Application of Stochastic Techniques to the ARM Cloud-Radiation Parameterization Problem

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Introduction

Stochastic shortwave radiative transfer through cloud fields has been shown to be a promising approach for modeling cloud-radiation interactions when the cloud field has a horizontal fraction between 0.2 and 0.8. The improvement of a stochastic technique over a plane-parallel one is that statistical information about the horizontal size and spacing of clouds may be incorporated in the radiative transfer calculations. However, several important factors must be considered in applying this approach to cloud-radiation parameterization such as the impact of the new scheme on atmospheric dynamics, and interaction of the algorithm with the model environment. More significantly, most atmospheric models do not calculate horizontal cloud scale information. Therefore, the determination of when a stochastic approach is appropriate, given the information available in current atmospheric general circulation models, and how to apply that approach is critical. Results from preliminary studies exploring the coupling of the SIO single-column model with the stochastic model are shown. Recent work exploring the difficulties in incorporating horizontal cloud-scale information from an AGCM environment into the stochastic model using regional scale model cloud liquid water fields will also be discussed. The stochastic technique is also being explored as a method for modeling shortwave radiative transfer through mixed phase clouds.

Stochastic Shortwave Cloud-Radiation Parameterization

The single-column model (SCM) developed at the Scripps Institution of Oceanography by Iacobellis and Somerville (1991a, b) is used in this study to investigate the new stochastic cloud-radiation parameterization. The SCM has a similar horizontal domain as that of an AGCM grid cell, but the dynamic and radiative processes in the column do not feed back to the surrounding environment. This allows for detailed study of the physical processes occurring within the column, which makes the single-column model a good testbed for the evolving parameterization.

Initially, the SCM is run at the Atmospheric Radiation Measurement Program's (ARM) Southern Great Plains (SGP) site for the year 2000 with the Tiedtke (1993) prognostic cloud scheme. The SCM was forced with observational data from the ARM SGP site, prepared using variational analysis of Zhang and Lin (1997) and Zhang et al. (2001). The SCM was run in ensemble mode with a run-length of 24-hr after an initial 12-hr spin-up period. The runs were performed at 6-hr intervals and then averaged together. This series of simulations is designated as the control.

The second set of simulations, again run in ensemble mode for the year 2000, differs from the control run in that the cloud properties such as cloud base height, cloud fraction, liquid droplet effective radius, and liquid water path are taken from the cloud climatology described earlier instead of prognosed. Figure 1 compares the predicted cloud fraction using the Tiedtke (1993) scheme and observed cloud fraction at the ARM SGP site for June, 2000.

Figure 2 highlights some results from the control run, and the observed cloud property run for 10 days in March of 2000. The single column model does a reasonably good job of matching with observed column liquid water content. However, during the 14th, and the 21st through 23rd of March, there is considerable variability in the observed cloud fraction, whereas the predicted fraction remains close to 100%. It is in areas such as these where the stochastic model could potentially be most effective. Figure 3 indicates that in general, the downwelling shortwave radiation at the surface predicted by the SCM with the Tiedtke cloud properties is larger than that predicted by the SCM with observed cloud properties.

The next set of simulations will provide the shortwave radiative fluxes calculated by the multiple-cloud layer stochastic code to the single-column model each time that the shortwave radiation routine is called. This will yield insight into changes in the heating rates due to the stochastic approach. The final series of SCM runs will allow full coupling between the stochastic model and the single-column model. As it is not possible to run the stochastic model as a parameterization in an AGCM, interpretation of these model results will yield the final details of the stochastic cloud-radiation parameterization. Currently, the parameterization takes the form of a correction term to the radiation radiative transfer equations. Preliminary results suggest that a stochastic cloud-radiation parameterization provides a more realistic radiation field in the Tropical Western Pacific, particularly in strong convective conditions (not shown).

Stochastic Modeling of Mixed-Phase Clouds in the Arctic

Recent research has indicated that mixed phase clouds make up about one-third of all Arctic clouds (Pinto 1998; Intrieri et al. 2002; McFarquhar and Cober 2004). Liquid and ice phases of clouds have very different microphysical properties, and these properties have a vast impact on the radiative transfer (Shupe and Intrieri 2004). Similarly, the microphysical composition is one of the most sensitive input characteristics of cloud-radiation models (Lane-Veron and Somerville 2004). Therefore, having a model that accurately simulates the impact that mixed-phase clouds have on the radiative fields would be beneficial to accurately simulating the radiative transfer in the Arctic.

