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A SCHEME FOR PARAMETERIZING CIRRUS CLOUD ICE WATER CONTENT IN GENERAL CIRCULATION MODELS

by

Andrew J. Heymsfield
National Center for Atmospheric Research
P.O. Box 3000
Boulder, Colorado 80307

Leo J. Donner
Department of Geophysical Sciences
University of Chicago
Chicago, Illinois 60637

1. INTRODUCTION

Clouds strongly influence the earth's energy budget. They control the amount of solar radiative energy absorbed by the climate system, partitioning the energy between the atmosphere and the earth's surface. They also control the loss of energy to space by their effect on thermal emission. Cirrus and altostratus are the most frequent cloud types, having an annual average global coverage of 35% and 40%, respectively. (Compiled from Hahn, et al., 1984, who used surface synoptic observations for the period 1971-1980). Cirrus is composed almost entirely of ice crystals and the same is frequently true of the upper portions of altostratus since they are often formed by the thickening of cirrostratus and by the spreading of the middle or upper portions of thunderstorms. Thus, since ice clouds cover such a large portion of the earth's surface, they almost certainly have an important effect on climate. With this recognition, researchers developing climate models are seeking largely unavailable methods for specifying the conditions for ice cloud formation, and quantifying the spatial distribution of ice water content, IWC, a necessary step in deriving their radiative characteristics since radiative properties are apparently related to IWC (e.g. Griffith, et. al., 1980). This study develops a method for specifying ice water content in climate models, based on theory and measurements in cirrus during FIRE and other experiments.

2. APPROACH

A conceptual model of the production of ice within a lifting layer is illustrated in Fig. 1. The horizontal extent of the layer is commensurate with one GCM grid, $\geq$ 100 km, and in the vertical it is 1 km. The parameterization will generate mean IWC for this layer, whose horizontal dimensions do not enter the parameterization, and whose vertical dimensions enter only weakly. The layer lifts at constant velocity, w (taken as the large-scale vertical velocity prognosed by the GCM or obtained from aircraft data in the verification experiments), from some initial state characterized by temperatures T_i and $\tilde{T}_i$, and pressures p_i and $\tilde{p}_i$, at its base and top, respectively. The relative humidity is assumed to be at ice saturation. After lifting for time t, the layer contains an ice water content given by the difference between the vapor mass sublimated onto the ice crystals and the net fallout of ice mass from the layer. Fallout must be considered since ice crystals have terminal velocities of tens of cm s^{-1}, much more than synoptic scale vertical velocities.

In this section the theoretical development of this conceptual view is given, and a discussion of aircraft flights used to characterize the ice mass distribution in deep ice clouds will be presented. The IWC's from the aircraft measurements are enhanced in some instances by horizontal advection of ice formed above and outside of the layers in cirrus convective cells, a factor which must be considered in comparing the measurements to the model results.

A. Theoretical Development

The total water mass in a layer undergoing ascent and cooling is constant, except for the accumulated mass which settles out of the layer:

$$X_{vs}(1+S_s)+X_s=C-F, \tag{1}$$

where X_{vs} is the mixing ratio of the vapor at saturation with respect to the solid (ice), X_s is the ice mass mixing ratio, S_s is the supersaturation with respect to ice, C is the initial water mass, and F is the mass mixing ratio of ice which has settled out of the layer.

The mass settled out of the layer (in a Lagrangian framework) is given by the vertical divergence of the ice mass mixing ratio integrated over the time of the parcel's ascent:

$$F=\int_0^t \frac{1}{\rho}\frac{\partial}{\partial z}\left[\int_0^{D_{max}} N(D,t')m(D,t')V_t(D,t')dD\right]dt'$$

$$=\int_0^t \frac{1}{\rho}\frac{\partial}{\partial z}\left[\rho X_s \overline{V}_t\right](p_i,t')dt', \tag{2}$$

where ρ is the density of air, z is the height, p is the pressure, t is the time, N, m, and V_t the concentration, mass and terminal velocity of ice crystals of dimension D, and $\overline{V}_t$ the mean mass-weighted terminal velocity. The bracketed term on the right-hand side of Eq. (2) is the precipitation mass flux (or precipitation rate) relative to the lifting layer.

