Planetary boundary layer parameterizations and their effects in the model world

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What is the Planetary Boundary Layer (PBL)?

- The bottom layer of the troposphere
  - Often turbulent and capped by statically stable air
  - Height varies from tens of m to several km
  - Typically has a strong diurnal cycle
  - Interacts with the surface layer

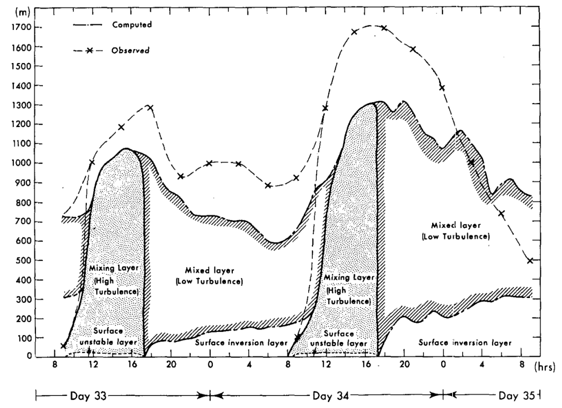
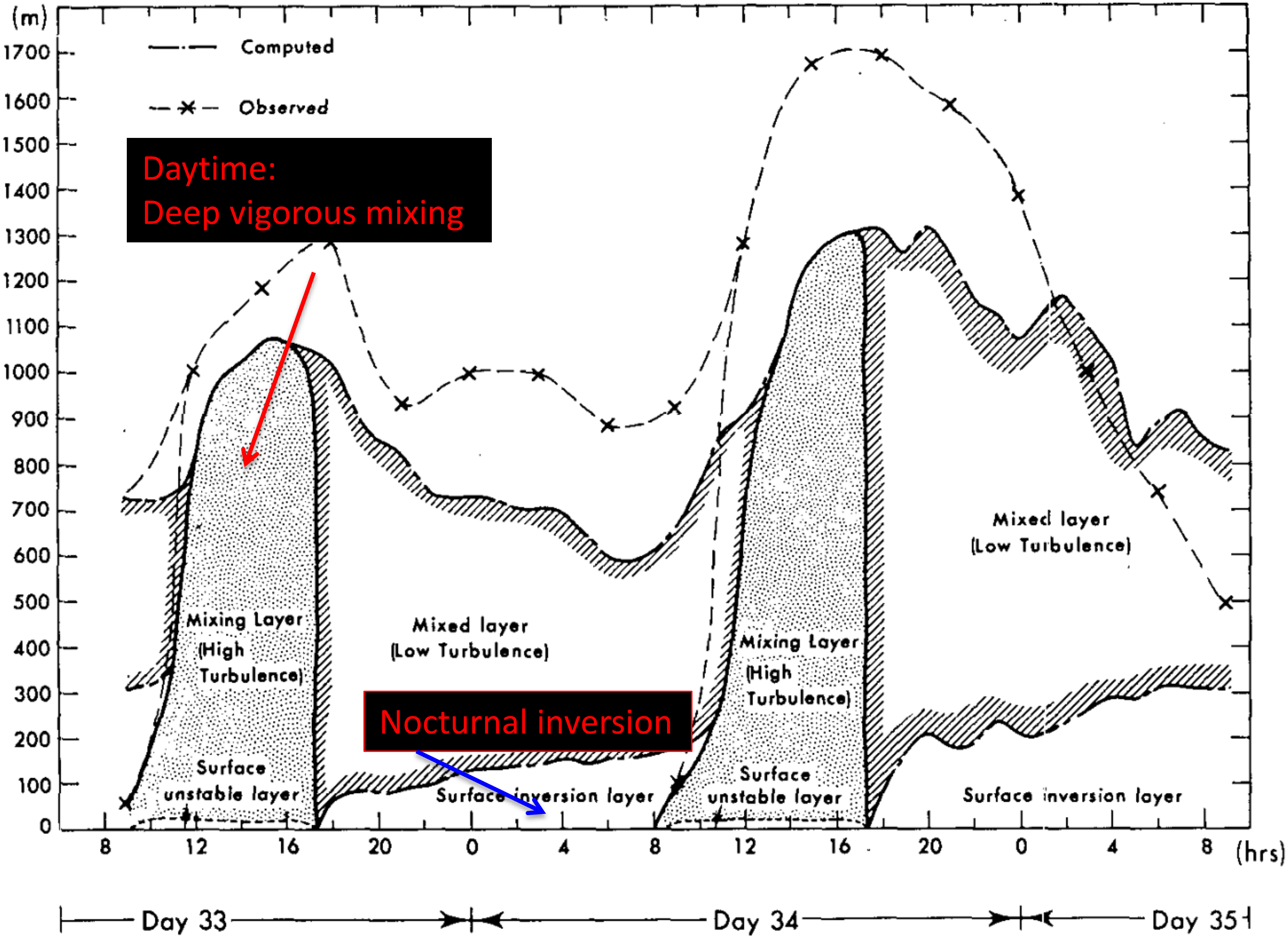


