Aerosols, Inversion Layer and Onset of Fog

Micro-Physical Processes and Modeling

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International Workshop on
Cloud Dynamics, Micro physics, and
Small-Scale Simulation
13-17 August 2018-IITM Pune

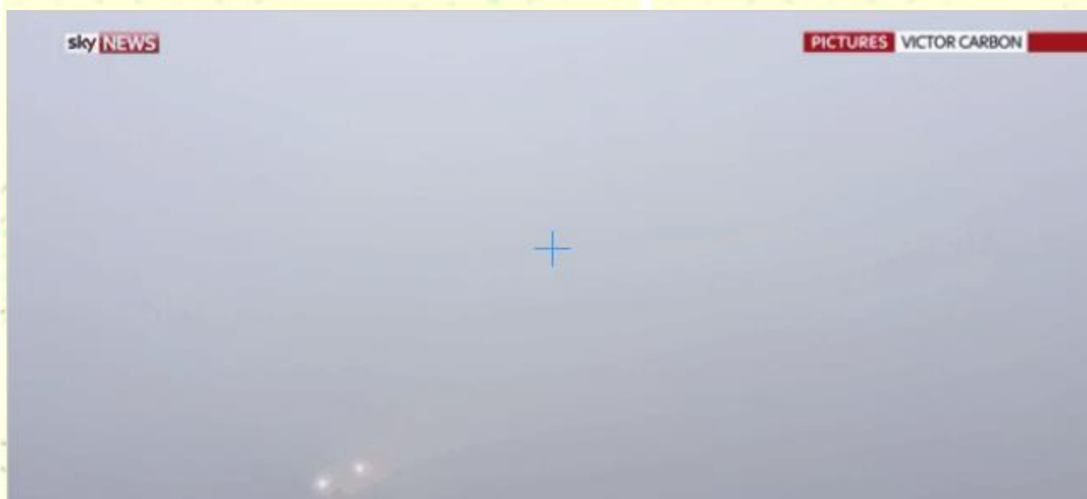
Beautiful Misty Mornings …..

MORNING NEWS…

Heathrow and Schiphol airports are experiencing delays after a second day of heavy fog across the UK and Netherlands …..

OR

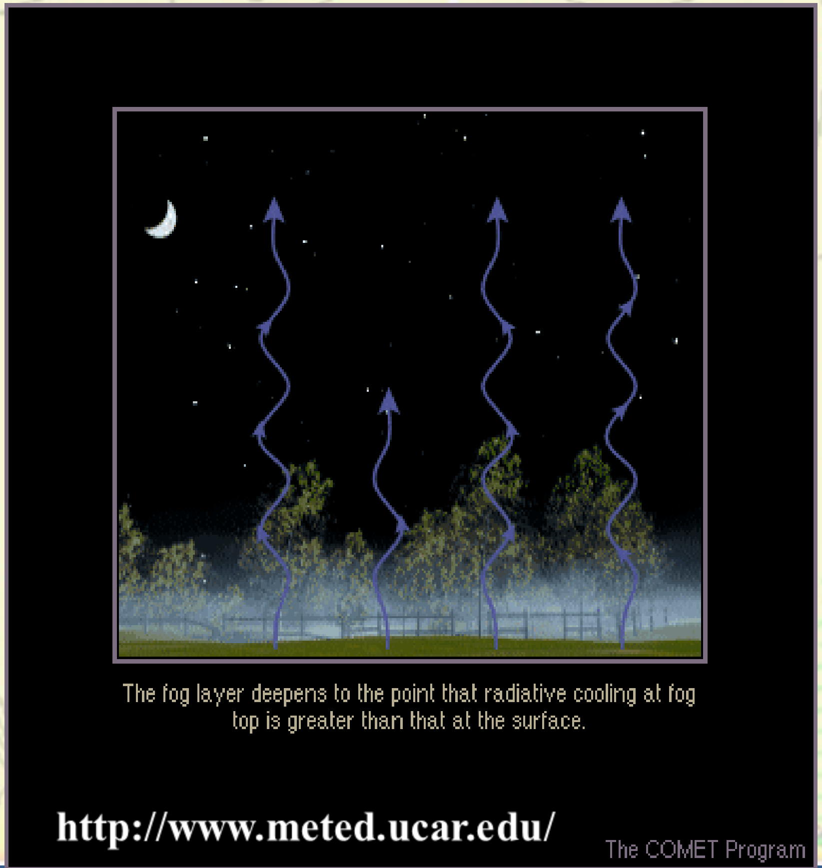
Fog hits flights at KIA Bengaluru …..



Operational Definition: Fog is the reduction in surface-based visibility to 1 km or less by atmospheric water droplets exhibiting diameters from a few to several tens of micrometers.

Meteorological Definition: Fog is a ground-based cloud layer

Fog occurs:
- **a) Clear skies and rapid cooling after sunset.**
- **b) High RH at low levels.**
- **c) Calm or light wind conditions**



❖ Fog , is a natural phenomenon which has Impact on travel, transport and airport management.

What are the Objectives?

To Predict :

- Time of onset
- Intensity of the Fog
- Fog Development & Depth
- Fog dissipation /lifting

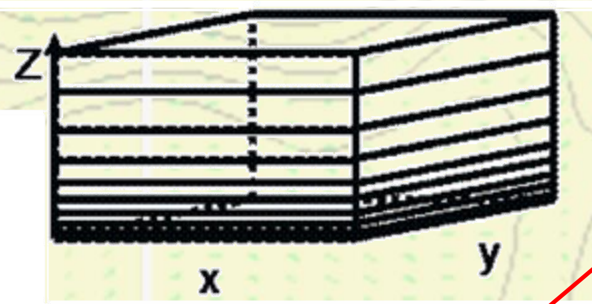
Visibility range

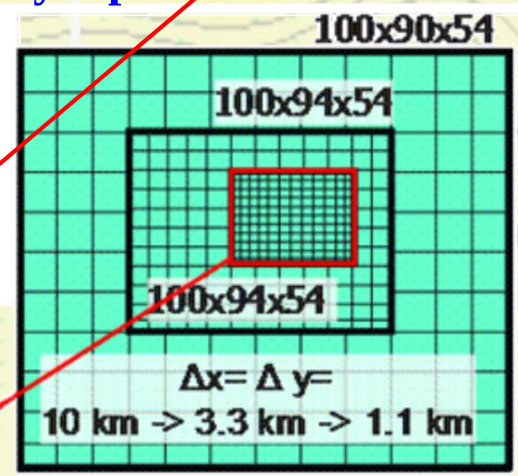
500m-1000m	Shallow Fog
200m-500m	Moderate Fog
50m -200m	Dense Fog
<50m	Very Dense Fog

Present Approach ….

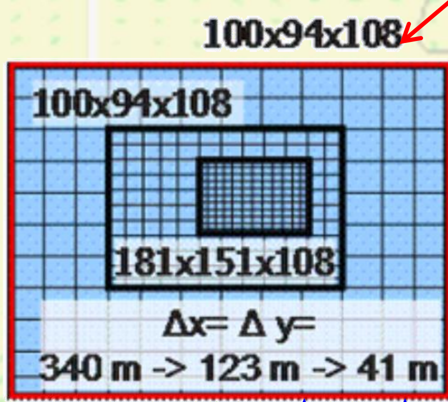
Weather Research and Forecasting (WRF) Model, a mesoscale numerical weather prediction system is used for both atmospheric research and Fog forecasting.

Synoptic-scale : 1000s km





Meteorological data
~50 km



Mesoscale : 5-100s km
(sea **breeze)**

- Model top: ~20 km
- Larger 3 domains :"mesoscale mode"
- Smaller 3 domains: "LES mode"

Δx=Δy=41m and Δz=185m

http://efm.princeton.edu/Multiscale_Atmospheric_Simulations.htm

Fog droplet spectrum and Radiation Forcing ….

Fog observation and prediction ….

Impact on visibility prediction, and radiative properties

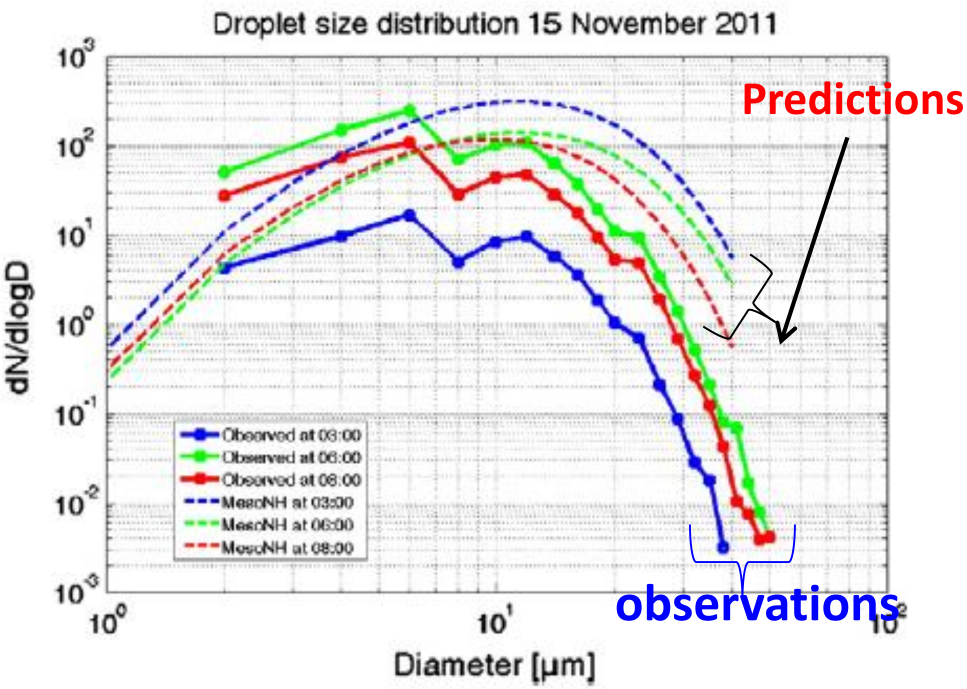
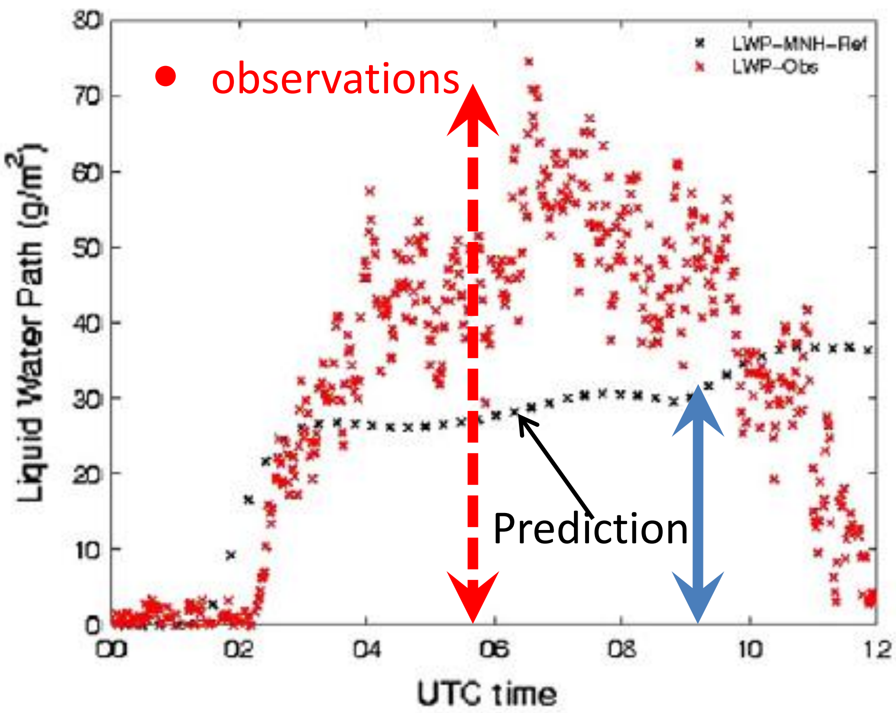


Fig. 8. Observed (FM-100) and modeled droplet size distribution at 03, 06 and 08 UTC. Reference run.



Stolaki, S., et al. "Influence of aerosols on the life cycle of a radiation fog event. A numerical and observational study." *Atmospheric Research* 151 (2015): 146-161.

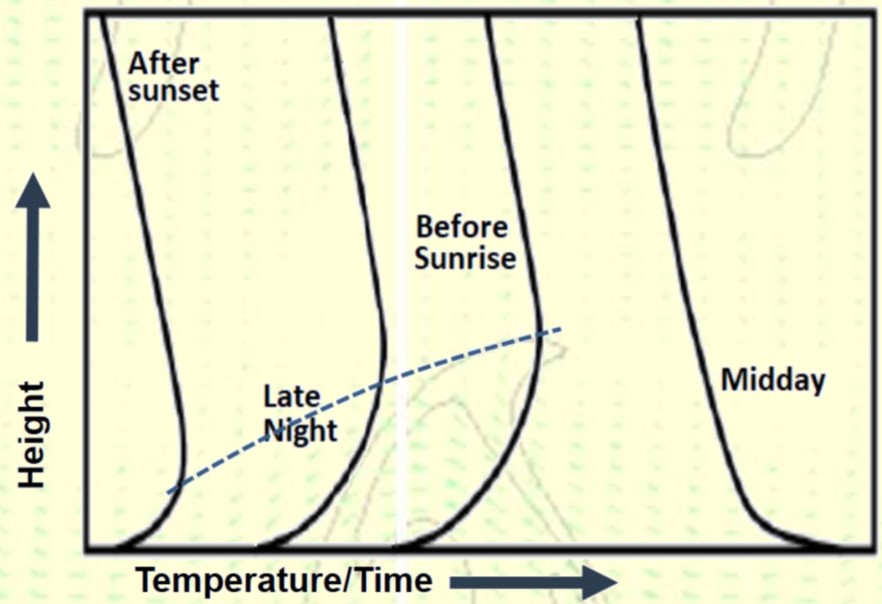
Radiation Fog Prediction involves many Microphysical Processes

- Time of onset
- Intensity of the Fog
- Fog Development & Depth
- Fog dissipation /lifting

Nocturnal boundary layer:
Thermal Structure
Radiative cooling
Thermodynamics
Fog Droplet characteristics
Pollution & smog
Convection & Entrainment

Nocturnal boundary layer:

Thermal structure

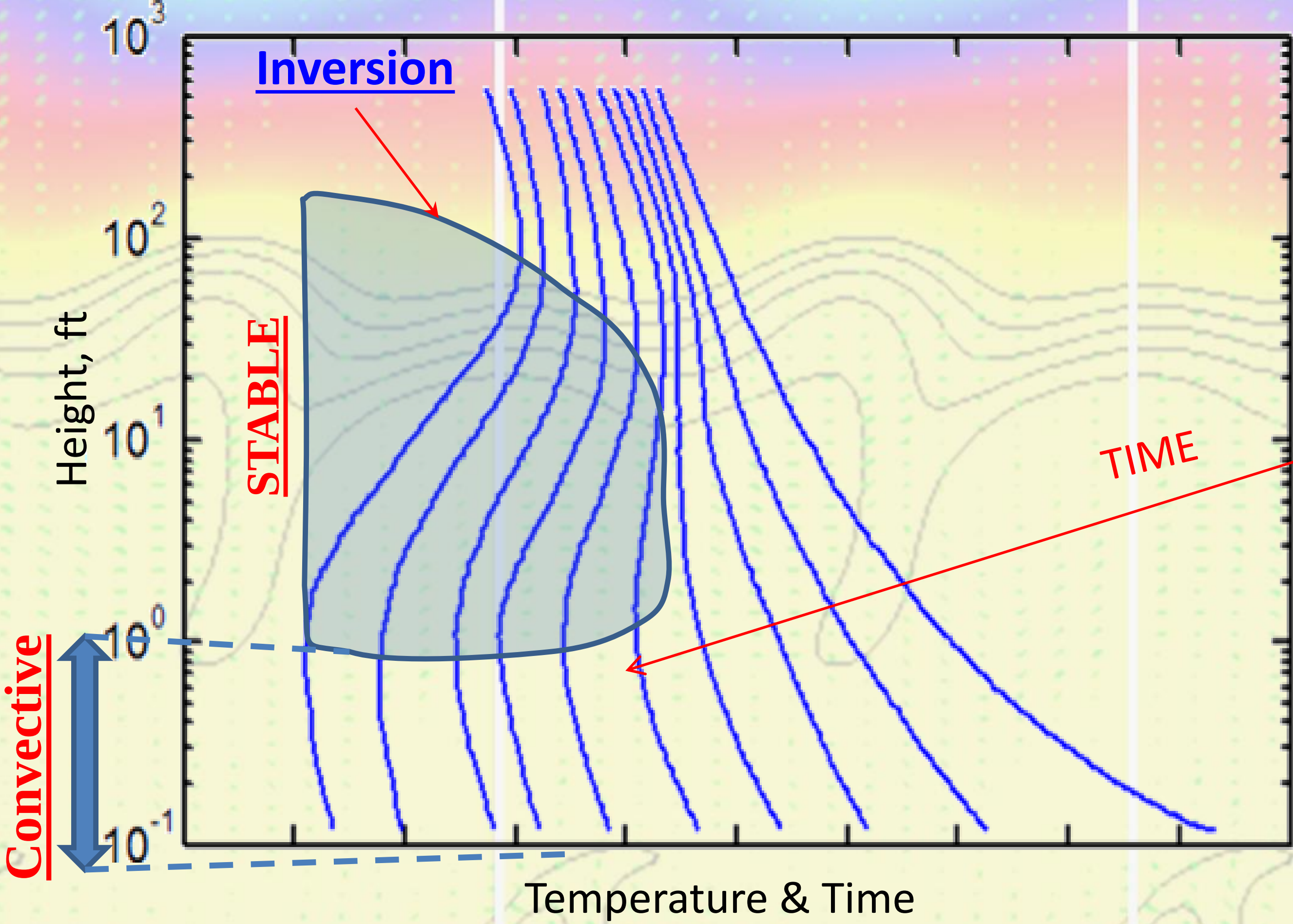


Adopted from- "An Introduction to Boundary Layer Meteorology" - RB Stull,1988

Observations @ Pune , India

Ramdas LA, Atmanathan S (1932)

Under Calm (low wind) and Clear sky conditions



Time evolution of Temperature Profiles in Pune at 17:00, 18:00, 19:00, 19:30, 20:00, 20:30, 21:00, 23:00, +1 day- 03:00 and 07:00 hrs Respectively

