## GACP ACCOMPLISHMENT REPORT

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**Title:** Limits to Cloud Susceptibility

### Tasks Completed, Year 3

Tasks completed during the third year were as follows: 1) Ship tracks found in NOAA-14 observations for July 1999 were analyzed and an assessment of the strength of the indirect effect based on those ship tracks was prepared for publication. 2) Ship tracks found in NOAA-11 and NOAA-12 observations for June 1994 and in NOAA-12 observations for July 1999 were also analyzed. 3) Ship tracks were sought in TRMM VIRS data, but the search was abandoned because the 2-km spatial resolution and the narrow swath of the radiometer severely limited the number of ship tracks that could be found and analyzed. 4) Searches for tracks in MODIS observations began and are under way. 5) While the study was originally based on the assumption that unpolluted clouds near ship tracks were identical to the polluted clouds, analysis of the spatial variability of marine stratus revealed that the properties of clouds separated by even small distances were statistically different, even for clouds imbedded in layers that extended for hundreds of kilometers. Because such variability also affects strategies for validating cloud properties, analyses were performed to determine the discrepancies that might arise when comparing satellite derived properties with *in situ* aircraft observations and inferences of cloud properties based on surface observations.

### Results

The analysis of the ship tracks in the NOAA-14 AVHRR observations for the U.S. west coast in July 1999 revealed that clouds polluted by ship plumes appeared to lose liquid water when compared with their uncontaminated counter parts. In addition, the analysis resolved discrepancies that had arisen in previous studies of ship tracks, namely that in some studies, the polluted clouds seemed to have excess liquid water, and in others, as was found in the analysis of the NOAA-14 data, the polluted clouds appeared to have less liquid water.

If cloud liquid water is kept constant, then the fractional change in the visible optical depth is directly related to the fractional change in the droplet effective radius. That is,

$$\frac{\Delta\tau}{\tau} = -\frac{\Delta R_e}{R_e}\text{, or equivalently, } -\frac{\Delta \ln\tau}{\Delta \ln R_e} = 1.$$

Figure 1 shows the distribution of the ratio for changes in logarithmic values based on the NOAA-14 observations. The observations are for 30-km track segments in which the average droplet effective radius retrieved for the polluted clouds was at least 2 μm smaller than that for the nearby unpolluted clouds. Such clouds were taken to be the most heavily affected by the pollution plumes. The figure summarizes the findings for 244 30-km track segments, approximately half of all the track segments analyzed. The average value for the ratio was 0.46 with a 90% confidence range of ± 0.1. The ratio was significantly less than 1.0, the value that would have indicated that cloud liquid water remained constant. For comparison, the ratio was also computed for the uncontaminated clouds that appeared on either side of the ship tracks, as indicated by the results for control 1 – control 2. The comparison of the uncontaminated clouds provides a measure of the statistical significance of the differences between the polluted and the unpolluted clouds. Clearly, the polluted clouds had higher optical depths, and thus reflected more sunlight than their unpolluted counter parts, as expected for the indirect effect, but the enhancement in reflectivity was considerably less than would have been obtained had cloud liquid water remained constant. As the results in the figure indicate, for the majority of cases, polluted clouds had less liquid water than the nearby unpolluted clouds.

Figure 1 also shows that in a few cases, cloud liquid water was enhanced in the polluted clouds. Further analysis revealed that for the 30-km ship track segments in which the larger liquid water amounts were found, the tracks were often detectable at visible wavelengths. This finding explains those of previous studies in which ship tracks were identified using reflected sunlight at visible wavelengths. In these earlier studies the polluted clouds were found to contain more liquid water than the unpolluted clouds. Analysis of the NOAA-14 data revealed that tracks which were detectable at visible wavelengths generally had polluted clouds with more liquid water than the surrounding uncontaminated clouds, but such tracks represented only a small fraction of the total number of tracks that were identified using radiances at 3.7 μm to detect the change in droplet radius. While reflected sunlight at visible wavelengths occasionally reveals tracks in otherwise cloud-free regions, evidence that the clouds would not be present without the condensation nuclei provided by the pollution sources, few ship tracks imbedded in extensive layers of marine stratus are detectable in the visible spectrum.

