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The Role of Radiative Transfer in Maintaining the Indian Summer Monsoon Circulation

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Abstract—The radiative-convective feedback and land-sea thermal forcing play significant roles in maintenance of the summer monsoon circulation over the Indian sub-continent. In this study, the role of radiative transfer in maintaining the monsoon circulation is examined with numerical sensitivity experiments. For this purpose, a sixteen layer primitive equation limited area model is used to perform numerical simulations with and without atmospheric radiative transfer processes parameterized in the model. The initial values and boundary conditions for the numerical integrations of the model are derived from operational analyses of the ECMWF, UK. The results show that the radiative transfer is essential in maintaining the intensity of the low level Somali Jet as well as the upper level Tropical Easterly Jet (TEJ) over the Indian sub-continent and adjoining seas. The meridional circulation over the region is also well simulated. As a result, enough moisture transports from the warm equatorial region to simulate more realistic orographic precipitation in the windward side of the mountains along the West coast of India. Without radiative transfer processes in the model atmosphere the simulated monsoon circulation weakens, moisture transport decreases and the precipitation lessens.

Key words: Atmospheric radiative transfer, circulation, Indian summer monsoon, thermal forcing.

1. Introduction

Atmospheric radiative transfer is an important thermodynamic forcing for the Indian summer monsoon which is a component of a larger scale circulation system. The principal components of this system are the Hadley cell and the Walker circulation. The Hadley cell is a thermally direct circulation which transports heat towards the poles. In the northern hemispheric summer, the ascending branch of the Hadley cell moves northward, driven by heating of the land masses. This ascending branch of the Hadley cell is often merged with the Intertropical Convergence Zone (ITCZ). At the surface, the ITCZ is marked by convergence of northerly surface winds from the north and southerly surface winds from the south.

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The surface convergence at the ITCZ is a driving mechanism for the summer monsoon circulation. The northward drift of the Hadley cell in the summer part of the ITCZ is the heating of the Asiatic land mass and deep convection over the warm pool of water in the western tropical Pacific Ocean, located at about 150 E and 10 N. The latent heating in the deep convection drives another direct circulation, known as the Walker circulation. The upper branch of the Walker circulation over south Asia is easterly winds created by the deep convection in the western tropical Pacific and over south Asia. Convective activity over the Indian peninsula interacts with the Walker circulation, creating a jet-like structure over the Bay of Bengal, the southern part of India and the Arabian Sea known as Tropical Easterly Jet (TEJ). Secondary circulations associated with the Indian convection also help to maintain low-level temperature gradients (SAHA and CHANG, 1983) which are essential to the development of monsoon depression, the maintenance of the monsoon trough, and in general the circulation and hydrological cycle of the region.

The sensitivity of the atmospheric thermal structure to the radiation parameterization shows that a better representation of radiative transfer (RAMANATHAN *et al.*, 1983) leads to stronger climatic scale circulation. A cloud more nearly approximates a black body radiator than does clear air. The presence of a cloud produces longwave radiative flux divergence at the cloud boundaries, resulting in cooling at the cloud top and warming at the cloud base. Effectively, this interaction of radiation with deep convective clouds in the equatorial tropics leads to warming in the upper tropical troposphere and cooling in the lower stratosphere. These deep convective clouds extend through the depth of the troposphere. The heating in the upper troposphere is due to latent heating and radiative warming of the cirrus anvils. Radiative flux divergence at the tops of these clouds is responsible for the lower stratospheric cooling. 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 deep tropics.

SLINGO and SLINGO (1988) studied the interaction of cloud radiation forcing and dynamics. Their results are consistent with those of RAMANATHAN *et al.* (1983). With improved parameterization of radiative transfer processes, more clouds are predicted leading to enhanced latent heating and stronger circulations. There is increased precipitation, especially at low latitudes. The stronger circulations include an intense Hadley circulation and a 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.

SUD and MOLOD (1988) carried out a number of sensitivity experiments on simulation of July climatology with Goddard Laboratory for Atmospheres General Circulation Model (GLA-GCM). Inclusion of convective cloud-radiation interaction leads to a better radiation balance at the earth's surface and resulted in a realistic surface hydrological cycle over desert regions. A close interaction of cloud-radiation, PBL fluxes and surface processes are also demonstrated as a physical basis for realistic simulation with a GCM beyond 5 days integration.

KRISHNAMURTI *et al.* (1991) used a global spectral model to forecast the evolution and movement 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. Radiative cooling of shallow clouds preconditions the environment by maintaining a minimum in equivalent potential temperature near the 700 hPa level, ensuring a supply of conditionally unstable low-level air as inflow to the storm. They compared two radiation parameterization schemes, a resolved spectral band model and a simple cooling to space emissivity model. The results are consistent with results from climate models, circulation increased with the improved radiation parameterization (the band model). Precipitation rates were 40% greater than those simulated with the emissivity model and inflow into the storm circulation has increased with the band model as a consequence to 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 parameterization scheme. The radiative 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.

Tests with more realistic radiation parameterization schemes in the European Center for Medium-Range Weather Forecasts (SLINGO *et al.*, 1988; MORCRETTE, 1990) also show improvements, especially in the upper tropical tropospheric temperature distribution. They also illustrate 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 enhancement of the hydrological cycle and increase in the strength of circulation. Differential heating between the tropics (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 wave numbers. In general, with more realistic radiation parameterization, the model is more active. Also, improvement in radiative transfer processes through the atmosphere leads to a more accurate prediction of temperature over land and large-scale circulation forced by the land-sea interface.

The cloud-radiative feedback maintains the potential instability of the tropical atmosphere. In general, radiative cooling at cloud top and heating below cloud base destabilizes the atmosphere. Without this effect, latent heating produces excessive warming in the middle and upper tropospheres. With relatively cooler temperatures in the lower troposphere, the entire atmospheric column becomes stable. Clouds and convectively driven circulation would diminish as the atmosphere stabilizes, and the entire monsoon circulation would shut down.

The effects of atmospheric radiative transfer on the Indian monsoon are investigated in this study. Radiative transfer increases circulation by maintaining both potential instability and horizontal temperature gradients. The potential instability is maintained by radiative cooling through the first few kilometers of the atmosphere. The horizontal temperature gradients are maintained by horizontal advection and by secondary circulations associated with convective activity. The increased circulation enhances the precipitation processes, leading to greater rainfall amounts in the monsoon region. At the same time, increased latent heating associated with the precipitation processes increases circulation. The interactive feedback of radiative transfer with clouds, precipitation processes and enhanced circulation in the monsoon region are presented in this paper.