Lane et al. (2002) used a stochastic algorithm to simulate the shortwave radiative transfer through a broken cloud field. By making modifications to the statistical shortwave model (DSTOC) from Lane-Veron and Somerville (2004), the stochastic approach can be applied to the distribution of phases within a mixed-phase layer cloud. The new model, MX-STOC, requires cloud base height, cloud top height, liquid and ice water content, droplet/particle effective radius, ice fraction, and the characteristic horizontal scale of the ice and liquid patches. The new model has been tested using various ice/liquid ratios to determine its functionality, and the output compared to runs using a single phase cloud in the standard DSTOC model (Figure 4).

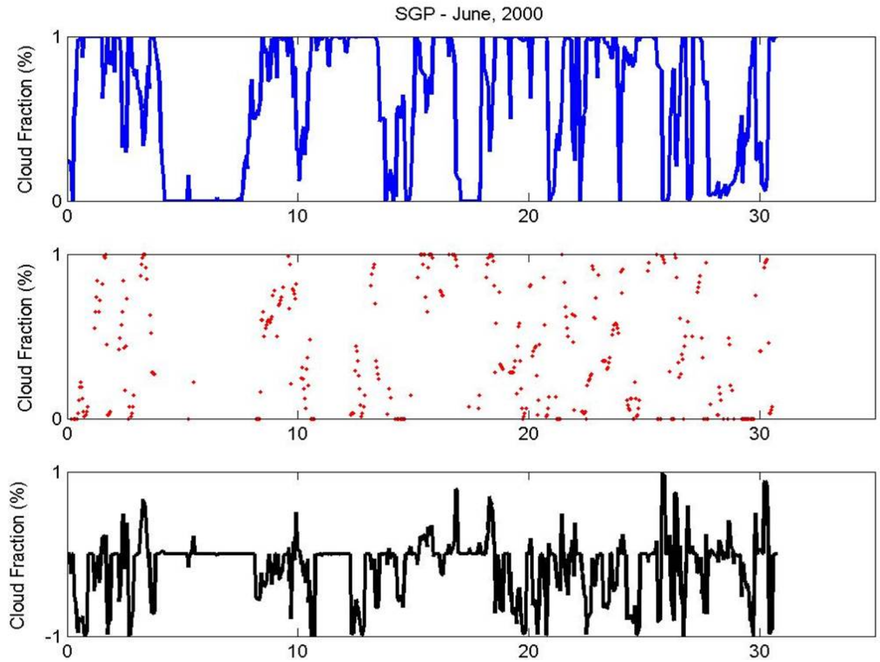

Figure 1. Cloud fraction values at SGP site for a) Tiedtke (1993) cloud parameterization (blue), b) observed cloud fraction (red) and c) difference

