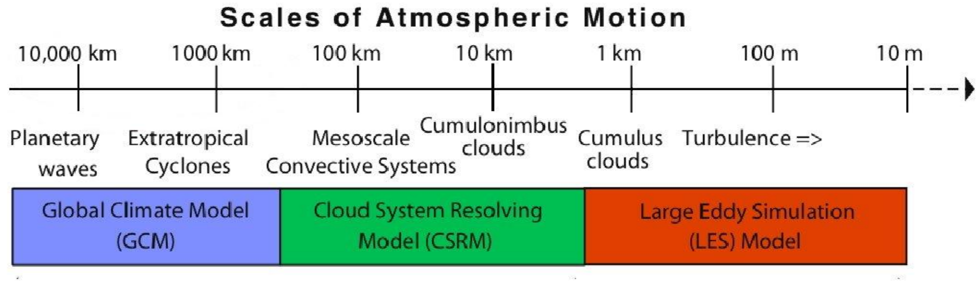
Unified Parameterization of Moist Convective Processes in a GCM – Few findings from CRM and LES

Ravi S. Nanjundiah
Indian Institute of Tropical Meteorology Pune & Indian Institute of Science, Bengaluru
Deepeshkumar Jain
National Centre for Medium Range Weather Forecasting, NOIDA
Arindam Chakraborty
Indian Institute of Science, Bengaluru

Unification of Parameterization Across Scales & Processes

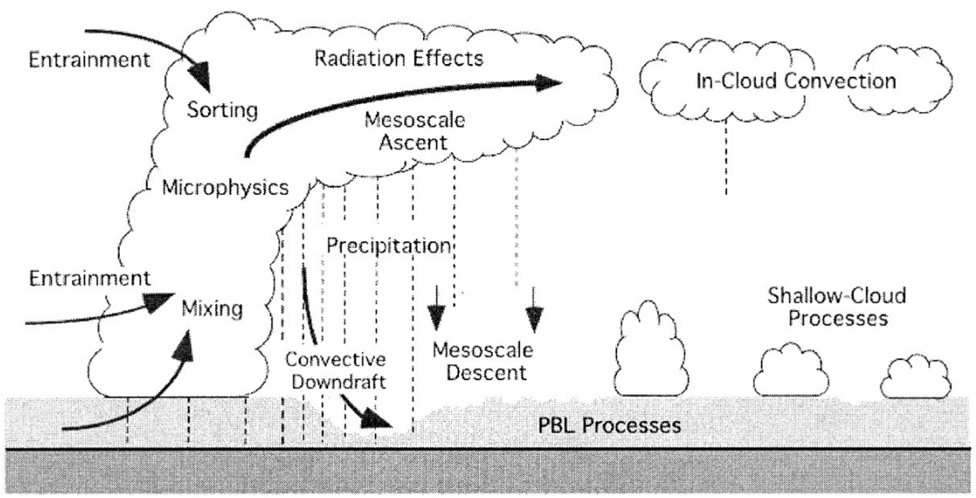
Unified Parameterization attempts to represent convective processes across scales and tries to bring convergence between processes



Unification Across Scales

- governed by different equations
- applied to different scales
- used by different groups of researchers

UNCERTAINTIES IN FORMULATING CLOUD AND ASSOCIATED POCESSES

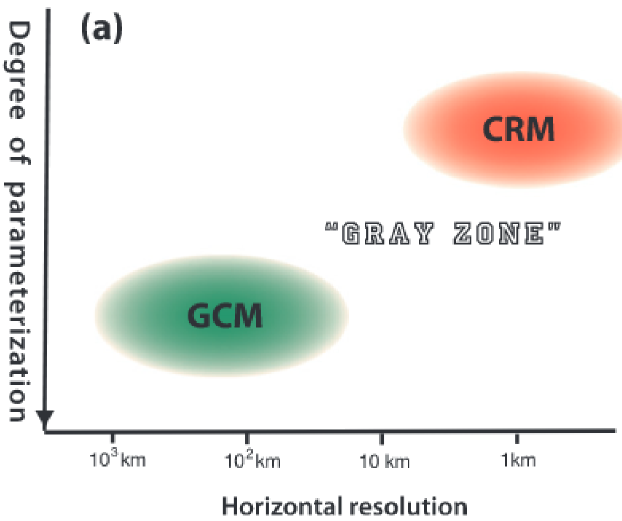


Unification Across Processes

State of art in Unified parameterization

1. Unification across scales - eg. Arakawa, 2013

- **Most of the present day cumulus parameterizations use CAPE closure**
- **Making assumptions scale aware.**



2. Unification across processes – Bringing consistency between processes – eg. Combining PBL with free troposphere, Lappen, 2001

- **Using same closure assumptions for boundary layer as in cumulus with an equation for moisture**
- **One of the most prominent one is based on assumed PDFs for turbulent flux quantities.**

$$\sigma = \frac{1}{2} - \frac{S_w}{2(4 + S_w^2)^{1/2}},$$

$$M_c = \rho\sigma(1 - \sigma)(w_{\mathrm{up}} - w_{\mathrm{dn}}) = \frac{m(w'^2)^{1/2}}{(4 + S_w^2)^{1/2}},$$

where

$$S_w = \frac{\overline{w'^3}}{(\overline{w'^2})^{3/2}}$$

Assumed PDF based Unified parameterizations

- **Using same closure assumptions for boundary layer as in cumulus with an equation for moisture**
- **One of the most prominent one is based on assumed PDFs for turbulent flux quantities.**
- **Such Closure assumptions depend heavily on the local turbulent structure of the boundary layer and upper troposphere.**
- **Similar closure assumptions such as the one based on local PBL TKE and CINE have also been proposed.**

  Our purpose in todays presentation is to show the cases where such types of closure assumtions could be valid

  and
- **Where we may need to include the non-local effects (organized MCSs)**

$$\sigma = \frac{1}{2} - \frac{S_w}{2(4 + S_w^2)^{1/2}},$$

$$M_c = \rho\sigma(1 - \sigma)(w_{\mathrm{up}} - w_{\mathrm{dn}}) = \frac{m(w'^2)^{1/2}}{(4 + S_w^2)^{1/2}},$$

where

$$S_w = \frac{\overline{w'^3}}{\overline{(w'^2)}^{3/2}}$$

$$m_{\mathrm{cb}} = c_1 W \exp(-c_2 \mathrm{CIN/TKE}),$$

TKE Turbulent kinetic energy

½$(u'^2 + v'^2 + w'^2)$, averaged horizontally and vertically below Cu base.

W Vertical velocity scale in CIN closure

$W = a\mathrm{TKE}^{1/2} + b$ for any a or b.

(Fletcher et al 2009)

(Fletcher et al 2009)

Outline

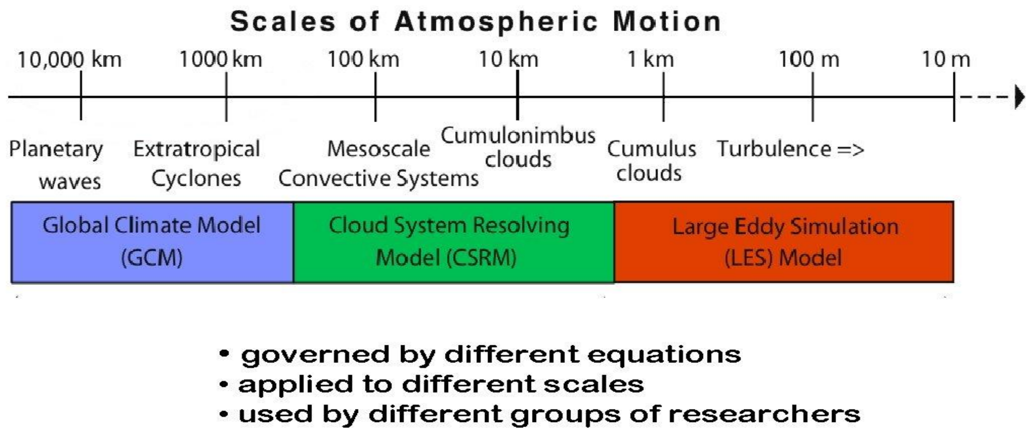
Where such unified Closure schemes might have difficulties?

- **Southward Propagating MCSs over Bay of Bengal**

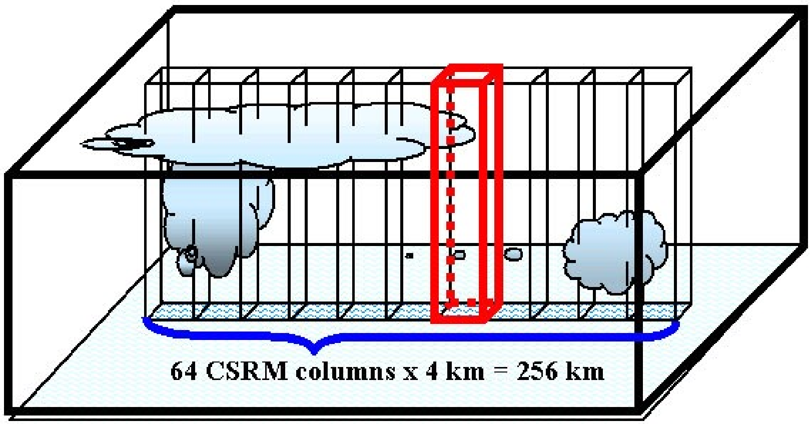
Where such unified Closure schemes might work better?

- **Thermal Plumes models for the boundary layer and the clouds**

Southward Propagations Over Bay of Bengal in Cloud Resolving Model Simulations of ISMR



C(S)RM – Typical Horizontal resolution ~ 1 to 5 km



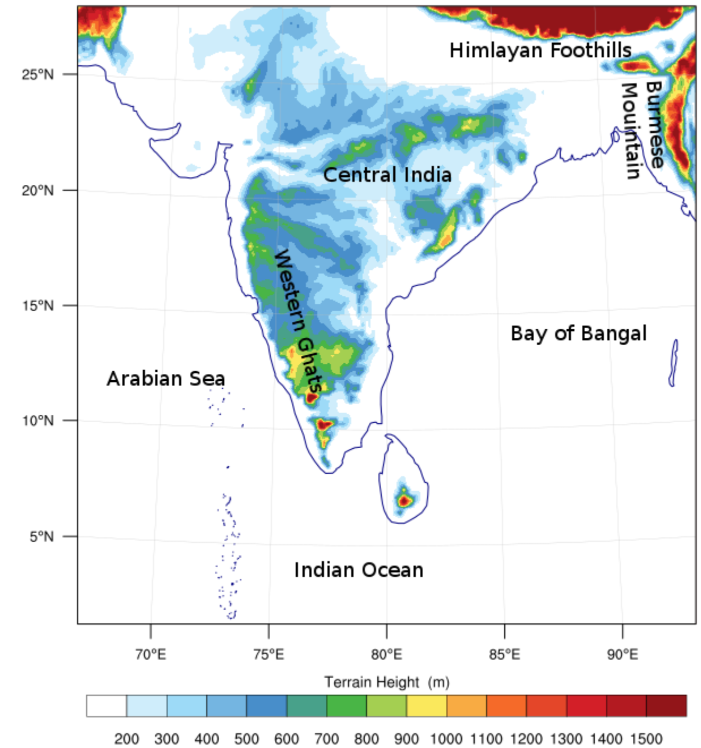
Jain et al. (2018), Journal of Geophysical Research: Atmospheres, 123, 3893–3913.

Model Details

- **We use WRF version 3.4 for the present study. WRF is a non-hydrostatic mesoscale model developed by Mesoscale and Microscale Meteorology Division of National Centre for Atmospheric Research (Skamarock and Klemp (2008)).**
- **The model has fully compressible and non-hydrostatic equations. It uses mass-based terrain-following coordinate system.**
- **The vertical grid spacing varies with height. The horizontal grids follow Arakawa C-grid staggering. The time stepping follows Runge-Kutta 3rd-order time step.**
- **The lateral boundary conditions for the model are specied with relaxation zone of 4 grid points. Upper boundary has an absorbing layer with Rayleigh relaxation damping.**
- **We use WRF single moment class-3 (WSM3) microphysics scheme by Hong et al. (2004) for bulk microphysical processes in the model. WSM3 is a 3-class microphysics scheme which treats water vapor, cloud water, and rain water mixing ratio above 0^{0}C and water vapor, ice water, and snow water mixing ratio below 0^{0}C.**
- **The model uses Yonsei University (YSU) scheme (Hong et al. (2006)) to represent planetary boundary layer processes.**
- **The model time step is 5 seconds and the model output is saved every 3 hours.**

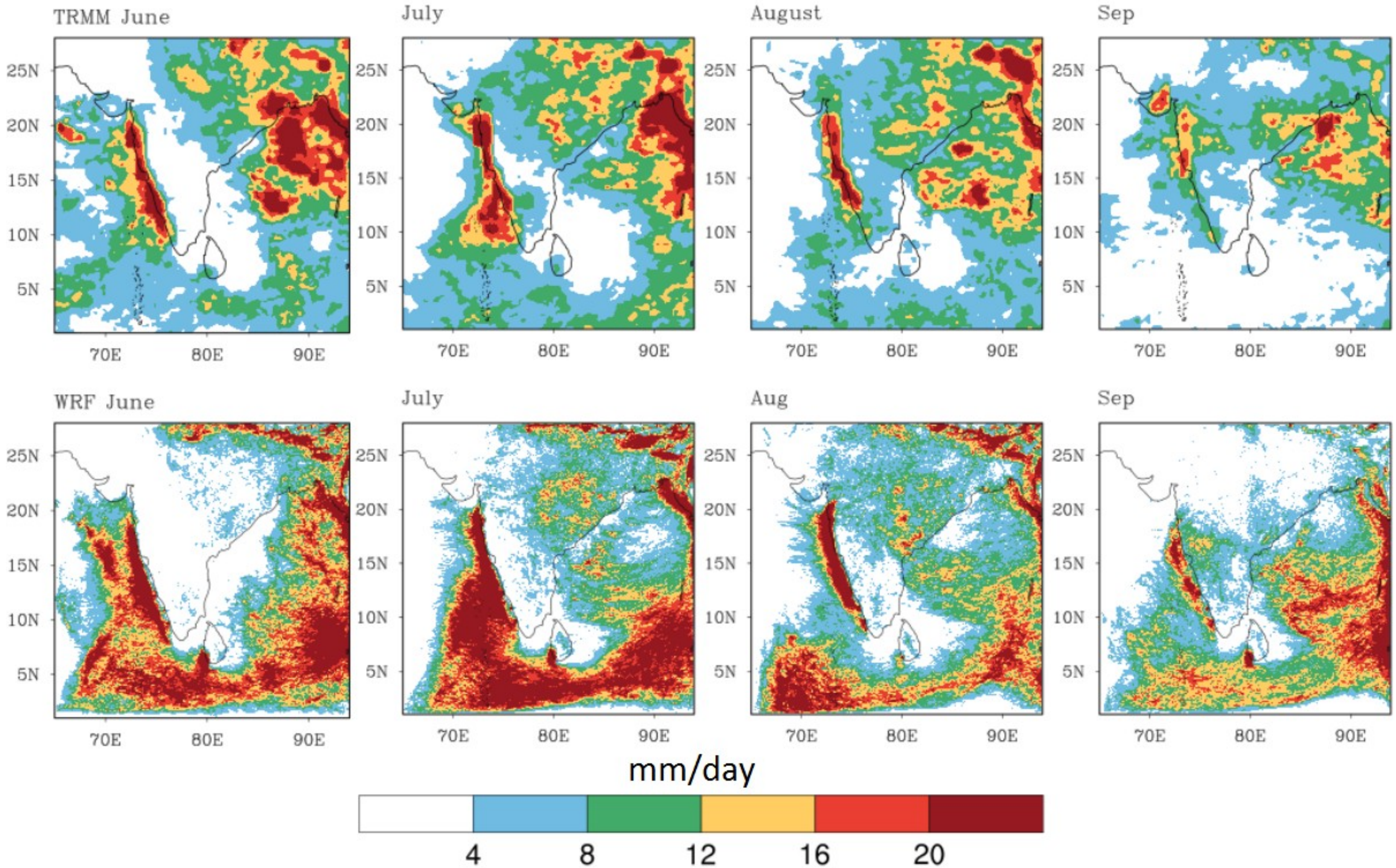
Experimental Details

- **Horizontal resolution of 3km,**
- **Explicit microphysics**
- **Duration June to September of 2008**
- **Control has 1000x1000 grid points in the horizontal and 100 levels in the vertical with eta-coordinate system.**
- **The initial condition is provided at the start of the simulation while the boundary conditions are provided every 6 hours using NCEP FNL analysis dataset**
- **The model time step is 5 seconds and the model output is saved every 3 hours.**