2. *Model Description*

The model is a 16-layer version of a primitive equation model developed jointly by the Naval Research Laboratory (NRL) and North Carolina State University (NCSU). A 10-layer version of the NRL/NCSU model has been described elsewhere (MADALA *et al.*, 1987). The additional layers in the 16-layer version are to increase resolution in the boundary layer, where one and half order TKE-ε closure (MELLOR and YAMADA, 1982) is used for the turbulence parameterization. The implementation of the TKE-ε scheme has been described by HOLT and RAMAN (1988) and HOLT *et al.* (1990). The model employs the cumulus parameterization scheme of KUO (1974) as modified by ANTHES (1977). A partial saturation scheme is used for grid-scale condensation and precipitation.

The radiative transfer parameterization scheme of HARSHVARDHAN *et al.* (1987) has been included for the numerical experiments in this study. The scheme calculates the transfer of both longwave and shortwave radiation. Broadband approximations for absorption and transmission of shortwave radiation depend on fractional cloudiness and water vapor distribution. Shortwave transmission also depends on the ozone (O_3) distribution, but since the meteorological model does not calculate O_3, the distribution was specified. Broadband approximations also are used to represent longwave radiative transfer. Again, fractional cloudiness, water vapor and O_3 affect the absorption and emission of longwave radiation. Flux divergence in the various bands are used to estimate heating rates for each level in the model. The heating rates are the thermodynamic forcings that maintain circulation in the atmosphere in general, and in particular in the monsoon region of south Asia.

3. Experiment Design

An experiment has been designed to determine the effects of atmospheric radiative transfer in maintaining circulation as a forecast is extended to time periods normally regarded as medium range weather forecasting. The initial conditions and lateral boundary conditions are taken from the operational analyses of the European Center for Medium-Range Weather Forecasting (ECMWF) from July 1988. The forecasts are started at 1200 UTC on July 16 and the period of the forecasts is 10 days. The forecast domain is from 0 to 180 E and from 30 S to 60 N. Horizontal grid spacing is 1.5 by 1.5 degrees (i.e., 121 by 61 grid points). The boundary conditions are obtained from the ECMWF analysis for every 24 hours, at 1200 UTC on each subsequent day of the integration of the model. For this purpose, tendencies are estimated at boundaries from analyses and kept constant during the 24-hour integration. The model simulations are produced with radiative transfer and without radiative transfer parameterization in the model. Radiation is included in the surface energy budget in the run without radiative transfer, including the effects of clouds on solar insolation. However, no longwave radiative flux divergence through the atmosphere is included and no shortwave effects are included due to water vapor or ozone absorption. Results are compared by examining the mean features of the hydrologic cycle and the circulation fields. The effects on the circulation characteristics of the summer monsoon over India are also examined.

4. Results and Discussion

The thermodynamic feedback effects of atmospheric radiative transfer affect the Indian monsoon circulation in a variety of ways: 1) the overall hydrology and precipitation in the region, 2) the structure and position of the Somali Jet (SJ), which is located off the east coast of Africa and the induced circulation around the Indian sub-continent, and 3) the tropical easterly jet (TEJ) located above southern India which is an enhancement of the easterly flow that is part of the large-scale Walker circulation.

a) Hydrology

The observed rainfall rate estimated from outgoing longwave radiation (OLR) data from Indian Geo-stationary satellite (INSAT) valid for day 10 of the forecast (corresponding to July 26, 1988) is shown in Figure 1. Here, the rainfall rate is estimated from the OLR by using an empirical formulation as given by PURI and MILLER (1990). The OLR estimate is an integrated value for one day, from the eight available satellite observations. The satellite derived precipitation field is typical of the precipitation distribution during the Indian summer monsoon. Heavy precipitation occurs along the west coast of India, with rainfall also in northern India and in the northeast part of India near the Bangladesh border. The west coast rainfall is principally driven by the orography of the region, where low-level westerly flow is forced up the west side of the western Ghats mountain range. Latent heat released by monsoon rainfall generates its own circulation. The summer monsoon is characterized by a heat low that forms in northwest India and adjoining Pakistan. Most of the precipitation in that region and across northern India results from storm centers that track along the monsoon trough. The monsoon trough extends from the heat low southeastward to the east coast of India just over the head of the Bay of Bengal. The trough is a weak baroclinic zone maintained by the northerly transport of relatively cool air, opposing the southerly transport of warm air off the hot land mass.

In Figure 2, the convective precipitation forecasts at day 10 for both the radiative transfer and the nonradiative transfer cases are shown. Figure 2a, the radiative case shows generally greater amounts in all areas where precipitation occurs as well as the greater areal extent. This is especially true over the Indian

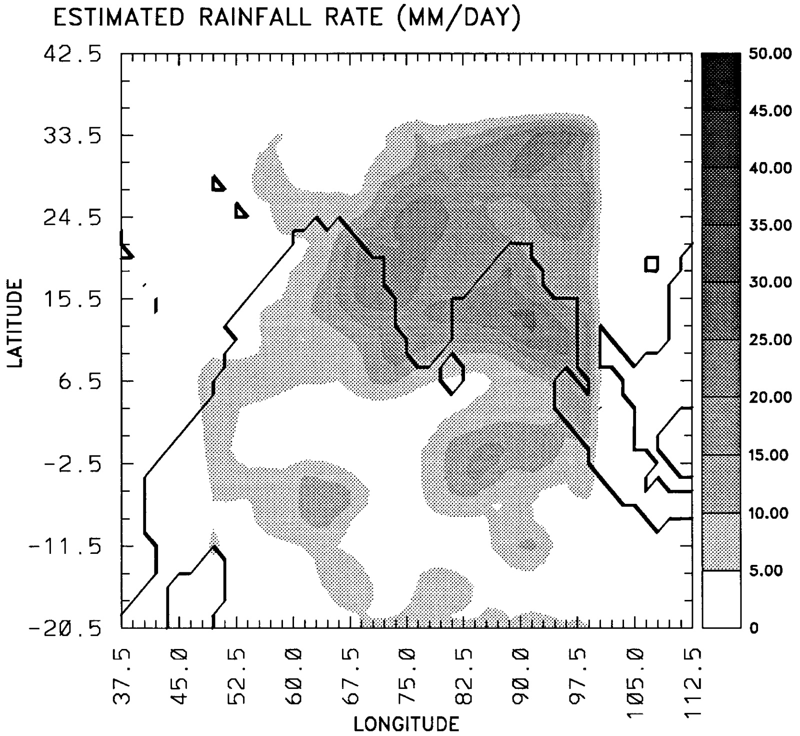
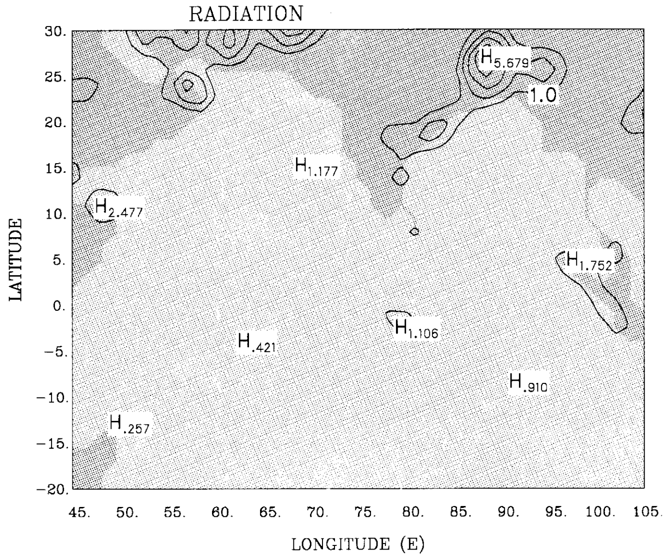


