closely matched the background. In this case, the background provides both high and low radiance background values.

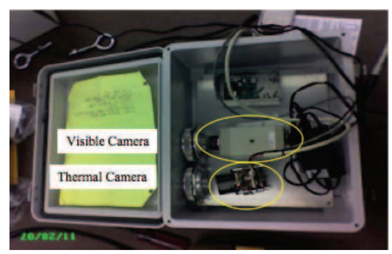

Fig. 3. Image showing LWIR and visible camera package that was used inside the HUCAPS human subject chamber. This camera setup along with two other cameras captured video images recorded by a 4-channel DVR system.

3. EXPERIMENTAL RESULTS

The initial phase experiments showed no detectable plume in either the visible or thermal region. This is probably due to the short path length of the physical plume for the particle number density and size distribution achieved in the chamber. The anomalies that were observed in the thermal airborne imagery, however, were detected from sensor altitudes between 6,000 and 16,000 meters. The temperature in the chamber was not representative of high-altitude conditions. To simulate this, the aerosol stream plumbing was extended

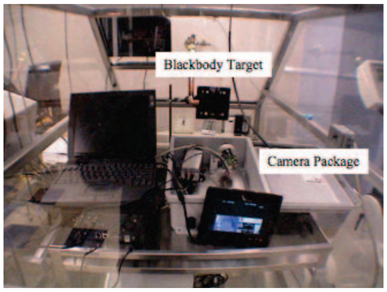

Fig. 4. A LWIR/VIS camera setup was setup in the chamber to view an aerosol stream over a blackbody resolution target

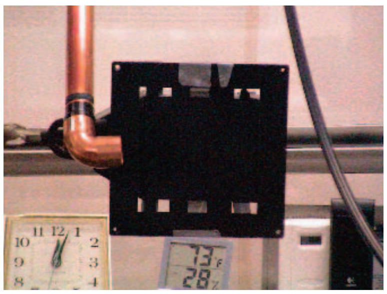

Fig. 5. Blackbody resolution target as a background against which the aerosol plume is imaged.

and passed through a small bed of dry ice (*cf.* Figure 7). This change to the temperature condition was influenced by the sensitivity of the relationship of equilibrium radius (the size at which aerosol particle will tend to grow) as function of temperature[5]. The plot in Figure 6 shows that a tendency toward larger particle sizes occurs at lower temperature observed at high altitudes. The output of this stream was then imaged showing a detectable plume in both the visible and thermal imagery. Figure 8 shows the four camera view video frame of cooled exit plume from HUCAPS output *without* a plume detected by either cameras. The upper left corner image show current IR camera settings. The upper right corner image shows view of humidity monitor near the exit throat into the chamber. The lower left corner image shows LWIR camera view with sub-region near exit throat enhanced. The lower right corner image show corresponding visible camera view with the same sub-region enhanced. The first few minutes of video captured did not detect the aerosol plume in either the thermal channel or the visible channel. This was followed by the transient appearance of a visible plume which rapidly dissipated a few inches from the exit throat. The plume was detected in both the thermal and visible images and enhanced/highlighted in Figure 9. A study of the video image frames before and after the appearance of the plume in both cameras did not show any conditions where the thermal camera detected the plume but not appearing in the

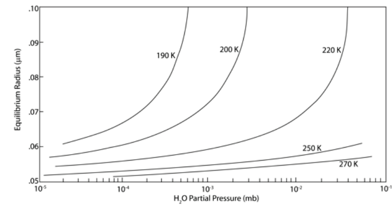

Fig. 6. A modeled relationship suggesting the increase of aerosol particle equilibrium radius as temperature decreased at high altitudes (Steele 1981).

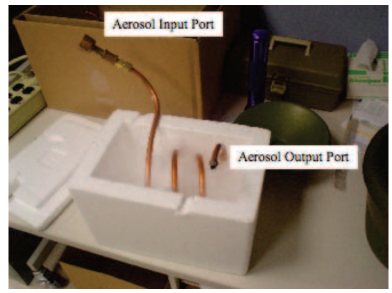

Fig. 7. Aerosol output stream from the HUCAPS instrument was passed through a dry ice bath to simulate a rapid cooling condition at high altitude conditions.

visible camera. It is likely that the detected plume was due to the rapid condensational growth of the aerosols followed by an equally rapid evaporation back to the nano-particle sizes prior to the cooling section by the dry ice.

