FORM A: GACP ACCOMPLISHMENT REPORT

James A. Coakley, Jr.

College of Oceanic and Atmospheric Sciences
Oregon State University
Corvallis, OR 97331-5503

Title: Limits to Cloud Susceptibility

Abstract:

1-km AVHRR, VIRS, and MODIS observations of ship tracks in low-level clouds off the west coast of the U.S. will be used to derive limits for the degree to which clouds might be altered by increases in anthropogenic aerosols. The goal is to analyze several thousand ship tracks to determine whether changes in droplet radii, visible optical depths, and cloud top altitudes are consistent with the pre-existing optical depths, radii, and altitudes as anticipated for fixed liquid water paths. A unique feature of this study is that it will rely only on observations for which the ~ 1-km field of view of the satellite radiometer is overcast for both the portions of the cloud affected by the ship and the nearby portions of the cloud that are unaffected. Use of only the overcast pixels will greatly reduce the variability in the observed radiances through which the effects due to the ships must be extracted. Changes due to ships will be examined as functions of distance from the start of the track to distinguish between freshly contaminated clouds and clouds that have been affected for several hours. By allowing for effects due to dispersion, the portions of the tracks far from the ship should reflect influences, if any, of the changes in droplet sizes and numbers on the interaction of the cloud with its environment. The frequency with which ship tracks are found in pixels overcast by marine stratus but the layer is broken in the nearby surrounding region will be used as a measure of effects due to the changes in droplet sizes. Regions where ship tracks intersect will be analyzed to determine whether the changes in droplet sizes and numbers reach saturation, based on the changes expected from analysis of the changes in the separate tracks comprising the intersection. Previous work has indicated that the retrieved optical depths and effective droplet radii are likely to be sensitive to viewing geometry; consequently, the sensitivity of the results to viewing geometry will also be studied. Likewise, previous work has indicated that retrievals of effective droplet radii may be sensitive to the near infrared wavelengths used in the retrieval. Observations from VIRS and MODIS will be analyzed to determine how the findings change with the wavelengths of the near infrared radiances used in the retrievals.

Goals:

The primary goal of this research is to analyze a statistically large number of ship tracks to determine how changes in cloud droplet radii induced by ships are linked to changes in the cloud visible optical depths, and possibly cloud altitudes. How the changes are related to the pre-existing droplet radii, optical depths, and altitudes, as deduced from comparisons with the nearby unperturbed clouds, indicates whether cloud liquid water amounts remain reasonably fixed while droplet numbers increase and radii decrease. Because the changes can be analyzed as a function of distance from the start of the track, the analysis also provides information on how changes in the cloud droplet size distribution affects the evolution of the clouds. In fact, ship tracks occasionally extend into regions where the marine layer becomes broken suggesting that the ship induced changes have altered cloud evolution. The frequency with which ship tracks extend into regions of broken clouds will be determined. A second goal is to use analyses of the intersection of tracks to determine the sensitivity of polluted clouds to additional particle concentrations. A third goal is to document the sensitivity of the retrieved cloud properties to viewing geometry and to the wavelengths of the observations used to derive the properties.

Approach:

Following Platnick and Twomey (1994), for fixed cloud liquid water amount, a given change in the effective droplet radius should lead to a corresponding change in the cloud albedo at visible wavelengths. The relationship between the changes is approximately given by

$$\frac{\Delta R}{\Delta r_e} = -\frac{R(1-R)}{r_e} \tag{1}$$

where R is the albedo at visible wavelengths and r_e is the effective droplet radius. For fixed liquid water amount and known effective radius, the cloud albedo is directly related to the visible optical depth. As is commonly done, plane-parallel radiative transfer theory is used to establish the relationship. The approach then is to determine whether changes in the visible optical depth and changes in the effective droplet radius are determined through the pre-existing droplet radius and optical depth as given by (1). For example, for simple, single-layered cloud systems, an increase in optical depth larger than expected from the decrease in droplet size would indicate an increase in cloud liquid water and thus an enhancement of the expected sensitivity of clouds to particle pollution, also known as the Twomey effect. The approach then is to use 1-km AVHRR, VIRS, and MODIS observations to obtain visible optical depths, effective droplet radii, and cloud altitudes for marine stratus affected by ships and to determine the ship-induced changes by comparing the retrieved quantities with those obtained for the surrounding unperturbed clouds.