Figure 1
Rainfall rate derived from OLR data for 26 July 1988. Units are in mm day^{-1}.

(a) CONVECTIVE PRECIPITATION DAY 10



(b) CONVECTIVE PRECIPITATION DAY 10

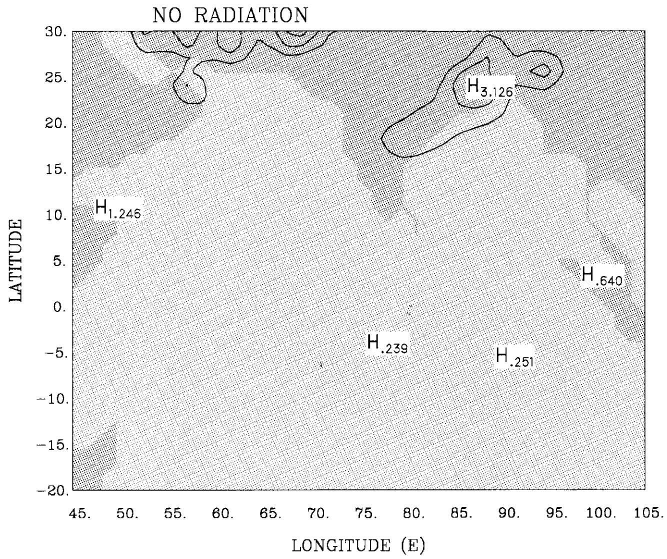


Figure 2
Convective 24-hr accumulated precipitation in cm on day 10 (a) with radiation and (b) without radiation.

sub-continent. In the radiative case, the precipitation extends over the entire peninsula of India, there is evidence of the precipitation in the monsoon trough region and along the east coast of India through Bangladesh and into Indo-China. In comparison to the radiative case, the nonradiative case shows less rain everywhere, in particular, over the Indian Peninsula and considerably less rain in the monsoon trough region.

Precipitation estimates from the OLR technique are coarsely resolved, however there are maxima over the west coast of India, and in the northern part of the Bay of Bengal. In the simulated precipitation shown in Figure 2a, there is a maximum at the northern end of the Bay of Bengal, with precipitation extending over most of the India sub-continent. The exact positions of the maxima do not agree well with the OLR estimates in Figure 1, however the general pattern over India and in the monsoon trough region does agree reasonably well.

The time sequence of a box-budget of precipitation is shown in Figure 3. The budgets are for a box that encompasses the Indian monsoon region. The limits of the box are (45 E, 105 E) and (5 N, 30 N). The results from the simulation with radiative transfer are illustrated in Figure 3a; the results without radiative transfer are shown in Figure 3b. The abscissa is time. The curves shown are for the convective precipitation over land (CL), convective precipitation over water (CW), and stable precipitation over land (SL). Stable precipitation over water is zero for both cases, except in the last 12 hours, where small amounts appear. There are several differences between the two cases. There are substantially larger CL (about 60% greater) precipitation amounts in the radiation case. The CL increases early in the forecast and then exhibits a diurnal cycle. The diurnal cycle is about 10 mm with a mean value of CL of about 240 mm. The peak of the diurnal cycle occurs at 1200 UTC, which is late afternoon in this region. The peak is due to the increased solar heating of water vapor in the lower atmosphere, creating more local instability and convective activity during late afternoon hours. The overall increase in CL with radiation is due to the role that radiative transfer plays in maintaining the circulation, through destabilizing the atmosphere on a ‘non-local’ scale. The CW decreases rapidly in both cases through the first three days of the forecasts. This rapid decrease of the CW is an indication of the model’s spin-up problem in the first few days of the integration. The main emphasis of this investigation is circulation and precipitation processes that are affected by atmospheric radiative transfer. From the start of the integration the model spins up to near balance between the circulation in the model and the lateral boundary forcing. The numerical scheme filters the fastest three gravity modes, accelerating the spin-up and contributing to the near balanced state. After about three days, the leveling of the CW indicates that the spin-up cycle of the forecast is complete. The SL for radiation case (R) is also about 60% greater than the NR case. There is also a small diurnal cycle 12 hours out of phase with the CL for the R case. During the night, radiative cooling of lower atmosphere water vapor and cloud tops continues, while