Taking the time differential of Eq. (2), using the Clausius-Clapeyron and hydrostatic equations, and taking $\frac{d}{dt}=w\frac{d}{dz}$, where w is the layer ascent velocity, the following is obtained [2]:

[2] We have denoted Lagrangian derivates as total derivatives, although strictly speaking these are partial time derivatives with the initial position of the layer held constant, as noted explicitly in Eq. (2).

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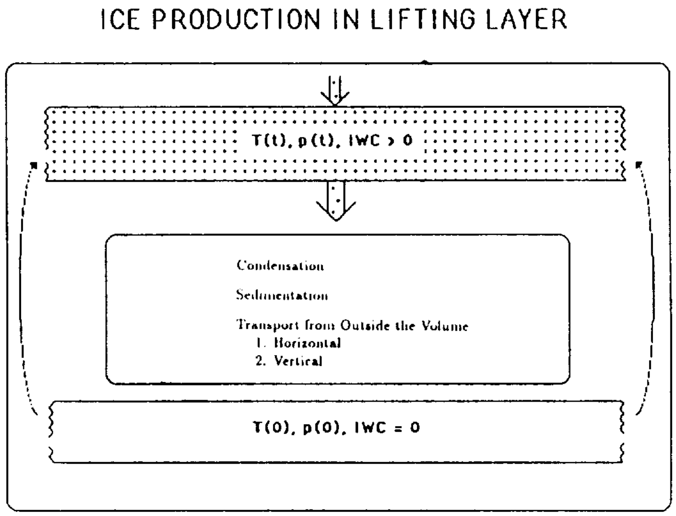

Figure 1. A conceptual model of the production of condensate in an ice cloud.

$$\frac{dX_s}{dt} = \underbrace{-(1+S_s)\,wX_s\left(\frac{L_s}{R_vT^2}\frac{dT}{dz}+\frac{g}{R_dT}\right) - X_{vs}\frac{dS_s}{dt}}_{supply}$$

$$\underbrace{-X_s\overline{V}_t\left[\frac{1}{\overline{V}_t}\frac{d\overline{V}_t}{dz}+\frac{1}{X_s}\frac{dX_s}{dz}-\frac{1}{T}\frac{dT}{dz}-\frac{g}{R_dT}\right]}_{sedimentation}, \qquad (3)$$

where L_s is the latent heat of sublimation, R_v and R_d are the ideal gas constants for water vapor and dry air, T is the air temperature, and g is the gravitational acceleration constant. The change in temperature is computed on the basis of dry adiabatic ascent and latent heat released due to vapor deposition onto ice crystals:

$$\frac{dT}{dz} = -\frac{g}{c_p} - \frac{L_s}{c_p}\frac{d}{dz}\left[(1+S_s)X_{vs}\right]. \qquad (4)$$

If supersaturation with respect to ice S_s is known [3] as a function of z, Eq. (4) provides an expression for $\frac{dT}{dz}$ for use in Eq. (3).

The $\overline{V}_t$ is evaluated from calculations of the ice mass precipitation rate in deep ice clouds by Heymsfield (1977). Converting to the terms used here,

$$\overline{V}_t = 1.09\,(\rho X_s)^{0.16}, \qquad (5)$$

where V_t is in units of m s^{-1}, ρ is in units of g m^{-3}, and X_s is unitless. Values predicted from this equation are in accord with estimated particle terminal velocities of 0.3 to 2.0 m s^{-1} in virga falling from ice and snow generating cells (e.g., cirrus uncinus).

[3] Our calculations assume an ice-saturated mixing ratio through the cloud depth.

Fig. 2 illustrates the ice water content for several layers undergoing ascent for t=10,000 sec., obtained by solving Eq. (3). Temperatures indicated are those at the end of the time period, and vertical velocity is held constant throughout. A common characteristic is a phase during which IWC increases with time, followed by a phase during which it decreases. Ice mass first increases in the layer by condensation; as the ice content increases, settling becomes increasingly important in removing ice, eventually dominating as the layer continues to cool moist adiabatically and the condensation rate decreases. Thus,