FIG. 33. Time evolution of the computed (basic case) and observed mixed layer height.



Daytime:
Deep vigorous mixing

Nocturnal inversion

FIG. 33. Time evolution of the computed (basic case) and observed mixed layer height.

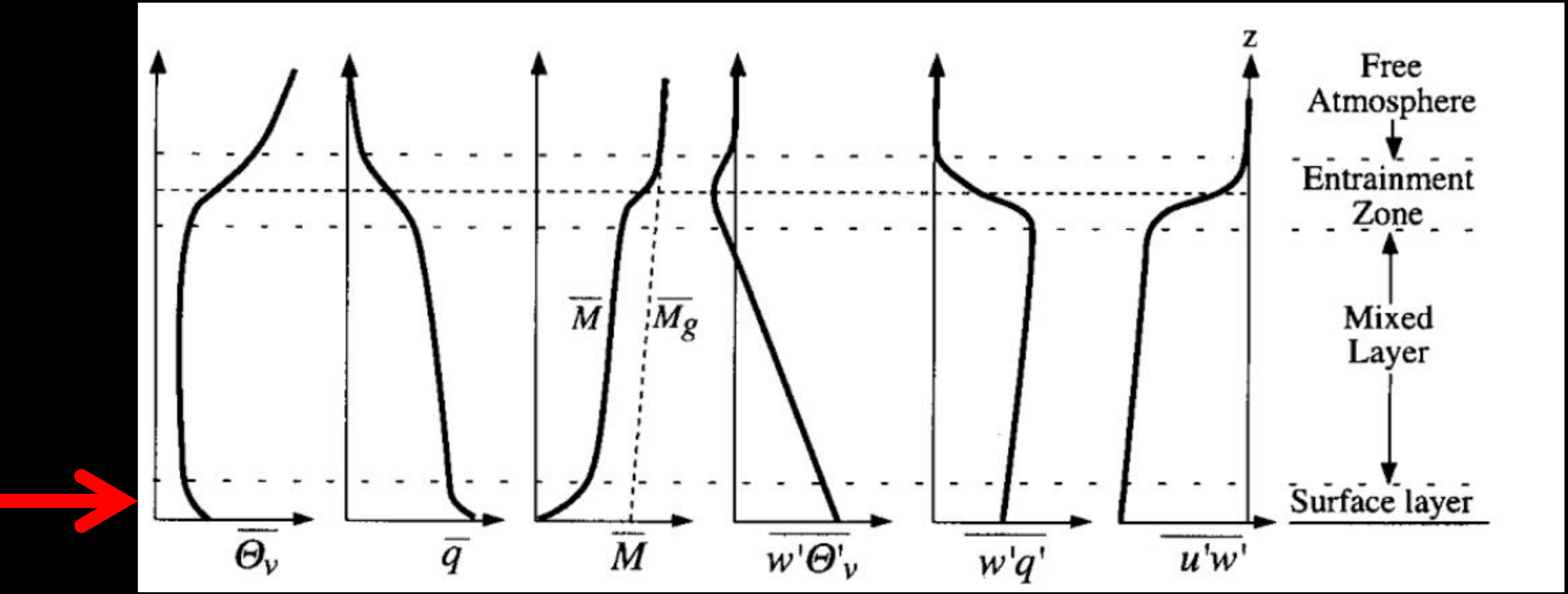
Yamada and Mellor (1975)