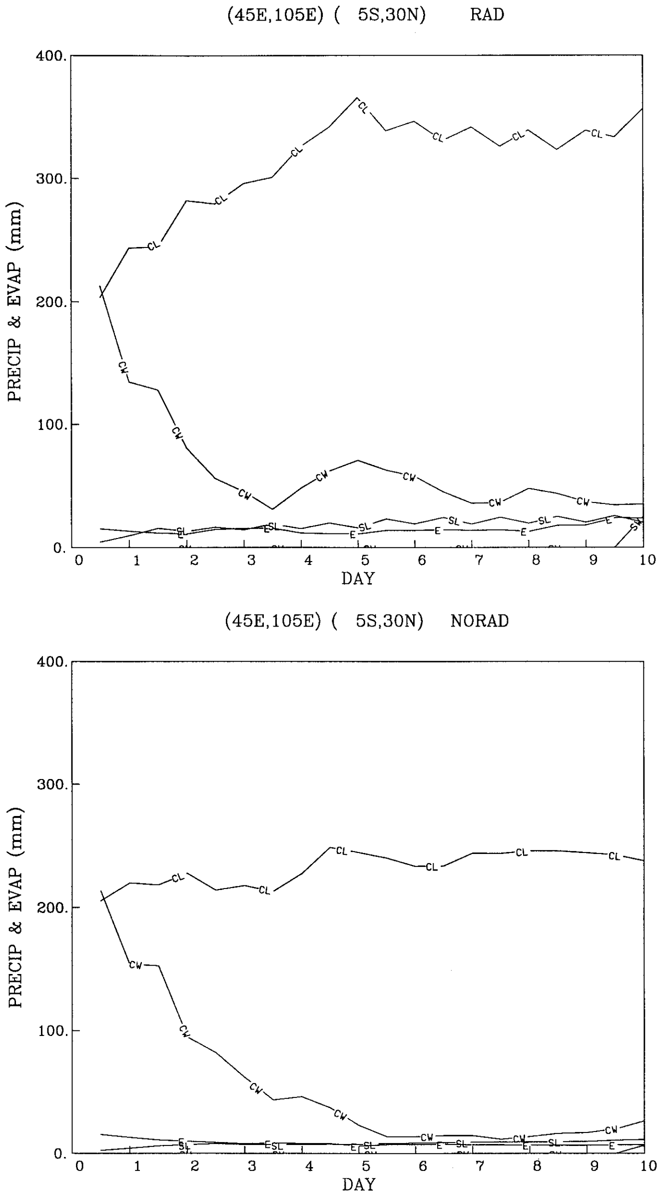


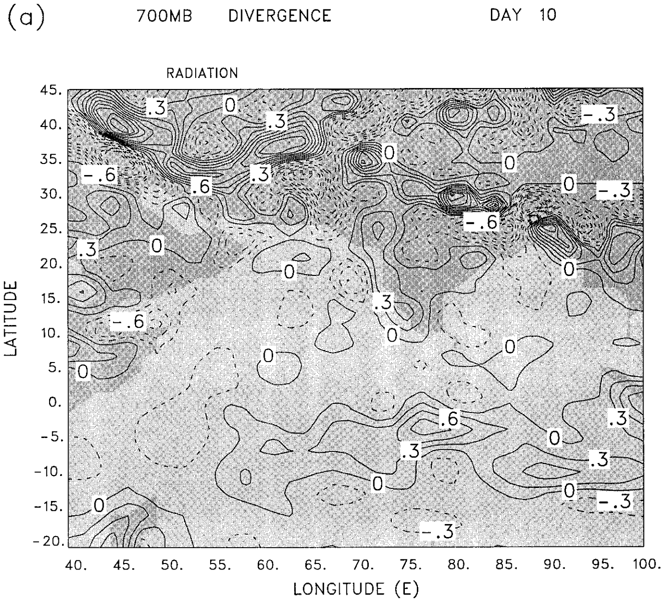
Figure 3
Convective precipitation in mm over land (CL) and over water (CW), stable precipitation over land (SL) and over water (SW) and evaporation (E). The values are area averages for the domain bounded by 45–105 E and 5 S–30 N. (a) For the radiative transfer case and (b) for nonradiative transfer case.

there is no compensating solar heating. The cooling brings the atmosphere closer to saturation, resulting in the maximum of SL at night.

b) Somali Jet

The horizontal wind components at 900 hPa after 10 days of simulation are shown in Figure 4. The velocity vectors are overlaid on the contours of wind speed. Figures 4a and b are for the radiative transfer case, Figures 4c and d are for the nonradiative transfer case. The effect of radiative transfer processes on all the fields is striking. The wind speed maximum along the east coast of Africa is the Somali Jet. The Somali Jet transports water vapor and relatively cold air from the equatorial ocean into the monsoon region. The water vapor feeds the precipitation systems in the region, and the cold air converges with the heated air from the land masses, maintaining temperature gradients in the region. In the radiative transfer case, the Somali Jet is much stronger with its center farther northward. The wind vectors indicate that much of the increased wind speed is due to the southerly wind component. It is this northward extension that vitally contributes to the maintenance of the monsoon circulation. The meridional wind component (v) is 50% stronger when radiative transfer processes are included, with the jet-like structure extending into the northern part of the Arabian Sea and into the western sector of India and Pakistan. The maximum zonal component is considerably farther north, near the northern end of the Arabian Sea approaching Saudi Arabia. Without radiative transfer, the much weaker v component and equatorial displacement of the u component indicate a more zonal character of the flow, illustrating the loss of an intense Hadley circulation. A similar situation is seen by examining the velocity fields over the Bay of Bengal. The same effect is apparent, although not as dramatic. There is more meridional transport with radiative transfer processes.

The larger meridional transports are important feedback of the cloud-radiation interaction into the monsoon circulation. Without the meridional transport, horizontal temperature gradients are not maintained and the circulation ebbs. SAHA and CHANG (1983) have shown through observations that the maintenance of baroclinicity over both the Arabian Sea and the Bay of Bengal is important for the maintenance of the monsoon trough and the subsequent development of monsoon depressions. They suggest that the baroclinicity over both water bodies results from secondary circulations associated with the primary monsoon circulation. In the radiative transfer case, there is an area of convergence at 700 hPa over the Arabian Sea (Fig. 4a), with weaker convergence over the northern Bay of Bengal. The maximum convergence region is in northeastern India. An area of organized divergence exists along the western Ghats, and the convergence extends deep into central India from the maximum in the northeast. In contrast, there is less convergence over the Arabian Sea without radiative transfer included (Fig. 4b). The convergence area over the Bay of Bengal has a secondary maximum south over the


(a) 700MB DIVERGENCE DAY 10

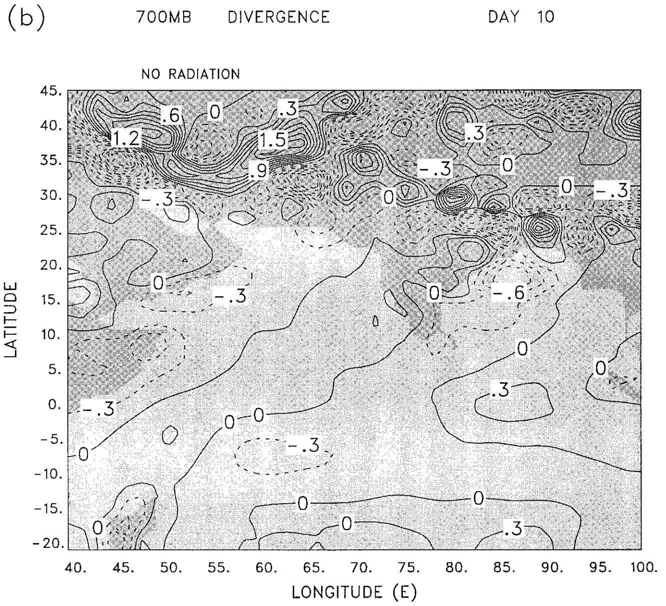

(b) 700MB DIVERGENCE DAY 10

Figure 4
Divergence at 700 hPa on day 10. Units are 10–5 s^{-1}. Negative contours, which imply convergence are dashed. (a) Divergence with radiative transfer, and (b) divergence without radiative transfer.

open water, and the divergence over the western Ghats is weaker and less well organized. The convergence/divergence pattern over the Indian peninsula is one of the primary features of the monsoon circulation: the convergence area over the Arabian Sea and Bay of Bengal results from the induced convection over the Indian land mass. In general, by inference from the divergence, there is more convection and more intense circulation when radiative transfer is included, with a more realistic simulation of monsoon features.