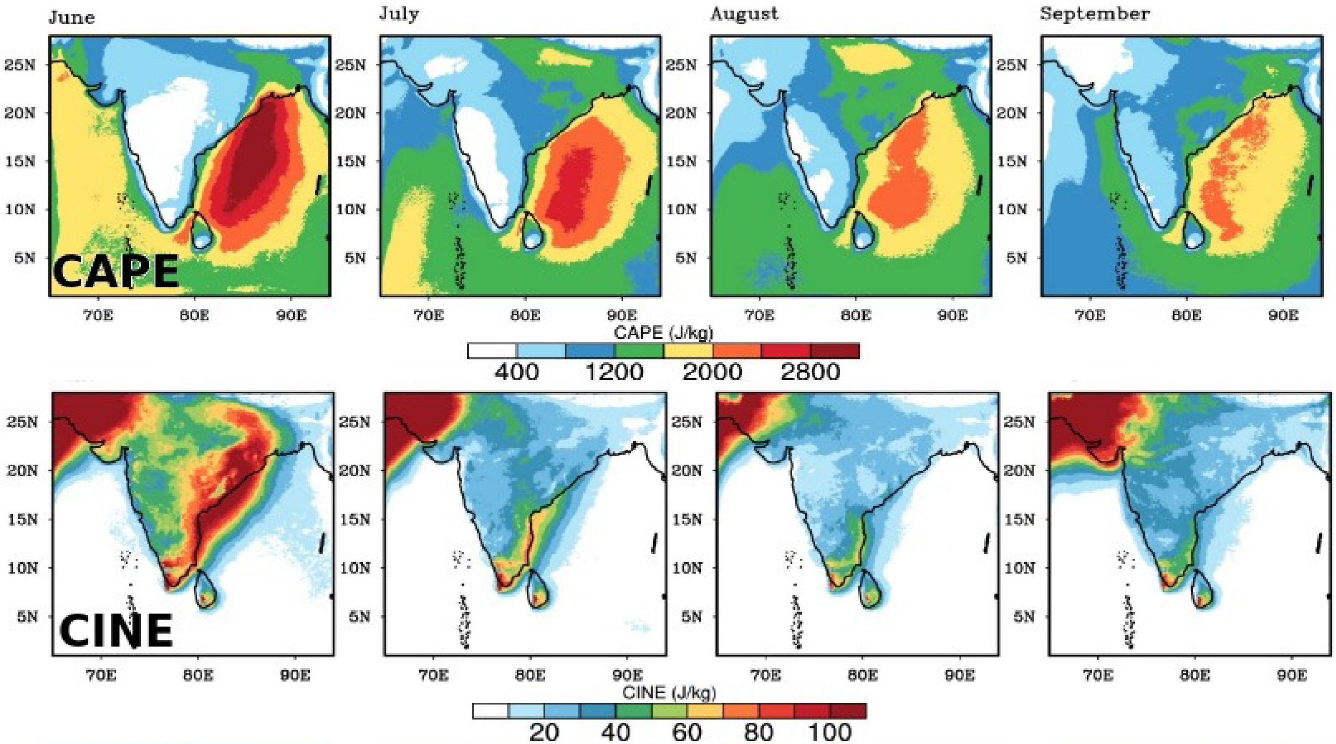
Domain of model simulation

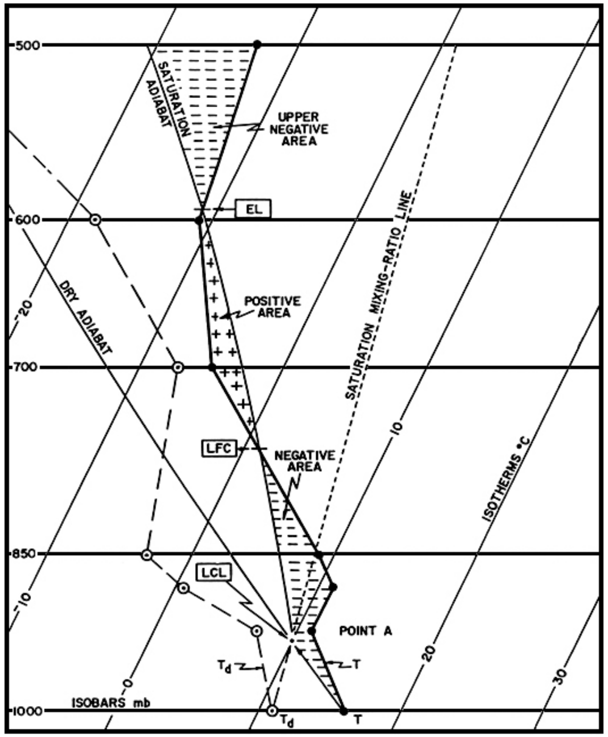
Mean Simulated ISMR



June-September monthly precipitation (mm/day) from satellite observations (TRMM) and from model (WRF) simulations showing high precipitation over BoB, west of WG, and near the Himalayan foothills.

Simulated CAPE and CINE





- **BoB is characterized by high CAPE and CINE Over EIO, the CINE values are nearly zero.**
- **This results in lot of precipitation in the model over EIO.**
- **This could motivate us to have a convective closure based on the ratio of CINE and boundary layer turbulent kinetic energy as the control parameters.**

$$m_{cb} = c_1 W \exp(-c_2 \mathrm{CIN/TKE}),$$

TKE Turbulent kinetic energy

$\frac{1}{2}(u'^2 + v'^2 + w'^2)$, averaged horizontally and vertically below Cu base.

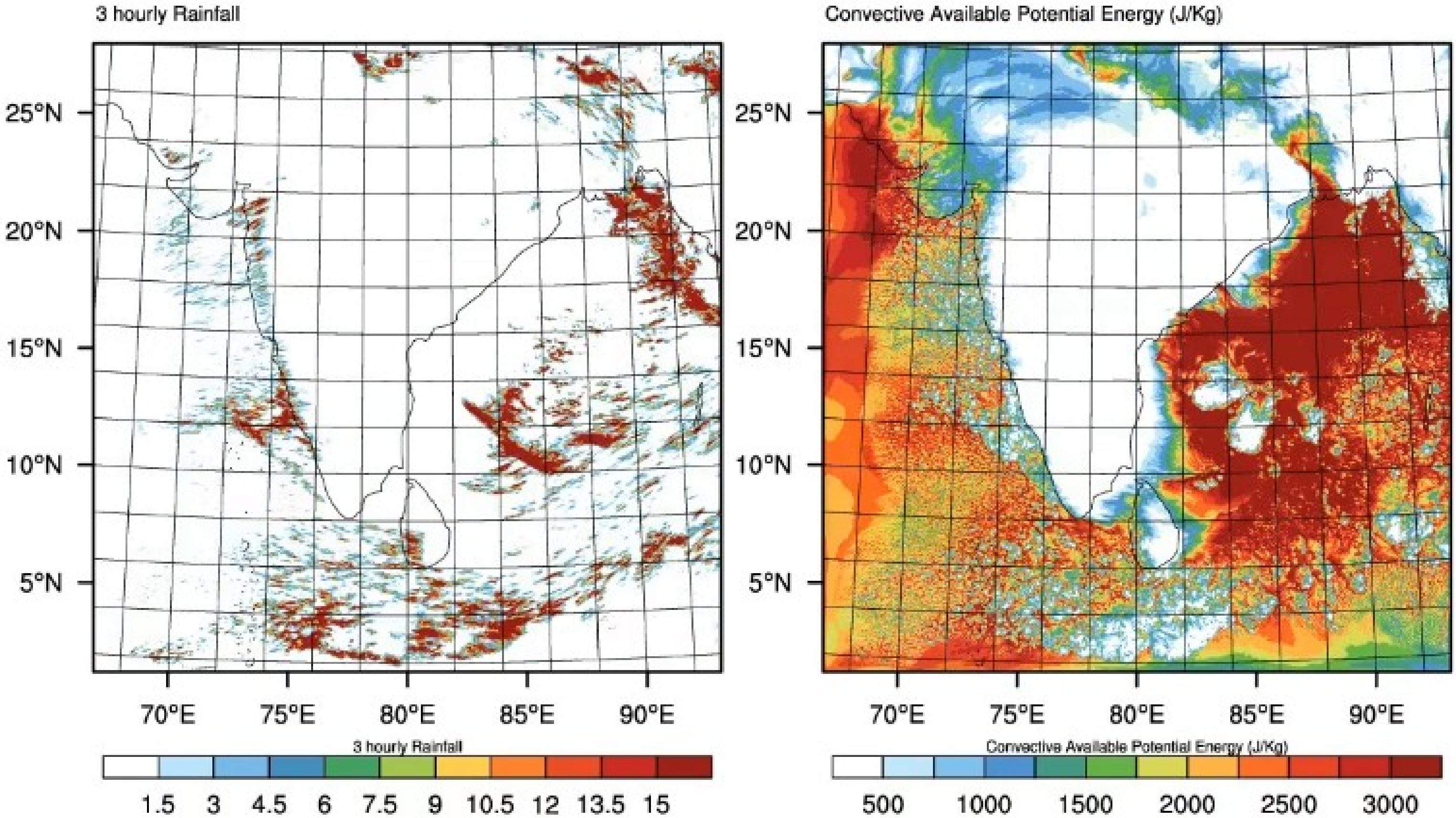
W Vertical velocity scale in CIN closure

$W = a\mathrm{TKE}^{1/2} + b$ for any a or b.

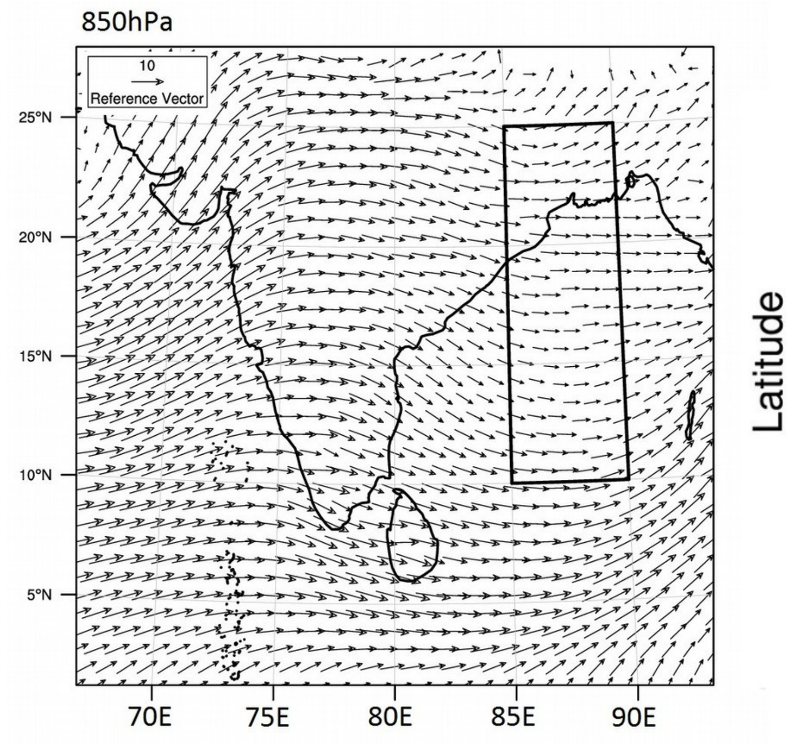
(Fletcher et al 2009)

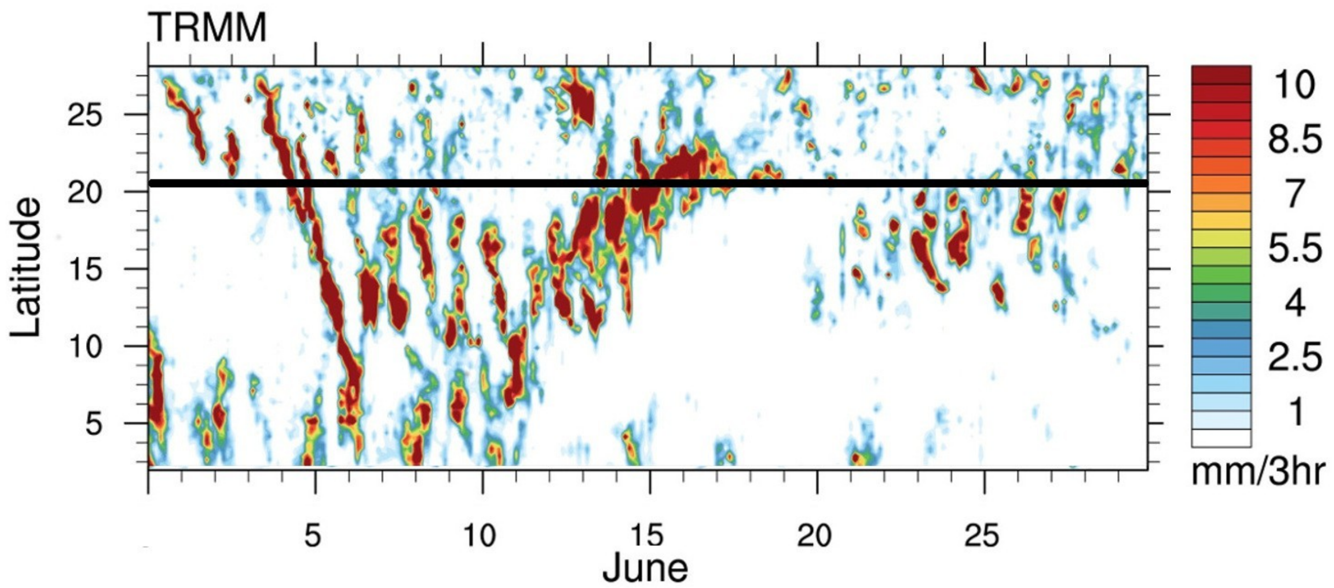
CAPE Consumption by MCSs

- Significant contribution to overall precipitation came from Mesoscale Convective Systems.
- One such MCS is the southward propagating one over the BoB.



Southward Propagating MCSs over BoB

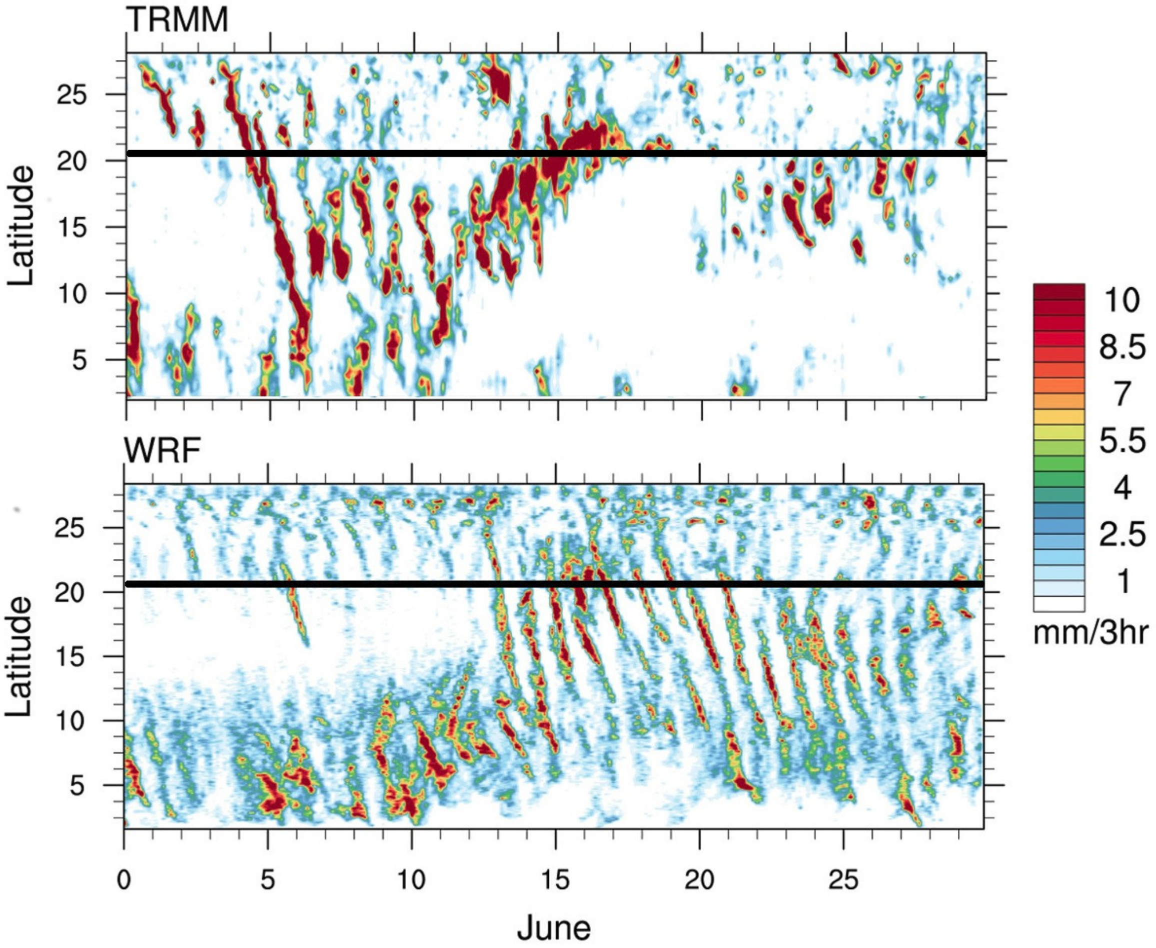




- **These systems move orthogonal to lower tropospheric winds and in the direction of mean mid-tropospheric winds.**
- **The speed of propagation can not be explained solely by mean wind speeds at any level.**

Jain et al. (2018), Journal of Geophysical Research: Atmospheres, 123, 3893–3913.

Southward Propagating MCS over BoB



Latitude-time Hovmoller plot of observed (Tropical Rainfall Measuring Mission) and modeled (Weather Research and Forecast, 3Micro) precipitation averaged over 85–90°E over the Bay of Bengal. The horizontal line refers to mean coastline over 85–90°E.

Southward propagations were found to be most prominent during the pre-monsoon months of May and June

These mesoscale diurnal southward propagating precipitation episodes are Embedded in large-scale northward propagations.

Southward Propagating MCS

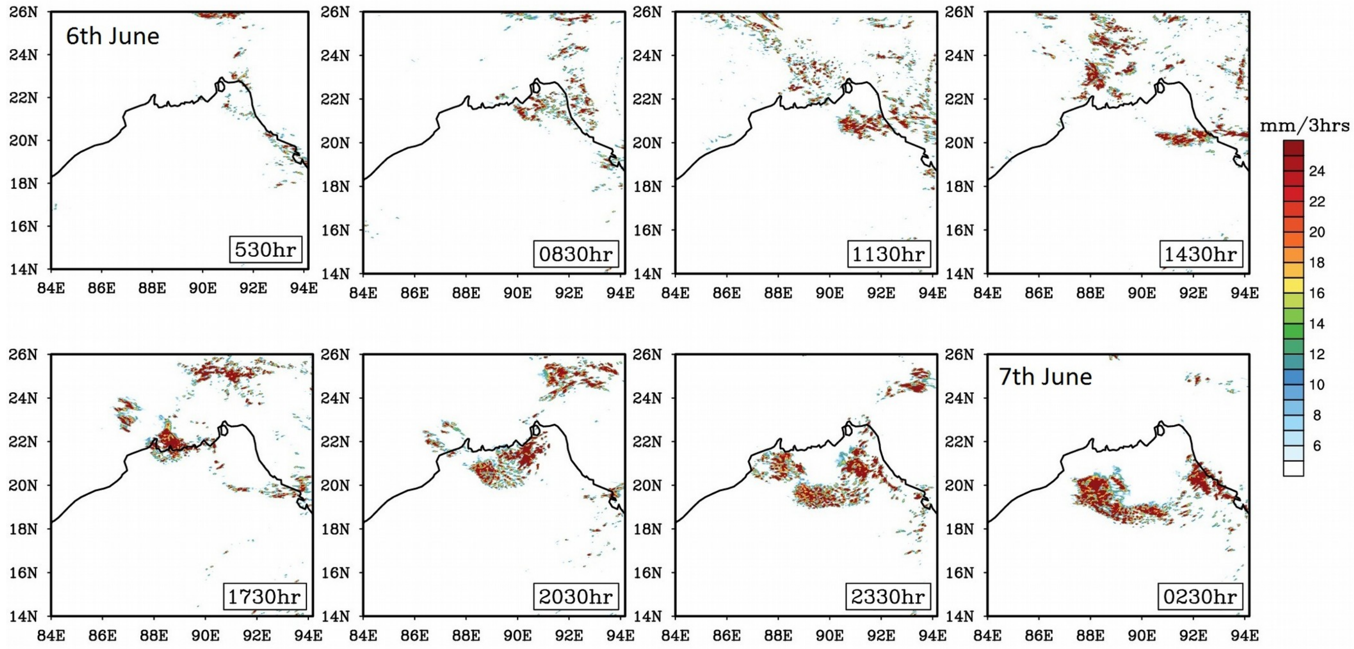
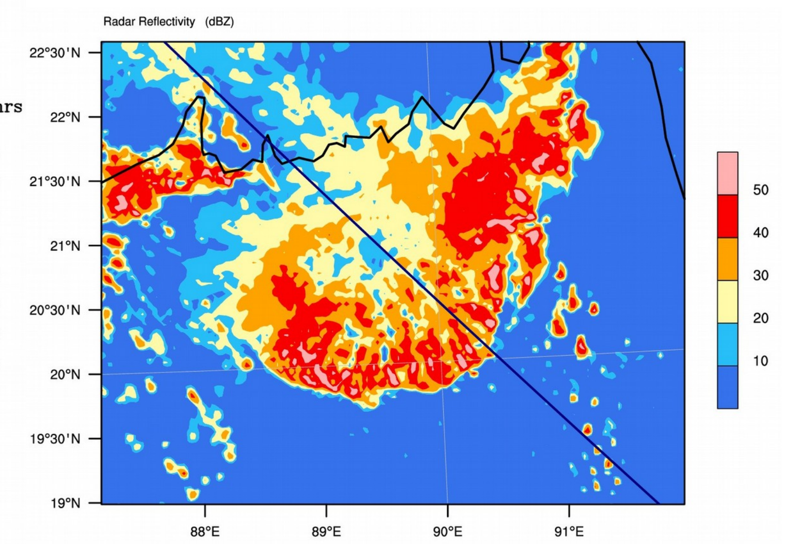


Figure shows model-simulated 3-hourly precipitation for one of the propagating episodes.

