Raman Lidar Measurements of Cirrus Clouds and Their Influence on Satellite Radiances

D. N. Whiteman, D. O'C. Starr, G. Schwemmer

NASA/Goddard Space Flight Center, Greenbelt, MD 20771

K. Evans, B. Demoz, T. Berkoff, S. H. Melfi, M. Cadirola

University of Maryland, Baltimore County, Baltimore, MD 21250

G. Jedlovec

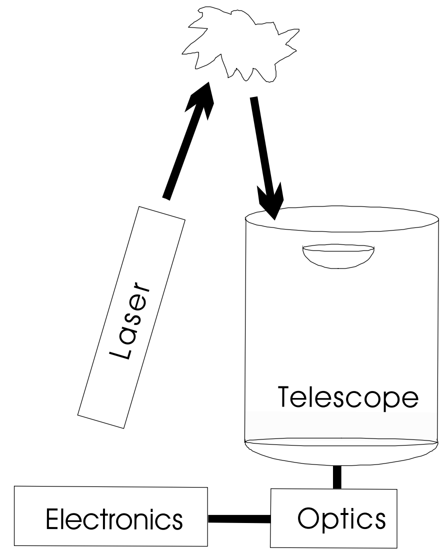
NASA/Global Hydrology Center, Marshall Space Flight Center, Huntsville, AL

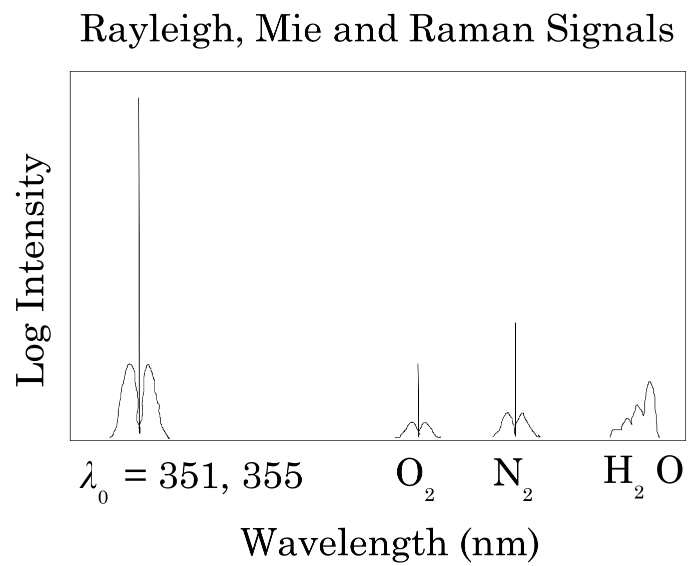
E. W. Eloranta

University of Wisconsin, Madison

Raman Lidar

- Laser transmitter (UV better)
  - excites Raman scattering in atmospheric species. Energy shifts and return wavelengths for 351, 355 excitation are:
    - O_2 (1555 cm^{-1}) => 371, 375 nm
    - N_2 (2330 cm^{-1}) => 382, 387 nm
    - H_2O (3657 cm^{-1}) => 403, 408 nm
- Telescope receiver
  - wavelength selection optics separate the wavelengths
- Time gated data acquisition gives range information





Raman Lidar Measurement Capability

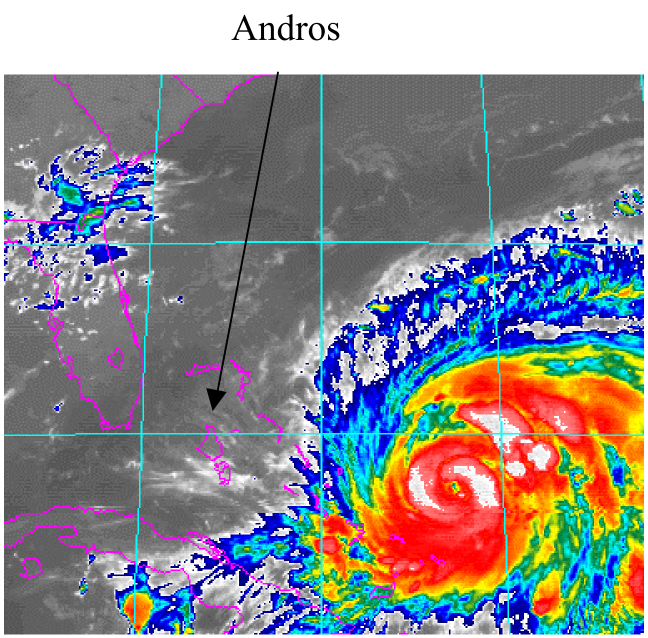
- Raman lidar is a well-established technology for measuring atmospheric water vapor, aerosols, and temperature
- It can also be used to measure cloud properties which are important in radiation studies
  - Cloud backscatter coefficient and cloud liquid water
    - Simultaneous measurement of these two allow cloud droplet radius, cloud number density retrievals (Whiteman, 1999b)
  - Cirrus cloud optical depth, extinction to backscatter ratio
    - Optical depth determines cloud radiative capacity, extinction to backscatter ratio is related to the scattering phase function
    - Unlike a normal backscatter lidar, cirrus optical depth can be determined directly from the molecular nitrogen signal measured by a Raman lidar. As in any lidar, multiple scattering is an influence and must be considered.