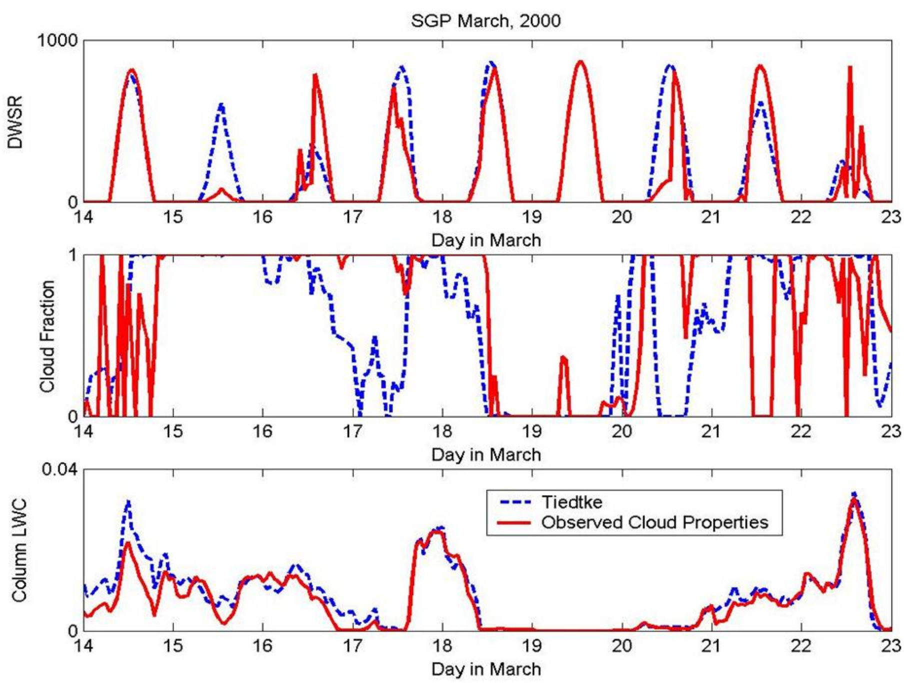

Figure 2. Comparison between single-column model runs using the Tiedtke (1993) cloud parameterization (dashed blue) and using observed values of cloud fraction, base height, droplet effective radius, and liquid water path (red) for a) downwelling shortwave at the surface b) cloud fraction and c) column liquid water content.

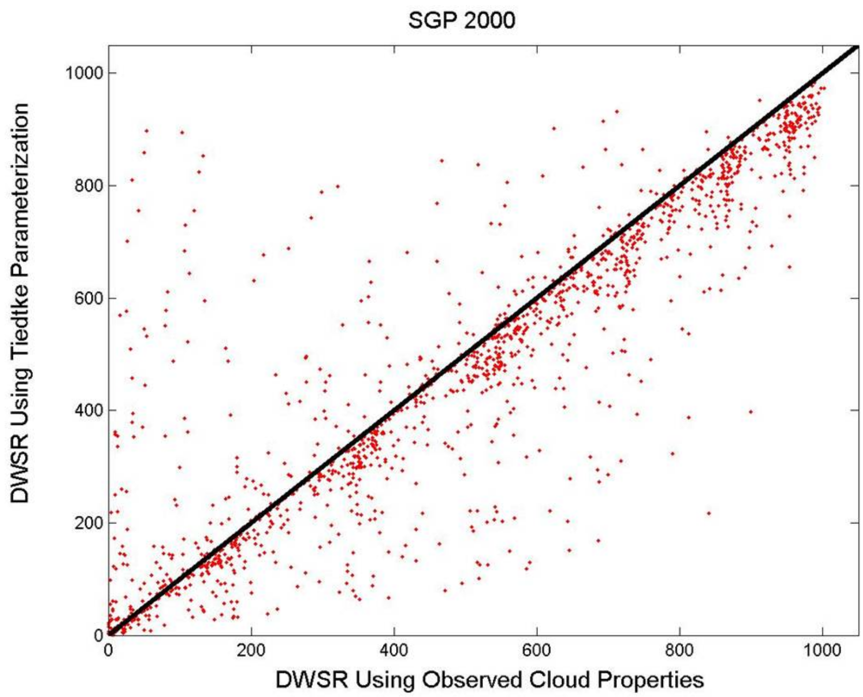

Figure 3. Scatter plot showing the predicted downwelling shortwave radiation at the surface for the SGP site using cloud fraction from the Tiedtke (1993) scheme versus that predicted using observed for all cloudy hours in the year 2000.

