From Earth to Heavens -- Modeling The Earth's Atmosphere.

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Our Plan

- How can we extend what we know about incompressible fluids (water) to understand the behavior of the atmosphere?
- How do atmospheric models work? What are the different types of models?
- What can we do with those?

Rules of the Game

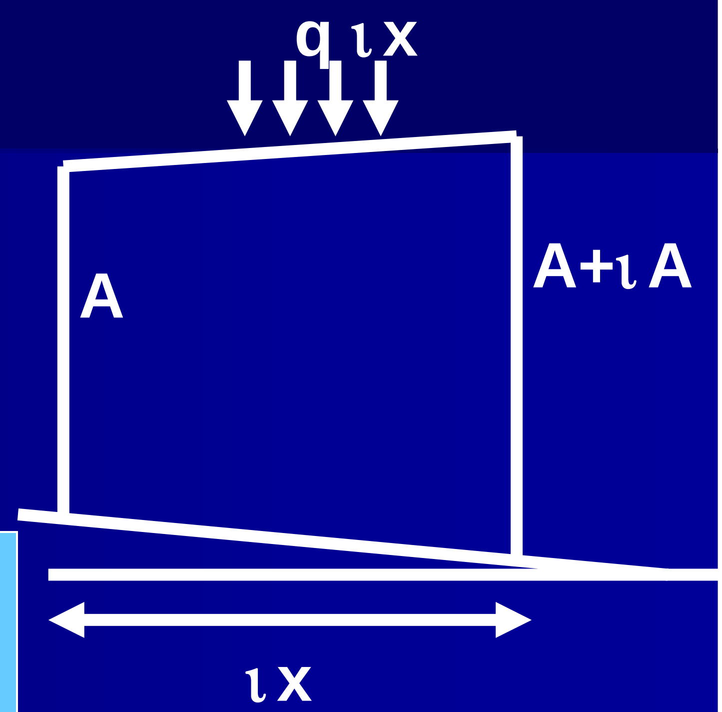
- We do not worry too much about the equations.
- We ask questions on-the-spot, without waiting for a specific ‘discussion time’ (of course there will be a one for additional discussion)
- This is a hybrid between a seminar and a lecture.

Motion of water

- Â Conservation of mass
- Â Conservation of momentum

Mass Conservation

Â 1-D example



$$\frac{\in A}{\in t} 2 \, A\frac{\in v}{\in x} 2 \, v\frac{\in A}{\in x} \mid \; q/x,t0$$

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q\left(x, t\right)$$

(Inflow) – (Outflow) + (lateral inflow) = (increase in storage)

Conservation of Momentum

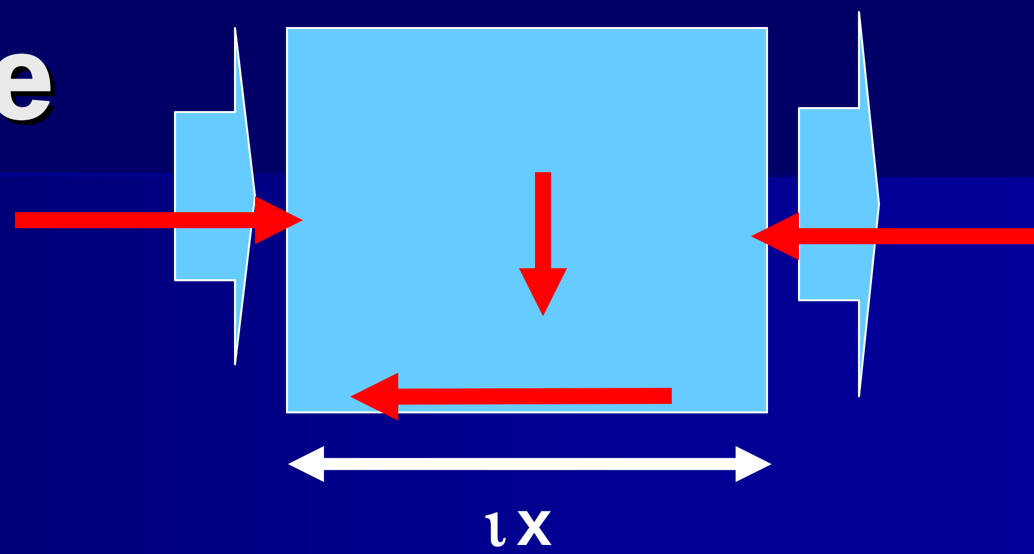
- Applying "Newton's" Second Law*

  Force = mass x acceleration

- Problem: Unlike solid objects, it is difficult to identify & follow a fluid element
  - Thus its particularly hard to consider forces on a moving fluid volume.
  - Instead we go for 'Control Volume' Approach.
  - Forces on a 'Control volume', which allows entry and exit of matter (fluid)

* Newtons 1st and 2nd law were in fact first proposed very clearly by Galileo

Forces on a control volume



Forces on the control volume:

$$\frac{\partial(\rho g h)}{\partial x} \quad \text{– Pressure force} \qquad (1)$$

$$-F \quad \text{– Frictional forces} \qquad (2)$$

$$\rho g \quad \text{– Gravity forces} \qquad (3)$$

Conservation of Momentum (Dynamic Equation)

$$ma = \frac{dv}{dt}$$

- Acceleration of a particle:
- Above is with respect to a moving frame of reference (*Eulerian reference frame*). In order to transform this to a non-moving frame of reference (*Lagrangian reference frame*):

In rectangular Cartesian coordinates: $$\left(\frac{dv}{dt}\right) \rightarrow \frac{Dv}{Dt} = v\frac{\partial v}{\partial x} + \frac{\partial v}{\partial t}$$

or

In any Lagrangian coordinates: $$\frac{D\mathbf{u}}{Dt} = \frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u}$$

Saint Venant Equation

$$S_f \mid S_0 \; 4 \; \frac{\in y}{\in x} \; 4 \; \frac{v}{g}\frac{\in v}{\in x} \; 4 \; \frac{1}{g}\frac{\in v}{\in t}$$

- Good for incompressible fluids, that do not show significant expansion due to heating.

$$\psi \prod \psi[T, P]$$

Atmosphere: Compressible gases behave significantly different from water

- They compress/expand due to
  - application of pressure.
  - application of heat.

$$\psi \,|\, \psi[T,P]$$

- Need a heat conservation relationship.
- Need to consider a relationship between Pressure – Volume – Temperature in other relationships.

The additional complications

Â Perfect gas law.

$$PV \mid mRT$$

$$P\zeta \mid RT$$

Â First law of thermodynamics

(Increase in internal energy
= Heat input - Work output)

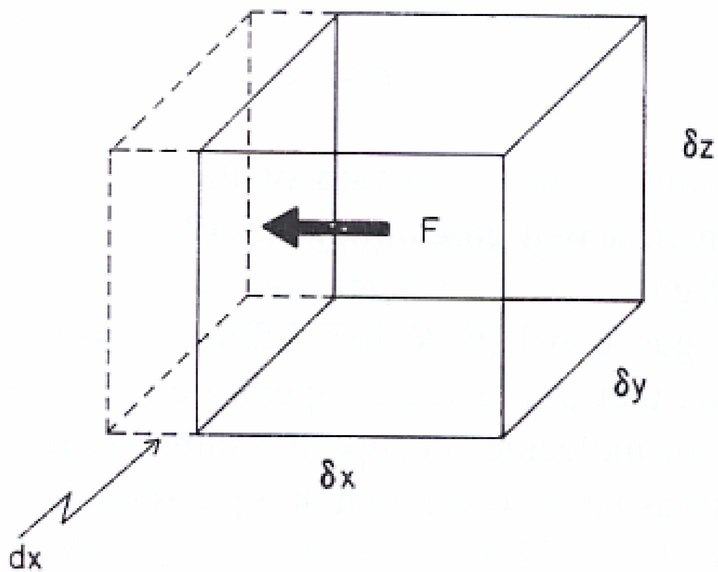
$$dq = c_p dT - \alpha dp$$

Conservation of Heat

$$dQ = dW + dI.$$

$$dW = F\,dx, \qquad dW = p\,\delta y\,\delta z\,\delta x.$$

$$dW = p\,dV,$$



For a unit mass:

$$dw = p d\alpha$$

- Perfect gas law: $P\alpha = RT$
- Entropy : $\not{h}/T_v = ds$
- Potential temperature: $\theta = T_v(1000/p)^{R_d/C_p}$
- Δentropy $=$ Δpotential temperature

$$\frac{C_p}{\theta}\frac{d\theta}{dt} = \frac{ds}{dt} = \frac{1}{T_v}\frac{\not{d}h}{dt} = S_\theta \frac{C_p}{\theta}$$

Gives : $\frac{d\theta}{dt} = S_\theta$

$$\frac{d\theta}{dt} = \frac{\partial\theta}{\partial t} + \frac{\partial\theta}{\partial x}\frac{dx}{dt} + \frac{\partial\theta}{\partial y}\frac{dy}{dt} + \frac{\partial\theta}{\partial z}\frac{dz}{dt} = S_\theta$$

$$\frac{\partial\theta}{\partial t} = -u\frac{\partial\theta}{\partial x} - v\frac{\partial\theta}{\partial y} - w\frac{\partial\theta}{\partial z} + S_\theta = -\vec{V}\cdot\nabla\theta + S_\theta,$$

Modeling the atmosphere

- Conservation equations:
  - Mass
  - Heat
  - Momentum
  - Water
  - Trace quantities (e.g. Aerosols)

The equations

$$\partial \rho / \partial t = -(\nabla \cdot \rho \vec{V}),$$

Mass

$$\partial \theta / \partial t = -\vec{V} \cdot \nabla \theta + S_\theta,$$

Heat

$$\partial \vec{V} / \partial t = -\vec{V} \cdot \nabla \vec{V} - 1/\rho \nabla p - g\vec{k} - 2\vec{\Omega} \times \vec{V}.$$

Momentum

$$\partial q_n / \partial t = -\vec{V} \cdot \nabla q_n + S_{q_n}, \qquad n = 1, 2, 3,$$

Water (Liquid, ice, vapor)

$$\partial \chi_m / \partial t = -\vec{V} \cdot \nabla \chi_m + S_{\chi_m}, \qquad m = 1, 2, \ldots, M.$$

Traces (e.g. aerosol)

Solving

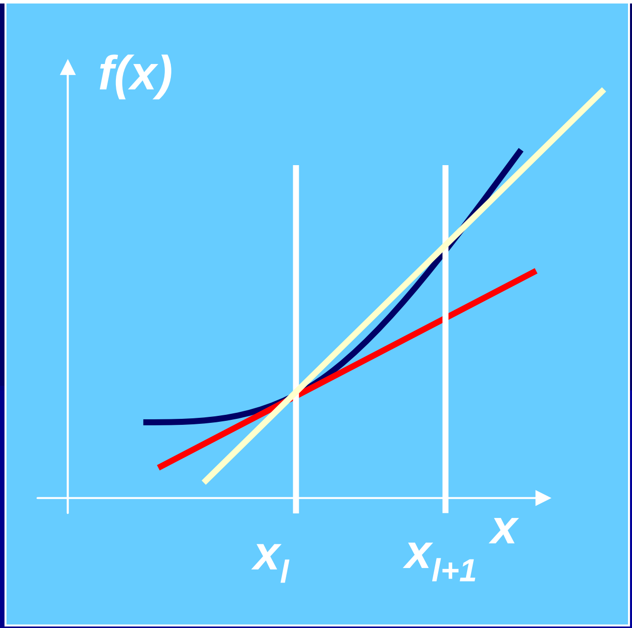
- It is not practical to solve these equations analytically, numerical methods are used.
- The traditional approach is the finite difference method (FDM)

FDM

- "Solving" differential equations without really solving (Analytically Integrating) them.
- Write differential terms as approximations

FDM

- Approximation of the derivatives



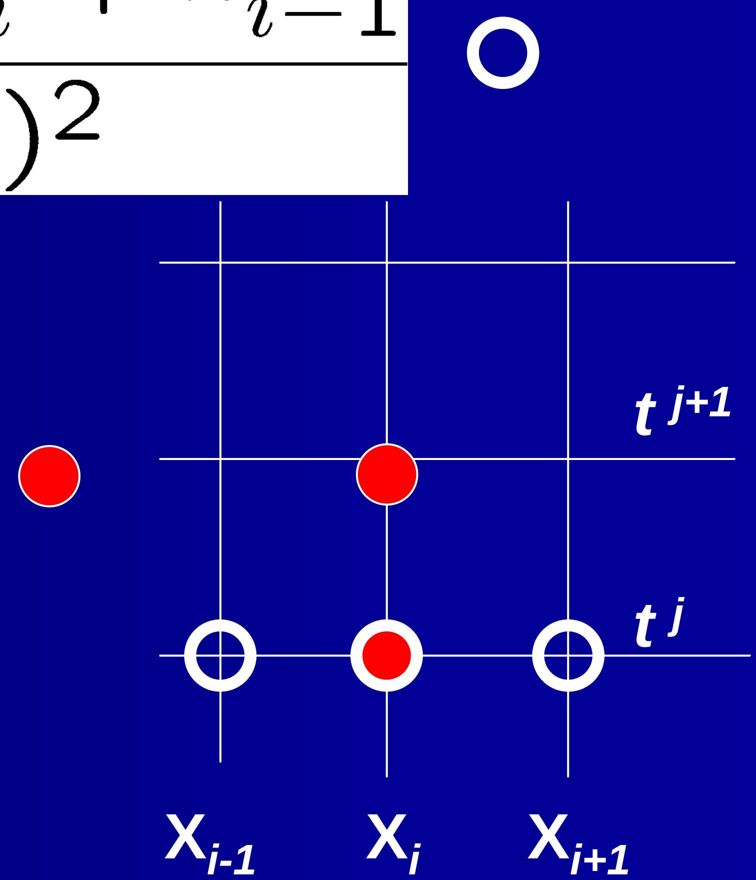
$$f'(x) = \frac{f(x_l) - f(x_{l-1})}{\Delta x}$$

- Based on Taylor series expansion

Explicit Method

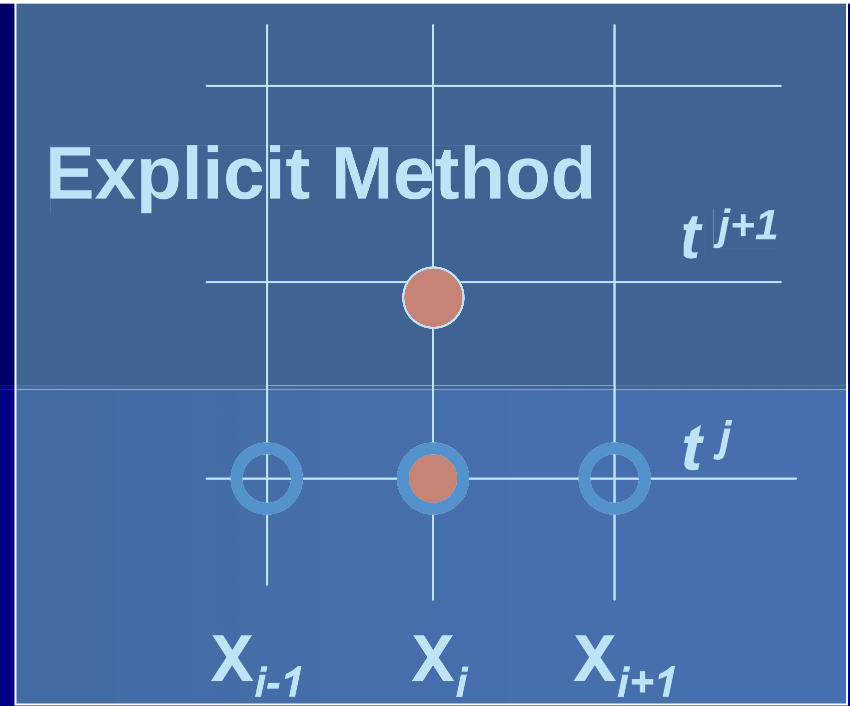
$$\frac{\partial^2 h}{\partial x^2} = \frac{h_{i+1}^j - 2h_i^j + h_{i-1}^j}{(\Delta x)^2}$$

