6.4 APPLICATION OF A STOCHASTIC CLOUD MODEL TO MIXED PHASE ARCTIC CLOUDS: AN OVERVIEW

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1. BACKGROUND

Recent research has indicated that mixed phase clouds make up about one-third of all Arctic clouds (Pinto 1998; Intrieri et al. 2002[a]; McFarquhar and Cober 2004). Mixed phase clouds are typically composed of distinct regions of supercooled water and regions that are mostly ice. Additionally, the microphysical composition of clouds is one of the major influences on radiative characteristics (Shupe and Intrieri 2004). Despite the uniqueness and prevalence of mixed phase clouds at high latitudes, most climate models are not capable of handling clouds of mixed phase, and must assume that the clouds are either all liquid or all ice. However, incorporating a stochastic algorithm such as that explored by Lane, Goris, and Somerville (2002) can permit models to simulate the regions of phase that occur in Arctic clouds. By modifying the statistical shortwave model described in Lane-Veron and Somerville (DSTOC; 2004), radiative transfer through mixed phase clouds can be calculated, and compared to observational data and earlier models, such as Sunray (Figure 1; Fouquart and Bonnel 1980; Morcrette and Fouquart 1985).

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.

Recent data gathered using radar and lidar to observe Arctic clouds shows that liquid and ice are not homogeneously distributed throughout the cloud (Intrieri et al. 2002[b]). According to recent theory, mixed phase clouds are composed primarily of supercooled water droplets, with regions of predominantly ice mixed in (McFarquhar and Cober 2004). Due to this fact, the average asymmetry parameter (g) of mixed phase clouds is 0.85, similar to the value of g=0.86 for liquid water clouds, and higher than g=0.75 for ice clouds. Additionally, according to McFarquhar and Cober (2004), there is a greater than 10% variation in single-scattering properties calculated using mixed phase cloud observations instead of using a parameterization describing average water/ice fraction.

2. THE STOCHASTIC TECHNIQUE

Most cloud-radiation parameterizations employed in modern Atmospheric General Circulations Models (AGCMs) are capable of handling one of two situations in a given model layer: either there is no cloud, or there is a fractional cloud amount composed of either liquid or ice. Macroscale cloud field characteristics, such as size and spacing, are not accounted for. The stochastic approach to radiative transfer (e.g. Malvagi et al. 1993; Byrne et al. 1996; Lane-Veron and Somerville 2004) approximates cloud field geometry by permitting a given layer to have a distribution of clouds.

In typical plane-parallel cloud-radiation parameterizations, radiative transfer through the clear atmosphere and through a cloudy atmosphere is combined using a sum weighted by the cloud fraction. Using this theory, photons can only be in one of two situations: either in clear sky, or within a cloud. Stochastic theory elaborates on this idea by recognizing that as photons travel through the atmosphere they may be in any of four situations. The photon can be located either in clear sky, within a cloud, or in one of two transition states: passing from clear sky to cloud or from cloud to clear sky (Figure 2). This effectively adds two transition probabilities to the radiative transfer equation.

These elaborations to cloud-radiation theory allow the stochastic model to do two things that a standard model cannot. The first is that radiation can in fact be refracted from one cloud to another, thereby allowing one cloud to be a source region for another. Secondly, this property allows the stochastic model to handle a broken cloud field, not simply a solid cloud deck. To do this, the model uses a Markovian distribution of horizontal