Simple radiative transfer calculations were performed to determine whether absorption by particles in the ship plumes might explain the shortfall for the changes in visible optical depths that were interpreted as being due to a loss of liquid water in the polluted clouds. The amount of particle absorption required to explain the shortfall was orders of magnitude greater than the amounts that could possibly be generated by ships. Likewise, the analysis of cloud emission temperatures revealed no significant shifts in the cloud top altitudes for the polluted clouds. These results led to the conclusion that the polluted clouds had less liquid water than their nearby unpolluted counterparts. Perhaps the absorption by the pollution particles in the clouds suppresses convection so that the flux of water vapor into the polluted clouds is reduced compared with the fluxes for neighboring uncontaminated clouds. Over time, the suppression leads to a deficit in liquid water. Polluted clouds have 15-20% less liquid water than the neighboring unpolluted clouds.

Analyses of the NOAA-11 and NOAA-12 observations for June 1994 showed even greater losses in cloud liquid water for the polluted clouds. Indeed, the NOAA-11 (afternoon)

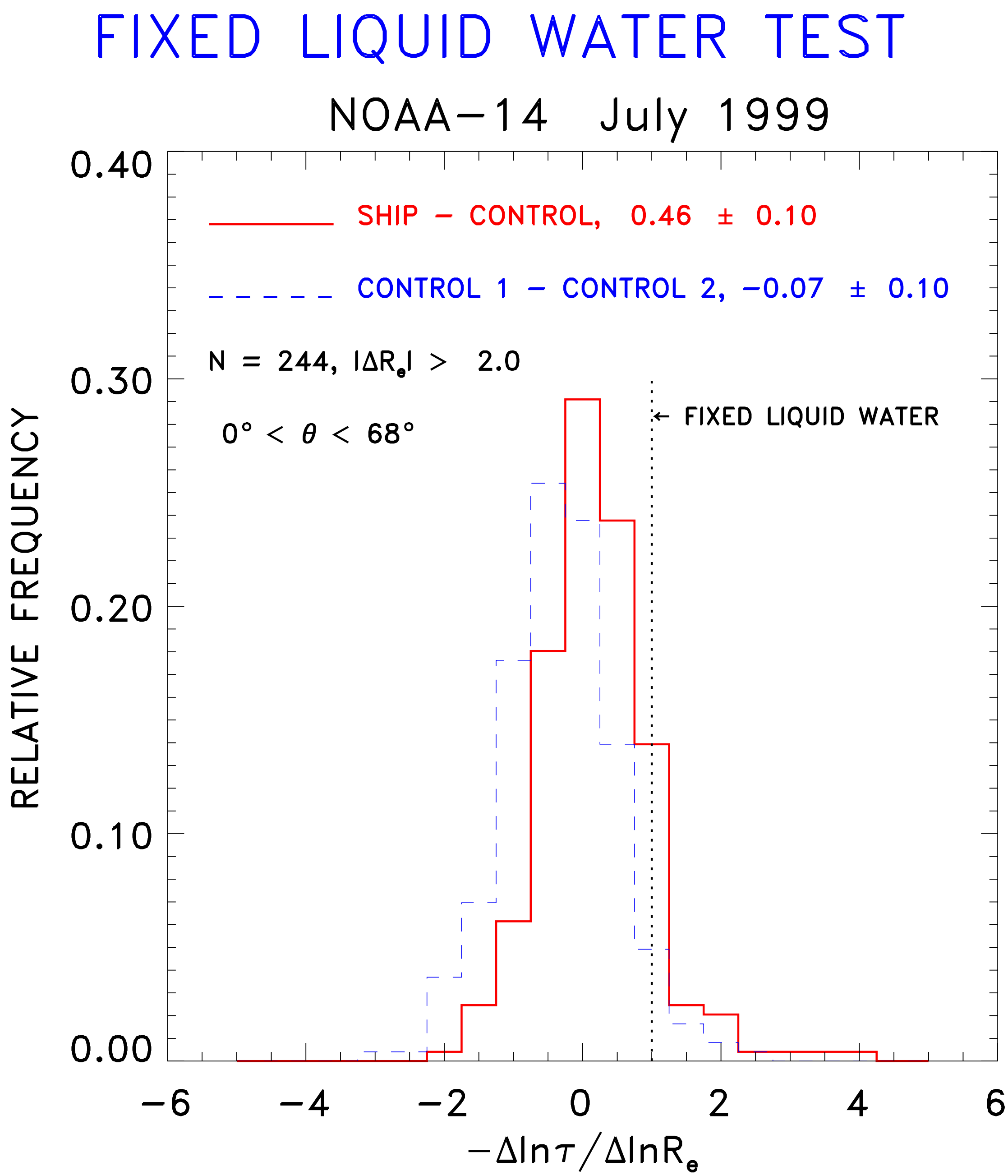