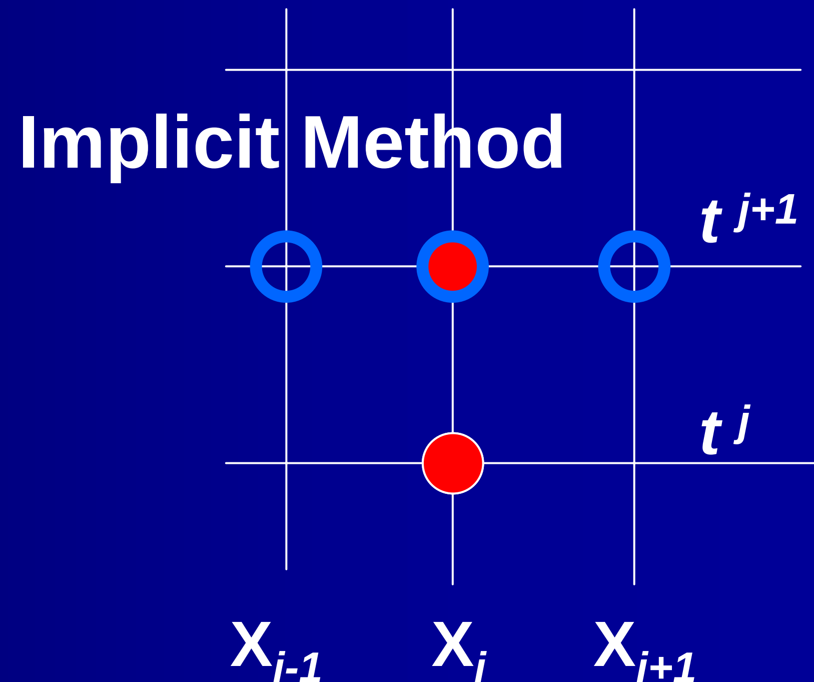
$$\frac{\partial h}{\partial t} = \frac{h_i^{j+1} - h_i^j}{\Delta t}$$

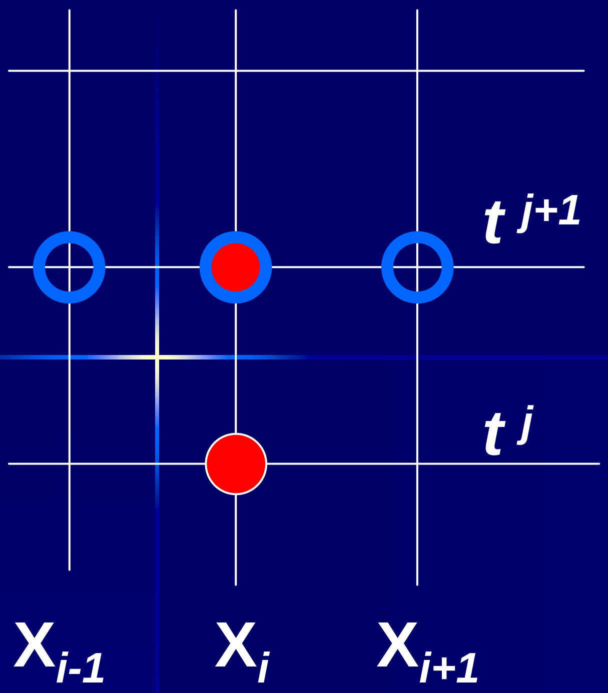


Implicit Method

- Grids involved in space differencing
- Grids involved in time differencing







$$\frac{\partial^2 h}{\partial x^2} = \frac{h_{i+1}^{j+1} - 2h_i^{j+1} + h_{i-1}^{j+1}}{(\Delta x)^2}$$

$$\frac{\partial h}{\partial t} = \frac{h_i^{j+1} - h_i^j}{\Delta t}$$

- This equation can not be solved by itself.
- But it is possible to write similar equations for all ***(n-2)*** inner points in ***x*** dimension (***n-2*** equations). And together with ***2*** boundary conditions, they form a set of ***n*** linear equations with ***n*** unknowns.

Explicit vs. Implicit

- Implicit methods are usually superior in stability and are recommended if at all possible.

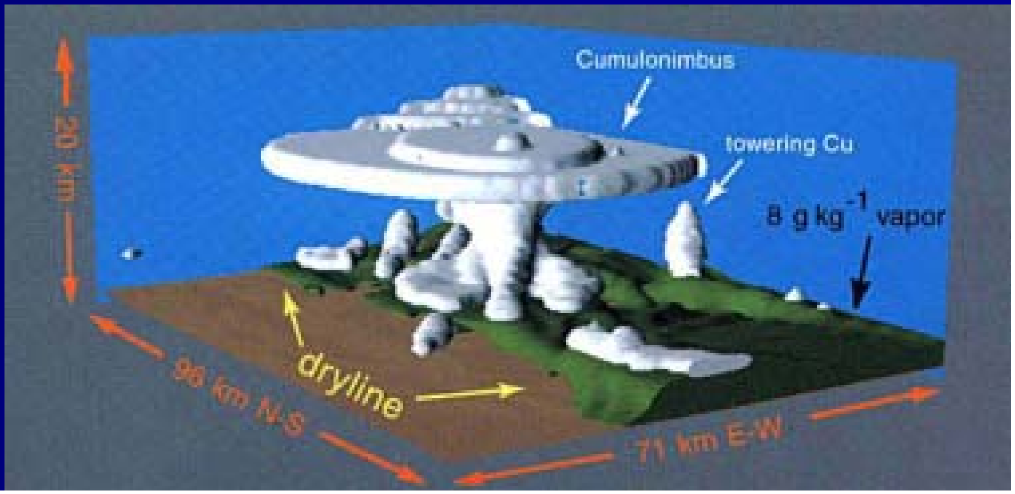
Atmospheric Models

- Almost all atmospheric models use Explicit method. Why?
- Large 3D computational domains – solving simultaneous equations can be impractical.
  - e.g. A 'Limited area model' of 1km grid resolution covering Sri Lanka. 500x300 horizontal resolution and a typical 60 layer model – 500x300x60=900000 approximately one million equations at every time step.

How does an Atmospheric model work?

- e.g., A model covering the entire globe – We discretize the entire globe to a grid system. Setup the numerical model (FD) on the grid.
  - Provide Initial conditions (what is the situation today).
  - Solve for the future (What will happen tomorrow).

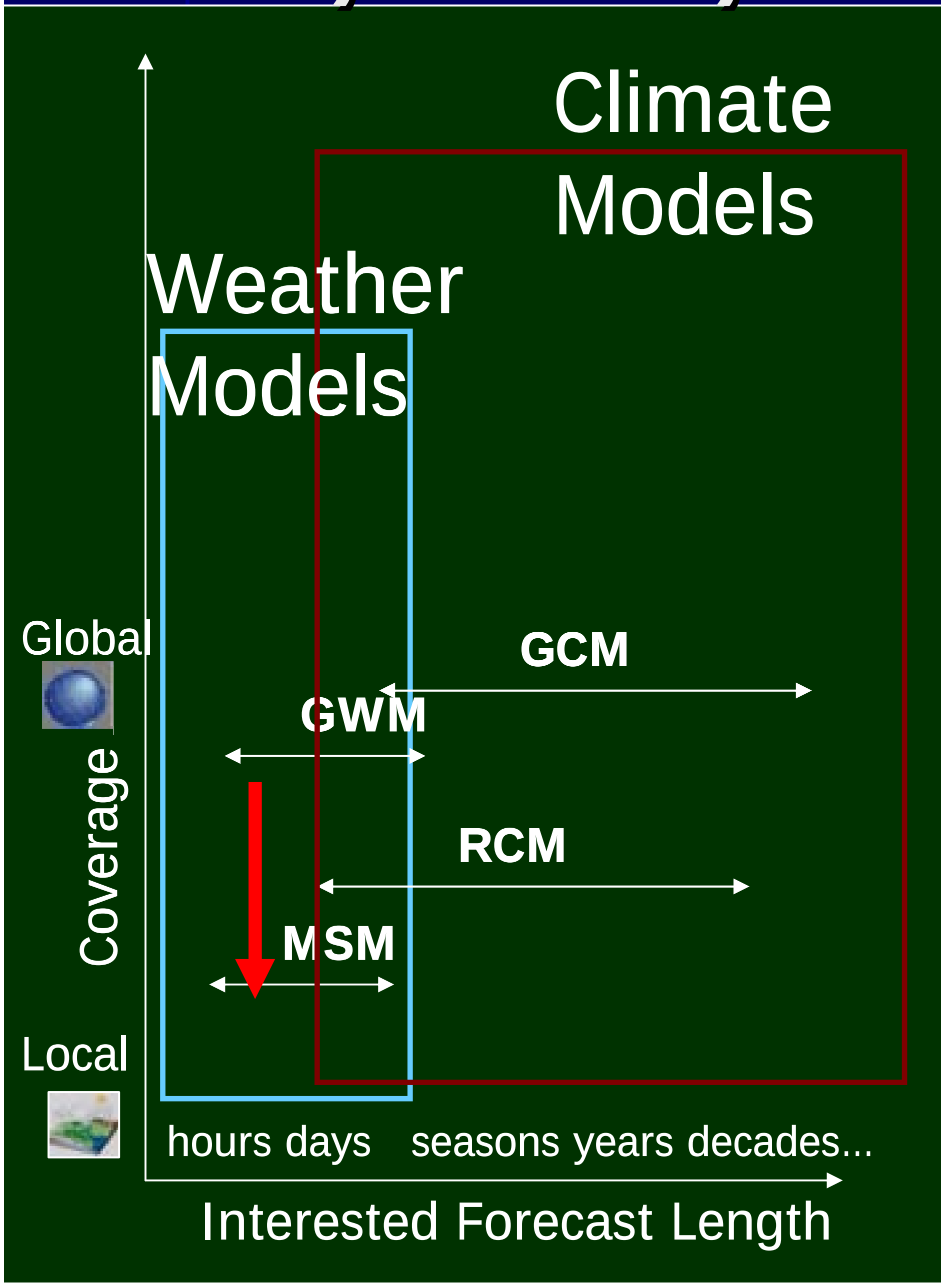
- Of course the above is an understatement of the complexity. We have
- Model top
  - Usually negligible mass transfer.
  - Known heat exchange (solar radiation)
- Model bottom
  - Atmospheric boundary layer.
  - Surface heat, mass exchange.
  - We often parameterize these.
  - Sometimes use secondary models to provide surface feedback.



Global vs. Limited Area models

- Global models need only initial conditions, for they cover the entire atmosphere.
- Limited-area models cover only a part of the atmosphere (e.g. Weather prediction for Sri Lanka), and hence need specification of the state of the boundaries in the future (lateral boundary conditions).

GCM, GWM, RCM, Mesoscale…



Â **GCM – long-term** trends – climate (global)

– Validation – statistical

Â **MSM / GWM – short-term** – weather (global/regional/smaller)

Â Global models

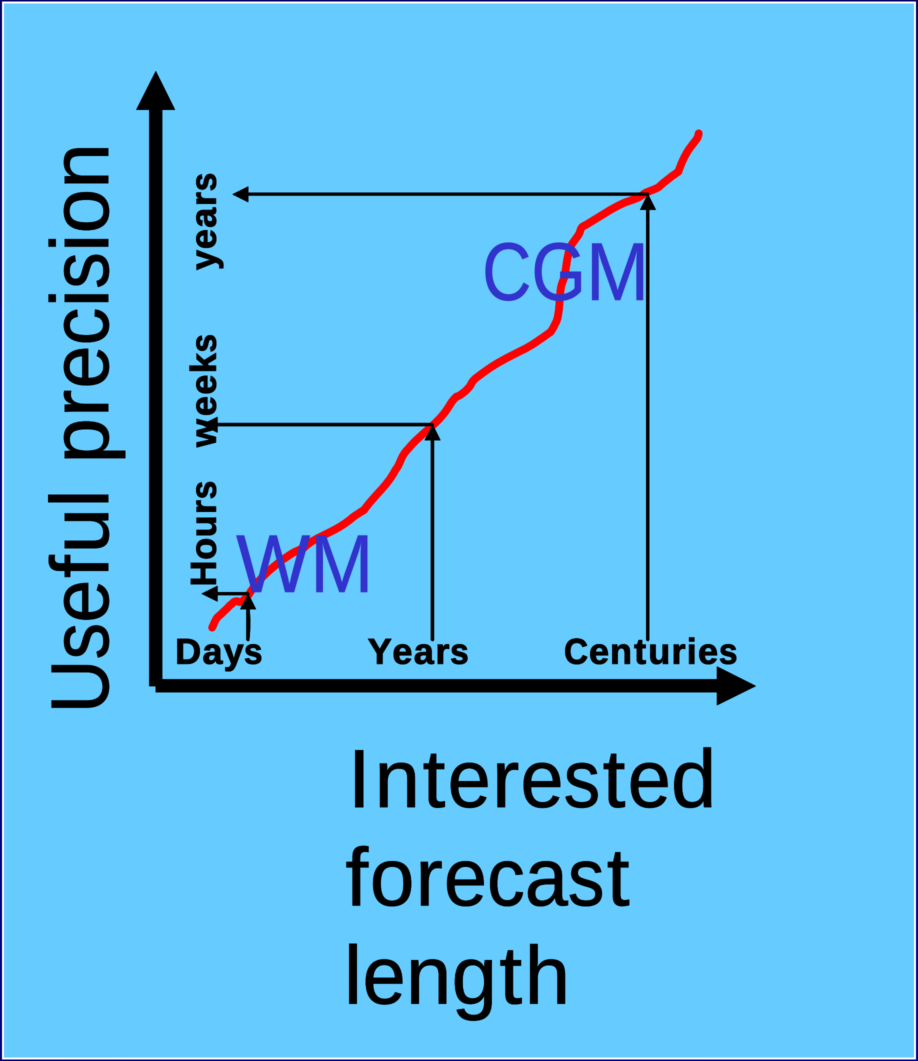
– **really forecast_.**

Â Regional/mesoscale models

– need **boundary conditions**

What is Predictable?

- Complex system – atmosphere
- Sensitive dependence on initial condition.
- Weather forecasts rarely demonstrate skill beyond a week.
- However, **statistical forecasting** is possible (Climatological predictions) even for centuries.



What can we do with Atmospheric Models

Â Long-tem trends in the earth-atmospheric (global) system.

Â Weather prediction.

