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RADIATIVE FORCING BY PARAMETERIZED ICE CLOUDS IN A GENERAL CIRCULATION MODEL

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1. INTRODUCTION

Atmospheric ice clouds are potentially very important to climate and climate change, since they can interact with both solar and terrestrial radiation, altering the albedo in the former case and the greenhouse effect in the latter. In this study, a procedure for parameterizing a large class of ice clouds in a general circulation model (GCM) is reported.

Heymsfield and Donner (1990) developed a parameterization for the ice content of large-scale ice clouds, *i.e.*, clouds which form in a horizontally homogeneous large-scale flow undergoing ascent while saturated with respect to ice at sufficiently cold temperatures. Anvil ice clouds associated with deep convection are not included and can be treated in conjunction with a cumulus parameterization (not discussed here). This paper provides a brief description of the parameterization, which calculates separately the ice content in a saturated layer and in the subsaturated layer beneath it. Both the ice content and cloud thickness are parameterized, to allow for vertically thin clouds. Observational evidence supporting the parameterization from aircraft and satellites is summarized, and the implementation of the parameterization in the Community Climate Model-1 of the National Center for Atmospheric Research (NCAR CCM1) (Williamson *et al.*, 1987) is described.

2. PHYSICAL PARAMETERIZATION FOR LARGE-SCALE ICE CLOUDS

2.1 Saturated Ice Clouds

In an ice-saturated layer undergoing ascent below 258 K, Heymsfield and Donner (1990) calculated the ice content at equilibrium between the rates of deposition from vapor to ice and ice removal by sedimentation. The resulting ice contents provided a parameterization dependent on temperature, vertical velocity, lapse rate, and pressure.

Heymsfield and Donner (1990) calculated the rate at which ice is removed by sedimentation, Fa, by considering the local gradient of the ice flux:

$$-\frac{1}{\rho}\frac{\partial}{\partial z}(\rho X_s \overline{V}_t) \;=\; Fa, \tag{1}$$

where ρ is the air density, X_s is the ice mass mixing ratio, and $\overline{V}_t$ is the mean terminal speed for a distribution of ice particles. The gradient on the left side of (1) is calculated by applying the large-scale lapse rate across a layer in the cloud interior. Since the temperature varies across the layer, deposition proceeds at different rates, and the ice mass flux depends on z. The average value of X_s in the layer is taken to be representative of the saturated ice cloud for the purposes of the parameterization. However, if this is so, the sedimentation rate Fa must also apply for the cloud as a whole. For the entire saturated cloud, no ice enters the top, while ice settles from the base of the saturated region. If the value of Fa obtained from (1) is to hold for the entire cloud, the cloud thickness Δz is determined:

$$\Delta z \;=\; \frac{\overline{V}_t X_s}{Fa}. \tag{2}$$

For typical parameter ranges, Δz varies from about 100 m to over 3 km. Thus, the ice clouds can be considerably thinner than a GCM layer. (In using the parameterization in a GCM, the cloud thickness is restricted to be at most the thickness of the GCM layer where the cloud forms; multiple layers are allowed.)

The ice water content and geometric thickness together yield the ice water path, which is central to calculating the radiative properties of ice clouds.

2.2 Sublimating Ice Clouds

In the subsaturated region below the saturated ice cloud, into which ice falls from above, ice crystals sublimate. The thickness of the sublimating region is calculated following Heymsfield and Donner (1990), in which the maximum ice-crystal survival distance z_{max} is parameterized as a function of temperature, ice water content, and relative humidity. The thickness of the sublimating cloud is z_{max}. Within the sublimating ice cloud, the ice content at a distance z_{sub} below the base of the saturated cloud is a fraction FR of the ice content in the saturated cloud:

$$FR = (1 - \frac{z_{sub}}{z_{max}})^2 \qquad (3)$$

3. OBSERVATIONAL EVIDENCE SUPPORTING PARAMETERIZATION

Heymsfield and Donner (1990) compared parameterized ice contents as functions of temperature and vertical velocity with those observed by aircraft in one tropical and two North American field experiments. Reasonable agreement was found in most cases, although ice contents at low vertical velocities measured over Wisconsin during a 1986 field program were an exception. Further analysis of this aircraft data, recently completed by J. Warren at Princeton, shows that agreement between parameterized and observed ice contents is explained mostly by temperature and vertical velocity.

