PARAMETERIZATION OF CIRRUS CLOUDS IN GCMS

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Summary: GCM parameterizations for cirrus clouds are described. Evidence supporting the parameterizations from aircraft measurements and satellite observations is summarized. Preliminary GCM integrations are presented.

1. INTRODUCTION

Their potential importance in both the solar and terrestrial radiation balances and in the hydrological cycle in the upper troposphere has led to strong interest in parameterizing cirrus clouds in GCMs. Cirrus clouds can occur in an immense variety of morphologies. To simplify, two broad classes are considered here: large-scale ice clouds, in which ice formation is mostly due to cooling associated with synoptic-scale vertical ascent, and anvil ice clouds, which occur in the presence of deep cumulus convection where horizontal transfers of water are important. For both classes, simple conceptual, physical models are used to develop the GCM parameterizations. Observational evidence, independent of GCMs, is presented to support the parameterizations. Procedures for using the parameterization in GCMs are discussed.

2. LARGE-SCALE ICE CLOUDS

Large-scale ice clouds are assumed to consist of a saturated upper region and an unsaturated lower region. Ice crystals sublimate in the unsaturated region. The ice content in the saturated region is calculated by assuming an equilibrium between the rates of deposition from water vapor to ice and gravitational sedimentation of ice. The geometric thickness of the saturated ice cloud, which, with the ice content, determines the ice water path, is evaluated by requiring consistency between the cloud thickness and the sedimentation rate used to calculate the ice content. The ice content is assumed to decrease quadratically from the base of the saturated cloud through the sublimating layer. The thickness of the sublimating layer depends on the ice content in the saturated layer above, relative humidity, and temperature. Details can be found in *Heymsfield and Donner* (1990) and *Soden and Donner* (1994).

With an assumption regarding particle size, the ice water path can be used to parameterize the reflectivity, absorption, and emissivity of ice clouds (*Liou et al.,* 1991). Ice-particle sizes have been parameterized as a function of temperature by *Heymsfield and Platt* (1984).

The parameterization for ice water content is diagnostic, but the changes in ice with time and the partitioning of ice between the saturated and sublimating ice clouds imply changes in the distribution of water and heat. Details are discussed in *Donner* (1994). Saturated stable adjustments, which have frequently been employed in the past, often remove excess water to ground precipitation. The present approach instead allows it to re-vaporize in the upper troposphere.

Parameterized ice contents have been compared with those obtained from aircraft measurements (*Heymsfield and Donner,* 1990) and satellite retrievals (*Soden and Donner,* 1994). These comparisons showed modest success for the parameterization in tests independent of GCMs. The comparisons themselves are subject to limitations. For examples, independent determination of ice contents and vertical velocities by aircraft is quite difficult, and aircraft-measurement scales are significantly smaller than those resolved by GCMs. Although the satellite observations are on the scale resolved by GCMs, there are large uncertainties associated with retrieval methods, including assumed particle sizes. Subgrid variations in dynamic and thermodynamic properties which drive the large-scale ice parameterization can also account for differences between satellite-observed cirrus optical properties and those obtained by the parameterization.

The parameterization for large-scale ice clouds has been incorporated in the Skyhi GCM developed at the Geophysical Fluid Dynamics Laboratory (GFDL) at Princeton University. Fig. 1 shows vertically integrated ice water paths over a 24-hr period during January. In the tropics, note the presence of ice in the western Pacific in the upward branch of the Walker cell. In the northern middle latitudes, ice clouds are associated with synoptic eddies. Figs. 2 and 3 illustrate the zonally averaged ice contents associated with saturated and sublimating ice clouds. Note that the sublimating ice is displaced downward relative to the saturated ice. Note also that the sublimating ice contents can be substantial relative to the saturated ice contents. Fig. 4 shows the water-vapor tendency associated with the formation, maintenance, and dissipation of these ice clouds. Note that magnitudes of over 1 g kg^{-1} day^{-1}occur in the upper troposphere and that the different heights at which the clouds form and dissipate leads to a tendency to redistribute water vapor in the upper troposphere.