Brief Outline

- Types of PBLs
  - Daytime (convective)
  - Nocturnal (inversion)
- PBL schemes in WRF
  - Local
  - Nonlocal
- PBL influences on forecasts
  - Biases and case study examples
  - Influence on extratropical cyclones
  - Influence on tropical cyclones

Convective Boundary Layer

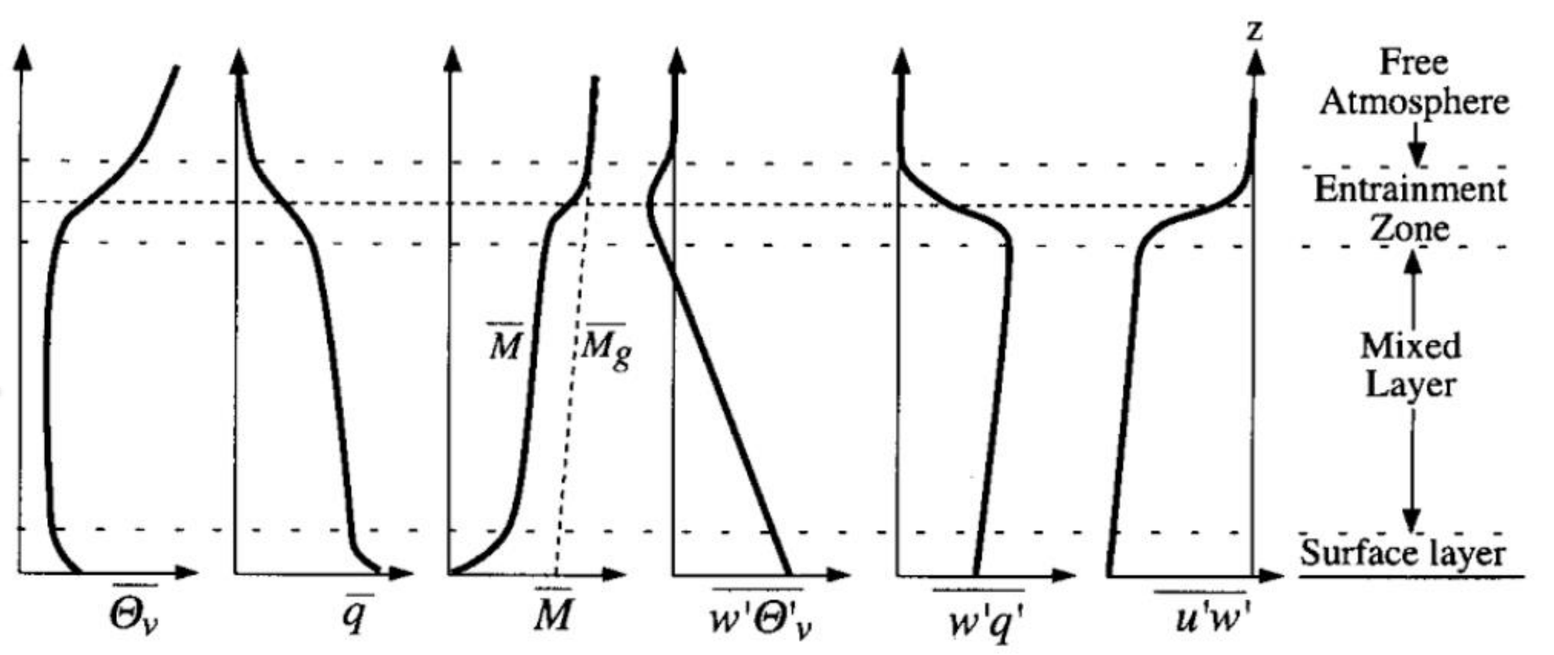
- Strong surface heating creates surface layer



Hartmann (1994)