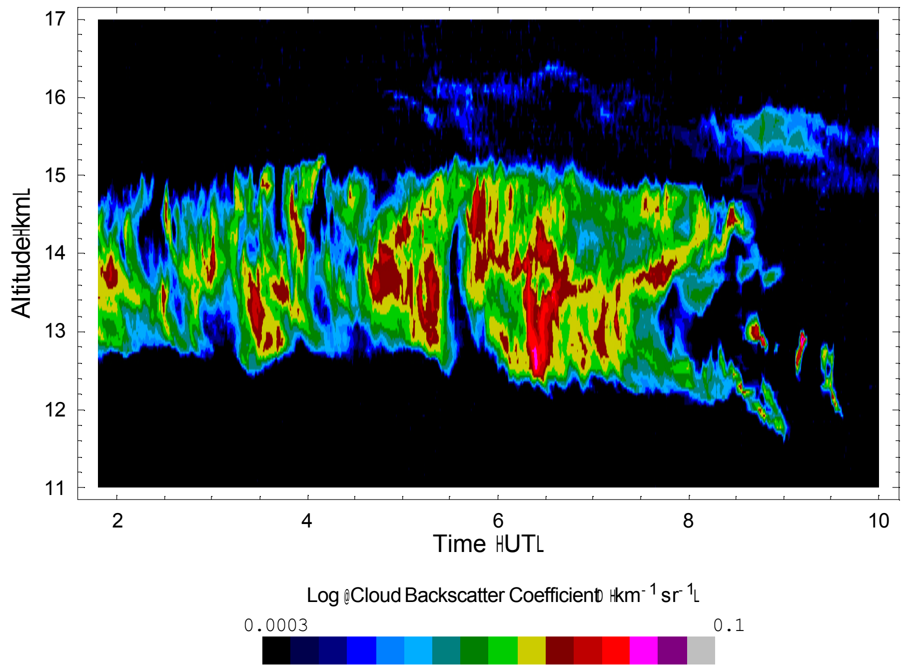
NASA/GSFC Scanning Raman Lidar (SRL)

- Single trailer mobile system
- Two lasers: XeF excimer, Nd:YAG
- 0.75 meter telescope
- Full aperture scanning capability
- Day and night measurements of water vapor, aerosols, clouds
- All weather operations

SRL on location at Andros Island, Bahamas for the third Convection and Moisture Experiment (CAMEX-3)

