# P2.8 TESTING PROGNOSTIC CLOUD PARAMETERIZATIONS FOR CONVECTIVELY GENERATED CIRRUS USING CLOUD-RESOLVING MODEL SIMULATIONS

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## 1. INTRODUCTION

Observations show that tropical cirrus clouds often result from the life cycle of tropical convective cloud systems. Machado and Rossow (1993) used satellite imagery to examine the properties of tropical convective cloud systems. They found that relatively thin high clouds consitute a large part of the area covered by such systems, especially when the system's entire life cycle is considered. Figure 1 (from Machado and Rossow) is a schematic of the life cycle of a convective system that is consistent with their results and previous studies of convective systems. During the mature stage, Machado and Rossow determined that the average tropical convective system consists of 20 percent deep convective clouds, 28 percent transition anvil cloud, and 52 percent cirrus anvil cloud. During the dissipating stages, first the deep convective clouds disappear, then the transition anvil cloud, leaving only scattered fragments of cirrus anvil cloud.

A unique aspect of convectively generated cirrus anvils is their origin from a concentrated source, at least in the case of isolated cumulonimbi that detrain directly into the cloud-free environment. In the case of convective cloud systems with a precipitating anvil, one may consider the source of cirrus to be more extensive, because much of the ice mass is generated in the precipitating anvil, and the cumulonimbi detrain into the precipitating anvil, not the clear environment. However, from a GCM perspective, these two types of convective cloud systems are often not distinguished because the precipitating anvil, and its mesoscale circulation, are sub-grid scale. In this case, all sub-grid scale circulations associated with a convective system, including the mesoscale circulation, are represented by the cumulus parameterization.

In GCMs, the radiative effects of convective cells are generally neglected, while those of the anvils are not. Not too long ago, presence of anvils was simply diagnosed based on the existence of deep convection. Now, with the widespread adoption of prognostic cloud water/ice schemes, anvils are represented as a source term due to detrainment from deep cumulus convection. However, even with prognostic cloud water/ice schemes, there remains the difficult problem of determining the fractional cloud cover at each level. It should be obvious that the fraction of a grid cell occupied by anvil cloud is largely determined by the history of that grid cell, so that a prognostic cloud fraction parameterization is appropriate.

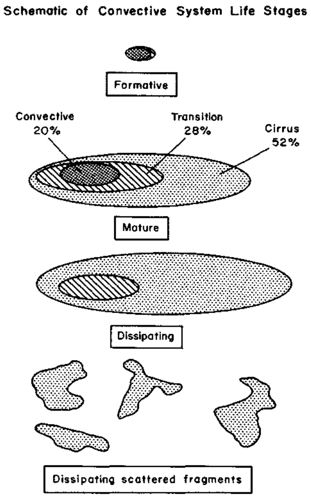

Figure 1: Schematic of the life cycle of a convective system. [From Machado and Rossow (1993).]

In order to more realistically represent both radiative and microphysical processes in anvil clouds in GCMs, the cloud fraction due to anvil clouds should be included by representing, in a simplified fashion, the physical processes that form, maintain, and dissipate anvil clouds. Such an approach has been developed by Tiedtke (1993) and extended by Randall and Fowler (1999).

We are using a cloud-resolving model (CRM) to study the cirrus clouds that result from the life cycle of tropical convective cloud systems. Cloud-resolving modeling studies of thin, non-precipitating stratiform clouds (e.g., stratocumulus, altocumulus, and cirrus) have demonstrated the importance of radiative destabilization and the resulting shallow convection in the maintenance of such clouds. The strong coupling of small-scale physical processes makes parameterization of such clouds in large-scale models challenging. CRMs have been successfully used to simulate many aspects of such thin stratiform clouds.

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### 1.1 Previous work on cloud ice parameterization

Heymsfield and Donner (1990), Donner et al. (1997), and Köhler (1999), among others, have proposed physically based parameterizations for cirrus cloud properties and/or processes. These investigators have proposed that the properties of cirrus clouds that form *in situ* as a result of large-scale ascent ("large-scale" cirrus) can be largely explained as an approximate balance between ice production by deposition, due to the decrease of saturation mixing ratio, and ice loss due to sedimentation.