3. ANVIL-ICE CLOUDS

Unlike large-scale ice clouds, mesoscale ice clouds associated with deep cumulus convection depend much more obviously on horizontal transfers of water. A parameterization for these clouds should be linked to a cumulus parameterization which provides a water budget, including

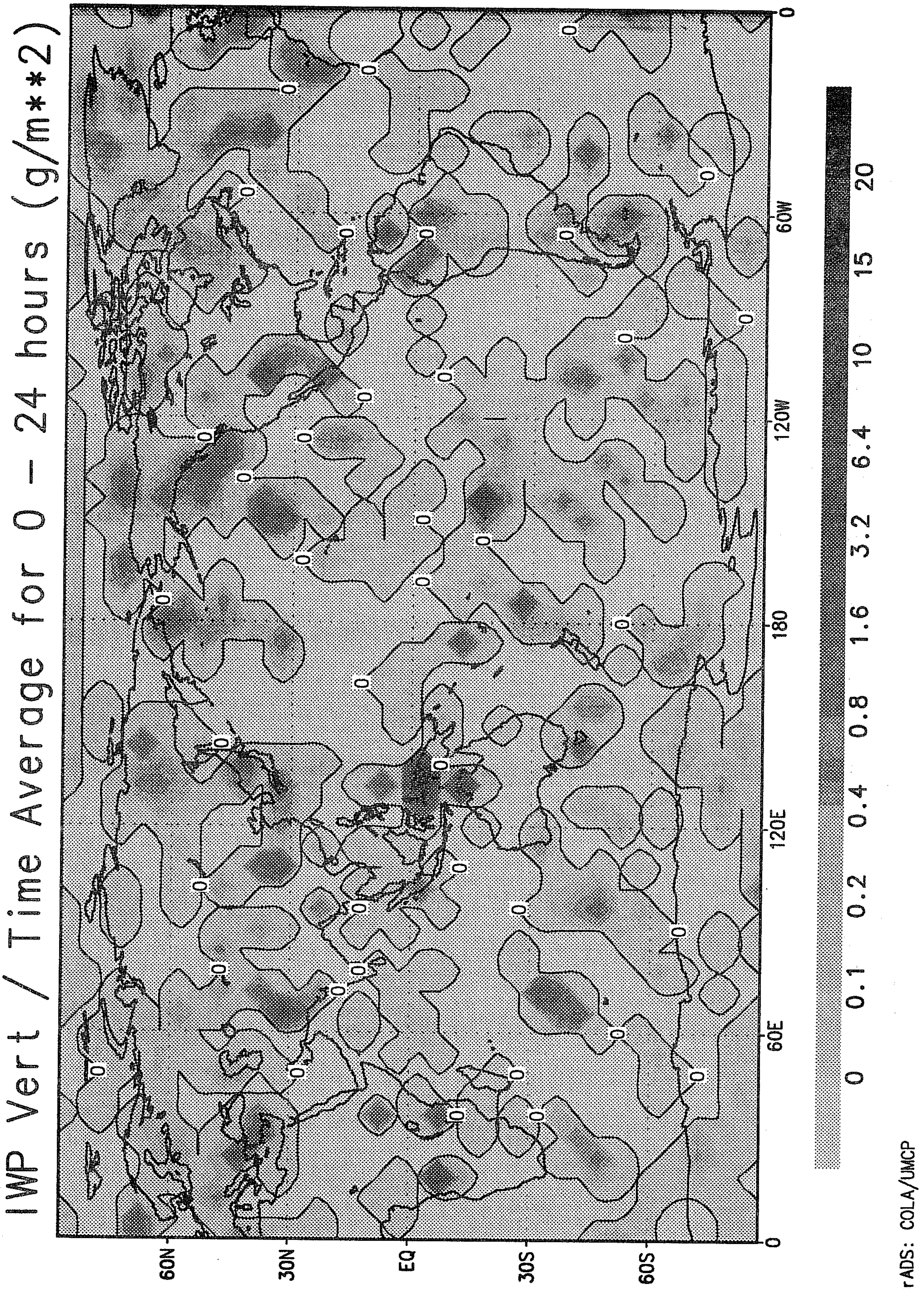

Fig. 1. Vertically integrated ice water paths. When no cloud is present, a value of zero is assigned.