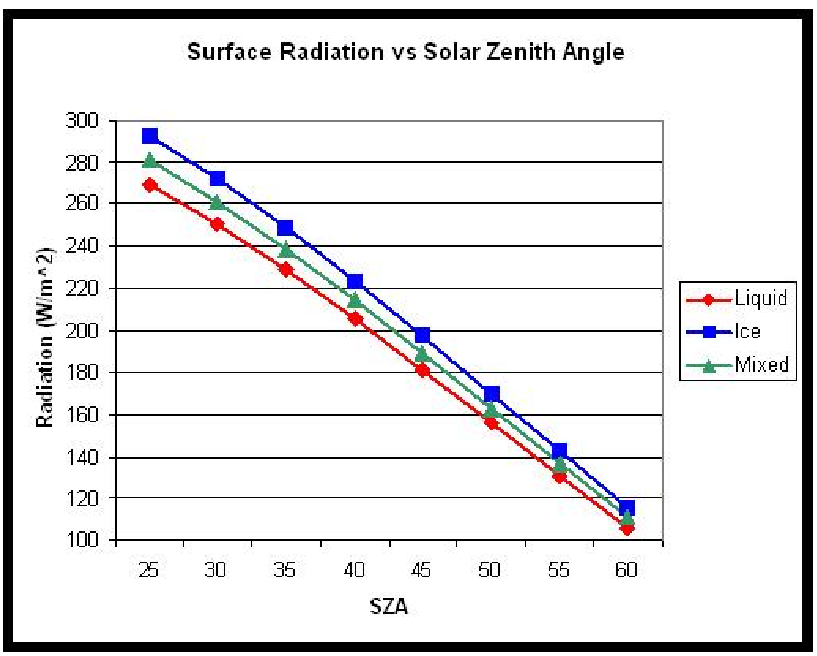

Figure 4. In order to test the new model, test runs were performed using a variety of solar zenith angles, and a sample ice fraction of 50%. Additionally, comparison runs were performed using a solid 100% cloud layer of single phase for both liquid and ice in the standard DSTOC model.

In order to test the realism of the new model, the cloud field properties will be derived from observations made at the ARM North Slopes of Alaska site and during the Surface Heat Budget of the Arctic (SHEBA; Uttal et al. 2002) campaign. Current case study days selected from the SHEBA field program are shown in Table 1. These cases were selected by examining radar images and cloud masks and determined to have boundary layer cloud that showed horizontal variability in total liquid water and in ice production without the presence of additional cloudy layers. Examples of the cloud mask and cloud radar data from the ETL data browser are shown in Figure 5 (from http://www.etl.noaa.gov/et6/arctic/sheba/browser/index.html). The cloud field characteristics of cloud base height, top height and liquid water path will be determined following by Lane et al. (2002). Cloud phase is determined using lidar data such as that seen in Figure 6. In general, cloud liquid produces a relatively high backscatter in the lidar and a depolarization ratio less than 0.1. Cloud ice produces a much weaker backscatter and depolarization ratios above about 0.15 (Matt Shupe, personal communication). Figure 6 shows an example of the lidar depolarization ratio for May 2, 1998. In this figure an ice/water threshold of 0.11 has been applied.

Table 1. This table lists the days used in the mixed phase cloud case study. Days were chosen for having a relatively constant, solid mixed-phase cloud throughout much of the day, with a uniform cloud base and height (stratus, non-convective clouds).

SHEBA Mixed Phase Case Study Days (all 1998)	
1 May	6 June
2 May	7 June
3 May	8 June
4 May	9 June
5 May	25 June
6 May	
30 May	
31 May	

