A Mechanism for the Southward Propagation of Mesoscale Convective Systems Over the Bay of Bengal

Ravi S. Nanjundiah Deepeshkumar Jain Arindam Chakraborty* Indian Institute of Tropical Meteorology, Pune and *Centre for Atmospheric & Oceanic Sciences, IISc Bengaluru

Outline

- Southward Propagating Mesoscale Systems over the Bay of Bengal (BoB)
 Model and Experimental Details
- Propagations in the model
- Effects of resolution and cumulus
 - parameterization
- Coupling with diurnal land heating

Southward Propagations over BoB

850hPa

70E

75E

80E

85E

90F



- Southward propagating precipitation episodes over the BoB have been documented in many previous observational studies.
- Proposed propagation mechanisms include mean surface to mid-tropospheric wind shear driving the convection orthogonal to the lower tropospheric winds and the gravity currents generated by outflow from convection initiated by the diurnally varying land-ocean circulations dispersing south.
- In this study, we perform high-resolution simulations using the Weather Research and Forecast model capable of resolving meso-scale convective systems during the South Asian summer monsoon season.

Model and Experimental Details

- We use WRF version 3.4 for the present study.
- We use the WRF single-moment class-3 (WSM3) microphysics scheme by Hong et al. (2004). This scheme treats water vapor, cloud water, and rainwater mixing ratio above 0 °C and water vapor, ice water, and snow water mixing ratio below 0 °C.
- The Yonsei University scheme (Hong et al., 2006) is used to represent planetary boundary layer processes.
- The model time step is 5s, and the model output is archived every 3 hr.
- The selection of the spatial domain was dictated by our requirement to simulate convection over the central Indian landmass and over the BoB.



elevation and important geographical regions in the Indian subcontinent.

Model and Experimental Details

- The primary simulation capable of simulating the southward propagations at a CRM resolution of 3 km with explicit microphysics was run from June to August of 2008 over the Indian region.
- The simulation has 1,000 × 1,000 grid points in the horizontal and 100 levels in the vertical Arakawa C-grid staggering (Arakawa and the vertical resolution varies with height.
- The lateral boundary conditions for the model are specified with relaxation zone of four grid points. The initial condition and the boundary conditions (updated every 6 hr) are from the NCEP Final analysis (Operational Global Analysis).
- We carried out additional simulations at varying resolutions and cumulus parameterization (Kain and Fritcsh) for the month of June, 2018.



Model domain showing orographic elevation and important geographical regions in the Indian subcontinent.

Model and Experimental Details

Case	Horizontal	Number of		Cumulus	Simulation
name	resolution	vertical levels	Microphysics	parameterization	duration
3Micro	3 km	100	WSM3	None	June to August
3Cu	3 km	100	None	Kain-Fritsch	June
12Micro	12 km	50	WSM3	None	June
12Cu	12 km	50	None	Kain-Fritsch	June
30Micro	30 km	50	WSM3	None	June
30Cu	30 km	50	None	Kain-Fritsch	June
12MicroCu	12 km	50	WSM3	Kain-Fritsch	June (not shown)
30MicroCu	30 km	50	WSM3	Kain-Fritsch	June (not shown)



Model domain showing orographic elevation and important geographical regions in the Indian subcontinent.

Comparison of WRF and TRMM Precipitation



June–August monthly precipitation (mm/day) from TRMM estimates and from model simulations (3Micro). Panels a, c, and e are from TRMM, while b, d, and f are from the model.

- Figure shows the monthly precipitation from the TRMM satellite estimates and from the model (3Micro) for the simulated period.
- Orographic precipitation on the windward side (west) of the Western Ghats can be seen in TRMM and in simulations.
- On the leeward side, lower rainfall in both the TRMM and the simulation.
- Himalayan orography also interacts with moisture-laden winds from the BoB, and the combination of land-sea heating contrast gives frequent episodes of precipitation over the foothills.