Hurricane Bonnie Induced Cirrus Cloud

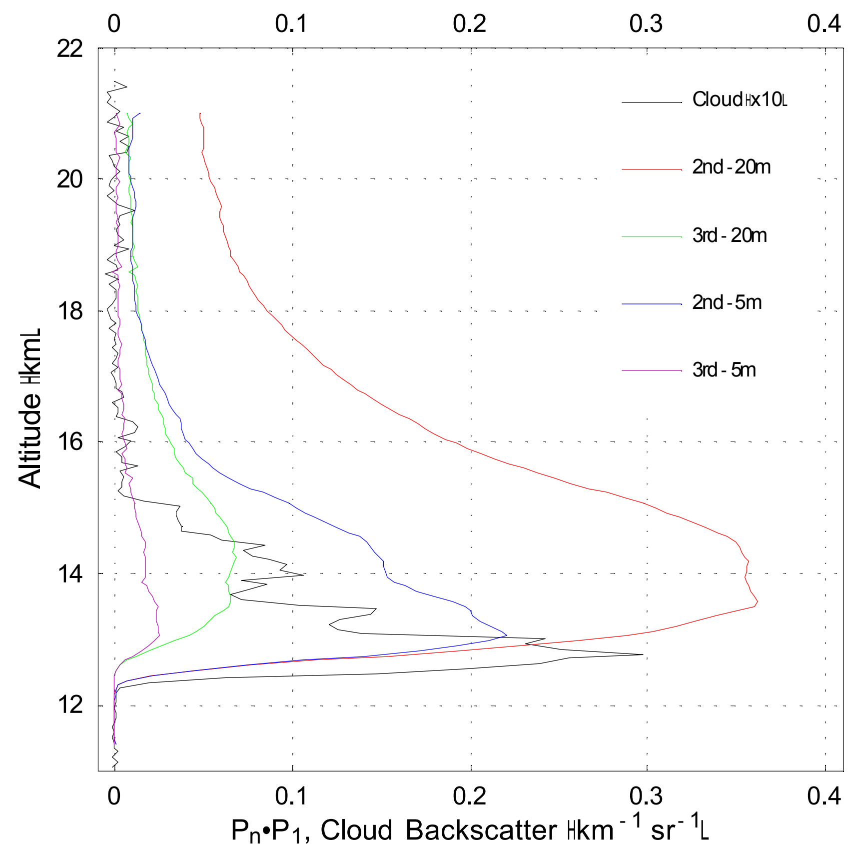




GOES IR satellite photo at 0345 UT on the night of August 23, 1998 during the approach of Hurricane Bonnie to Andros Island. On the right are the SRL cirrus backscatter coefficient measurements during this period. Values varied between 3×10^{-4} to 3×10^{-2} (km^{-1} sr^{-1}). Before calculating the optical depth of this cloud, the influence of multiple scattering must be studied.

Multiple Scattering in Cirrus Clouds

- The formulation of Eloranta was used to study second and third order multiple scattering. In the example shown, cirrus particles of 5 microns (blue and purple) and 20 microns (red and green) were simulated with extinction to backscatter ratio of 20. The ratio of n^{th} order scattering (where n = 2 or 3) to first order scattering is plotted along with the cloud backscatter coefficient. The backscatter coefficient has been multiplied by 10 for easier viewing.
- Notice that the influence of multiple scattering decreases with altitude above the most intense portion of the cloud.



Optical Depth Equation

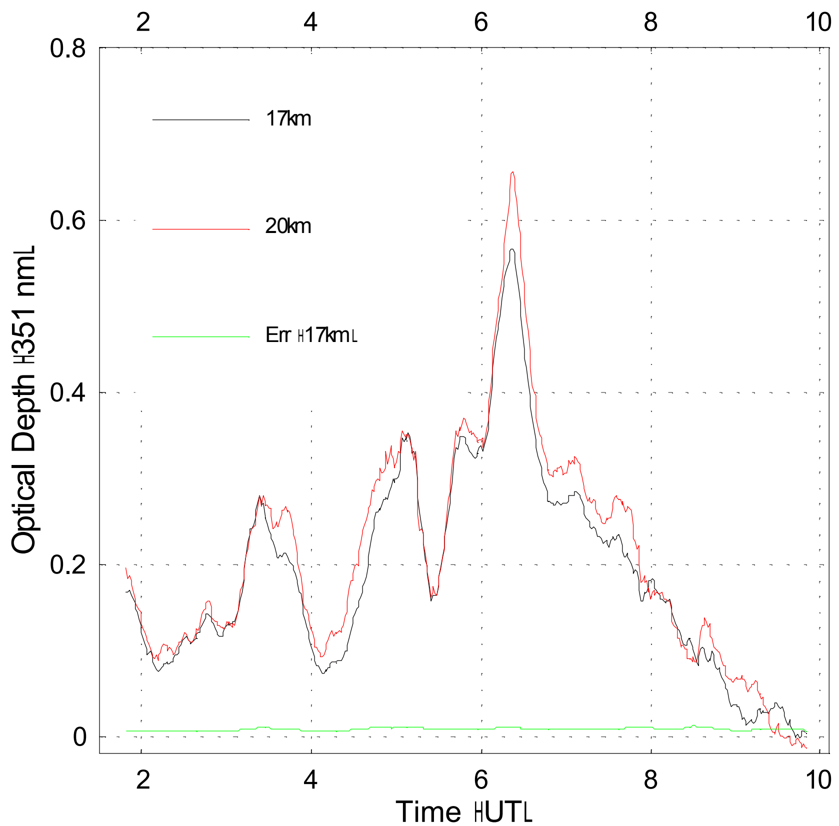
$$TwoWayOD = \int_{r1}^{r2} [\alpha(\lambda_L, r) + \alpha(\lambda_N, r)] dr$$