Implication of this Observation

Development of Inversion layer & Developmen of Fog

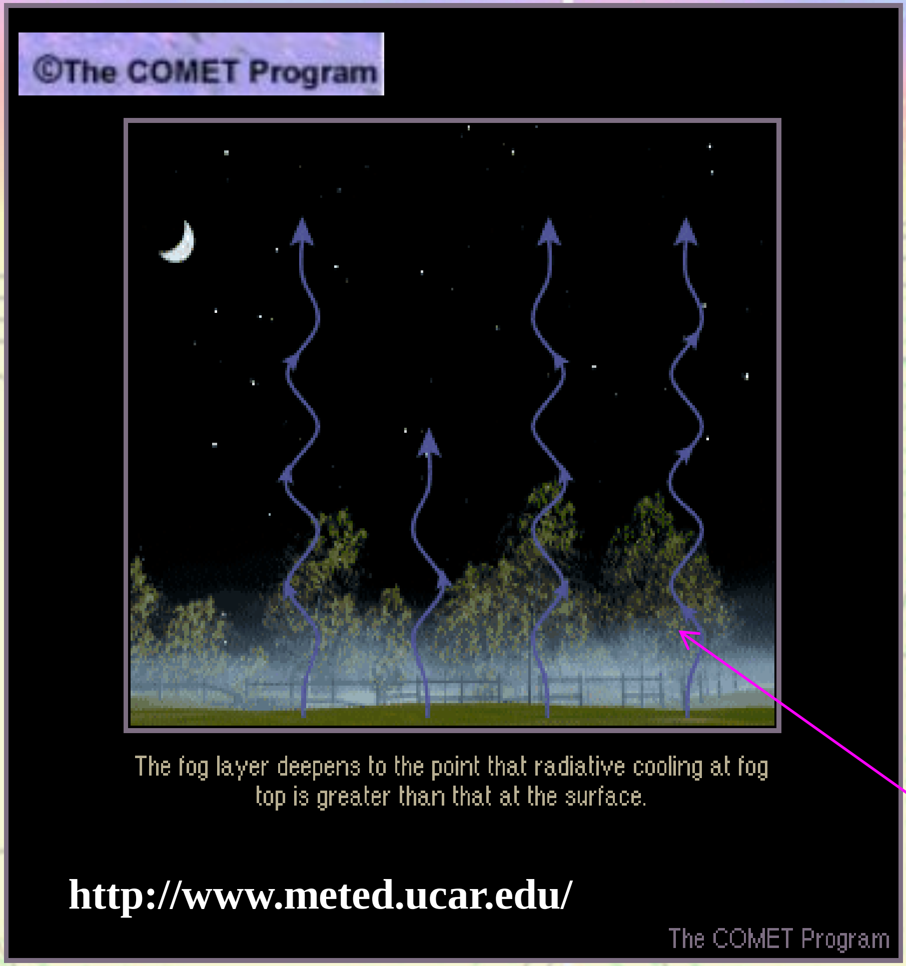
Origin of cold air layer in the warmer surrounding

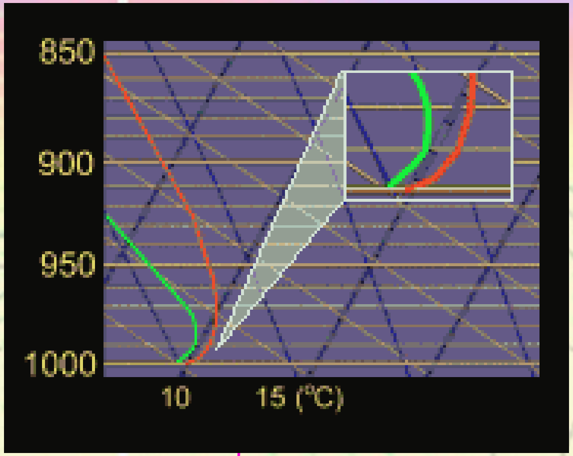
- Convection & Transport in surface layer

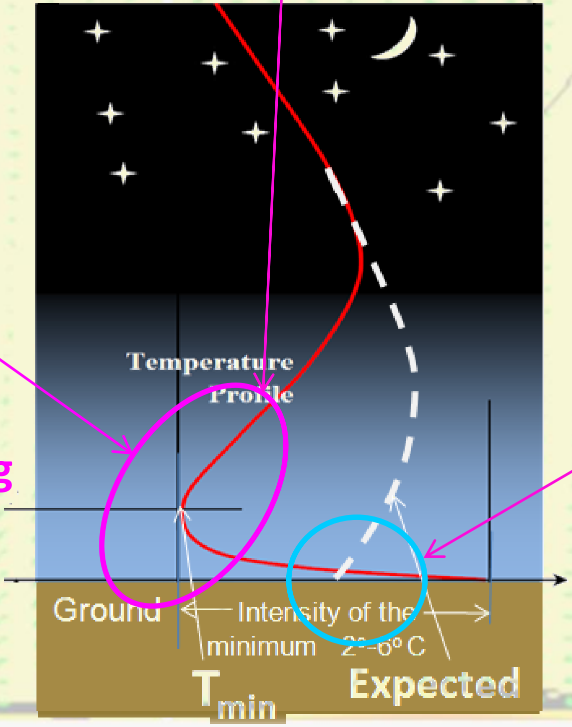
Radiation Fog

Radiation fog:

- Light-wind
- Moisture @ low level
- Clear sky – Radiative cooling







Local temperature falling bellow Dew-point

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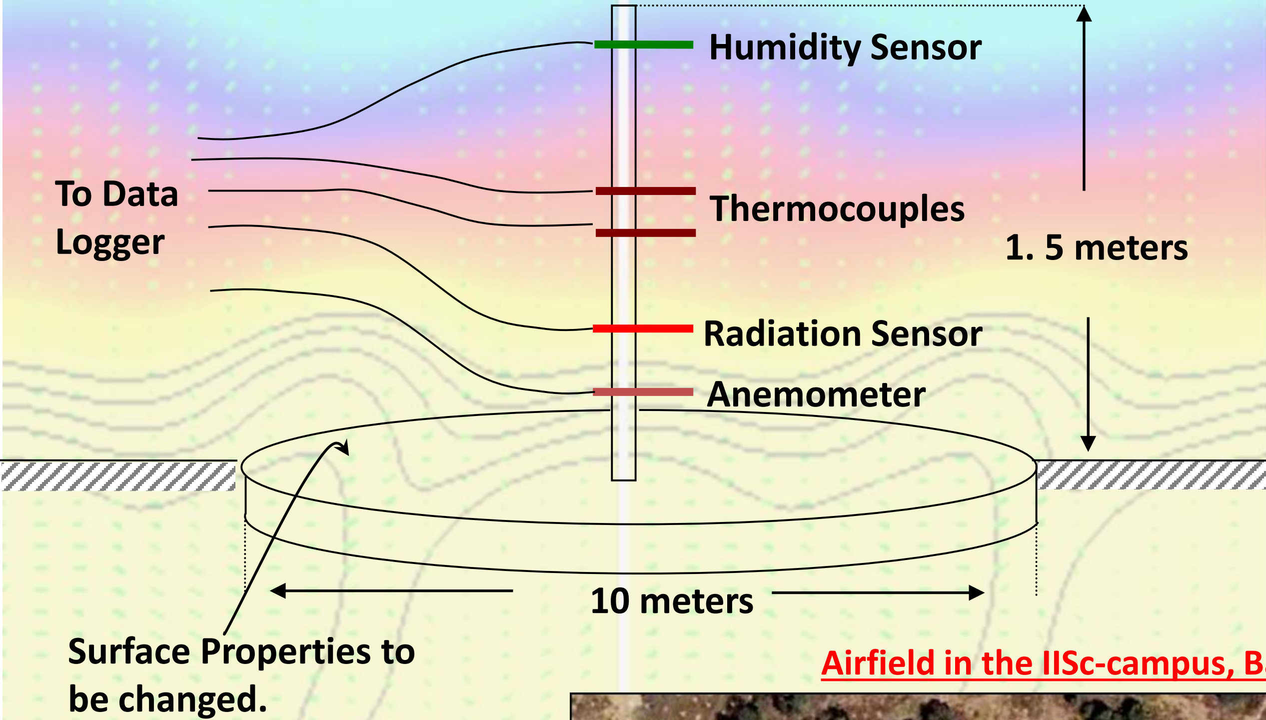
SCHEMATIC OF THE OBSERVATIONAL SET UP



Temperature Sensors
Copper/Const. Thermocouples.

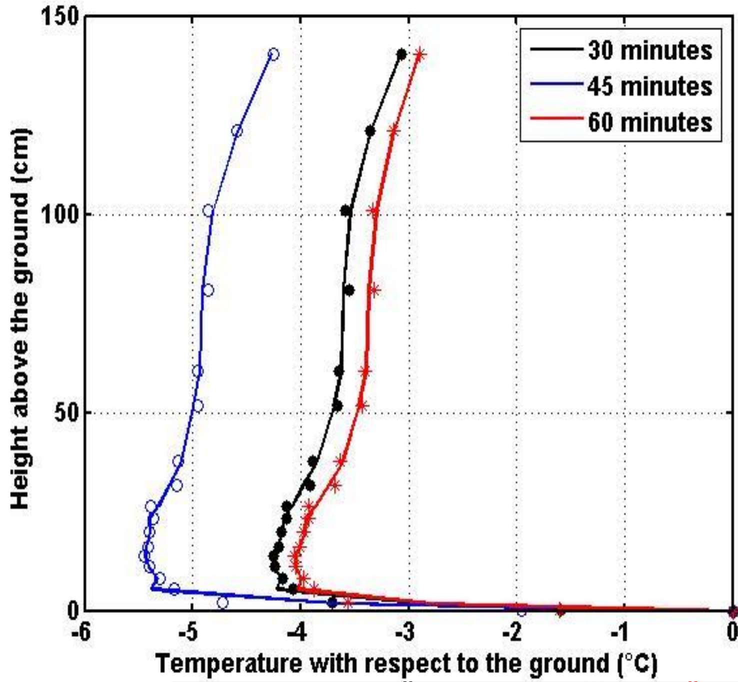
Wind Sensor:
Thermistor based - ®Accusense.

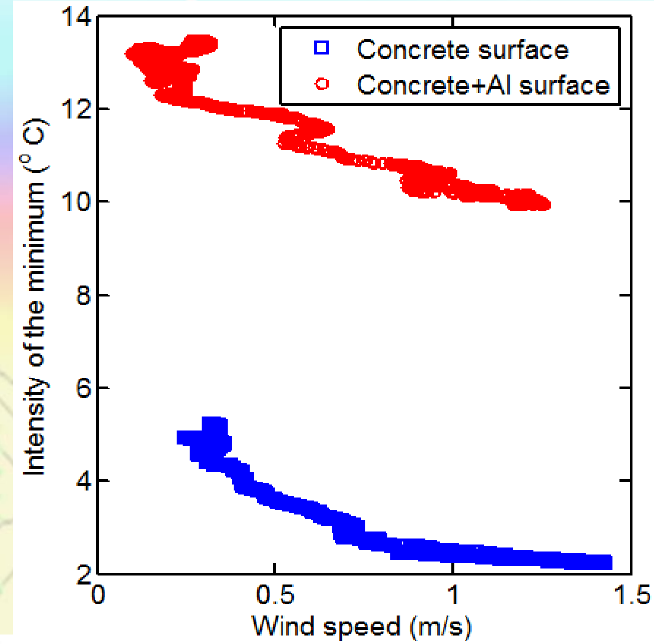
Humidity Sensor:
Capacitance based –®Honeywell

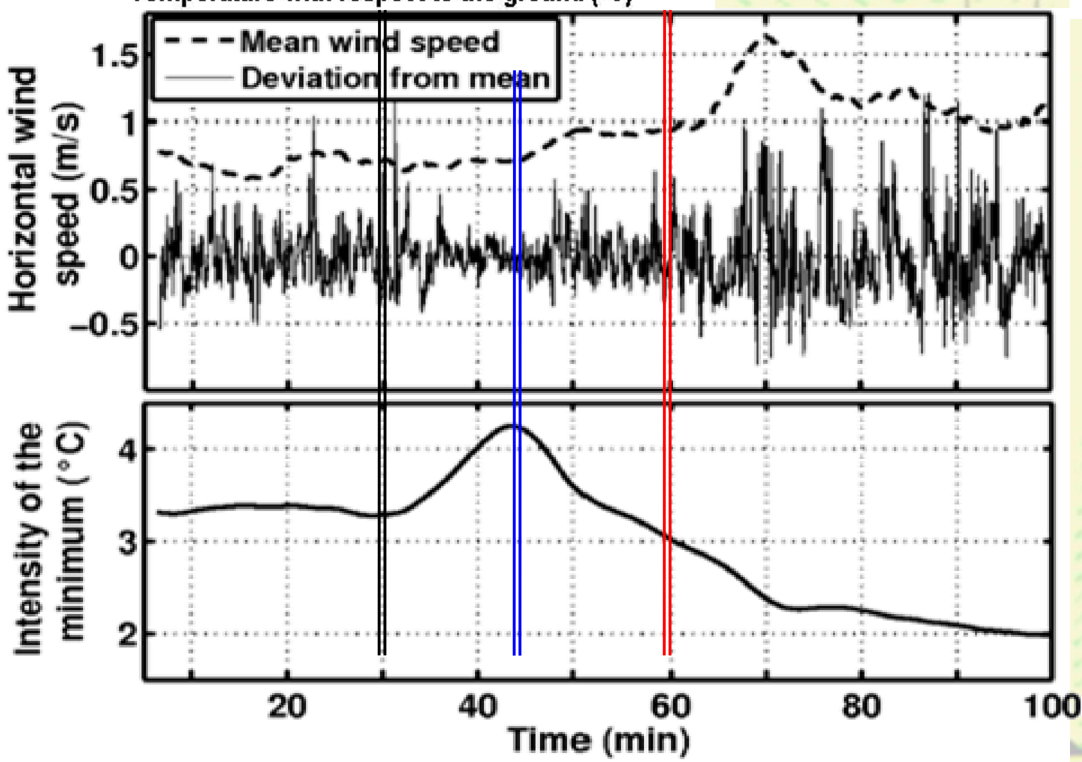
Radiation Sensors
Made using Peltier modules.

Airfield in the IISc-campus, Bangalore, India

We thank Prof. ON Ramesh Aero. Engg. Dept., IISc, and Prof. GS Bhat, CAOS, IISc


30 minutes
45 minutes
60 minutes
Height above the ground (cm)
Temperature with respect to the ground (°C)
150
100
50
0
-6
-5
-4
-3
-2
-1
0


Concrete surface
Concrete+Al surface
Intensity of the minimum (° C)
Wind speed (m/s)
14
12
10
8
6
4
2
0
0.5
1
1.5


Mean wind speed
Deviation from mean
Horizontal wind speed (m/s)
1.5
1
0.5
0
−0.5
Intensity of the minimum (° C)
4
3
2
20
40
60
80
100
Time (min)

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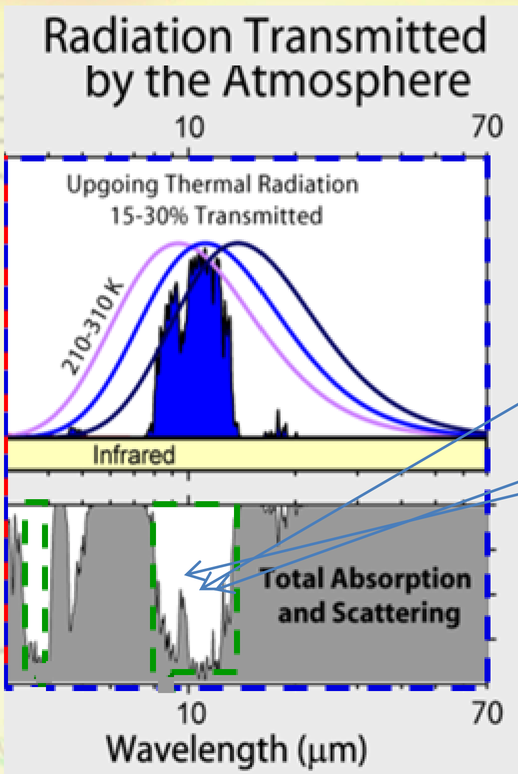
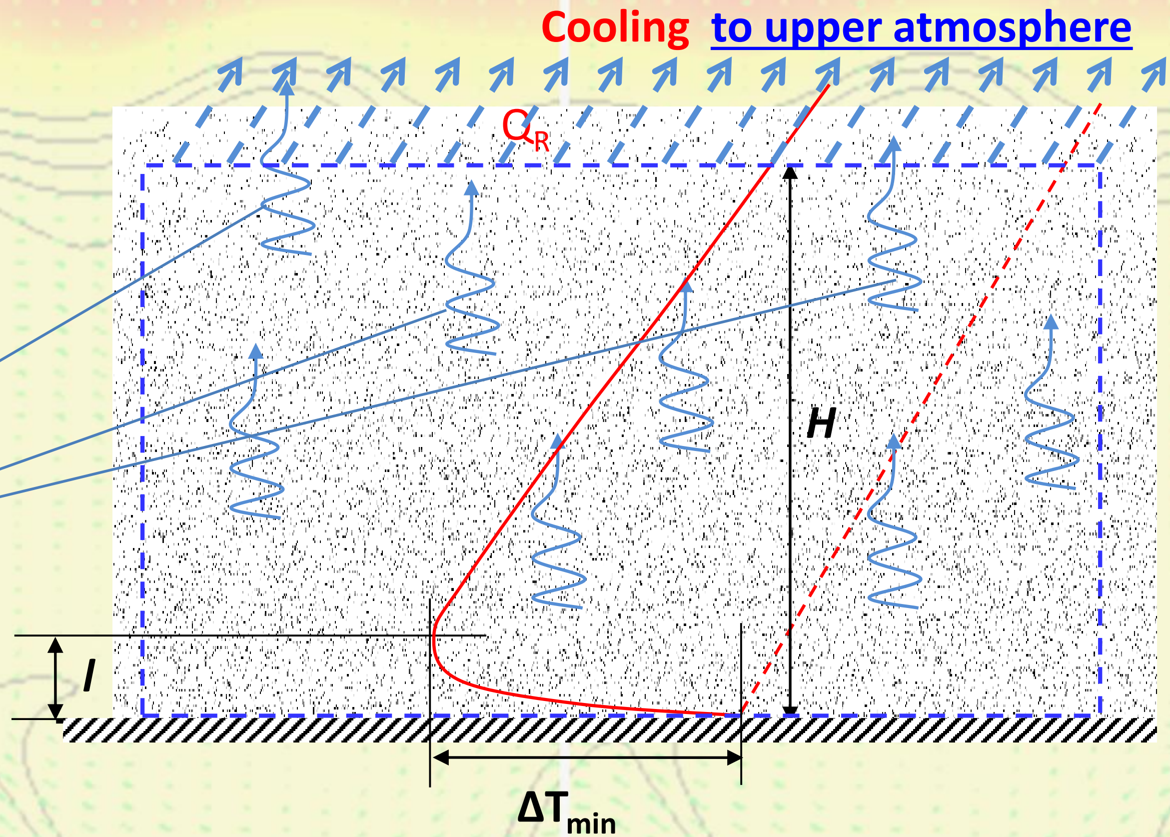
Correct Explanation :