Latitude-time Hovmoller plot of observed (Tropical Rainfall Measuring Mission) and modeled (Weather Research and Forecast, 3Micro) precipitation averaged over 85–90°E showing diurnally propagating signals over the Bay of Bengal. The horizontal line refers to mean coastline over 85–90°E. The southern tip of India is at 7°N.

- We analyzed TRMM data from 1998–2014 and found that the southward propagations were most prominent during the onset phase of the monsoon.
- Southward propagations were also found to be prominent during the month of June in the simulations
- We show here the latitude-time Hovmoller diagrams of the 3-hourly precipitation data from model and from TRMM averaged over 85° to 90°E for 2008
- A very distinct large-scale northward propagating precipitation signal can be seen in TRMM from 7 to 17 June.
- Embedded in this large-scale propagation are the mesoscale diurnal southward propagating precipitation episodes. The extent of these signals varies from less than 5° for the smallest signal to more than 25° for the largest signal seen on 5 June.



Latitude-time Hovmoller plot of observed (Tropical Rainfall Measuring Mission) and modeled (Weather Research and Forecast, 3Micro) precipitation averaged over 85–90°E showing diurnally propagating signals over the Bay of Bengal. The horizontal line refers to mean coastline over 85–90°E. The southern tip of India is at 7°N.

- The unbroken signal signifies a continuously propagating MCS originating on the coast north of the BoB. The mean speed of this structure (approximately 15 m/s) cannot be explained solely by the mean tropospheric advection (Liu et al., 2008) but is similar to gravity wave speeds.
 The model simulations also show southward propagating diurnal precipitation episodes embedded within larger
 - northward propagating rain band. The number of episodes is considerably higher in the model than in TRMM.
- The smallest signals span less than 5° and the largest 15° to 20° in the model simulation.
- In both the TRMM and the model these signals sometimes originate over the coastal regions and sometimes over the Ocean.
- The duration of the simulated MCSs is opposite of observations with the shorter MCSs occurring first and the longer occurring later.

Initiation and Propagation of an Episode in the Model



Particular precipitation episode (near 20°N–90°E) from model simulation propagating south. The system can be seen to have a curved bow structure. The label on the bottom right corner of each panel represents local time on 6 June at which these snapshots were taken.

- Figure shows model-simulated 3-hourly precipitation for one of the propagating episodes.
- This episode occurred on 6 June (an isolated event) and was selected for further investigation.
- This precipitation signal originated at the coastal region north of the BoB between 1430 and 1730 local time, intensified for the next 3 hr over the north BoB, and then started propagating southward in a bow structure.
- Comparing this with the radar echoes reported by Houze (2004), our model is able to simulate the structure of these precipitation events reasonably well.

Structure of Simulated Radar Echoes

Radar Reflectivity (dBZ)



Time snapshot (at 2030 local time on 6 June 2008) of the maximum model simulated (radar) reflectivity (dBZ) of the propagating rain band. The inclined black line refers to the section along which the vertical dynamic and thermodynamic conditions are further analyzed.

- Maximum radar reflectivity in dBZ of the propagating MCS by the model as seen at 2030 hr on 6 June in previous Figure.
- The system comprises a leading convective/trailing stratiform bow structure and agrees well with the one reported in Webster et al. (2002) and Houze (2004).

Surface Temperature



Surface temperature corresponding to the event shown in previous Slide.

- The diurnal cycle in surface temperature over the land is shown here.
- Maxima in land temperature occur late in the afternoon, the precipitation over land can be first seen at 830 local time in previous Figure, and by the time of maximum surface temperature (1430 in the previous Figure), we see a mature precipitating system (20°N in previous Figure).
- It is interesting to note that the system intensifies when the land surface is warmer than the ocean.
- This system forms a bow structure and starts propagating south from 1730 local time onward.

Wind Structure During June



and 850 hPa.

