A review of the effect of radiation transfer on the simulation of atmospheric circulations of different scales

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Abstract. Radiation from the sun is the principal external energy source for the atmospheric thermodynamic engineer. The absorption of infrared radiation by atmospheric constituents is the source of the so called greenhouse effect. It is well known that an accurate description of the radiative balance is essential for climate studies. On smaller scales, radiative contributions to the surface energy balance are also well known, leading to phenomena such as land/sea breezes and the mountain/valley circulation. However, the forcing due to radiative flux divergence in the atmosphere has often been neglected due to its relatively small magnitude compared to other forces. Nevertheless, radiative flux divergence contributes to the evolution of atmospheric phenomena from large scale circulations, such as the Hadley cell, to smaller scale features such as fogs and stratocumulus.

This paper reviews the effect of atmospheric radiation transfer in circulation systems on all time and space scales, from climate to cloud scale, especially as determined from nonlinear numerical modeling studies. Emphasis is placed on circulation forced by radiative flux divergence in the atmosphere, rather than at the earth's surface. Examples of the effect of radiation transfer on several scales are described, with the conclusion that radiation transfer is an important component in the evolution of circulation systems on all scales. Finally, results from the author's own work are presented.

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1. Introduction

Absorption of solar radiation is the primary source of the atmosphere. The emission, transmission, and absorption of longwave radiation plays an important role in the atmospheric circulation and structure. The interaction of clouds with radiation remains a primary uncertainty in climate simulations. Such interaction also contributes to the evolution of circulations on smaller time and space scales. An accurate representation of radiative transfer, especially in the presence of clouds, is necessary for the study of atmospheric circulation systems. Radiative transfer is especially important as the time scale of the integration grows larger, and is absolutely critical for climate studies. However, it is becoming more apparent (e.g.

Tripoli and Cotton [23]) that radiation forcing also plays a role in the development of circulation on smaller time and space scales.

Historically, because the relative size of the forcing due to radiative flux divergence is small compared to latent heating for example, the radiative forcing on short time scales has been ignored or represented simplistically in meoscale models of atmospheric circulation. For some cases, with strong large scale forcing, this remains valid. However, several situations exist where radiation is an important driving force in the circulation. This paper reviews examples of atmospheric circulation from all space and time scales where radiation plays a role in the development or maintenance of those circulations. All of the examples cited involve modeling studies. Section 2 briefly reviews radiative transfer parameterizations. Section 3 documents examples of the effects of radiation forcing on all atmospheric space and time scales. Section 4 includes a simple example from the authors' own modeling studies that illustrates how cloud-radiation interaction influences the circulation in a mesoscale numerical model, and Section 5 provides a brief summary.

2. Radiative transfer in numerical models

The parameterization of radiative transfer in atmospheric circulation models necessitates several approximations (Stephens [21]). Some of the approximations and inherent inaccuracies and difficulties are summarized here.

Incorporating radiative transfer in numerical models is limited by two major factors. The first is the inadequate treatment of the physical fields in the numerical models that control radiative transfer, the other is the incomplete understanding of radiative transfer in the wide range of conditions that exist in the atmosphere (real or modeled). In some sense the two are not completely separate. For example, cloud processes in larger scale models are based on crude parameterizations, incorrectly forecasting the existence of specific cloud types with little chance of treating the microphysical characteristics of the clouds, while other cloud types are principally radiation drive. A weakness in radiative transfer theory in general is a lack of complete understanding of the interaction of the radiative fields with the dynamic, thermodynamic, and moisture fields.

Most atmospheric models treat radiative transfer as two separate problems, shortwave and longwave transfer. This justified because of the separation of the peaks in the solar and terrestrial radiation spectra, although there is a small overlap in the wings near 3 to 4 micrometers. Hence, the explicit formulations of radiative transfer are treated separately. However, the two interact implicitly through the source term for longwave radiation.

The radiative transfer equations are characterized by integrals over four physical "dimensions"; the angle of radiation, the absorption path of the radiation, the radiation frequency (electromagnetic spectrum), and the contribution to any level in the atmosphere from the surface and the other parts of the atmosphere.