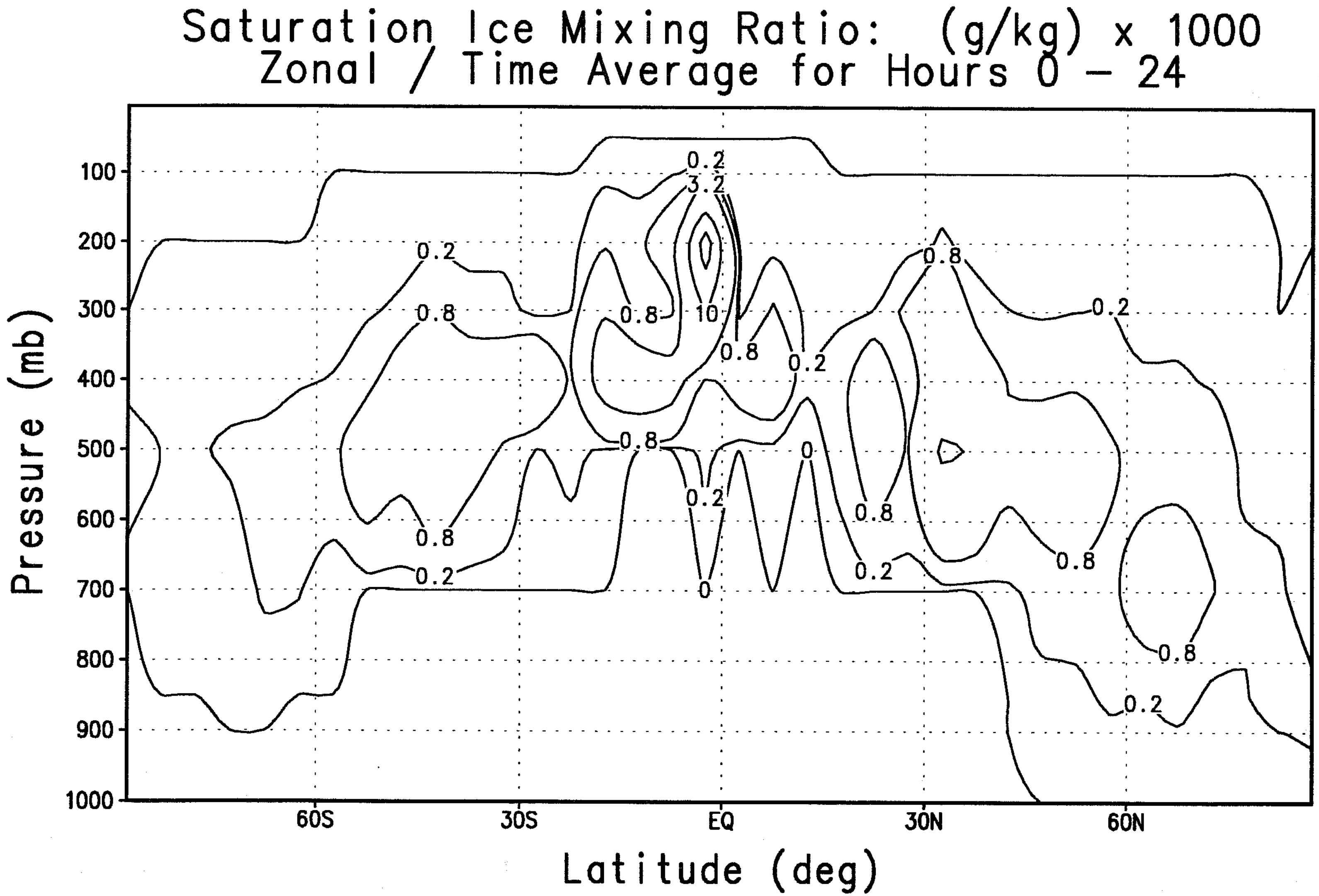

Fig. 2. Saturated ice mass mixing ratios. When no cloud is present, a value of zero is assigned. Contour intervals at 0, .2, .8, 3.2, 10, and 15 g kg^{-1}.