- Miyakawa and Satomura (2006) showed seasonal mean 600-hPa winds to have a southward component.
- Here we show mean of model simulated 600 and 850hPa wind speed for the month of June. The 850hPa winds are orthogonal to the direction of propagation; however, at 600 hPa, it can be seen that the horizontal winds have a southeastward component over the region of interest (85–90°E).
- These winds are in the direction of propagation. These winds were attributed by Miyakawa and Satomura (2006) to the trough over the BoB at the height of 600 hPa.
- We analyzed winds in many reanalysis data sets (not shown) and found midtropospheric southward winds during the onset phase of the monsoon.
- We also analyzed winds at all the levels in our model simulation and found the midtropospheric winds (from 700 to 500 hPa) to be in the direction of propagations.
- The mean magnitude of 600-hPa winds (10 m/s) during June, however, was lower than the overall speed of the propagating MCS (15 m/s), and Miyakawa and Satomura (2006) speculated that the discrepancy may be attributed to rebuilding of convective cells provoked by cold pool outflows.



Cross-section plots every 3 hr (local time on top right corner) showing the initiation of convection with equivalent potential temperature (color shaded), cloud water mixing ratio (red contour at 0.01 g/kg), rainwater mixing ratio (black contour at 0.3 g/kg), and meridional winds (vectors [m/s]) for the event shown previously

- We show here the cross-sectional plot of equivalent potential temperature, meridional wind vectors, cloud water mixing ratio, and rainwater mixing ratio of the propagating episode shown previously along the line shown previously.
- In the left panel, the surface to 875-hPa height meridional winds have northward component, whereas the midtropospheric winds (700 to 500 hPa) have a southward wind component.
- Left panels show the initiation phase of convection, while the right panels show the mature phase of convective system which propagates south.
- It can be seen that initially, the surface is warmer than the midtroposphere. As the day progresses, the surface gets warmer still.
- A deep convective cloud is formed at 1430 local time. As this system matures and starts precipitating (rainwater mixing ratio shown by the black contour), it gives rise to convective downdrafts driven by the evaporation of precipitating rainwater.
- As these downdrafts hit the ground and encounter warm surface winds, a front-like structure forms (at 20.6°N). It can be seen that the convective system is intense and possesses a strong downdraft which creates a density current.



365 364

360

356

352

348

344

340

Similar to previous figure showing cross-section plot with equivalent potential temperature (colored), cloud water mixing ratio (black contour), rainwater mixing ratio (white contour) with separate meridional (top panel, greater than 5 m/s) and vertical (bottom panel, greater than 1 m/s) winds vectors along the cross section for an event at 2330 hr, 6 June 2008.

- Shown here are the meridional wind velocities. (greater than 5 m/s) and vertical wind velocities (greater than 1 m/s) for the system.
- The southward winds behind the system is the rear inflow jet and can be clearly seen.
- It can also be seen that the speed of rear inflow jet near the surface (surface to 875 hPa) is around 15 **m**/**s** which is the speed of propagation of this MCS.
- It is important to note that although we are showing the rear inflow jet only near the surface, the rear inflow jet has a vertical extent spanning from surface to midtroposphere.



Top panel shows anomaly of equivalent potential temperature when the system is present (2330 local time, 6 June) and actual winds (no anomaly) in the region from when there is no system 6 hr back. The contour (0.01 g/kg) shows cloud water mixing ratio. Middle panel shows perturbation pressure for the MCS. The thick dashed contour line shows negative equivalent temperature. The bottom panel shows actual air temperature of the system.

- Top panel shows the near-surface anomaly of equivalent potential temperature of the episode at 2330 hr on 6 June.
- The anomaly is calculated by taking difference from when the system was not present, that is, at the exact location in this figure 6 hr back.
- Figure also shows the perturbation pressure (middle panel) and absolute temperature values for the system (lower panel). The downdraft-associated cold pool is clearly visible on the lower right corner having negative θe anomaly. In this cold pool region, the mean meridional speed was found to be 15.2 m/s. The warmer air can be seen to be lifted up by this cold pool to the lifting condensation level (LCL, which in this case was around 500 to 600 m or around 975 to 950 hPa).
- The mean wind speed below the LCL ahead of the system was found to be 1.5 m/s. So one can argue that the convection initiation zone would be moving at the speed of around 15 m/s, which is indeed the case.
 Hence, the propagation of this MCS is indeed governed by gravity current mechanism.

