The Effects of Radiative Transfer in Maintaining the Indian Summer Monsoon

M. J. Leach and S. Raman
Department of Marine, Earth and Atmospheric Sciences
North Carolina State University
Raleigh, North Carolina

Introduction

Atmospheric radiative transfer is an important thermodynamic forcing for the Indian summer monsoon. The Indian summer monsoon is a component of a larger scale circulation system the principal components of which are the Hadley cell and the Walker Circulation.

The Hadley cell is a thermally direct circulation that transports heat toward 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 commonly referred to as the Intertropical Convergence Zone (ITCZ). The return branch of the Hadley cell is characterized by southwesterly surface winds. At the surface, the ITCZ is marked by convergence of southwesterly surface winds from the south and northeasterly surface winds from the north. As the ITCZ moves northward, the southern extent of the northerly surface winds also moves northward, and southerly surface winds from the south side of the ITCZ also move northward. The surface convergence at the ITCZ is a driving mechanism for the summer monsoon circulation. The northward drift of the Hadley cell in the northern summer ITCZ is the deep convection over the warm pool of water in the western tropical Pacific ocean, located at about 160E.

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. Convective activity over the Indian peninsula interacts with the Walker Circulation, creating a jet structure over the western part of India and the eastern Arabian Sea. This structure is known as the Tropical Easterly Jet (TEJ). Secondary circulations associated with the Indian convection also help to maintain the baroclinicity (Saha and Chang 1983), which is essential to the development of monsoon depression, the maintenance of the monsoon trough, and the circulation and hydrology of the region in general.

Experiment Design

An experiment has been designed to determine the effects of atmospheric radiative transfer in maintaining circulation as the forecast is extended to time periods normally regarded as medium-range weather forecasting (3 to 10 days). The initial conditions and boundary conditions at later times are taken from the European Centre for Medium-Range Weather Forecasts (ECMWF) operational analysis for the period July 1988.

The forecasts start at 1200 UTC on July 16; the period of the forecasts is 10 days. The forecast domain is from 0 to 180E and from 30S to 60N. The boundary conditions from the ECMWF analysis are provided every 24 hours, at 1200 UTC on each subsequent day of the forecast.

The model simulations are produced with radiative transfer (R) and without radiative transfer (NR). Results are compared examining the mean features of the hydrologic cycle and the circulation fields. The effects on the structure of several components of circulation that contribute to the overall structure of summer monsoon over India are examined.

Results

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, which is located off the east coast of Africa; 3) the weak baroclinic zones located around the Indian sub-continent which contribute to the orographic rain over India; and 4) the TEJ located above southern India, which is an enhancement of the easterly flow that is part of the large scale Walker Circulation.

During a typically active southwest monsoon, heavy precipitation occurs along the west coast of India, with rainfall also in northern and northeastern India. 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. The precipitation that forms creates latent heat release that generates its own circulation.

The summer monsoon is characterized by a heat low that forms in northwest India or 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 to the head of the Bay of Bengal.

The time sequence of area-averaged precipitation amounts for the radiative transfer case is shown in Figure 1. The precipitation is for a box that encompasses the Indian monsoon region. The limits of the box are (45E,105E) and (5S,30N).

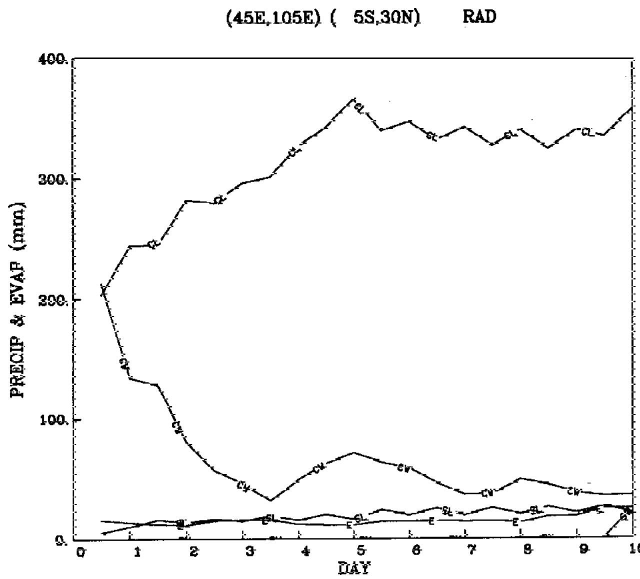

Figure 1. The convective precipitation over land (CL) and water (CW), the stable precipitation over land (SL) and water (SW), and the evaporation (E), for the *radiative* transfer case. The values are area averages for a domain bounded by 45E and 105E longitude and 5S and 30N latitude. The abscissa is time in days.

