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Project Title: Characterization of 3D Cirrus Cloud and Radiation Fields Using ARS/AIRS/MODIS data and its Application to Climate Model

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The report below serves the final report of the project.

(1) Satellite remote sensing of the aerosol indirect effect on cloud formation (Ou et al. 2009): We have performed correlation analysis for a number of MODIS scenes containing heavy dust events and ice clouds, covering the regions of frequent dust outbreaks in East Asia, the Middle East, and West Africa, as well as the areas associated with long-range dust transportation such as the Equatorial Tropical Atlantic Ocean. Based on visual inspection and cloud mask results, a number of impressive MODIS dust scenes have been chosen to study the Twomey effect on ice clouds. These scenes contain both dust/aerosols and clouds. For these scenes, we collected suitable aerosol/ice-cloud data, correlated ice cloud and aerosol parameters by means of a statistical analysis, and interpreted resulting correlation trends based on the physical principles governing cloud microphysics. Aerosol and cloud optical depths and cloud effective particle size inferred from MODIS for selected domains were analyzed from which the parameters including dust aerosol number concentration, ice cloud water path (*IWP*), and ice particle number concentration were subsequently derived. To correlate aerosol and cloud properties using aerosol/cloud optical depth and particle size that have been routinely retrieved by MODIS algorithms, we divided the identified aerosol/cloud domain into a number of multi-pixel sub-grids. Because the MODIS cloud mask program identifies a pixel either as clear/aerosol or cloud, and because the current MODIS cloud and aerosol algorithms cannot simultaneously detect/retrieve aerosol and cloud parameters for a single pixel, we performed the correlation analysis using the average aerosol and cloud properties within each sub-grid that contains both aerosol and cloudy pixels. In this manner, meaningful statistical correlations between sub-grid mean cirrus clouds and dust parameters can be developed, while variability in and significance of these correlations can be investigated and physically understood. The MODIS-derived cloud number concentrations have been cross-checked with the collocated *in situ* measurements for validation purposes. The Twomey effect can be statistically quantified based on the slope of best-fit straight lines in the correlation study. The slope values are indicative of the sensitivity of cloud properties to variation in aerosol properties and are dependent on such factors as relative humidity and dust aerosol and cloud optical properties that vary with location and time. We selected contrasting regions which contained different dust loadings mixed with ice clouds. Analysis of aerosol and cloud retrieval products revealed that for all cases, the region with a larger dust aerosol optical depth is always characterized by a smaller cloud particle size, consistent with the Twomey hypothesis for aerosol-cloud interactions.

A prominent case study of dust aerosol indirect effect on glaciated ice clouds has been performed for 29 July, 2002, detected by the Pulse Detecting Lidar during the Cirrus Regional Study of Tropical Anvil and Cirrus Layers-Florida Area Cirrus Experiment (CRYSTAL-FACE) in the southwest coast of Florida, a campaign to study sub-tropical high-level cirrus and aerosols (Ou et al. 2009). Based on a linear fitting of the data points, it is shown that both cloud optical depth and *IWP* generally increase with aerosol optical depth, whereas cloud effective particle radius decreases with increasing aerosol optical depth. The trend of cloud effective particle radius vs. aerosol optical depth illustrates that there is a correlation between these two parameters, in line with the hypothesis of the Twomey effect involving dust and ice clouds.

(2) Parameterization of the ice microphysics data obtained from ARM/ASR field campaigns for use in a GCM (Liou et al. 2008): Development in cloud modeling has recently included prognostic equations for the prediction of ice water content (*IWC*) for high-level clouds formed in GCMs and climate models. This is a milestone accomplishment from the standpoint of incorporating a physically-based cloud microphysics scheme in these models, and at the same time, it is also essential from the perspective of studying cloud-radiation interactions. However, cloud particle size is also an independent parameter that affects radiation transfer. For example, for a given *IWC* in clouds, smaller particles would reflect more sunlight than larger counterparts, an effect that has been recognized by Twomey et al. (1984) and Liou and Ou (1989) in conjunction with aerosol-cloud indirect effects.

Ice crystal growth is governed by diffusion processes and subsequent actions by means of collision and coalescence. These physical processes are complicated by the nature of the ice crystal hexagonal and irregular shape. Incorporating a fully interactive ice microphysics based on the first principle in GCMs and climate models appears to be a challenging but an extremely difficult computational task. For this reason, innovative parameterization of a mean effective ice crystal size (D_e, an ice crystal maximum dimension weighted by its size and shape distributions) based on theory and observation must be developed in connection with *IWC* for GCM and climate model applications.