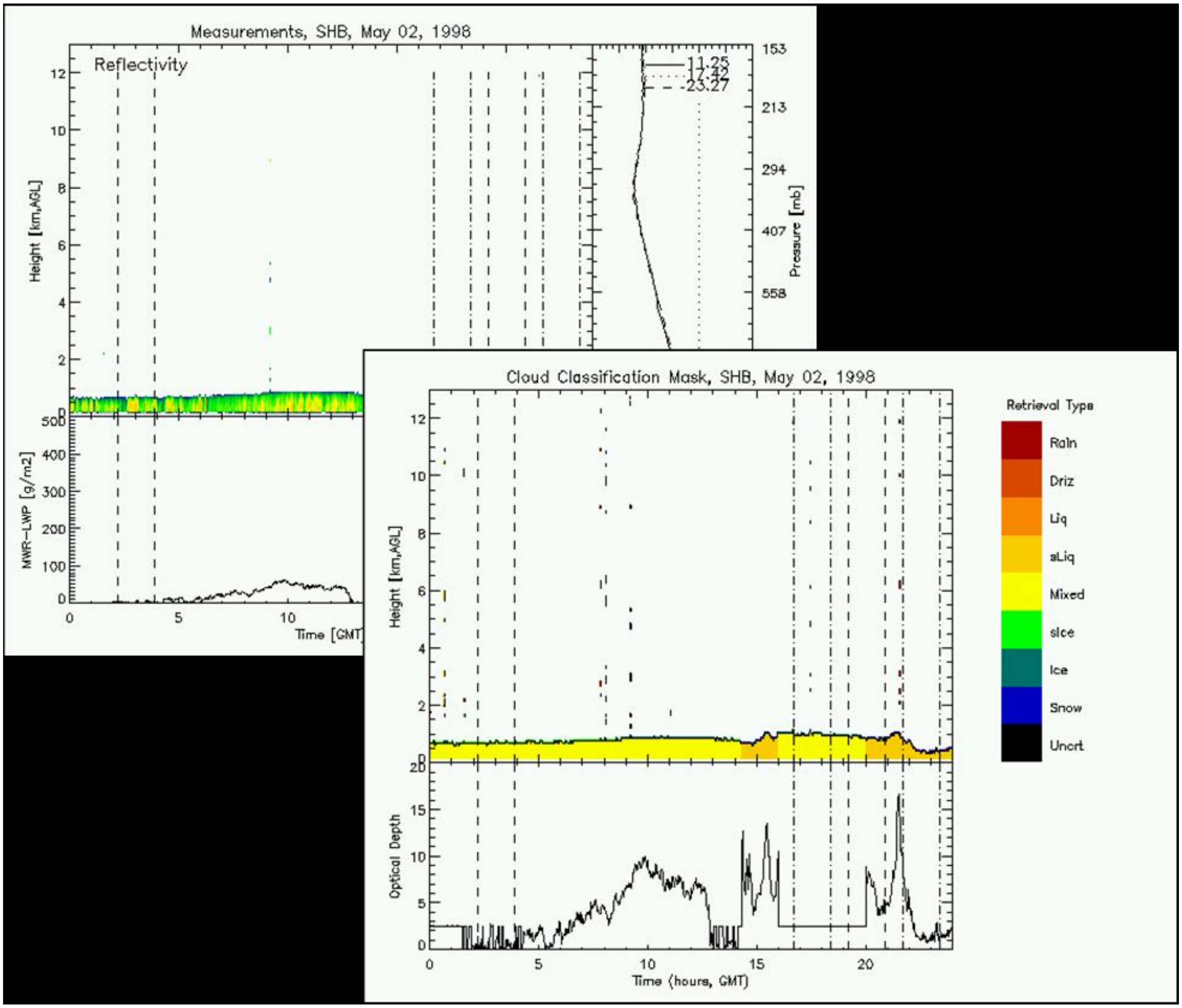

Figure 5. Radar reflectivity and cloud mask browser images for 2 May 1998. (http://www.etl.noaa.gov/et6/arctic/sheba/browser/index.html)