Various approximations and assumptions are used to simplify the complex integral equations that results. These assumptions differ for the shortwave and longwave equations.

a) *Longwave*

The transfer of longwave radiation is complicated by the simultaneous existence of absorption and emission terms. At the same time, the treatment of scattering by longwave radiation is treated very simply. The scattering of longwave radiation is very large in the atmosphere, so much so that it is treated as a diffusivity problem, analogous to turbulent transfer of momentum or heat. The diffusivity (integral over zenith angles) approximation is used to remove the angle dependence. This approximates the hemispheric radiation as if the radiation was all from one angle (approximately 53 degrees). Absorption path approximations are based on laboratory data and extended to the atmosphere. The coefficients are scaled to account for fluctuations in the thermodynamic quantities (pressure and temperature). It remains difficult to isolate and assess the effect of theses scaling approximations, especially over all of the absorption bands.

The integration over the electromagnetic spectrum is complicated by the very different scale so that it exists in the frequency domain. Theoretically, the solution is the convolution of the Planck function with absorption spectrum, including all frequencies. This would be intractable analytically and prohibitively expensive computationally, even if the absorption lines were well defined at all frequencies. The usual practice is to treat the molecular absorption with band models and to approximate the absorption coefficient in the H_2O continuum with scaled analytical functions. The overlapping of the H_2O and CO_2 absorption is also treated analytically, as long as their respective absorptions are treated consistently. These band models are calibrated using line by line models.

The clear sky case uses many approximations and assumptions. The approximations become cruder when clouds are present. The models assume that in the infrared, clouds radiate as black bodies. Further, it is assumed that any cloud present occupies the entire vertical level, producing little resolution to cloud base and cloud top. This arbitrarily imposes an equivalent radiating temperature. Further problems arise when the clouds occupy more than one adjacent layer, when the clouds are optically thick or optically thin.

b) *Shortwave*

The representation of short wave transfer processes is equally difficult. The shortwave is simplified by the non-existence of an atmospheric source, but made much more difficult because of the importance of scattering. The equations still depend on the angle, optical path, and electromagnetic frequency. Scattering is most often approximated by the introduction of a phase function. Absorption by water vapor in the lower atmosphere is a significant heat source, but is strongly dependent on frequency, as well as on pressure and temperature. Problems also arise from the overlap of the water vapor and water droplet absorption spectra. In the stratosphere, shortwave absorption by O_3 is the major heat source. The top level in numerical models is often below the atmospheric level where the heating due to O_3 absorption is maximum, resulting in inaccurate representation of this heating.

The treatment of shortwave radiation when clouds are present introduces questionable assumptions. Again, the radiative parameterization requires a description of the cloud optical properties in terms of the appropriate macrophysical or microphysical variables. Most large scale atmospheric models prescribe fixed values to shortwave radiation characteristics in the presence of clouds. However, the radiative properties of real clouds change with the cloud character and changing elevation angle of the sun. Attenuation in the clouds includes important contributions by the scattering and absorption by cloud particles as well as the gas absorption. As clouds become optically thick, multiple scattering tends to cancel and the phase function is relatively unimportant. This is obviously not the case for optically thin clouds, and especially when ice crystals are present, as is often the case for cirrus.

As with longwave radiation, it is not straightforward to include the effects of multiple cloud layers, to include broken or scattered clouds, or to account for the presence of more than one type of cloud. It remains difficult to formulate transmission functions which correctly overlap gas absorption, droplet absorption, and droplet scattering.

3. Radiation transfer effects on different time and space scales

a) *Climate Scale*

The sensitivity of the atmosphere structure to the radiation parameterization shows that a better representation of radiative transfer (Ramanathan, et al., [19]) leads to stronger climate scale circulation. Effectively, the interaction of radiation with deep convective clouds near the equator leads to warming in the upper tropical troposphere and cooling in the stratosphere. This leads to an increased slope of the tropopause from the equator to the poles, enhancing the strength of the Hadley cell circulation, increasing the strength of the subtropical jet, and leading to greater rainfall amounts, especially in the subtropics.

Slingo and Slingo [20] studied the interaction of cloud radiation forcing and dynamics. Their results are consistent with those of Ramanathan et al. [19]. With improved radiation, more clouds are formed leading to enhanced latent heating and stronger circulations. There is increased precipitation, especially at low latitudes. The stronger circulations include a stronger Hadley circulation and subtropical jet, again due to warmer upper troposphere and cooler lower stratosphere in the tropics. They emphasize that a large uncertainty in climate models is the distribution of vertical heating as cloud tops and bases are confined to model levels.