Figure 1. $-\Delta \ln \tau / \Delta \ln R_e$ for the 30-km ship track segments in which the average change in droplet effective radius, uncontaminated – contaminated, was greater than 2 μm. $-\Delta \ln \tau / \Delta \ln R_e = 1$ if the cloud liquid water amount remains constant. The number of segments, means, and estimates of two standard deviations for the ensemble means are given.

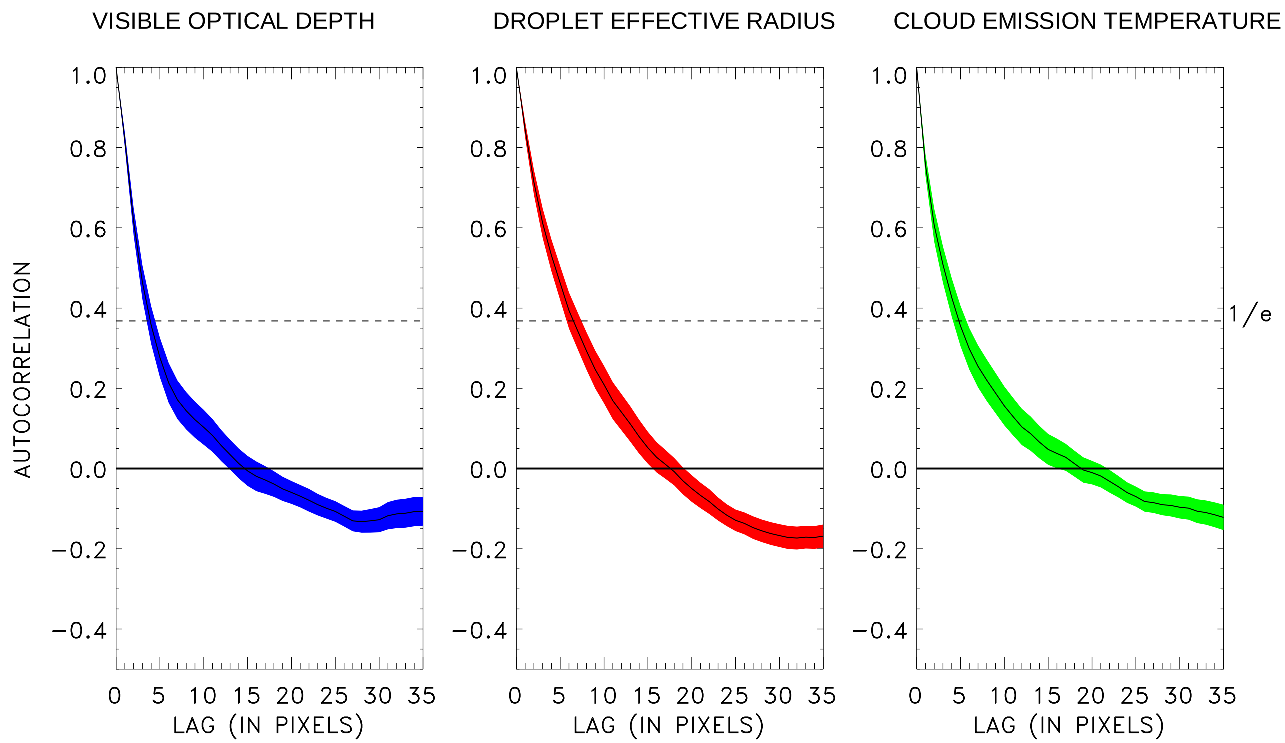
observations showed no detectable increase in optical depth for the polluted clouds, even when the observations were restricted to cases for which the change in the droplet effective radius was greater than 2 μm. The change in optical depth for the NOAA-12 (morning) observations was just detectable at the 90% confidence level, but the loss in liquid water inferred for the NOAA-12 observations was even greater than that for the July 1999 NOAA-14 observations. For the June 1994 observations, the number of ship tracks satisfying the conditions for analysis was far below that for the NOAA-14 July 1999 observations, perhaps reflecting substantial year to year variability in the marine stratus off the west coast of the U.S. In any case, the analysis of ship tracks provides overwhelming evidence that the indirect effect is less than would be inferred assuming that droplet sizes become smaller and droplet numbers become larger so that liquid water remains constant.