Heterogeneous atmospheric surface layer is a must to explain the formation of LTM

Heterogeneity: Aerosols – Dust, droplets , any particulates





Emissivity (ε) of aerosols is >> air & can emit over all wavelengths . ∴ aerosols can cool to upper atmosphere

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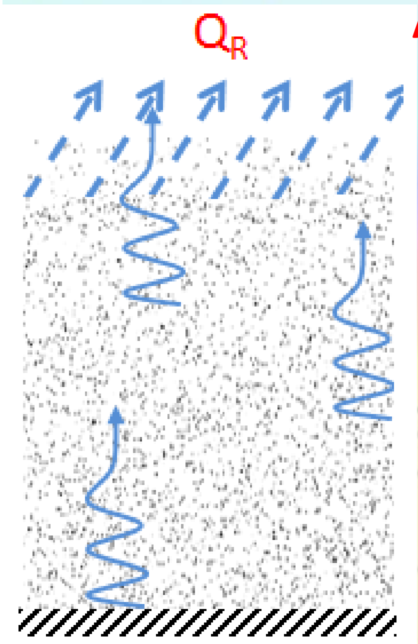
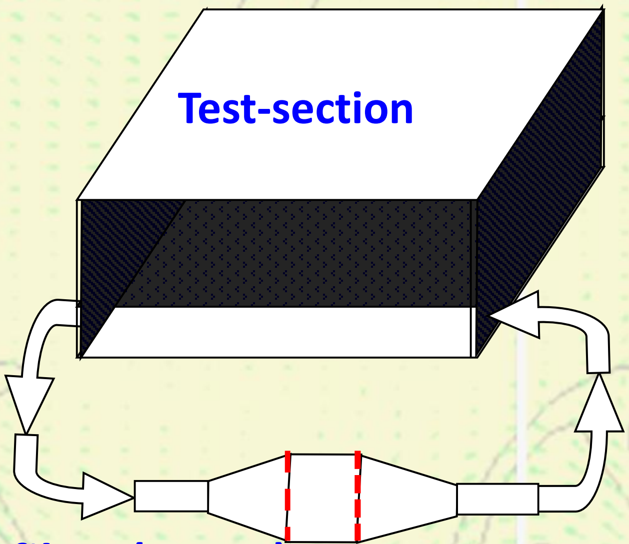
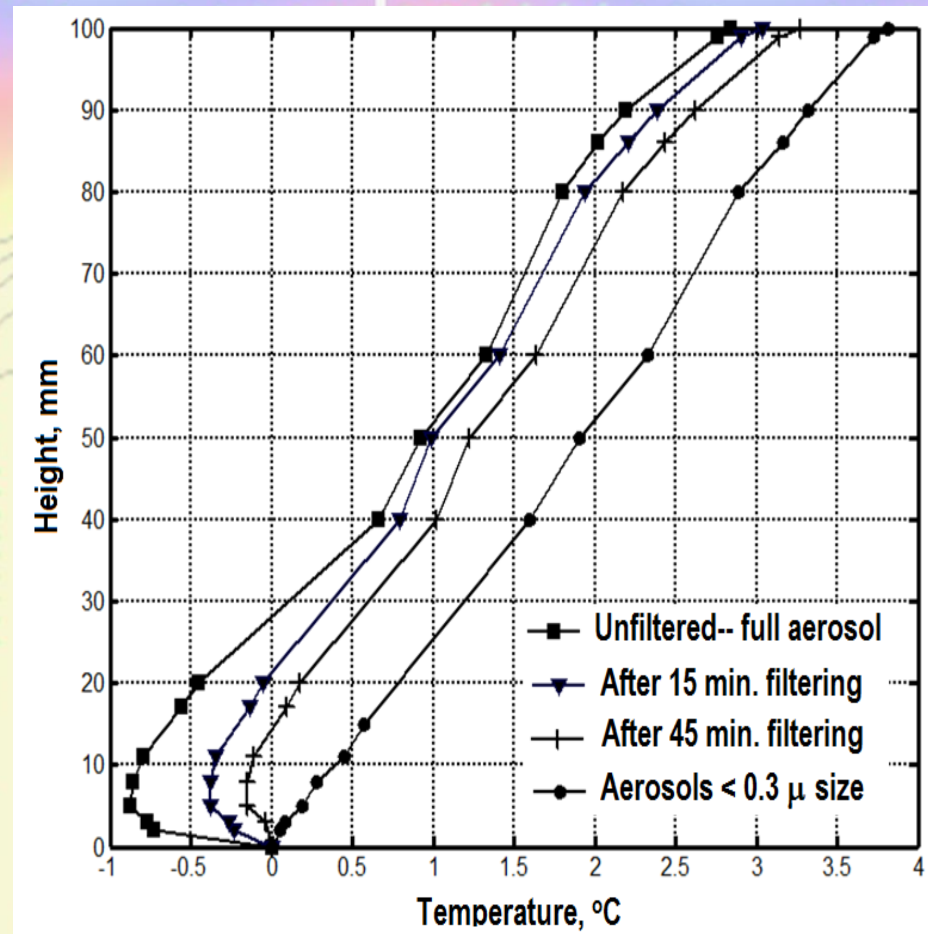
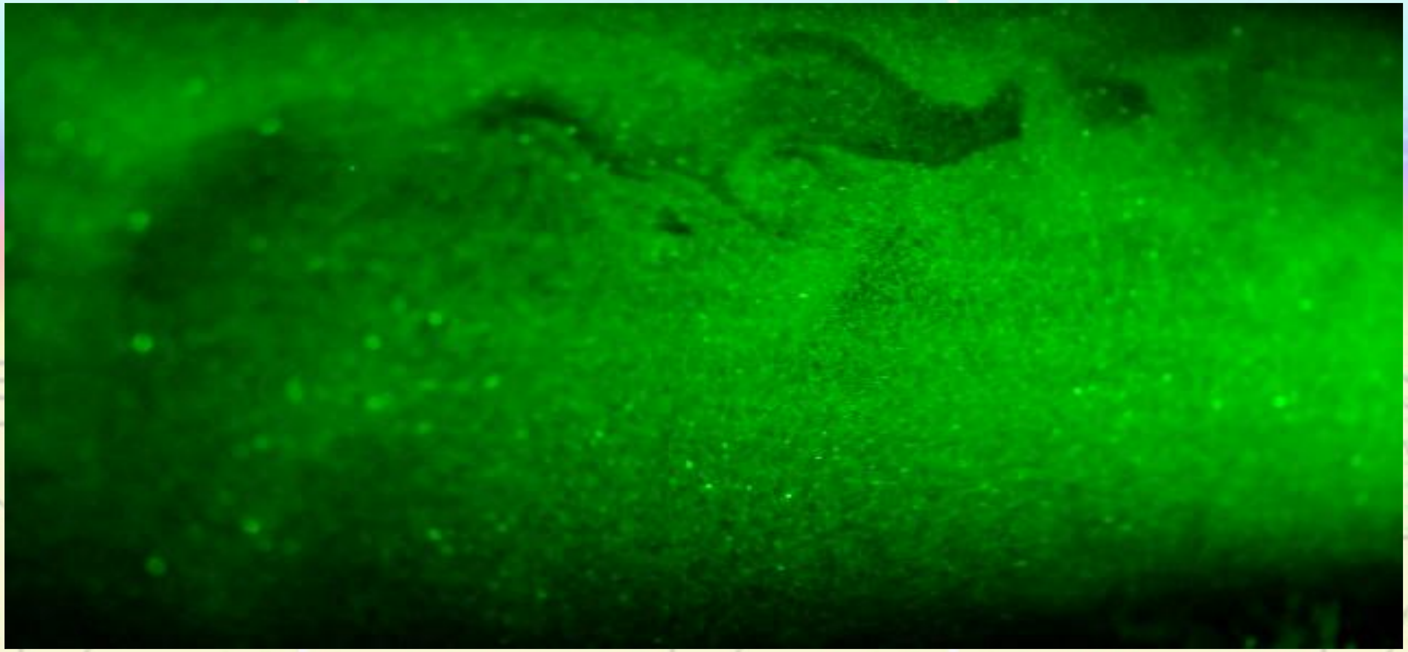
Aerosols cooling to upper atmosphere

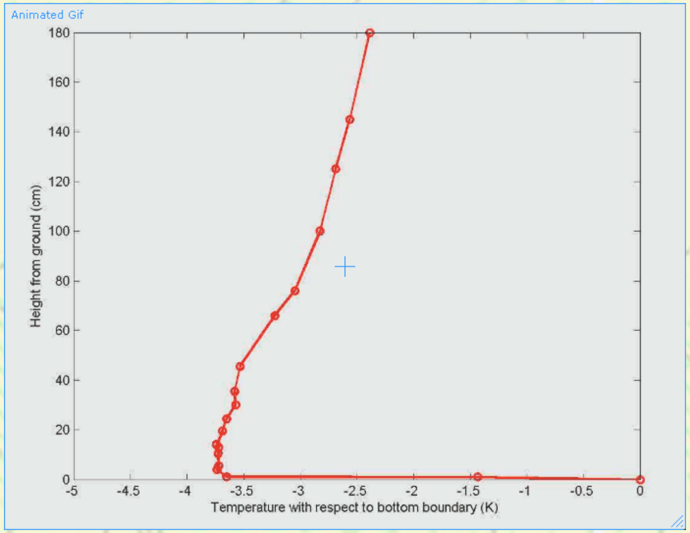


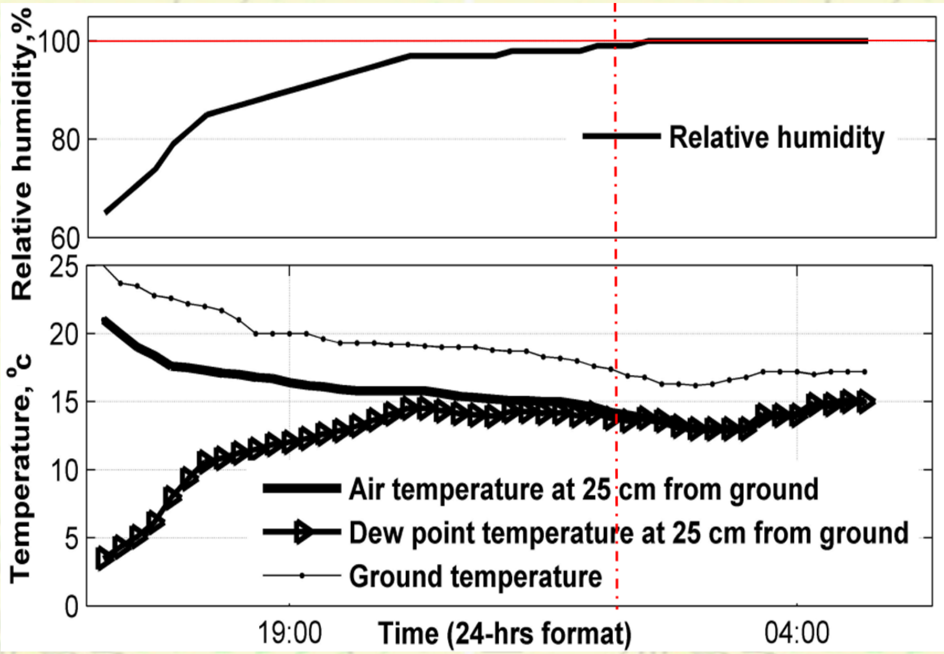




Movie-Fog

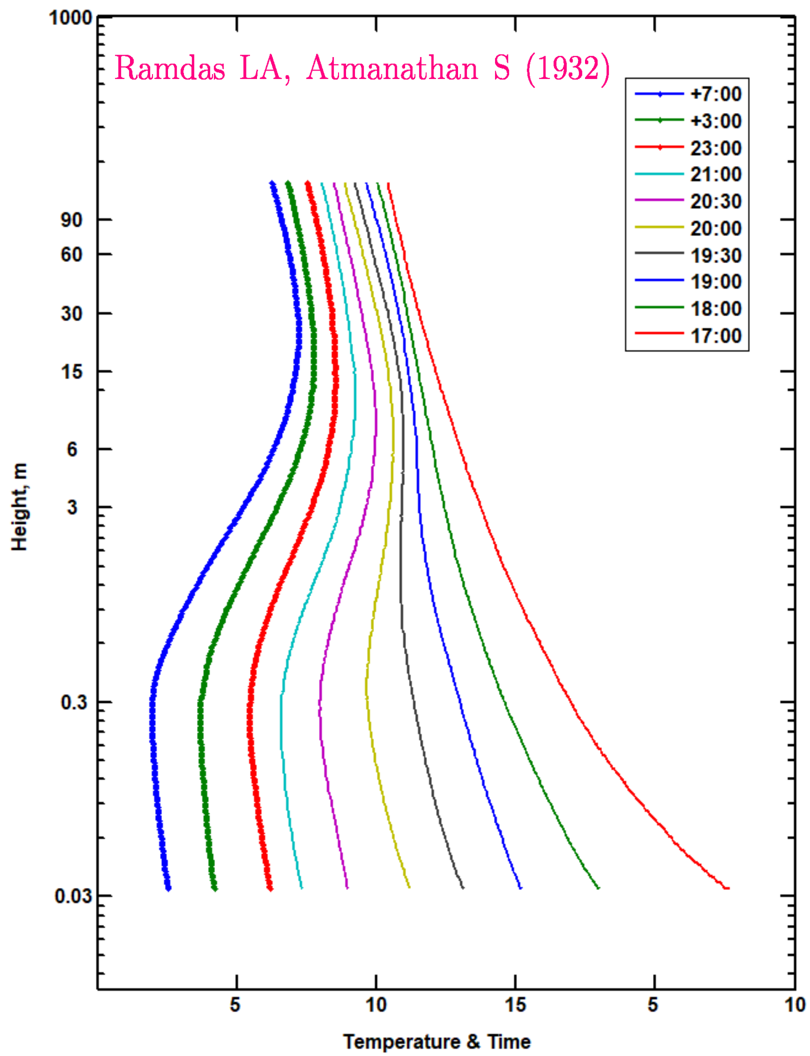


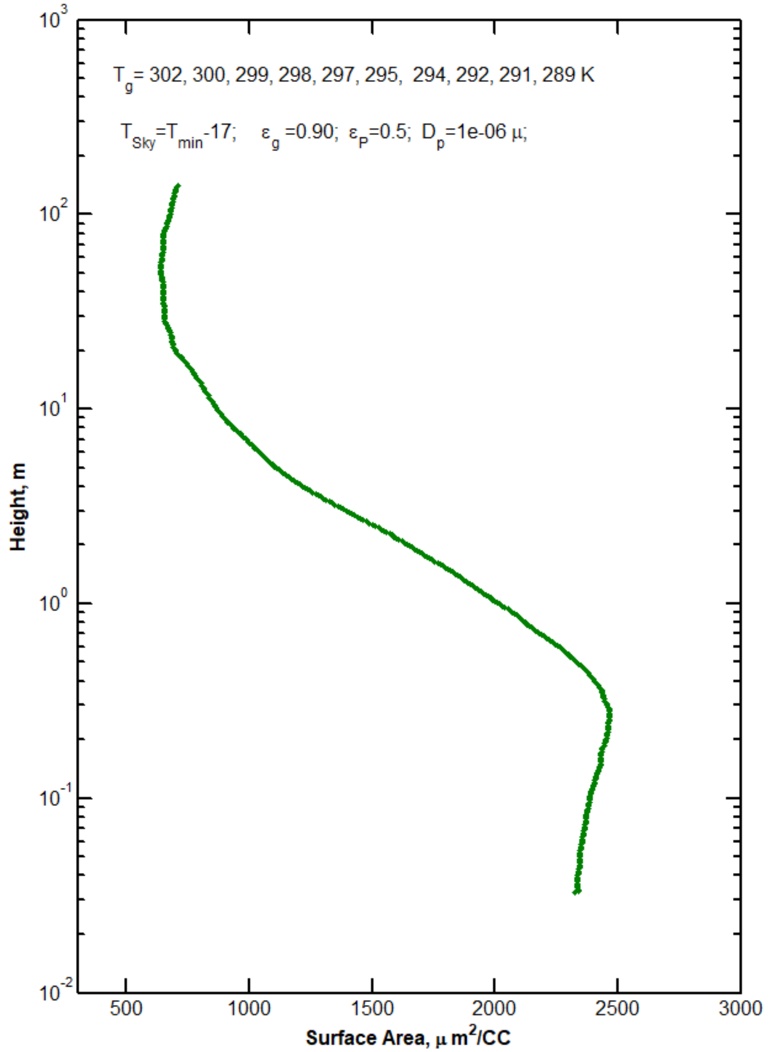


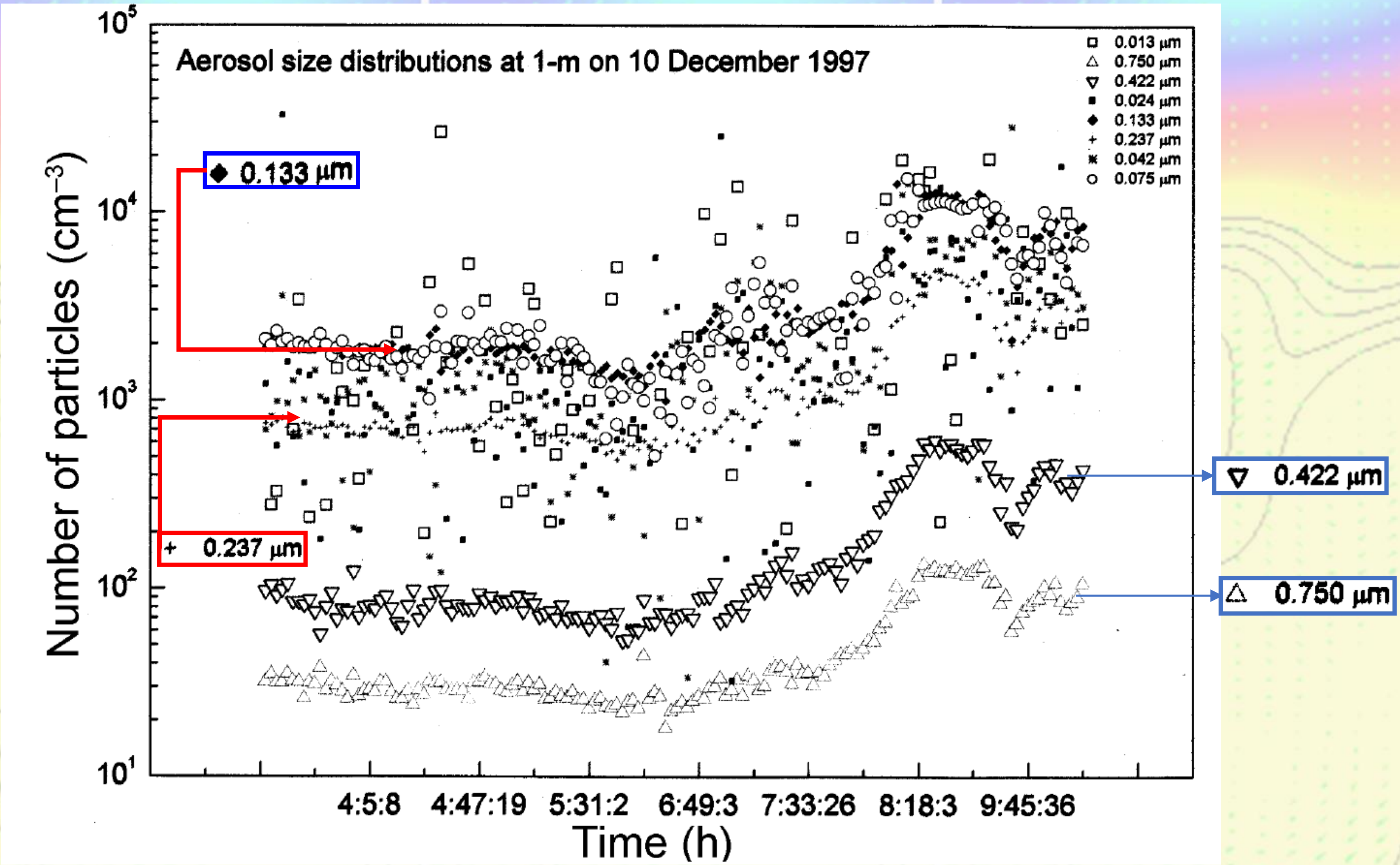


Movie-Temp NOT synchronized

Estimated Aerosol Area: without considering Water vapour …..