Speed of Propagation (First Guess)

- To a first theoretical approximation, we can use the following equation (Simpson, 1997) to derive gravity current speed in the atmosphere $u = \sqrt{gh\Delta T/T}$
- where u is the propagation speed of gravity current, h is the depth of density current (500 m to 1 km), T is the environmental air temperature, and ΔT is the air temperature difference of cold pool from the environment. The depth of cold pool in our simulation is around 700 m to 1 km. The temperature difference is around 5 to 10 K, and the environmental air temperature is 300 K. Then the gravity current speed is in the range of 12 to 18 m/s.
- A better understanding of the environmental contribution to the propagation of the MCSs comes from **Corfidi et al. (1996) and Corfidi (2003)** approach. They divide contribution to overall propagation into advective component (900 to 350 hPa in our case), contribution from **Iow-level jet (990 to 960 hPa ahead of the system)**, and the cold pool.



Left panel shows convergence at the leading edge of mesoscale convective system (MCS) at 975 hPa (blue contour line), the color map shows equivalent potential temperature averaged over 990 to 960 hPa, and vectors are averaged over 990 to 960 hPa. Right panel shows convergence at the leading edge of MCS at 975 hPa and velocity vector averaged over cloud layer (900 to 350 hPa). Low-level jet refers to the winds south of convergence zone in the left panel where the equivalent potential temperature is generally greater than 360 K. This is the region which is ahead of the southward propagating MCS. The rear inflow jet or the cold pool velocity refers to the wind vectors in the left panel just north of convergence zone (here the equivalent potential temperature is generally less than 350 K). The wind vectors in the right panel refers to the advective component of the MCS.

- Figure shows equivalent potential temperature averaged over 990 to 960 hPa, the low-level velocities (averaged over 990 to 960 hPa) associated with cold pool and low-level jet, and the cloud-scale velocities (averaged over 900 to 350 hPa).
- Figure also shows the leading edge of convergence at 975 hPa. We can see that the cold pool produces outflow boundaries. These outflows lift the warm southwesterlies to form new convective cells.
- The leading edge does move in the direction of vector sum of the cloud layer velocity (or cold pool velocity) and the negative of low-level jet.

Effects of Cumulus Parameterization and model resolution

Case	Horizontal	Number of		Cumulus	Simulation
name	resolution	vertical levels	Microphysics	parameterization	duration
3Micro	3 km	100	WSM3	None	June to August
3Cu	3 km	100	None	Kain-Fritsch	June
12Micro	12 km	50	WSM3	None	June
12Cu	12 km	50	None	Kain-Fritsch	June
30Micro	30 km	50	WSM3	None	June
30Cu	30 km	50	None	Kain-Fritsch	June
12MicroCu	12 km	50	WSM3	Kain-Fritsch	June (not shown)
30MicroCu	30 km	50	WSM3	Kain-Fritsch	June (not shown)



Model domain showing orographic elevation and important geographical regions in the Indian subcontinent.



Monthly mean (June) model precipitation at 3, 12, and 30 km horizontal resolutions and with explicit (a–c) microphysics and (d–f) cumulus parameterization. The details of the simulations are mentioned in Table

- Figure shows the precipitation simulated by the various physics and resolution configurations in the model shown in Table.
 Similarities exist between the different
- resolutions using the same convection representation.
- In simulations using microphysics, all the resolutions get higher Western Ghats precipitation and all the resolutions overprecipitate over ocean and underprecipitate on land compared to TRMM estimates shown previously.
- It can be seen in that much finer structures are resolved by the microphysics case compared to cumulus case.
- The rainfall is overestimated by the coarser-resolution microphysics cases (12Micro and 30Micro). However, the large-scale features are very similar between the different resolutions.