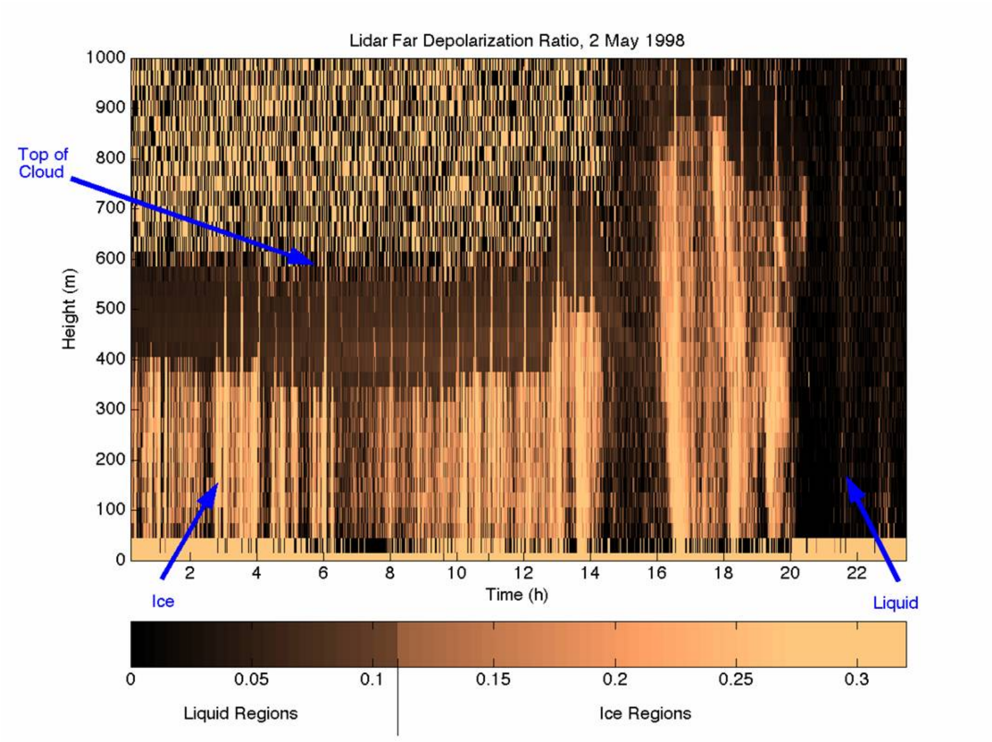

Figure 6. Lidar far depolarization ratio image for 2 May 1998. Analysis by Intrieri et al. (2002) shows that a depolarization ratio less than 0.11 indicates a liquid phase region, while a ratio greater than this indicates ice crystals. This particular image shows a predominantly mixed-phase cloud being sustained throughout the day, and is an example of the cloud type used in the mixed phase case study.

Derivation of Cloud Field Statistic from Regional Atmospheric Modeling System

In the development of a stochastic radiative transfer parameterization, an important step is determining how an Atmospheric General Circulation model would provide sub-grid scale cloud size or cloud phase information to a stochastic routine. An effort to determine how the stochastic model would utilize model cloud field information is underway using cloud fields generated by the Regional Atmospheric Modeling System (RAMS). This preliminary work is focusing on two storm periods during the March 2000 IOP, shown below, that are described in further detail in Weaver et al. (2004).

Each simulation used two nested grids, both centered on the ARM SGP site (Figure 7). The outermost grid (Grid 1) covered roughly 2200 x 2200 km^2, with 12-km horizontal grid spacing. The purpose of this grid is to downscale the synoptic-scale meteorology provided by these boundary conditions in order to provide suitable forcing for the high-resolution domain of interest. This high-resolution domain (Grid 2) covered 750 x 750 km^2 with 3-km horizontal grid spacing. This domain corresponds to the area covered by several typical GCM grid cells. While computationally expensive, this combination of high