$$= \left[\ln\left(\frac{O_N(r) N_N(r)}{r^2 P(\lambda_N, r)} \right) \right]_{r1}^{r2} - \int_{r1}^{r2} [\alpha_{mol}(\lambda_L, r) + \alpha_{mol}(\lambda_N, r)] dr$$

The important point of this slide is that r_1 is a point below the cloud and r_2 is a point above the cloud (for the definition of the other terms, please ask!). In the case of only single scattering, the choice of r_2 would not influence the outcome. But multiple scattering makes the world more complicated…

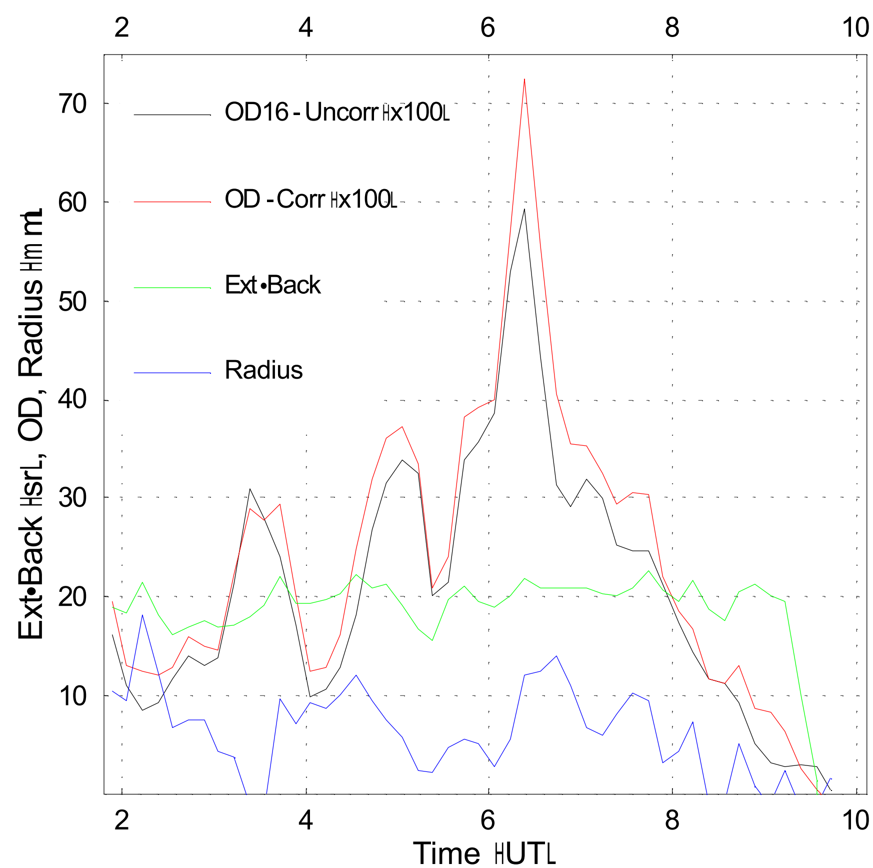
Optical Depth Calculations at Different Altitudes

- But, the multiple scattering simulations shown earlier imply that if the upper altitude r_2 in the optical depth calculation is increased, the optical depth should also increase since the influence of multiple scattering is decreasing.
- This behavior is seen on the right where two values of r_2 have been used to determine optical depth: 17 km and 20 km. Notice that the 20 km results are generally higher.
- This implies that the change in the calculated value of optical depth versus r_2 can be used as a measure of the multiple scattering in the cloud.



Cirrus Retrieval Technique

- Using the cirrus optical depth calculated with two different values of r_2 and the cirrus backscatter coefficient (which has essentially no multiple scattering influence), an iterative solution is found for the following:
  - multiple scattering in the cloud
  - layer average extinction/backscatter ratio
  - layer average diffraction equivalent particle radius
- Using multiple-scattering corrected cirrus optical depths, the influence of cirrus clouds on satellite measurements can be studied.