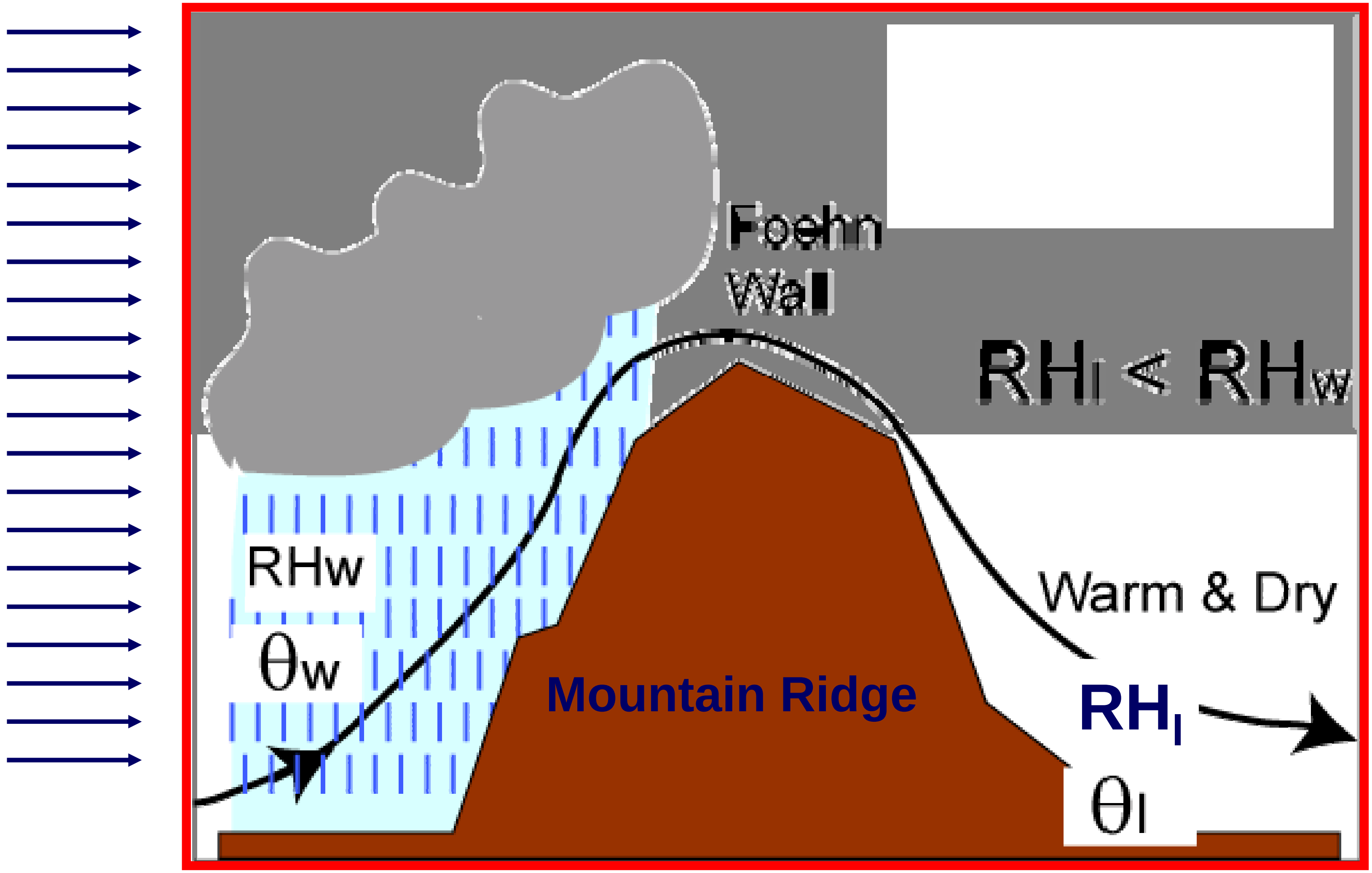
Â Understanding the link between atmospheric processes and surface processes. (Hydrologic cycle)

Â Understanding climatologies (e.g. Why Watawala gets largest rainfall in Sri Lanka)

Â ...

Â ...

Orography and Rainfall

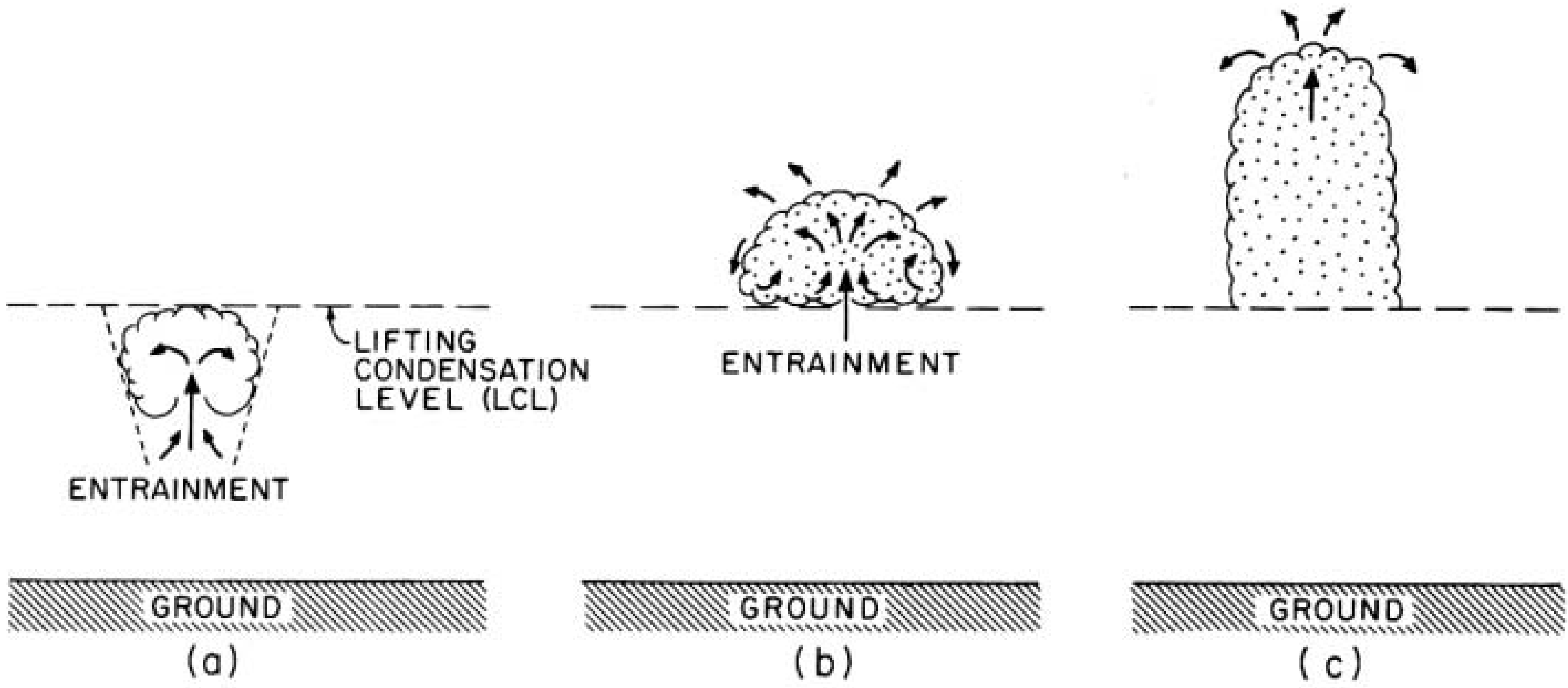


In Reality …

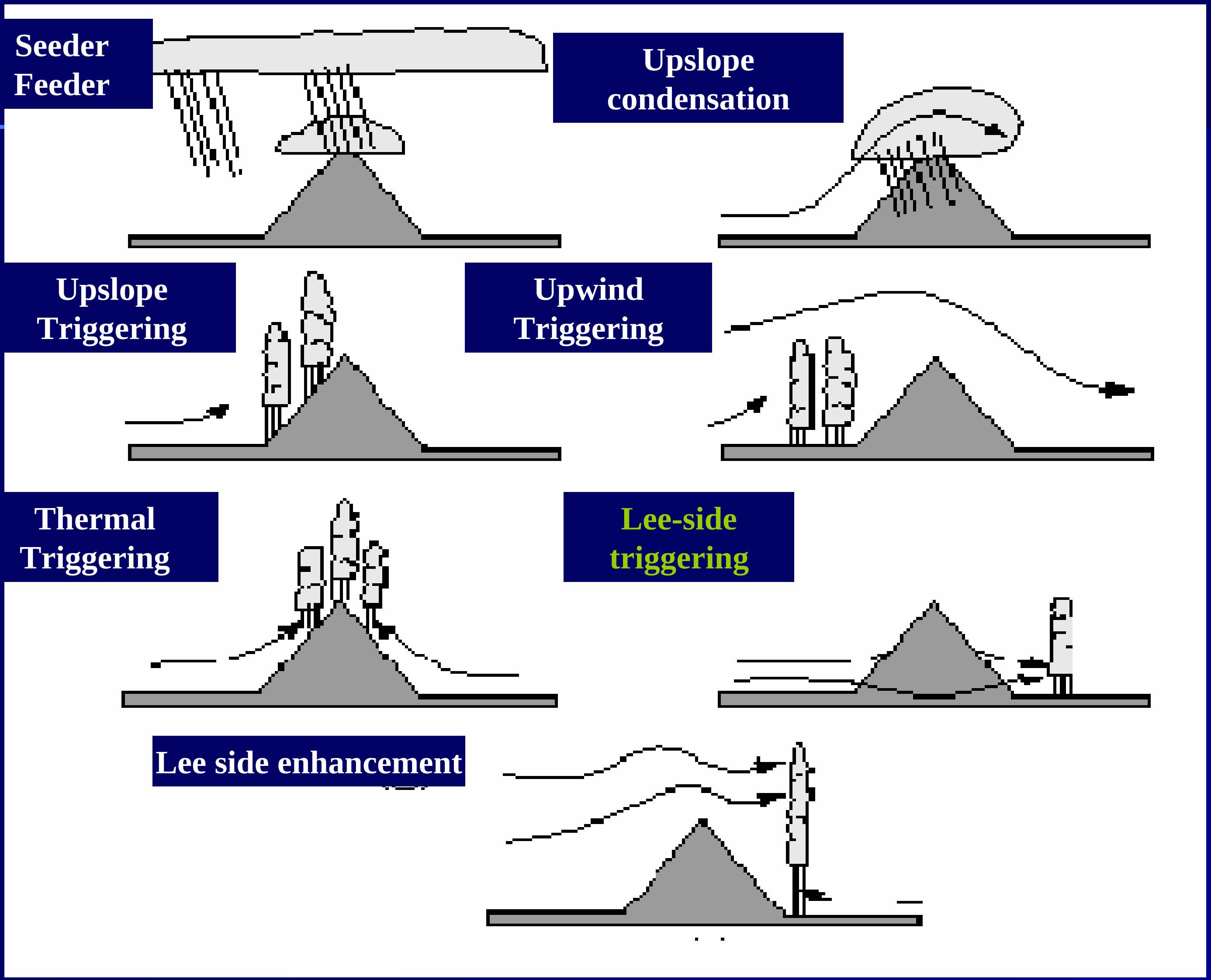
- Solar heating of surface and resulting convection interact with (wind + mountain) system resulting in a complex picture.

Convective Cloud Development

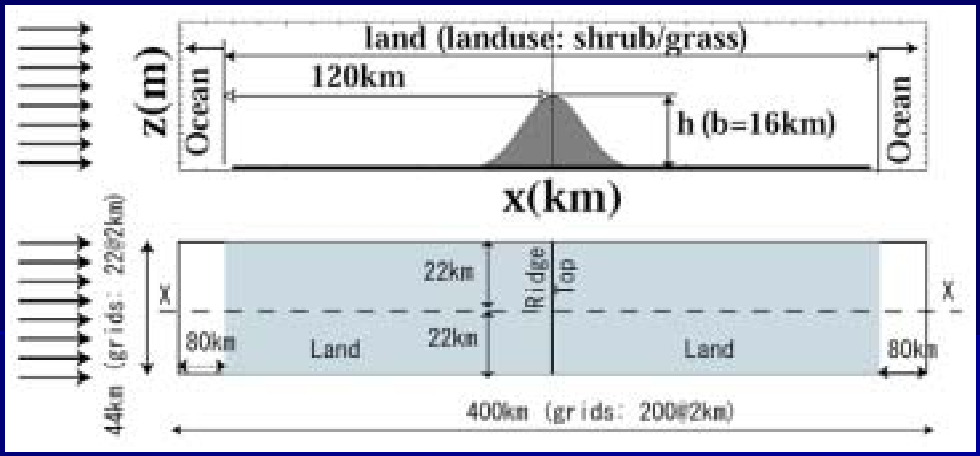
Cumulus



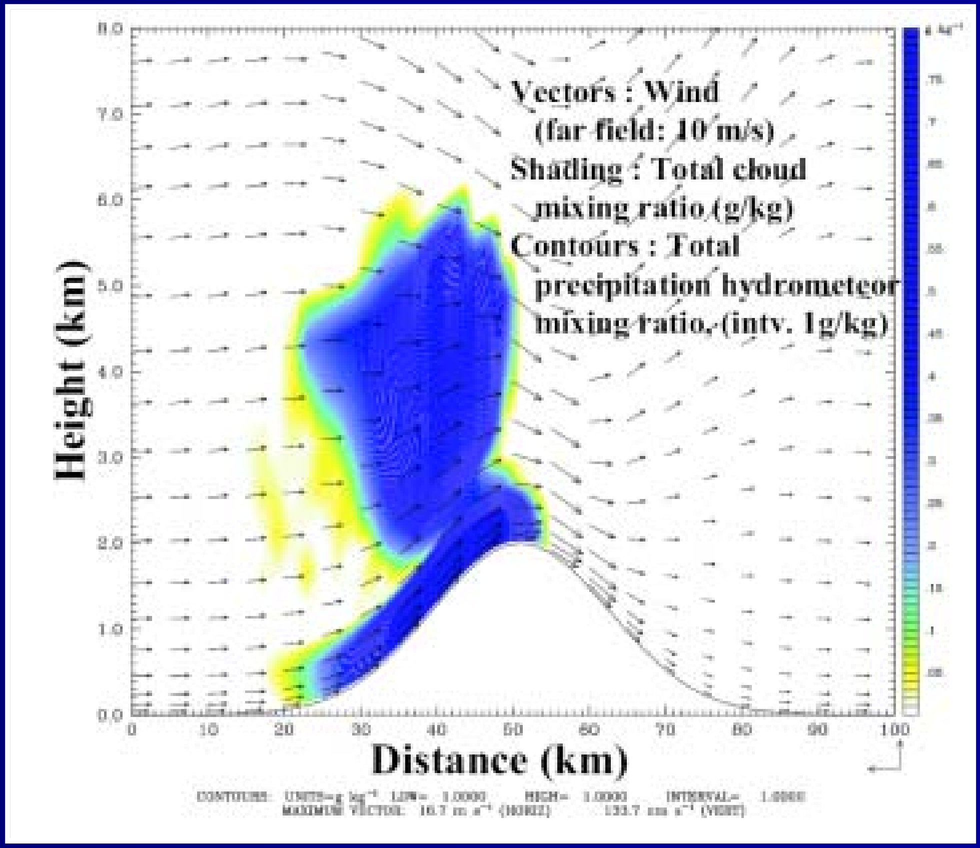
Different Mechanisms



Source: Houze, R.A. (1993), *Cloud Dynamics*



land (landuse: shrub/grass)
120km
z(m)
Ocean
h (b=16km)
Ocean
x(km)
44km (grids: 22@2km)
22km
22km
Ridge Top
X
X
80km
Land
Land
80km
400km (grids: 200@2km)