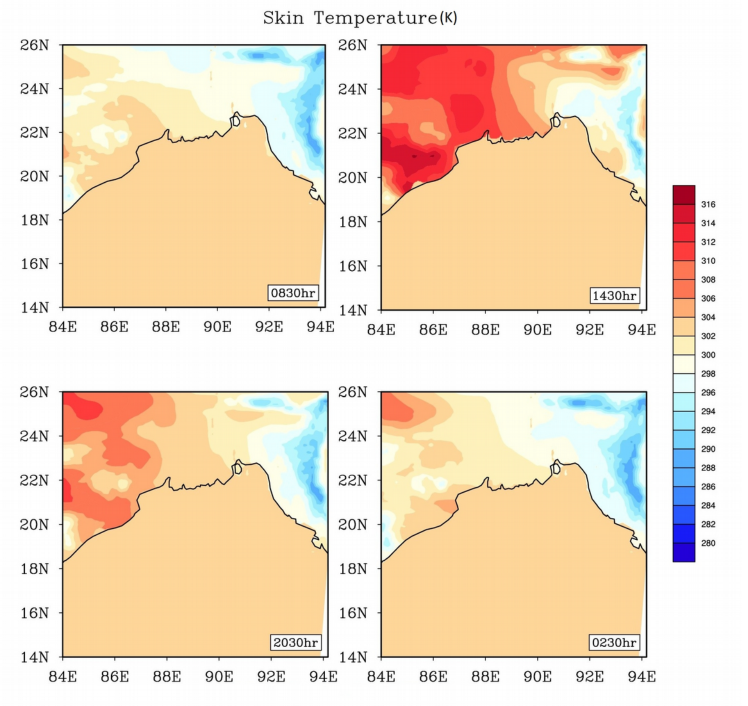
Comparing this with the radar echoes reported by Houze (2004), our model is able to simulate the structure of these precipitation events reasonably well.



Maximum radar reflectivity in dBZ simulated at 2030 hr on 6 June

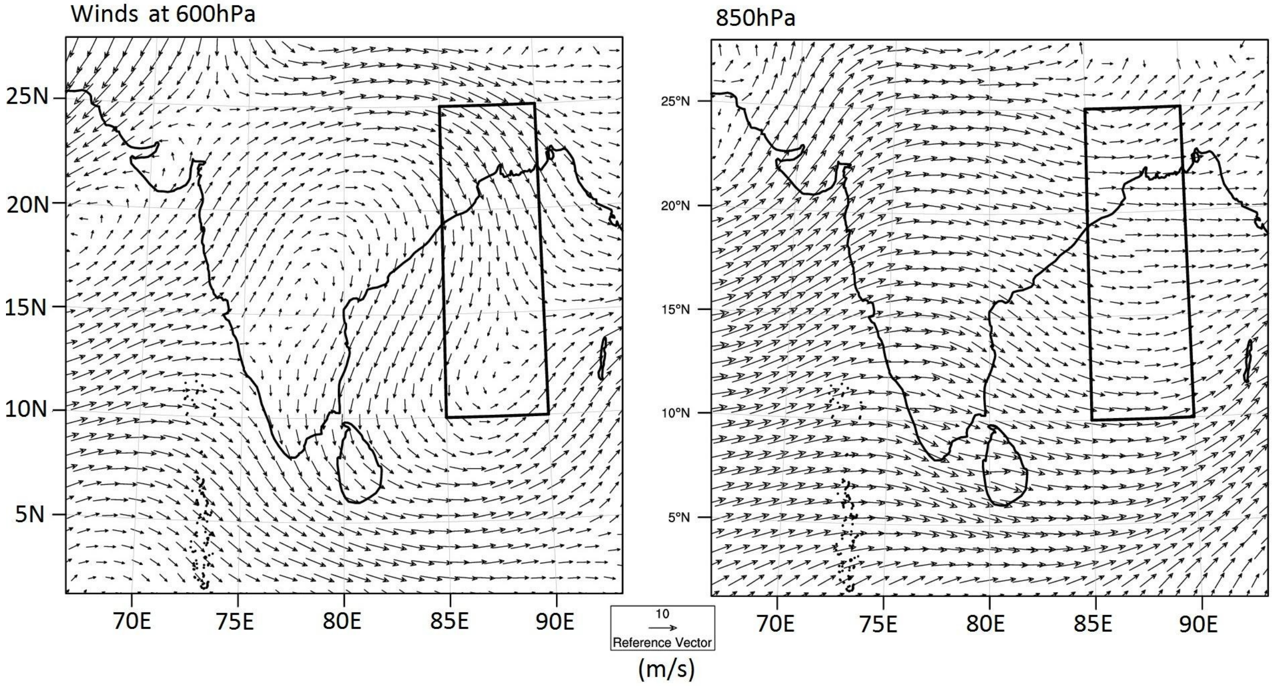
Leading convective/trailing stratiform bow structure agrees well with the one reported in Webster et al. (2002) and Houze (2004).

Surface Temperature and Winds



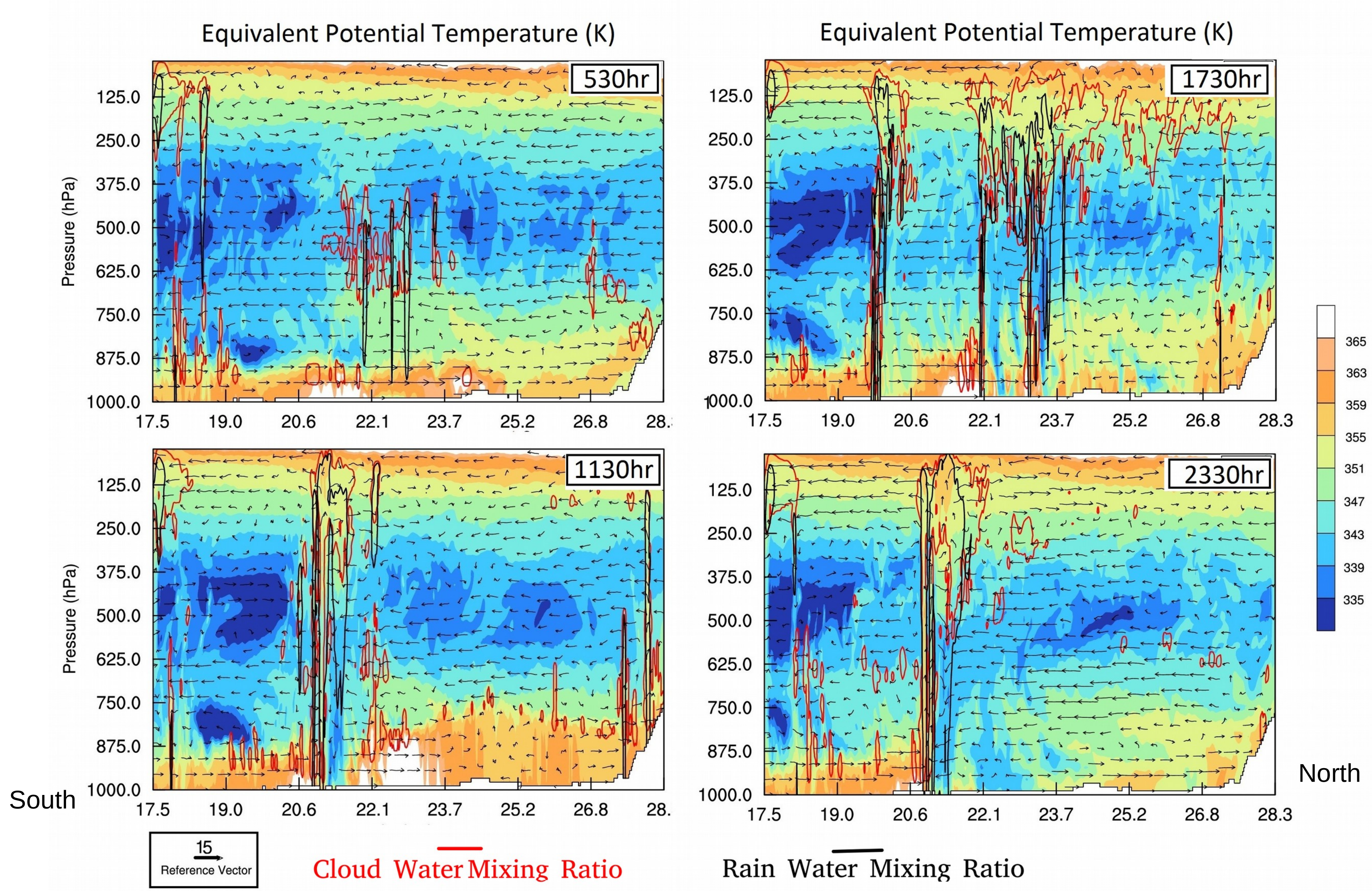
The diurnal cycle in surface temperature over the land is shown here.

Convection is triggered at around 1430hrs



- **Miyakawa and Satomura (2006) showed seasonal mean 600-hPa winds to have a southward component.**
- **We found the mid tropospheric winds (from 700 to 500 hPa) to be in the direction of propagations.**
- **The mean magnitude of 600-hPa winds (10 m/s) was lower than the overall speed of the propagating MCS (15 m/s)**

Cross-Section of Propagating System

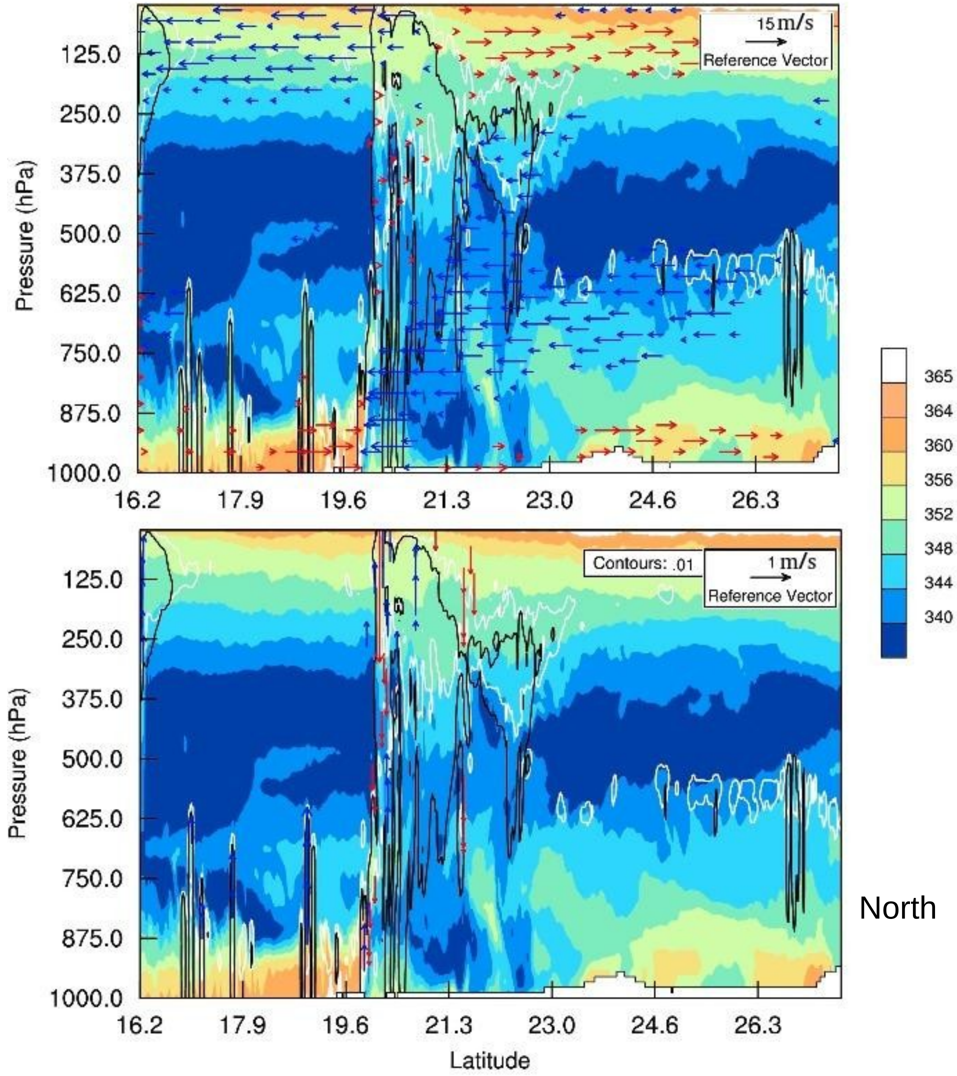


The System initiates between 530 and 1130hrs, intensifies till 1730hrs and start propagating at 2330hrs. We can see downdrafts hitting the surface behind the system (blue shading)

Cross-Section of Propagating System

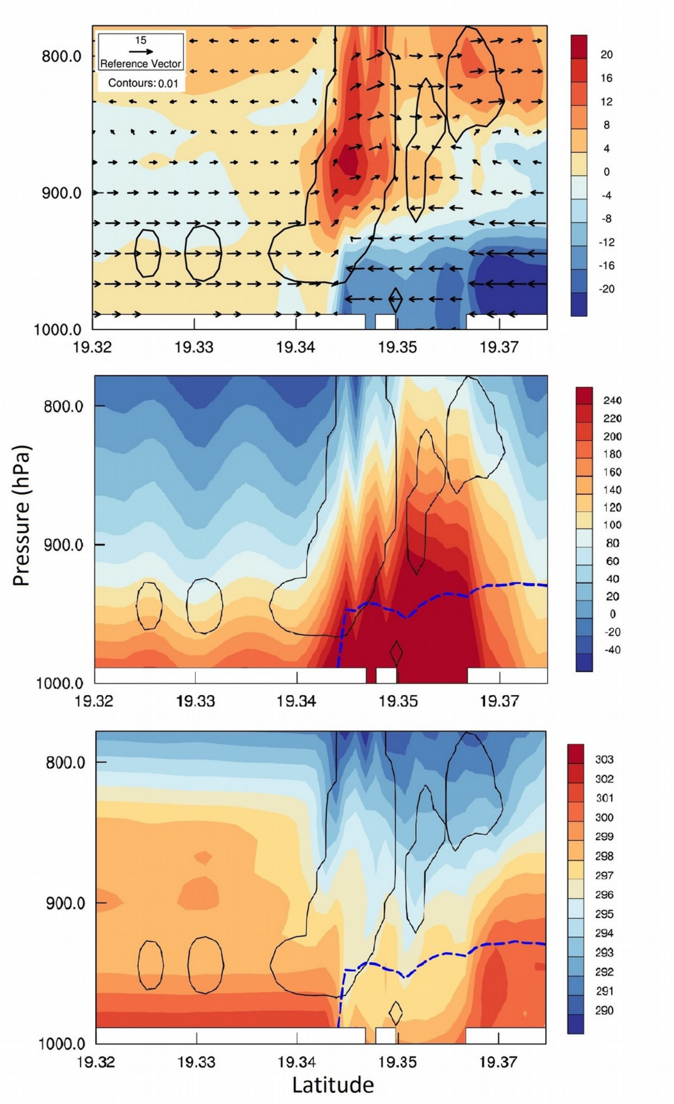
- Shown here are the meridional wind velocities (greater than 5 m/s, right) and vertical wind velocities (greater than 1 m/s, below) for the system. Black contours show rain water mixing ratio
- The southward winds behind the system is the rear inflow jet (blue vectors) and can be clearly seen.
- It 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.