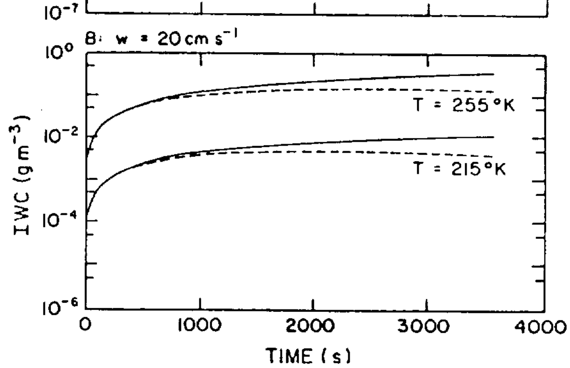

Figure 2. The ice water content as a function of time for several layers undergoing ascent for various temperatures (at the end of the ascent) and vertical velocities. A: w = 1 cm s^{-1}. B: w = 20 cm s^{-1}

the ice content of a layer depends on its ascent time. In later comparisons with aircraft measurements the ice content for a fully developed ice cloud will be taken as the maximum value during the layer ascent. These contents are appropriate for comparison with ice contents measured in clouds by aircraft which typically sample the densest regions of clouds undergoing penetration.

Later in this paper we will be comparing data from aircraft taken at particular temperatures and pressures with those predicted from Eq. (3). The comparison should be for the time the maximum IWC is reached in the parcel. Therefore, the history of parcel ascent must be reconstructed so that the initial conditions of the parcels ascent can be deduced. An estimate of the ascent time to maximum ice content for the conditions at the end of the parcel's ascent is made by tracing a parcels ascent backwards in time. The estimated initial temperature and pressure is iterated using the ascent times to maximum ice content until the cycle does not change the ice content significantly.

B. Aircraft Data Collection

Data were collected by aircraft in cold clouds over the continental United States in the mid-1970's during the Environmental Definition Program (EDP) (Heymsfield, 1977) and from the FIRE cirrus IFO. Measurements in the twenty EDP flights were acquired in the densest (visually) regions of deep winter- and springtime ice clouds associated with warm frontal overrunning systems, warm frontal occlusions, closed lows aloft, and jet stream bands. Sampling patterns consisted of 25-km-long constant altitude legs oriented parallel to the wind direction, beginning at the cloud top (8.5 to 11.0 km), and descending in 600-m steps to below cloud base (1 to 5 km). Four of the flights were coincident with single Doppler radar measurements. The FIRE data reported here were collected during eight flights by the NCAR King Air aircraft in visually dense cloud during spiral descents which began near cloud top (8 to 9 km) and ended at or below cloud base (5 to 6 km). The aircraft drifted with the wind and descended at a rate of about 2 m s^{-1} to follow approximately the fallout of the ice particles. The flights occurred on 19 October, 22 October, 25 October (2 flights), 28 October (2 flights), 1 November, and 2 November 1986. Horizontal distances covered by each loop of the spiral were from 5 to 10 km. Synoptic systems sampled were the same as those discussed above for the EDP data.

Aircraft size spectra measurements were used in conjunction with the ice crystal shape data to calculate the ice water content and precipitation rate. Vertical air velocity was calculated by equating the change in the calculated precipitation rate between two sampling levels to the vertical flux of moisture producing this change (Heymsfield, 1977).

3. RESULTS

The variation of ice water content with temperature and vertical velocity from the parameterization is illustrated by the lines in Fig. 3. These curves are computed by assuming ice-saturated ascent in Eq. (4) over times required for condensation and settling to balance (about 1800 to 4000 seconds). Pressure at the end of the ascent time is taken as the average for a specified vertical velocity from the aircraft data. The IWC depends primarily upon T, varying by four orders of magnitude over temperatures found in the troposphere. Increasing