In such circumstances, ice production, $P$, depends primarily on temperature and large-scale vertical velocity, (greater at higher temperatures and for larger vertical velocities), while sedimentation loss, $L$, depends on the ice mixing ratio, $q_i$, and the residence time of ice in the layer, $\tau$. The residence time depends on the layer thickness, $h$, and the ice fall speed, $V_i$. The result is

$$\frac{dq_i}{dt} = P - L = P - \frac{q_i}{\tau} = P - \frac{q_i V_i}{h}. \qquad (1)$$

The steady-state ice mixing ratio is then given by $q_i = P\tau = Ph/V_i$, and therefore depends on several large-scale parameters (temperature, vertical velocity, and cloud thickness) as well as a microphysical parameter (the ice fall speed). This analysis confirms what is well-known from observational studies of cirrus. It also illustrates that a parameterization of cirrus IWC that depends only on temperature is not universal, because IWC depends on (at least) the joint frequency distribution of ice water mixing ratio with temperature, vertical velocity, cloud thickness, and fall speed.

In recent years, many GCMs and NWP models have implemented prognostic cloud water/ice parameterizations, based on equations similar to (1). This should make the dependence of IWC on large-scale processes in such models more realistic. It is also relatively straightforward to include a source due to cumulus detrainment with the prognostic approach.

In the simplest case of anvil cirrus formation and decay, there is no ice production due to large-scale vertical motion. Idealized experiments were performed using the UCLA-University of Utah cloud resolving model (UUU CRM) to study anvil cloud cloud maintenance and decay mechanisms under these conditions (Köhler, 1999). Radiation and turbulence were found to have major effect on the life-time of cirrus clouds. Optically thick ice clouds decay significantly slower than expected from microphysical crystal fall-out due to the upward turbulent flux of water from IR destabilization, which in turn is partially balanced by the downward transport of water by snowfall. Solar radiation further slows the ice water decay by removing the inversion above cloud-top and the increasing the upward transport of water.

Based on the CRM results, Köhler developed an empirical parameterization of the effects of upward turbulent water fluxes in cloud layers by (1) identifying the time-scale of conversion of cloud ice to snow as the key parameter, and (2) regressing it onto cloud differential IR heating and environmental static stability. The results from UCLA GCM simulations showed that artificially suppressing the impact of cloud turbulent fluxes reduces the global mean ice water path by a factor of 3 and produces errors in each of solar and IR fluxes at the top of atmosphere of about 5-6 W m$^{-2}$ (Köhler, 1999). Aircraft measurements also indicate that neglecting the cloud-scale circulations in cirrus clouds may underestimate the grid-averaged IWC by a factor of 2 (Donner et al. 1997).

Köhler did not address the evolution of the fractional area covered by cirrus anvils. Progress on this aspect of anvil cirrus parameterization has been slower than that for the IWC. In order to more realistically represent both radiative and microphysical processes in anvil clouds in GCMs, the cloud fraction due to anvil clouds should be included by representing, in a simplfied fashion, the physical processes that form, maintain, and dissipate anvil clouds. Such an approach has been developed by Tiedtke (1993) and extended by Randall and Fowler (1999), but has not been examined using CRMs or tested against observations except indirectly using global, monthly averaged datasets.

### 1.2 Previous work on cloud fraction parameterization

Tiedtke used the following budget equation for the fractional area of cloud, $a$, in a grid volume:

$$\frac{\partial a}{\partial t} = A(a) + S(a)_{\mathsf{cv}} + S(a)_{\mathsf{BL}} + S(a)_C - D(a), \qquad (2)$$

where $A(a)$ is the transport of cloud area through the boundaries of the grid volume, $S(a)_{\mathsf{cv}}$, $S(a)_{\mathsf{BL}}$, and $S(a)_C$ represent the formation of cloud area by cumulus convection, boundary-layer turbulence, and stratiform condensation processes, respectively, and $D(a)$ is the rate of decrease of cloud area due to evaporation/sublimation.

For completeness, and to aid in the dicussion of anvil cloud processes, we include Tiedtke's budget equation for grid-averaged cloud water/ice content, $l$:

$$\frac{\partial l}{\partial t} = A(l) + S(l)_{\mathsf{cv}} + S(l)_{\mathsf{BL}} + S(l)_C - D(l) - G_p, \qquad (3)$$

where the terms are analogous to those in Eq. (2) except for $G_p$ which is the rate of generation of precipitation from cloud water/ice.