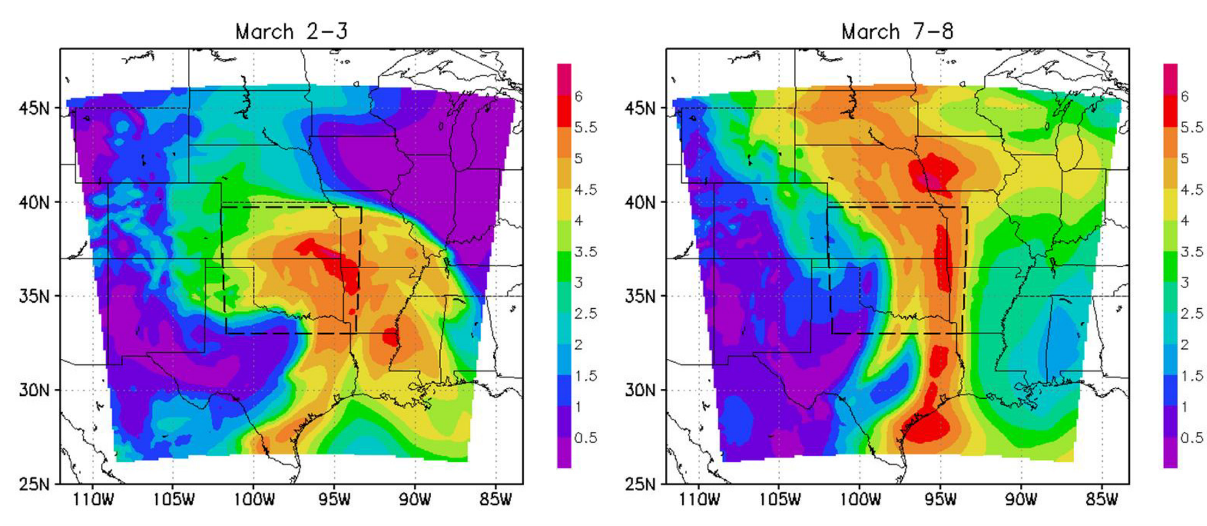

Figure 7. Two storm periods during the March 2000 IOP were simulated: March 2-3 and March 7-8. Both periods experienced well-developed cyclones but with different amounts of cloudiness and cloud variability over the ARM site.

resolution and relatively large domain size enable us to characterize the sub-GCM-grid-cell statistics of dynamic, thermodynamic, and cloud variables and their link with the large scale. Both Grids 1 and 2 resolve vertical processes with 45 terrain-following, stretched-grid levels.

The time-slices used in the above analysis are from 0200Z on March 3 (a relatively heterogeneous, frontal scene with a variety of cloud types) and from 0400Z on March 7 (a relatively homogeneous, pre-frontal stratocumulus scene). Cloud horizontal scale is determined from the cloud water content field (Figure 8) using image processing techniques. A series of ellipses are fit to patches of cloud water content that exceed a given threshold. Then the equivalent radius of the ellipse is calculated to give a measure of the horizontal cloud scale.

Note that the number and size of the ellipses fit to the cloud water content field is sensitive to the threshold (Figure 9). Preliminary results (Figure 10) from March 3 indicate that the stochastic model has difficulty simulating radiative transfer through low fraction, high water content fields.

Conclusions

The stochastic approach to modeling shortwave radiative transfer through a cloudy layer that has large-scale inhomogeneities in cloud properties, such as cloud size and spacing or spacing of cloud phase patches, allows for a more physically real cloud scene without huge computational expense. Our group is developing a stochastic cloud-radiation parameterization from numerous stand-alone calculations that can be used in modern atmospheric general circulation models. Current results indicate that the stochastic model outperforms a plane-parallel radiative transfer model, when compared to observations, in strongly convective states. The impact of a stochastic parameterization on model heating rates is currently being studied. Preliminary use of the stochastic model to represent radiative transfer through