An interesting study of smaller scale features that can effect climate simulations is a study of mountain waves with clouds present (Weissbluth and Cotton [25], hereafter WC). Mountain waves according to classical theory (Eliassen and Palm, 1964) produce a momentum stress profile independent of height. It is the vertical divergence of momentum stress which affects the mean momentum fields, so gravity waves in general are thought to affect the momentum fields only through wave breaking. This wave breaking has been parameterized into climate simulations to properly decelerate the westerly momentum. WC hypothesized that radiation cooling at the top of mountain induced clouds will destabilize the environment, allowing conditional instability to develop, effectively trapping the gravity wave energy below cloud top. This trapping of the gravity wave energy leads to systematic changes in the vertical momentum flux and therefore leads to bias in the gravity wave drag parameterization schemes. WC recommend including moisture in these parameterization schemes, while recognizing the difficulties involved, especially in the presence of several cloud layers or with different moisture profiles above cloud top.

b) *Synoptic Scale*

Krishnamurti et al., [14] used a global spectral model to forecast the movement and evolution of a tropical typhoon for 10 days. Their objective was to investigate the role that shallow clouds in a storm environment play in the radiative destabilization of the environment. Radiation cooling of shallow clouds preconditions the environment by maintaining a minimum in equivalent potential temperature near the 700 mb level, ensuring a supply of conditionally unstable low-level air as inflow to the storm. They compared two radiation schemes, a band model and a emissivity model. The results are consistent with the results from climate models, circulation increased with the improved radiation parameterization (the band model). Precipitation rates were 40% greater and inflow into the storm circulation was increased with the band model representing radiative transfer. The emissivity model produced weaker inflow, weaker radiative destabilization of the storm environment in the shallow cloud layers, and stronger stabilization of the surface layer. Weakening of the storm circulation resulted with the simpler radiation scheme. The radiation forcing acts on a larger time and space scale than the circulation of the storm itself. It creates the necessary conditionally unstable air that is eventually ingested by the storm. The preconditioned, convectively unstable air feeding into the storm system results in greater latent heat release, more precipitation and stronger circulation.

Krishnamurti et al. performed an interesting predictability experiment in the course of their sensitivity studies. They ran the model for 3 (out of 10) days with the band model, then switched to the emissivity model. There was a significant weakening of the storm circulation and a divergence of solutions after the emissivity model was substituted. This suggests the need for more studies, especially with the growing emphasis on climate simulations, atmospheric and climate predictability, and cloud-radiation feedback to climate.

Tests with improved radiation schemes in the European Center for Medium-Range Weather Forecasts (Morcrette, [18]) also show improvements, especially in the upper tropical troposphere temperature distribution. They also show that improved radiative balance at the surface, together with overall cooling of the entire troposphere leads to large turbulent heat fluxes, resulting in greater convective activity and a general increase in the strength of circulation. Differential heating between the topics (due to increased latent heat release and increased radiative heating in the upper troposphere) and the subtropics (radiative cooling in clear skies) leads to a more energetic model atmosphere at all wavenumbers. In general, with the improved radiation parameterization, the model is more active. Also, improved radiative transfer through the atmosphere leads to more accurate temperature forecasts over land and to improved predictions of circulation forced by the land-sea interface.

Lee et al, [15] investigated the role of improved cloud physics with a radiative transfer scheme in a kinematic global cloud model. They specified the winds from a general circulation model. Without this feedback to the dynamics, they show that radiative cooling leads to increased relative humidity and mode clouds. It would be expected that increased clouds an consequent release of latent heat would increase the strength of circulation.

c) *Mesoscale*

Radiative transfer can have a significant effect on mesoscale circulation, both as a driving force when large scale forcing is weak, and as a mechanism for organization and scale interaction. Zhang and Fritsch [27] suggest the importance of the stratiform precipitation region in the organization of rotating Mesoscale Convective Systems (MCS). Although they did not study the effect of radiative transfer, they emphasize the point that rotating MCS's are basically barotropic in nature and tend to form when the large scale forcing is weak. This has two implications for including radiation transfer: 1) it may be an organization mechanism through the interaction with the cirrus shield and ambient environment, or 2) it can be a primary forcing mechanism of a steady state system such as Emanuel's [11] cannot cycle model of a hurricane, where he suggest that radiative cooling at cloud top is necessary to maintain the storm circulation.