The strategy underlying the analysis of ship tracks was that clouds identified as being polluted by ships could be compared with nearby clouds drawn from the same layer that were identical except for the effects of the pollution. The comparison of cloud properties derived from overcast pixels located on one side of the track and those for pixels located on the opposite side revealed, however, that the clouds were rather dissimilar, even for pixels separated by only a few kilometers. Autocorrelation functions for the cloud properties, like those shown in Figure 2, revealed that the autocorrelation lengths for visible optical depth, droplet effective radius, and even for cloud emission temperature, were typically less than 10 km. That is, even for layered, overcast, marine stratus, clouds separated by as little as 20 km were statistically different. Such variability hampered the analysis of ship tracks in that large ensembles of ship track segments were required in order to achieve the desired detection levels for changes in the visible optical depth. This same variability could also hamper the validation of cloud properties using *in situ* aircraft or remotely sensed surface observations as done in FIRE and ARM. To investigate the implications of the spatial variability for validation studies, cloud properties were derived for transects, i.e., for a fixed pixel location within a scan line, and compared with averaged properties for pixels surrounding the transect. The comparison is designed to represent aircraft measurements along a flight path, or observations of clouds advecting over a surface site, compared with an area average of retrieved products derived from satellite data. Figure 3 shows that for marine stratus, comparing 30-km scale area averages with the corresponding transect averages leads to relatively small differences in optical depth, droplet radius, and cloud emission temperature. Also, as expected, biases in the inferred visible optical depth arise when observing systems with coarse resolution, such as pyranometers, are used to derive cloud optical depths and the optical depths are compared with high resolution satellite measurements. The results of this study will be reported at the Fall 2001 AGU meeting: M.A. Matheson and J.A. Coakley, Jr., 2001: Spatial Variability of Derived Properties for Marine Stratus Clouds. The results are also being prepared for publication.

**Future Work**

Under the existing no-cost extension, work is continuing on the search for ship tracks in MODIS observations. Work on algorithms for retrieving cloud properties from the MODIS observations has begun and will be completed shortly. Once completed, retrieved cloud properties will be compared with the corresponding MODIS products. Because of the need to