Soden (1993) used analyses from the European Centre for Medium-Range Weather Forecasts (ECMWF) to drive the parameterization. The visible optical depths and longwave emissivities were calculated, using the ice water paths from the parameterization, along with further assumptions regarding particle sizes. The visible optical depths were compared with those of the International Satellite Cloud Climatology Project (ISCCP), and effective cloud amounts (products of cloud amounts and emissivities) were compared with those obtained using carbon dioxide slicing with satellite observations. Agreement between the observations and parametered properties was generally good, although parameterized visible optical depths were somewhat lower than the ISCCP values in the winter hemisphere baroclinic zones, at least for the assumed particle sizes. The agreement held both for monthly means and an individual synoptic case examined. The comparison was subject to significant uncertainty, due a lack of knowledge of particle sizes, required to calculate optical properties from ice water path. Unlike the aircraft data, vertical velocity did not contribute to improving the agreement between radiative properties observed by satellite and parameterized properties. This could be a consequence of the significant difference in scales between the aircraft observations and the satellite datasets; the coarser-resolution satellite data and ECMWF analyses may average over variations in vertical velocity that are detected by aircraft measurement.

4. LARGE-SCALE ICE CLOUDS IN CCM1

The large-scale ice parameterization has been implemented experimentally in CCM1. The Heymsfield and Donner (1990) parameterization for ice content in saturated clouds has been supplemented by the parameterization for geometric thickness described in 2.1. Sublimating clouds in subsaturated layers have also been treated.

The clouds are allowed to persist, build up, or dissipate across time steps, allowing a local "memory;" ice need not (and usually does not) precipitate to the ground. The phase changes associated with ice-cloud formation and dissipation are linked to the thermodynamic and hydrological cycles in the model. Since vapor is generally deposited to ice at greater altitudes than it is sublimated back to vapor, a mechanism for the vertical redistribution of water vapor is introduced. In particular, the water vapor required to build an ice cloud, I_1, is

$$I_1 = \int_{saturated} \frac{X_s}{g} dp + \int_{sublimating} \frac{X_s}{g} dp, (4)$$

where p denotes pressure and g is the gravity constant. If I_1 increases over a time step Δt, then water vapor is removed at the saturated layer to account for the increase. If

$$\int_{sublimating} \frac{X_s(t+\Delta t)}{g} dp < \int_{sublimating} \frac{X_s(t)}{g} dp,$$

then water vapor is added to the sublimating layer to account for the difference; water vapor may either be added or removed from the associated saturated layer as necessitated by the change in I_1.

Effective crystal sizes in the ice clouds are parameterized using Heymsfield and Platt (1984). (Heymsfield and Platt (1984) treated only particles larger than 20 μm; a further adjustment to account for the effects of smaller particles, following Table 5 in their paper, has also been included.) Bulk albedo and emissivity for the ice clouds are then parameterized in terms of ice water path and effective crystal size using the method of Liou *et al.* (1991). The zenith-angle dependence for albedo of Ramanathan *el al.* (1983) is retained.

Preliminary studies with CCM1 show that the radiative properties of ice clouds in the model are highly variable in height, latitude, longitude, and time. Thus, there is significant potential for feedbacks of various types involving ice clouds. As an example of this variability, Fig. 1 shows the emissivities for ice clouds on the .245 sigma surface, averaged over a two-day period. Variations in both ice water path and particle size are important in determining the emissivity patterns. For example, for a typical sample at the .355 sigma surface, an ice cloud at 30° S with an ice water path of 25.4 g m^{-2}had an emissivity of .63, while at the same longitude at about 60° S, a cloud with an ice water path of 5.7 g m^{-2}had an emissivity of .52. The emissivity of the cloud with less ice was larger than linear variation with ice path would suggest because its effective particle size (42 μm) was considerably smaller than for the cloud with the larger ice path (93 μm).

5. CONCLUSION

A parameterization for the radiative properties of large-scale ice clouds has been incorporated in a GCM. Ice in both saturated and sublimating (unsaturated) regions is included, and the ice optical properties are treated consistently with the hydrological cycle in the model. Variations in albedo and emissivity are related to regional variations in both ice water path and particle-size distribution.