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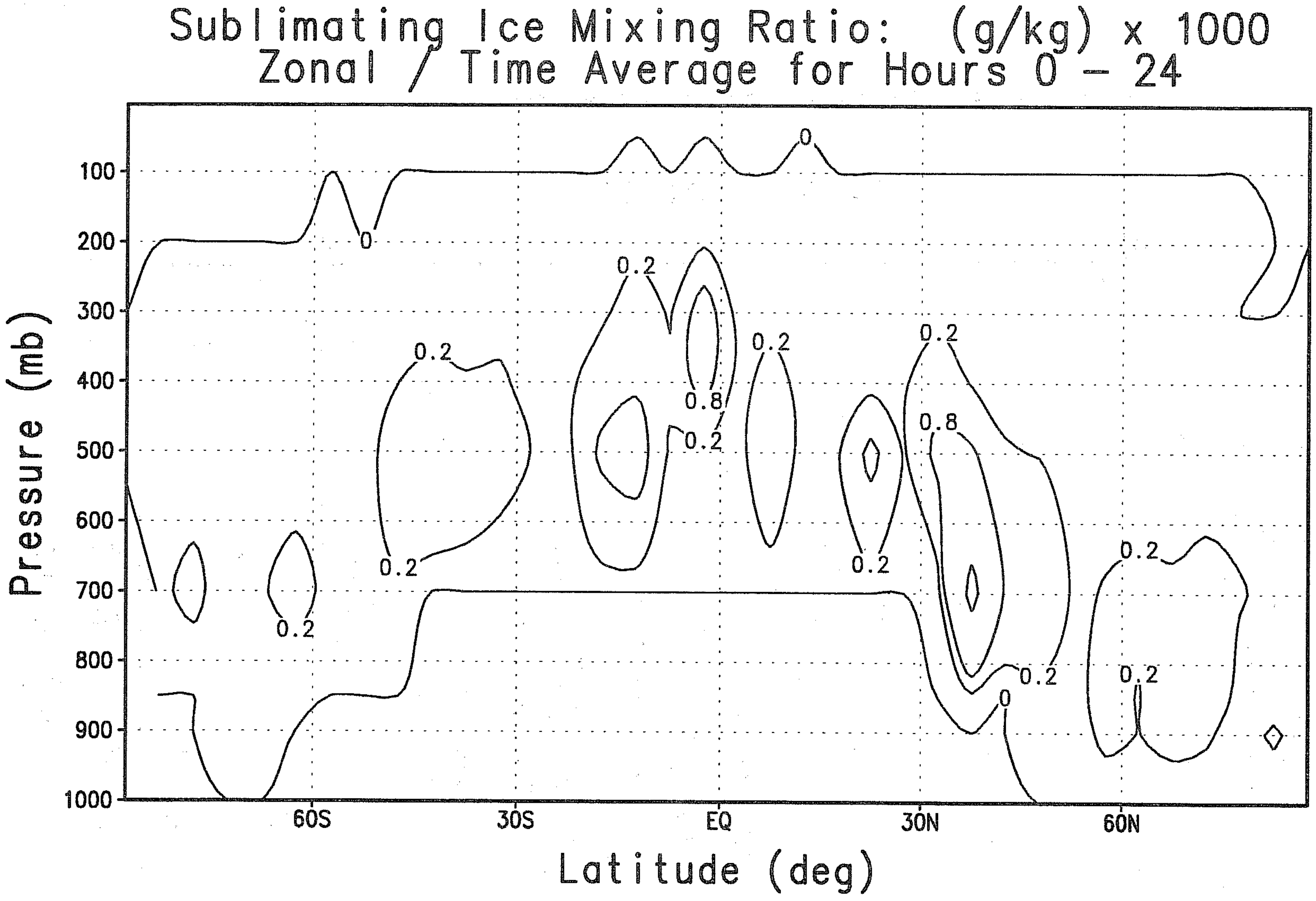

Fig. 3. As in Fig. 2, except for sublimating ice.