The results from the simulation without radiation transfer are shown in Figure 2. The curves shown are for the convective precipitation over land (CL), the convective precipitation over water (CW), and the stable precipitation over land (SL). The 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. Precipitation amounts are about 60% greater in the radiation case than in the NR 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 increased solar heating of water vapor in the lower atmosphere, creating more local instability during the sunlight hours. The overall increase in CL with radiation is due to the role that radiative transfer plays in maintaining the circulation, by destabilizing the atmosphere on a "non-local" scale. The CW decreases in both cases rapidly through the first three days of the forecasts. This rapid decrease of the CW is an indication of the model spin-up. The model was not "initialized."

The emphasis of this investigation is circulation processes and precipitation processes affected by atmospheric radiative transfer. The accuracy of the pressure field or momentum field is important only in a qualitative sense. The model numerical scheme filters the first three gravity wave modes, essentially creating the balance that the initialization scheme achieves as the integration continues. After about three days, the leveling of the CW indicates that the spin-up cycle of the forecast is complete.

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

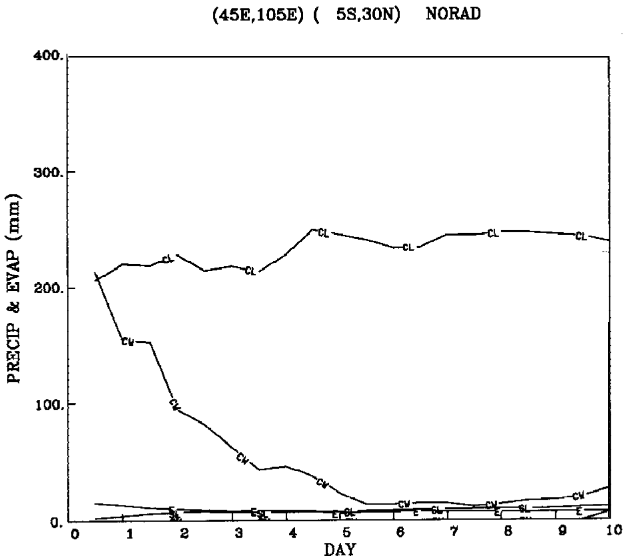

Figure 2. The convective precipitation over land (CL) and water (CW), the stable precipitation over land (SL) and water (SW), and the evaporation (E), for the *nonradiative* transfer case. The values are area averages for a domain bounded by 45E and 105E longitude and 5S and 30N latitude. The abscissa is time in days.

A wind speed maximum along the east coast of Africa is the Somali Jet (SJ). The SJ evaporates and transports water vapor 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 heat from the land masses, maintaining baroclinicity in the region.

In the radiative transfer case, the SJ is much stronger, with its center farther northward. The contribution of this northward extension is vital to the maintenance of the monsoon circulation. The meridional wind component (v) is 50% stronger for R, with the jet-like structure extending into the northern part of the Arabian Sea and into Pakistan. The maximum zonal component is much farther north for R than for NR, near the northern end of the Arabian Sea close to Saudi Arabia. Without R, the much weaker v component and the equatorial displacement of the u component indicate a more zonal character of the flow, illustrating the loss of circulation in NR. The larger meridional transport is an important feedback in R that causes more intense monsoon circulation. Without the meridional transport, baroclinicity is not maintained and the circulation ebbs.

Saha and Chang (1983) have shown through observations that the 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 R, there is an area of convergence over the Arabian Sea, with a weaker convergence over the northern Bay of Bengal.

These convergence zones are not present without radiation. There is much stronger convergence over the entire Indian peninsula, with more organized divergence along the west coast, on the windward side of the western Ghats. The maximum convergence region is in northeastern India. The convergence/divergence pattern over the Indian Peninsula is the primary monsoon circulation; the convergences over the Arabian Sea and Bay of Bengal result from the induced convection over the Indian land mass. The velocity vectors emphasize the strength of the Somali Jet; the cyclonic curvature along the east coast of India; and, in general, a more energetic flow and greater meridional transport occurs for R than for NR.

At the west coast of India, the wind speeds are much greater when radiative transfer is included. These stronger winds result from the stronger SJ and the maintained baroclinicity or circulation in the region. Stronger onshore winds, laden with moisture evaporated from the Arabian Sea, drive 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 leads to easterly winds over the west coast of India and over the eastern portion of the Arabian Sea. These easterly winds forming the return flow of the convective region at the Indian land mass provide positive feedback to the large-scale circulation.

Wind speeds are also 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. Radiative transfer clearly contributes to the maintenance of the monsoon trough, a necessary phenomenon for further development of monsoon depressions at the southeastern sector over the head of the Bay of Bengal.

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 SJ transports water vapor into the monsoon region; increased upslope winds maintain the precipitation processes over the Indian peninsula; and the baroclinic circulation is maintained, especially in the monsoon trough region.

The structure of the SJ can be partially explained by thermal influences. Colder air from the equator penetrates to the north when radiation is included. The colder air contrasts more strongly with the heated 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 stronger circulation. This is an important positive feedback mechanism. Circulation is driven by temperature differences, but the circulation enhances the temperature differences by increasing the evaporation.