The wind speeds and velocity vectors shown in Figures 5(a,b,c,d) for the cases with and without radiative transfer emphasize the strength of the Somali Jet, the cyclonic curvature along the east coast of India, and in general more energetic flow and greater meridional transport when radiative processes are included.

At the west coast of India, the wind speeds are much greater when radiative transfer is included in the model. These stronger winds result from the stronger Somali Jet and maintain the circulation in the region. Stronger onshore winds, laden with moisture evaporated from the equatorial ocean, maintain the orographic precipitation system over the western Ghats. The latent heating over the Indian peninsula, resulting from the orographic precipitation system, is an effective heat source. The circulation that results from this heating creates easterly winds in the upper troposphere over the west coast of India and the eastern portion of the Arabian Sea. These easterly winds amplify the easterly winds due to the Walker circulation, resulting in the Tropical Easterly Jet. The jet is present in both cases, although the structure is somewhat different. The structure of the jet and the differences are discussed in the subsection below.

Wind speeds are much greater in the northern portion of the Bay of Bengal when radiative transfer is included. The increased wind speeds are also due largely to an increased meridional component. There is greater cyclonic curvature along the east coast of India, with the wind speeds decreasing to a minimum over northeast India, in the vicinity of the monsoon trough. It is clear that radiative transfer contributes to the baroclinic instability that maintains the monsoon trough, a necessary phenomenon for further development of monsoon depressions.

From the low-level horizontal wind field, the role of radiative transfer in the maintenance of several smaller circulation systems that synergistically interact to maintain the monsoon circulation is evident. The Somali Jet transports water vapor and cooler air into the monsoon region and causes increased upslope winds over the western Ghats, maintaining the precipitation processes over the Indian peninsula.

The meridional circulation and thermal structure, sensitive to radiative forcing in the troposphere, are illustrated in Figure 6, which are y-z cross sections at 52.5 E. The cross sections show the meridional (v) velocity component and the equivalent potential temperature (θ_e). The core of the Somali jet is farther to the north and stronger with radiative transfer, consistent with the horizontal winds shown earlier. The stronger winds are also trapped lower in the boundary layer when radiative transfer is not included, where the southerly winds spread throughout much of the troposphere. There is also strong return flow (northerly winds) in the northern part of the cross section through the middle of the troposphere with radiative transfer. The weak return flow in the case without radiative transfer is confined to a narrow region in the lower stratosphere. The θ_e structure also explains the differences in the

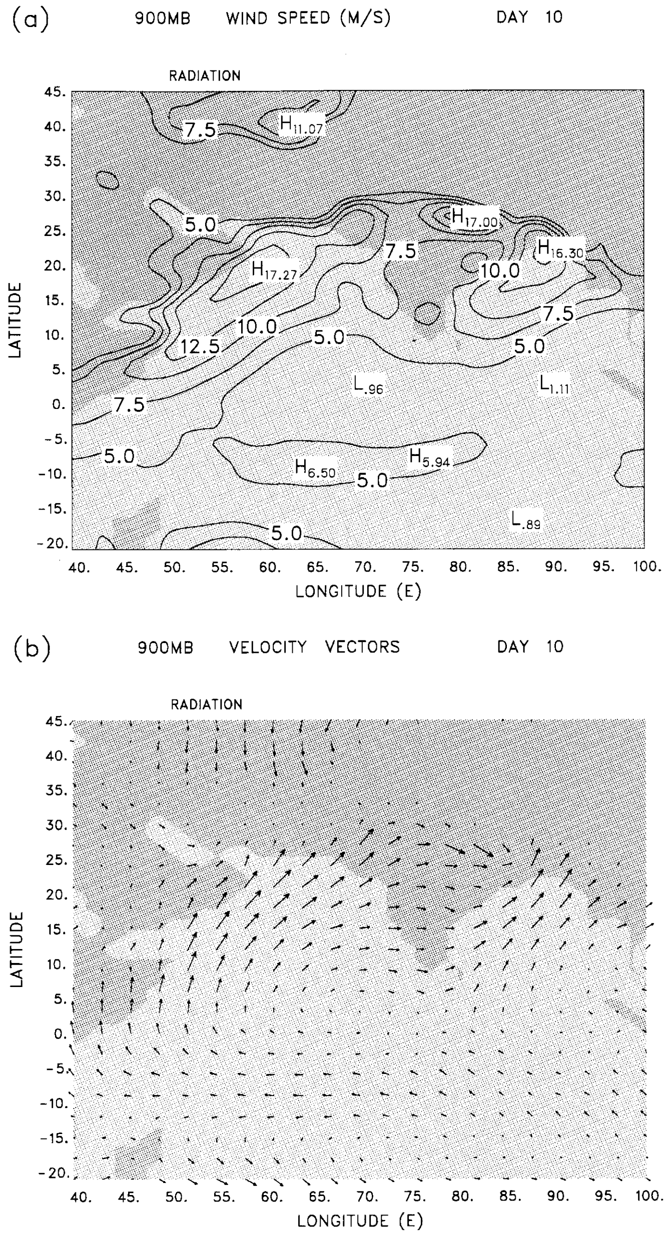
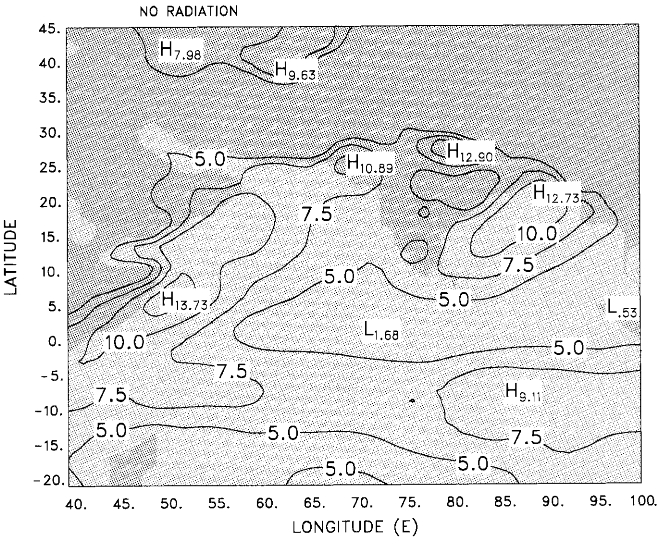


Figure 5 (a) and (b)

