An Interhemispheric Comparison of Cirrus Cloud Properties Using MODIS and GOES

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1. INTRODUCTION

The Interhemispheric Differences in Cirrus Properties from Anthropogenic Emissions (INCA) experiment obtained aircraft-based measurements of upper tropospheric properties in the northern and southern hemispheres for comparable latitudes, seasons and backgrounds to determine any differences in cirrus clouds that may be attributable to air pollution. As a follow-up to this study, we compare ice cloud properties in the southern (without strong pollution) and northern (with strong pollution) hemisphere at mid-latitudes by using multi-spectral cloud property retrievals to compile the cirrus properties for one month each over both INCA regions (around Scotland and southern Chile). Data from the Geostationary Operational Environmental Satellite (*GOES-8*) imager and the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the *Terra* satellite are used in the remote sensing retrievals. Various screening criteria are tested to minimize complicating factors such as surface differences and viewing geometry. The satellite-derived cirrus cloud properties are also compared to the aircraft-based measurements from the INCA campaign.

2. DATA

2.1 *MODIS*

The Clouds and Earth's Radiant Energy System (CERES) daytime cloud property retrieval subsystem was used to derive cloud properties from the *Terra* MODIS measurements. Radiance data from the 0.65, 1.64, 3.75, 11.0 and 12.0 µm channels at a 2-km resolution were used from the MODIS instrument. The *Terra* satellite is in sun-synchronous orbit, with an equatorial crossing time at 1030 local time. For each MODIS pixel, the CERES processing system assigns a scene classification of clear or cloudy (Trepte et al., 1999), estimates of clear-sky radiance for each channel, a temperature and humidity profile, and surface elevation. Thirty-five satellite overpasses from 18 March 2001 through 15 April 2001 over southern Chile and 22 overpasses between 20 September 2000 and 17 October 2000 over northern Scotland were analyzed.

2.2 *GOES*

Four-km resolution images at 0.65, 3.9, 10.8 and 12.0 µm were collected from the GOES imager at 3-hour intervals from 19 March 2000 to 16 April 2000 over southern Chile. A total of 31 images were used in the analysis. The satellite sub-point of *GOES-8* is at 75ºW.

3. RETRIEVAL TECHNIQUE

The VIST (Visible Infrared Solar-Infrared Technique) was used to derive cloud height, optical depth, phase, effective particle size and water path for each pixel from several GOES and MODIS channels for daytime scenes (the solar zenith angle must be ≤ 78º). This algorithm is described in detail by Minnis et al. (1995), and an example of a VIST retrieval is presented in Figure 1.

Given the clear-sky radiance estimates for each channel and the sun/satellite geometry, the VIST computes the spectral radiances expected for both liquid-droplet and ice-water clouds for a range of particle sizes and optical depths (τ = 0.25 to 128). The effective radii r_e for the water model clouds range from 2 to 32 µm and the effective diameters D_e for the hexagonal ice column model clouds vary from 6 to 135 µm. The model cloud radiances are computed using the cloud emittance and reflectance parameterizations of Minnis et al. (1998) and a visible channel surface-atmosphere-cloud reflectance parameterization (Arduini et al. 2002). The VIST determines the cloud properties by matching the observed visible (0.65 µm), solar infrared (3.75 µm), and infrared (10.8 µm) radiances to the same quantities computed with the parameterizations and corrected to the top of the atmosphere. The process is iterative and computes results for both ice and liquid water clouds.

A combination of tests that incorporate the final cloud temperature T_c, the initially derived cloud altitude, and a reflectance ratio of 1.6 µm (if available) to 0.65 µm determine cloud phase. The phase selection is also required to be physically reasonable; no ice clouds are