The formation of anvils and cirrus by cumulus convection involve the sources of cloud water content, $S(l)_{\mathsf{cv}}$, and cloud area, $S(a)_{\mathsf{cv}}$, due to detrainment from cumulus updrafts:

$$S(l)_{\mathsf{cv}} = \frac{D_u}{\rho} l_u,$$

$$S(a)_{\mathsf{cv}} = (1-a)\frac{D_u}{\rho},$$

where $D_u$ is the rate of detrainment of mass from cumulus updrafts and $l_u$ is the cloud water/ice content in the updrafts. Both $D_u$ and $l_u$ are obtained from the GCM's cumulus parameterization.

During and after its formation, an anvil or cirrus cloud is subject to non-convective processes that tend to increase its area and ice content, including large-scale ascent, radiative cooling, turbulent mixing, and mesoscale circulations, and to precipitation and sublimation that tend to decrease its area and ice content.

Based on numerical simulations of cirrus clouds (e.g., Starr and Cox 1985a,b; Fu et al. 1995; Köhler 1999; Luo et al. 2002), the evolution of (thin, non-precipitating) cirrus clouds after their formation by detrainment is governed by the same processes that determine the structure of non-convective ("large-scale") cirrus clouds: large-scale vertical motion, sedimentation and sublimation below cloud base, radiative destabilization, and cloud-scale convective circulations. The role of vertical shear remains uncertain.

There is a great deal of uncertainty in how to represent cloud evaporation/sublimation. Tiedtke proposed that clouds evaporate by two processes: (1) warming due to large-scale descent and/or diabatic heating and (2) (horizontal) turbulent mixing of cloud air and unsaturated environmental air. Tiedtke assumed that the first process decreases the cloud water but does not change the cloud area until the cloud water is gone, and that the second process decreases the cloud area while the in-cloud cloud water content remains unchanged. Randall and Fowler, on the other hand, allow the cloud area to decrease along with the cloud water during the first process, and neglect the second process, but include a diagnosis of subgrid-scale mesoscale vertical motions.

## 2. APPROACH

We are using the 2D University of Utah Cloud Resolving Model (UU CRM) for idealized-case simulations of the life cycle of cirrus anvils. The goal of the simulations is to better understand the processes that determine the evolution of cloud area in cirrus anvils, and to test some of the assumptions proposed by Tiedtke and by Randall and Fowler.

Previous studies of cirrus cloud-scale physics, for example those by Starr and Cox (1985a,b) and Köhler (1999), have shown the utility of idealized cloud-resolving model simulations to better understand the roles of various physical processes in cirrus clouds. Such CRM studies have by necessity used bulk microphysical schemes.

Although many CRM simulations of convective cloud systems have been performed, only a few have examined the evolution of anvil cirrus. The emphasis in most has been on the convective core and precipitating anvil partions of the systems. Fu et al. (1995) used the UU CRM to study the evolution of anvil cirrus in an idealized tropical squall-line system. They found that direct destabilization of anvil clouds via IR cloud top cooling and cloud base warming generates more in-cloud turbulence and contributes to the longevity and extent of the anvil clouds. Köhler (1999) also used the UU CRM to study in detail the factors that determine the decay time scale of anvil cirrus clouds, as already described.

### 2.1 The UU 2D Cloud Resolving Model

The University of Utah Cloud Resolving Model (UU CRM) is a 2D cloud-scale model. It explicitly resolves the motions associated with clouds, but parameterizes the 3D turbulent motions. It can be considered as a very detailed sub-grid scale parameterization for a GCM grid column. This makes it ideal for simulating cloud-scale processes that must be parameterized in a GCM.

The UU CRM was designed and is used for long-term (e.g., 5-30 days), large-domain (e.g., 500 km) simulations of cloud systems, primarily in order to study the large-scale properties, rather than their detailed structure, of cloud systems. For this reason, the model is 2D and uses a bulk microphysics parameterization. The model has also been successfully used as a small-scale "eddy-resolving" model to study stratiform cloud systems, in the same way that Starr and Cox (1985a,b) used their 2D cirrus model (e.g., Krueger et al. 1995c,d).