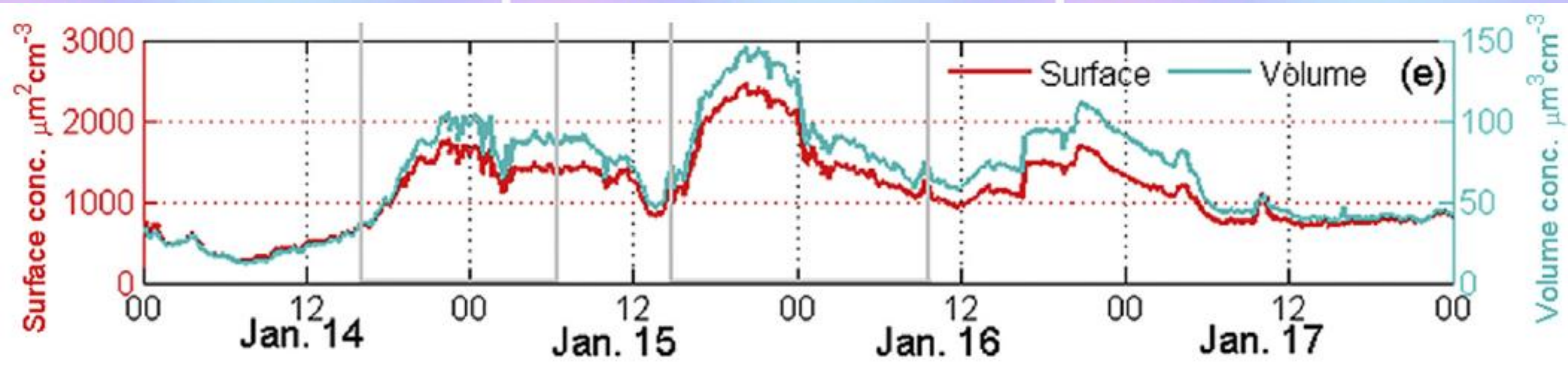




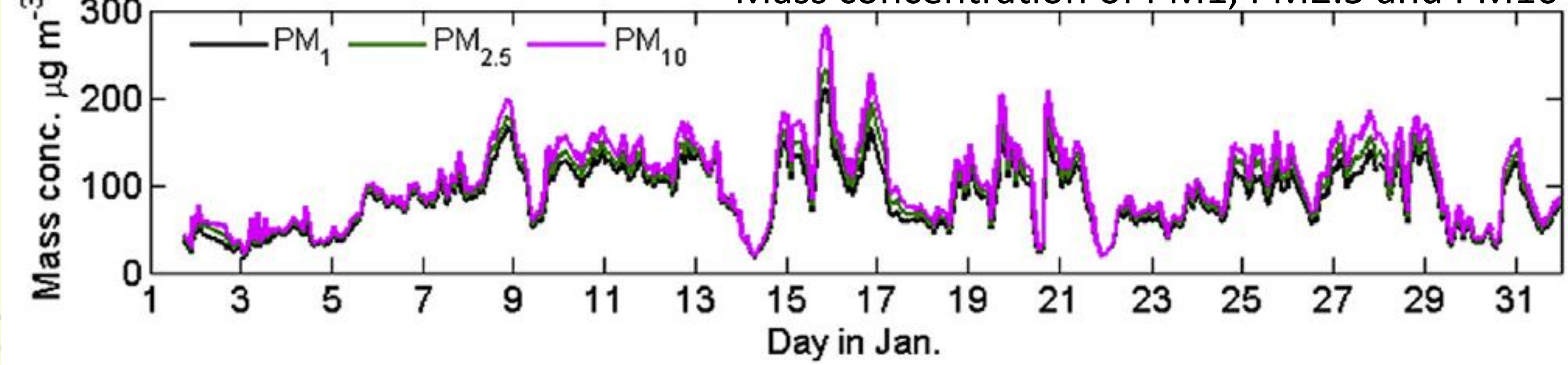


Field measurements of sub-micron aerosol concentration during cold season in India (@Pune)

D. M. Chate1, and T. S. Pranesha, Current Science, V86, 2004.

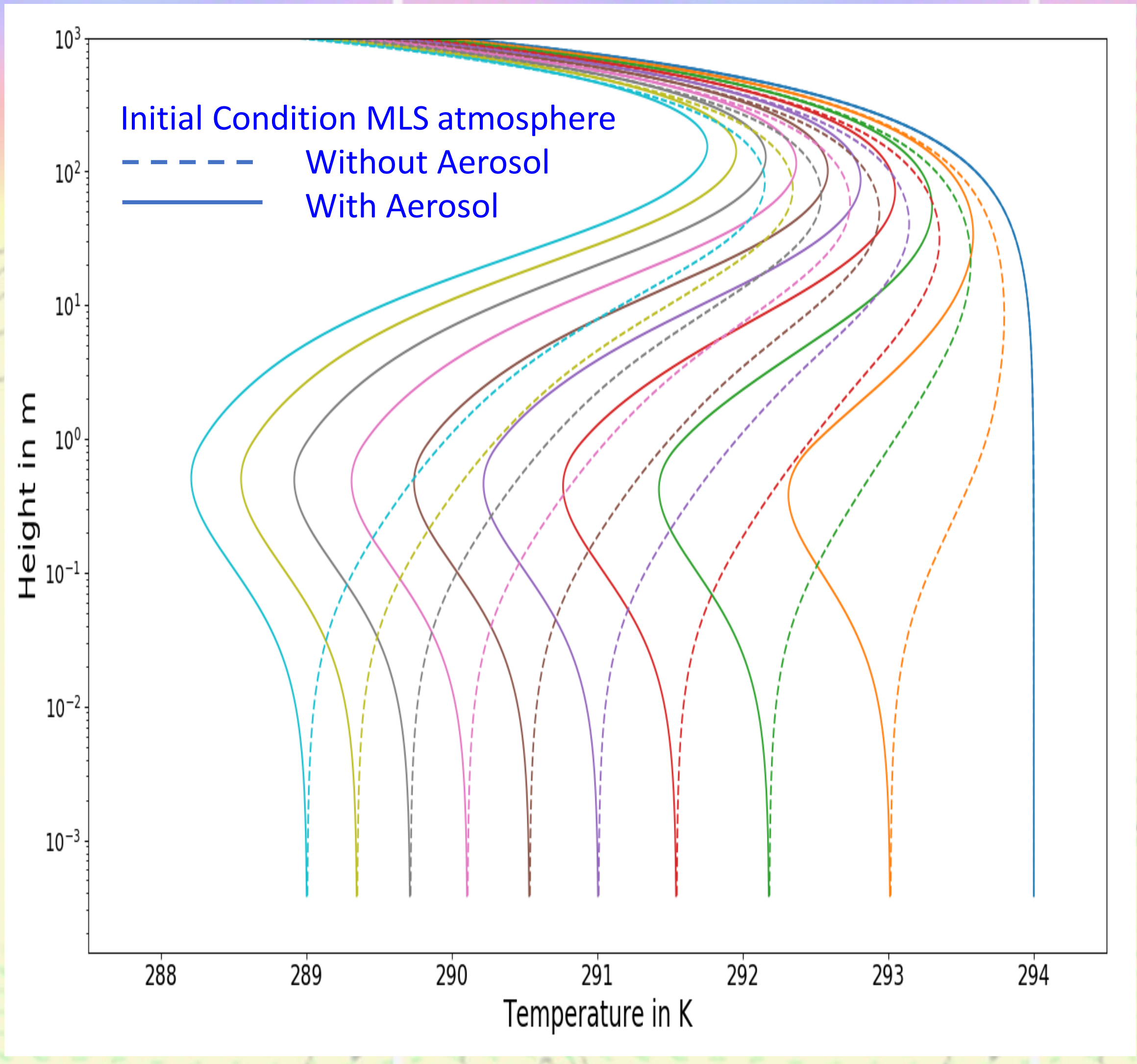


Mass concentration of PM1, PM2.5 and PM10



Characterization of submicron aerosols and effect on visibility during a severe haze-fog episode in Yangtze River Delta, China, Shen et. al. Atmospheric Environment 120 (2015) 307-316

ε_g= 0.95; Ground Cooling rate = 2K / $hr^{0.5}$; ϕ =1.0 μm; RI of Particles = 1.0 + 0.6j



Convection in the surface layer

Governing equations (2D)

$$\nabla.(\rho \mathbf{u}) + \frac{\partial \rho}{\partial t} = 0$$

Conservation of mass

Conservation of momentum

$$\rho(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}) = -\frac{\partial p}{\partial x} + \mu\Delta u$$

$$\rho(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}) = -\frac{\partial p}{\partial y} + \mu\Delta v - \rho g$$

Conservation of energy

$$\rho C_p(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}) = k\Delta T + q$$

Radiation

$$\frac{\partial C}{\partial t} + \mathbf{u}.\nabla C = 0$$

Transport of aerosols

where , normalized concentration $C = \frac{N-Nt}{Nb-Nt}$

Computational setup (2D)

Properties of interest

- Density of fluid
- Velocity and Temperature
- Concentration of aerosol

Transient simulation

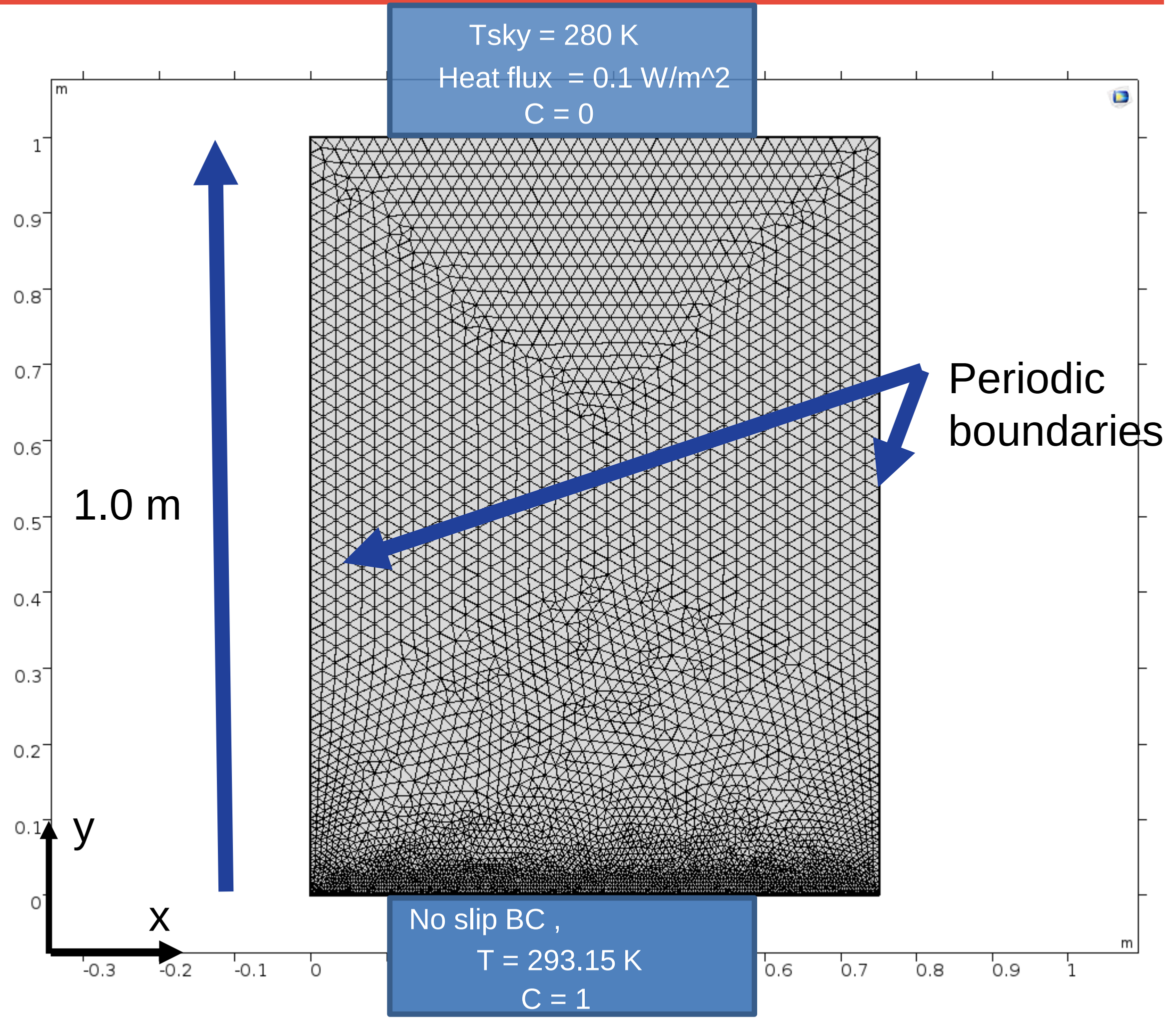
- Run for 600 seconds

Physics used

- Heat transfer in fluids
- Laminar flow
- Coefficient form PDE

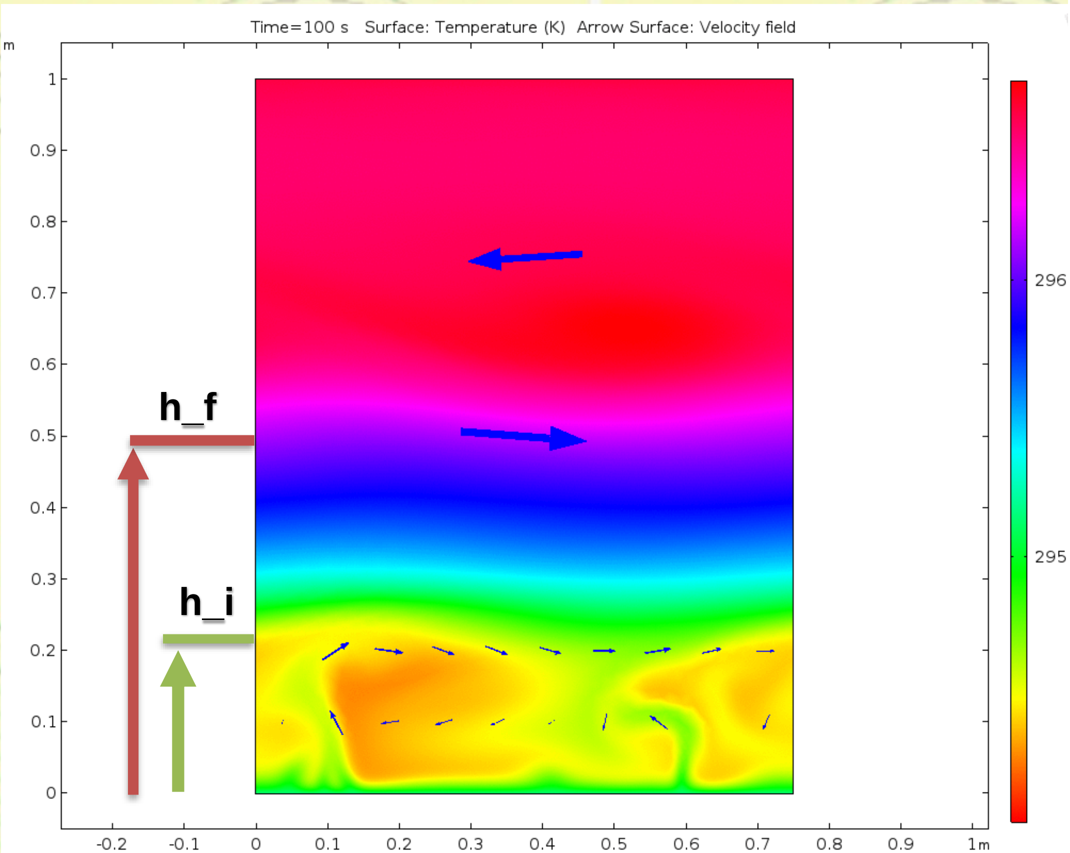
Mesh used

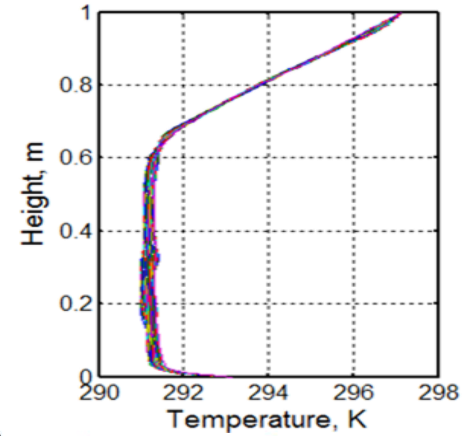
- Physics-controlled mesh
- Element size : Extra Fine