South



North

Near Surface Structure of the System



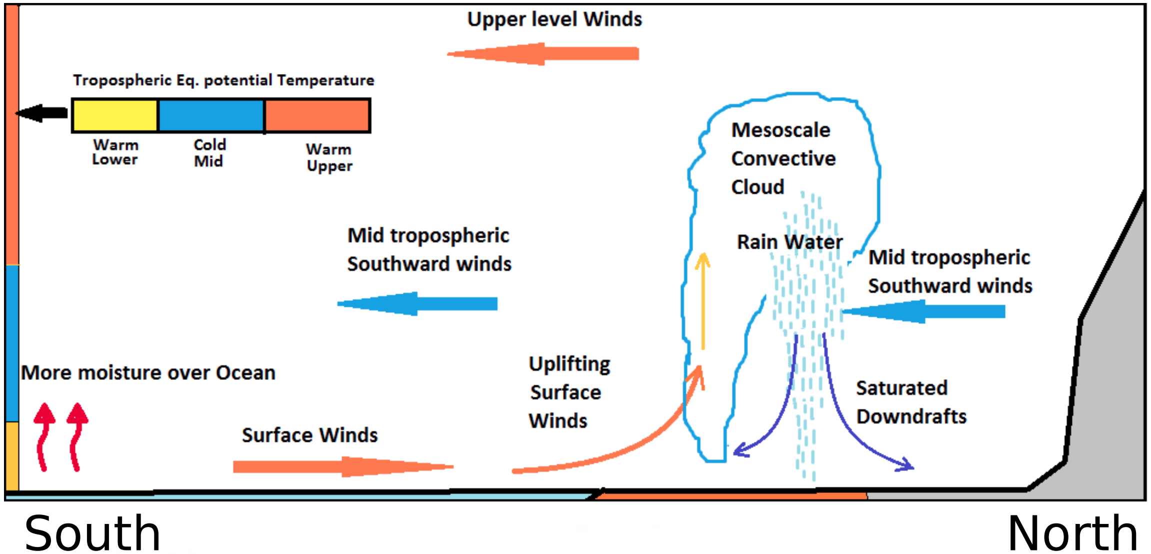
Top panel shows the near-surface anomaly of **equivalent potential temperature** of the episode at 2330 hr on 6 June.

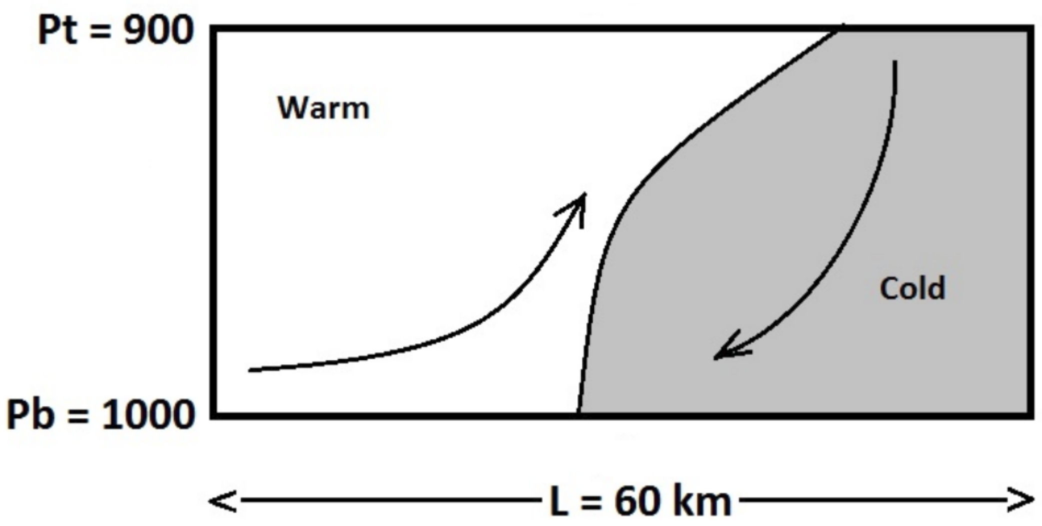
- **The anomaly is calculated by taking difference from when the system was not present, that is, at the exact location in this figure 6 hr back.**

- Figure also shows the **perturbation pressure (middle panel)** and absolute temperature values for the system (**lower panel**).

- In this cold pool region, **the mean meridional speed was found to be about 15 m/s**.

The Structure of MCS: Mechanism





- As the cloud system is initiated and Intensifies, it produces rain water, which comes down.
- Some or all of this rain water re-evaporates causing the formation of downdrafts.
- These saturated downdrafts hit the surface and spread everywhere.
- When this cold pool air converges with warmer surface air, it tries to lift this warm air.
- Since the surface wind is usually north-westwards, the maximum convergence between downdraft and warmer surface air happens to be south of the convective system.
- This is like gravity current, where the colder liquid tries to lift the warmer fluid.
- We can easily see that the speed of the movement of the system will be the speed at which the convergence zone (Figure below) moves

Speed of Propagation

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.

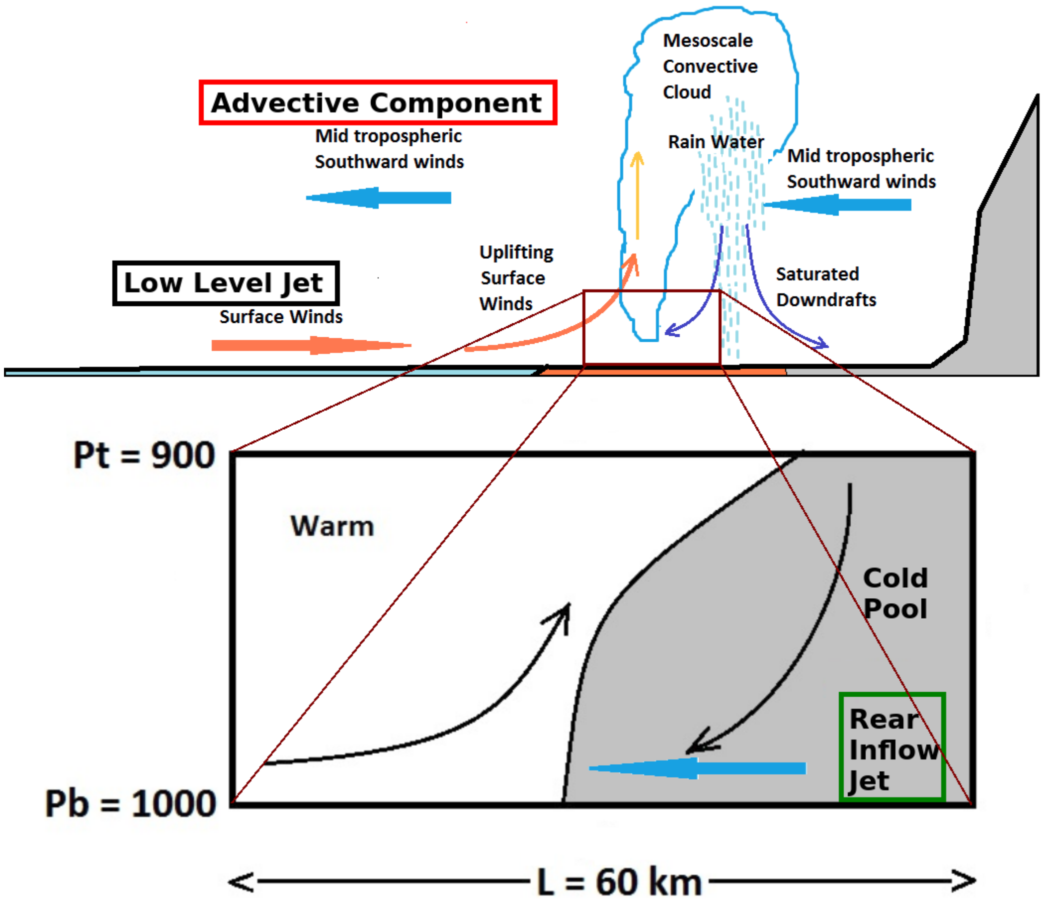
The depth of cold pool in our simulation is around 700 m to 1 km.

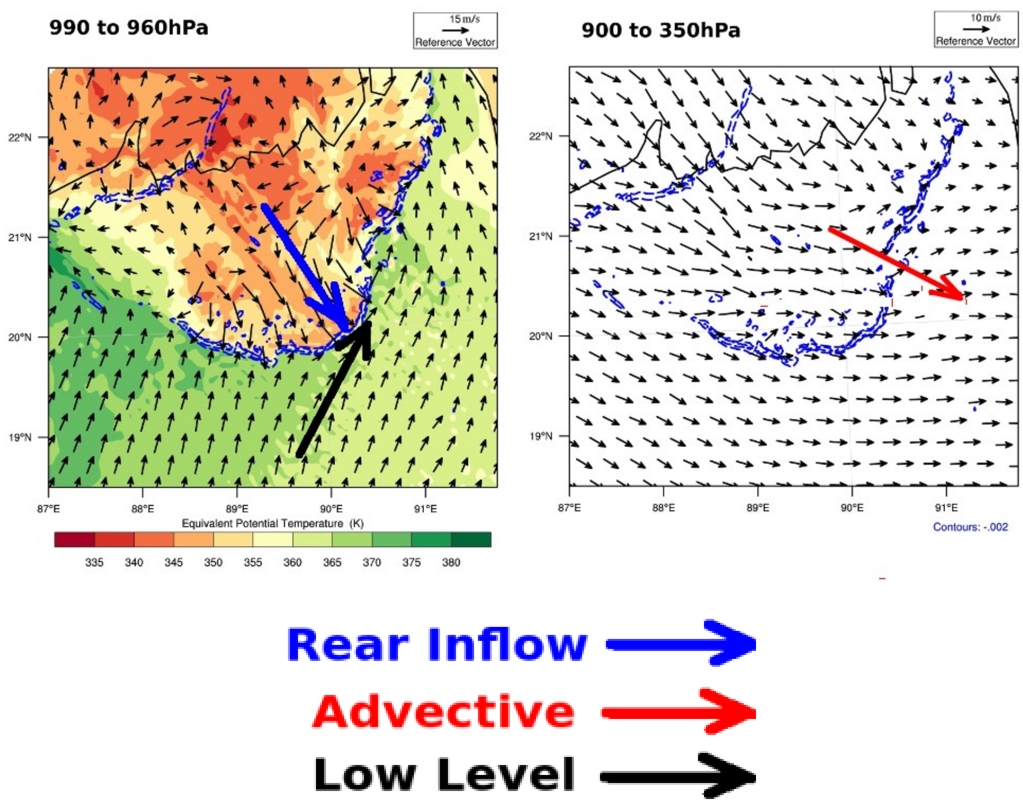
The temperature difference is around 5 to 10 K, and the environmental air temperature is 300 K. Then the gravity current speed is in the range of **12 to 18 m/s**.

A better understanding of the environmental contribution to the propagation of the MCSs comes from **Corfidi et al. (1996) and Corfidi (2003)** approach.

For Corfidi 1996 and 2002, Lets define few vectors

Low Level Jet – Surface winds ahead of the system
Advective component of wind is mean mid-tropospheric winds
Rear inflow (downdraft near surface) is surface winds behind the system





Corfidi 1996 and Corfidi 2003

1. Low Level Jet – Surface winds ahead of the system
2. Advective component of wind is mean mid-tropospheric winds
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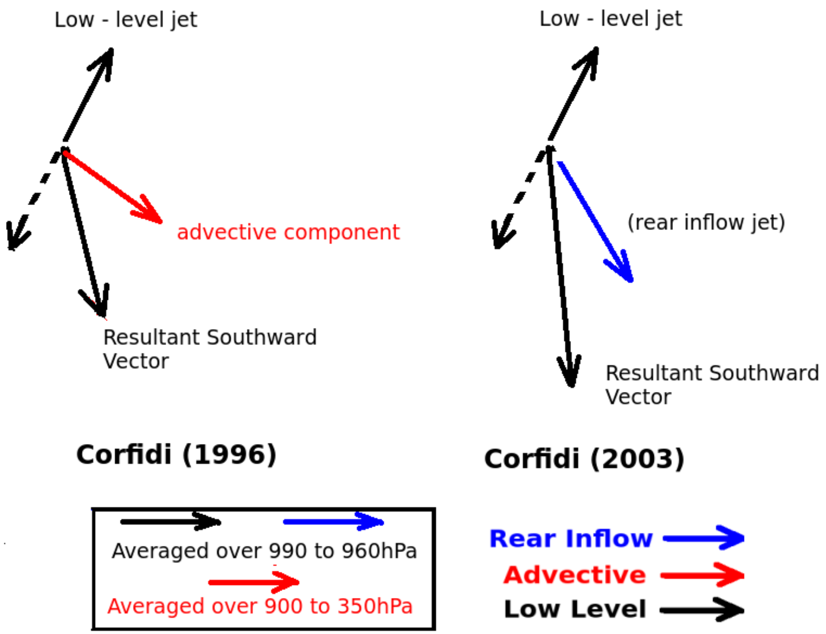
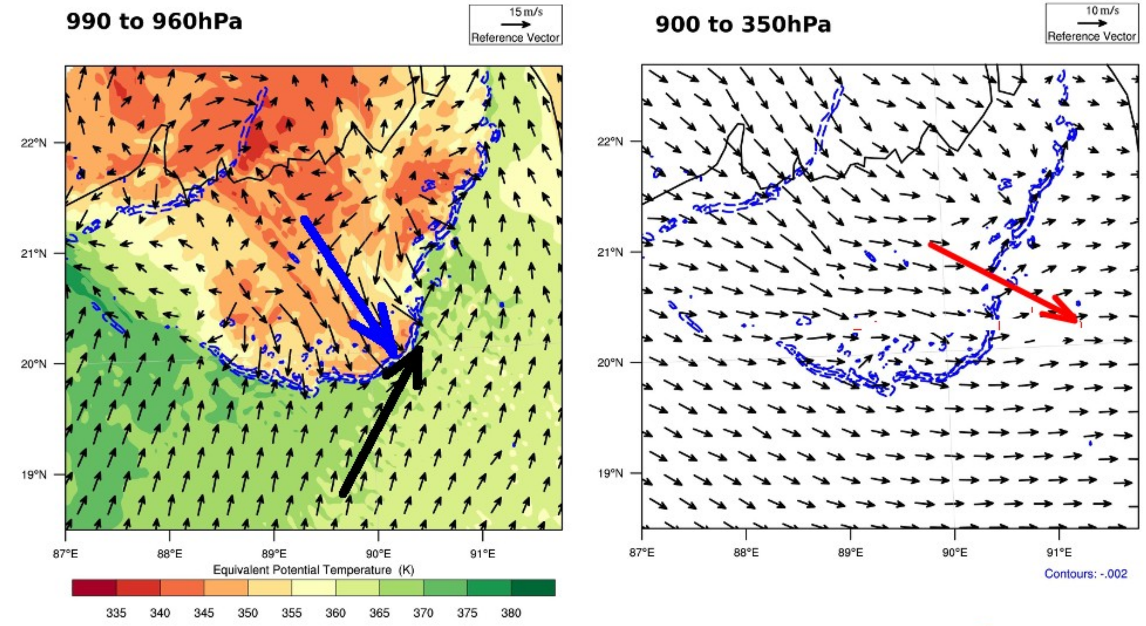
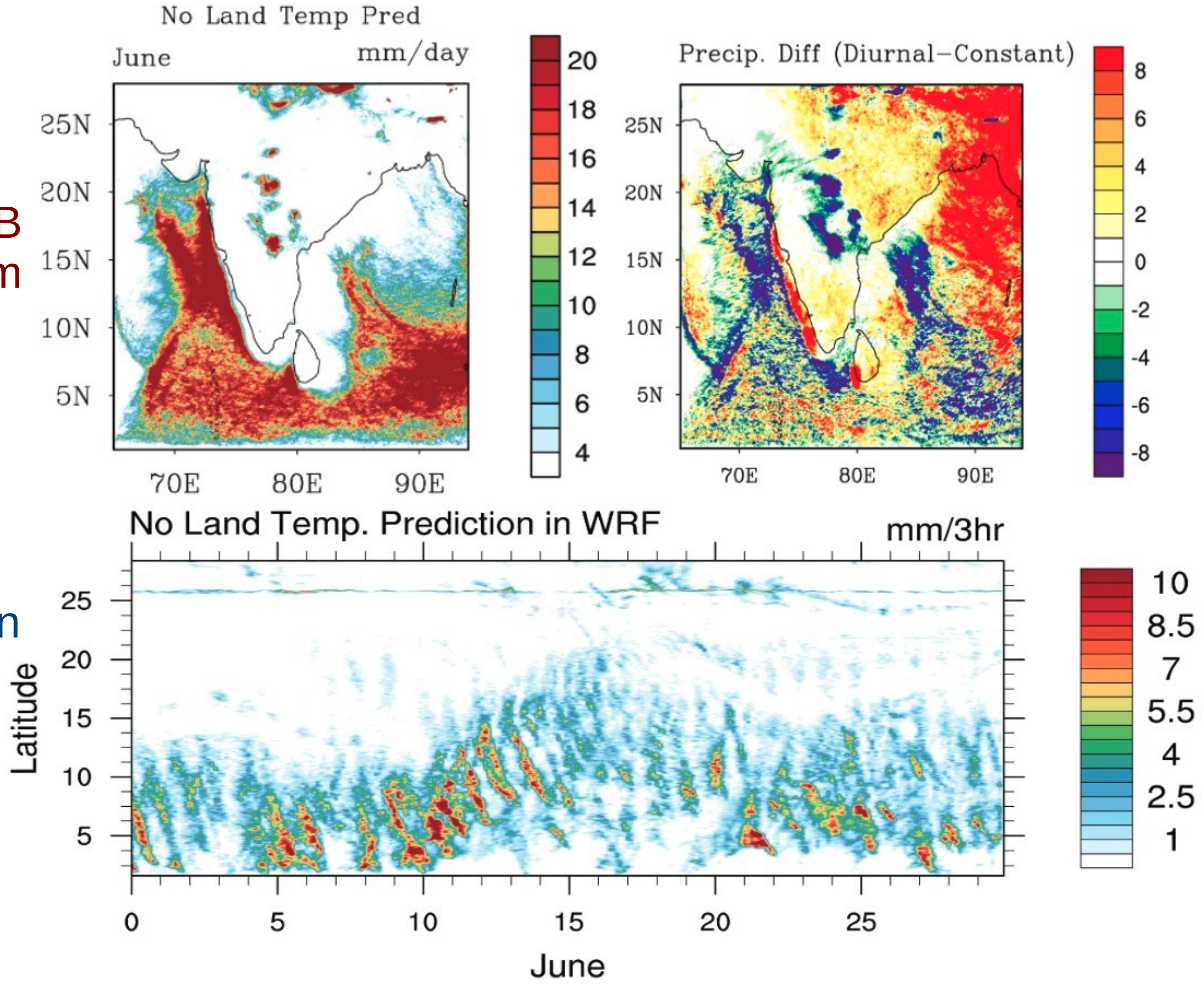




- **Figure shows equivalent potential temperature averaged over 990 to 960 hPa, the low-level velocities associated with cold pool and low-level jet, and the cloud-scale velocities (averaged over 900 to 350 hPa).**
- **The leading edge does move in the direction of vector sum of the cloud layer velocity (or cold pool velocity, rear inflow jet) and the negative of low-level jet (free surface winds ahead of the system).**

Effect of Diurnal Land Heating

- Most of the north BoB precipitation comes from systems originating over land.
- To understand the role of diurnal heating we conducted experiments in land-surface temperature was prescribed.
- The southward propagations are missing from this simulation in the north BoB though there are MCSs which initiated over ocean and propagated south.