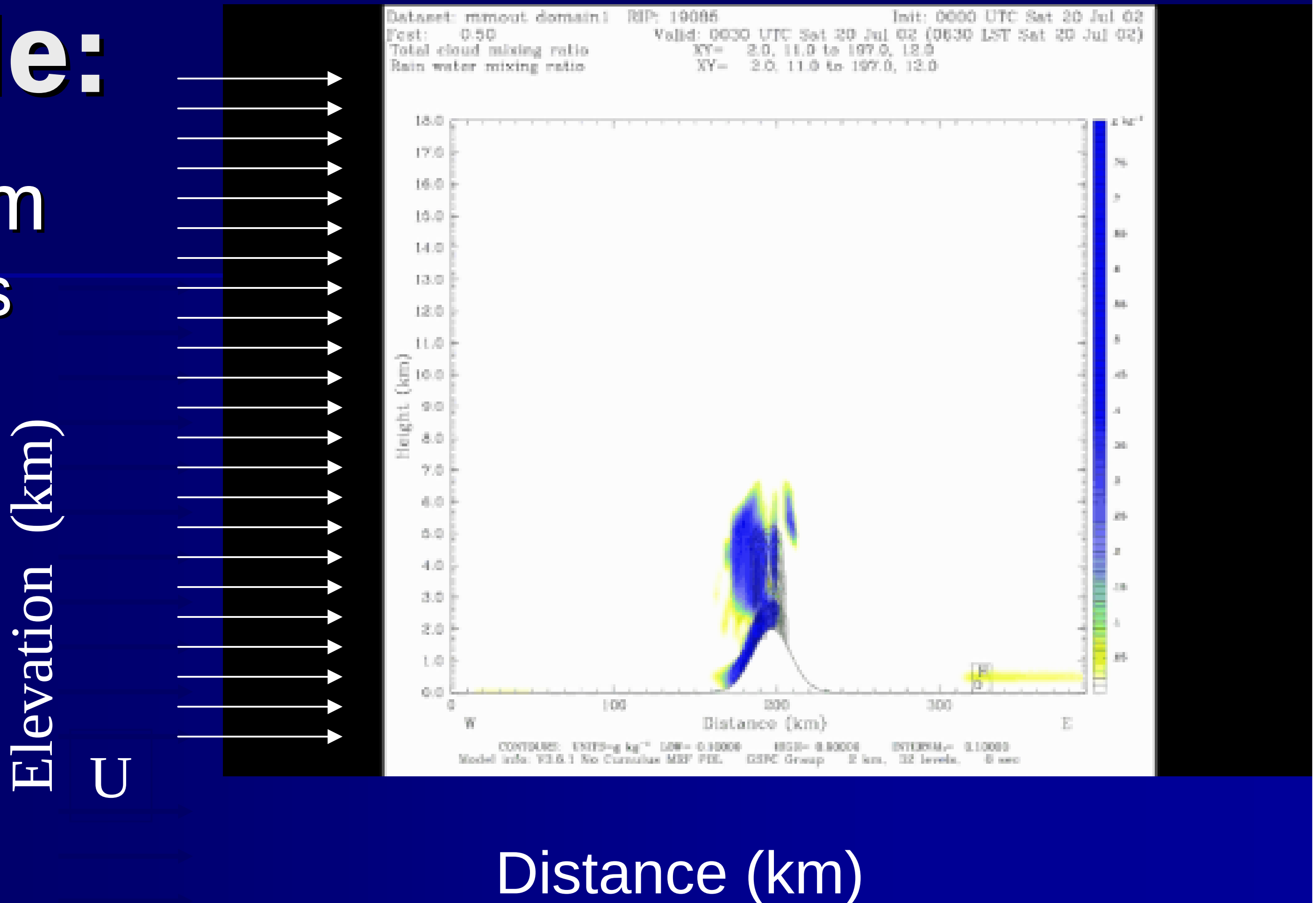
Vectors : Wind
(far field: 10 m/s)
Shading : Total cloud mixing ratio (g/kg)
Contours : Total precipitation hydrometeor mixing ratio, (intv. 1g/kg)
Height (km)
Distance (km)

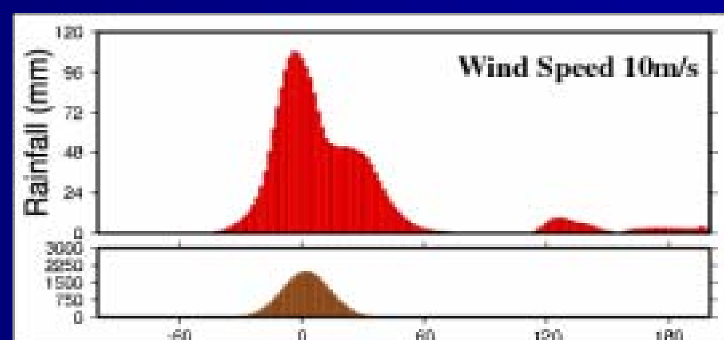
Example:

- Height 2km
  Wind 10m/s
  (uniform)

Color: Cloud Water Mixing Ratio

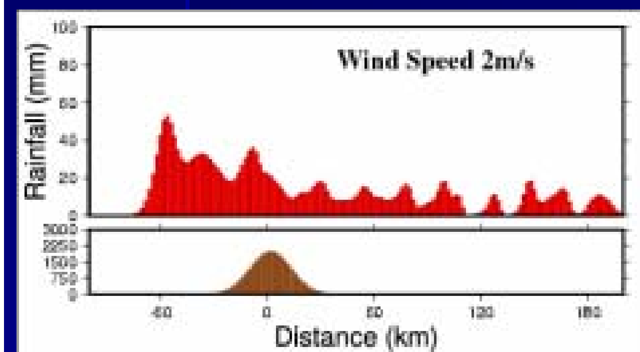
Contours: Rain Water Mixing Ratio



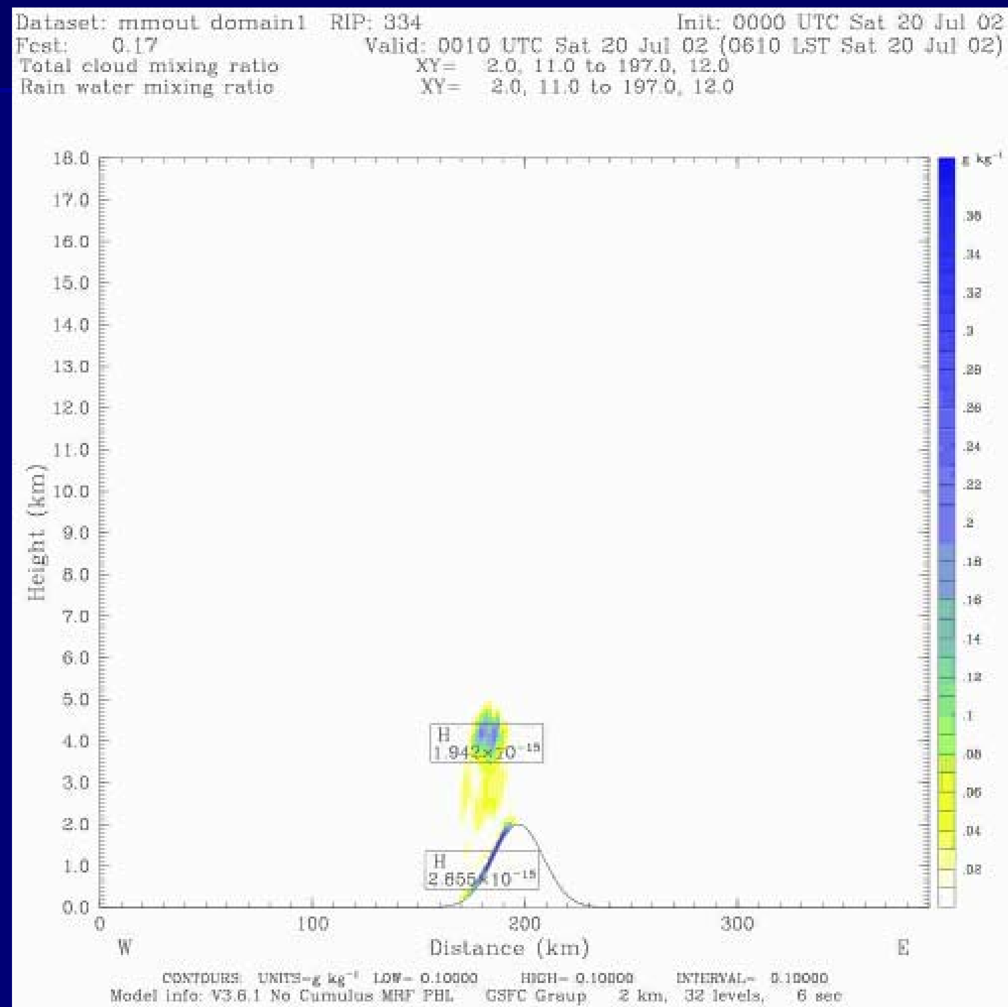


Slower winds

- Height 2km
  Wind 2m/s



Height (km)



Distance (km)

(2) Impacts of Climatic Change

- Case: Increase of **anthropogenic aerosols** in South Asia.

The 'Popular' Climate Change

Â Global warming due to increase of greenhouse gases.

‘Greenhouse Effect*’

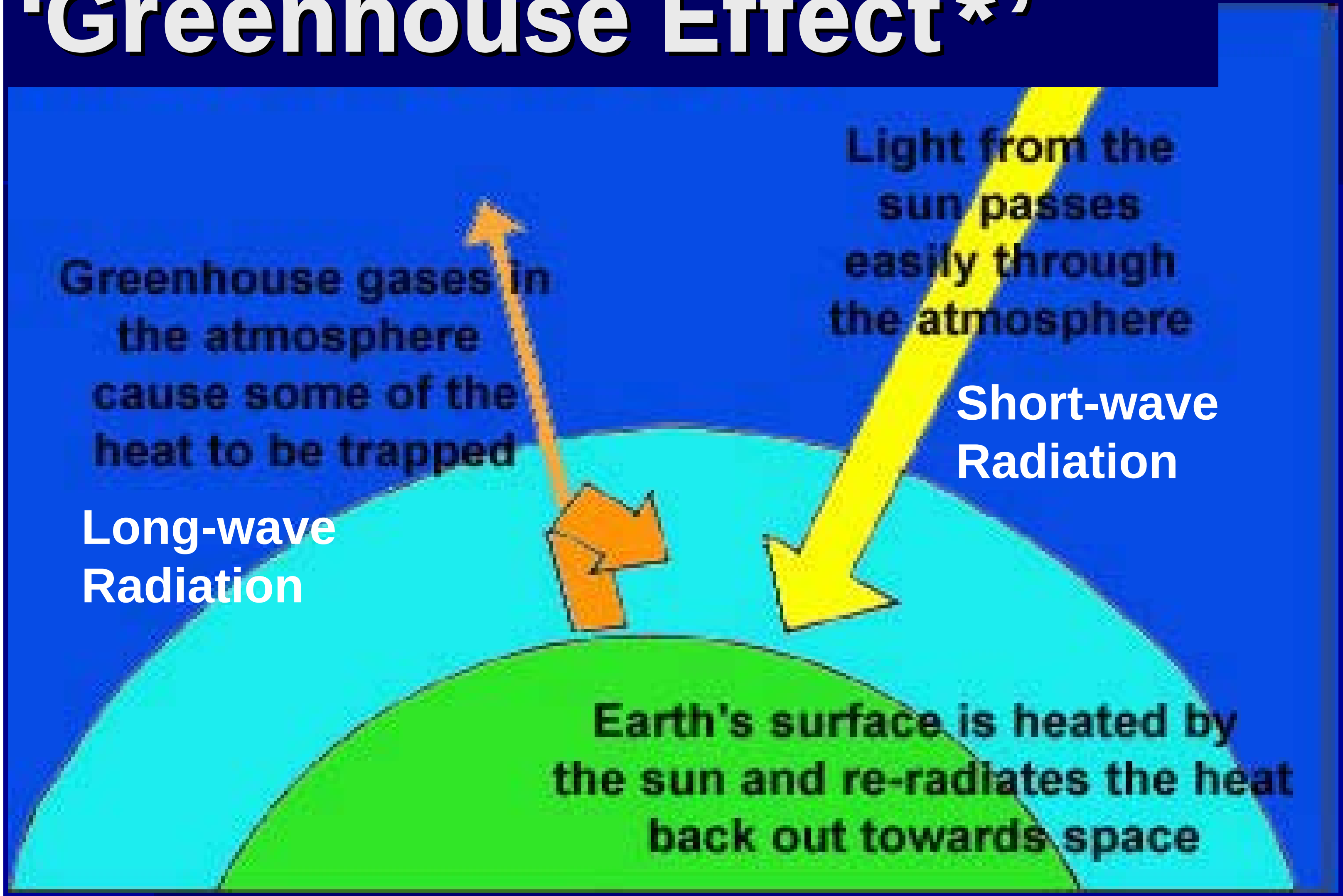
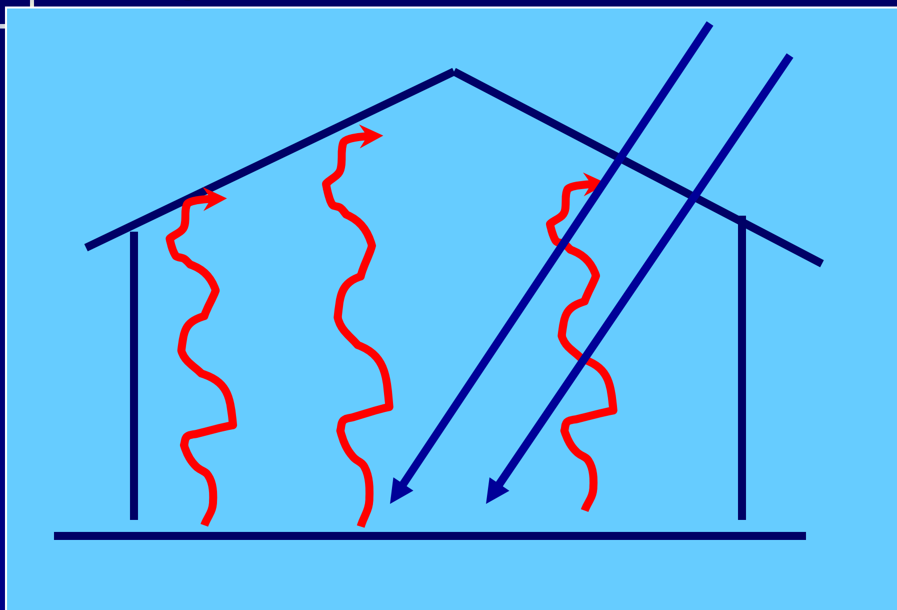
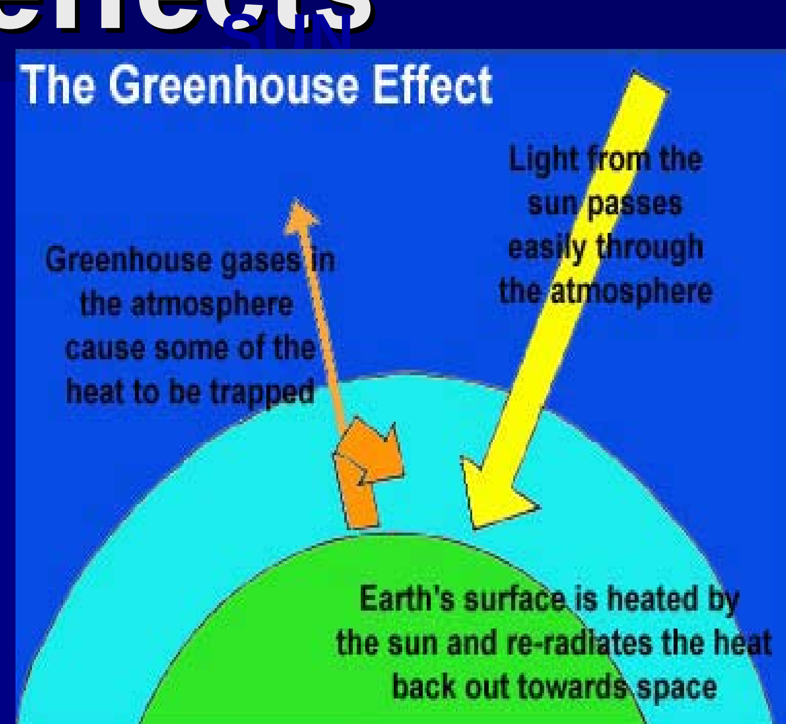


Image : BNSC

* An unfortunate misnomer suggesting convective phenomenon for a radiative issue.