(c) 900MB WIND SPEED (M/S) DAY 10



(d) 900MB VELOCITY VECTORS DAY 10

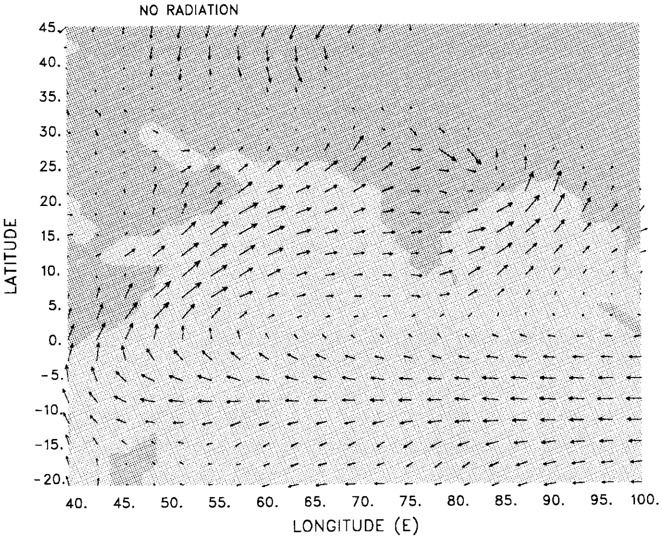
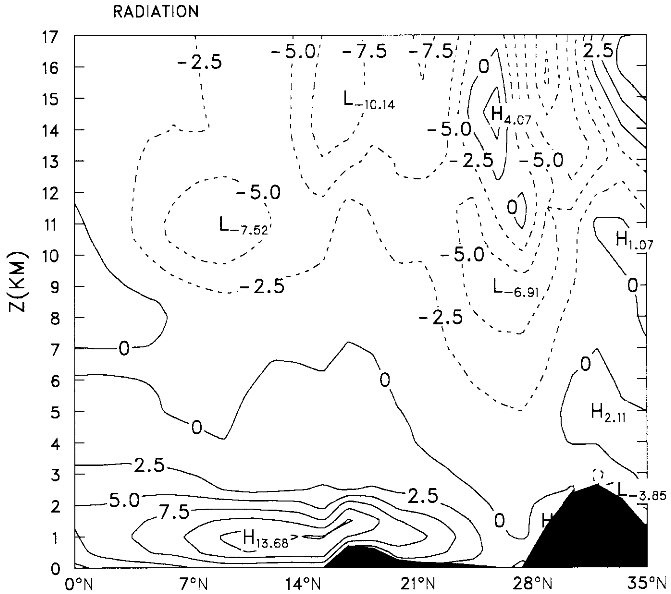


Figure 5 (c) and (d)

Wind speed (m/s) and velocity vectors at 900 hPa on day 10. (a) Wind speed with radiative transfer. (b) Velocity vectors with radiative transfer. (c) Wind speed without radiative transfer and (d) velocity vectors without radiative transfer.

(a) V-COMPONENT DAY 10



(b) THETA-e (K) DAY 10

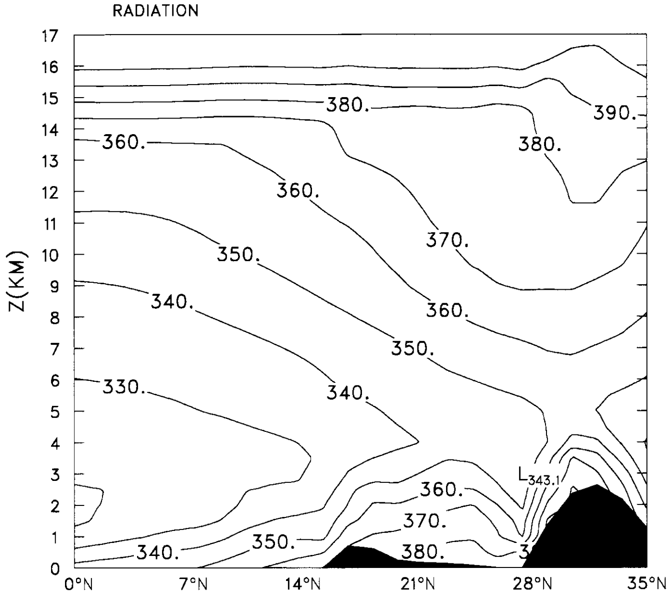
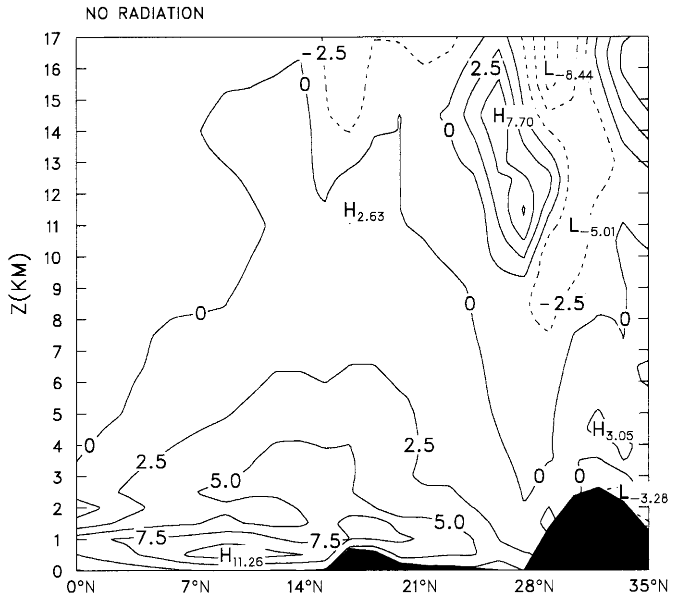
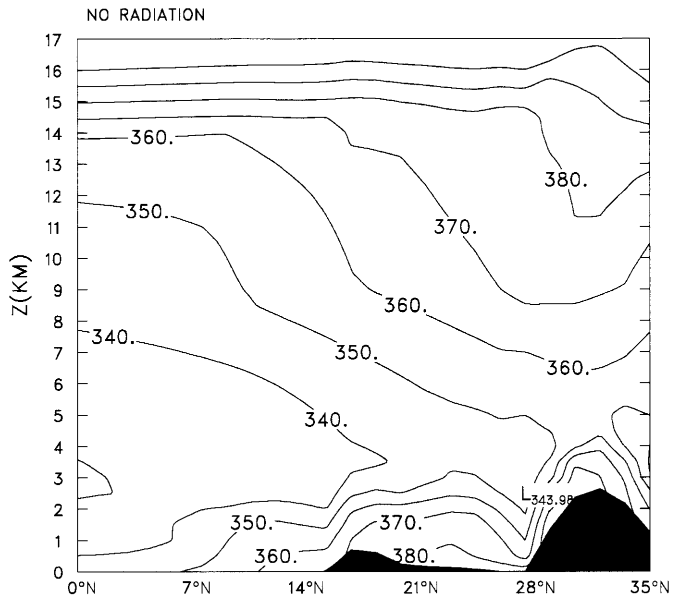