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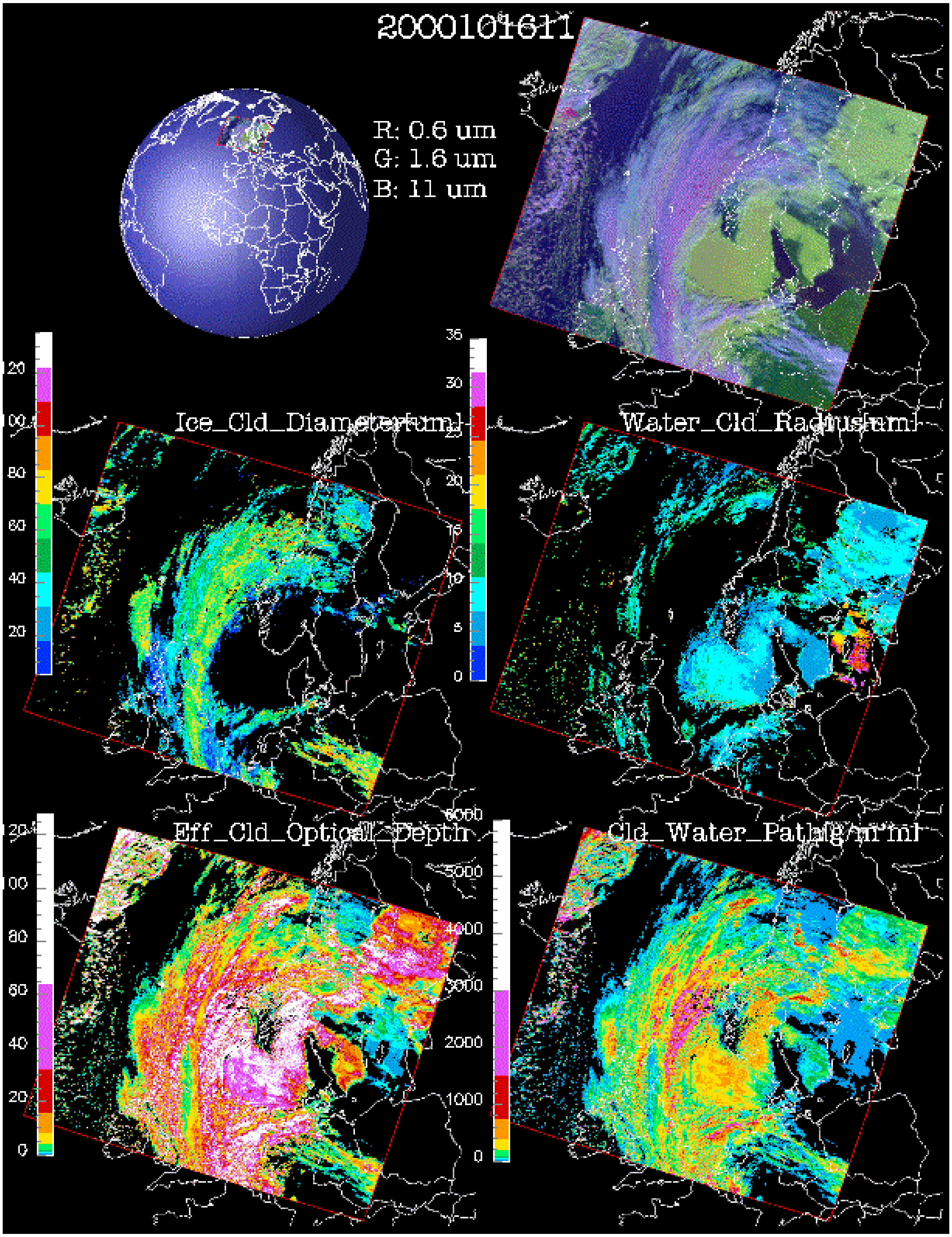

Figure 1. CERES cloud property retrieval from MODIS imagery on 16 October 2000. Top right hand figure is 3-channel composite highlighting the water cloud (green) and ice cloud (blue) regions. The images in the second row show ice particle diameter and water droplet radius in microns, while the bottom figure present the effective cloud optical depth and cloud water path.

allowed for T_c > 273 K and no liquid clouds are permitted for T_c < 233 K.

The cloud liquid water path *LWP* and ice water path *IWP* are derived from the retrieved values of τ and particle size. The effective cloud-top height is the altitude or pressure from the nearest vertical temperature profile that corresponds to T_c. The cloud thickness is defined using a set of crude empirical parameterizations based on τ, T_c, and altitude. Cloud base height is defined as the difference between the cloud-top height and the thickness.

The VIST retrieval algorithm has been compared to passive and active radiometric measurements at surface sites, primarily at the Atmospheric Radiation Measurement (ARM) southern Great Plains (SGP) central facility in Oklahoma (Dong et al., 1997; Mace et al. 1998; Garreaud et al. 2001). Cloud property retrievals using the VIST with the Visible Infrared Scanner (VIRS) radiances on the Tropical Rainfall Measuring Mission (TRMM) satellite show good agreement with the ground-based measurements. The mean difference between the satellite and ground-based retrievals of mean particle diameter in single-layered stratus was 1.2 µm with a standard deviation of 3.6 µm. VIST retrievals using GOES data have also compared well to in situ measurements of a wave cloud containing small ice crystals during the spring 1996 Subsonic Clouds and Contrails Effects Special Study experiment (SUCCESS; Young et al. 1998).

Figure 2 presents the retrieval of ice cloud particle size during the INCA experiment on 6 October 2000 over northern Scotland. The flight track of the Falcon research aircraft is superimposed on the picture. Only retrieved ice clouds are included in the picture.

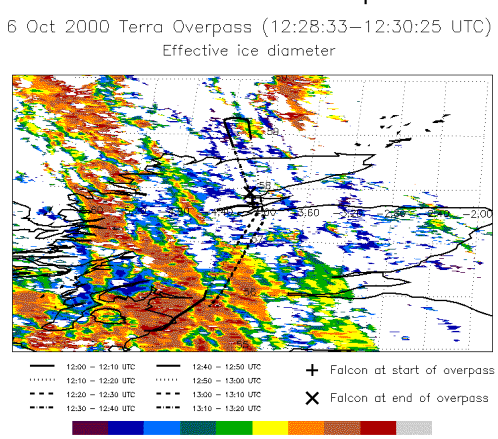

Figure 2. CERES ice cloud diameter retrieval from MODIS imagery on 6 October 2000. The cloud particle diameters are in microns. The flight track of the INCA research aircraft (Falcon) and the location of the aircraft during the satellite overpass are also shown.