Simulations with Cumulus Parameterization

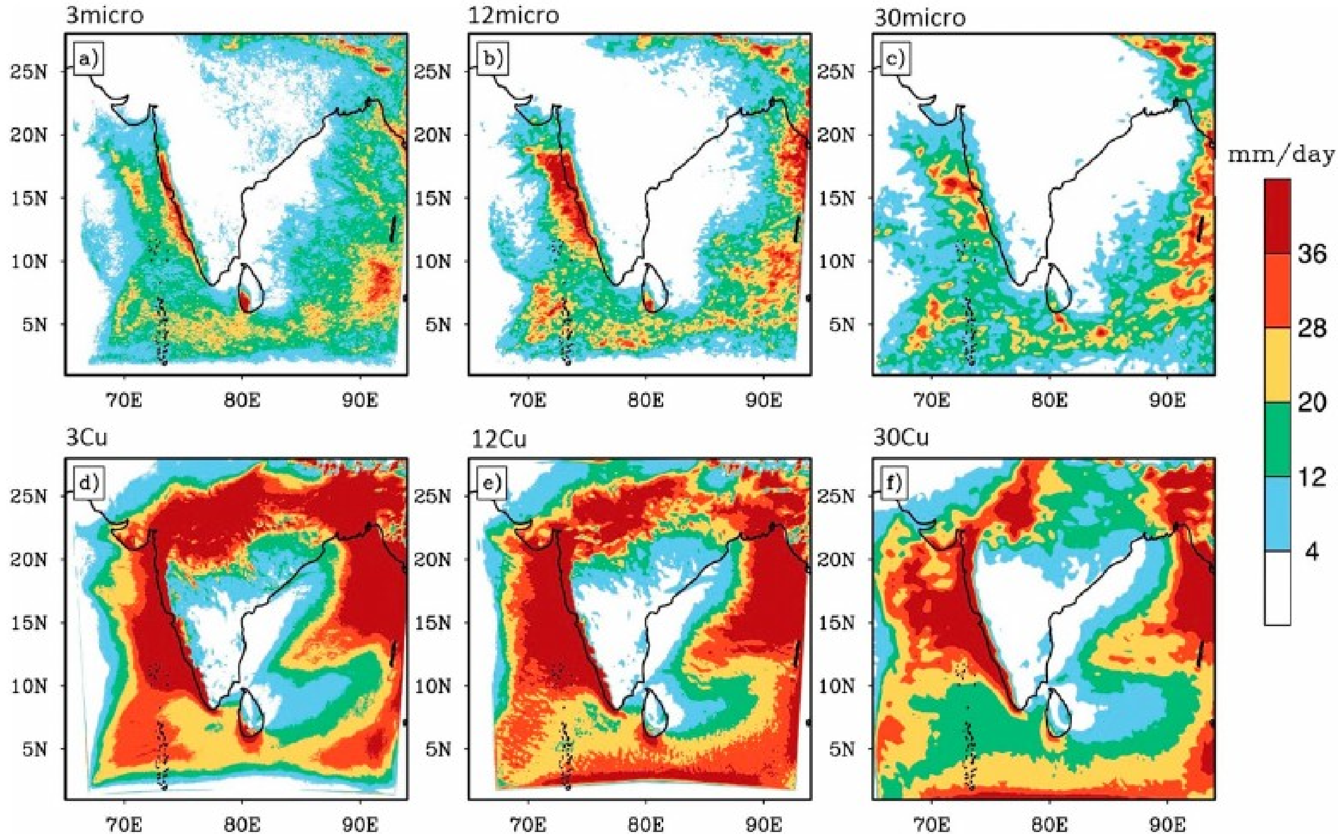


Figure 13. Monthly mean (June) model precipitation at 3, 12, and 30 km horizontal resolutions and with explicit (a–c) microphysics and (d–f) cumulus parameterization. The details of the simulations are mentioned in Table 1.

- Cumulus parameterization (KF) gives rainfall everywhere
- Southward propagations not simulated

CAPE Consuming Characteristics of MCS

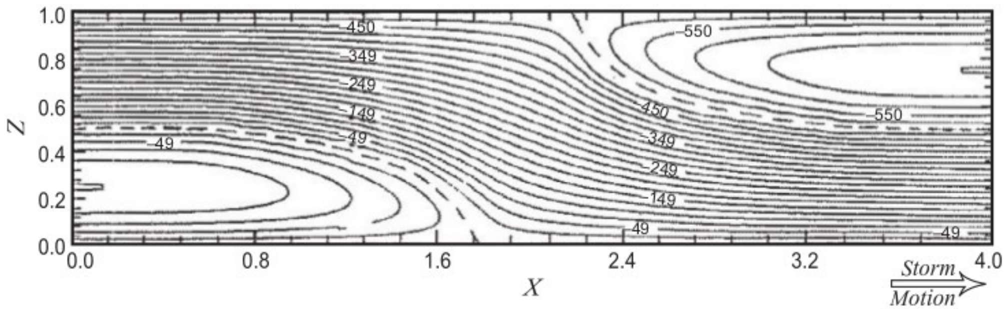
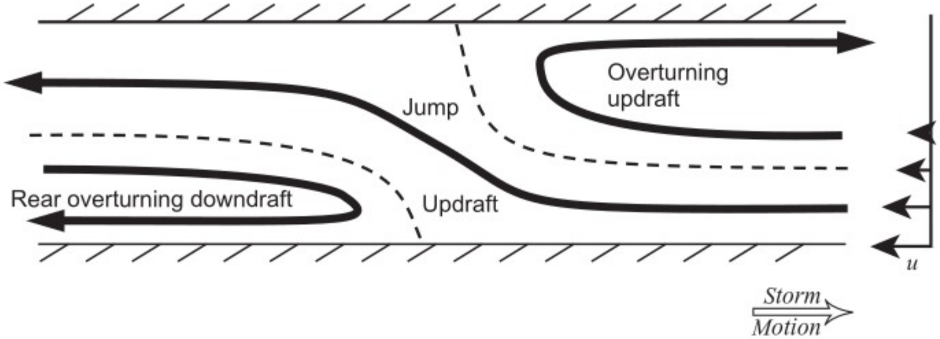


FIGURE 9.20 Schematic diagram of the airflow in a squall-line MCS occurring in an environment with low-level shear, as indicated on the right-hand side. The flow consists of three characteristic branches: the jump updraft, the rear overturning downdraft, and the overturning updraft. *Adapted from Moncrieff (1992). Republished with permission of the Royal Meteorological Society.*



$$\frac{1}{2}(u^2 + w^2) + \frac{p^*}{\rho_0} - \int_{Z_{in}}^{Z_{out}} g\frac{\theta^*}{\hat{\theta}}dz = \quad \text{Constant on a Streamline}$$

where u = horizontal velocity, w = vertical velocity, p* = pressure perturbation (deviation from hydrostatic pressure), θ^* = perturbation potential temperature, $\hat{\theta}$ = environmental potential temperature, Z_{in} and Z_{out} refers to height of streamline. The above equation states that the CAPE (or energy from buoyancy) does not necessarily manifest itself as vertical motion. It may get converted to any combination of enthalpy $(\frac{p}{\rho_0})$, horizontal motion, and vertical motion.

CAPE is consumed in creating vertical as well as horizontal motion of the MCSs. In such cases, we can not have closure assumptions based on local stability.

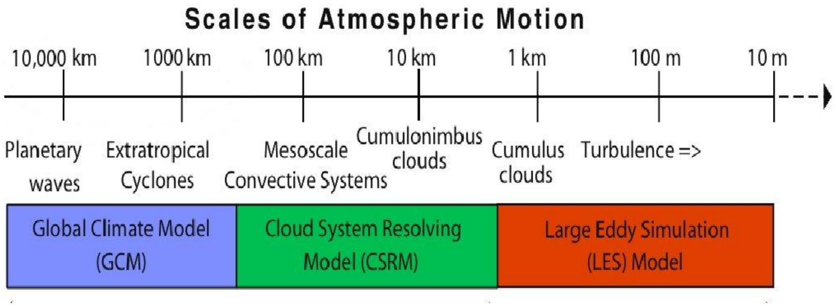
Summary (so far)

- Southward Propagating MCSs have gravity current structure
- They move with the velocity of vector difference of cold pool velocity and low level jet
- They are initiated due to diurnal heating for MCSs over north BoB
- They are also initiated over ocean when we switch off diurnal land heating

- We find that high model resolution is needed to resolve the updraft-downdraft pair.
- Using cloud microphysics exclusively becomes essential in simulating these mesoscale systems.

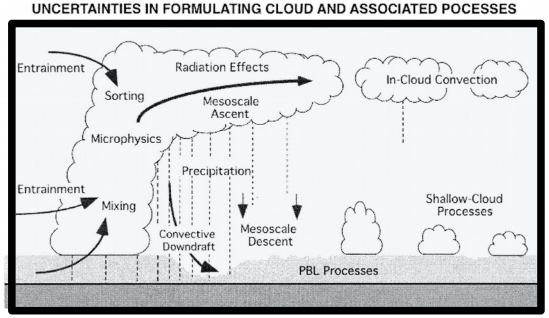
A closure based on CINE and TKE (or PDFs of local variables fluxes) can not solely be used in such cases where cloud organization and large scale forcing dominates the convective triggering. Including the effects of organized convection in a typical GCM parameterization could be essential.

Where can such closure can be used?

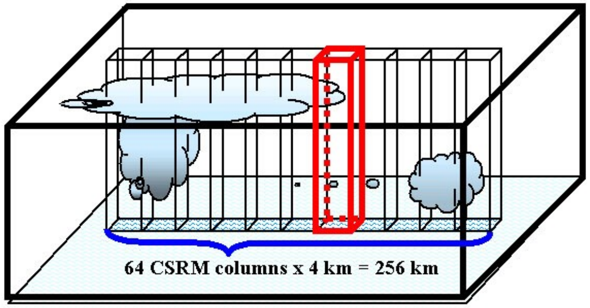


- governed by different equations
- applied to different scales
- used by different groups of researchers

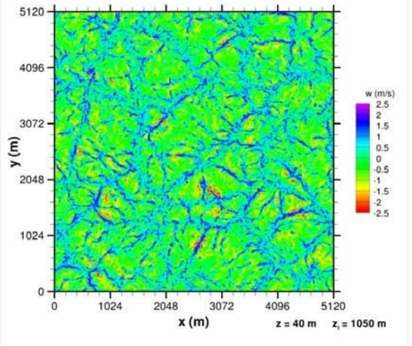
GCM – Typical Horizontal resolution ~ 50 to 100 km



C(S)RM – Typical Horizontal resolution ~ 1 to 5 km

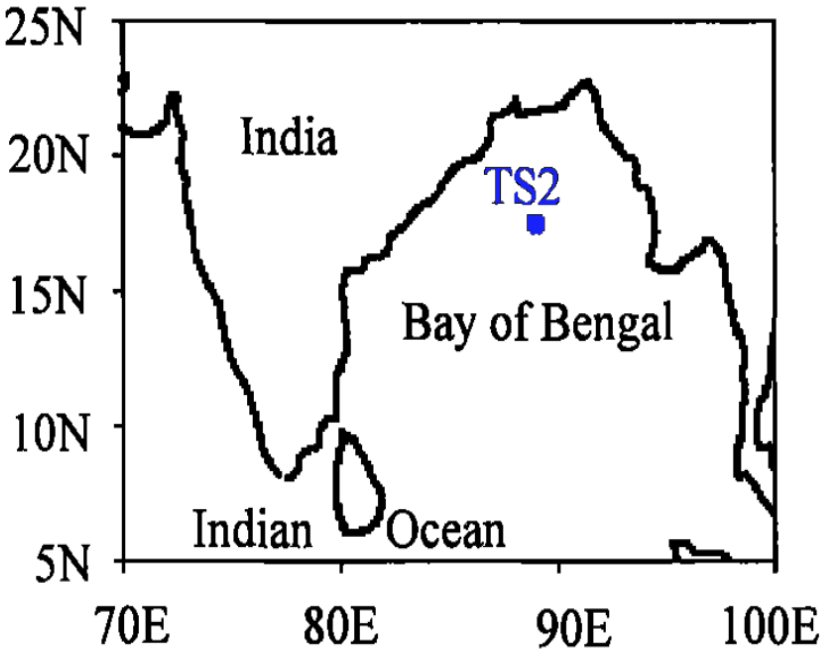


LES – Typical Horizontal resolution ~ 50 to 200 m



Model Details

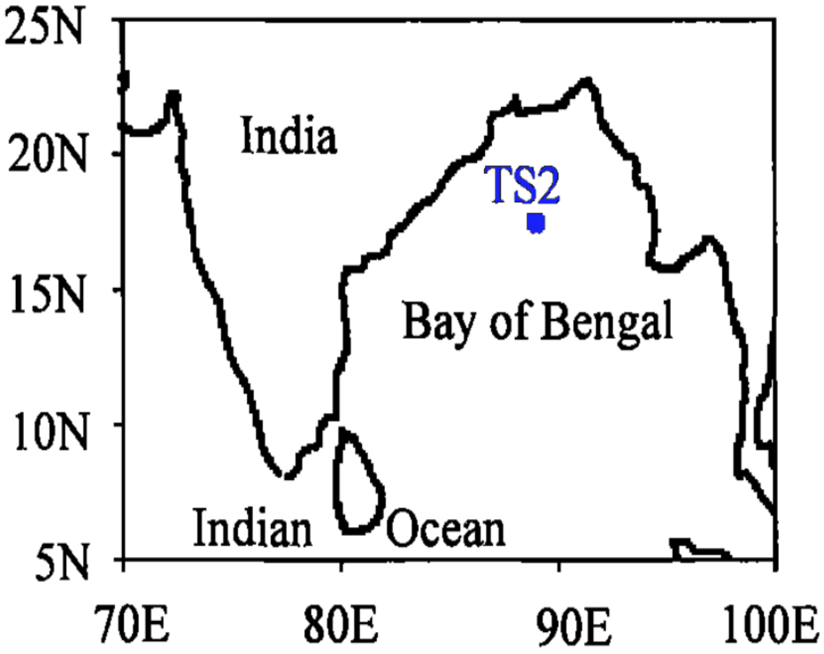
- **For the present study we use University of California Large Eddy Simulation (UCLALES) model version 2.0 developed by Stevens et al. (1998).**
- **Prognostic equations for winds, liquid water potential temperature, total water mixing ratio.**
- **Explicit warm-rain microphysics**
- **x-y periodic boundary conditions**
- **SST is specified and surface fluxes are calculated based on Monin-Obukhov similarity theory.**



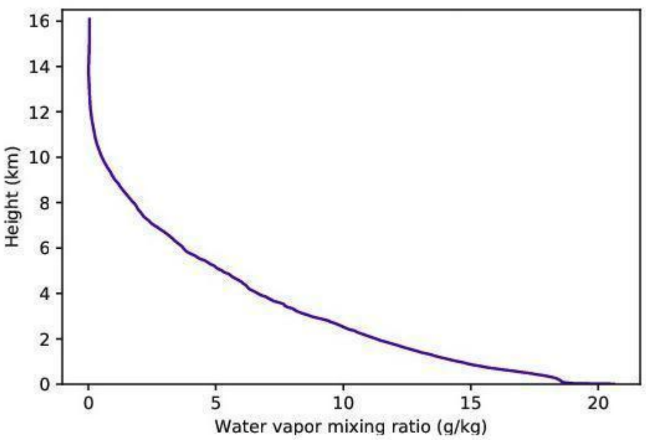
Map shows the Bay of Bengal and time series observation location (TS2) during BOBMEX.

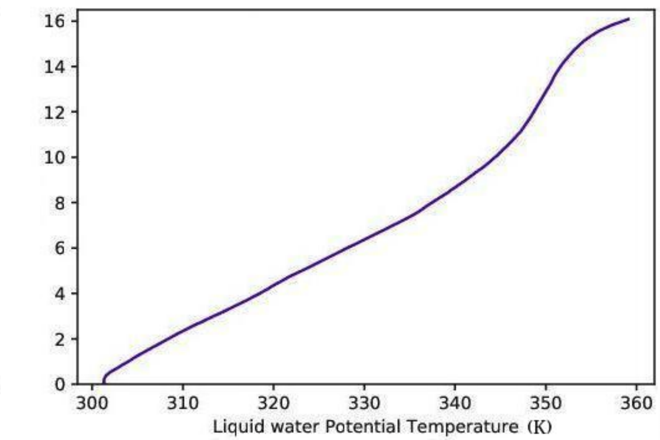
Experimental Details

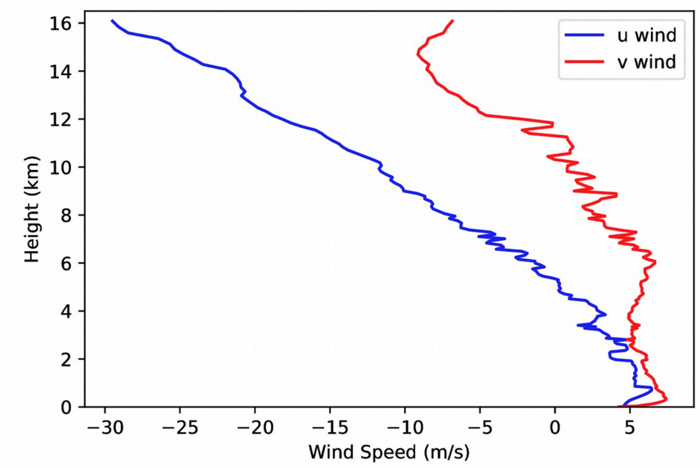
- 25.6x25.6 km Domain
- 100m horizontal resolution, 25m vertical resolution
- Domain centered at 17.5N
- Initial conditions for the model are taken from Bay of Bengal Monsoon Experiment (BOBMEX, Bhat et al. (2001) and Bhat and Chandrasekhar (2001)) which was carried out during June to August of 1999.
- SST varied from 298 to 303K in steps of 0.5K