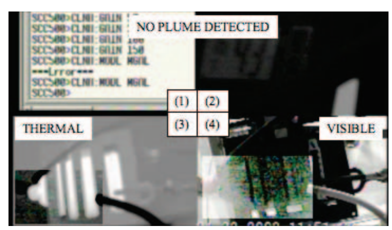

Fig. 8. 4-channel view from DVR shows (1) LWIR camera settings , (2) chamber environmental conditions, (3) LWIR camera image [enhanced, no plume], (4) Visible camera [enhanced, no plume]

4. DISCUSSION

The results of this experiment suggest that it is unlikely that a high concentration of small hygroscopic aerosol particles will produce a detectable absorption effect in the LWIR region, while having negligible scattering effects in the visible region. The current physical experimental setup does not

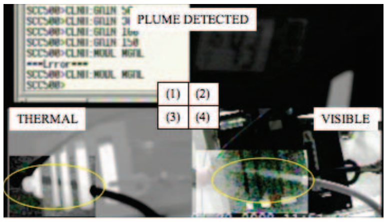

Fig. 9. 4-channel view from DVR shows (1) LWIR camera settings , (2) chamber environmental conditions, (3) LWIR camera image [enhanced, plume], (4) Visible camera [enhanced, plume]

conclusively address this because of the short imaging path lengths in the chamber. Because the HUCAPS system and the human subject chamber was not designed for optical measurements of the incoming aerosol particle stream, the physical configuration needs to be modified to streamline future experiments. An improved chamber design would consist of a long temperature controlled cylindrical tube to which aerosol particles introduced at one end and evacuated at the other. The camera package would be positioned at one end imaging a blackbody target at the other. This configuration may also be more amenable to LWIR spectroscopic analysis because of the extended path length allowing quantitative measurements of the aerosol stream.

The change to the setup (dry ice cooling) to simulate high altitude conditions suggest that the anomalous transmission effects may be due to a rapid growth of particles from nascent cloud condensation nuclei causing detectable sizes in both the visible and thermal regions as captured by the cameras. These transient effects observed in the chamber is possible at remote sensing scales where unstable atmospheric conditions can cause the mode of the particle sizes to oscillate in and out of the detectable size regime. A modeling analysis using Mie codes [6] coupled with the MODTRAN model [7] can be used to verify these findings and quantify the extent of particle growth that made the plume optically detectable. This can then be compared with aerosol growth model predictions simulating the rapid cooling and heating conditions of these high humidity aerosol plumes in the chamber. Future work extended to other numerical models that govern the physical formation of natural aerosols [8] can be studied to confirm the likelihood of these aerosol characteristics based on more realistic environmental factors at remote sensing scales.

.

5. REFERENCES

[1] J.M. Wallace and P.V. Hobbs, *Atmospheric Science: An Introductory Survey*, Academic Press, 1977.

[2] Mark Z. Jacobson, *Fundamentals of Atmospheric Modeling*, Cambridge University Press, New York, NY, 2nd edition, 2005.

[3] Philip Demokritou, Tarun Gupta, and Petros Koutrakis., “A high volume apparatus for the condensational growth of ultrafine particles for inhalationtoxicological studies,” *Aerosol science and technology*, , no. 36, 2002.

[4] Tarun Gupta, Philip Demokritou, and Petros Koutrakis, “Development and performance evaluation of a high-volume ultrafine particle concentrator for inhalation toxicological studies,” *Inhalation Toxicology*, , no. 16, pp. 851–864, 2004.

[5] H.M. Steele and P. Hamill, “Effects of temperature and humidity on the growth and optical properties of sulfuric acid-water droplets in the stratosphere,” *Journal of aerosol science*, vol. 12, no. 6, pp. 517–528, 1981.

[6] C. F. Bohren and D. R. Huffman, *Absorption and Scattering of Light by Small Particles*, Wiley, New York, 1983.

[7] A. Berk, G.P. Anderson, P.K. Acharya, J.H. Chetwynd, L.S. Bernstein, E.P. Shettle, M.W. Matthew, and S.M. Adler-Golden, *MODTRAN4 USER’S MANUAL*, HANSCOM AFB, MA 01731-3010, June 1999.

[8] Mark Z. Jacobson, “Analysis of aerosol interactions with numerical techniques for solving coagulation, nucleation, condensation, dissolution, and reversible chemistry among multiple size distributions,” *Journal of Geophysical Research*, vol. 107, no. D19, 2002.