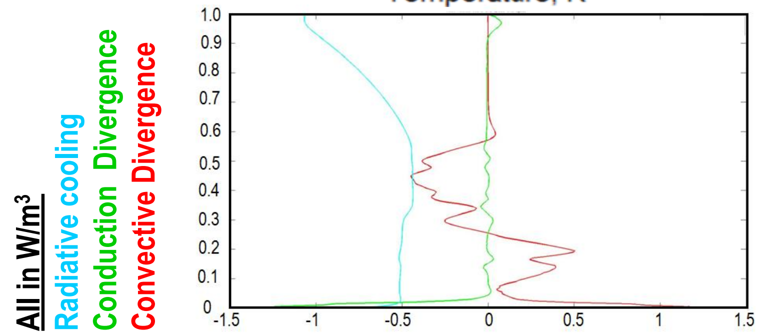


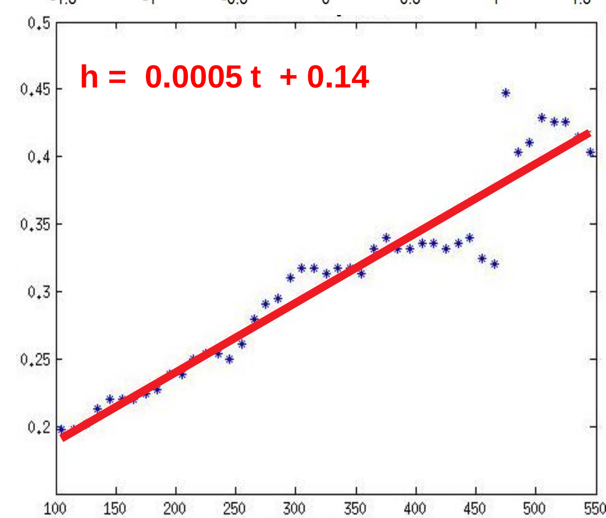
Simulation results

- Convective rolls in the lower half of the domain with a stable stratification on top
- Inversion layer and LTM is observed
- Growth of the mixed layer



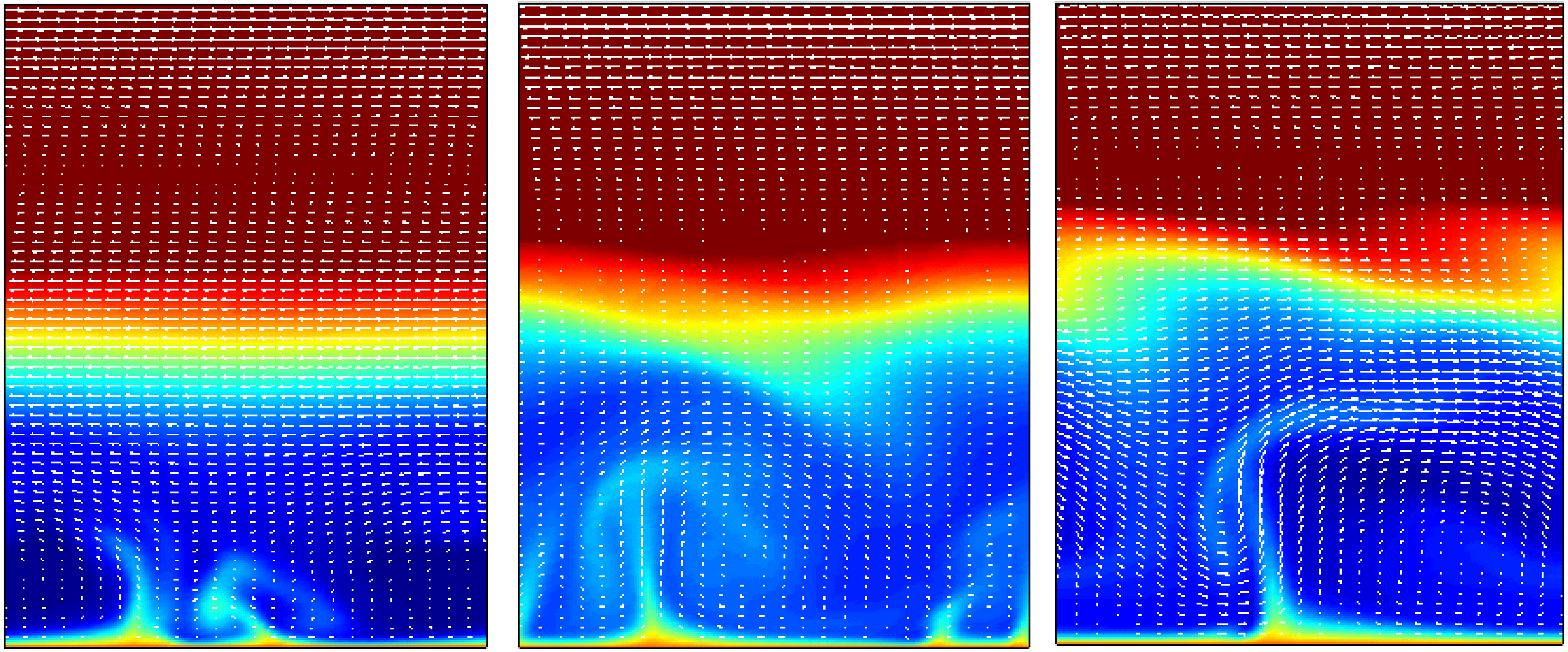






Varying radiative cooling

- Higher cooling rates result in larger mixed layer heights
- Typical cooling observed in field experiments : 4 – 6 W/m^2



Radiative cooling : 1 W/m^2 Radiative cooling : 3 W/m^2 Radiative cooling : 5 W/m^2

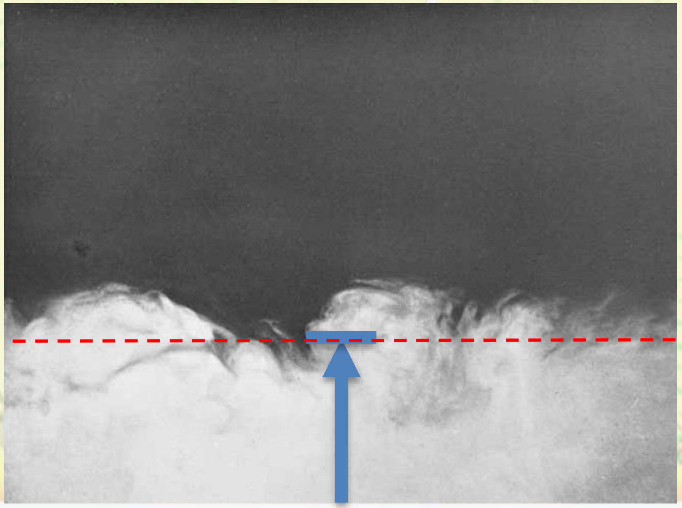
Penetrative convection analysis

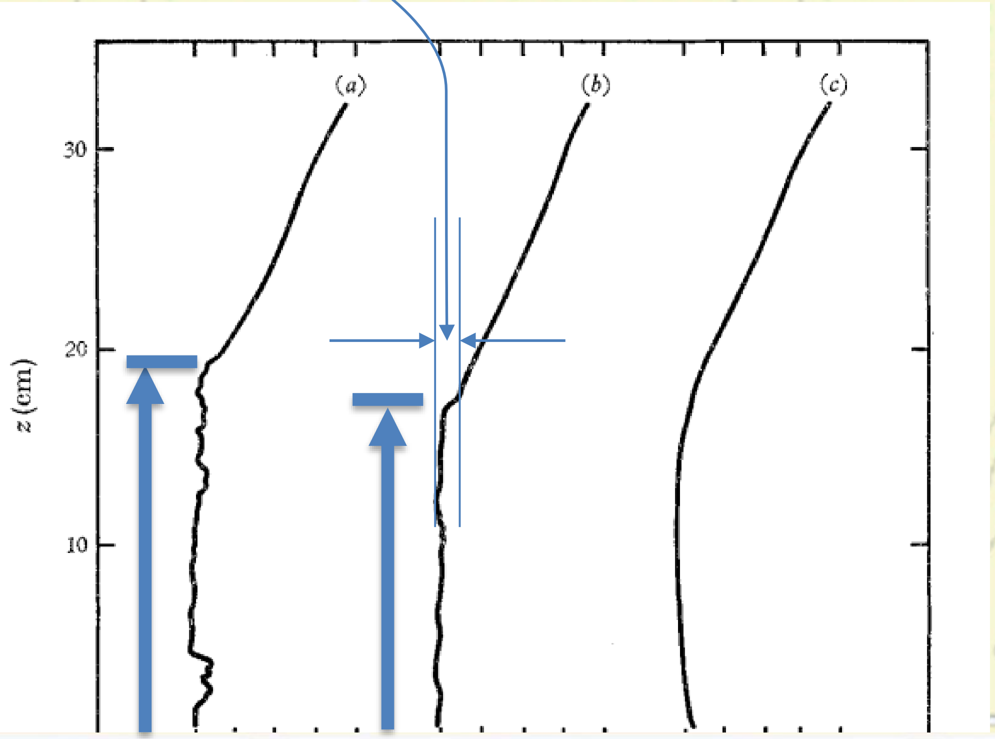
- Deardorff and Willis in 1969, conducted laboratory investigation of non-steady penetrative convection

$$\frac{dh}{dt} = C_1 U_* Ri^{-n} \qquad Ri = \frac{g\Delta\rho h}{\rho U_*^2} \qquad U_* = \left[\frac{g\beta Q h}{\rho C_P}\right]^{\frac{1}{3}}$$

- h : convective layer height $\Delta\rho$: Density jump U$_*$: velocity scale Q : Bottom heat flux

- Ri : Richardson number predicts fluid turbulence and stability

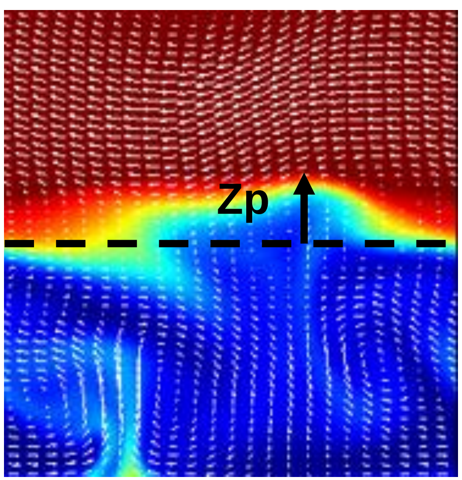




Comparison with Deardorff scales

$$\frac{dh}{dt} = C_1 U_* Ri^{-n} \qquad Ri = \frac{g\Delta\rho h}{\rho U_*^2} \qquad U_* = \left[\frac{g\beta Q h}{\rho C_P}\right]^{\frac{1}{3}}$$

- Zangrando and Fernando (1991) suggested that in such cases $\Delta\rho$ should be calculated by : $\Delta\rho = \frac{d\rho}{dy}$ "h"
- They suggest the interfacial height '**h**' to be the appropriate length scale (L)
- However, that is an overestimation. The correct length scale comes from the energy balance at the interface

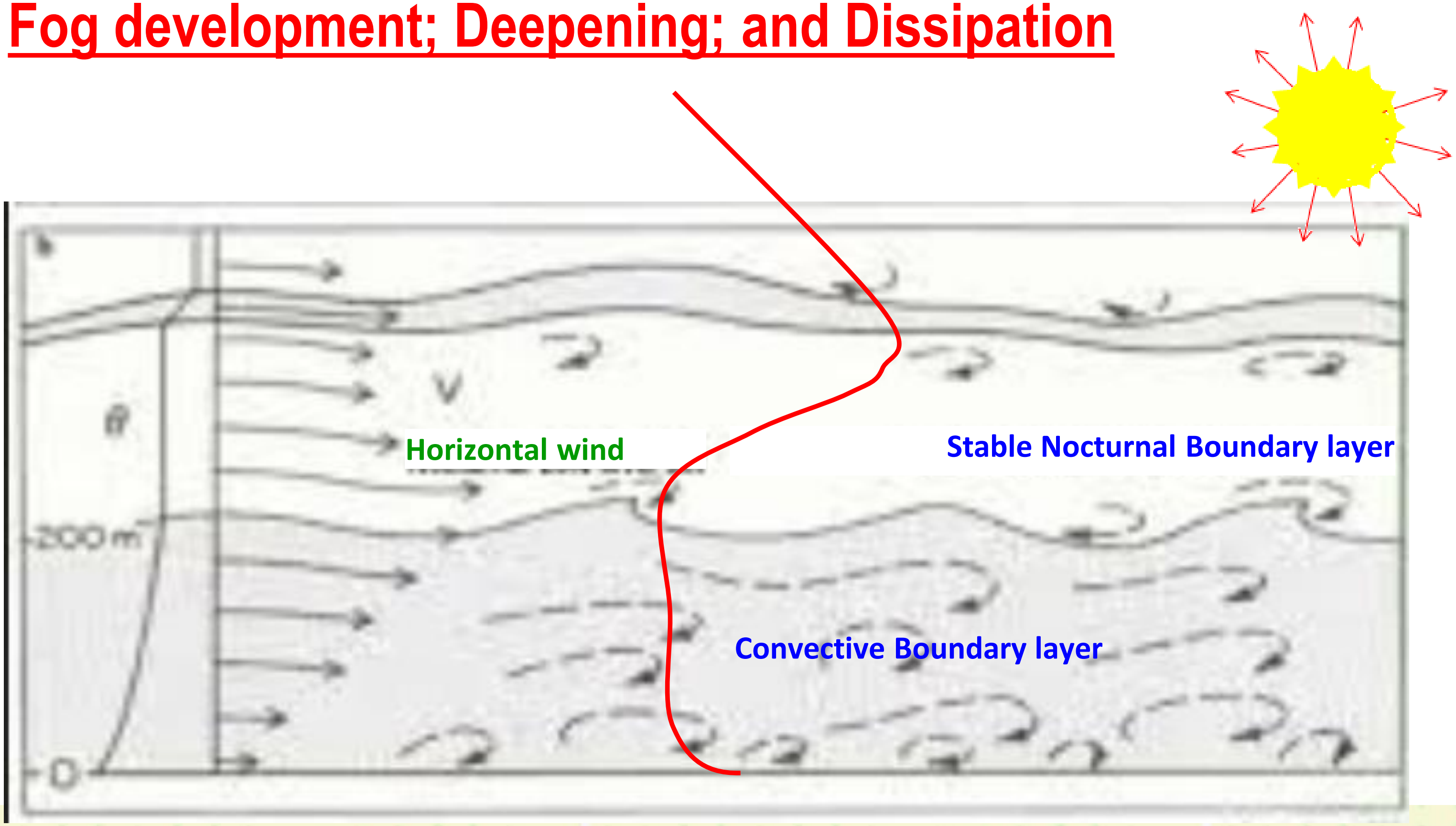


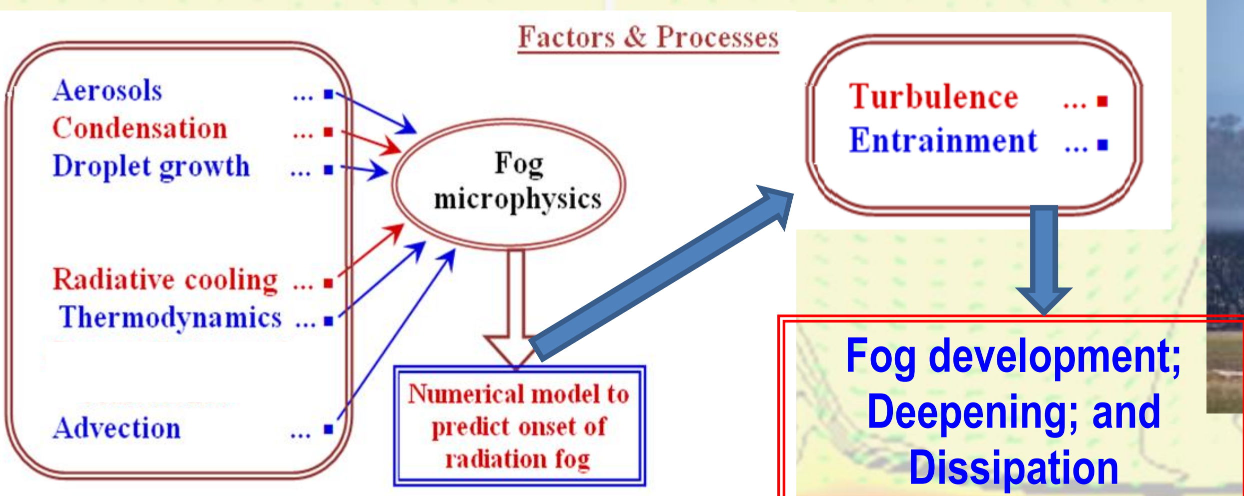
Correct length scale for calculating $\Delta\rho$ *is* **Zp**

		q = 1.0	q = 2.5	q = 5.0
Mixed layer height (m)	: h	0.39	0.38	0.39
Bottom heat flux (W/m^2)	: Qb	0.49	0.74	1.34
Convective velocity scale(m/s)	: u*	0.017	0.02	0.024
Penetration depth (m)	: Zp	0.022	0.025	0.041
Richardson number	: Ri	8.76	7.68	4.71
Maximum observed u_rms (m/s)		0.1	0.125	0.195
Maximum observed v_rms (m/s)		0.014	0.011	0.02

Results match with theoretical values

Fog development; Deepening; and Dissipation





1] Mukund, V., Ponnulakshmi, V. K., Singh, D. K., Subramanian, G., & Sreenivas, K. R. (2010). Hyper-cooling in the nocturnal boundary layer: the Ramdas paradox. *Physica Scripta*, *2010*(T142), 014041.