Radiative Transfer Model

- In order to assess the influence of cirrus clouds on satellite radiances, a simple radiative transfer model was used
  - R_{sat} is the radiance seen by the satellite
  - e_c, e_s are the cloud and surface emissivities
  - $P(L_{sat}, T_s)$ is the Planck function at the satellite wavelength L_{sat} and surface temperature, T_s.
  - T_c is the mean cloud radiating temperature

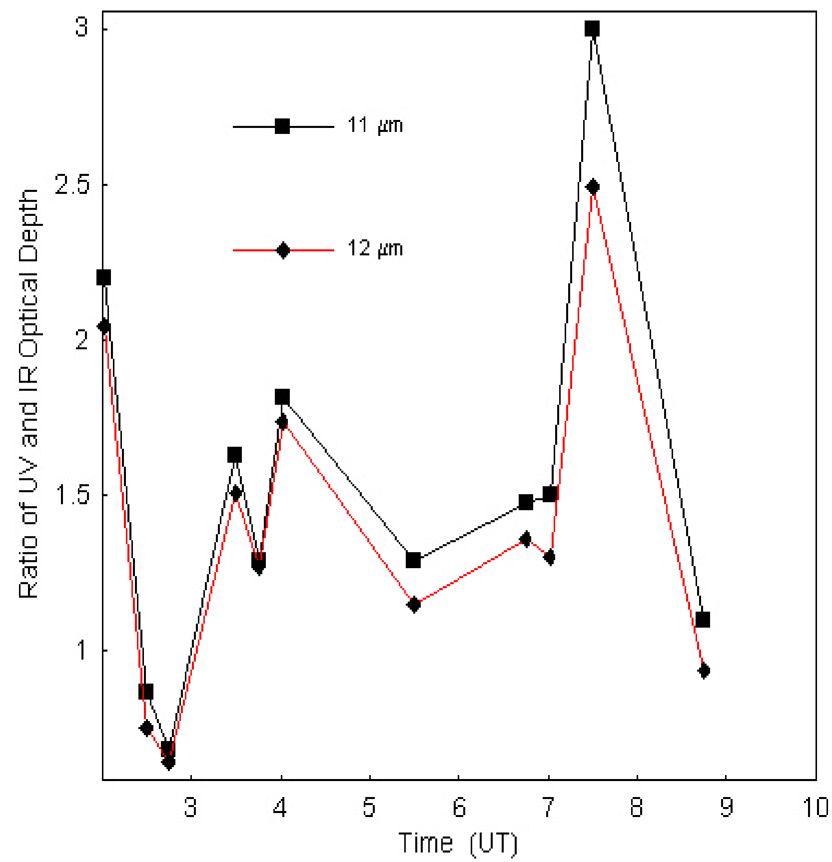
$$R_{sat} = (1 - e_c) e_s P(L_{sat}, T_s) + e_c P(L_{sat}, \overline{T_c})$$

Need IR optical depths!

- But the SRL measures optical depth in the UV. We want to use the radiative transfer equation to simulate GOES 11- and 12-micron channels in the IR. IR optical depths are required! Use the equations below to calculate IR optical depth from GOES data. Then compute UV(SRL)/IR(GOES) optical depth ratio.
- Mean values of UV/IR ratio: 1.6 (11-micron), 1.4 (12-micron).
- These values will be used to scale the SRL optical depths to the IR for use in the radiative transfer equation.