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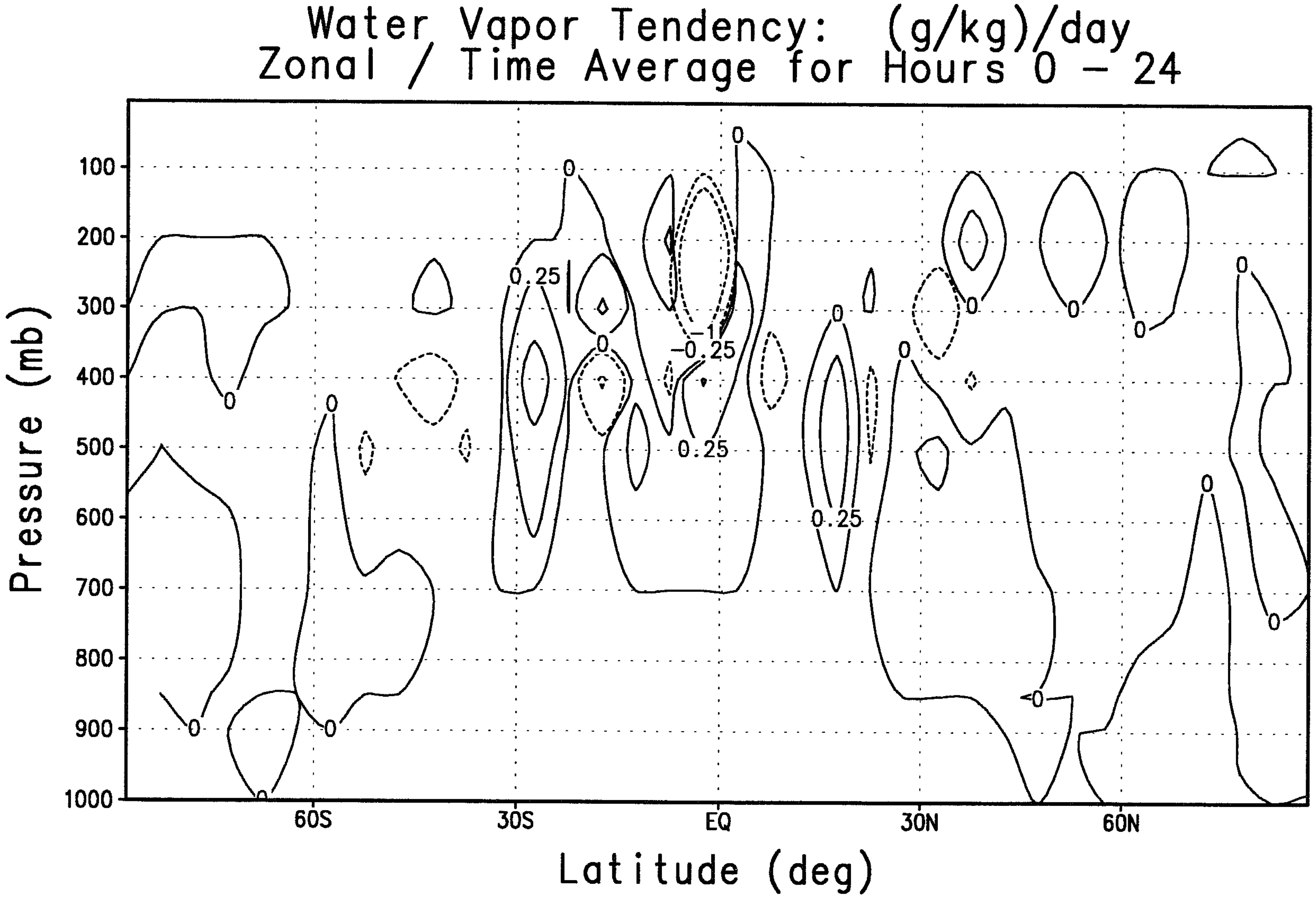

Fig. 4. Mixing-ratio tendency associated with formation and dissipation of large-scale ice clouds.

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the supply of water to the anvil. *Donner* (1993) developed a parameterization which includes a water budget for the anvils associated with convective systems. His cumulus parameterization includes details for calculating C_{mu}, the rate at which water vapor is deposited to ice in the convective anvil; C_A, the rate at which condensed water is transferred from deep cumulus updrafts to mesoscale anvils; and E_{me}, the rate at which ice sublimates to vapor from the convective anvil. These rates depend on the characteristics of deep cumulus convection and vary widely with synoptic environment. These sources and sinks must balance the ice fallout at the anvil base over the life cycle of the anvil. The ice-fallout rate is $a_m \rho_m X V_t$, where a_m is the area of the mesoscale anvil, ρ_m is the air density in the anvil, X is the ice mass mixing ratio in the anvil, and V_t is the terminal speed of the anvil ice. *Donner* (1993) provides a method to calculate a_m, and *Heymsfield and Donner* (1990) show that V_t can be expressed as a function of X. Thus,

$$C_A + C_{mu} - E_{me} = a_m \rho_m X V_t, \qquad (1)$$

which can be solved for X.

The anvil-ice parameterization has been tested using large-scale observations from the east Atlantic and west Pacific. The observations were from field programs which also diagnosed large-scale heat sources and moisture sinks due to deep convection, and the parameterization reproduced these well, *cf., Donner* (1993). The parameterized anvil ice contents were around 1.5 g kg^{-1}. For the east Atlantic, the anvil area agreed well with observations; observed anvil areas were not available for the west Pacific. No observations of ice content were available for these two cases. However, measurements of ice content for anvils at comparable heights in other regions suggested ice contents ranging from .5 - 2.5 g kg^{-1}(*Griffith et al.,* 1980; *Churchill and Houze,* 1984).

4. CONCLUSION

Parameterizations for the ice content of large-scale and anvil cirrus for use in GCMs have been developed by using simple physical models of the processes which control the ice sources and sinks for these clouds. The parameterizations are diagnostic, which represents a substantial simplification, since the parameterized clouds have life cycles which are longer than time steps used in GCMs. The observed ice contents agree reasonably with limited observations, which provides some measure of confidence in them independent of GCMs. The basic features of the large-scale cirrus distribution in a GFDL GCM appear to be reasonable.

5. REFERENCES

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