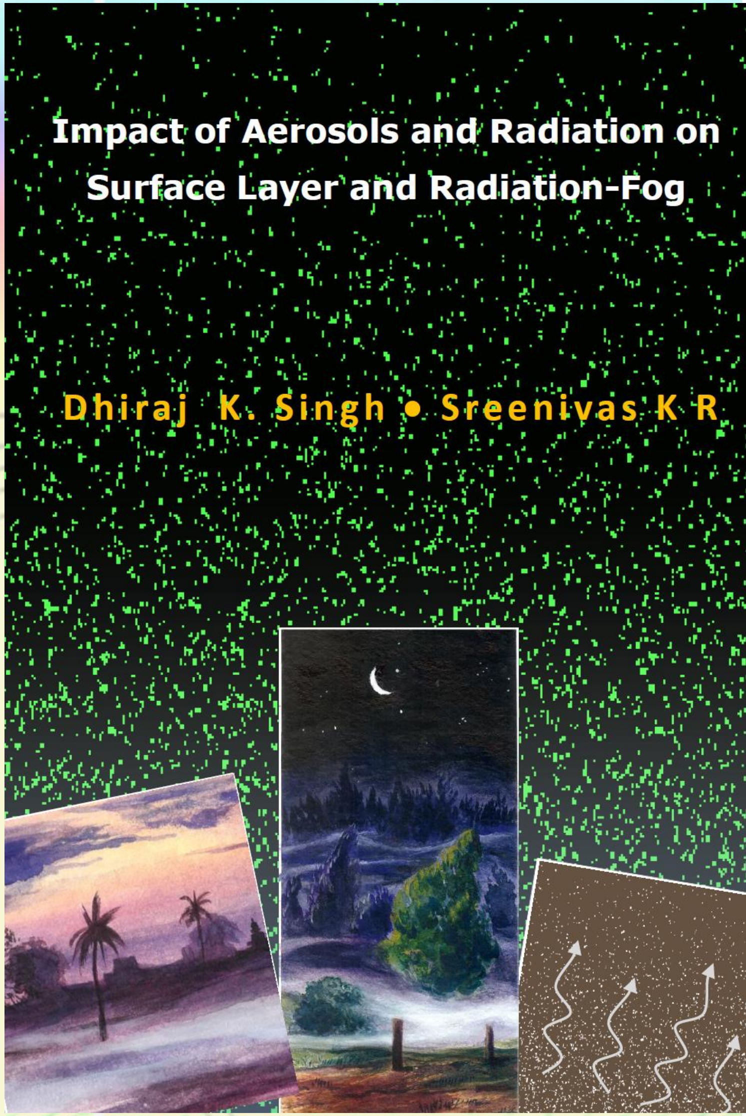
2] Ponnulakshmi, V. K., Mukund, V., Singh, D. K., Sreenivas, K. R., & Subramanian, G. (2012). Hypercooling in the nocturnal boundary layer: Broadband emissivity schemes. *Journal of the Atmospheric Sciences*, *69*(9), 2892-2905.

3] Ponnulakshmi, V. K., Singh, D. K., Mukund, V., Sreenivas, K. R., & Subramanian, G. (2013). Hypercooling in the atmospheric boundary layer: beyond broadband emissivity schemes. *Journal of the Atmospheric Sciences*, *70*(1), 278-283.

4] Mukund, V., Singh, D. K., Ponnulakshmi, V. K., Subramanian, G., & Sreenivas, K. R. (2013). Field and laboratory experiments on aerosol-induced cooling in the nocturnal boundary layer. *Quarterly Journal of the Royal Meteorological Society*.

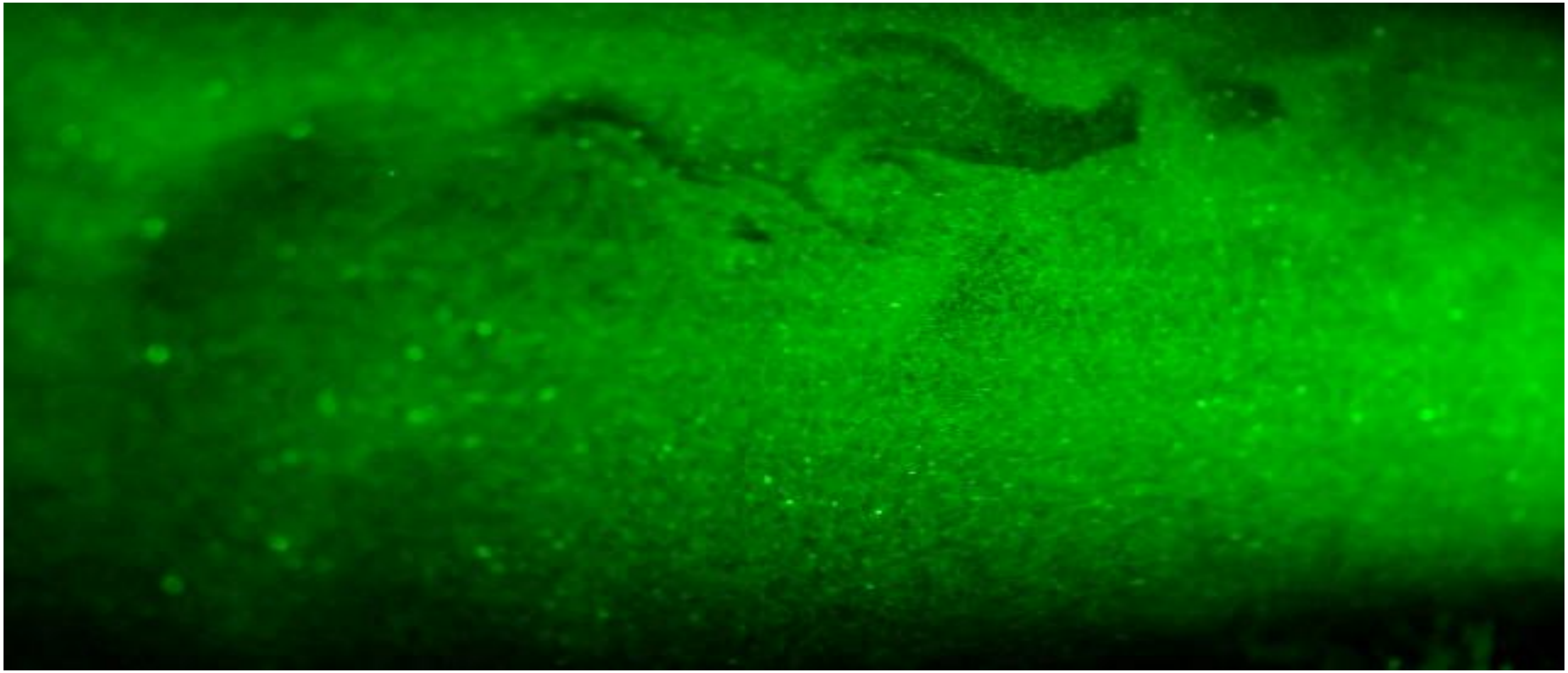
5] Singh, D. K., et al. "Radiation forcing by the atmospheric aerosols in the nocturnal boundary layer." *RADIATION PROCESSES IN THE ATMOSPHERE AND OCEAN (IRS2012): Proceedings of the International Radiation Symposium (IRC/IAMAS)*. Vol. 1531. No. 1. AIP Publishing, 2013.

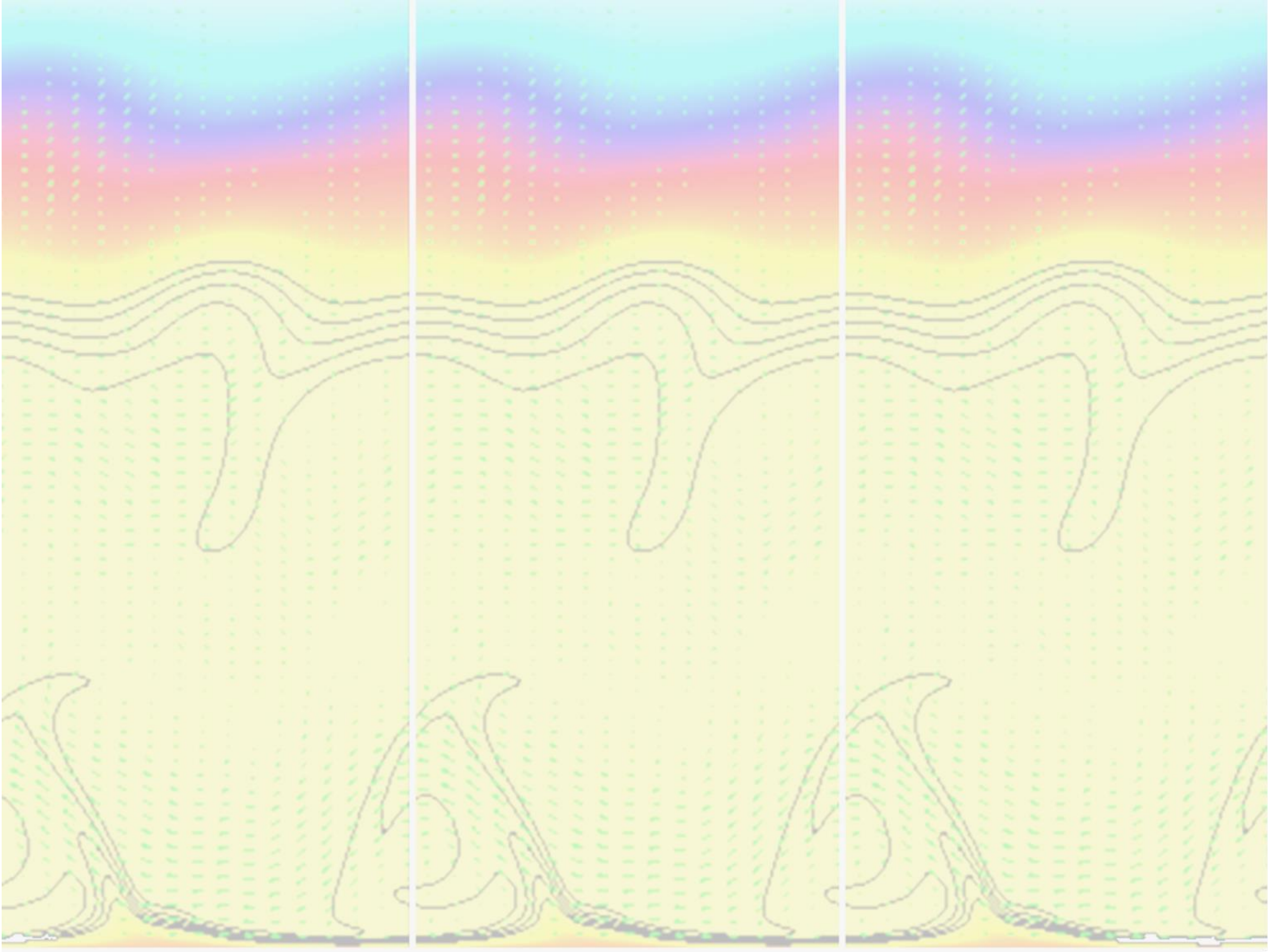
6] Importance of Aerosols in Predicting the onset of Radiation Fog 14th EMS Annual Meeting & 10th European Conference on Applied Climatology (ECAC) | 06 – 10 October 2014 | Prague, Czech Republic