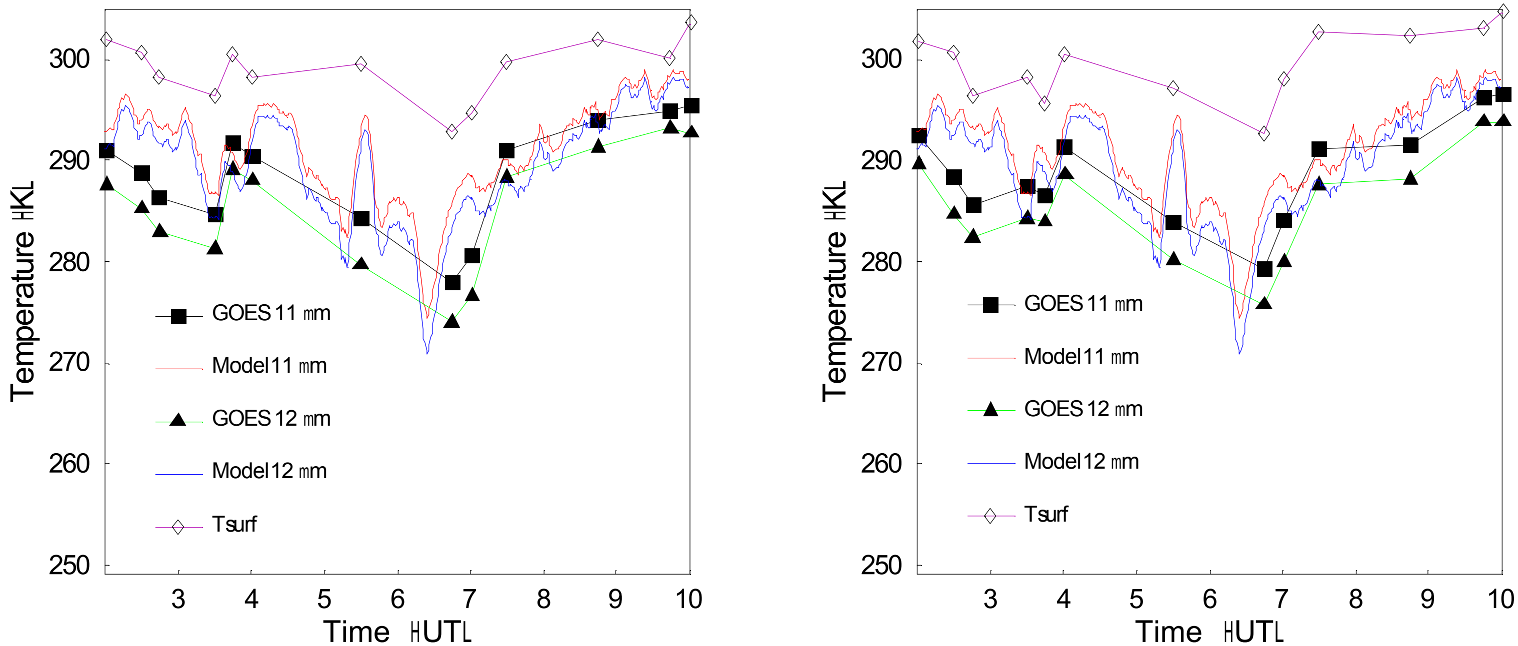
$$t_c = -\ln(1 - e_c)$$

$$e_c = (R_{clr} - R_{sat})/(R_{clr} - R(\overline{T}_c))$$



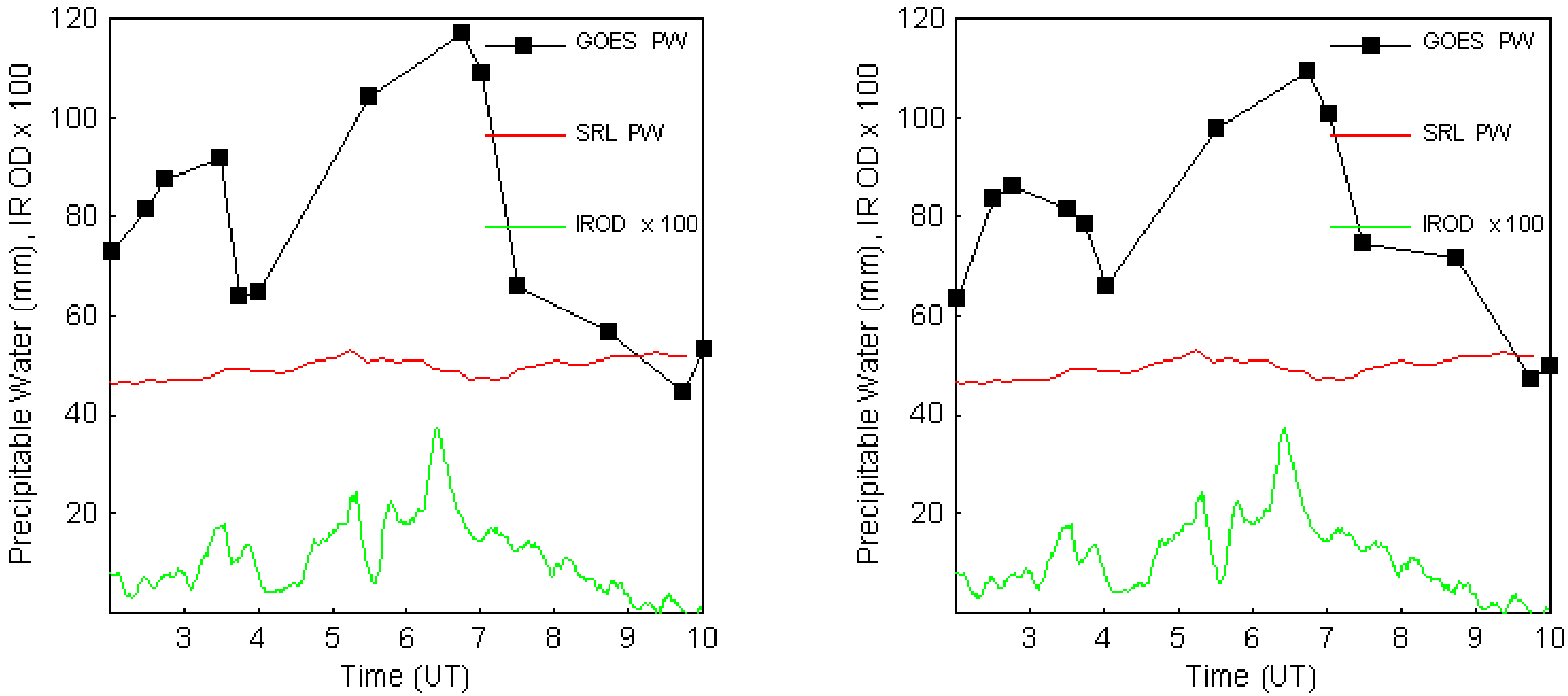
This ratio is a function of particle size and exact spectral location due to the greatly varying index of refraction of ice. An 11-micron ratio that is larger than the 12-micron ratio is consistent with small crystals. This could be indicative of a top-of-cloud bias in the satellite radiances, however.

Model and GOES Radiances, Retrieved T_{surf}



Radiative transfer model and GOES brightness temperatures (T_b) were compared for two pixels: the one directly over the lidar site (left) and the adjacent pixel to the east (right), which was completely over the ocean. Model calculations of GOES T_b using SRL-measured, IR-adjusted optical depths are shown in red (11-micron) and blue (12-micron). Actual GOES radiances, shown with boxes (11-micron) and triangles (12-micron), compare well. Also shown is the retrieved surface temperature using the split-window technique (Suggs et. al., 1998) with no cloud screening.

SRL-Measured and GOES-Retrieved TPW



Comparison of SRL-measured total precipitable water (TPW) and that derived from GOES for the same two pixels. Cirrus optical depths are also shown. There are several points to be made:

1. The pixels over the lidar and over the ocean show very similar results. The constant surface temperature assumption in the model is therefore justified.
2. It is apparent that retrieved TPW is more influenced by cirrus clouds than is surface temperature.