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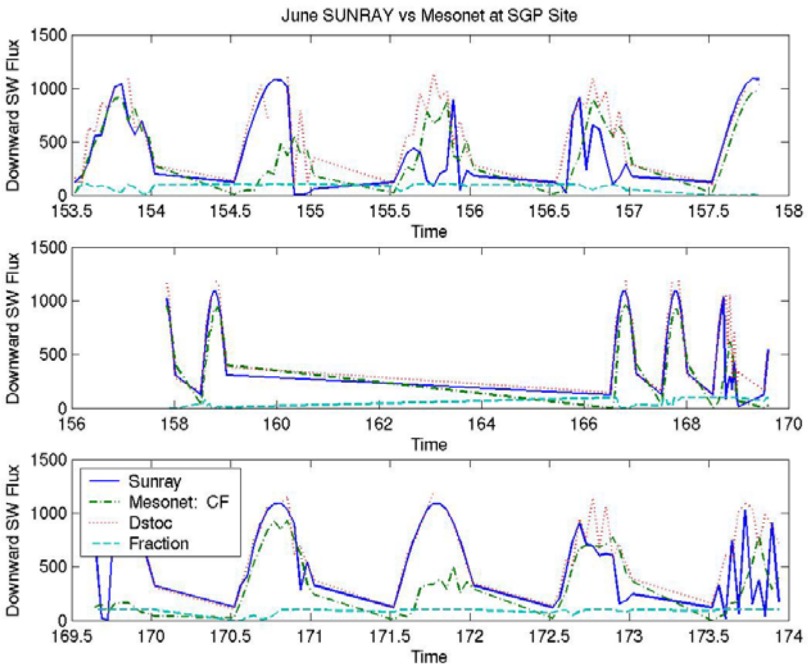

Figure 1: Example results of downwelling shortwave radiation at the surface at the ARM Southern Great Plains site during June 2000. The blue solid line depicts Sunray output, while the red dotted line depicts DSTOC. The green dashed line indicates averaged Oklahoma Mesonet observations, and the cyan dashed line is cloud fraction. Gaps in the time series indicate a lack of forcing data for the models.

chord lengths to represent the cloud size and spacing.

3. CURRENT WORK

In previous research, the stochastic approach was applied to a cloudy layer, using a Markovian distribution to describe the mixture of clouds and clear sky (a broken layer). As recent research has indicated that mixed phase clouds are composed of primarily liquid, but contain regions which are predominantly ice, the stochastic approach can now be applied to a solid cloudy layer that contains a mixture of liquid water and ice. Again, a Markovian distribution will be used to indicate where within a liquid cloudy layer there is ice.

In order to evaluate the ability of the stochastic algorithm to represent the impact mixed phase clouds on the shortwave radiative budget, the model used by Lane, Goris, and Somerville (2002) is updated to include more current research on the properties of ice in the atmosphere, using data from McFarquhar and Cober (2004) and Chou, Lee, and Yang (2002).

To parameterize the distribution of liquid water and ice regions within the mixed phase clouds, observational radar and lidar data from both the Surface Heat Budget of the Arctic (SHEBA; Uttal et al. 2002) field experiment and the Atmospheric Radiation Measurement (ARM) program's North Slopes of Alaska Cloud and Radiation Testbed Site (Stokes and Schwartz 1994) are used. The resulting probability distributions of these features will be input into the mixed-phase stochastic

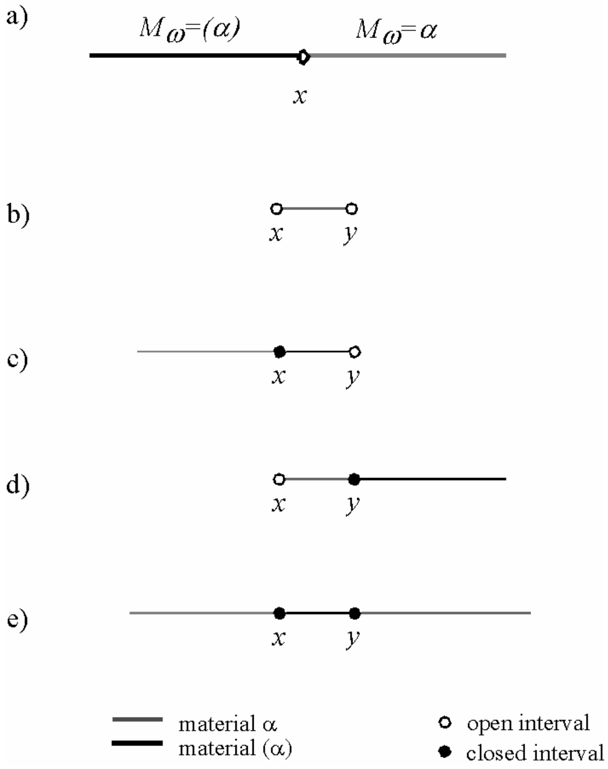

Figure 2: Illustration of DSTOC line statistic transitions. a) illustrates a transition from material (α) to α at point *x*. b) illustrates an interval in material α between open transition points *x* and *y*. c) illustrates a transition from material α to (α) at point *x* which is on the segment *x*-*y*. d) illustrates a transition from material α to (α) at point *y*. e) illustrates a transition from (α) to α at point *x* and then from α to (α) at point *y*. Open intervals are indicated by open circles, closed intervals by solid circles. Adapted from Lane-Veron and Somerville (2004)

model (MX-STOC) and the output radiative fluxes will be compared to established cloud-radiation models, as well as observations.

