Measurements and Modeling of the Effect of Convective Clouds on the Upper Tropospheric Moisture Budget

S. E. Bisson and J.E.M. Goldsmith
Sandia National Laboratories
Livermore, California

A. D. Del Genio
NASA/Goddard Space Flight Center
Institute for Space Studies
New York, New York

Introduction

The goal of this study is to determine the upper tropospheric moisture budget associated with convective events and, in particular, to extend process models to higher altitudes than have been achieved previously. Although upper tropospheric moisture concentrations are several orders of magnitude lower than those near the surface, upper tropospheric moisture exerts an important influence on climate. On a per-molecule basis, greenhouse absorption due to water vapor is about one hundred times more effective at high altitudes than at low altitudes. Several one-dimensional radiative convective models have been used to demonstrate the importance of upper tropospheric moisture on climate. These models show that for a given *fractional* increase in water vapor at a given altitude, the response or change in surface temperature is qualitatively the same. Figure 1 (Arking 1993) shows the change in surface temperature for a 50% increase of the specific humidity in a 40-mbar layer in clear skies.

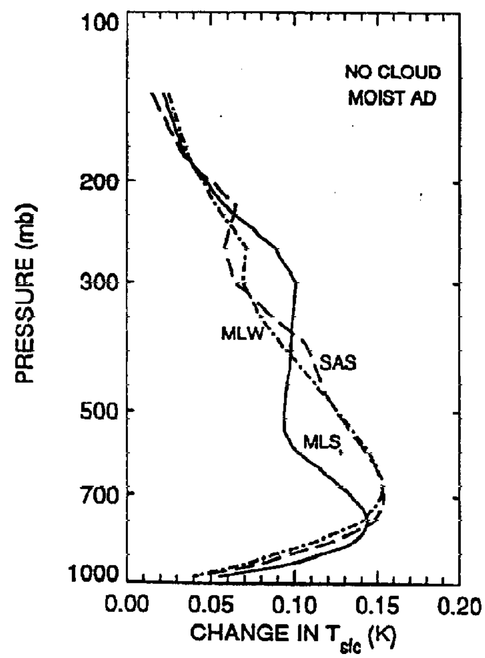

Figure 1. Change in the surface temperature for a 50% increase of the specific humidity in a 40-mbar layer under clear skies (Arking[(a)]). Regardless of latitude or season, (mid-latitude summer [MLS], mid-latitude winter [MLW] sub-arctic summer [SAS]) the effect of a fractional increase in water vapor on surface temperature is within a factor of 3 up to 150 mbar.

At present, considerable controversy exists over the nature of the vertical redistribution of water vapor in a changing climate, particularly the distribution of water vapor in the upper troposphere. Because suitable data are lacking, this controversy is also reflected in the cumulus parameterization schemes currently used in models. Understanding upper tropospheric moistening processes is therefore of prime importance in addressing the water vapor feedback question.

This study will focus on upper tropospheric moistening processes with the goal of improving cumulus parameterization schemes and subsequent implementation in a

(a) Arking, A. Water vapor feedback and lapse rate feedback: Insight from a one-dimensional climate model. Submitted to *J. Clim.*

general circulation model (GCM). It meshes perfectly with the current measurement capabilities of the Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site and builds on our previous Raman lidar efforts funded by the Atmospheric Radiation Measurement (ARM) Program. The approach we plan to take at the ARM CART site is modeled after GATE,[(a)] taking advantage of the existing measurement capabilities at the central and boundary sites to estimate the large-scale (i.e., GCM grid size) heat and moisture budgets and tendencies.

The Sandia Raman lidar system will be located at the central site to provide accurate water vapor measurements to higher altitudes and much better temporal coverage than can be achieved with conventional radiosondes. Our primary goal is to determine the moisture budget of the upper troposphere on a scale similar to that of a GCM gridbox; this will provide a constraint on the performance of any cumulus parameterization. Next, we will attempt to diagnose the individual subgrid scale physical processes which make up the water vapor budget of a typical convective cluster and combine to produce the observed upper tropospheric water vapor distribution. Successful execution of this step will give us clues as to which aspects of cumulus parameterizations are primarily responsible for any disagreements with the observed larger scale humidity field. Finally, we will synthesize our results by validating the cumulus parameterization of the Goddard Institute for Space Studies (GISS) GCM against the lidar data and then improve the physics of the model to produce a more faithful representation of upper tropospheric water vapor feedback.

Proposed Research

To a significant degree, this study is modeled after GATE, a comprehensive study conducted in the Atlantic ITCZ (intertropical convergence zone) and designed to study convection. In GATE, a network of ships was configured to form two concentric rings with a central ship to measure moisture, horizontal winds, and precipitation fields through a combination of radiosondes, radar, aircraft, and satellite imagery. We plan to use the Sandia Raman lidar at the CART site to determine the moisture over the central facility. By combining these water vapor measurements with atmospheric characterization provided by the CART instrumentation, we will be able to study a larger altitude range than that addressed by GATE or other studies; in particular, we will be able to study the important (and currently controversial) region of the upper troposphere.

$$\frac{\partial \bar{q}}{\partial t} = -\nabla \bullet (\bar{v}\bar{q}) - \frac{\partial}{\partial p}(\bar{\omega}\bar{q}) - \frac{\partial}{\partial p}(\overline{\omega' q'}) + (c - e) \quad (1)$$

The equation that describes the moisture budget per unit mass of air is given by Thompson et al. (1979)

where

- q = specific humidity
- v = horizontal wind velocity
- p = pressure
- w = vertical velocity (dp/dt)
- c = rate of condensation per unit mass of air
- e = rate of evaporation of water per unit mass of air
- ( ) denotes an area mean
- ( )' denotes deviation from area mean