Convective Boundary Layer

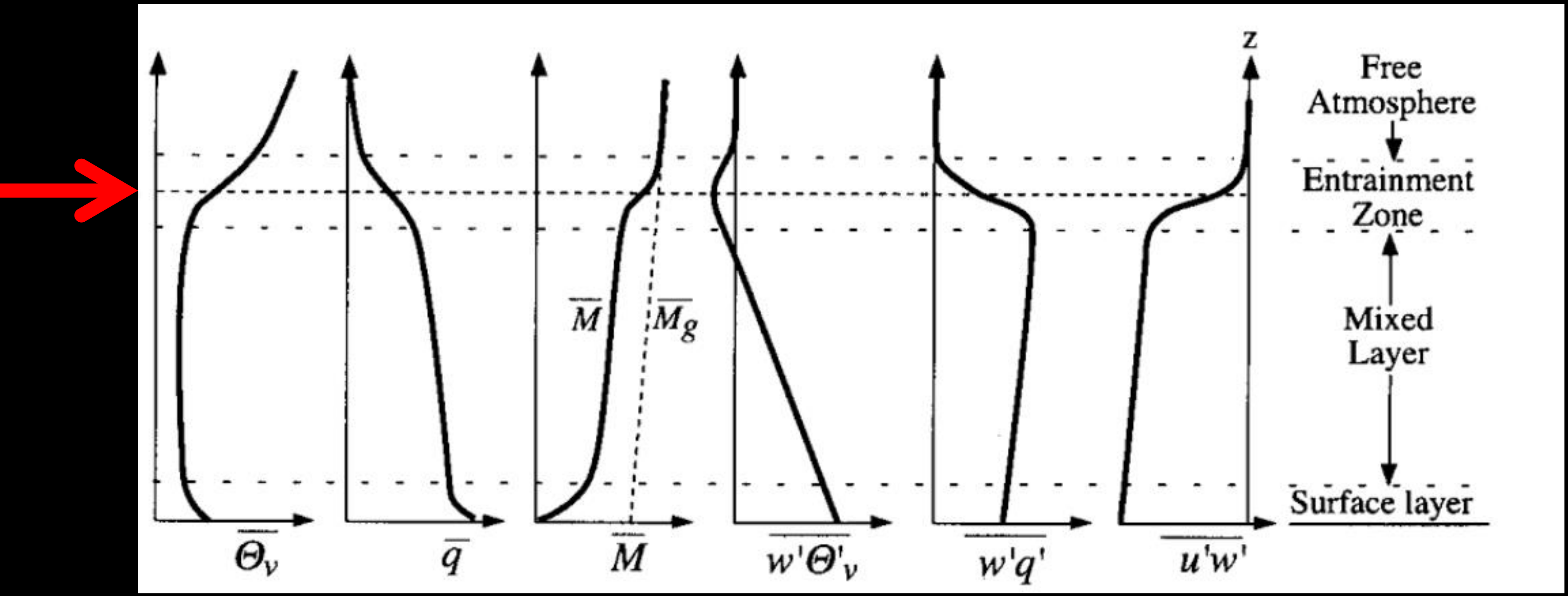
- Above surface layer, well-mixed layer forms



Hartmann (1994)