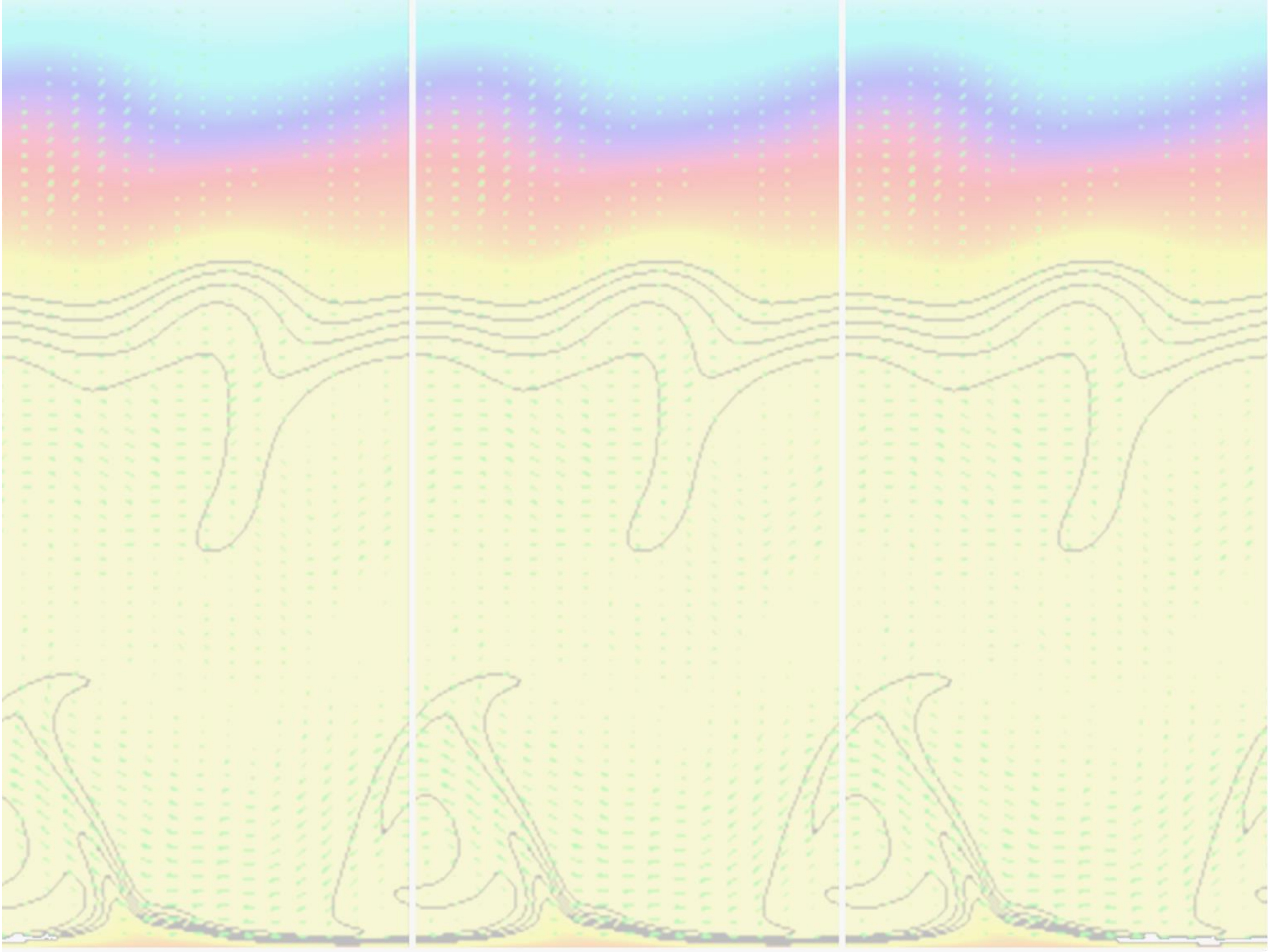


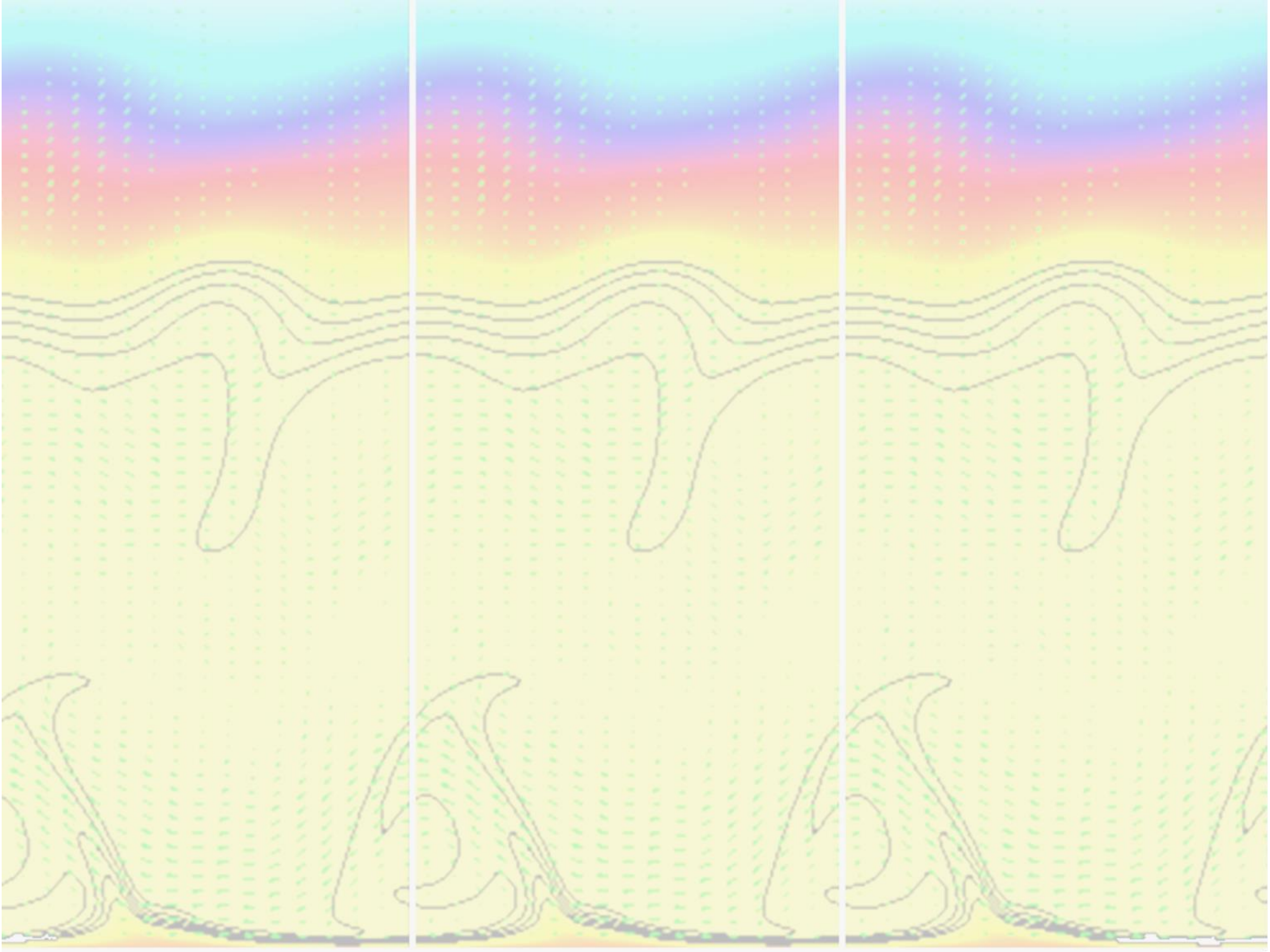
THANK YOU

Questions



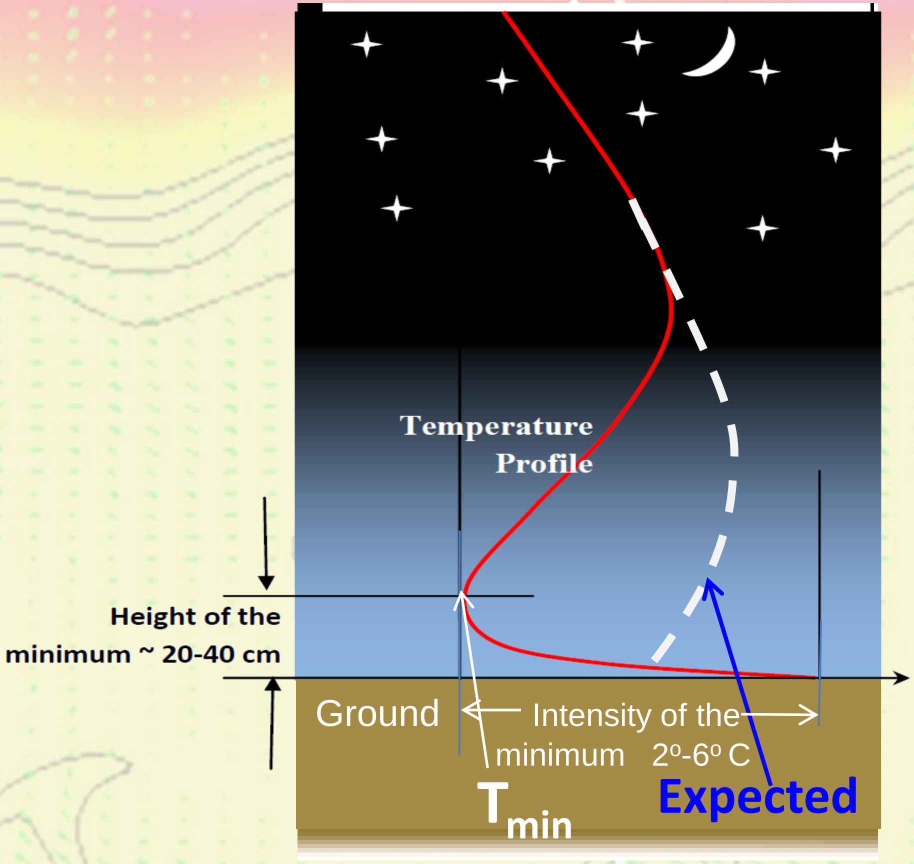






Nocturnal Atmospheric Surface layer :

Lifted Temperature minimum (LTM) – Ramdas layer (1932)

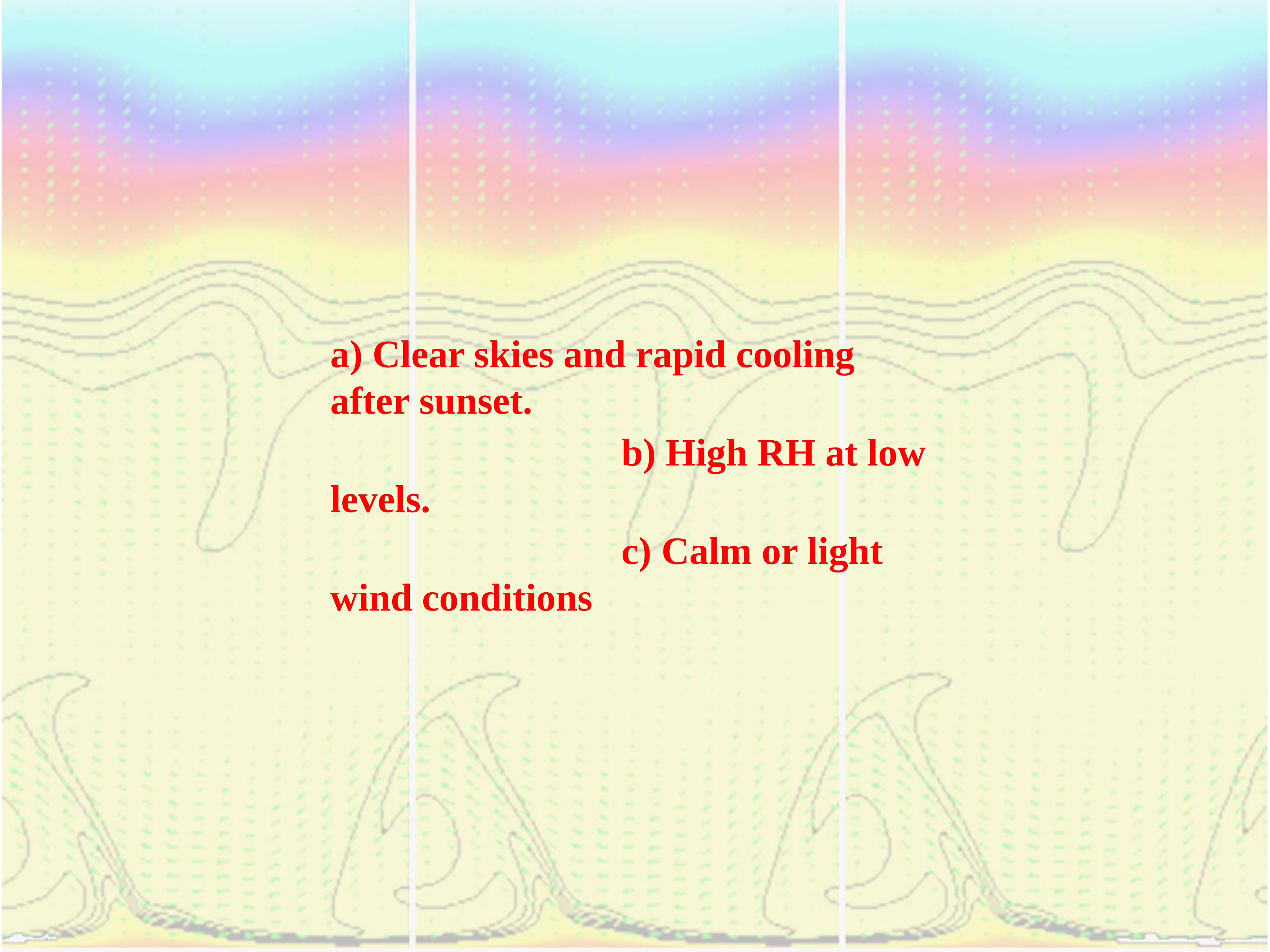


- During calm (low wind) and clear sky nights--Radiation dominates over other heat transfer processes in the boundary layer.
- In tropics this condition prevails in more than 75% of the time.

Liu, et. al., 2008

Origin of cold air layer in the warmer surrounding

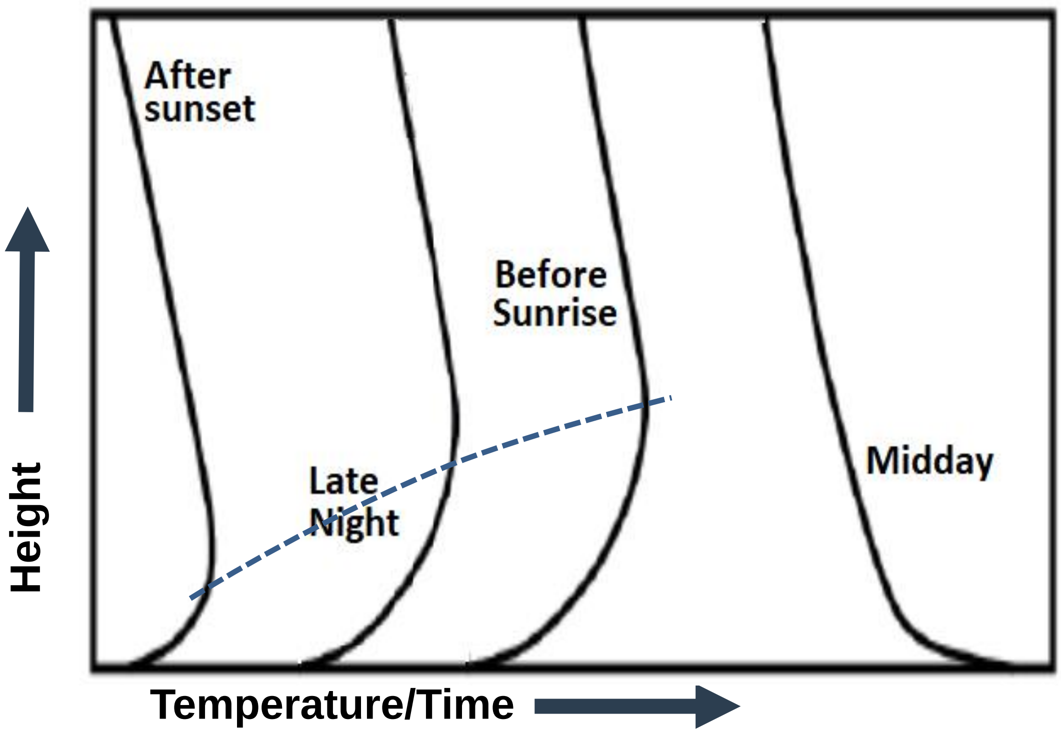
- Ra_T for Ramdas layer is ~ 10^6
- **Stability & Transport**

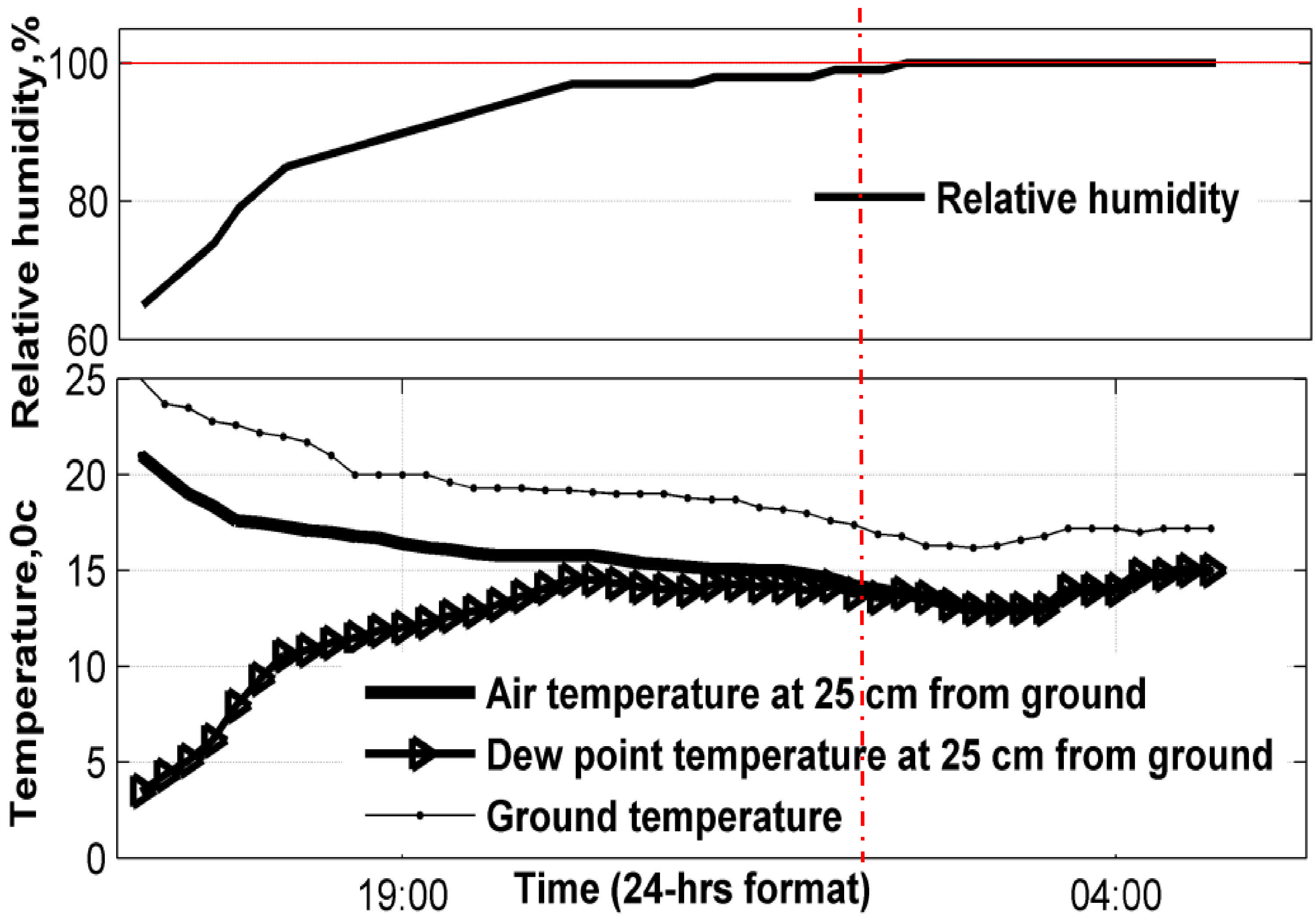


a) Clear skies and rapid cooling after sunset.

b) High RH at low levels.

c) Calm or light wind conditions


After sunset
Late Night
Before Sunrise
Midday
Height
Temperature/Time

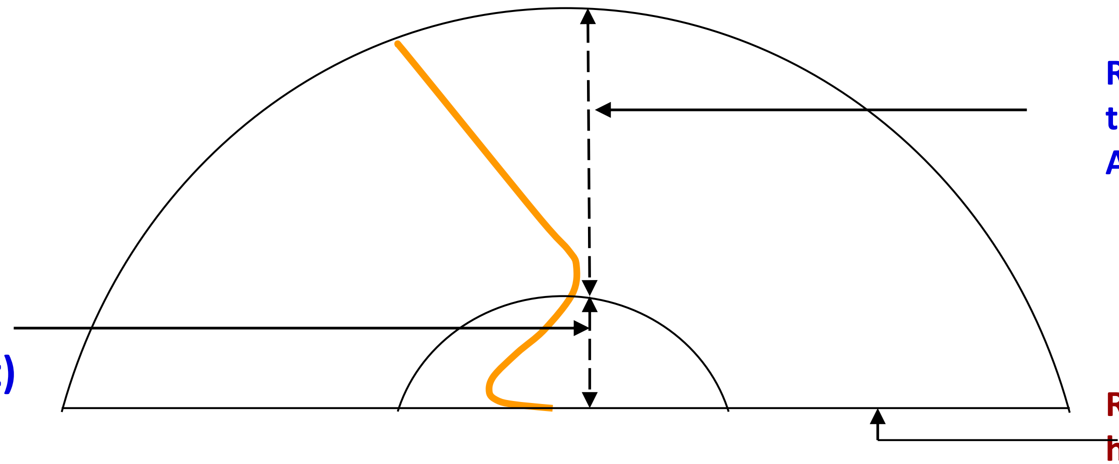


Relative humidity,%
100
80
60
Relative humidity
Temperature,0c
25
20
15
10
5
0
Air temperature at 25 cm from ground
Dew point temperature at 25 cm from ground
Ground temperature
19:00
04:00
Time (24-hrs format)