The UU CRM is more fully described in Krueger (1988), Xu and Krueger (1991), Krueger et al. (1995b), and Fu et al. (1995). The current version includes third-moment turbulence closure, a bulk ice-phase microphysics parameterization (Lin et al. 1983; Lord et al. 1984; Krueger et al. 1995a; Fu et al. 1995) and an advanced radiation code.

The bulk ice microphysics parameterization includes five hydrometeor species: cloud water, cloud ice, snow, graupel, and rain. The parameterization currently uses size distributions and particle densities that are appropriate for tropical oceanic deep convection (Lord et al. 1984; Krueger et al. 1995a).

The predominant species in cirrus clouds are small ice crystals and large ice crystals. In the CRM, these are represented as "cloud ice" and "snow." Cloud ice has zero fall speed, and snow has a mass-weighted mean terminal velocity that depends on the density and size distribution assumed. For snow, the exponential size distribution is assumed. (A modified gamma distribution is probably more realistic for the large ice crystals in cirrus clouds.) Representing ice in cirrus clouds with two species provides the scheme with the advantages of a two-size-class model, which includes sedimentation size sorting. For comparison, Starr and Cox's model (1985) used a single class of ice, so all ice at a grid point falls at the same speed. Another advantage of two size classes is that the effective radius or size of the ice particles (needed by the RT code) can vary according to proportions of small and large ice crystals.

The microphysics parameterization includes a generalized saturation adjustment scheme for cloud water and cloud ice (Lord et al. 1984) and an ice-crystal nucleation process (Lin et al. 1983). The combination of these is able to reproduce the observed large supersaturation with respect to ice that occurs just before ice forms, and the lower but still significant supersaturation that persists once ice is present.

### 2.2 Description of simulations

Our goal is to extend Köhler's study to investigate what determines cloud fraction for cirrus generated by convection. Tiedtke (1993) and Randall and Fowler (1999) proposed prognostic approaches. Many others have put forth diagnostic methods. These seem to be adequate for cirrus generated by large-scale ascent (e.g., Heymsfield and Donner 1990). Is the diagnostic method useful for cirrus generated by convection? Or is a prognostic approach necessary?

The UU-CRM specifications include a 200 m grid scale in both the horizontal and vertical directions. The spatial domain is selected as 51.2 km and 18.2 km in the horizontal and vertical directions. The horizontal domain size is a bit smaller than grid sizes used in most current climate GCMs, but should still be adequate to simulate most cloud internal circulation scales. The boundaries are specified to be cyclic horizontally and with zero vertical velocity at top and bottom. The lower boundary is the sea surface with a temperature fixed at the initial surface air temperature. Each simulation is 18 h long.

Table 1 describes the control simulation, i44, while Tables 2 and 3 describe 9 additional simulations. Cloud creation is forced by addition of cloud ice in a designated initial cloud layer of 9 to 11 km height and over a time period of 6 hours (except for run i58) following the initial time. The *horizontally averaged* rate of addition is $8 \times 10^{-5}$ kg kg$^{-1}$ h$^{-1}$ for all runs except i56. This is equivalent to an addition of horizontally averaged IWP of 0.067 kg m$^{-2}$ h$^{-1}$.

The Group 1 simulations differ from the control (i44) only in the *injection fraction*, which is the fraction of the domain that ice is injected into. The Group 2 simulations vary from i45 in a variety of aspects.

## 3. RESULTS

Our initial goal is to study the decay of cirrus in terms of the average IWP and the cloud amount. IWP is the domain average mass of cloud ice and snow per unit area. The cloud amount is the fraction of columns with IWP greater than $2\times10^{-3}$ kg m$^{-2}$. This criterion is based on the lower limit of detectable clouds from satellite (Rossow and Schiffer 1999). It corresponds to an optical depth of 0.2 for ice clouds with ice crystals that have an effective radius of 30 microns. . Figures 2 and 3 show the time series of IWP and cloud amount for Group 1, while Fig. 4 graphs the trajectories of the Group 1 simulations in the phase space of cloud amount and average IWP. Figures 5–7 contain the corresponding plots for Group 2.

The results suggest that there is not a unique diagnostic relationship between cloud amount and IWP. The final decay stage is quasi-steady although slowly decaying. All runs are similar during this stage, independent of injection fraction.