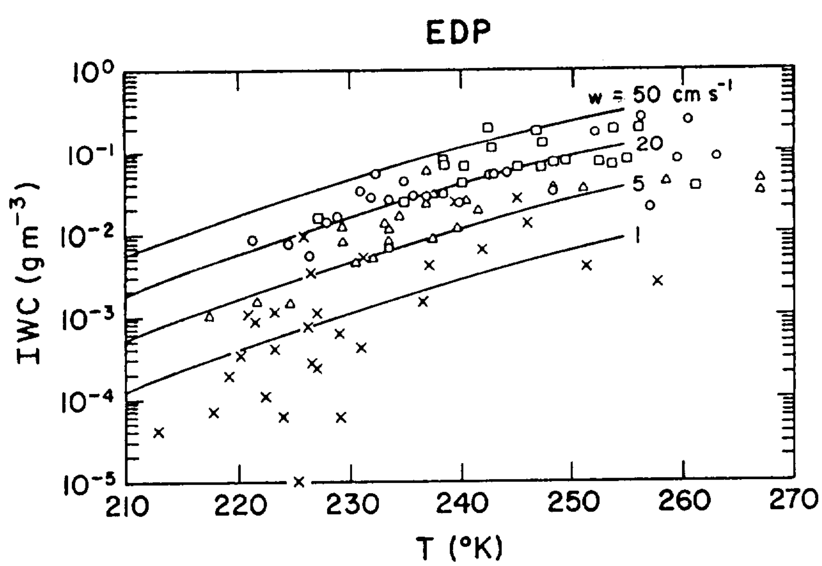

Figure 3. IWC values for each constant altitude penetration from the EDP data, plotted against temperature and partitioned into vertical air velocity intervals. Curves for the mid-point of the vertical velocity intervals from the parameterization are shown with dashed lines. Crosses: 0 to 2.5 cm s^{-1}; triangles: 2.5 to 10 cm s^{-1}; circles: 10 to 33 cm s^{-1}; squares: >33 cm s^{-1}.

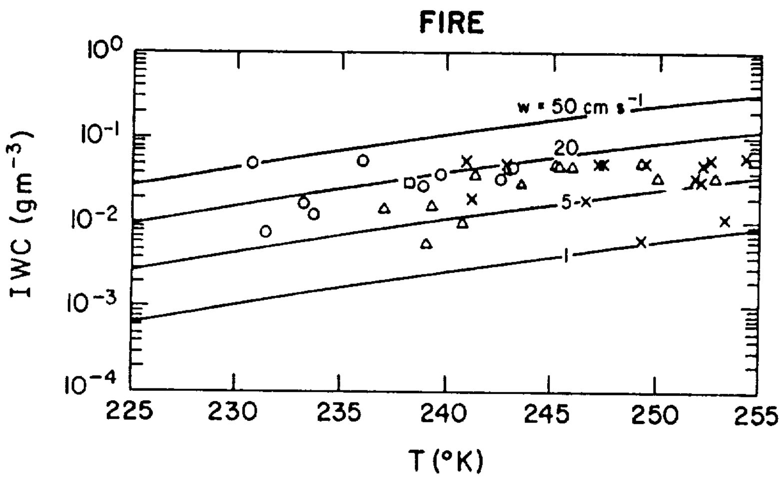

Figure 4. Same as Fig. 3, except for the FIRE measurements. Each data point is from the mid-altitude of a loop during a Lagrangian spiral descent.

w produces less than linear increases in IWC, because the ascent times required to reach equilibrium between settling and condensation are less at higher values of w.

Individual IWC from the EDP and FIRE data sets are partitioned into vertical velocity intervals bounding those from the parameterization and plotted against temperature in Figs. 3–4. The curves from Fig. 3 are reproduced in Fig. 4. In general, the parameterization has reasonably captured the variation of IWC with temperature and vertical velocity. The FIRE data at low w does not compare as favorably with the parameterization as the other methods; this might possibly be due to the small horizontal distances over which this data was averaged.

4. CONCLUSIONS

A simple parameterization for atmospheric ice water content can account reasonably well for ice water contents observed by aircraft in numerous synoptic contexts in mid-latitude and tropical areas. The physical processes are idealized condensation and crystal settling. Starr and Cox (1985) constructed a model in which many of the processes contributing to ice-cloud formation, as well as the circulation in which the cloud formed, were calculated explicitly over the development history of the cloud; phase changes, crystal settling, and radiative processes were the key elements in their model. The parameterization developed here is intended for use in large-scale models in which atmospheric ice distribution is sought diagnostically as a function of an instantaneous atmospheric state, so some of the details of the Starr and Cox model cannot be included. Atmospheric ice water content in large-scale models will, of course, interact with the radiative field, so feedbacks, which are likely to be significant, will develop between the cloud field and atmospheric dynamics and thermodynamics. This parameterization is essentially a simplification for the solution of large-scale equations for atmospheric ice, analogous to those for water vapor, which could added to large-scale models as a more explicit means of treating ice clouds (or atmospheric liquid water in general). Since the history of atmospheric ice which would be contained in such large-scale equations is absent, the parameterization has adopted assumptions to permit diagnostic solution.

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