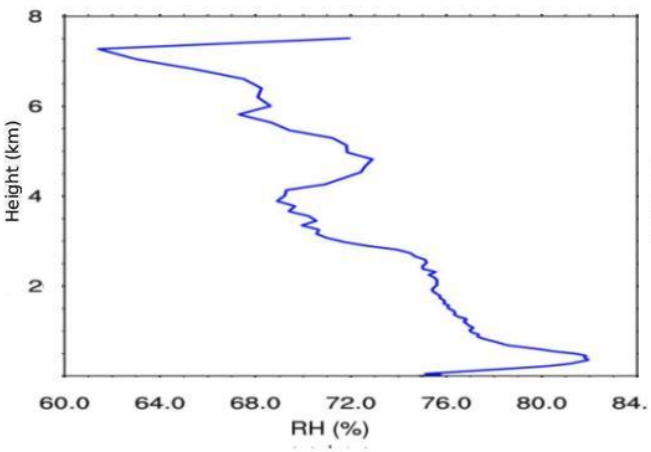


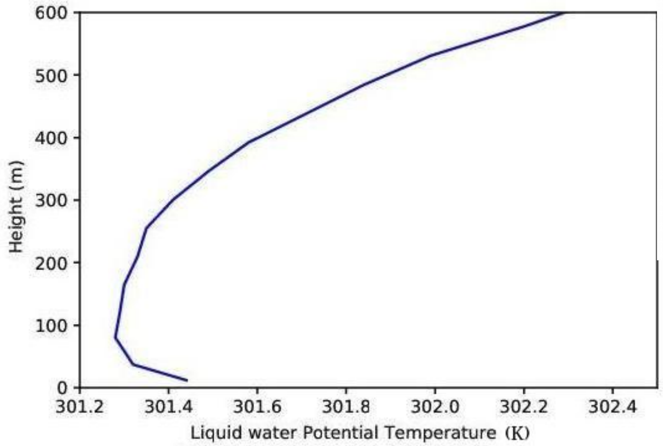
Initial BOBMEX Profiles







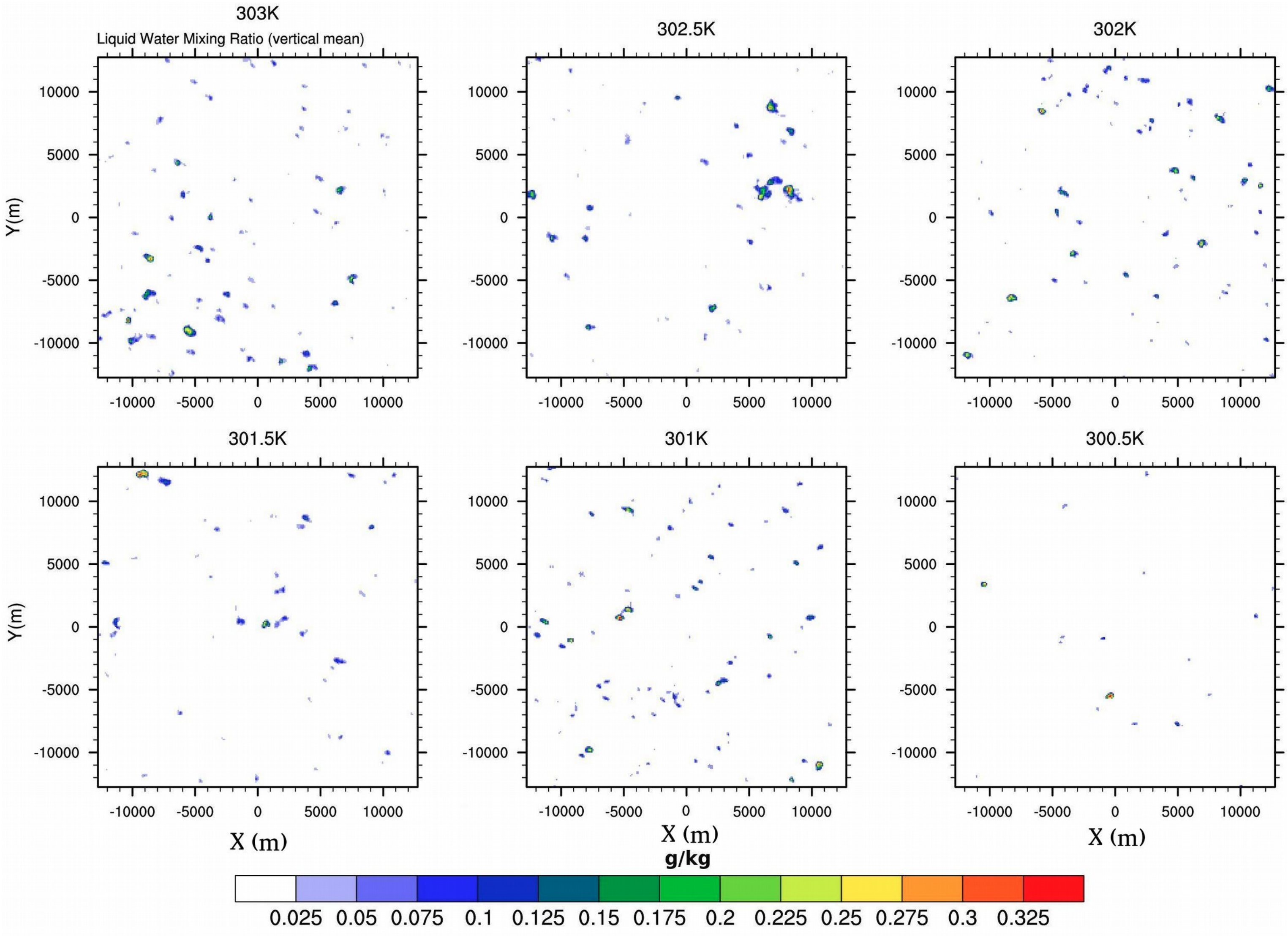




$$\theta_l = T\pi exp\left(-\frac{q_l L_v}{c_p T}\right)$$

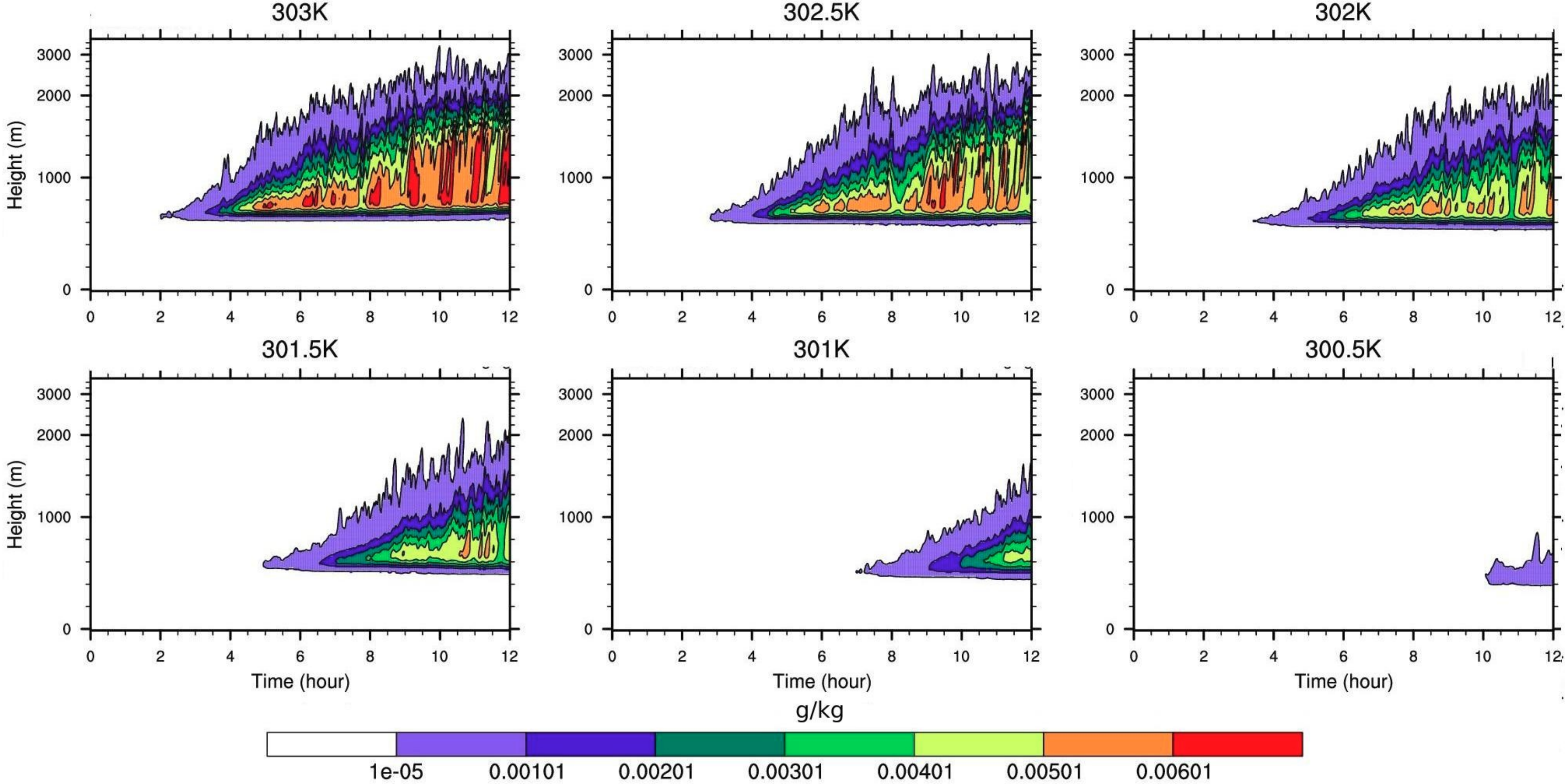
Initial input profiles to LES Note that although the mean sounding are upto 16km height, the model top is at 7.8km.

Simulated Clouds



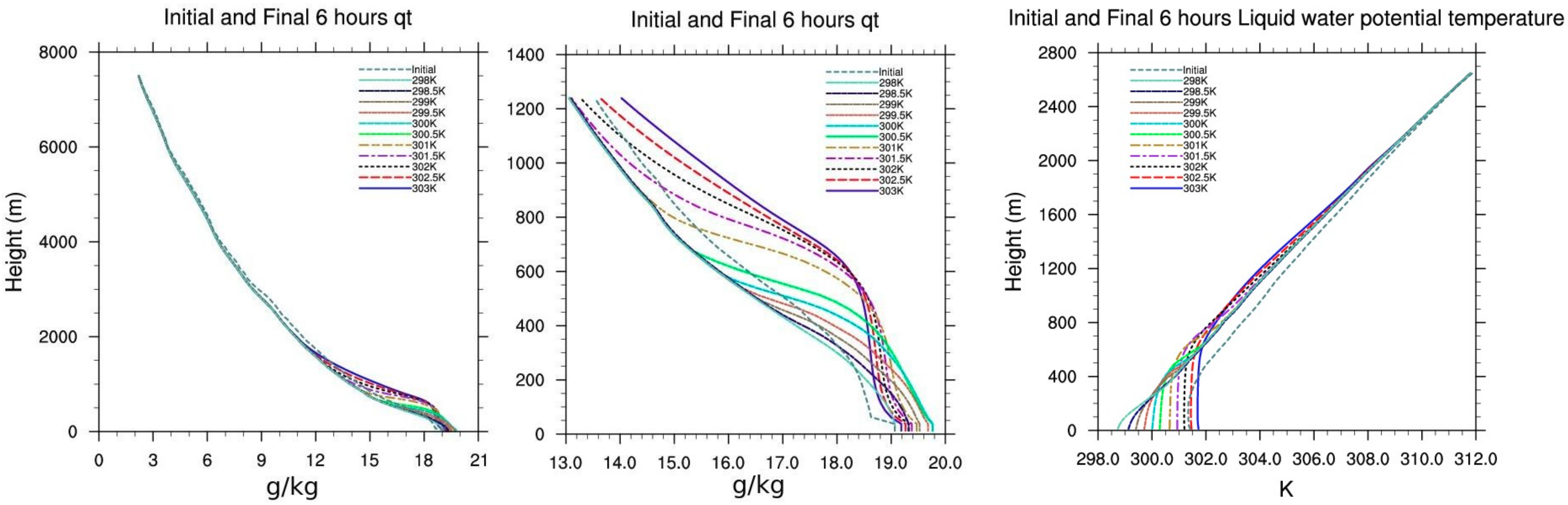
Snapshot of simulated vertical mean of liquid water mixing ratio for different SST values after 11 hours and 50 minutes of simulations.

Horizontal mean of Liquid Water Mixing Ratio



Simulated *x−y* mean of liquid water mixing ratio (g/kg) for different SST values. Note that no clouds formed below SST=300.5K.

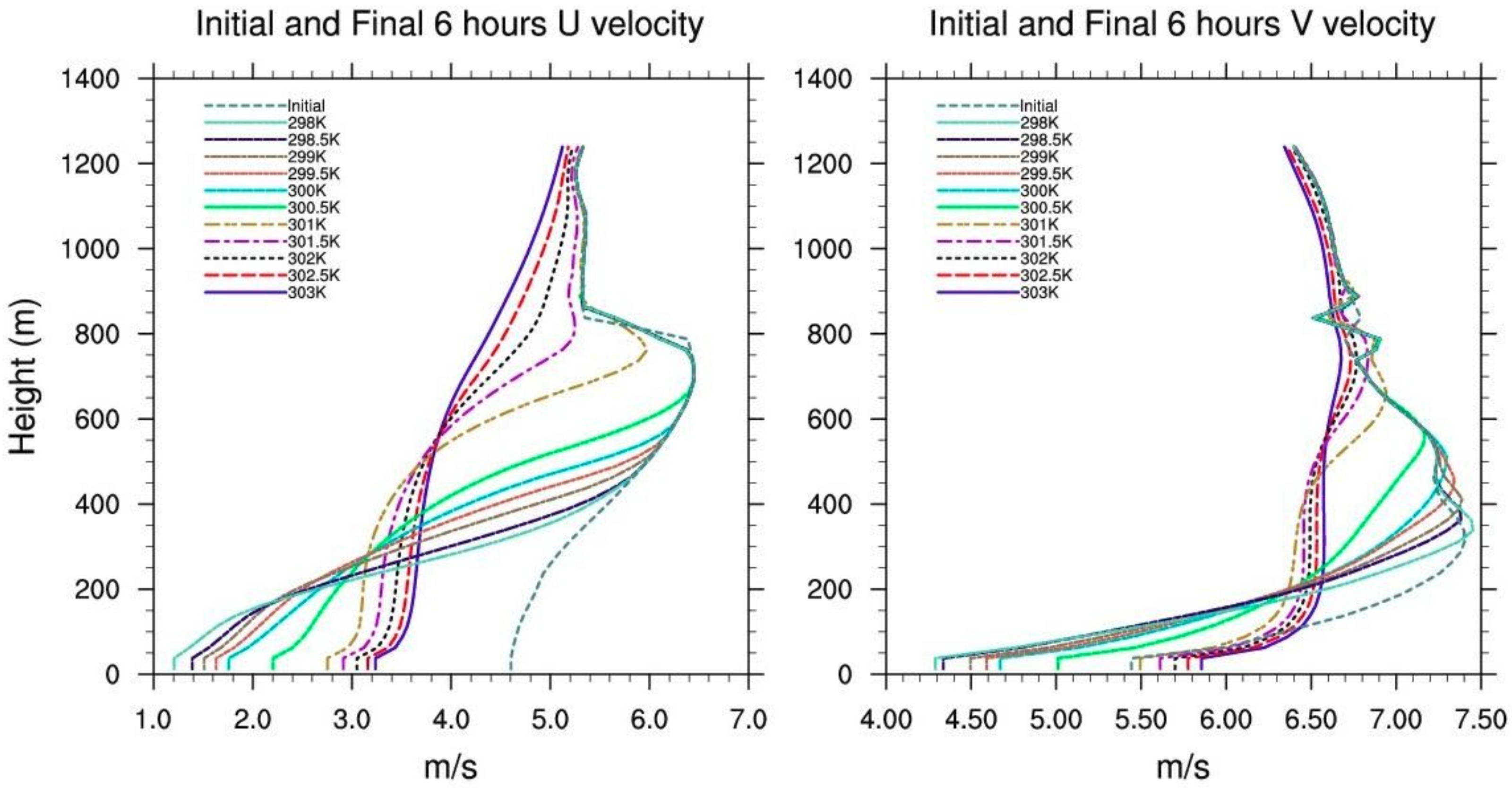
Total Water Mixing Ratio and θ_l



Left panels shows q_t for entire model domain, while mid panel zooms in on the lower troposphere. These panels show *x−y* mean of final 6 hour mean of model simulated total water mixing ratio (q_t) compared to initial sounding used as input.

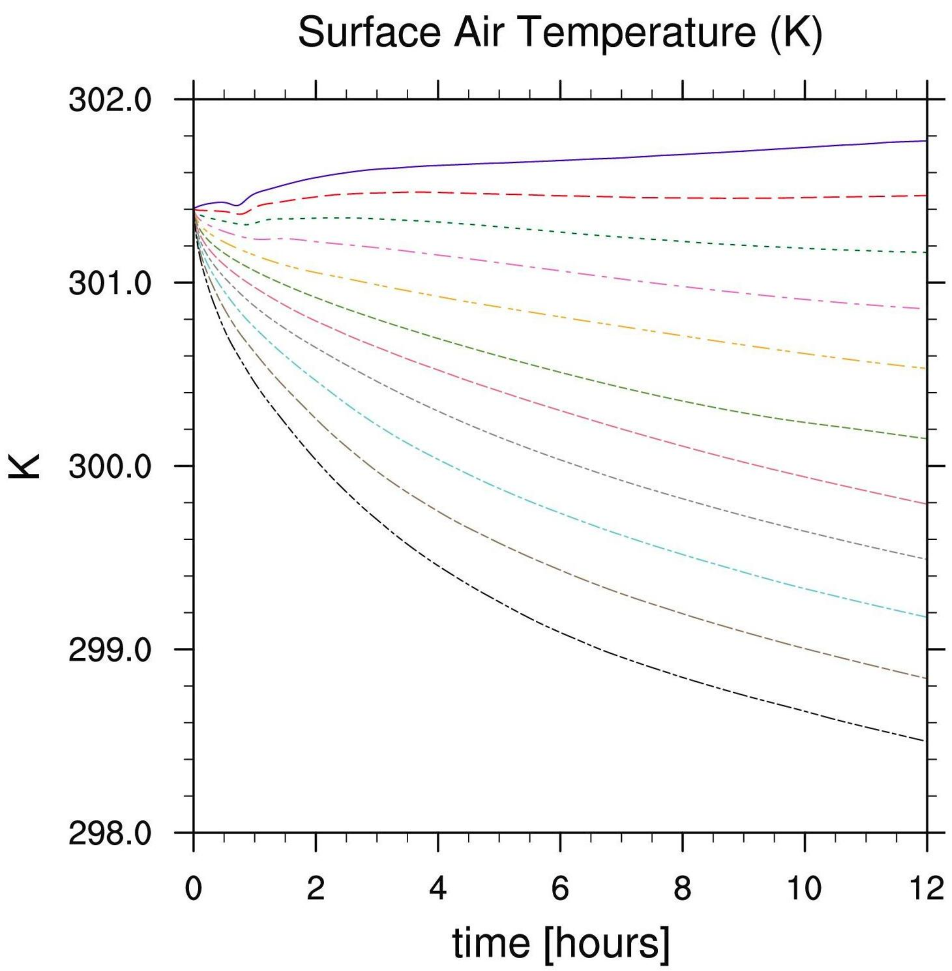
Right panel shows final 6 hour mean of model simulated liquid water potential temperature (θ_l) compared to initial sounding used as input.