Lilly [17] suggests that the radiative heating provides a continuing source of differential heating of the cirrus outflow. Radiative flux divergence drives convection in the cirrus layer in much the same way as radiatively drive stratocumulus clouds in the planetary boundary layer. He also suggests that as the cirrus layer expands horizontally, the radiation forcing increases, enhancing the mesoscale updraft.

Modeling studies support this hypothesis. Tripoli and Cotton [23] used a nonhydrostatic cloud model to study an organic MCS that formed in the Colorado Rockies and propagated to the east. They suggest that radiative transfer plays a role in the scale interaction process. Radiative heating of the anvil is on the order of 15-20 K/day and is largely meso-a scale. This compares to latent heating of 500 K/day for meso-g and 100 K/day for meso-b scale circulations within the MCS. The radiative transfer plays several key roles. The down shear stratiform region (cirrus) is warmed from below and cooled from above die to the longwave flux divergence. The effect is stronger at night, due to shortwave heating at cloud top during sunlight hours. This destabilization of the upper troposphere in the anvil region creates a gravity wave duct, trapping the tropospheric gravity wave energy. It translates into a horizontal spread of the kinetic energy released in the convective core, most likely leading to a larger area cirrus shield. This feeds back to a stronger divergence (both dynamic and radiative), further enhancing the overall circulation and the destabilization of the upper troposphere, which in turn leads to an overall intensification of the core vertical motion. Because of shortwave heating of the cloud top during the day, the effect appears to be greatest after sunset, which is qualitatively consistent with observations. Tripoli and Cotton [23] suggest that the organization of the MCS may be due to a CISK type mechanism, possibly wave-CISK. The interaction of radiation with the cirrus may be apart of that wave-CISK mechanism. They do emphasize, however, that the movement to the east is not the propagating mode of wave-CISK.

Using the same model, Chen and Cotton [3] specifically investigated the cirrus anvil in a mesoscale system and its associated motion field. With radiation included, they also found increased cloud top cooling and cloud base warming in the downshear stratiform cloud. This increased the internal cloud circulation noticeable. The front to rear mid level jet increased by 1 to 3 m/s, while the upper-level divergent outflow increased by 3 to 6 m/s. The precipitation rate does not appear to be affected; however they ran the model for only four hours.

Dudhia [8] compares the results of a hydrostatic model to observations over the South China Sea. The purpose was to study the important physical mechanisms in the development and maintenance of tropical cloud clusters, another form of MCS. Specifically, he investigated the effects of including cloud and radiative processes in the stratiform (cirrus) deck. He concluded that radiative heating at the base of the cirrus anvil and cooling at the top is the principal mechanism for including ascent in the upper troposphere. In the decaying stage, this mechanism works to delay the decay of the mesoscale ascent, especially at night. In the upper troposphere in the tropics, where there is already weak stability, small heating results in large vertical velocity. This is similar to the Tripoli and Cotton gravity wave duct. In the lower troposphere, differential radiative heating/cooling between clear air to cloudy air induces weak low level convergence, contributing to the diurnal cycle over tropical waters. During the daytime, solar radiation heats the clear air column so that the temperature differential between the clear and cloudy air is a minimum. At night, greater radiative cooling of the clear sky region creates a temperature gradient between the clear and cloudy air, inducing low level convergence in the cloud region. The differential radiative cooling is important over water but is not as important over land, where differential surface characteristics dominate. Furthermore, Dudhia found that including radiation transfer through the atmosphere increases sensible heat flux into the clear air. The clear air has been cooled by the outgoing radiation, increasing the air-sea temperature gradient. The increased heat flux counteracts the radiative cooling but destabilizes the clear air column. The destabilization leads to increased dynamic and convective activity as in the larger scale simulations. Without radiation, the overall convective activity in the model is decreased, with weaker circulation and smaller, weaker clouds. Most importantly the extent of the cirrus shield is larger with radiation included, which is an important feedback. As the cloud shield expands horizontally the radiative effect grows. These results are consistent with the results of studies at larger scales. Radiative transfer appears to be a critical component in the organization of some circulation systems in the tropics, where large scale forcing is less important.

The radiative cooling was vital to the case Dudhia studied, where there was no large scale forcing to impose large scale vertical velocities. In cases studied by other investigators, the latent heat release in the mid to upper troposphere was the dominant forcing.