Two different types of “green house effects”



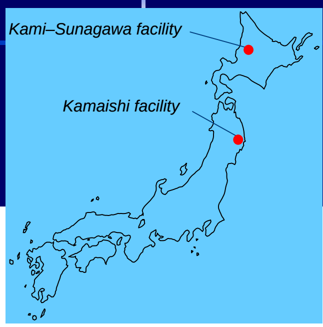


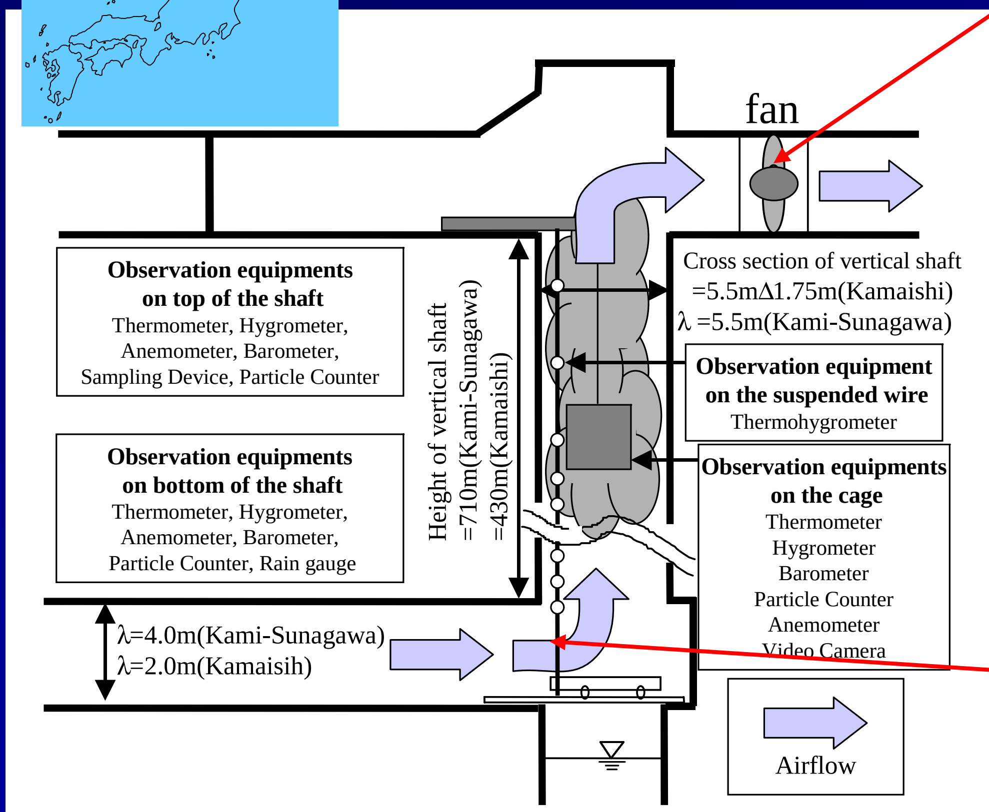
- An agricultural/horticultural greenhouse blocks the convective release of heat.
- The greenhouse effect is due to blocking of radiation (infrared from gasses that are good at absorbing them and converting to heat.

Aerosol effects – A less well-known climate change driver

- Aerosols are tiny particles that float in the atmosphere.
- By-far the most significant source is the ocean spray (NaCl)
- Aerosols play a crucial role in rain-making. They help forming droplets in clouds. However, too many of them can retard rainfall by creating lighter droplets that can not fall as rain.

Understanding Aerosols

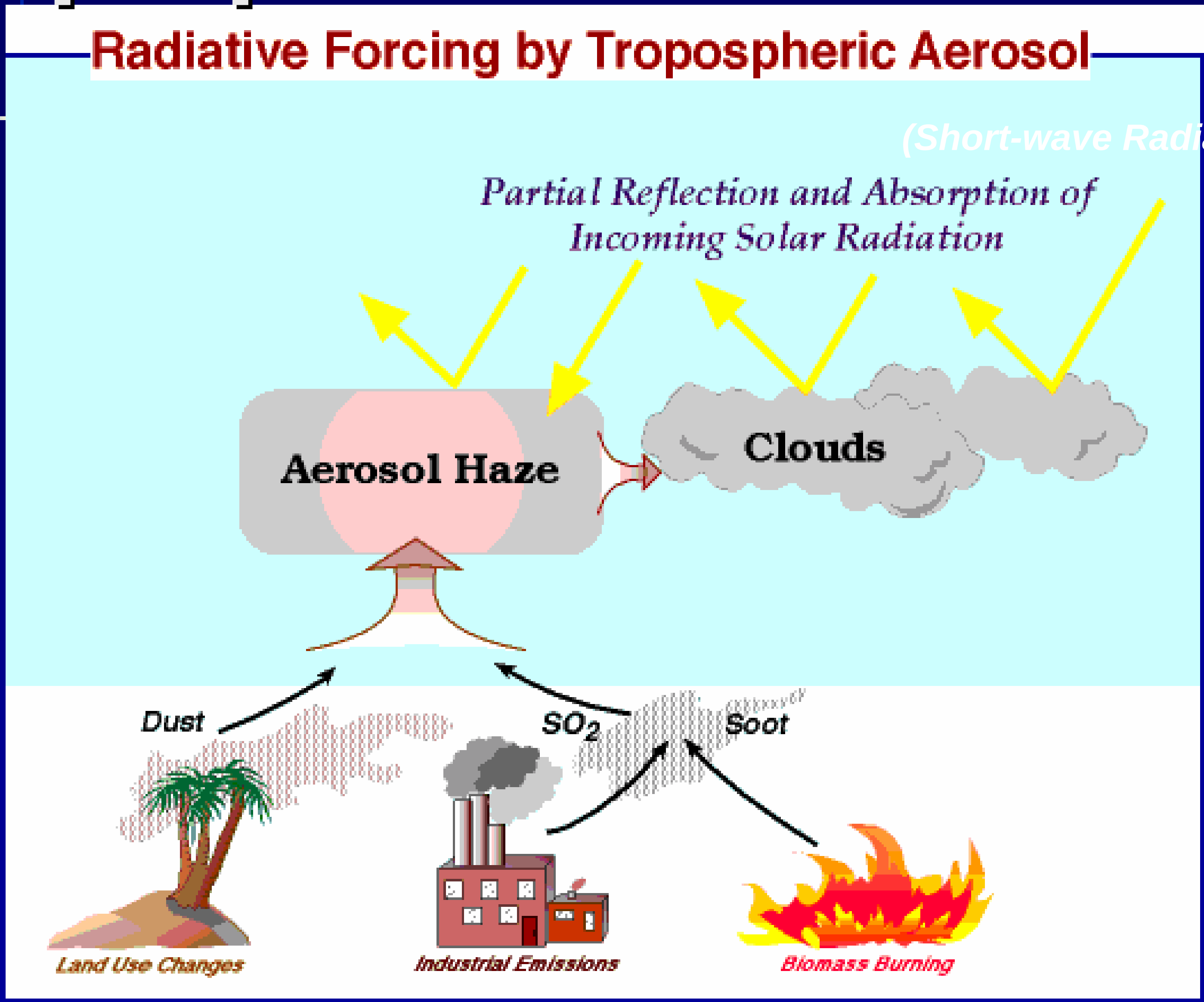




Large fans mounted on the top of shaft to generate and control the updraft velocity

Spray device put in the bottom of shaft to Supply aerosols

Radiative effects of Tropospheric Aerosols



(Short-wave Radiation)

Image Credit: NOAA

Major Sources – Sea, Volcanoes

The 'impact winter' hypothesis – how dinosaurs became extinct.

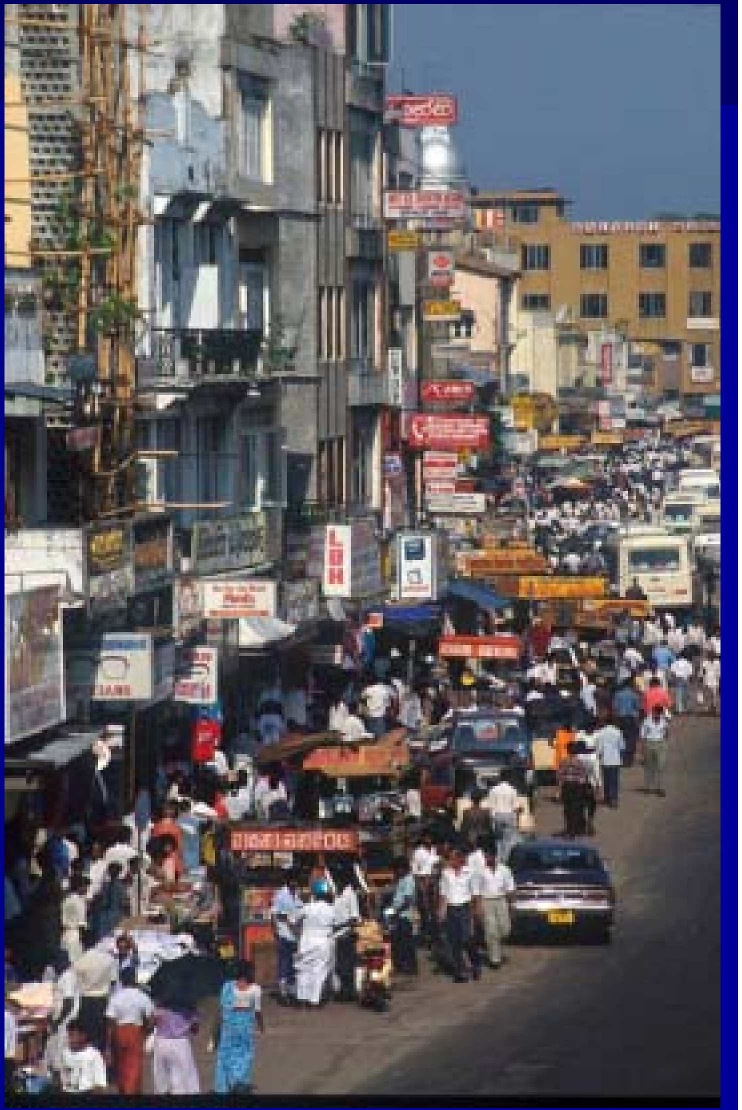
65m years ago, a large asteroid hit the earth (~15km)

Yucatan Peninsula in the Gulf of Mexico

Highly reflective aerosols in atmosphere cased sunlight to be reflected back. Severe winters fatal for large creatures.

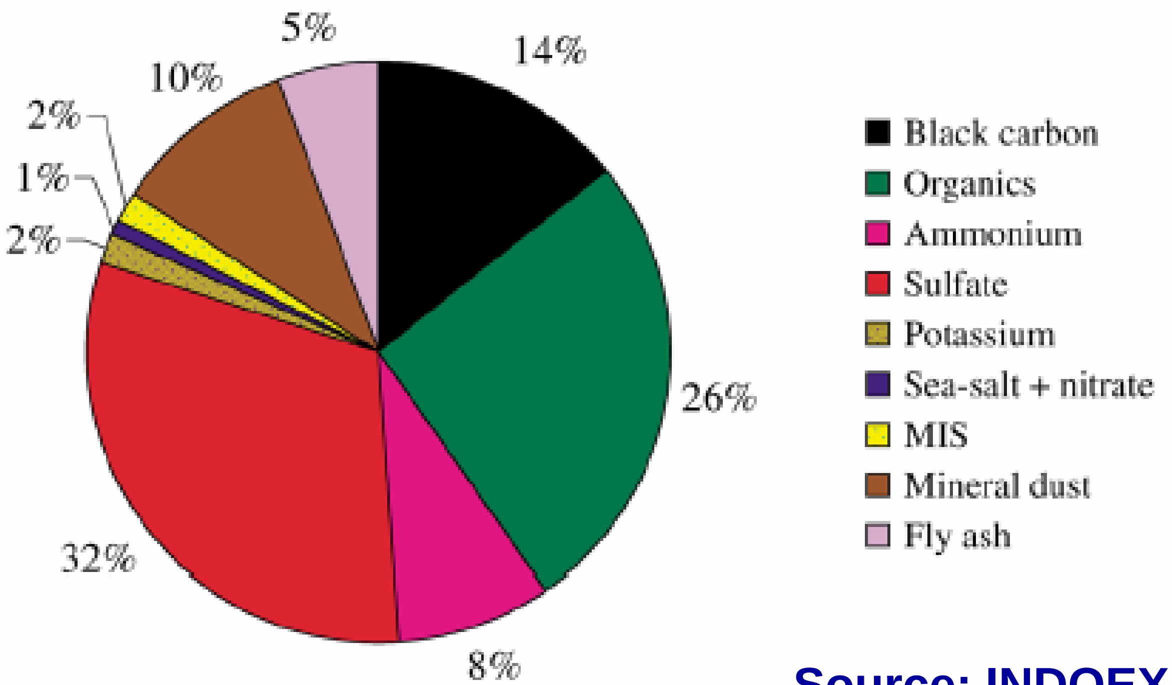
Anthropogenic causes: Air Pollution in South Asia

- 1/5th of world population crowded in 3% of landmass. 100-500 persons/km^2.
- High rates of urbanization, water stress, mega cities (population >10M), land use changes.
- Emission of greenhouse gases is still low, though growing.
- Widespread use of unclean energy sources (e.g. biomass burning)



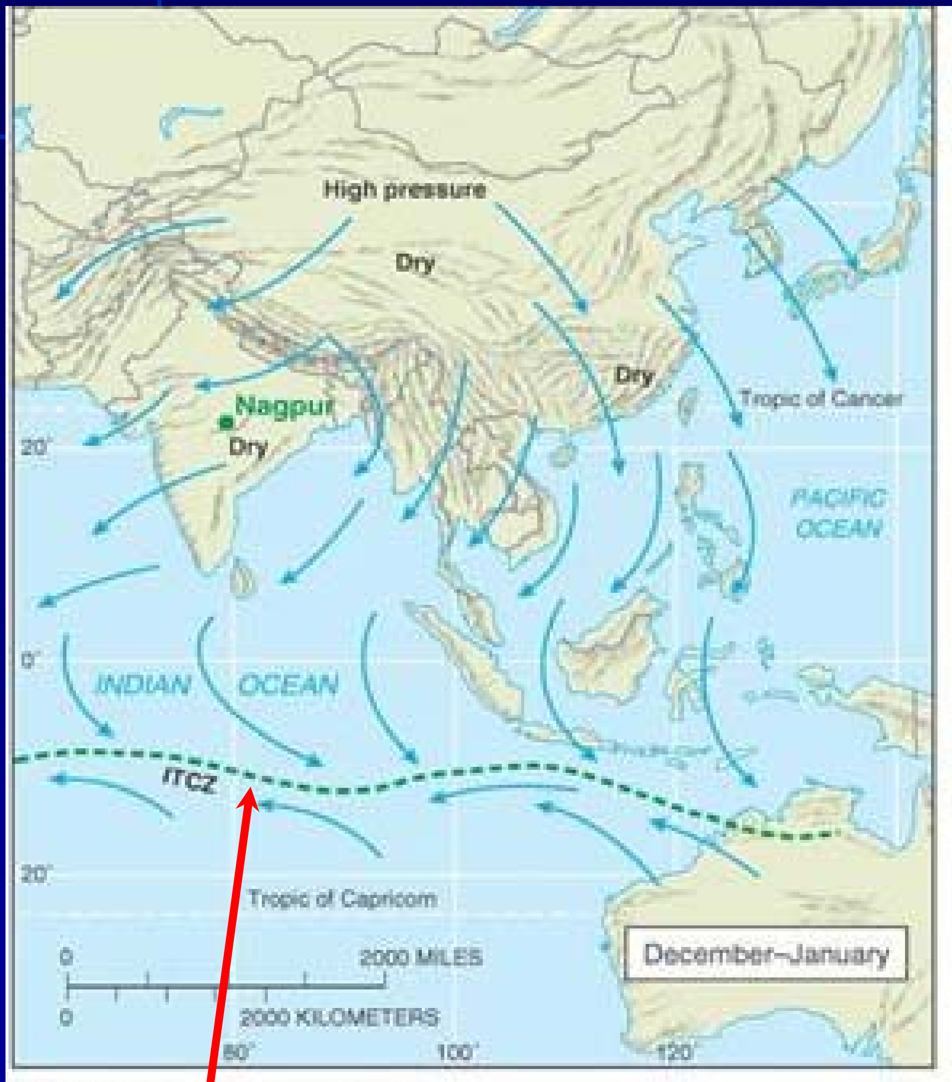
South Asian Aerosols (ABC – Atmospheric Brown Cloud)

- Recently a huge aerosol 'plume' was discovered over south Asia.
- 80-90% anthropogenic sources (Biomass and fossil-fuel burring)
- High Black C – **high absorption** of solar radiation.