Meridional propagation of precipitation averaged over 85–90°E with different model resolution and convection representation shown in previous Table

- Figure shows the time-latitude plot of the precipitation over the BoB with different model resolution and convection representation shown in Table.
- A strong diurnal cycle of precipitation can be seen in all the simulations. Also, it can be seen that the southward propagations in the model are resolution dependent as well as on the convection representation.
 In the 12Micro and 30Micro case, the propagations are nearly absent or the precipitation system is not continuous as in 3Micro case.
- For a few of the intense precipitating systems, 12Micro and 30Micro were able to resolve the updraft-downdraft pair for a short duration but could not continue to resolve the pair for long.
- We can attribute the failure of coarser resolution model simulation to the fact that propagation in the model requires correct simulation of updraft-downdraft pair and the associated circulation.



Cross section plot for 3Cu case showing equivalent potential temperature vertical structure for a raining system near 24°N. Left panel shows meridional winds greater than 5 m/s, while vertical winds greater than 1 m/s are shown in the right panel.

- Figure shows the vertical cross section of the equivalent potential temperature and meridional and vertical wind vectors for the nonpropagating system in 3Cu case. Note that cloud microphysical variables such as cloud water mixing ratio and rainwater mixing ratio are absent in the cumulus case.
- The surface to mid tropospheric winds simulated by the cumulus case are northward.
- It can also be seen that most of the convection in the cumulus case is initiated due to orographic lift by Himalayas. Cumulus parameterization assumes that the model grid is large enough to have updraft and downdraft inside the grid box, whereas in the microphysics case, true sources of heating-cooling and eddy transports (local and nonlocal) are calculated explicitly.
- Hence, high-resolution model with microphysics is able to simulate updraft-downdraft pair which is missing in cumulus case.



-5

-6 -7

-10

Vertical cross-section plot for cumulus convection (3Cu, top left) and explicit microphysics schemes (3Micro, top right) case showing heating tendency due to cumulus convection and explicit microphysics. The shaded region is the equivalent potential temperature anomaly, and the contour shows cloud water mixing ratio of the present system (in microphysics case only). Bottom panel shows horizontal mean of tendencies over the two top panels.

- Top two panels show heating and cooling tendencies of a precipitating system in 3Cu versus 3Micro case.
- Heating tendency is calculated by taking the difference between equivalent potential temperature when the system is present and when there was no system at the location 6 hr back. Most of the heating in the 3Cu case happens in the middle to upper troposphere.
- A very strong low-level cooling and a gravity current can be seen in the 3Micro case. The cooling of the lower troposphere in 3Cu is also present. But it is not as strong as the one seen in the 3Micro case.
- Lower panel shows surface winds change to be 15m/s



9

-3 -4 -5

-6 -7 -8 -9

-10

Vertical cross-section plot for cumulus convection (3Cu, top left) and explicit microphysics schemes (3Micro, top right) case showing heating tendency due to cumulus convection and explicit microphysics. The shaded region is the equivalent potential temperature anomaly, and the contour shows cloud water mixing ratio of the present system (in microphysics case only). Bottom panel shows horizontal mean of tendencies over the two top panels.

- Bottom panel shows the mean meridional momentum tendency horizontally averaged for the system shown in the top two panels.
- It can be seen that the MCS in the 3Micro case has a strong southward tendency in the lower troposphere.
- We took the mean of wind speeds in the cold pool in Figure and found that the mean wind in the cold pool (lower right corner) was 15.2 m/s, while the northward winds in the lower troposphere were 1.5 m/s (lower left corner).
- We can see in Figure that the initiation of convection is happening due to density current-like structure travelling in the southward direction.