Convective Boundary Layer

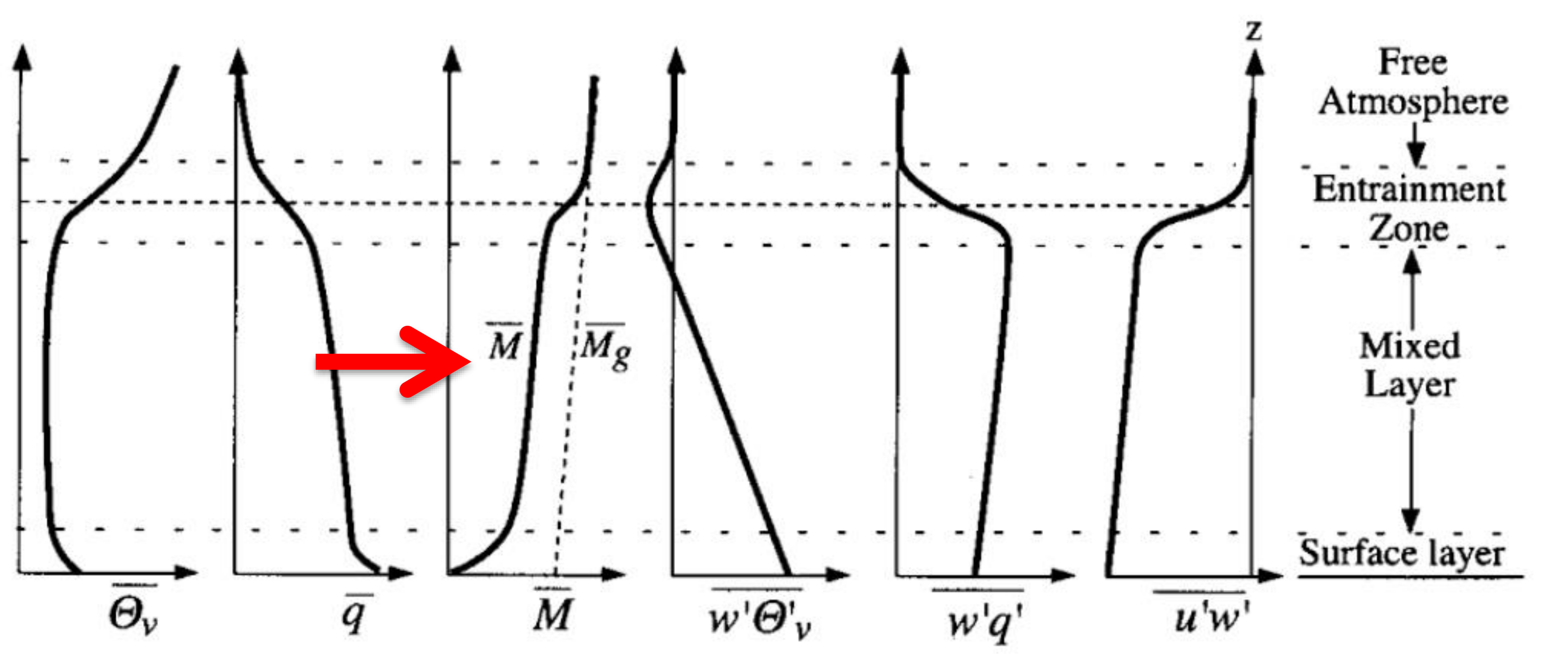
- Entrainment zone mixes with the free atmosphere



Hartmann (1994)

Convective Boundary Layer

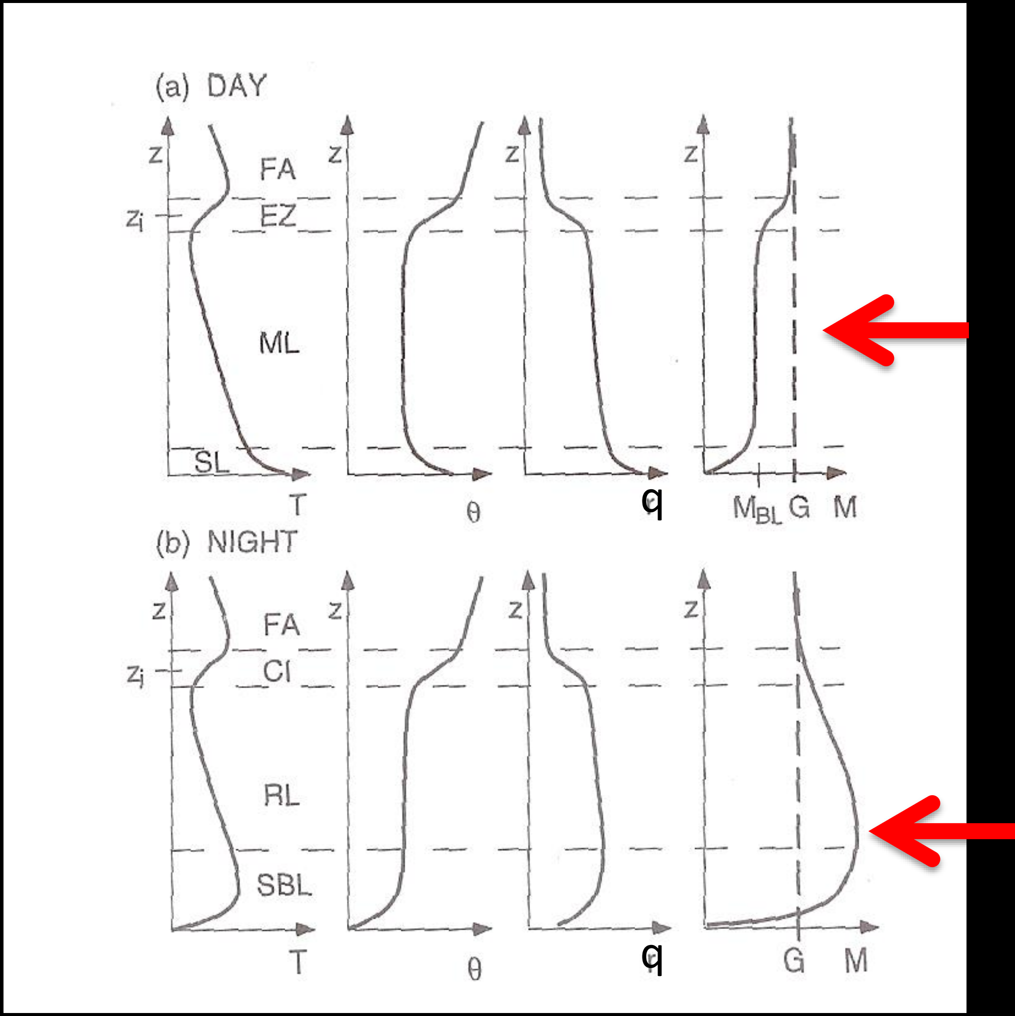
- Subgeostrophic wind due to frictional effects during the daytime