If the injection stage of these simulations resembles the generation of cirrus by detrainment, then in general we must conclude that a unique diagnostic relation between cloud amount and IWP does not exist. However, there is a unique diagnostic relation in the quasi-steady regime. This suggests that a prognostic approach is required to determine cloud fraction for convectively generated cirrus.

Table 1: Description of control simulation, i44.

| Parameter | Value |
|---|---|
| Injection fraction | 1.00 |
| RH | 40% |
| IWP injection rate | 0.067 kg m$^{-2}$h$^{-1}$ |
| SGS turbulent fluxes included | true |
| Ice injection interval | 6 h |
| Random perturbations added for | 300 s |

Table 2: Description of Group 1 simulations.

| Name | Difference from i44 |
|---|---|
| i44 | None |
| i45 | Injection fraction = 0.25 |
| i46 | Injection fraction = 0.5 |
| i47 | Injection fraction = 0.125 |
| i48 | Injection fraction = 0.0625 |

Table 3: Description of Group 2 simulations.

| Name | Difference from i45 |
|---|---|
| i45 | None |
| i52 | RH = 70% |
| i56 | IWP injection rate = 0.017 kg $m^{-2}h^{-1}$ |
| i57 | No subgrid-scale turbulent fluxes |
| i58 | Inject ice for 3 h |
| i59 | Random perturbations added for 3600 s |

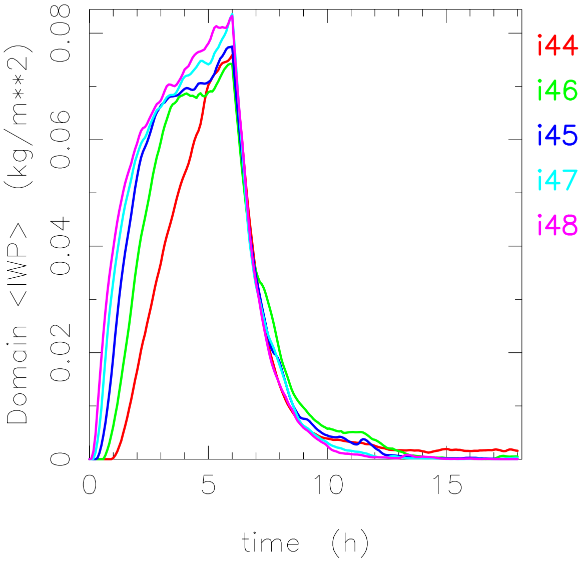

Figure 2: Time series of average IWP for Group 1.

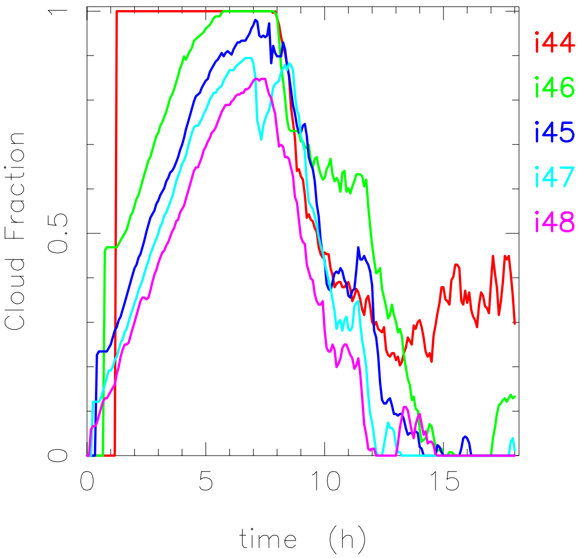

Figure 3: Time series of cloud amount for Group 1.

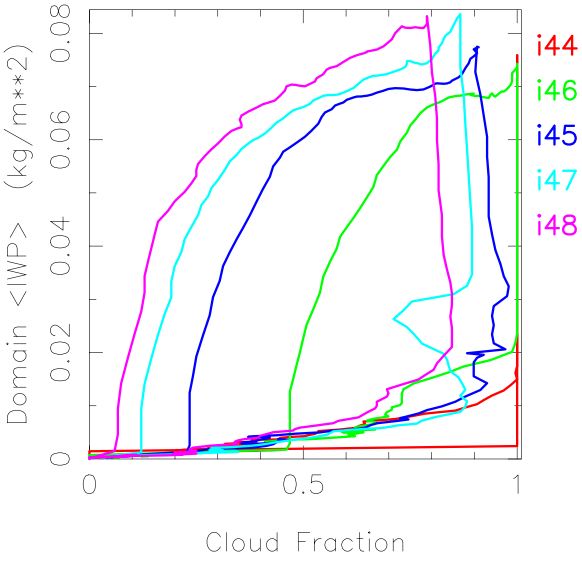

Figure 4: Average IWP versus cloud amount for Group 1.