Role of Land Surface Temperature



Precipitation produced by model with constant land surface temperature (top left), difference in precipitation of constant land surface temperature simulation from diurnal land surface temperature (top right), and southward propagations over the Bay of Bengal with constant land temperature (bottom panel).

- At the end of this study, we carried out one additional simulation in which we kept the land surface temperature constant for the month of June while keeping the rest of the physics options and model resolution the same as in 3Micro.
- Figure here shows the simulated precipitation and southward propagations in this simulation. Taking the difference of precipitation from our primary simulation (with diurnal land temperature variation) shows that most of the north BoB precipitation comes from systems originating over land.
- This can be verified by looking at the southward propagation in this simulation. The southward propagations are missing from this simulation in the north BoB though there are MCSs which initiated over ocean and propagated south.
- When a system initiates over the ocean, it produces cold pool outflows and results in MCSs formation. According to Corfidi (2003), an MCS will move in the downwind direction because it is the direction of most intense convergence. Over the BoB, this happens to be the southward direction.

Summary

- Equatorward propagating precipitation episodes over the Bay of Bengal have been documented in many previous observational studies. Proposed propagation mechanisms include mean surface to midtropospheric wind shear driving the convection orthogonal to the lower tropospheric winds and the gravity currents generated by outflow from convection initiated by the diurnally varying land-ocean circulations dispersing south.
- In this study, we perform high-resolution simulations using the Weather Research and Forecast model capable of resolving mesoscale convective systems during the South Asian summer monsoon season.
- This mesoscale system is shown to have squall line-like structure with leading line/trailing stratiform.
- The rear inflow due to saturated downdraft and jump updraft indicates a gravity current-like structure. The rear inflow jet produces horizontal momentum tendencies in the direction of propagation.
- The center of convection is shown to move faster than the midtropospheric winds and at the same speed as that of the rear inflow jet near the surface.

Summary

- These systems are also shown to be **tightly coupled to the diurnal land surface heating cycle**. We perform additional model simulations with varying horizontal resolution and with the inclusion of cumulus parameterization.
- A model with cumulus parameterization is unable to simulate the updraft-downdraft pair and the gravity current structure of this southward propagating mesoscale system.
- We find that high model resolution is needed to resolve the updraft-downdraft pair and cumulus parameterization assumptions break down at such high resolutions.
- Using cloud microphysics exclusively becomes essential in simulating these mesoscale systems.

Thank You

Questions????

•

References

- Hong, S.-Y., Noh, Y., and Dudhia, J. A new vertical diffusion package with an explicit treatment of entrainment processes. Monthly Weather Review, 134(9):2318–2341, 2006.
- Hong, S.-Y. and Pan, H.-L. Nonlocal boundary layer vertical diffusion in a medium-range forecast model. Monthly weather review, 124(10):2322–2339, 1996
- Liu, C., Moncrieff, M. W., and Tuttle, J. D. A note on propagating rainfall episodes over the bay of bengal. Quarterly Journal of the Royal Meteorological Society, 134 (632):787–792, 2008.
- Houze, R. A. Mesoscale convective systems. Reviews of Geophysics, 42(4), 2004.
- Webster, P., Bradley, E. F., Fairall, C., Godfrey, J., Hacker, P., Houze Jr, R., Lukas, R., Serra, Y., Hummon, J., Lawrence, T., et al. The jasmine pilot study. Bulletin of the American Meteorological Society, 83(11):1603–1630, 2002.

References

- Corfidi, S., Meritt, J., and Fritsch, J. Predicting the movement of mesoscale convective complexes. Weather and Forecasting, 11(1):41–46, 1996.
- Corfidi, S. F. Cold pools and mcs propagation: Forecasting the motion of downwinddeveloping mcss. Weather and forecasting, 18(6):997–1017, 2003.
- Miyakawa, T. and Satomura, T. Seasonal variation and environmental properties of southward propagating mesoscale convective systems over the bay of bengal. SOLA, 2:88–91, 2006.