A preliminary comparison between the satellite-retrieved ice cloud particle size and the *in situ* aircraft data is shown in Figure 3. The satellite-derived ice particle diameter (solid black line) was collocated with the mean ice particle diameter (divided by 2) from the Falcon's 2-DC probe (dashed light blue line). To collocate the satellite values, all retrieved satellite pixels within 4 km of the reported position of the Falcon were averaged together. No corrections for cloud advection have been included, so the best agreement between the datasets should occur at the time of the Terra overpass (around 1230 UTC on this day). The 2-DC probe primarily measures particles greater than 50 microns in diameter. In addition, the particle diameter from the microphysics probe is essentially the maximum dimension observed in the 2-DC images; therefore it is an overestimate of the true effective diameter. For the segment with a half hour of the satellite overpass of the MODIS instrument, the 2-DC and satellite results indicate that the satellite-observed variations are representative of the changes occurring within the clouds.

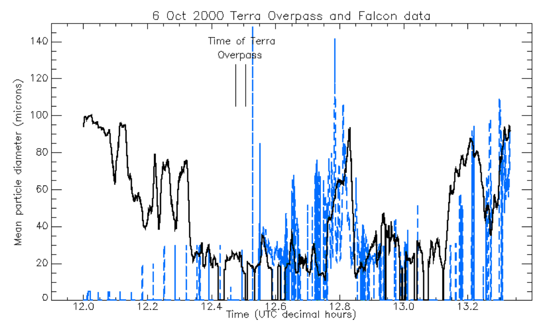

Figure 3. CERES ice cloud diameter retrieval from MODIS imagery on 6 October 2000 collocated with 2-DC measurements from the Falcon (divided by 2).

4. RESULTS AND DISCUSSION

To compile a dataset of cirrus cloud property statistics comparable in season and location to the INCA flight observations, MODIS data from all available *Terra* overpasses within a one month period during the fall season that included the sites of the INCA field campaigns (Prestwick, Scotland and Puenta Arenas, Chile) were analyzed. Several threshold criteria were used to classify clouds as cirrus and to improve the overall quality of the satellite retrievals. Only ocean pixels were included from both the GOES and MODIS retrievals to reduce satellite retrieval difficulties associated with variable surface properties. Cirrus clouds were defined as the remaining cloudy pixels with $T_c \leq$ 233 K and an *IWP* $\leq$ 20 g m^{-2} and a cloud top height of 7 km or higher. To reduce the effect of partial cloudiness on the retrievals, no edge pixels were included in the cloud property statistics; each ice cloud pixel had to be completely surrounded by other ice cloud pixels to be considered as a valid cirrus pixel. Finally, to investigate the effects of satellite viewing zenith angle (SVZA) on the retrievals, all valid cirrus pixels were binned by SVZA (in five degree intervals) and are shown in Figure 4.

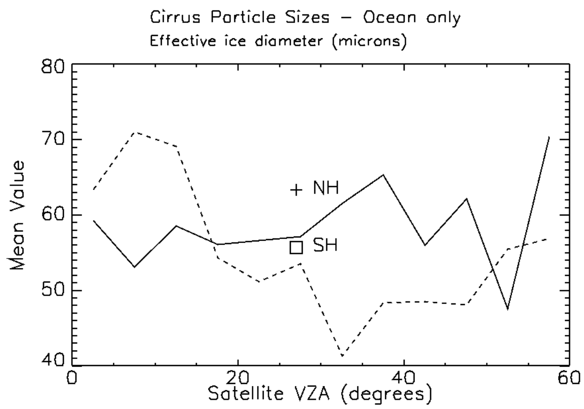

Figure 4. Mean CERES cirrus cloud particle size retrievals derived from northern hemispheric (NH, solid line) and southern hemispheric (SH, dashed line) MODIS observations as a function of satellite viewing zenith angle. The definition of cirrus is presented in the text. The plus sign and square represent the monthly means of all cirrus retrieved with a SVZA less than or equal to 60 degrees.

These preliminary MODIS results indicate a hemispheric difference in cirrus particle sizes that is opposite to the aircraft-based results from INCA, with slightly larger particles in the northern hemisphere (63.3 µm) than in the southern hemisphere (55.7 µm) analyses. The southern hemispheric analysis from the GOES observations (not shown, monthly mean of 51.9 µm) also yielded mean cirrus particle sizes smaller than those from the MODIS NH observations. Figure 4 suggests that the satellite viewing zenith angle has a strong effect on the VIST retrieval in this study. For the near-zenith viewing angles, the southern hemispheric ice crystal sizes are more than 10 µm larger than the northern hemispheric results, while the opposite result occurs for larger SVZA. Another unresolved factor that may account for part of the difference is the impact of low-cloud contamination. More analysis of the results is underway, including a more complete comparison of the satellite and aircraft data with the addition of FSSP observations. This comparison, and an improved estimate of cirrus cloud particle size (and other properties including optical depth) will be presented at the conference.

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