Tao, et al [22] used a two-dimensional time dependent non-hydrostatic cloud model to simulate subtropical squall line that occurred during TAMEX. The results are consistent with other studies. The strength of convective circulation is increased and there is greater precipitation when radiative transfer is included. There is also an effect on the could microphysics and the spatial distribution of heating. More ice particles are generated in the anvil when IR transfer, is included, due to cooler temperatures near the top of the anvil and enhanced ascent. The increased ice decomposition in the anvil leads to increased latent heating, further driving the ascent. Falling ice and precipitation particles leads to cooling at lower levels as they melt and evaporate. It results in a redistribution of heat that does not occur when the IR transfer is not included.

d) *Stratus and Stratocumulus*

Lilly [16] first suggested that stratocumulus clouds at the top of the boundary layer are maintained by negative buoyancy generated by radiative cooling at cloud top. The proper distribution of the long wave flux at the top of the Sc layers remains a problem in understanding the behavior and structure of Sc decks. Driedonks and Duynkerek [7] recently reviewed the dynamics of stratocumulus layers and the progress and problems associated with modeling these climatologically important clouds. Strong temperature and liquid water gradients near the top of the cloud layer create difficulty calculating the radiative flux divergence. Observations suggest the interface between cloud top and the air above is very sharp with thickness on the order of a meter, well below the resolution of existing numerical models. Longwave cooling also occurs in a small depth near cloud top where it is an important mechanism for the generation of turbulence in the ABL, at least in the Sc case. There is still some controversy about what happens in the entrainment zone. Entrainment often occurs over depths larger than the depth where the cooling occurs. Deardorff [5, 6] suggests that part of the longwave cooling is located in the entrainment zone, thus cooling the entrainment zone directly without generating any new turbulence. However, Kahn and Businger [13] argue that the cooling is associated only with the cloudy air and all of it generates cooling and contributes to the further generation of turbulence.

Albrecht [1] used a simple model of tradewind boundary layer cumulus and concluded that radiative cooling of the boundary layer affects the amount of boundary layer cumulus, with lesser cloud amounts occurring with decreased radiative cooling. His study shows that tradewind boundary layer cumulus is sensitive to both the sea surface temperature and radiative cooling in the boundary layer.

Heymsfield et al. [12] used a stratocumulus model to study altocumulus. The principle driving mechanism for maintenance of the altocumulus layer was negative buoyancy driven by radiative cooling at cloud top, analogous to the mechanism driving stratocumulus, first suggested by Lilly. The calculations were compared to observations and the results indicate that radiation plays a critical role in dynamically unstable altocumulus clouds, with a lesser effect in stable clouds.

Duynkerke [9] used a one-dimensional model to study the interaction between turbulence and radiation in the stratocumulus layer. An interesting finding is the *decoupling of the* subcloud layer and the cloud layer, showing how the radiation plays a pivotal role in this process. He compares model results to observations from two cases, November 16 and July 1 ("typical" cases from late fall and summer in mid-latitudes). The turbulence in the boundary layer is driven by longwave radiative cooling at cloud top, except very near the surface, where wind shear is important. The IR cooling can be strong enough to promote mixing all of the way to the cloud top (the depth of the boundary layer). In the summer case, with a high sun angle, the shortwave radiation approaches the same magnitude as the longwave radiation for the cloud layer as a whole. The shortwave radiative heating penetrates deeper in the cloud than longwave cooling, destabilizing the cloud. The net effect of the shortwave is to reduce the the magnitude of the buoyancy flux in the cloud. At some point, the buoyancy consumes, rather than produces TKE, suppressing turbulent mixing. The stable layer, because of the heating in the cloud, suppresses mixing from the surface and prevents moisture transport from the surface. Higher cloud base and thinner clouds result. With some buoyancy and shear production, there may still be moisture flux into the sub-cloud layer, which in turn can result in cumulus clouds below the stratus deck.

Duynkerke [10] also used a one-dimensional model to study the formation of radiation fogs. The model includes turbulence closure using K-theory, a vegetation and soil model, longwave radiation approximations, and a cloud droplet model including turbulent transport and gravitational setting of the fog droplets. He compared the model results to observations from a fall night in the Netherlands (16/17 October, 1988) and found that clear air radiative cooling is critical for fog formulation. Radiative cooling as also found important in determining the overall structure of the boundary layer. The model simulation qualitatively agrees with observations but underestimates the heat fluxes. This is most likely due to the model resolution, as pointed out in the discussion of stratocumulus.