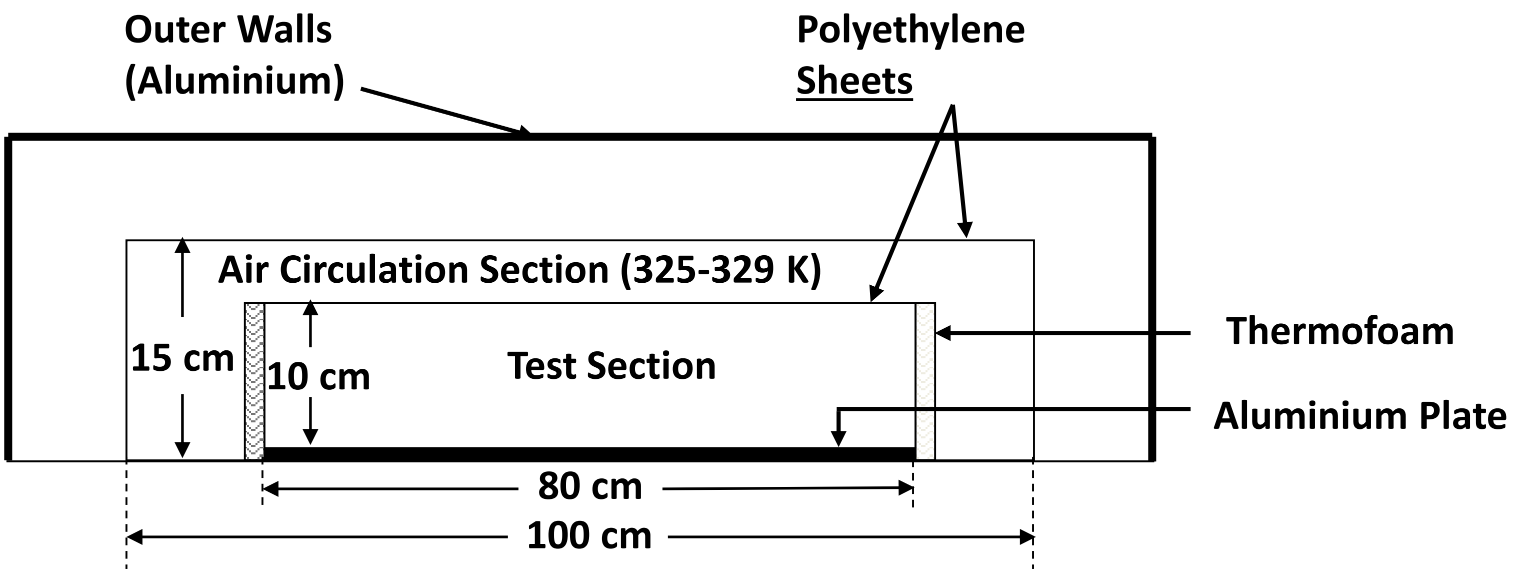
EMU, JNCASR

LABORATORY SETUP

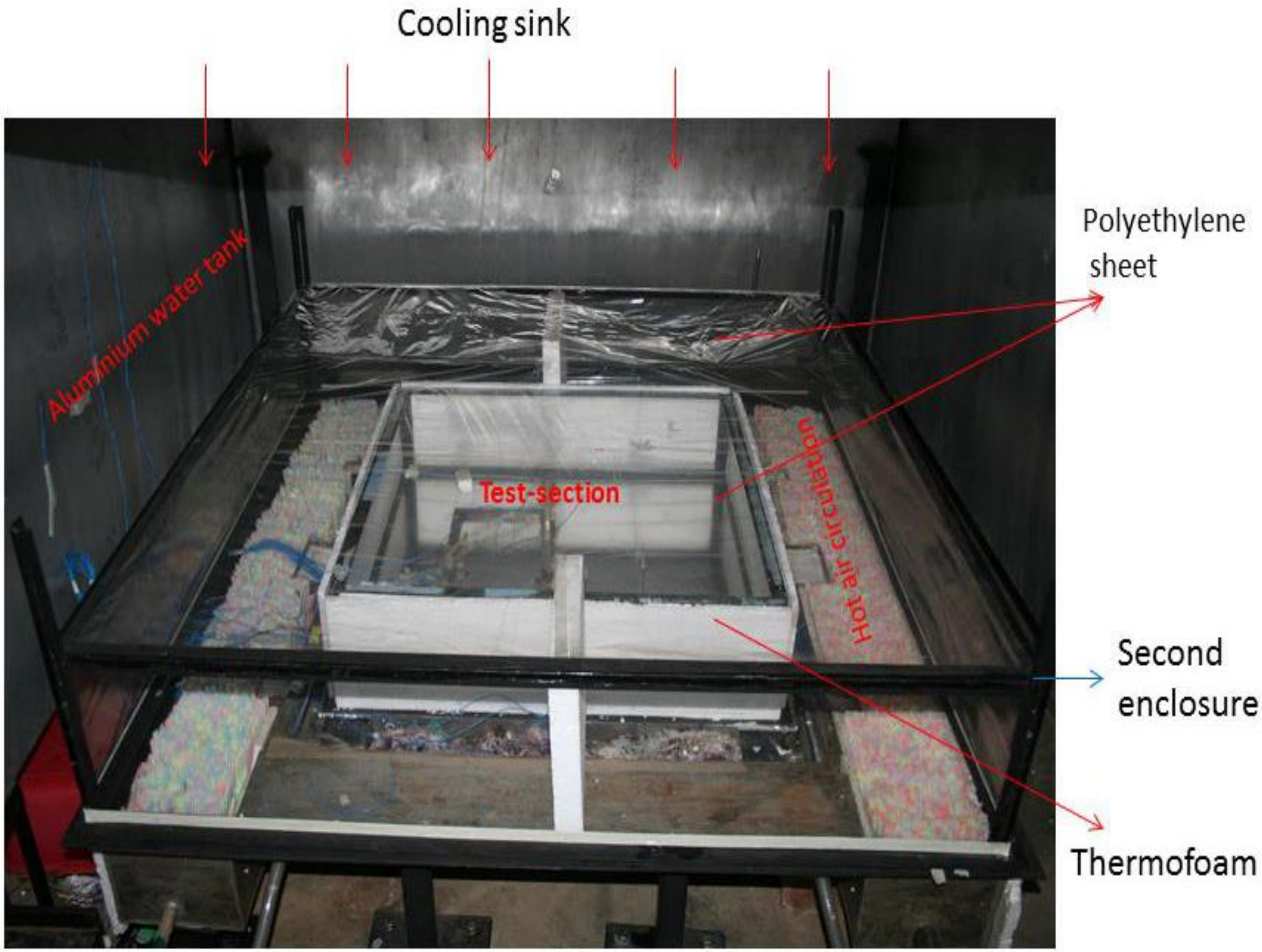
2006-2008



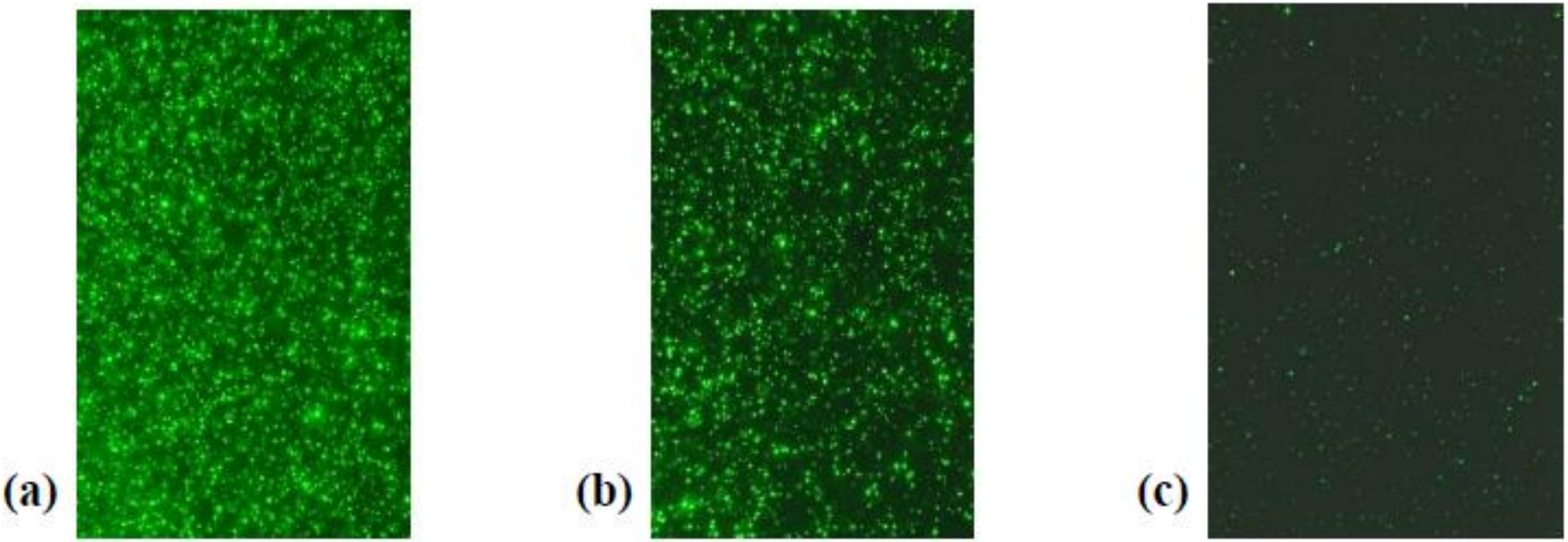
Decoupling of radiation and conduction/convection boundary conditions — necessary to produce LTM in Lab



Lab setup: Decoupling Radiation Boundary condition



EMU, JNCASR



(a) At 1.5cm 2.68×10^{10} particles/m^3

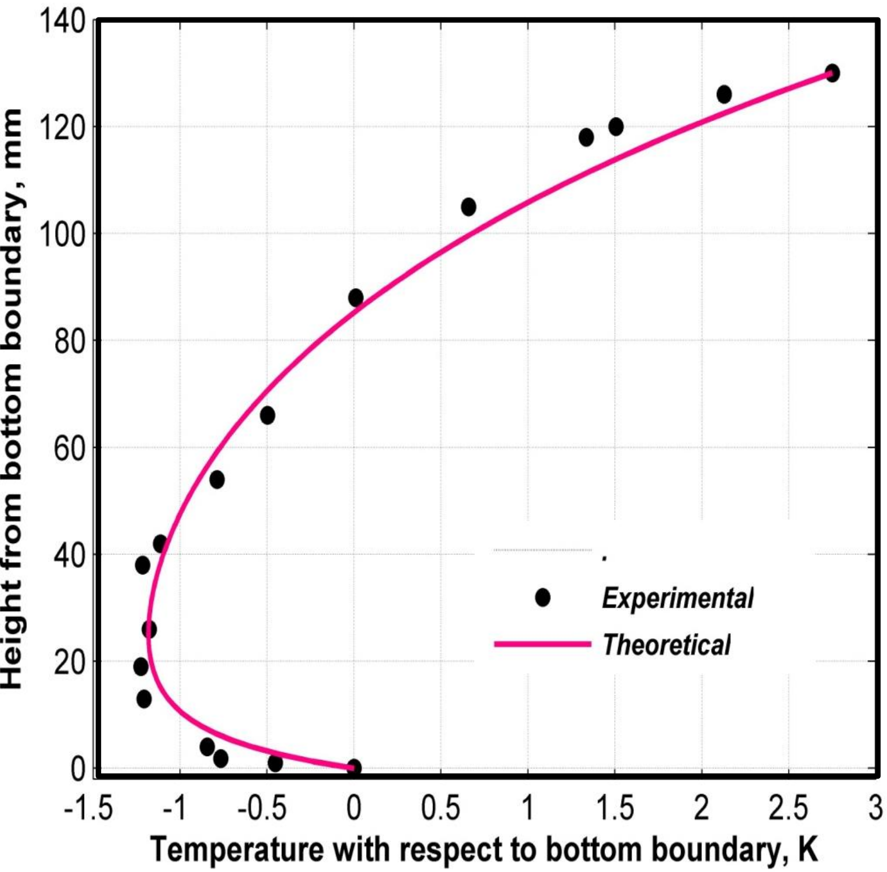
(b) at 3 cm 1.08×10^{10} particles/ m^3

(c) at10 cm 2.6×10^{9} particles/m^3

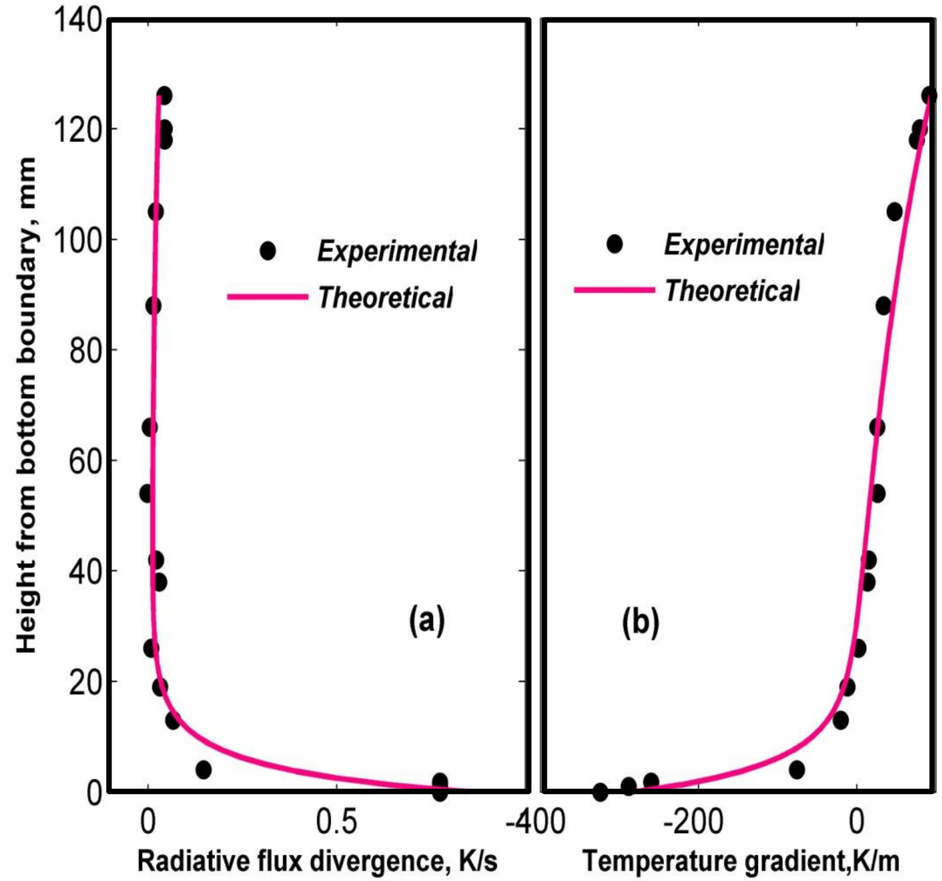
EMU, JNCASR

$$\alpha_{air+aerosol} = 1.4\, e^{-\left(\frac{z}{0.05}\right)} + 0.03$$

$$\alpha \rightarrow \text{absorption coefficient}$$



[Temperature Profile]()



[Cooling rate]()

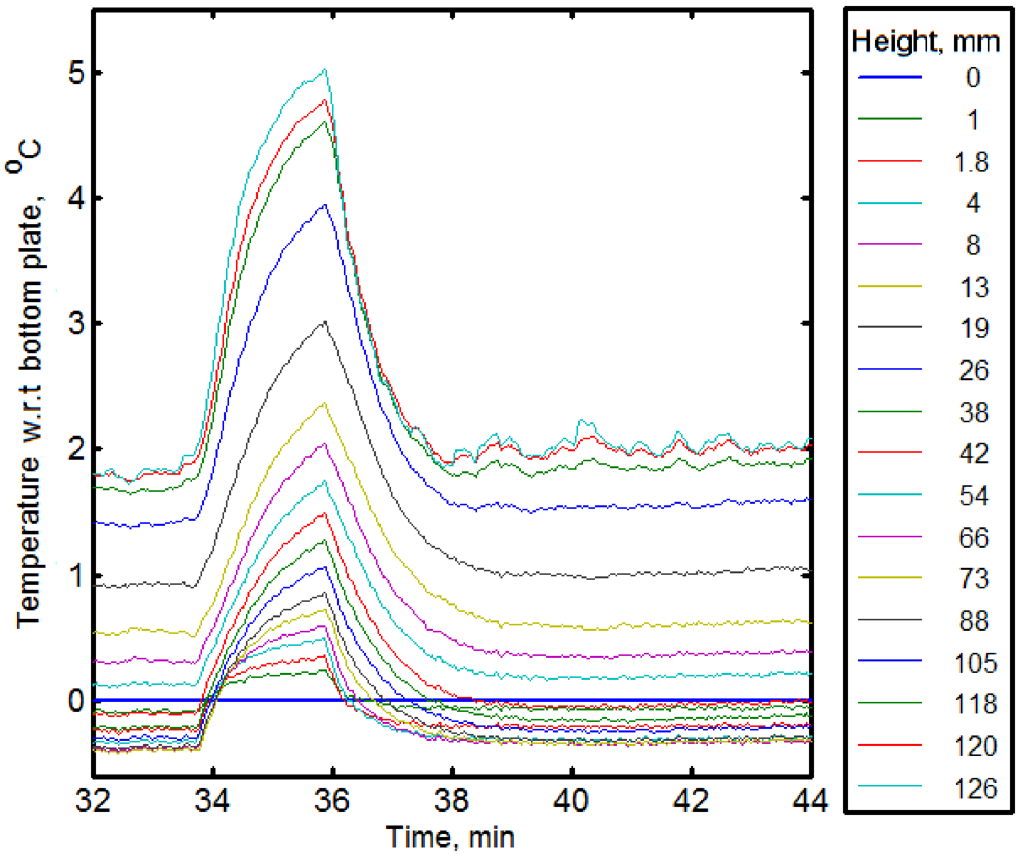
[Temperature gradient]()

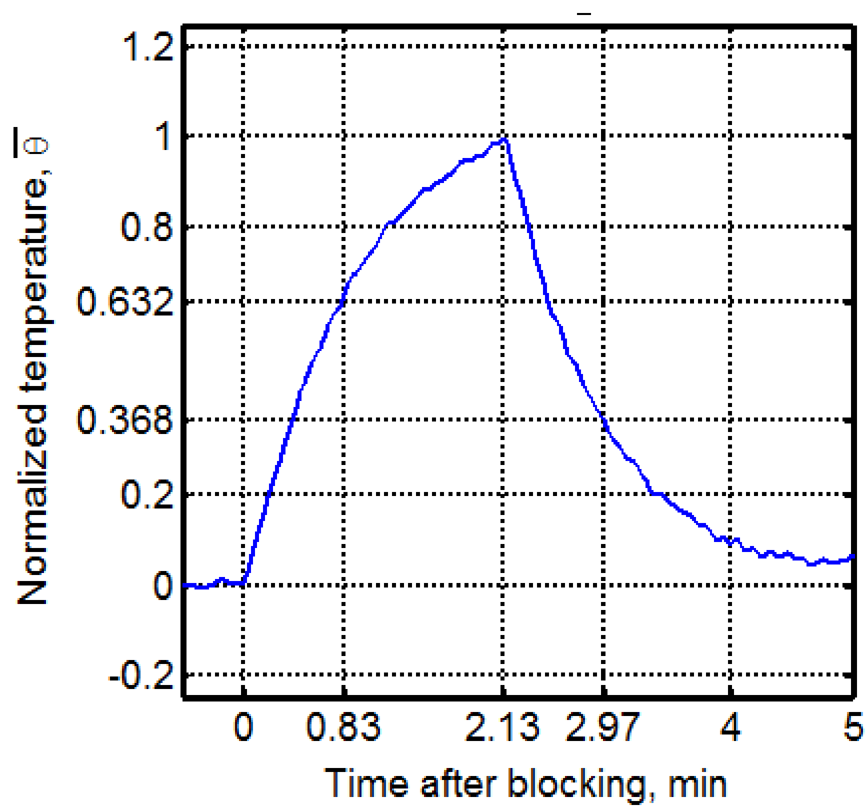
$$\alpha_{air+aerosol} = 1.4\, e^{-\left(\frac{z}{0.05}\right)} + 0.03$$

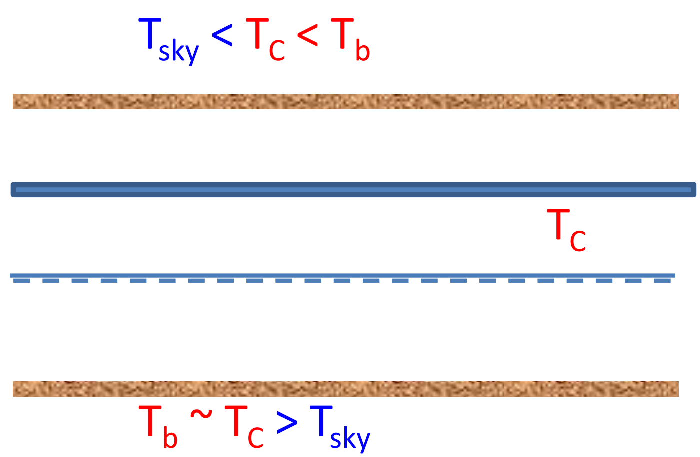
$$\alpha \rightarrow \text{absorption coefficient}$$

[*EMU, JNCASR*]()

Estimating response time of the system







EMU, JNCASR

Two Plate (RB convection)

Effect of boundary emissivities