# Cloud Property Autocorrelations



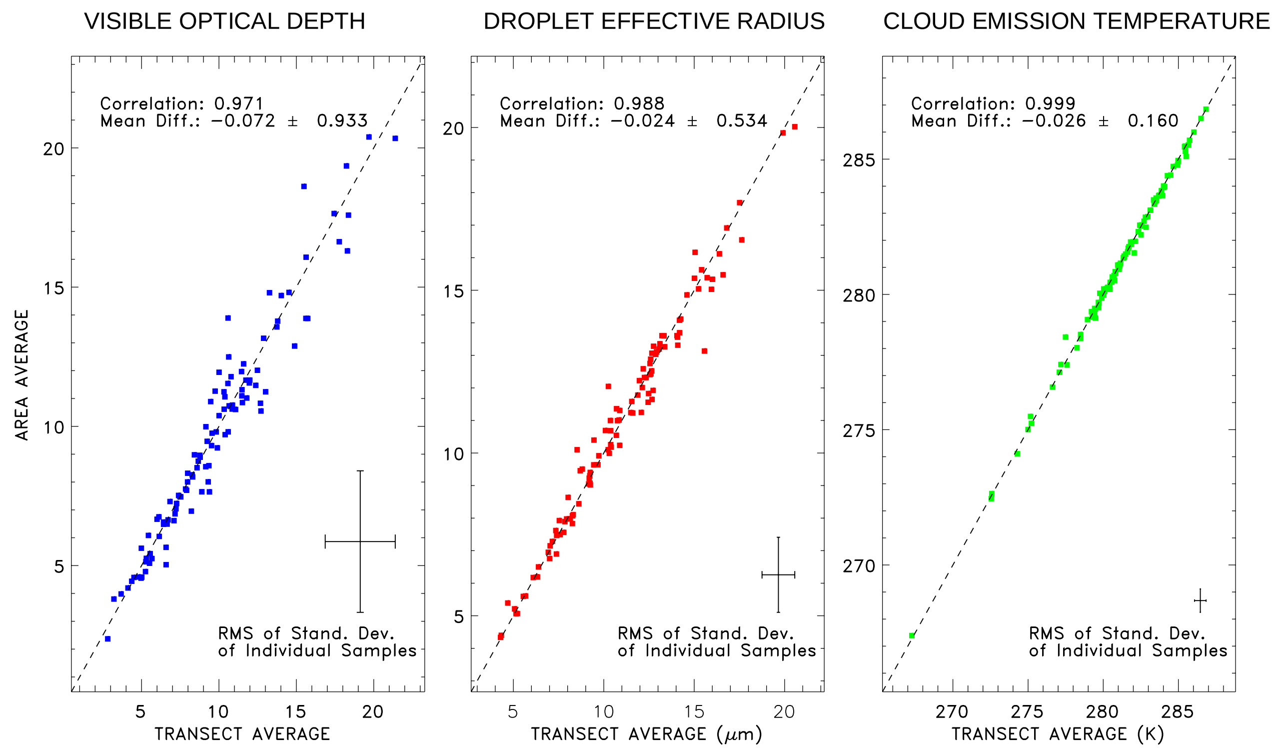

Notes: 106 Samples, 71 Pixels Long - NOAA-14, 25° of Nadir

Figure 2. Autocorrelation functions for visible optical depth, droplet effective radius, and cloud emission temperature derived from 1-km AVHRR observations. Each sample is derived from a 71-pixel transect for which all pixels are overcast by marine stratus. The shaded regions give the 90% confidence limits for the autocorrelation function.

restrict the analysis of ship tracks to pixels overcast by clouds, both for the clouds affected by the ship and the surrounding clouds that serve as a control, the retrievals of cloud properties must be performed as opposed to using MODIS products. In using MODIS observations, the intent is to compare assessments of the indirect effect derived using the other spectral channels available with MODIS in order to demonstrate the sensitivity of the inferences concerning cloud liquid water to the spectral radiances used to derive cloud properties. Such was the intent behind seeking ship tracks in the TRMM VIRS observations, but the 2-km resolution of the VIRS radiometer coupled with its narrow swath worked to sorely restrict the number of ship tracks that could be found.

In addition to the analysis of MODIS data, the results of the analysis of the spatial variability of marine stratus will be prepared for publication.

# Transect and Area Averages




Notes: 106 Samples (31x31 km Area, 1x31 km Transect) - NOAA-14, 25° of Nadir

Figure 3. Transect and area averages of cloud properties.