Source; INDOEX

Where, When and How



Inter-tropical Convergence Zone

Image Credit: Indiana University - Purdue University, Indianapolis

Inter-tropical convergence zone

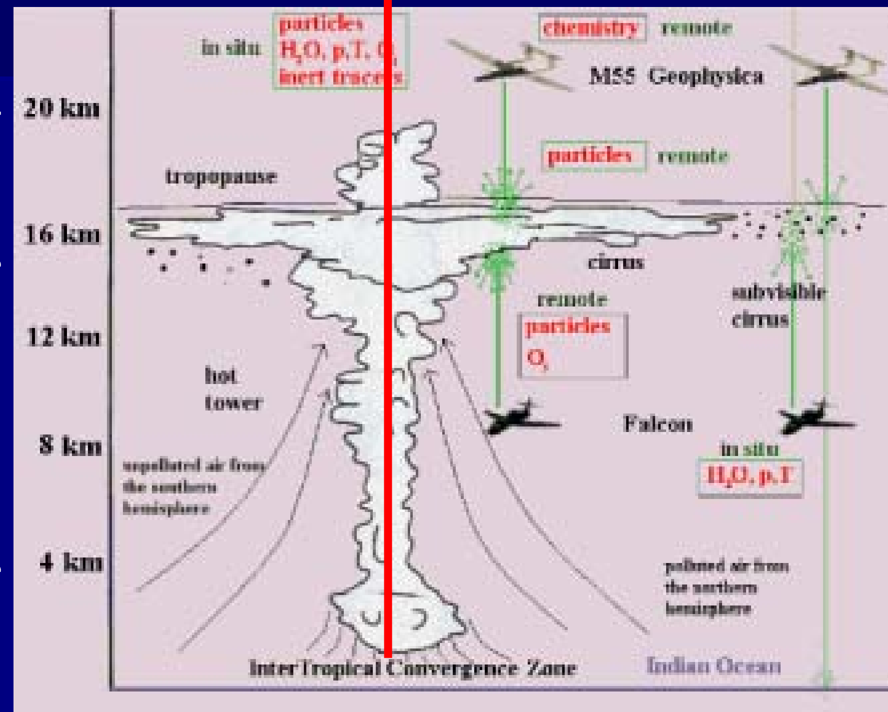


Image Credit: APE – UK office

Winter Monsoon.
From November to
March Every Year.

Sources of ABCs

- Diesel, biomass burning.

Polluted skies of new Delhi *(Assela)*

Sources of aerosols *(Assela)*

Major differences between Natural aerosols and ABCs

Â ABCs contain black carbon – an excellent absorber of radiation.

Â Natural aerosols reflect (scatter) solar radiation.

Â NA : Deprive the surface of solar energy.

Â ABC: (above) + Heating the troposphere

Modeling of ABC

- What changes can happen in the regional earth-atmosphere system and water cycle due to aerosol radiative forcing.
- We modified a limited area atmospheric model that can mimic the ABC impact on the radiative budget.

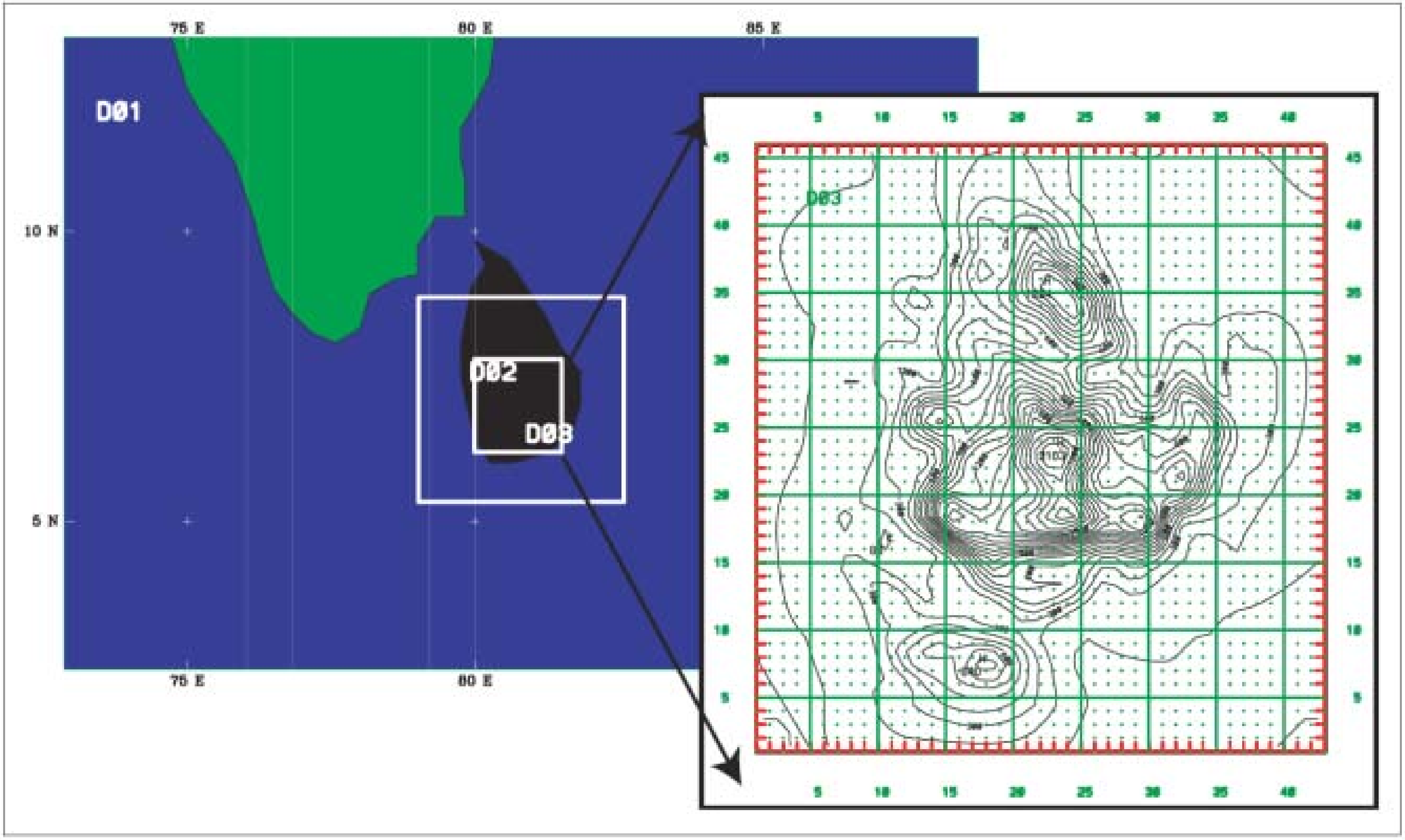
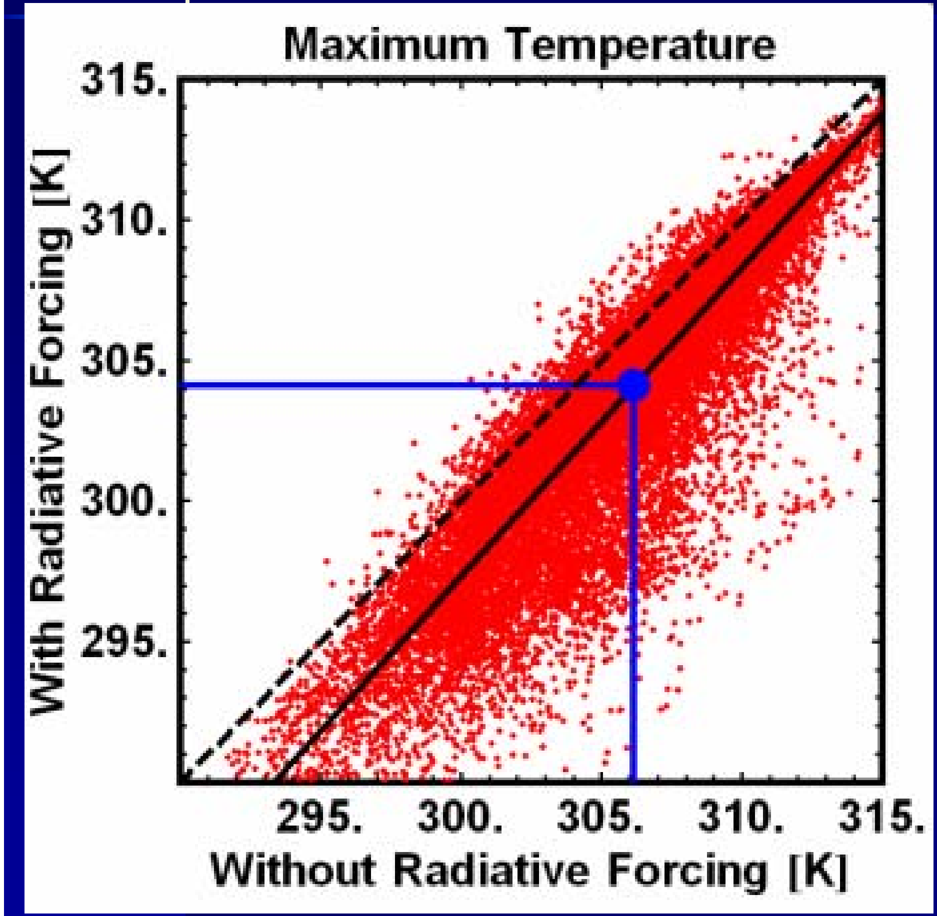
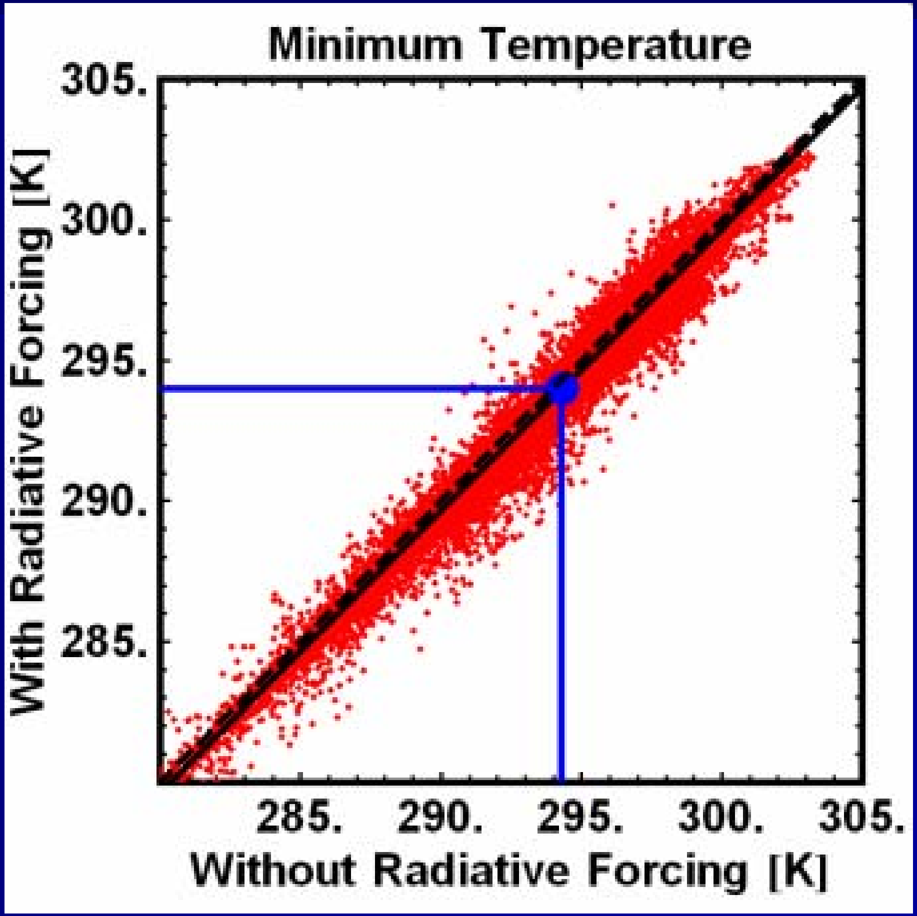


Figure 5. The model domain used for the simulations in Sri Lanka. There were three nested domains and the innermost (4km) grid (shown expanded with topography) was used for further analysis.

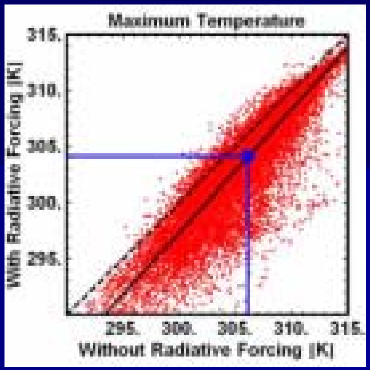
Surface Temperature (Max / Min)

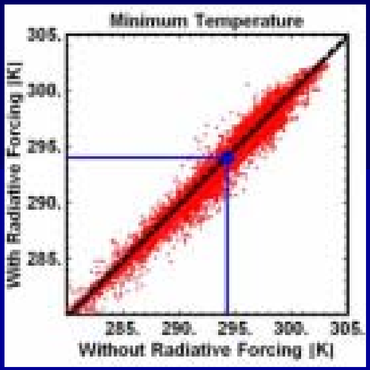




Results of a six months period simulation over southern part of Sri Lanka.

The Difference between GHW & ABC

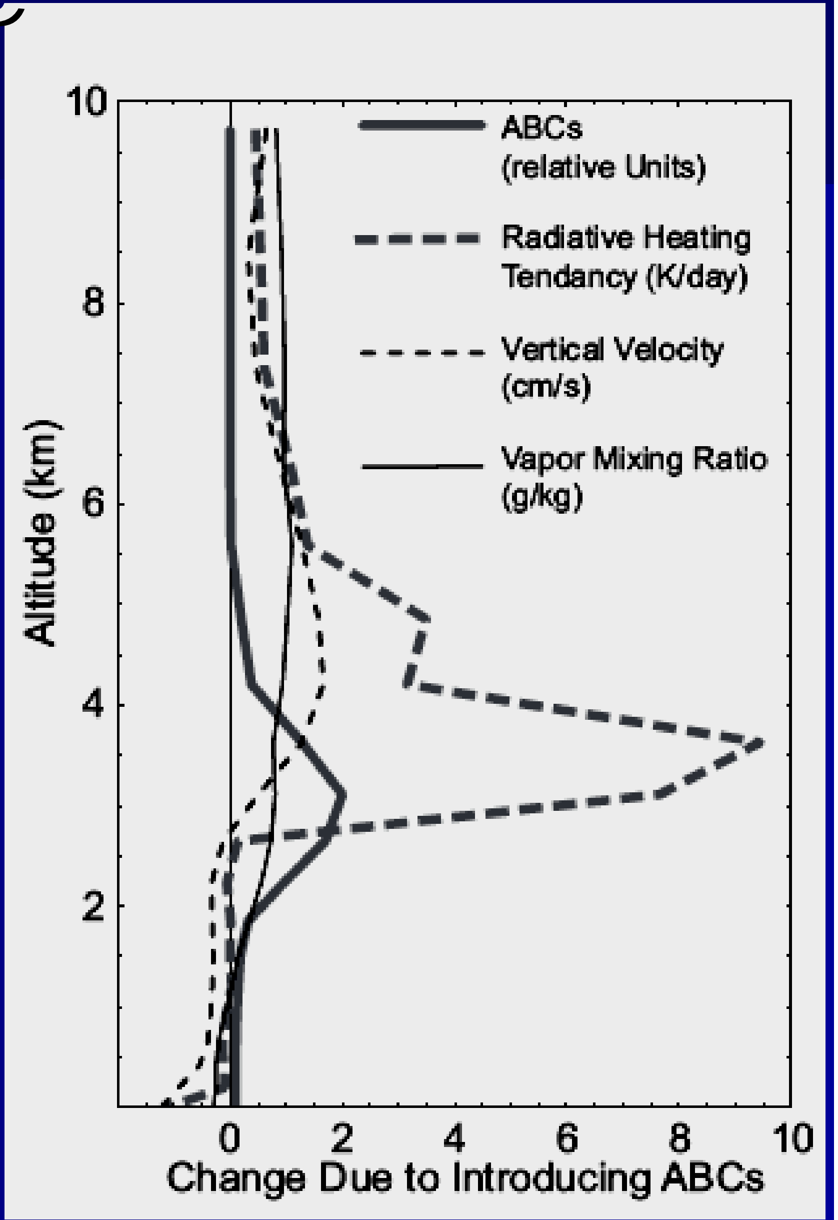




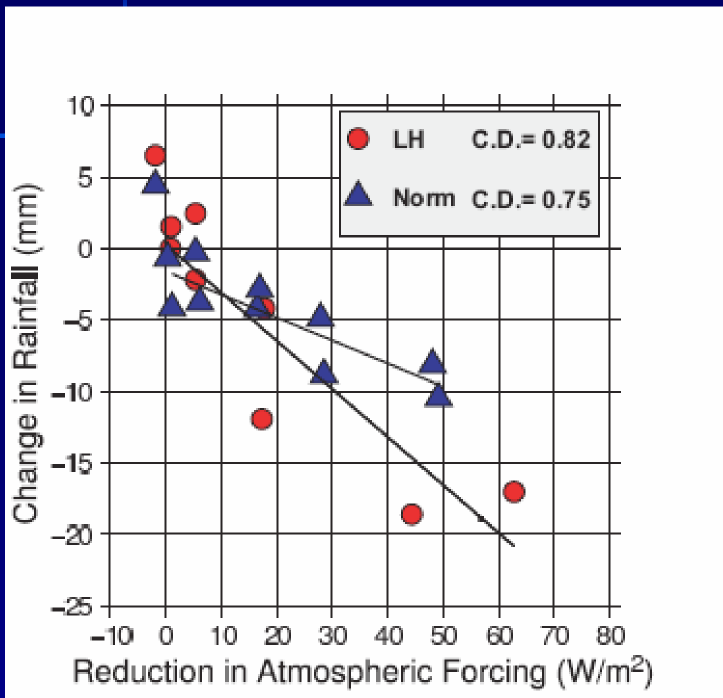
- GHW – blocking of Earth's radiation, warmer nights, higher minimum temperatures.
- ABC – blocking of solar radiation, coolar days, lower maximum temperatures.