Hartmann (1994)

Nocturnal Boundary layer

- Supergeostrophic wind can develop at night
- Stable layer develops at surface
- Residual layer (e.g., EML) can influence weather downstream



Stull (2000)

PBL Summary

- Bottom layer of the troposphere influenced by the surface
- Dominated by mechanically driven and buoyancy driven eddies
- Controls transport of momentum, heat, and moisture between free atmosphere and the surface layer

PBL Processes in WRF

- Turbulent PBL processes are too small to resolve for km-scale models
  - Subgrid scale processes must be parameterized
- Goal is to describe the mean turbulent vertical transport of heat, momentum and moisture by eddies
  - Two common approaches are through local (e.g., MYJ) and nonlocal (e.g., YSU) diffusion schemes

All about the eddies

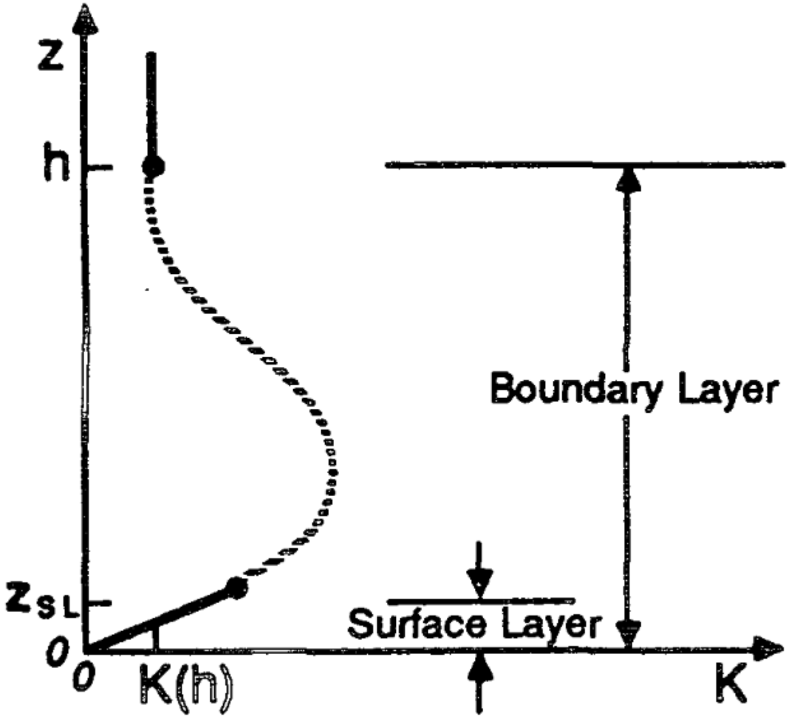


FIG. 1. Typical variation of eddy viscosity *K* with height in the boundary layer proposed by O'Brien (1970). Adopted from Stull (1988).