Figure 6 (a) and (b)



(c) V-COMPONENT DAY 10



(d) THETA-e (K) DAY 10

Figure 6 (c) and (d)

Zonal cross section at longitude 52.5 E on day 10. (a) Meridional component of the wind (m/s) with radiative transfer and (b) θ-e (K) with radiative transfer, (c) as in (a) without radiative transfer and (d) as in (b) without radiative transfer.

low-level Somali jet structure. Relatively colder air from the equator penetrates farther to the north when radiation is included. The colder air contrasts more strongly with the warmer air over the land mass to the north, creating a large thermal circulation similar to a sea-breeze. The colder air results from two processes: 1) radiative cooling of the lower troposphere, and 2) increased evaporation as the radiative transfer maintains a strong circulation. This is an important positive feedback mechanism for convection and intensification of monsoon circulation. This circulation is driven by the temperature differences, but the circulation enhances the temperature differences by increasing the evaporation.

c) Tropical Easterly Jet

The upper level easterly jet over the southern portion of India is another semi-permanent feature of the large-scale flow associated with the summer monsoon. This feature is part of the Walker cell that originates in the convection over the warm pool of water in the western Pacific at about 150 E. Heating over the southern part of India amplifies the easterly flow, resulting in a jet streak over that area.

The 200 hPa *u* velocity at day 10 of the model integration with radiative transfer processes included and without atmospheric radiative processes is shown in Figures 7a and b respectively. The effect of greater latent heating over the Indian sub-continent in the case with radiation is evident in a strong easterly jet-like structure over southern India. Air is forced to ascend by the convection and latent heating over the land, creating a secondary circulation. The easterly flow in the upper troposphere is accelerated on the west side of India and decelerated on the east side. These secondary circulations also contribute to the maintenance of low-level temperature gradients (SAHA and CHANG, 1983) necessary for the development of precipitation systems along the monsoon trough. The core of the jet is maintained over the Indian peninsula with radiative transfer included. Without radiative transfer, the maximum wind speed occurs at about 10 N and 65 E, over the Arabian Sea. In general, wind speeds are greater south of 10 N than in the case with radiative transfer. This results from less convection over the Indian peninsula, and in the monsoon region in general. As the convection over the Indian peninsula lessens, the jet maximum propagates westward as a gravity wave. By contrast, the radiative transfer maintains the convection and a standing wave is maintained over India, centered at 13 N and 77 E. The greater wind speeds south of 10 N in the no radiative transfer result from the lack of meridional transport. The more active convection in the monsoon region with radiative transport drives meridional circulation that does not exist without radiative transfer. Without a meridional component, the easterly component of the upper branch of the Walker circulation remains more zonal.

Composite cross sections at 72 E at day 10 of the model simulations are shown for both cases in Figure 8. The *u* component of the wind and θ_e is shown in the cross section. The structure of the tropical easterly jet is again more evident in the

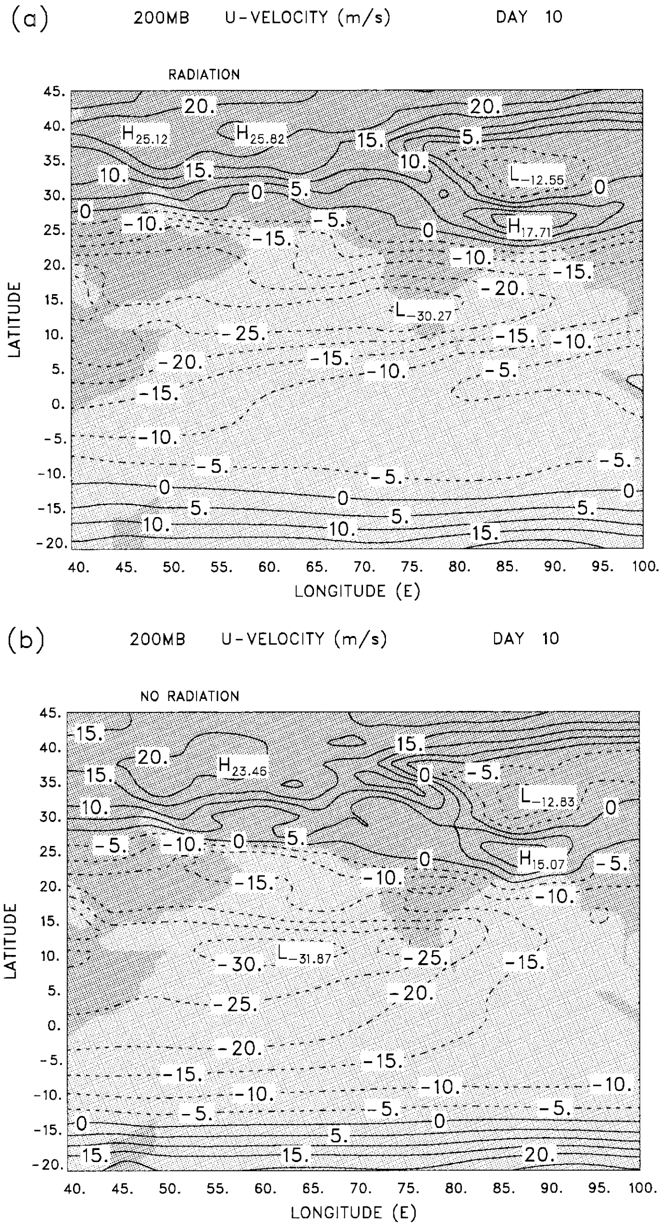
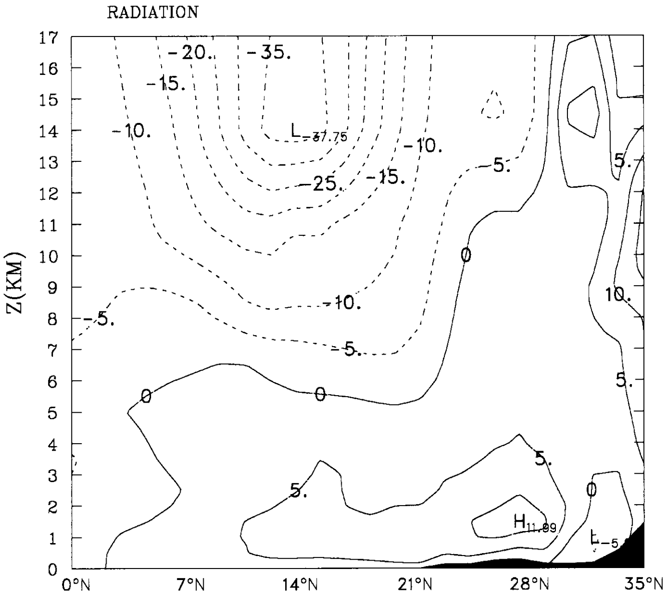
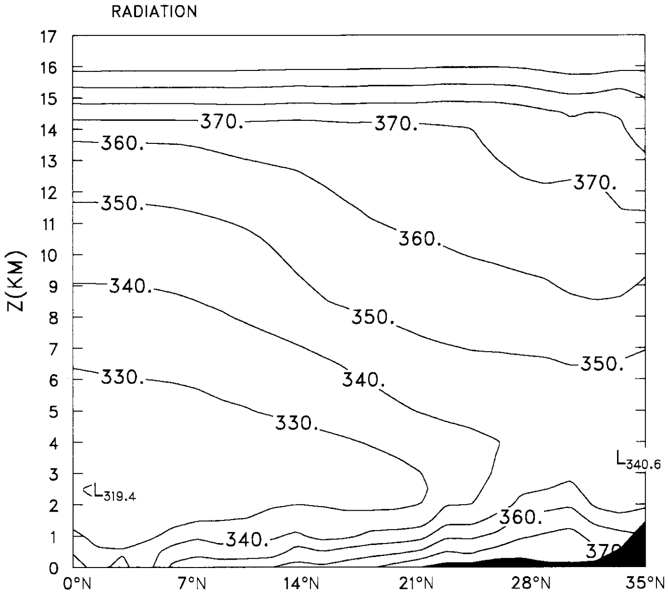