e) *Microphysics*

Churchill and Houze [4] used a kinematic cloud model to investigate the interaction of radiation with cloud physics in a tropical squall cluster. Their purpose was to separate large scale dynamics from the cloud physics, radiation and turbulence interactions. They wished to investigate the direct effect of radiation on the cloud physics the role radiation plays in the *destablization of the stratiform cloud* (i.e. cirrus) layer, the role radiation plays in the water budget of the stratiform region, and the relative magnitudes and distributions of the radiation terms and turbulent fluxes of sensible and latent heat in the stratiform region. They found that the radiation had little effect on the destabilization of the storm system, with it being limited to a very shallow region near cloud top. The hydrometer structure of the system was also unaffected, leading to little or no increased precipitation due to radiation forcing. The conclusion is that the radiation forcing is important as a feedback to the dynamics; for fixed airflow it has little effect on the structure or water budget of the stratiform region of the cloud system.

The size of cloud droplets in low level stratus clouds affects the cloud lifetime, with a feedback through the shortwave radiation budget. Increased condensation nuclei results in smaller cloud droplets, which are optically brighter clouds (Twomey et al., [24]). Smaller cloud droplets grow less efficiently than larger droplets, so less drizzle forms, increasing the cloud lifetime (Albrecht, [2]). This is an important question for anthropogenic influences on climate (Wigley, [26]).

Radiation transfer plays an important role in the structure and evolution of the atmosphere on all time and space scales. Besides determining the state of the climate, it affects the microphysical structure of clouds including the total water budget, drives the diurnal cycle, influences circulations from meso-γ to synoptic scale, and contributes to scale interaction processes especially through cirrus cloud top cooling. The review has illustrated examples of all of these processes. An example of how the radiation interacts with clouds to force a circulation is now presented.

4. An illustrative example

Longwave radiation warms the base of a cloud layer and cools the top of the cloud layer; shortwave radiation acts oppositely but with a smaller effect. A simple experiment has been devised to demonstrate these effects and the resulting changes in the dynamics and thermodynamics of the atmosphere. A hydrostatic model (Huang and Raman, 1990) was used incorporating clouds physics, (Rutledge and Hobbs, 1983) and radiation transfer (Harshvardhan, 1987). A circulation was artificially induced in the model through the introduction of a heat source. This artificial heating ceased after 42 minutes into the simulations. The result is an induced vertical velocity field which results in the formation of a cloud. Evolution of the cloud includes latent heat release, radiative transfer, gravity waves and other dynamic mechanisms. Cloud ice forms in the upper atmosphere in the model, due to initializing the model with a thermodynamic profile which is saturated with respect to ice, although not saturated with respect to water. In this situation, cloud ice represents cirrus clouds. Cirrus clouds are very important in the earth's radiation balance, as they effectively absorb and emit longwave radiation, but are semitransparent in the shortwave. The same initial conditions and heating function was run with and without radiative transfer.

Both cases form clouds in the lower troposphere, with the radiatively active case (hereafter case R, the non-radiatively active case will be NR) forming less cloud water, (Figure 1). However, in R more cloud ice forms than in NR (Figure 2) due to the differential heating and cooling of the ice layer due to the longwave radiation (Figure 3). This elevated heat source dominates the circulation induced by the imposed circulation in the lower troposphere. The effect on the circulation is shown in the v-component of the wind (Figure 4, positive is into the plan of the figures). Figure 4a is from R which shows a stronger, more organized circulation compared to NR in Figure 4b, consistent with the elevated heat source. For case NR, with no elevated heat source, the only circulation is what remains from the imposed forcing at the beginning of the simulation. Gravity waves propagating away from the area of the imposed forcing tend to destroy the organized circulation. However, the vertical velocities associated with these gravity waves produce larger cloud water in the lower troposphere. This is evident by examining the cloud water amounts in Figure 1 (a,b). In the radiation case, very small amounts of cloud water (note that the maximum amount is .15e-5(g/g)) form near the center of the initially imposed heat source. The initial conditions included wind shear, which is why the cloud water is not symmetric. Smaller amounts of cloud water result because the vertical velocity in R is elevated and more organized than in NR. In NR, the vertical velocity maximum are associated with the propagating gravity waves and correspond directly with the maximum cloud water amounts seen in Figure 1b.