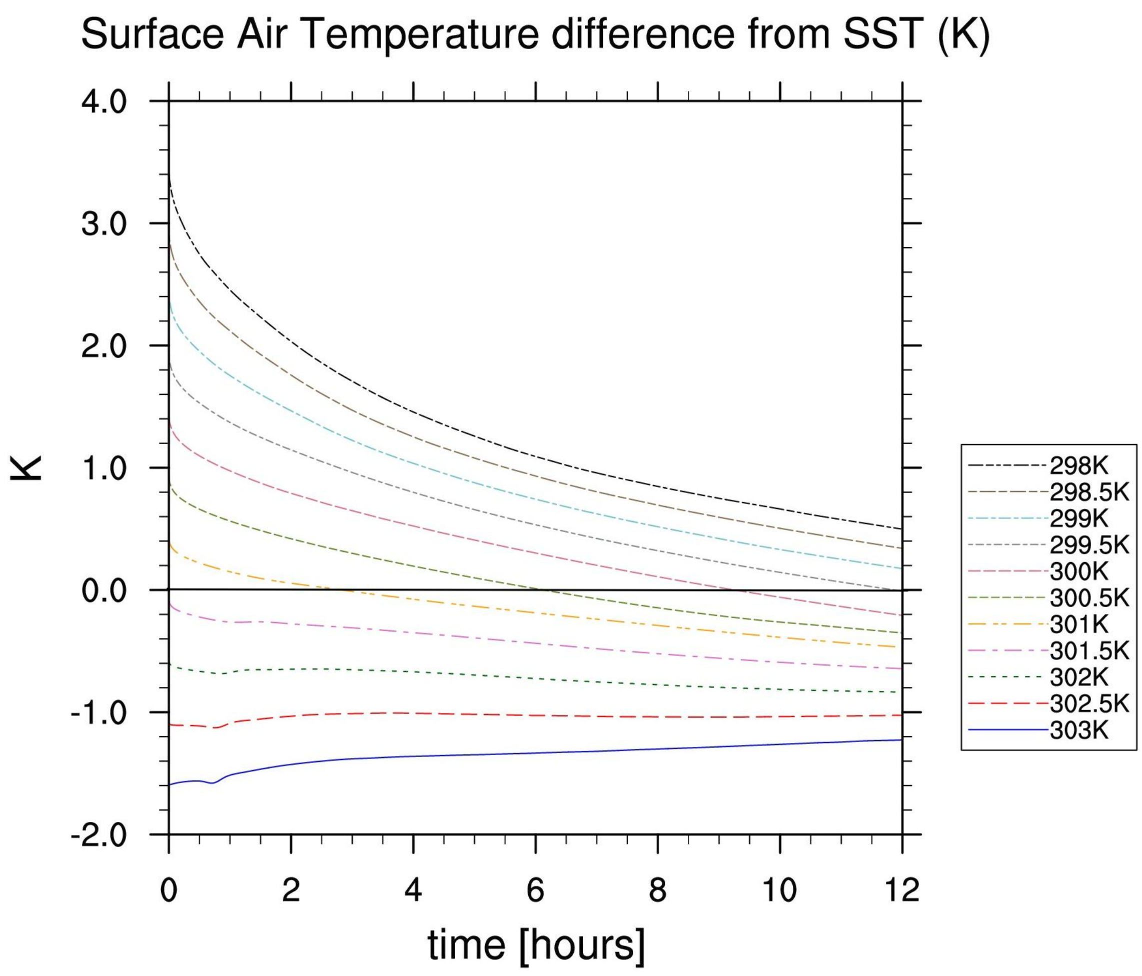
Horizontal Winds



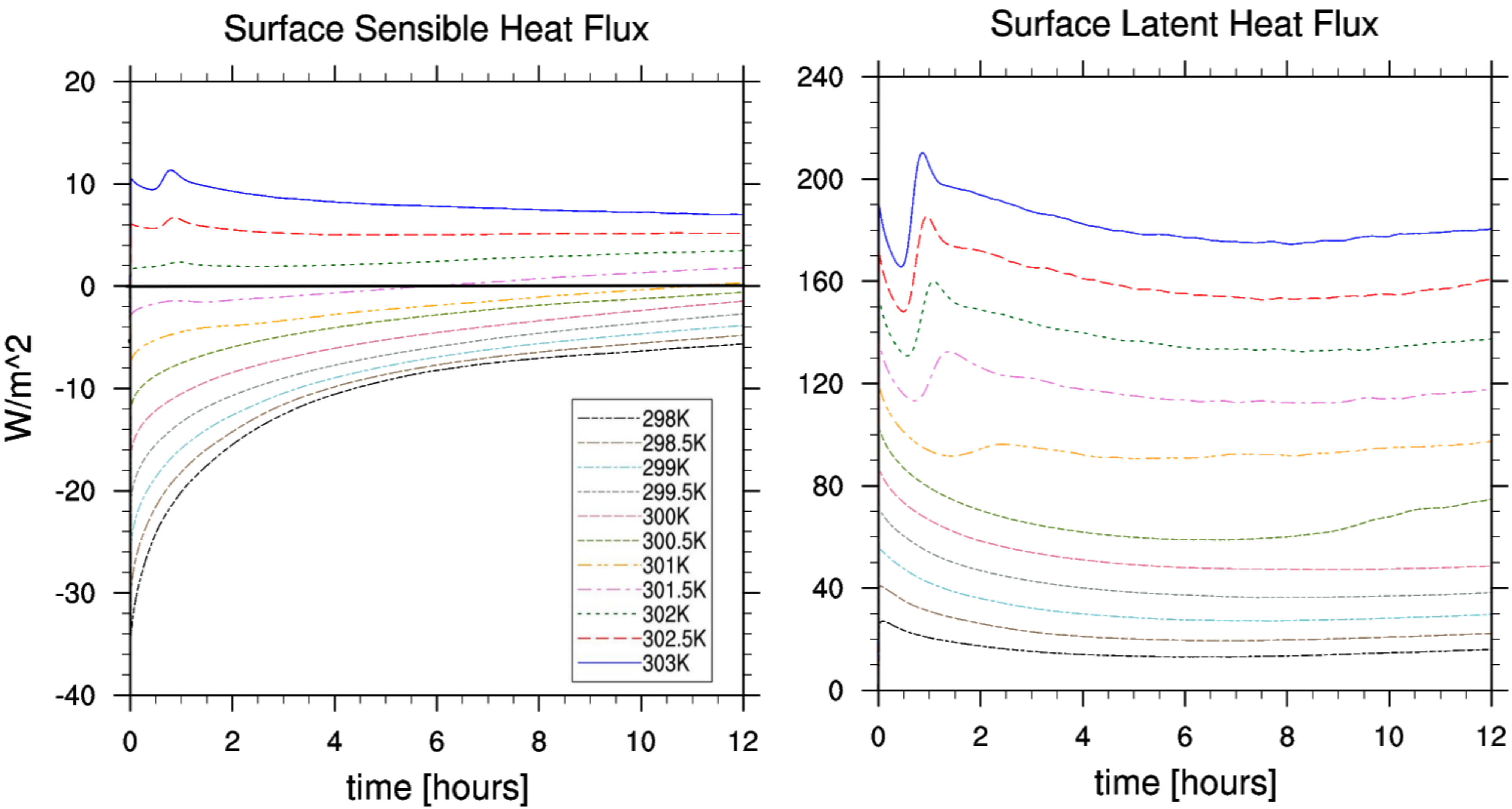
Model simulated *x and y* winds averaged over final 6 hours of simulations compared to the initial winds. Only the lower tropospheric winds are shown as the upper tropospheric winds are nearly identical to initial profile throughout the simulation period.

Change in Surface air temperature with SST

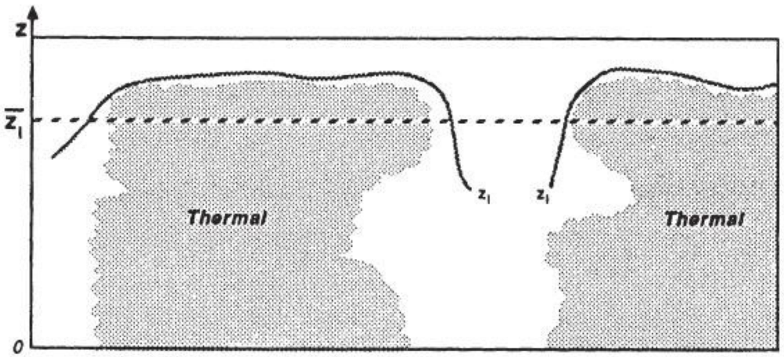


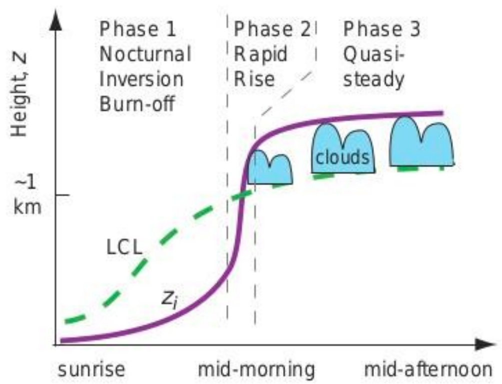


Change in PBL fluxes with SST

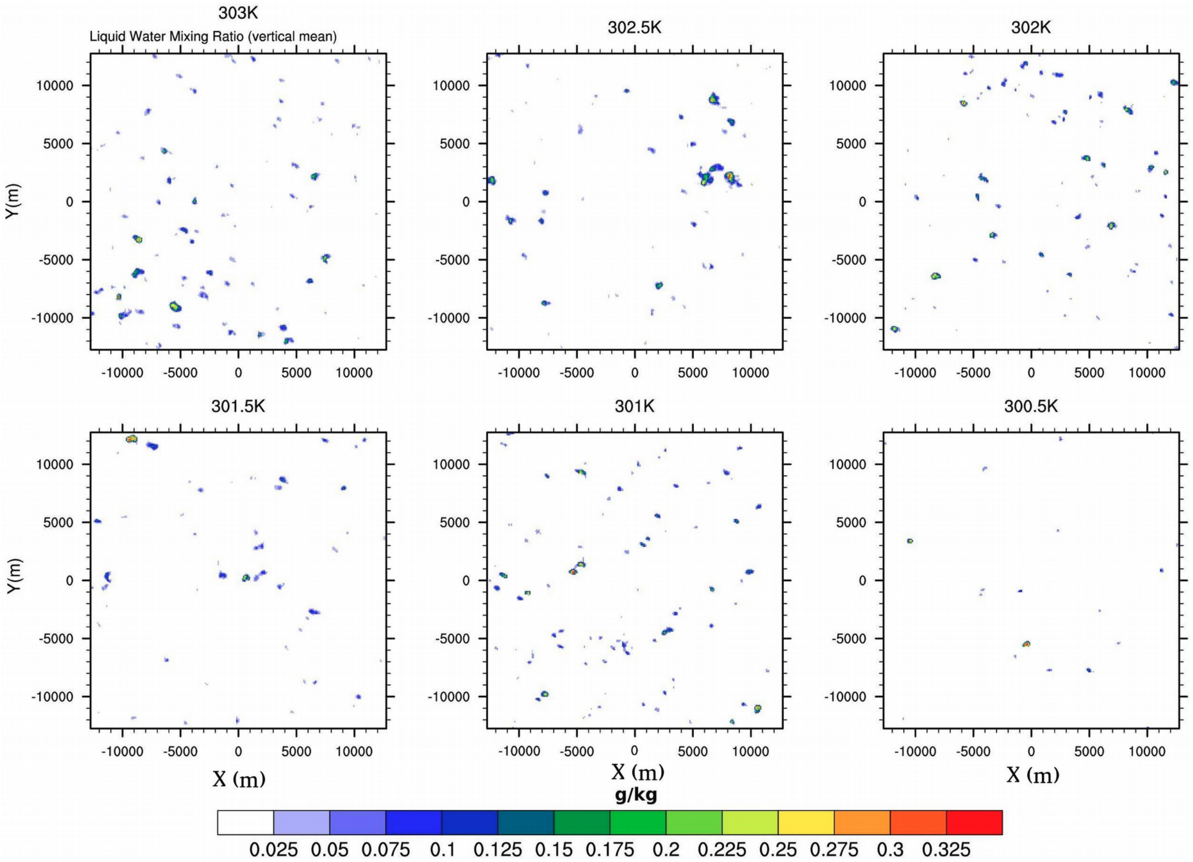


The structure of Boundary layer thermals





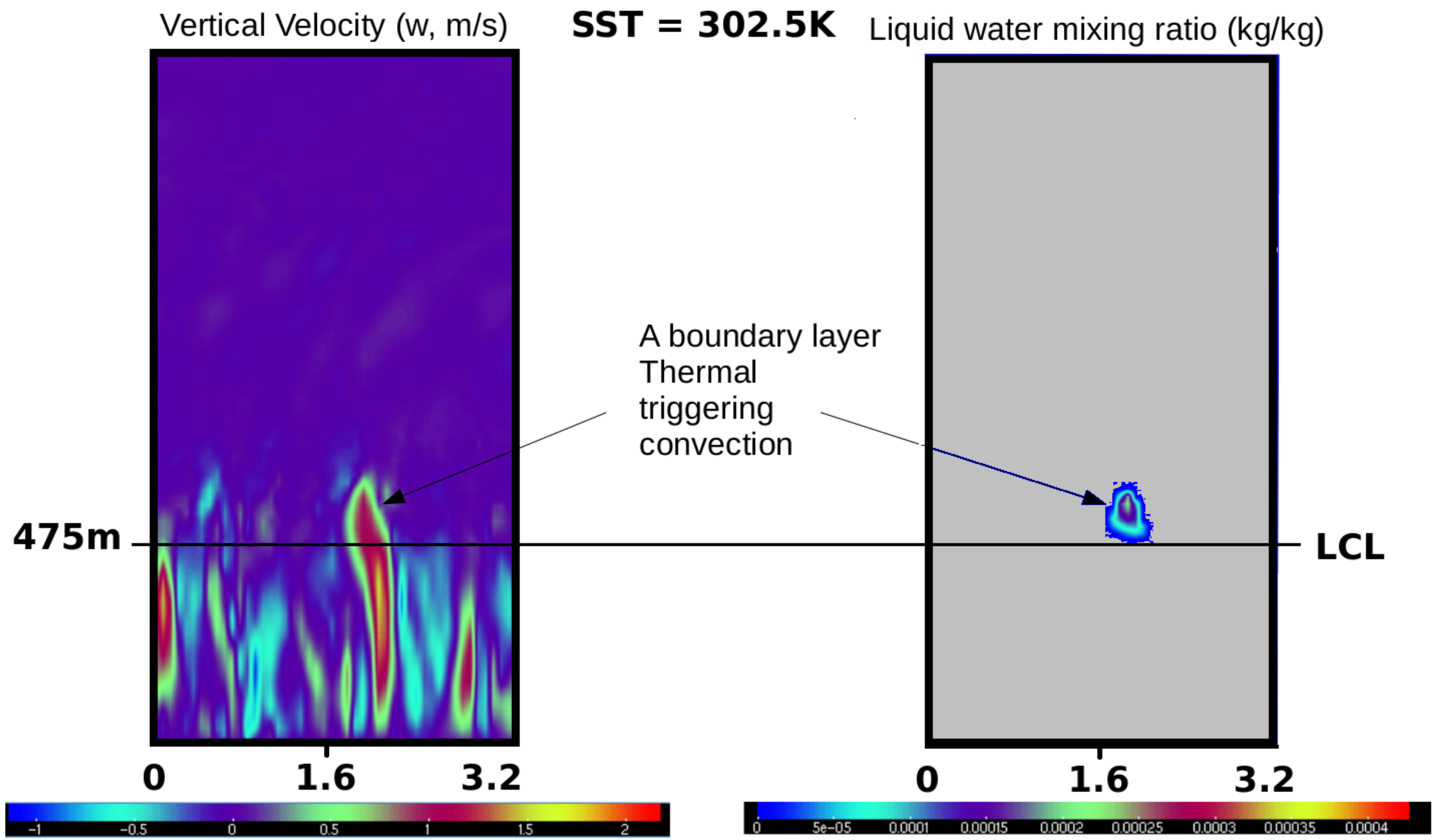
A representation of boundary layer thermals (top, taken from Stull (2012)) and the evolution of mixed layer due to these thermals which can trigger shallow PBL topped clouds (lower panel, Wallace and Hobbs (2006)). Clouds start forming when z_i crosses LCL zone.