We have developed mean correlation curves with uncertainties associated with small ice-crystal concentration observations for D_e and *IWC* by dividing the atmosphere into three characteristic regions: Tropics cirrus, Midlatitude cirrus, including a temperature classification to improve correlation, and Arctic ice clouds. Tropical cirrus *IWC* spans a wide range, 10^{-6}-1 g/m^3, with corresponding D_e values spanning from 20 to 200 um. Midlatitude cirrus clouds have ranges of 10^{-4}-10^{-1} g/m^3 for *IWC* and 30-140 um for D_e, while Arctic ice clouds have the narrowest *IWC* (10^{-2}-1 g/m^3) with a D_e range of 50-120 um. We illustrated that D_e has a high correlation with *IWC* based on theoretical consideration and analysis of thousands of observed ice crystal data obtained from a number of ARM-DOE field campaigns and other experiments. The correlation has the form: $\ln(D_e) = a + b \ln(IWC) + c\ ((\ln(IWC))^2$, where a, b, and c are fitting coefficients and are functions of three regions. We have demonstrated that this correlation can be effectively incorporated in GCMs and climate models that predict *IWC* - a significant advance in ice microphysics parameterization for interactive cloud-radiation analysis and feedback, as discussed in the following. Substantial July mean differences are shown in the OLR (W/m^2) and precipitation (mm/day) patterns between UCLA GCM simulations based on D_e*s* determined from the D_e-*IWC* correlations and the control run using a fixed ice crystal size. Differences (perturbation-control) in OLR closely follow variations in D_e since smaller ice particles trap more IR. Negative values are mostly located in lower latitudes where the parameterized D_e*s* are generally smaller than the prescribed value of 80 um in the control run, resulting in trapping more IR. Increased OLRs are shown in a number of midlatitude regions due to D_e*s* larger than 80 um. Differences are less significant in high latitudes since the parameterized D_e*s* in that region are closer to the fixed value of 80 um in the control run. In terms of precipitation, changes in the precipitation pattern are not directly related to the D_e effect, but are related to intricate interactions among cloud, radiation, and dynamic processes through the modified vertical heating profiles associated with the interactive D_e used in GCM simulations. Increases in precipitation are mostly located in tropical regions where OLRs are reduced, an indication of stronger convective activities. Reduced precipitation is shown in the areas corresponding to enhanced OLRs in tropical and midlatitude regions.

(3) Implementation of a new radiation and ice parameterization module in WRF (Gu et al. 2010, 2011): The WRF model (Skamarock et al. 2005) is a fully compressible, nonhydrostatic mode (with a hydrostatic option) suitable for a broad spectrum of applications across scales ranging from a few meters to thousands of kilometers. Currently, several physics components have been included in WRF: microphysics (bulk schemes ranging from simplified physics suitable for mesoscale modeling to sophisticated mixed-phase physics suitable for cloud-resolving modeling), cumulus parameterization, longwave radiation, shortwave radiation, boundary layer turbulence, surface layer, land-surface parameterization, and subgrid scale diffusion.

To improve the computation of spectral radiative transfer processes in the current WRF model, it is necessary to develop a consistent and efficient radiation scheme that can better resolve the spectral bands, determine the cloud optical properties, and provide more reliable and accurate radiative heating fields. The new radiation module, Fu-Liou-Gu scheme (Gu et al. 2010, 2011) that we implement in WRF is a modified and improved version based on the Fu-Liou radiative transfer model. The detailed description of the model and the relevant parameters used in this scheme have been given in Fu and Liou (1992) and Fu and Liou (1993). A combination of the delta-four-stream approximation for solar flux calculations (Liou et al. 1988) and delta-two-and-four-stream approximation for IR flux calculations (Fu et al. 1997) has been implemented in this scheme. This combination has been proven to be computationally efficient and at the same time to produce a high degree of accuracy. The incorporation of nongray gaseous absorption in multiple scattering atmospheres is based on the correlated *k*-distribution method developed by Fu and Liou (1992). The solar and IR spectra are divided into 6 and 12 bands, respectively, according to the location of absorption bands. In the solar spectrum, absorption due to H_2O (2500-14500 cm^{-1}), O_3 (50000-14500 cm^{-1}), CO_2 (2850-5200 cm^{-1}), and O_2 (A, B, and r bands) is taken into account. In the thermal IR region, absorption due to H_2O (0-2200 cm^{-1}), CO_2 (540-800 cm^{-1}), O_3 (980-1100 cm^{-1}), CH_4 (1100-1400 cm^{-1}), N_2O (1100-1400 cm^{-1}), and CFCs (in the 10 um region) is included. The continuum absorption of H_2O is accounted for in the spectral region 280-1250 cm^{-1}. In addition to the principal absorbing gases listed above (Fu and Liou, 1993; Gu et al., 2003), we have included absorption by the water vapor continuum and a number of minor absorbers in the solar spectrum, including CH_4, N_2O, NO_2, O_3, CO, SO_2, O_2-O_2, and N_2-O_2. This led to an additional absorption of solar flux in a clear atmosphere on the order of 1-3 W/m^2 depending on the solar zenith angle and the amount of water vapor employed in the calculations (Zhang et al. 2005).