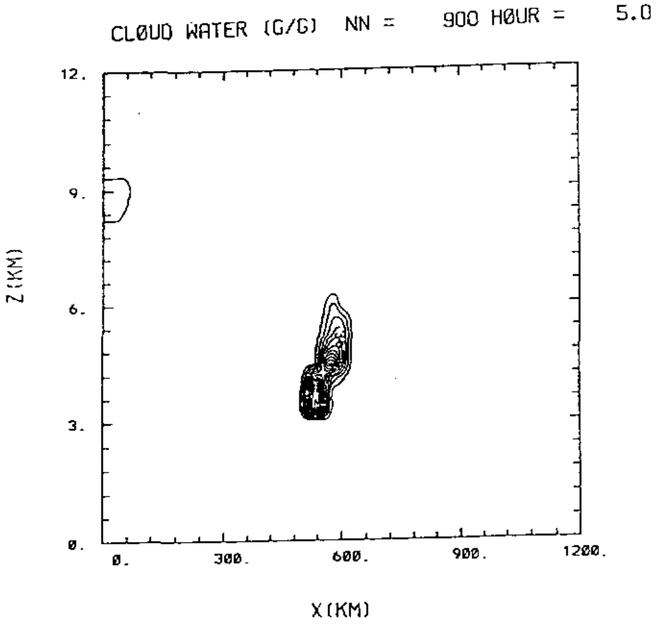

Figure 1a. Cloud Water (g/g) formed after 5 hours of simulation time for the case described in the text. This is the case that includes radiation.

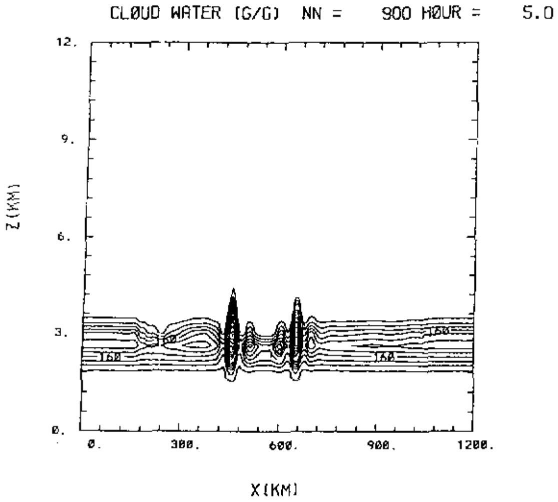

Figure 1b. Same as Figure 1a, but for the case without radiation.

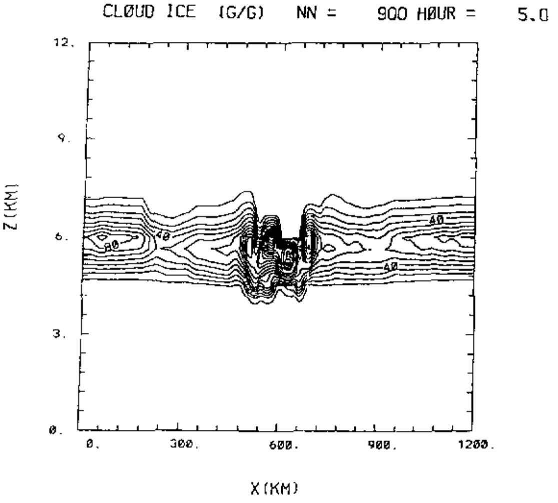

Figure 2a. Cloud Ice (g/g) formed 5 hours into the simulation described in the text. This is for the case that includes radiation.

5. Summary

The effects of radiation transfer on atmospheric circulation can be an important forcing for circulation systems on all time and space scales. This is especially true when large scale dynamic forcing of circulation systems is weak, and the radiation term becomes more important. It appears that radiation transfer forces

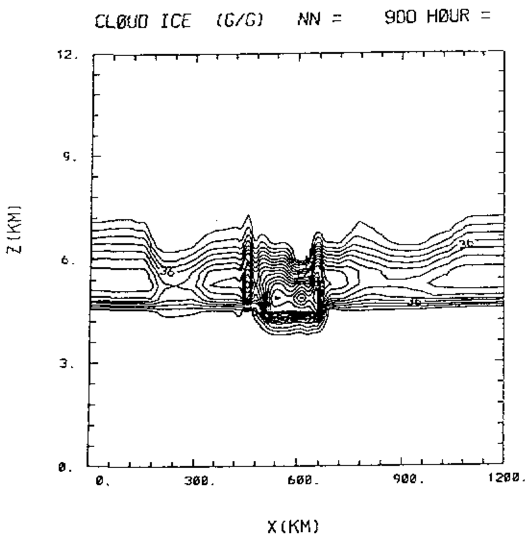

Figure 2b. Same as Figure 2a, but for the case without radiation.