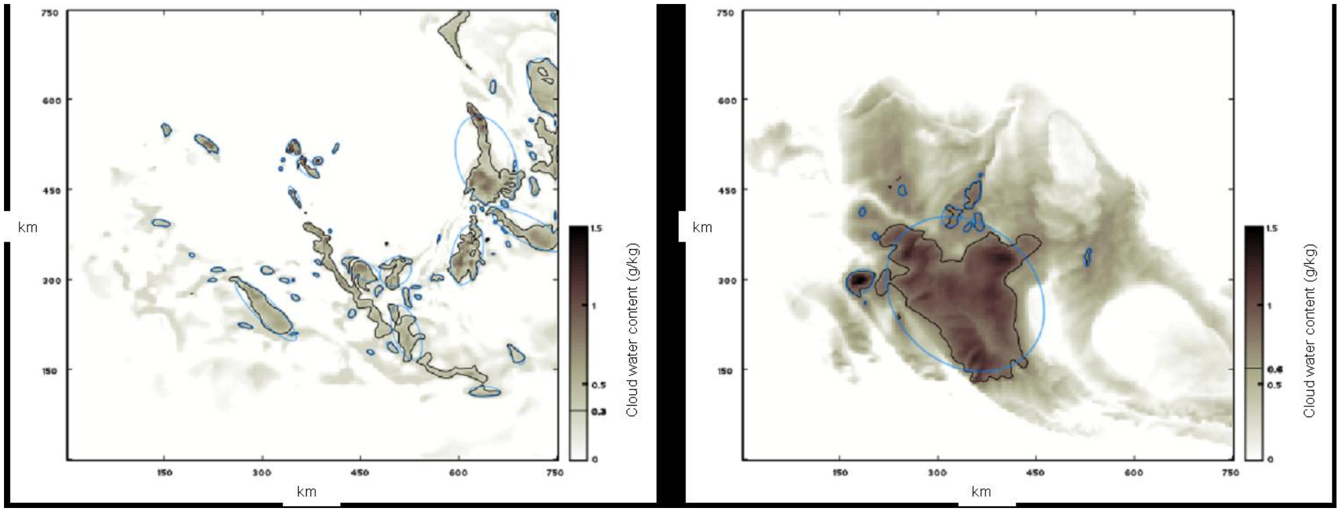

Figure 8. Cloud water content for a) March 3 and b) March 7. The dark line indicates the areas which have water content greater than the given threshold – 0.3 g/kg for March 3 and 0.6 g/kg for March 7. The blue ellipses shown are the fit to these areas.

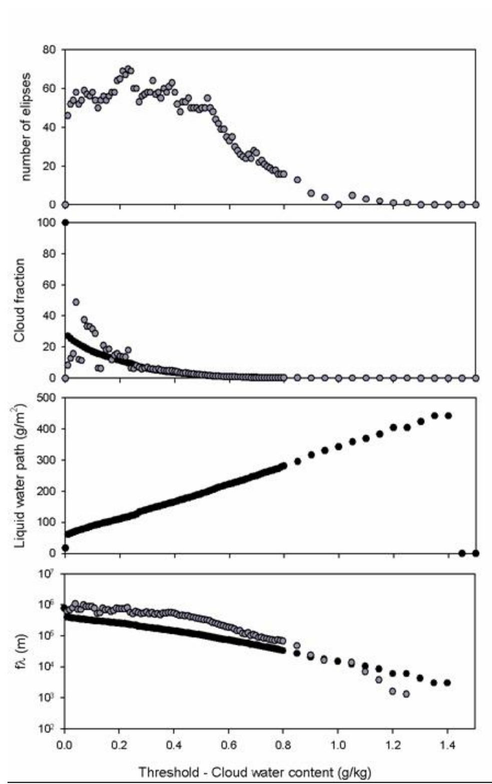

Figure 9. Analysis of the cloud field for March 3 shown as a) the number of ellipse b) cloud fraction, c) liquid water path and d) horizontal scale as a function of threshold. Black dots indicate where the variable was calculated using the number of pixels above the threshold, while grey dots show results using the ellipses.

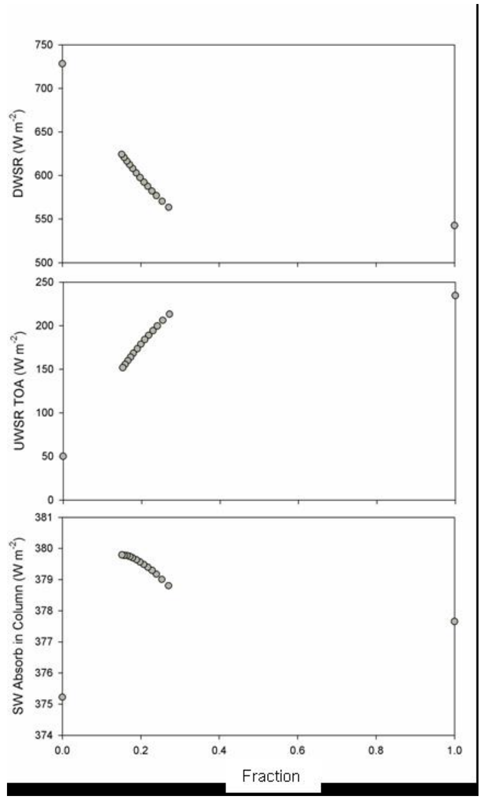

Figure 10. Results from DSTOC for March 3, 2000. The a) downwelling shortwave radiation at the surface, b) outgoing shortwave radiation at the top of the atmosphere and c) shortwave radiation absorbed in the column are shown as a function of cloud fraction (calculated as a fraction of pixels above threshold to total number of pixels).

Arctic mixed-phase clouds has shown strong sensitivity to the input liquid water content. Efforts to interpret a regional-scale model's cloud water content field to determine the horizontal cloud-field statistics needed by the stochastic model are underway as a possible link between the physics in a climate model and the details required by the stochastic approach.

Contact

Acknowledgments

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