3. Changes in cirrus cloud optical depth are the dominant factor influencing these satellite radiances.
4. Taking 1000 UT as the approximate time after which GOES radiances are no longer affected by the cirrus clouds, the optical depth threshold above which cirrus clouds significantly influence satellite radiances is 0.005.
5. Using the ISCCP cloud detection threshold of 2K(over water) on these data implies high biases of up to 20% in TPW in the GOES retrievals due to undetected thin cirrus. Over land biases of up to 40% result.

Summary and Conclusions

- The NASA/GSFC Scanning Raman Lidar is a mobile system that was deployed on Andros Island during the 3rd Convection and Moisture Experiment (CAMEX).
- Cirrus clouds due to the nearby passage of hurricane Bonnie were studied.
- A multiple scattering correction technique was used which derived corrected optical depth (OD), mean extinction to backscatter ratio and diffraction-equivalent mean particle radius.
- Radiative transfer model predictions, based on SRL-measured ODs, indicated that cirrus clouds with optical depths as low as 0.005 can significantly influence satellite radiances
- Using the International Satellite Cloud Climatology Project (ISCCP) cirrus detection threshold over water of 2K implies that cirrus clouds up to optical depths of 0.05 will not be detected. Over land a 4 K threshold is used which corresponds to ~0.1 cirrus OD. The results here indicate high biases in the GOES TPW retrievals of up to 20% and 40% due to these undetected cirrus over water and over land, respectively.

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