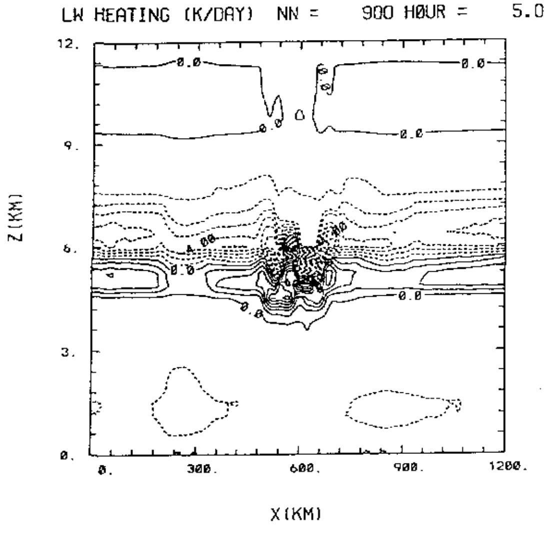

Figure 3. The heating rate (K/day) for the simulation described in the text. The heating rate for the case without radiation is 0.

circulations primarily through interaction with cirrus clouds, where the differential heating of the cirrus layer acts as an elevated heat source to drive and organize mesoscale ascent. In this paper, we have tried to summarize situations where the

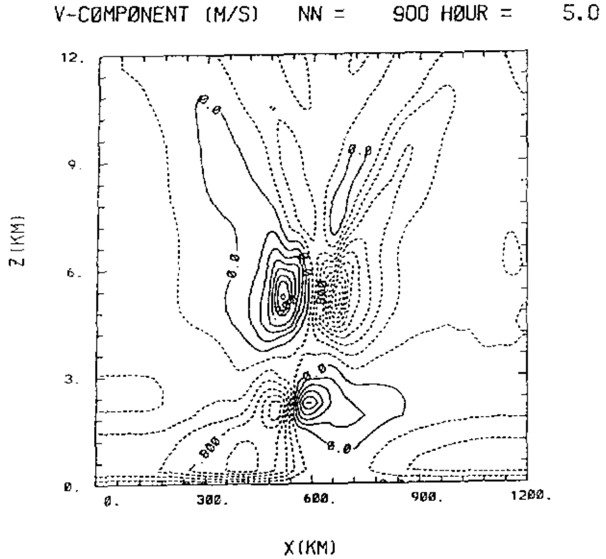

Figure 4a. The v-component of the velocity (m/s) that formed in response to the imposed heating together with the cloud-radiative feedback.

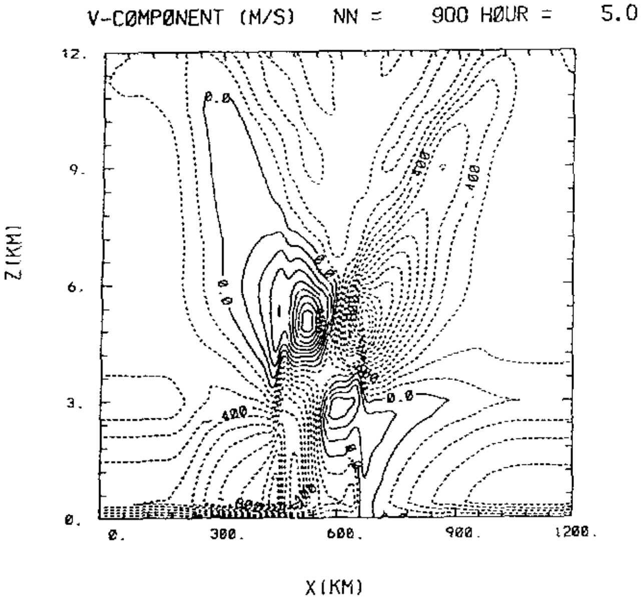

Figure 4b. The v-component of the velocity (m/s) that formed in response to the imposed heating without the cloud-radiative feedback.

radiative transfer is as important as a forcing function for atmospheric circulation.

In addition, we have provided a simple illustrative example from our own modeling studies which show how the radiative forcing alters the circulation system.

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