The first two terms on the right-hand side represent horizontal and vertical advection averaged over the area of the region. These terms will be obtained from combined radiosonde and wind profile measurements at the boundary sites. The storage term (LHS) will be evaluated directly with the Raman lidar. Taken together, the last two terms on the right hand-side of Equation (1) represent deviations from the average (the eddy flux divergence) and the net

$$\frac{\partial}{\partial p}(\overline{\omega' q'}) + (c - e) \quad (2)$$

sources and sinks and determine the net moistening or drying of the atmosphere

The sum of these terms is the focus of this study. If the sum of these terms is positive, there is a net drying of the atmosphere at that particular altitude; if the sum is negative, there is a net moistening. While it is generally believed (and supported by the GATE study) that drying is associated with convective systems below about 300 mbar, it is not clear whether there would be a moistening or drying above this level. With the Raman lidar system, we can measure the storage term with higher temporal and spatial resolution and to much higher altitudes than can be reliably performed with conventional radiosondes and, thus, directly address the very important upper tropospheric region of the atmosphere.

(a) GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment.

The CART site in Oklahoma is ideally suited to conduct such an investigation for several reasons. First, the frequency of convective events in this region is very high in the springtime, coincident with the Remote Cloud Sensing, (RCS) intensive observing period (IOP). The SGP site itself is the location of at least three distinct types of activity of interest to us:

- isolated air-mass thunderstorms without extensive anvils, for which small-scale transports can be expected to dominate
- organized mesoscale convective complexes, whose mesoscale updrafts may control upper level humidity
- baroclinic waves, which transport water on synoptic scales and along fronts.

All three phenomena can be expected to occur from April through July in this region. Meteorological data for Ponca City Oklahoma (Figure 2), show that the frequency of thunderstorms is highest in the May-June period and averages about 9-10 storms per month. Furthermore, the diurnal cycle of thunderstorm activity in the SGP region peaks near midnight (Wallace 1975), when Raman lidar measurements are most accurate and extend to highest altitude. To obtain good statistics, we would take measurements over a period of several weeks to ensure the passage of several systems.

Second, the CART site has instruments situated throughout which provide the data required for moisture and energy budget calculations. Most of the instruments can operate

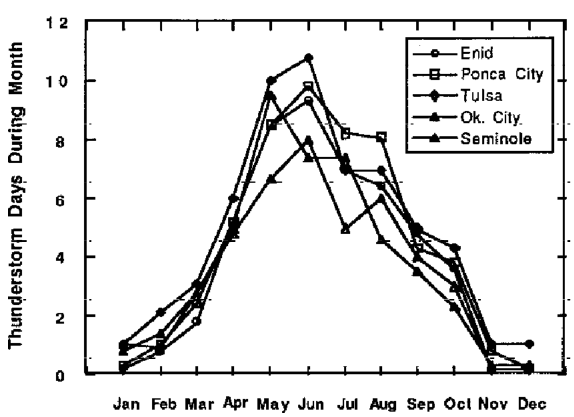

Figure 2. Average thunderstorm days for north central Oklahoma.

autonomously and continuously. In addition, a single-column model (SCM) IOP will be conducted during this period with a high frequency of radiosonde launches.

Because minute amounts of upper tropospheric water vapor can have a potentially large effect on climate, accurate measurements are important. Raman lidar is a powerful, proven technique for making nighttime water vapor measurements in clear skies (or up to the lowest cloud level). At Sandia, we have developed a Raman lidar which is capable of making accurate nighttime and *daytime* water vapor measurements.

We are making some minor modifications that will significantly enhance the system's performance. First, we will approximately double the laser energy by adding a XeCl amplifier to the system; the required laser head is already installed in the lidar system, requiring only a change in electrodes before it can be used for this purpose. Second, we will enhance the throughput of the high-sensitivity water vapor channel in the detection system by replacing the narrowband interference filter in the channel with a higher-transmission filter; the accompanying increase in filter bandwidth will not degrade the nighttime performance of the system (and the daytime performance can be recovered simply by swapping the existing filter back into the system). Third, we will install a low-noise photomultiplier tube in the high-sensitivity water vapor channel, leading to a significant enhancement in low-signal (i.e., long range), long-time-averaged measurements. We anticipate that with these modifications we will be able to measure nighttime water vapor profiles up to 10-12 km. The calculated improvement in system performance obtained by these modifications is shown in Figure 3.

References

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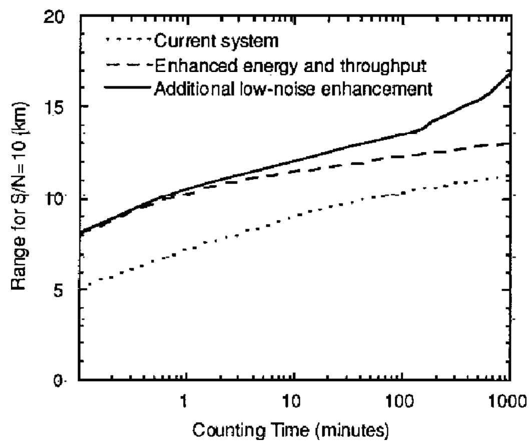

Figure 3. Performance calculations for the Sandia Raman lidar in its current configuration and with "enhancements" that require only very minor changes to our current system. The curves represent the vertical range obtained as a function of counting time using the mid-latitude summer AFGL atmospheric profile, and assuming upper altitude vertical resolution of 375 m.