The upper level easterly jet over southern India with a strong divergent circulation from the monsoon region is an essential feature of the large-scale flow associated with the summer monsoon. This feature is part of the Walker cell, which originates in the convection over the warm pool of water in the western Pacific at about 100E. Heating over the southern part of India amplifies the easterly flow, resulting in a jet streak over that area.

The 200-mb u velocities at hour 240 for the radiative and the nonradiative cases are shown in Figures 3 and 4. The effect of greater latent heating over the Indian subcontinent in the case with radiation is evident in the more jet-like structure over southern India. Air is forced to ascend by the latent heating over the land, creating secondary circulations. The easterly flow in the upper troposphere is accelerated on the east side of India and decelerated on the west side. These secondary circulations also contribute to maintenance of the low-level baroclinic zones (Saha and Chang 1983) necessary for the development of precipitation systems along the monsoon trough.

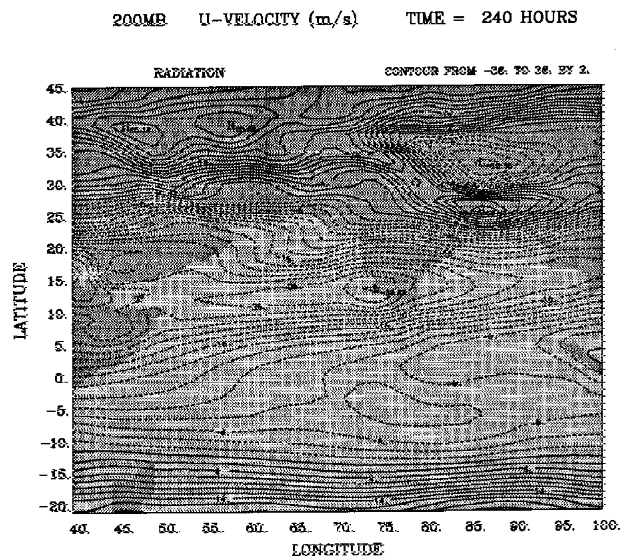

Figure 3. The zonal wind component u at 200 mb after 10 days, for the simulation *with* radiative transfer.

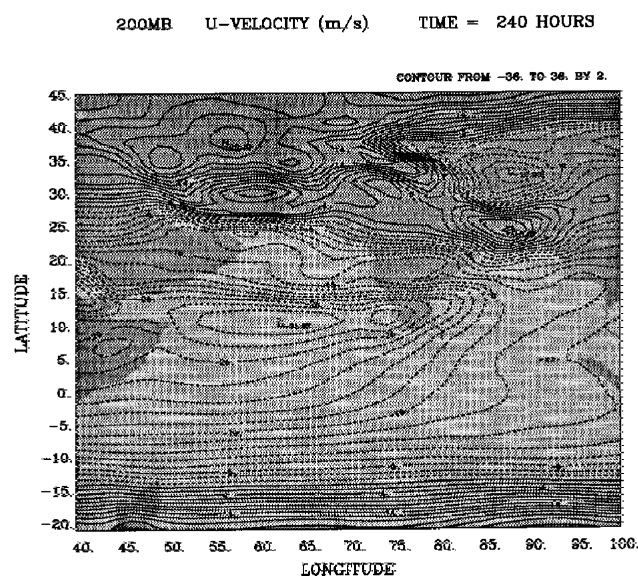

Figure 4. The zonal wind component u at 200 mb after 10 days, for the simulation *without* radiative transfer.

The greater easterly winds near the equator in the NR case result from the loss of identity of the ITCZ. The TEJ with radiative transfer indicates strong divergent flow because of the radiative cooling at cloud tops. Without radiative transfer, the flow is more zonal, resulting in a substantial decrease of the divergent circulation. The ITCZ is maintained by the baroclinicity, which is created by the cooling near the equator. The equatorial cooling results from both radiative cooling of the clear air and increased evaporation.

Summary and Conclusion

Atmospheric radiative transfer maintains intense circulation in the Indian monsoon region through important feedback processes. The atmosphere in the equatorial region is cooler, through radiative cooling at low levels and through feedback to a stronger circulation that increases the evaporation. Cooling from low-level clouds and from atmospheric water vapor maintains potential instability by creating a minimum of q_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 creates regional-scale circulation. Local circulation interacts with global circulation by enhancing the easterly winds that are due to the larger scale Walker Circulation, creating a jet-streak-like feature off the west coast of southern India.

Secondary circulations created by the convection contribute to the baroclinic zones 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 storm systems in the trough region. The resolution of the model simulations in this experiment is too coarse to develop closed circulation due to these mechanisms, but the precipitation patterns that are forecasted more closely resemble the observed patterns when radiative transfer is included in the simulation.

Reference

Saha, K., and C.-P. Chang. 1983. The Baroclinic Processes of Monsoon Depressions. *Mon.Wea. Rev.* **111**:1506-1514.