4. REFERENCES

Byrne, R. N., R. C. J. Somerville, and B. Subasilar, 1996: Broken cloud enhancement of solar radiation absorption. *J. Atmos. Sci.*,**53**, 878-886.

Chou, M.-D., K.-T. Lee, and P. Yang, 2002: Parameterization of shortwave cloud optical properties for a mixture of ice particle habits for use in atmospheric models. *J. Geophys. Res.*, **107**(D21), 4600, doi: 10.1029/ 2002JD002061.

Fouquart, Y., and B. Bonnel, 1980: Computation of solar heating of the Earth's atmosphere: a new parameterization. *Beitr. Phys. Atmos.*, **53**, 35-62.

Intrieri, J. M., C. W. Fairall, M. D. Shupe, P. O. G. Persson, E. L. Andreas, and P. S. Guest, 2002: An annual cycle of Arctic surface cloud forcing at SHEBA. *J. Geophys. Res.*, **107**(C10), 8039, doi: 10.1029/2000JC000439.

Intrieri, J. M., M. D. Shupe, T. Uttal, and B. J. McCarty, 2002: An annual cycle of Arctic cloud characteristics observed by radar and lidar at SHEBA. *J. Geophys. Res.*, **107**(C10), 8030, doi: 10.1029/2000JC000423.

Lane, D. E., K. Goris, and R. C. J. Somerville, 2002: Radiative transfer through broken clouds: observations and model validation. *J. Climate*, **15**, 2921-2933.

Lane-Veron, D. E., and R. C. J. Somerville, 2004: Stochastic theory of radiative transfer through generalized cloud fields. *J. Geophys. Res.*, **109**, D18113, doi: 10.29/2004JD004524.

Malvagi, F., R. N. Byrne, G. C. Pomraning, and R. C. J. Somerville, 1993: Stochastic radiative transfer in a partially cloudy atmosphere. *J. Atmos. Sci.*, **50**, 2146–2158.

McFarquhar, G. M., and S. G. Cober, 2004: Single-scattering properties of mixed-phase Arctic clouds at solar wavelengths: impacts on radiative transfer. *J. Climate*, **17**, 3799-3813.

Morcrette, J. J., and Y. Fouquart, 1985: On systematic errors in parameterized calculations of longwave radiative transfer. *Quart. J. Roy. Meteor. Soc.*, **111**, 691-708.

Pinto, J. O., 1998: Autumnal mixed-phase cloudy boundary layers in the Arctic. *J. Atmos. Sci.*, **55**, 2016-2038.

Shupe, M. D., and J. M. Intrieri, 2004: Cloud radiative forcing of the Arctic surface: the influence of cloud properties, surface albedo, and solar zenith angle. *J. Climate*, **17**, 616-628.

Stokes, G. M., and S. E. Schwartz, 1994: The Atmospheric Radiation Measurement (ARM) program: programmatic background and design of the cloud and radiation testbed. *Bull. Amer. Meteor. Soc.*, **75**, 1202-1221.

Uttal, T., J. A. Curry, M. G. McPhee, D. K. Perovich, R. E. Moritz, J. A. Maslanik, P. S. Guest, H. L. Stern, J. A. Moore, R. Turenne, A. Heiberg, M. C. Serreze, D. P. Wylie, O. G. Persson, C. A. Paulson, C. Halle, J. H. Morrison, P. A. Wheeler, A. Makshtas, H. Welch, M. D. Shupe, J. M. Intrieri, K. Stamnes, R. W. Lindsey, R. Pinkel, W. S. Pegau, T. P. Stanton, and T. C. Grenfeld, 2002: Surface Heat Budget of the Arctic Ocean. *Bull. Amer. Meteor. Soc.*, **83**, 255-275.