Figure 7
Zonal wind component (m/s) at 200 hPa on day 10 (a) with radiative transfer and (b) without.



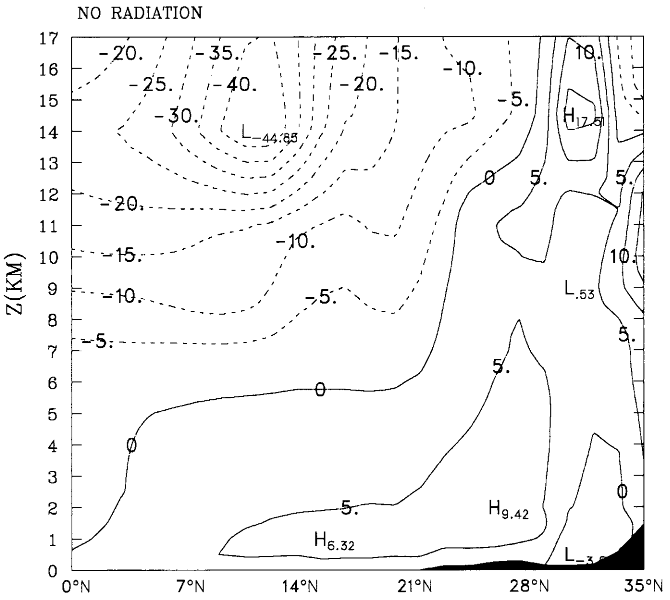
(a) U-COMPONENT DAY 10



(b) THETA-e (K) DAY 10

Figure 8 (a) and (b)

(c) U-COMPONENT DAY 10



(d) THETA-e (K) DAY 10

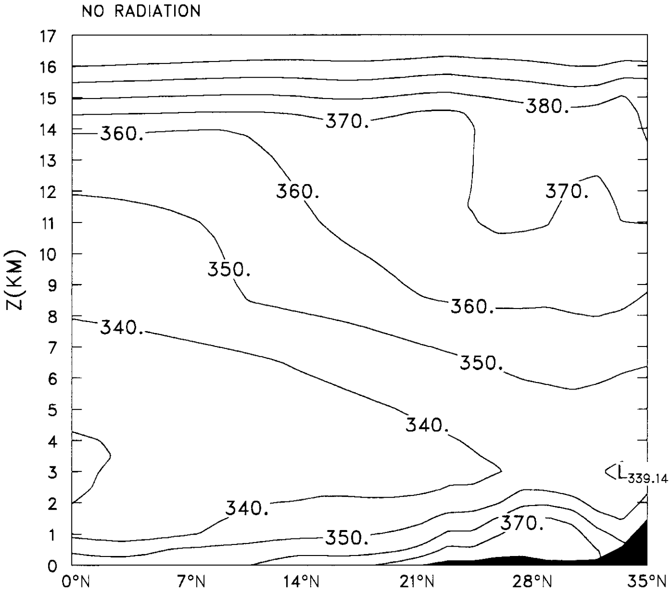


Figure 8 (c) and (d)

Zonal cross section at longitude 72 E on day 10. (a) Zonal component of wind (m/s) with radiative transfer, (b) θ-e with radiative transfer, (c) as in (a) without radiative transfer and (d) as in (b) without radiative transfer.

u component when radiative transfer processes are included. Speeds are greater at the core of the jet and the cyclonic shear south of the jet is also greater. Wind speeds are also faster at low levels, though they are from the west. The westerly winds are upslope, maintaining the orographic precipitation. We again see the important feedbacks of the complex circulation associated with the monsoon. The cooling to the south drives the meridional circulation, which transports moisture and momentum into the monsoon region, and at the same time maintains a temperature gradient between the relatively cooler waters and the hot land mass.

5. Summary and Conclusion

Atmospheric radiative transfer maintains the circulation in the Indian monsoon region through important feedback processes. The lower atmosphere over the equatorial oceans is cooler relative to the south Asian land mass, through radiative cooling at low levels and by feedback to a stronger circulation which increases the evaporation. Radiative cooling from low-level clouds and from atmospheric water vapor maintains potential instability by creating a minimum of θ_e in the lowest few kilometers. The increased circulation transports the cooler, more potentially unstable air northward into the monsoon region. More moisture is also transported into the region; increased evaporation increases the atmospheric water vapor, and increased circulation increases the northward transport. Once the moist, potentially unstable air is in the monsoon region, orographic effects force upward motion which releases the instability. Latent heating due to convective activity over the Indian land mass generates a circulation. This regional circulation over the Indian land mass interacts with the global circulation by enhancing the tropical easterly jet caused by the larger scale Walker circulation. Secondary circulations created by the convection contribute to horizontal temperature gradients in the Arabian Sea and the Bay of Bengal. These baroclinic zones are necessary for the maintenance of the monsoon trough and the development of monsoon depressions which originate in the trough region. The resolution of the model simulations in this experiment is too coarse to simulate closed circulation due to these mechanisms but the predicted precipitation patterns closely resemble the observed patterns when radiative transfer is included in the simulation.

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