The effect of the ice clouds on climate and radiation balances is now under study. Ice clouds formed in association with cumulus convection are also important and will be considered in future studies.

6. REFERENCES

Heymsfield, A.J., and L.J. Donner, 1990: A scheme for parameterizing ice-cloud water content in general circulation models. *J. Atmos. Sci.*, **47**, 1865-1877.

Heymsfield, A.J., and C.M.R. Platt, 1984: A parameterization of the particle size spectrum of ice clouds in terms of the ambient temperature and the ice water content. *J. Atmos. Sci.*, **41**, 846-855.

Liou, K.N., J.L. Lee, S.C. Ou, Q. Fu, and Y. Takano, 1991: Ice cloud microphysics, radiative transfer, and large-scale processes. *Met. and Atmos. Phys.*, **46**, 41-50.

Ramanathan, V., E.J. Pitcher, R.C. Malone, and M.L. Blackmon, 1983: The response of a spectral general circulation model to refinements in radiative processes. *J. Atmos. Sci.*, **40**, 605-630.

Soden, B.J., 1993: *Satellite Observations of Water Vapor and Clouds: Implications for GCM Cloud Parameterization*, Ph.D. thesis, University of Chicago, 332 pp.

Williamson, D.L., J.T. Kiehl, V. Ramanathan, R.E. Dickinson, and J.J. Hack, 1987: *Description of NCAR Community Climate Model (CCM1)*, NCAR Tech. Note NCAR/TN-285+STR, 112 pp. [Available from NCAR, P.O. Box 3000, Boulder, CO 80307-3000.]

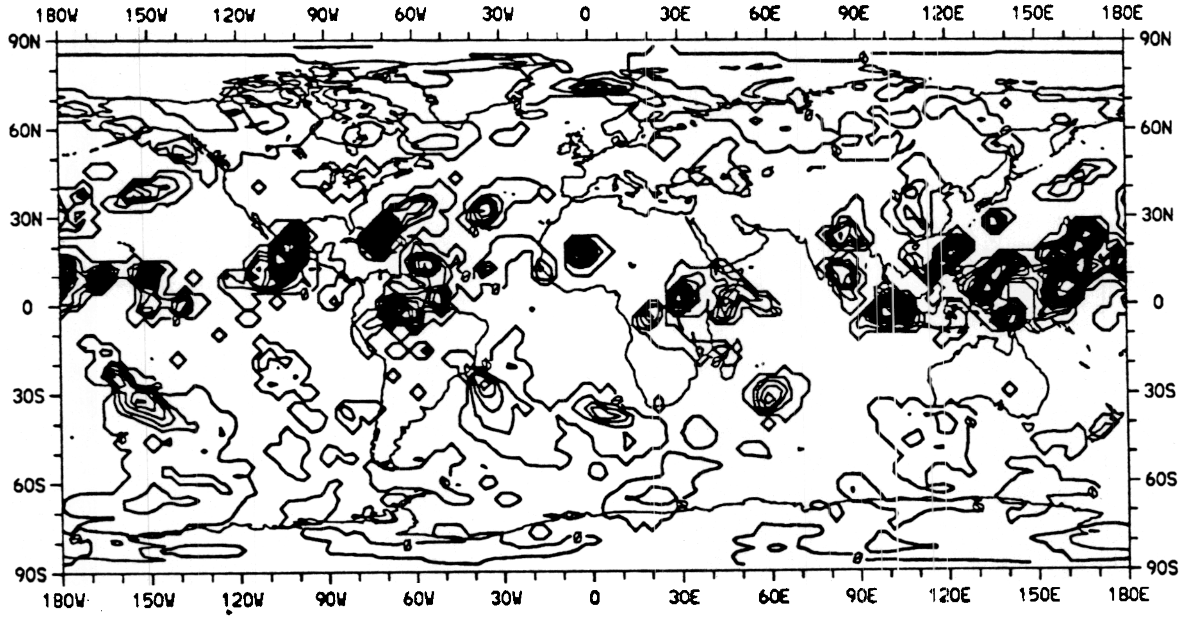

Fig. 1. Emissivities at sigma .245 surface. Contour from 0 to .95 by .05.