Hong and Pan (1996)

- How do you obtain an eddy diffusivity (K) profile?
  - Develop it (MYJ)
  - Impose it (YSU)

$$-\overline{(w'\phi')} = K_{\phi}\frac{\partial\overline{\phi}}{\partial z},$$

Coniglio et al. (2013)

Local Schemes

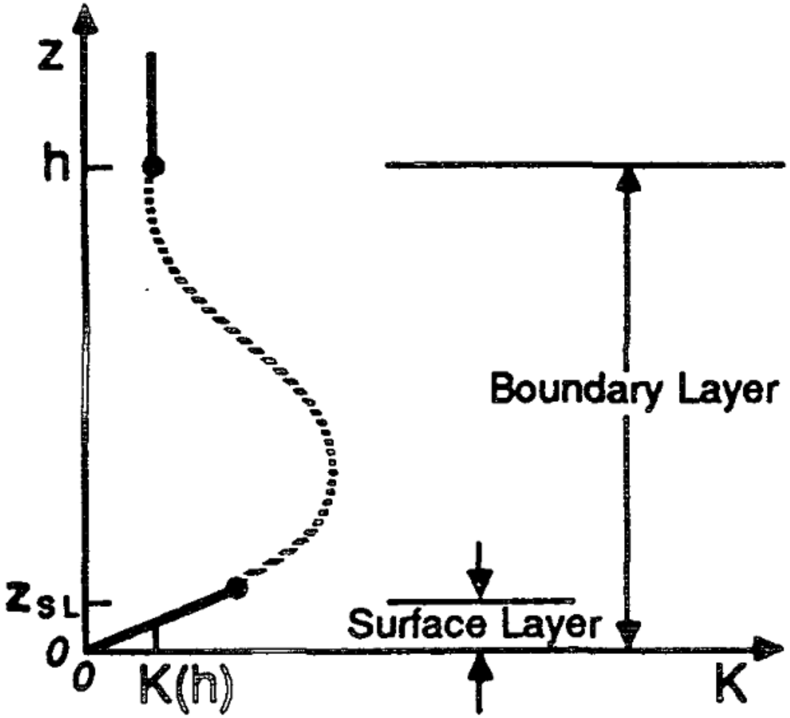


FIG. 1. Typical variation of eddy viscosity K with height in the boundary layer proposed by O'Brien (1970). Adopted from Stull (1988).

- Local scheme like MYJ uses **local** vertical gradients to predict turbulent kinetic energy and use it to get K as a function of height

Hong and Pan (1996)