We have also incorporated an ice microphysics parameterization to include an interactive mean effective ice crystal size (D_e) in connection with radiation parameterizations (Liou et al. 2008). As illustrated in (2), correlation analysis between *IWC* and D_e has been carried out using a large set of observed ice crystal size distributions obtained from a number of cirrus field campaigns in the tropics, midlatitude, and Arctic for GCM applications. It is showed that *IWC* and D_e are well-correlated using this regional division. Having included all the preceding ice crystal size and shape features, the Fu-Liou-Gu scheme is now an ideal tool for the simulation of radiative transfer and ice microphysics within the domain of WRF.

Additionally, in the current Fu-Liou-Gu radiation scheme, a total of 18 aerosol types have been parameterized by employing the Optical Properties of Aerosols and Clouds (OPAC) database (dAlmeida et al. 1991, Tegen and Lacis 1996, Hess et al. 1998), which provides the single-scattering properties for spherical aerosols computed from the Lorenz-Mie theory in which humidity effects are accounted for. The single-scattering properties of the 18 aerosol types for 60 wavelengths in the spectral region between 0.3 and 40 um are interpolated into the 18 Fu-Liou spectral bands of the current radiation scheme (Gu et al. 2006, Gu et al. 2010a). Aerosol types include maritime, continental, urban, five different sizes of mineral dust, insoluble, water soluble, soot (BC), sea salt in two modes (accumulation mode and coarse mode), mineral dust in four different modes (nucleation mode, accumulation mode, coarse mode, and transported mode), and sulfate droplets.

The new radiation and ice microphysics parameterization schemes presented above are particularly useful for studying direct and indirect aerosol radiative effects associated with ice cloud formation. Using the update WRF, a number of real-time WRF simulations have been carried out for cirrus cases that were observed in the coastal and western United States on March 29-30, 2007, and compared with available observations from MODIS and GOES-IR images over the same areas (Gu et al. 2011). The initial and boundary condition data were based on the NCEP FNL Operational Global Analysis on a 1.0x1.0 degree grid, continuously at every six hours. This product was available from GFS which is operational four times a day in near-real time at NCEP. For comparison purposes, we have selected a number of MODIS scenes: Terra Daytime on March 29, 2007 at 1825 UTC; and Aqua Daytime on March 29, 2007 at 2140 UTC and March 30, 2007 at 2045 UTC. GOES-11 visible and IR images were also obtained over the same general area for the dates and times that were close to MODIS/Terra/Aqua overpasses: March 29, 2007 at 1830 UTC; March 29, 2007 at 2130 UTC, and March 30, 2007 at 2030 UTC. Both MODIS and GOES-11 observations displayed the presence of frontal and non-frontal ice clouds at the dates and times listed above over the coastal and western United States areas. The corresponding simulated results obtained from WRF reproduce reasonably well the observed cirrus cloud fields and their movement and dissipation processes, especially those associated with the large scale frontal system. Radiative processes are important in cirrus cloud simulations by affecting the vertical thermal structure and hence convection. The newly implemented radiation module, the Fu-Liou-Gu scheme, has been demonstrated to work well in WRF and can be effectively used for studies related to cirrus cloud formation and evolution and aerosol-cloud-radiation interactions. With the newly implemented radiation scheme, the simulations of cloud cover and *IWP* have been improved for cirrus clouds, with a more consistent comparison with the corresponding MODIS observations in terms of *CWP* and *IWP* means and *CWP* frequency distribution, especially for optically thin cirrus with an improvement of about 20% in simulated mean *IWP*.

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