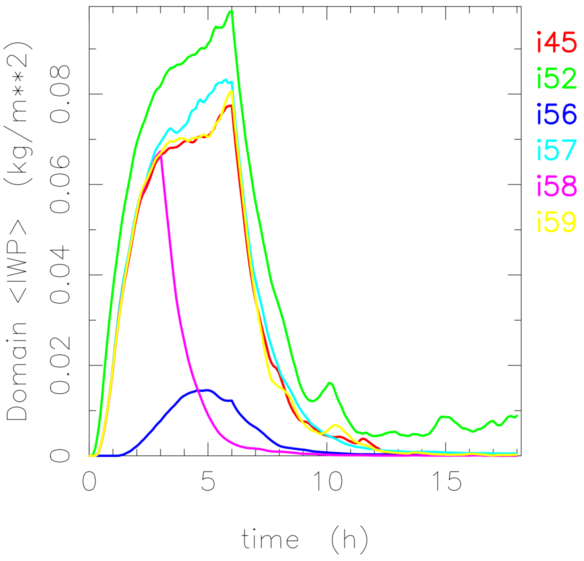

Figure 5: Time series of average IWP for Group 2.

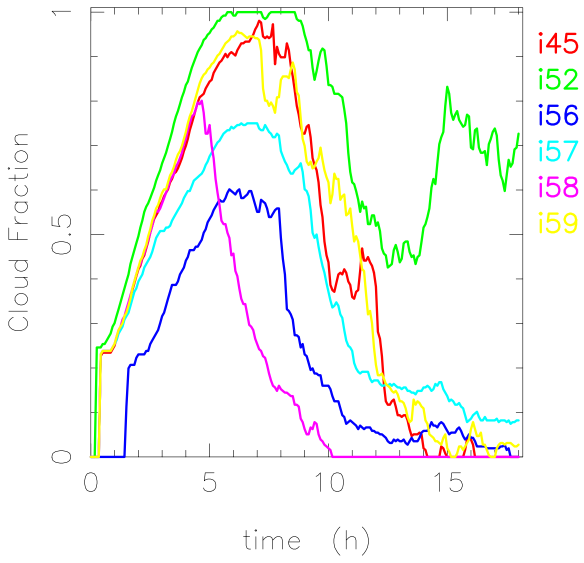

Figure 6: Time series of cloud amount for Group 2.

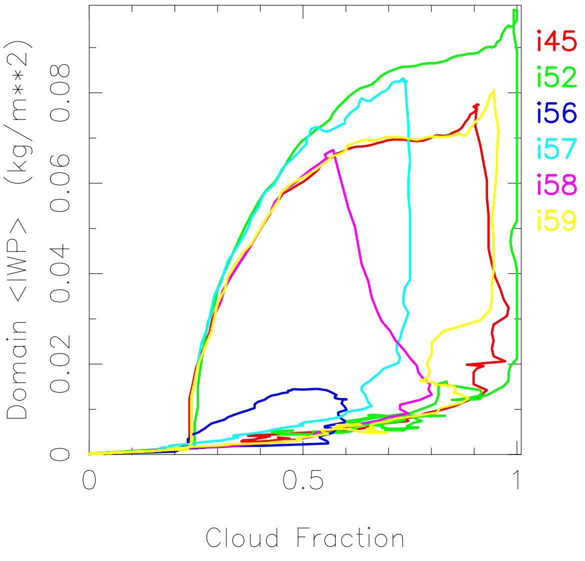

Figure 7: Average IWP versus cloud amount for Group 2.

## ACKNOWLEDGMENTS

This research was supported by NASA Grant NAG5-11504, Cloud-Scale and Large-Scale Modeling of Tropical Anvils and Cirrus Layers.

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