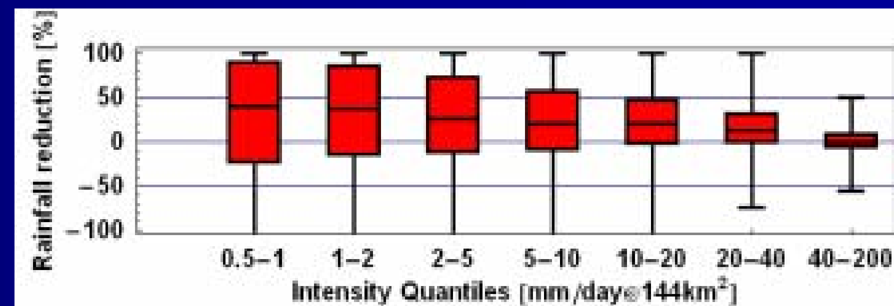
Change in the Atmospheric Profile due to ABCs.

- Vertical velocity is increased above the absorbing layer and decreased below.
- Moisture is reduced at the boundary layer, but is increased in the absorbing layers and above.



Results: Reduction of Rainfall





Results of a six months period simulation over southern part of Sri Lanka.

- For large rainfalls the % effect is small (for 100mm/day ~ 4%)
- For small rainfalls % effect is large (for 1-2mm/day ~ 40%)

Findings

- For rain dependant industries (agriculture), **water supply** and many other human activities, this dramatic reduction of small rainstorms can be detrimental.
- Presently we are conducting **multi-disciplinary research** on the possible impacts and policy implications.
- There can be severe implications on the surface-atmospheric heat balance.

A. Pathirana, S. Herath, T. Yamada and D. Swain, "Impacts of absorbing aerosols on South Asian rainfall – a modeling study", Climatic Change, 2007

Indirect Evidence

- We observed rainfall records of last 50 years in Sri Lanka (essentially same location as the model)
- Annual rainfall amounts do not show any statistically significant trends.
- But, when seasonal rainfall is examined...
  - Inter-monsoon rainfall (Nov-Mar) show significant reduction.
  - This is essentially the same period as the peak of ABC.
  - Also these rainfalls are usually small, intermittent in space time.
  - Implicitly supports our hypothesis.

(3) Numerical Weather Prediction

- It is possible to use a Limited Area Atmospheric Model, together with boundary conditions provided by a Global Weather Model to provide detailed forecasts of weather of a region.
- A standard procedure followed by many meteorological organizations.

The Hardware

Cluster Workstations

Pre-post processing computer

High-powered workstation

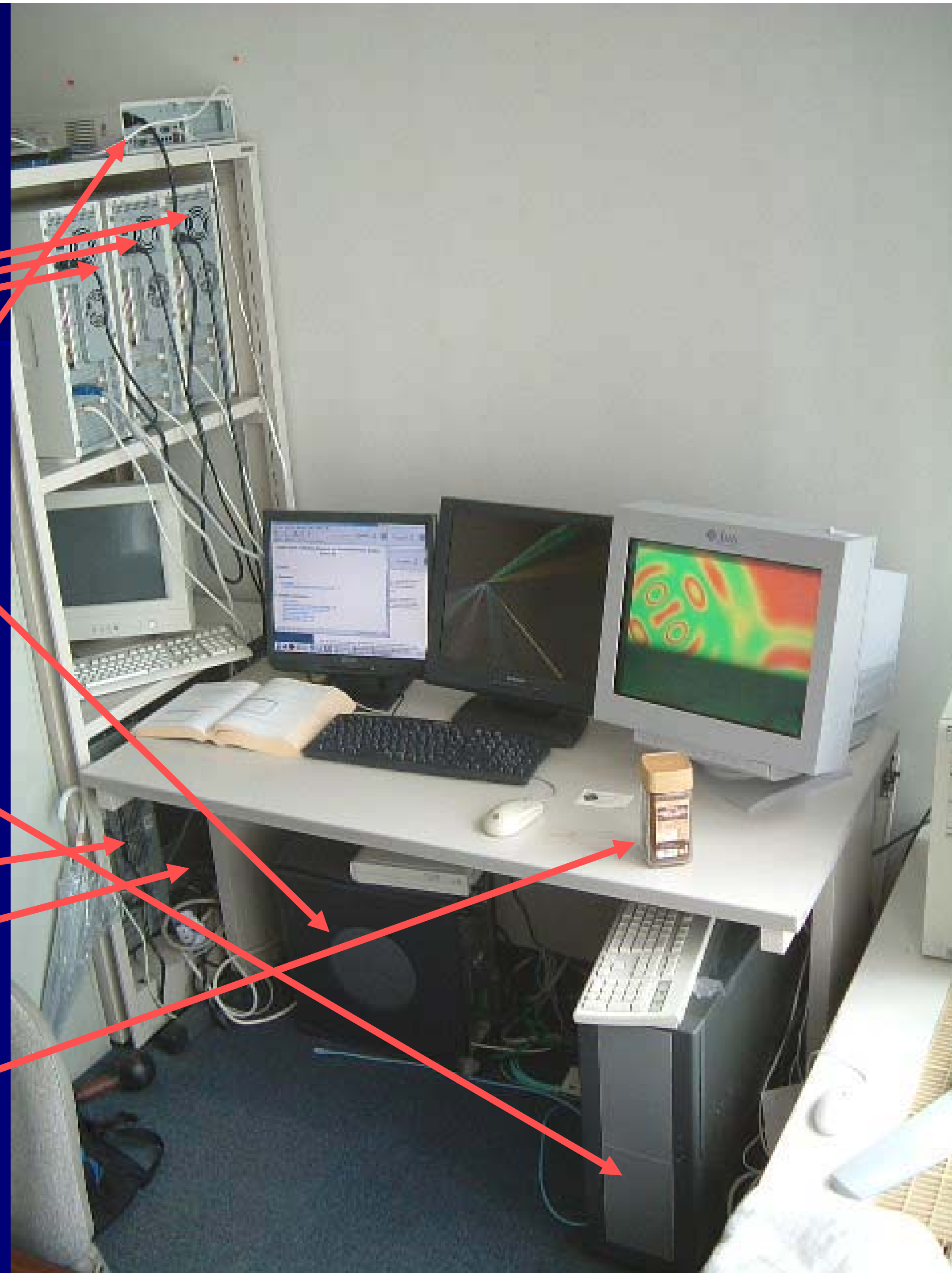
DNS server

Additional workstation

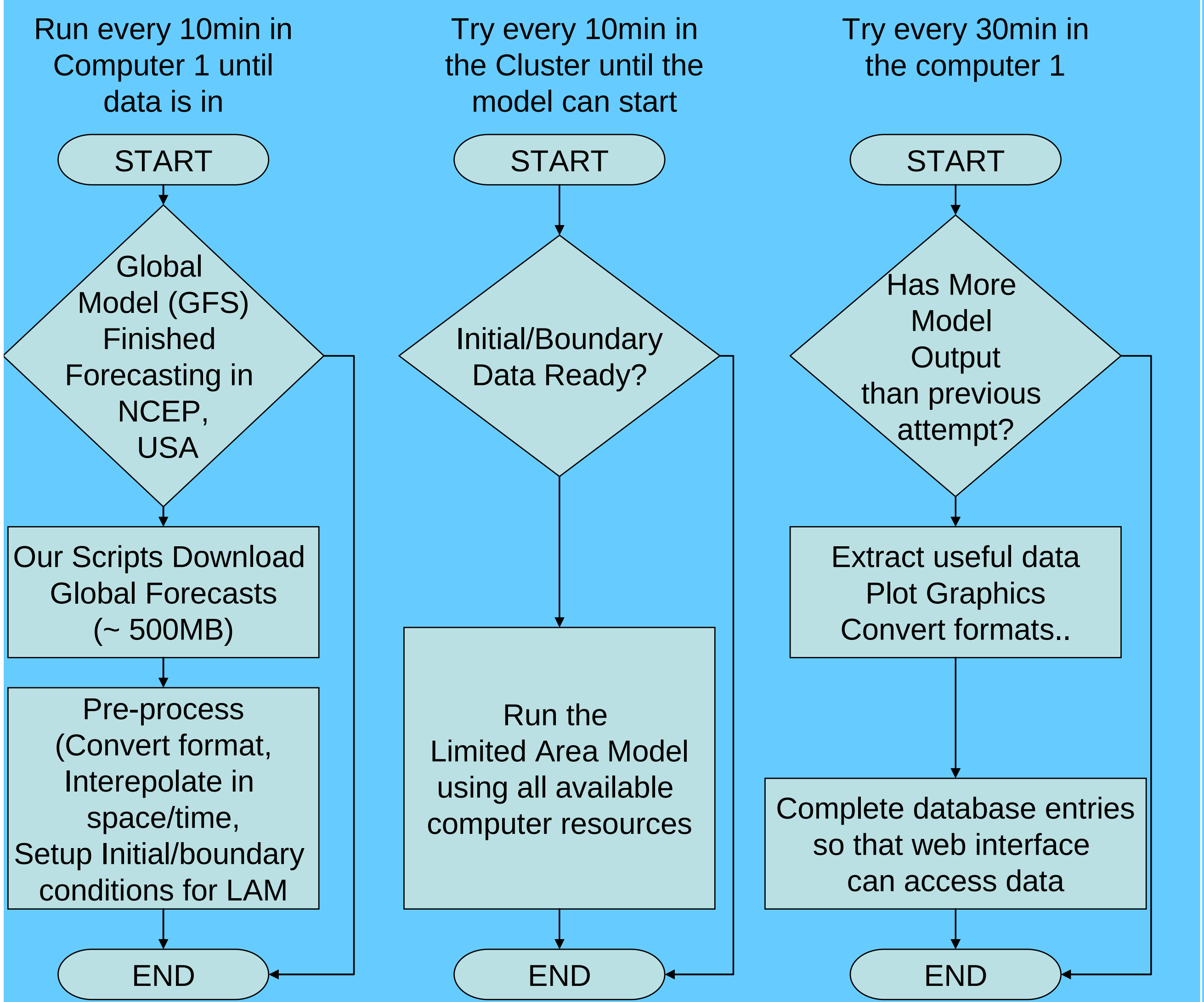
Server

Gateway/Router

Coffee



How it works



Tools Used:

Model:
Weather Research and Forecasting (WRF) Model of NCAR, USA

Operating Systems:
Linux (Redhat, Fedora & Scientific)

Database:
MySQL with InnoDB engine

Web Interface:
PHP front end on Apache server.

Graphics:
NCAR Graphics and ncl

Distributed Computing:
Message Passing Interface (MPICH2)

Automation:
Bash scripts with Cron

Main Utilities:
ImageMagick, Ghostscript, wget, awk, sed, GIFsicle

Daily operation of simulation

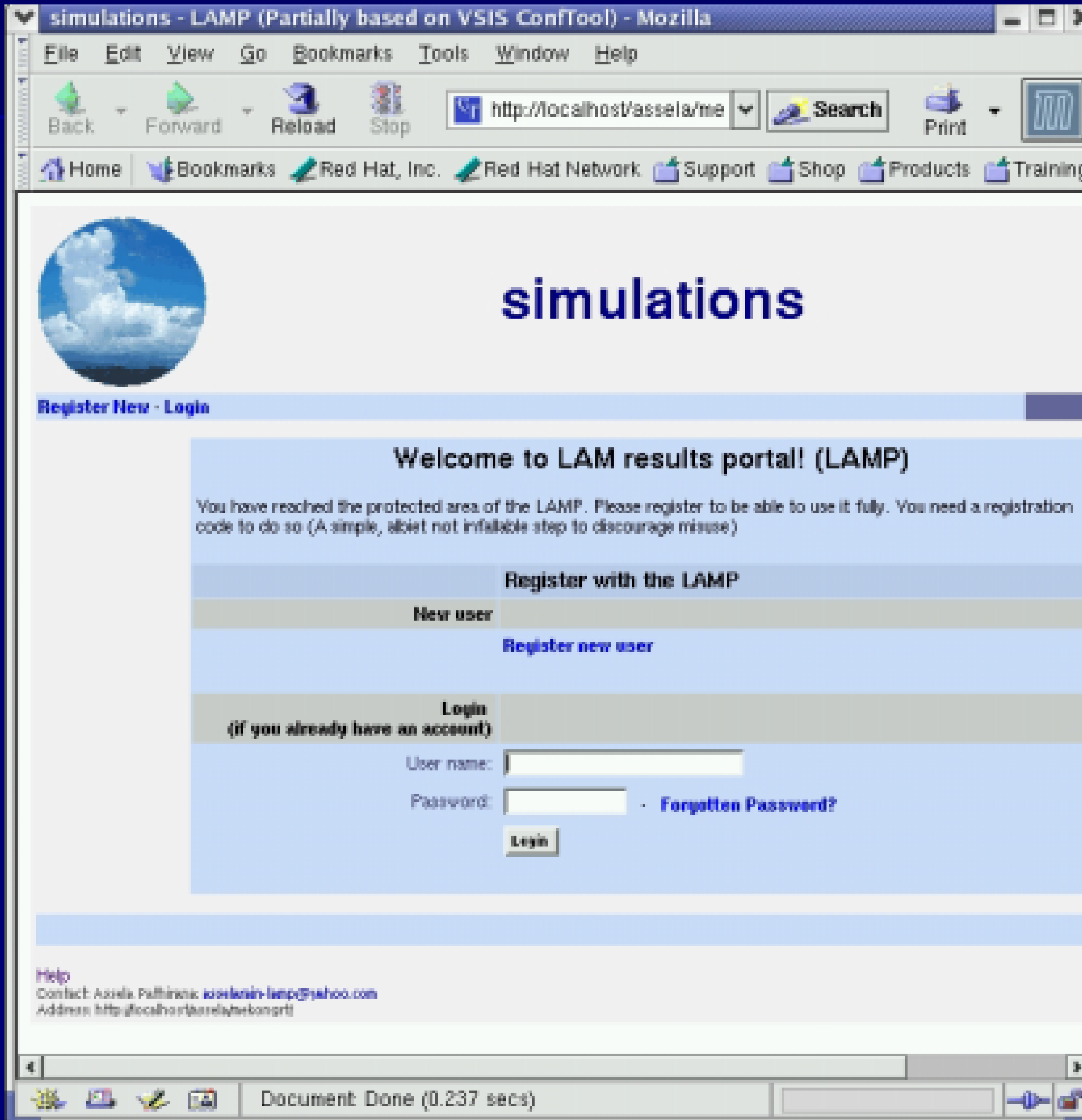
Â Works unattended every day.