In order to accomplish these objectives the following tasks need to be completed. Because the retrieved cloud properties are affected by the fractional cloud cover in the field of view of the radiometer, the observations must be screened so that perturbed and unperturbed cloud observations are treated uniformly. The strategy followed here is to restrict the analysis to clouds that completely overcast the imaging radiometer's field of view. This constraint not only improves the similarity in cloud characteristics for the perturbed and unperturbed pixels, it also reduces the variability of these characteristics brought about by natural variations within cloud fields. The constraint is accomplished through a scene identification scheme which distinguishes between fields of view that are overcast by single-layered clouds and those that are only partially cloud covered, or have clouds that are distributed in altitude. Once overcast pixels have been identified, a second identification scheme is required to distinguish between clouds affected by ships from those that are unaffected. As an aid in the identification of the ship-perturbed pixels, the location of tracks are first recorded through image analysis of each satellite overpass. The tabulated positions are then used in an automated scheme for locating the polluted clouds. In the automated scheme, the tracks are identified as pixels with enhanced 3.7-µm radiances that are linked to form a line with arbitrary thickness, length, and curvature within the image. Retrievals of cloud visible optical depth, effective droplet radius, and cloud altitude are performed for each pixel found to be overcast by clouds belonging to a single-layered system. The retrieved quantities are obtained by matching the observed visible, near infrared, and infrared radiances with values expected from plane-parallel radiative transfer calculations. The retrieved products are then analyzed statistically to address the goals of the research.

Tasks Completed:

During the first year, all daytime passes of NOAA-11 and NOAA-12 for June 1994 for the west coast of the U.S. were analyzed for ship tracks. Positions of 337 tracks were tabulated for the afternoon passes of the NOAA-11 and 421 tracks for the morning passes of NOAA-12. The positions of the tracks not only facilitate the partitioning of the observations to be analyzed, thereby reducing computational burden and simplifying the design of the algorithm needed to automatically distinguish between ship-perturbed and unperturbed pixels, but they also indicate the apparent locations of the ships, thereby facilitating studies of track and cloud evolution. Within the 758 tracks there were 203 intersections. These intersections can be used to study the sensitivity of polluted clouds to additional particle concentrations.

A scene identification scheme (see Form B--GACP SIGNIFICANT HIGHLIGHTS) has been developed for distinguishing between imager fields of view that are cloud-free, overcast by a single-layered cloud system or are only partly covered by clouds. Owing to differences in the spectral channels of the AVHRR and VIRS, separate schemes have been developed for the two instruments.

A plane-parallel radiative transfer code based on DISORT (Stamnes et al. 1988) has been developed for calculating reflected and emitted radiances for atmospheres with plane-parallel clouds and realistic distributions of gaseous absorbers. Absorption by gases is treated using the Kratz (1995) correlated-*k* models.

Future Plans:

During the coming year, work will be completed on the algorithm that uses the tabulated positions of the ship tracks to automatically identify the ship-perturbed pixels. Once the contaminated clouds have been identified and cloud properties have been retrieved for both the contaminated and uncontaminated clouds, the retrieved properties will be chosen at random equally from both the contaminated and uncontaminated pixels.

A look-up table retrieval scheme will be developed that derives cloud properties by searching the radiances produced by the plane-parallel radiative transfer code for values that match the observed radiances. To reduce computational burden, radiative transfer calculations will be performed for climatological profiles of temperature and humidity representative of the west coast of the U.S. Also, the clouds will be treated as infinitesimally thin layers imbedded in the atmosphere.

Once the retrieved properties have been obtained, ensembles of the properties for perturbed and unperturbed pixels will be built for each track. These ensembles will be used in parametric studies of changes in optical depths, cloud droplet radii, and cloud altitudes. Results will be searched for any dependence on distance along the track, starting with the apparent position of the ship, to determine if cloud evolution and dispersion affect the outcome. Also, frequencies will be determined for ship tracks that remain overcast while they extend into regions in which the cloud layer that contains the track is broken.

Finally, an additional month of AVHRR observations and a month of VIRS observations will be analyzed for tracks. In addition, retrievals of cloud properties using the VIRS 1.6-μm channel will be implemented.

Results:

Over 700 ship tracks have been tabulated for NOAA-11 and NOAA-12 observations of the west coast of the U.S. for June 1994. Within these tracks there were over 200 intersections. These intersections are candidates for investigating the sensitivity of polluted clouds to further increases in particle concentrations. Measures of the sensitivity of cloud properties to particle pollution awaits the development of the automated scheme for identifying pixels affected by ships and the look-up table retrieval scheme for deriving cloud properties from the observed radiances. Both the ship track identification algorithm and the cloud property retrieval scheme are expected to be ready in the early part of the second year.

References

Kratz, D.P., 1995: The correlated *k*-distribution technique as applied to the AVHRR channels. *J. Quant. Spectrosc. Radiat. Transfer*, **53**, 501-517.

Platnick, S., and S. Twomey, 1994: Determining the susceptibility of cloud albedo to changes in droplet concentration with the Advanced Very High Resolution Radiometer. *J. Appl. Meteor.*, **33**, 334-347.

Stamnes, K., S-Chee Tsay, W. Wiscombe, and K. Jayaweera, 1988: Numerically stable algorithm for discrete-ordinate-method radiative transfer in multiple scattering and emitting layered media. *Appl. Opt.* **27**, 2502-2509.