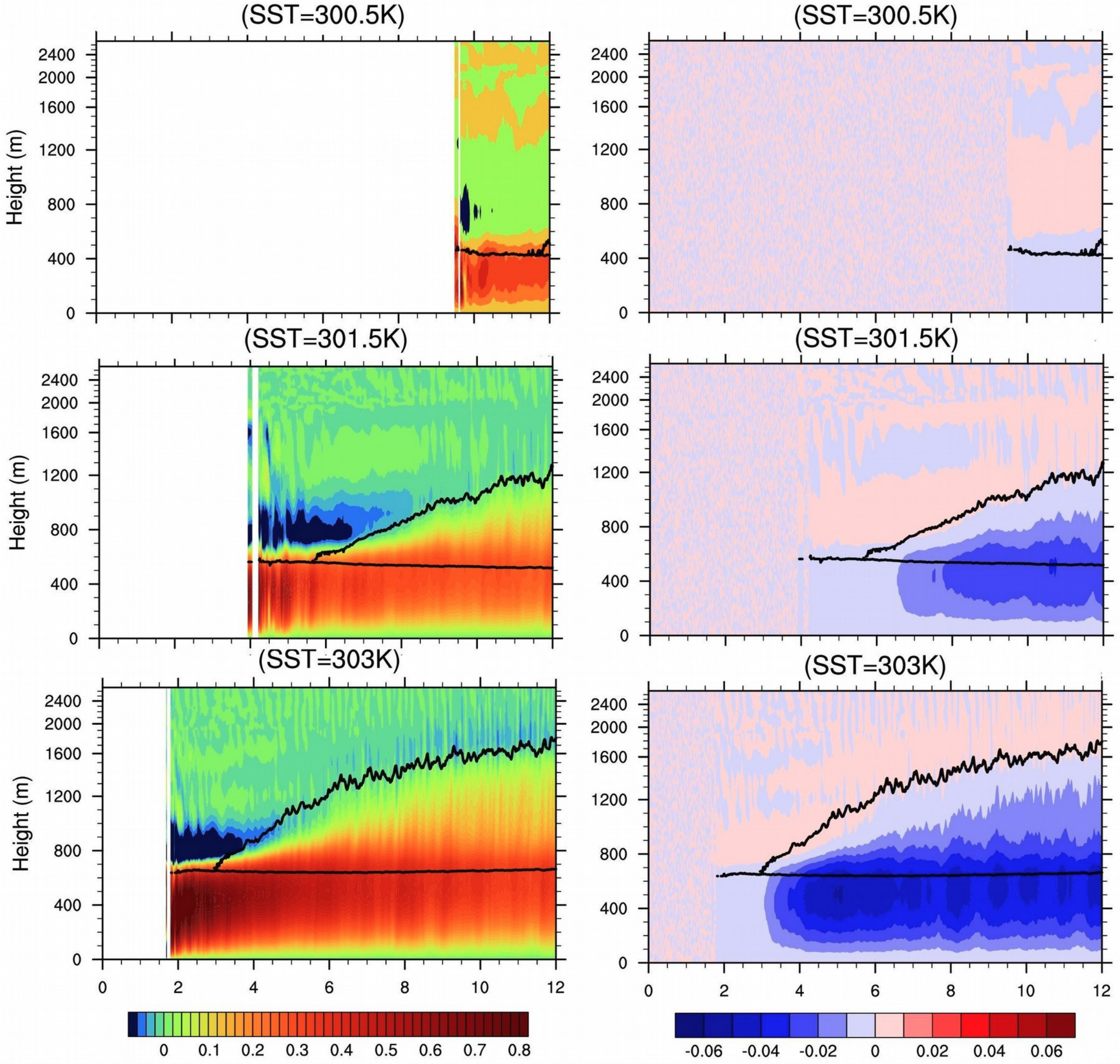
Snapshot of simulated vertical mean of liquid water mixing ratio for different SST values after 11 hours and 50 minutes of simulations.

$$m_{\mathrm{cb}} = c_1 W \exp(-c_2 \mathrm{CIN/TKE}),$$

Vertical Velocity in the Cloud



Vertical Velocity inside and outside cloud



- **In the cloud free region, we find subsidence region beneath the cloud base.**
- **Vertical subsidence starts above the cloud base and is maximum just below the cloud base.**
- **Clouds are a result of intense vertical thermals in the boundary layer and the subsidence in the cloud free area is due to these intense vertical thermals**

$x-y$ mean of simulated vertical velocity (m/s) in the cloudy column (Left) and cloud free region (right).

Should we use PBL TKE in Closure assumptions?

$$TKE/m = 1/2[\overline{u'^2} + \overline{v'^2} + \overline{w'^2}]$$

$$\frac{\partial(TKE/m)}{\partial t} = Ad + M + B + Tr - \varepsilon$$

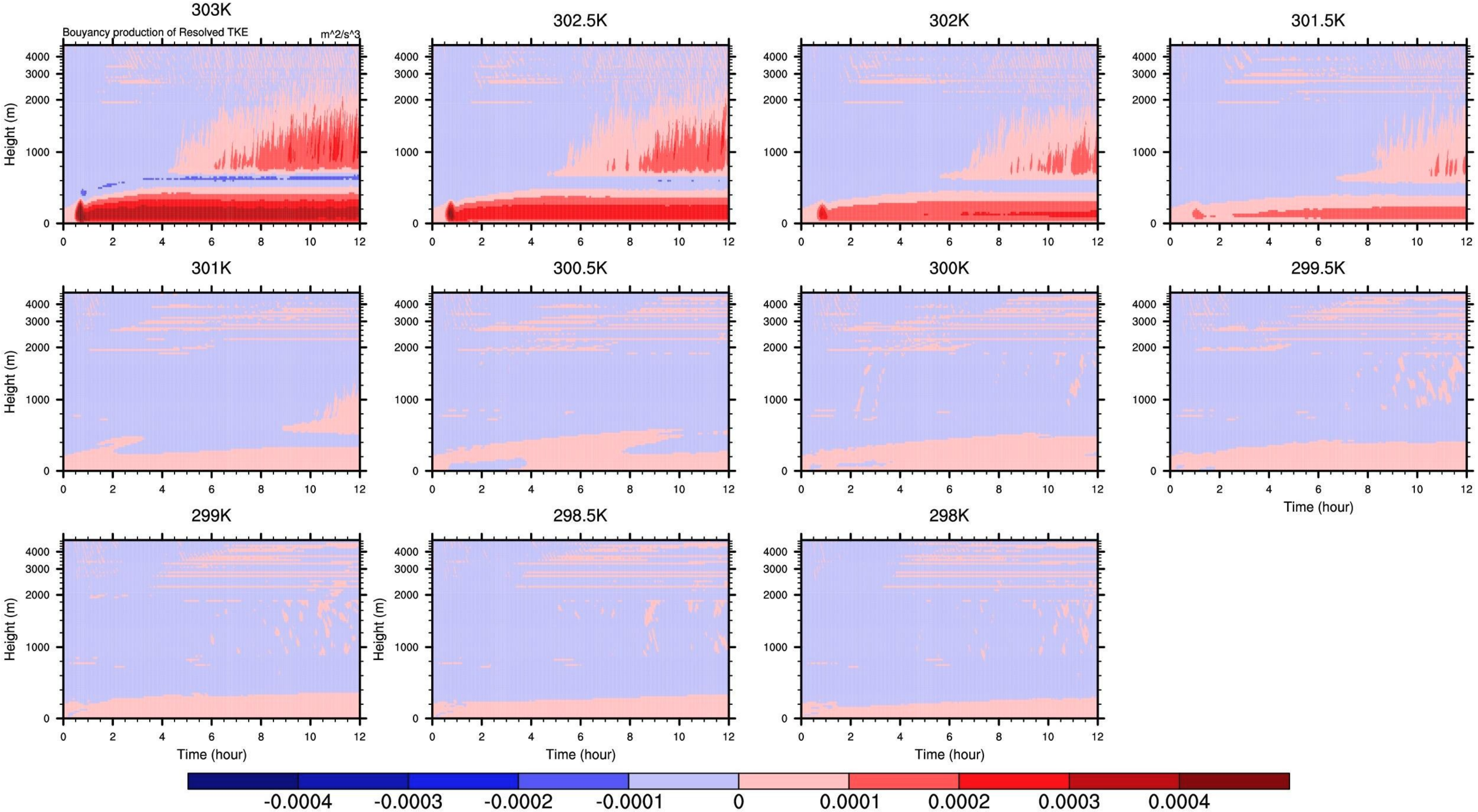
The buoyancy production of TKE can be calculated as

$$B = -\frac{g}{\overline{\overline{T_v}}} \frac{\partial \overline{\theta_v}}{\partial z}$$

and mechanical generation of TKE calculated as

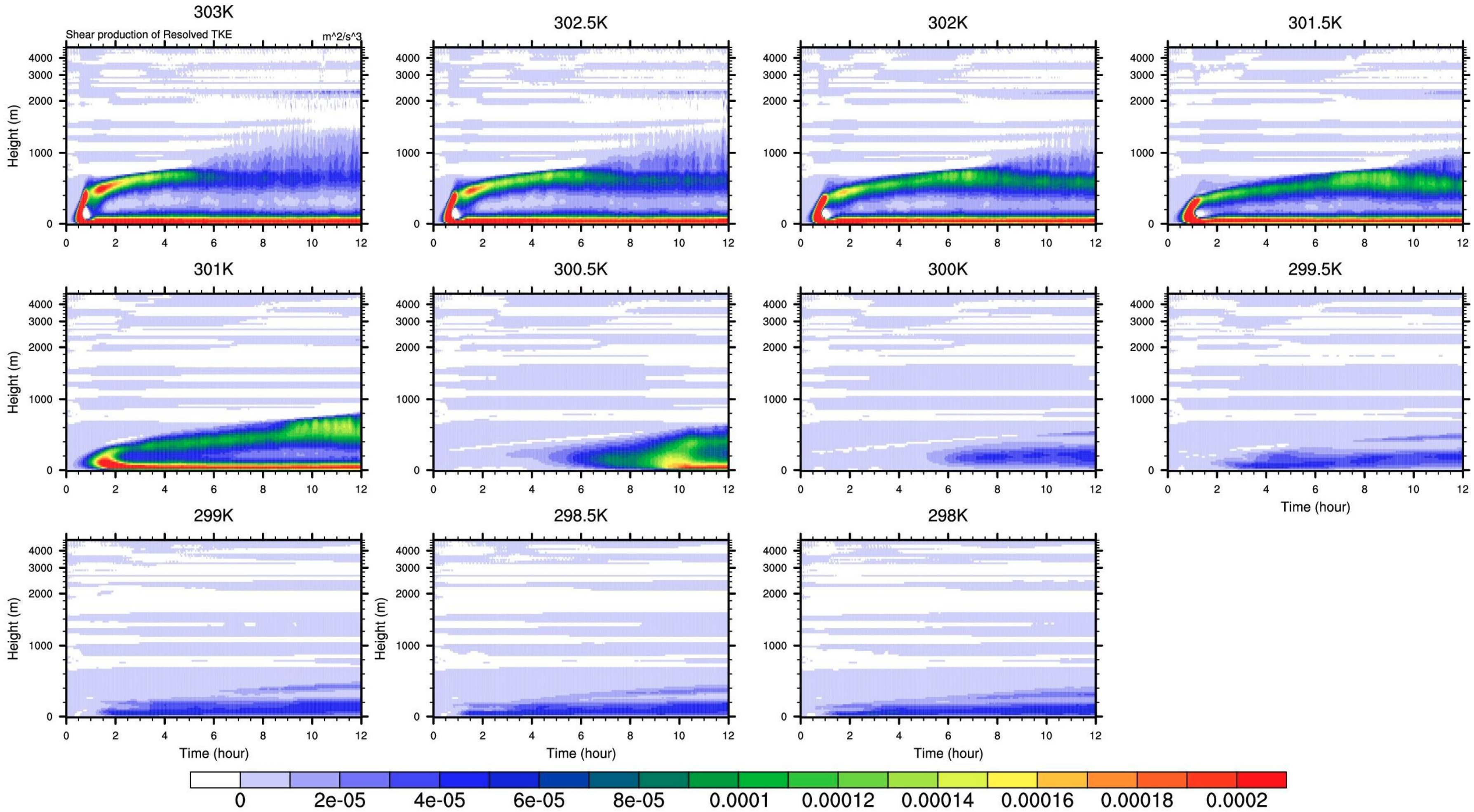
$$M = \left(\frac{\partial \overline{u}}{\partial(z)}\right)^2 + \left(\frac{\partial \overline{v}}{\partial(z)}\right)^2$$

Buoyancy Production of TKE



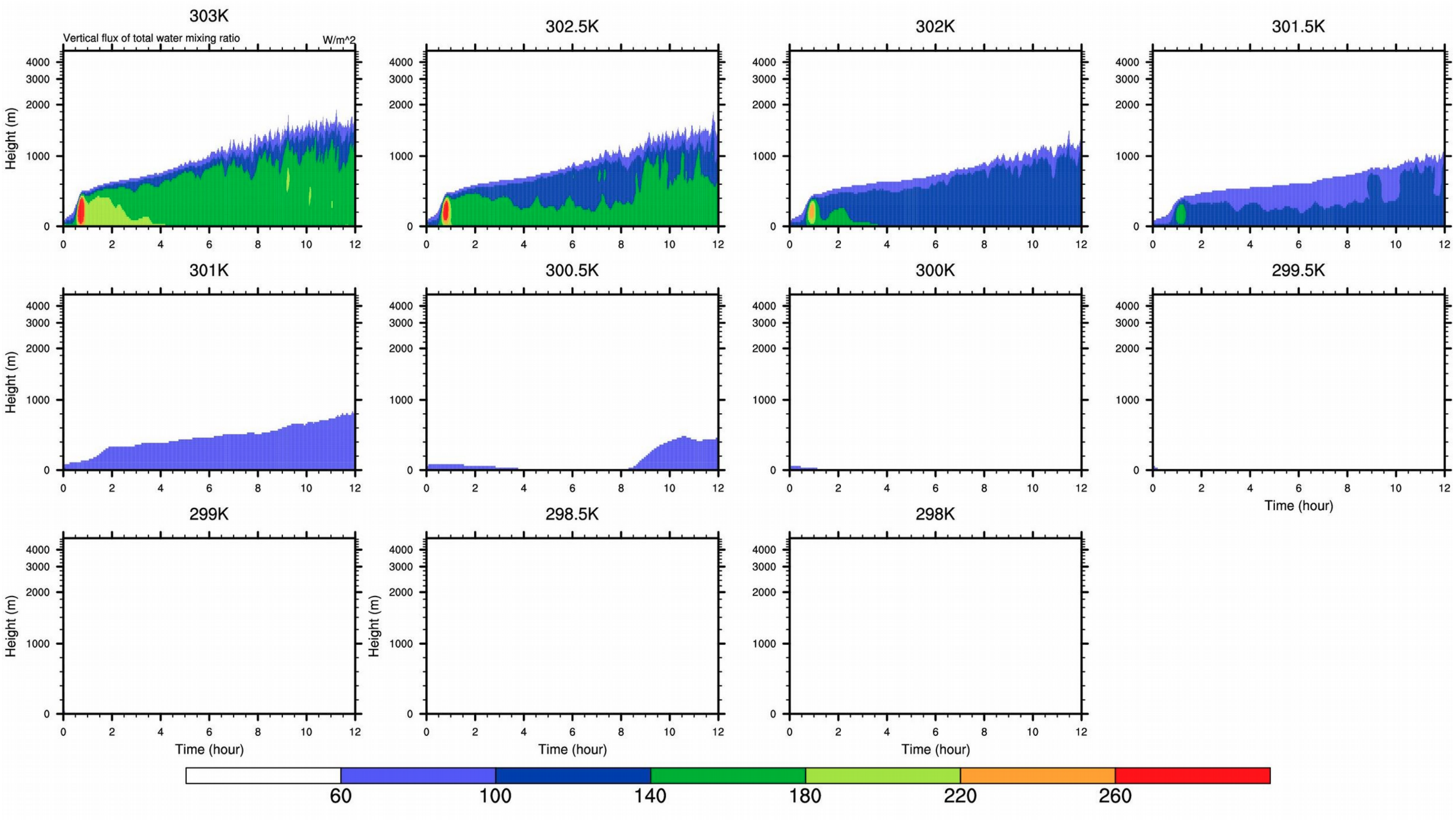
Evolution x−y mean buoyancy production of TKE (B) as a function of SST with time. For SST less than 301K, the surface buoyancy production remains lower than **0.0001**m^2/s^3. In fact, **the height of minimum B (just above the mixed layer) and the mean cloud base heights in the simulations are very nearly same**.

Shear Production of TKE with SST



Evolution *x−y* mean shear production of TKE (M) as a function of SST with time. For M, we can define the surface threshold value as **0.0002** m^2/s^3 (the red contour). We see that surface M increases with SST.

Vertical Flux of Total Water Mixing Ratio



Mean of simulated vertical flux of total water mixing ratio ($w'q'_t$). We see that a threshold value of 60W/m² for surface flux when the clouds form in the simulations (at SST=300.5K).

Summary

- Boundary layer thermals for higher SST are able to cross the LCL level and trigger moist convection. So we can develop plume models for boundary layer and clouds which can be consistent with each other.
- We can derive closure schemes based on CINE and TKE in the absence of large scale organized convection.
- However, as we have seen in the southward propagations, such closure (based on local TKE and CINE) will not always be a good representation.

Conclusions

CRM Study

- **CRM simulations show that location of precipitation does not always coincide with location of high CAPE. CINE plays an important role in modulating the location of precipitation**
- **CRM simulations show that most of the precipitation comes due to Mesoscale-convective organized systems.**
- **GCMs lack representation of organized MCSs. MCSs are characteristically different in consuming CAPE than are assumed in a typical GCM parameterization**
- **CRM is able to simulate southward propagating MCS over the BoB during the onset phase of monsoon**
- **CRM shows that this MCS moves with a gravity current structure and the speed of propagation can be derived from the vector difference of cold pool winds and low level jet ahead of the MCS**
- **Most of these MCSs over the north BoB are triggered due to diurnal land heating north of head Bay.**

LES Study

- Boundary layer thermals for higher SST are able to cross the LCL level and trigger moist convection
- We can derive closure schemes based on CINE and TKE in the absence of large scale organized convection.
- However, as we have seen in the southward propagations, such closure (based on local TKE and CINE) may not always be a good representation.

Conclusions

Future Work

- Inclusion of organized MCS representation in a GCM
- A better representation of boundary layer thermal triggering in the PBL schemes for GCM

Thank You

Assumed PDF based Unified parameterizations

- **Using same closure assumptions for boundary layer as in cumulus with an equation for moisture**
- **One of the most prominent one is based on assumed PDFs for turbulent flux quantities.**
- **Such Closure assumtions depend heavily on the local turbulent structure of the boundary layer and upper troposphere.**
- **Similar closure assumtions such as the one based on local PBL TKE and CINE have also been proposed.**

Our purpose in todays presentation is to show the cases where such types of closure assumtions are valid

and

- **Where we must include the non-local effects (organized MCSs)**

$$\sigma = \frac{1}{2} - \frac{S_w}{2(4 + S_w^2)^{1/2}},$$

$$M_c = \rho\sigma(1 - \sigma)(w_{\mathrm{up}} - w_{\mathrm{dn}}) = \frac{m(\overline{w'^2})^{1/2}}{(4 + S_w^2)^{1/2}},$$

where

$$S_w = \frac{\overline{w'^3}}{(\overline{w'^2})^{3/2}}$$

$$m_{\mathrm{cb}} = c_1 W \exp(-c_2 \mathrm{CIN/TKE}),$$

TKE Turbulent kinetic energy

½$(u'^2 + v'^2 + w'^2)$, averaged horizontally and vertically below Cu base.

W Vertical velocity scale in CIN closure

$W = a\mathrm{TKE}^{1/2} + b$ for any a or b.

(Fletcher et al 2009)

(Fletcher et al 2009)