Â Forecasts 48h into the future.

Â Results ready around 17:00H JST (10:00H UT)

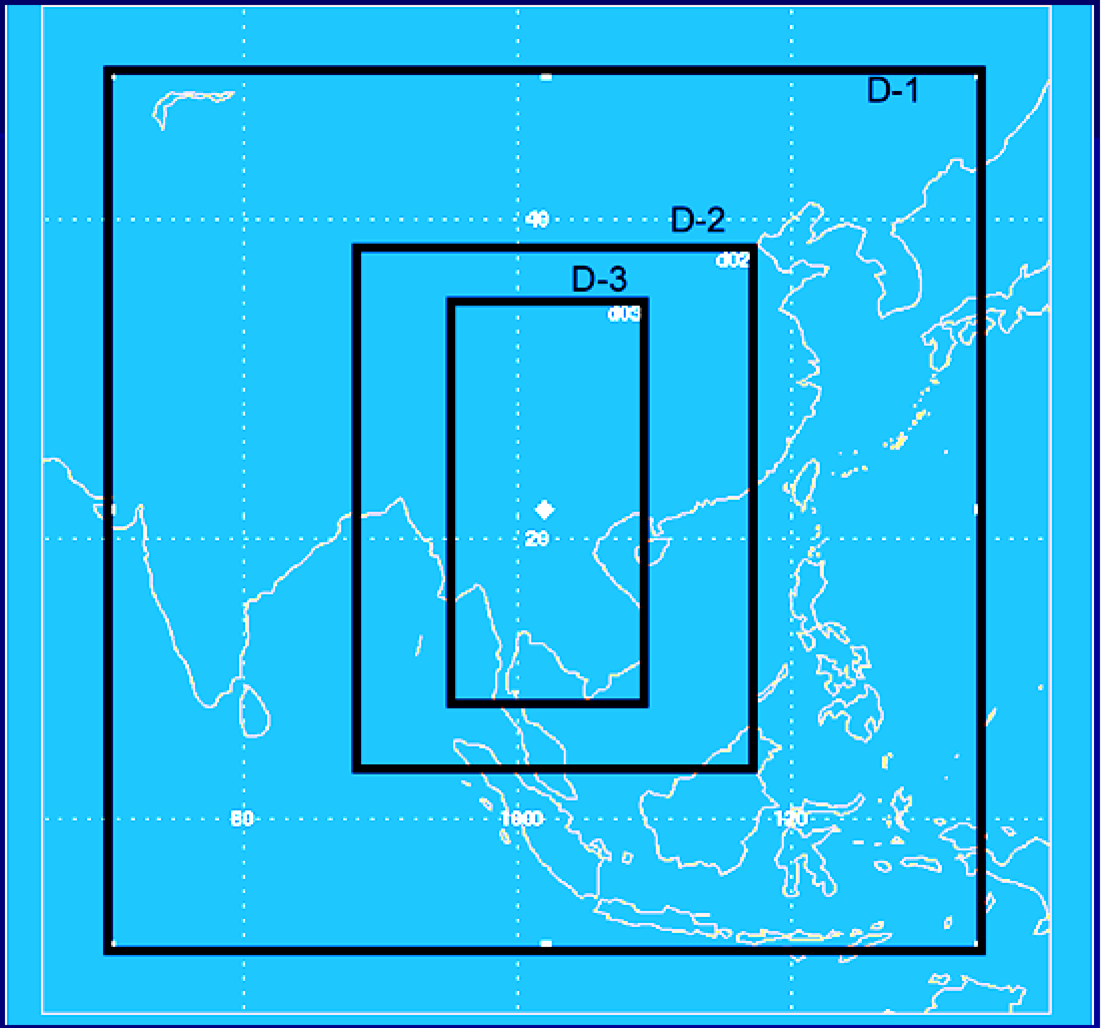
Â Access controlled site presently.

Â Feel free to ask for a password.

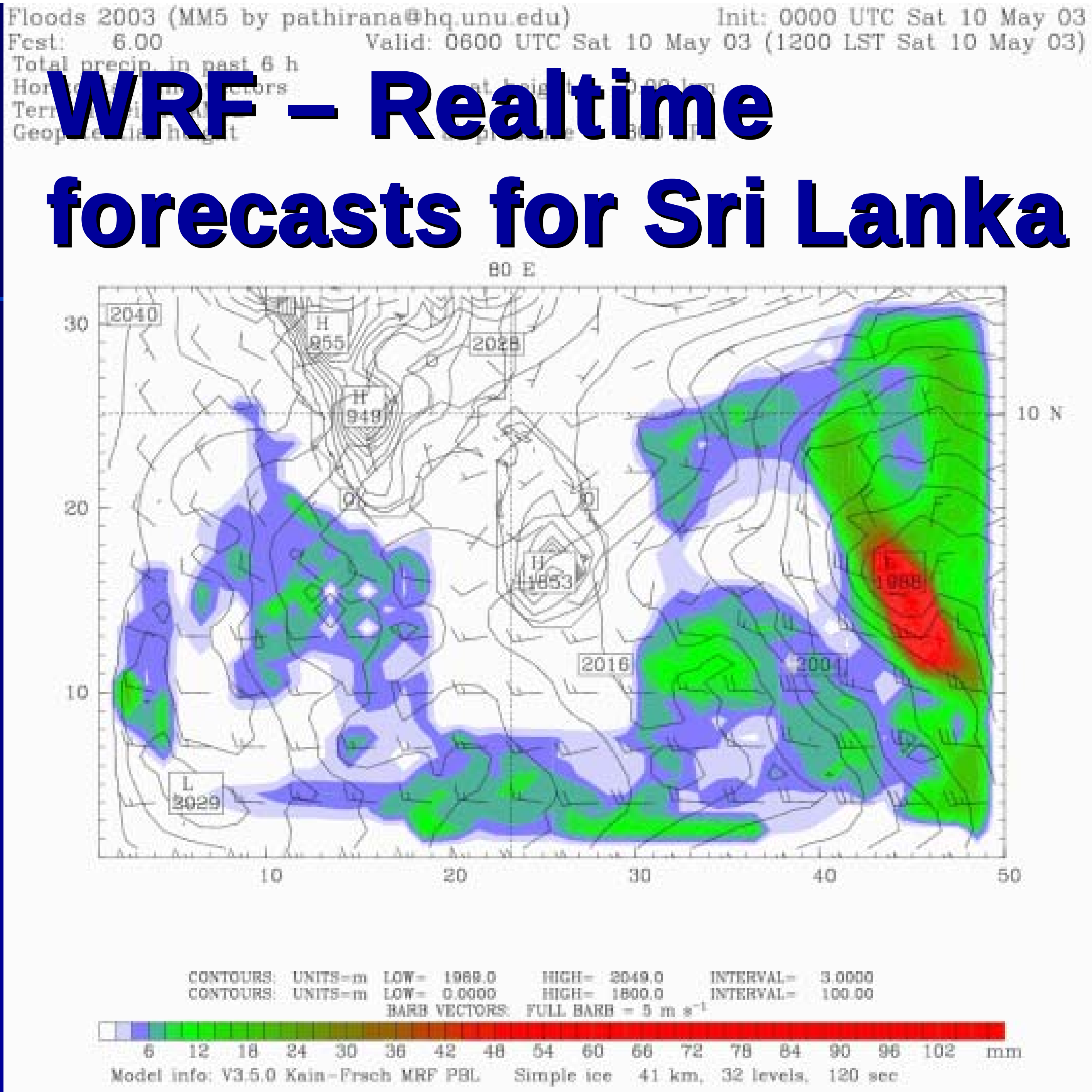


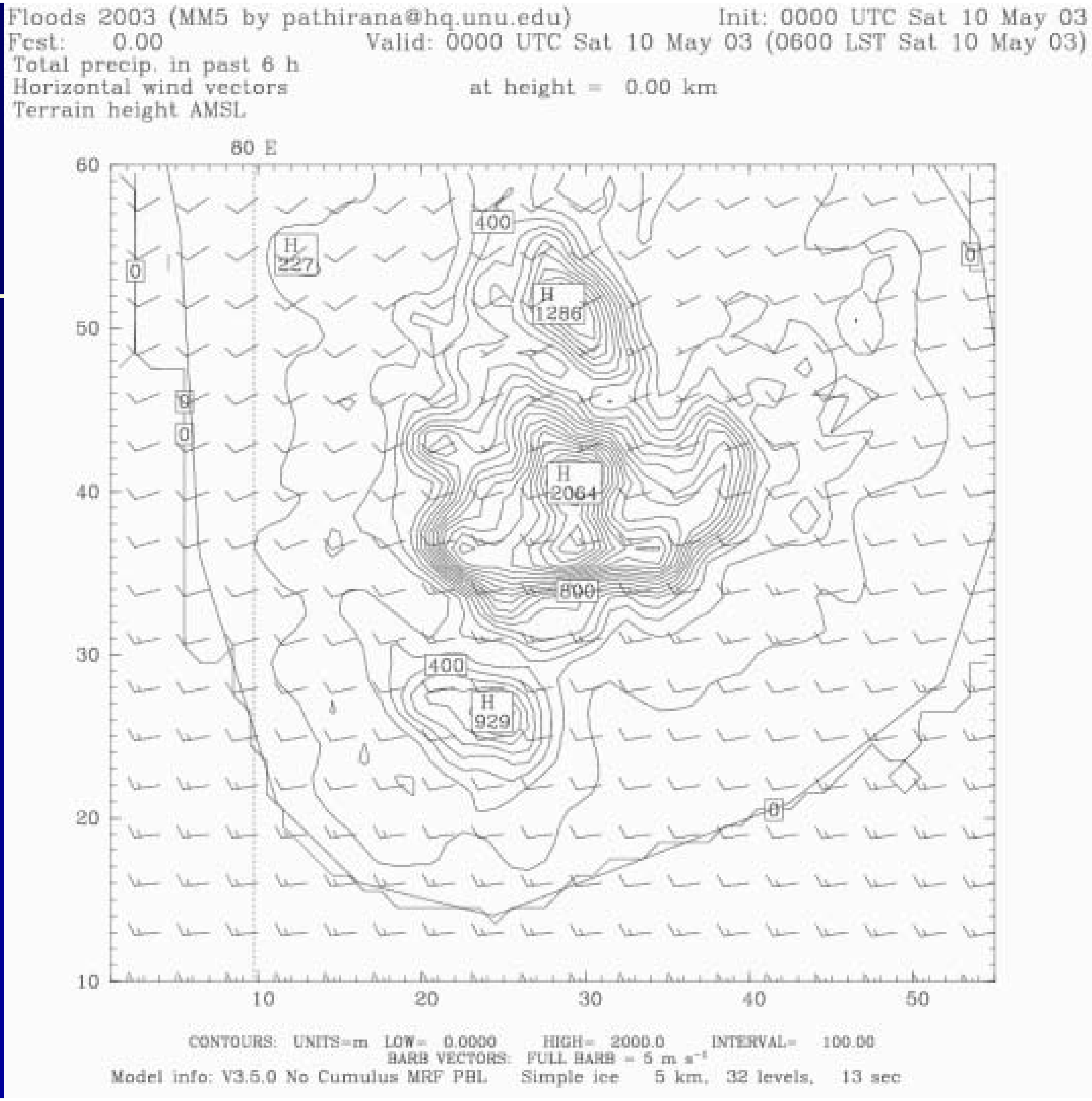
WRF forecast for Mekong

- Three nested domains
  - 135, 45, 15 km
- Model run everyday at UNU with GFS forcing data.



WRF – Realtime forecasts for Sri Lanka




Floods 2003 (MM5 by pathirana@hq.unu.edu)
Init: 0000 UTC Sat 10 May 03
Fcst: 0.00
Valid: 0000 UTC Sat 10 May 03 (0600 LST Sat 10 May 03)
Total precip. in past 6 h
Horizontal wind vectors
at height = 0.00 km
Terrain height AMSL
80 E
CONTOURS: UNITS=m LOW= 0.0000 HIGH= 2000.0 INTERVAL= 100.00
BARB VECTORS: FULL BARB = 5 m s⁻¹
Model info: V3.5.0 No Cumulus MRF PBL Simple ice 5 km, 32 levels, 13 sec

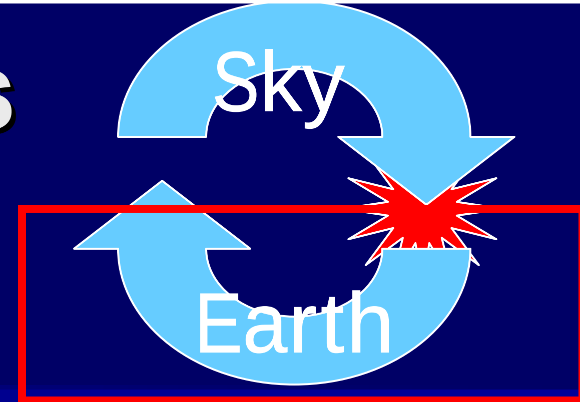
What we've covered

Â The conservation laws we've learned on water can easily be extended to model the atmosphere (add heat conservation).

Â Atmospheric models can be used to

- – Understand rainfall phenomena
- – Predict global change impacts on water cycle.
- – To forecast rainfall.

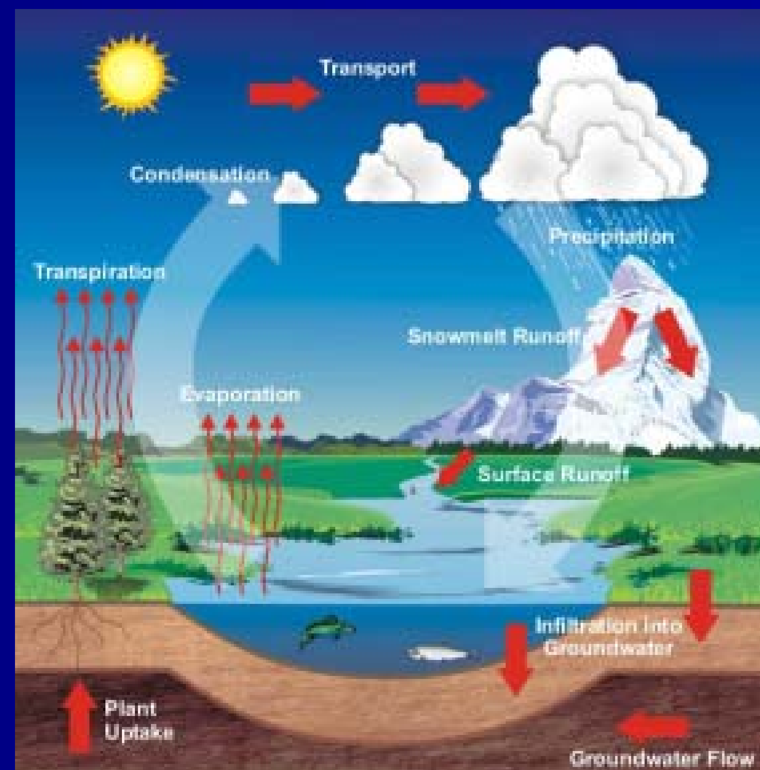
Modeling The Earth's Atmosphere



Re-linking the cycle …

Thank you !

…where heavens meet the earth!



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