Nonlocal Schemes

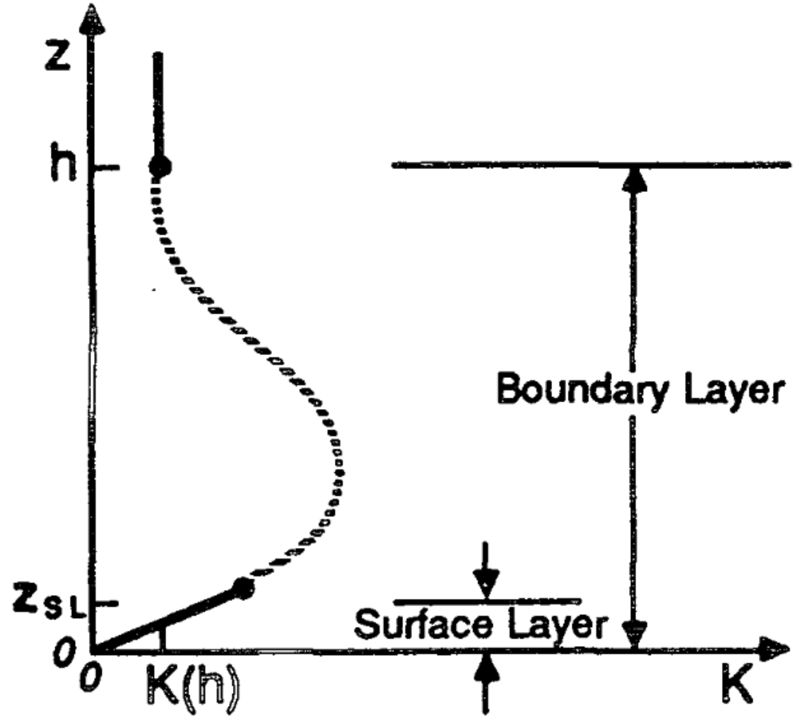


FIG. 1. Typical variation of eddy viscosity *K* with height in the boundary layer proposed by O'Brien (1970). Adopted from Stull (1988).

Hong and Pan (1996)

- Nonlocal schemes (YSU) estimate PBL height and use a prescribed profile shape to impose onto the PBL

Local vs. Nonlocal

- Simple local scheme that uses local gradients to establish K-profile

$$K = l^2 \left| \frac{\partial \overline{V}}{\partial z} \right| F(R_i).$$

$$R_i = \frac{\frac{g}{\theta} \frac{\partial \overline{\theta}}{\partial z}}{\left| \frac{\partial \vec{V}}{\partial z} \right|^2}$$

Krishnamurti et al. (2007)

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Mixing length
(function of height)

Krishnamurti et al. (2007)

Local gradients
at a given level

Local vs. **Nonlocal**

- Nonlocal scheme estimates PBL height and imposes K-profile shape function

$$K_{zm} = \kappa w_s z\left(1 - \frac{z}{h}\right)^2$$

Mixed-layer velocity scale (function of surface friction velocity and surface-layer physics-derived profile function)

Hong and Pan (1996)

Local vs. **Nonlocal**

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$$K_{zm} = \kappa w_s z\left(1 - \frac{z}{h}\right)^2$$

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Hong and Pan (1996)

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Potential temp at lowest model level

Appropriate surface potential temp

Hong and Pan (1996)

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Critical Richardson number. Varies with version (~0.75–0.25). Can be source of sensitivity.

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Hong and Pan (1996)

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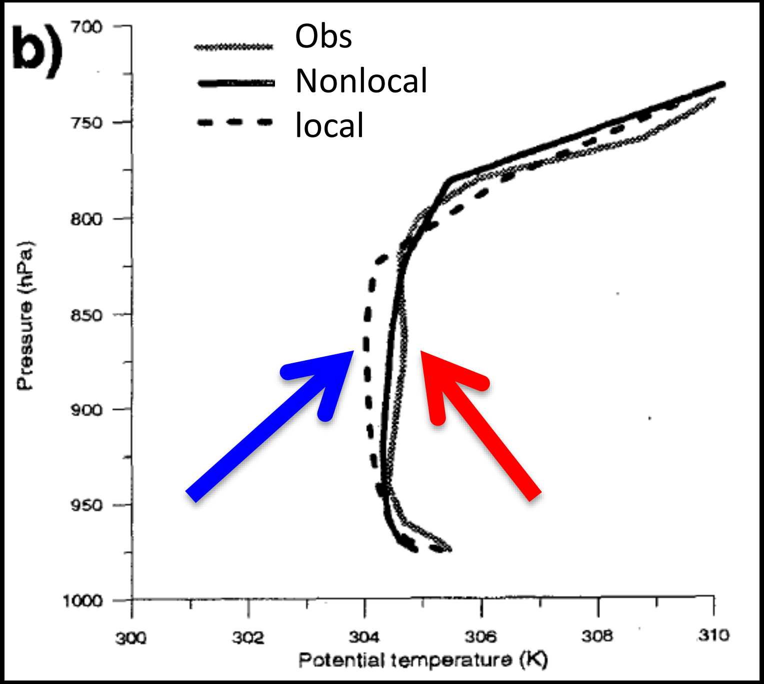
Hong and Pan (1996)

Common biases in PBL schemes

Convective PBL conditions

2145 UTC 9 August 1987



Hong and Pan (1996)

- Nonlocal schemes tend to build mixed layers more effectively

Convective PBL conditions

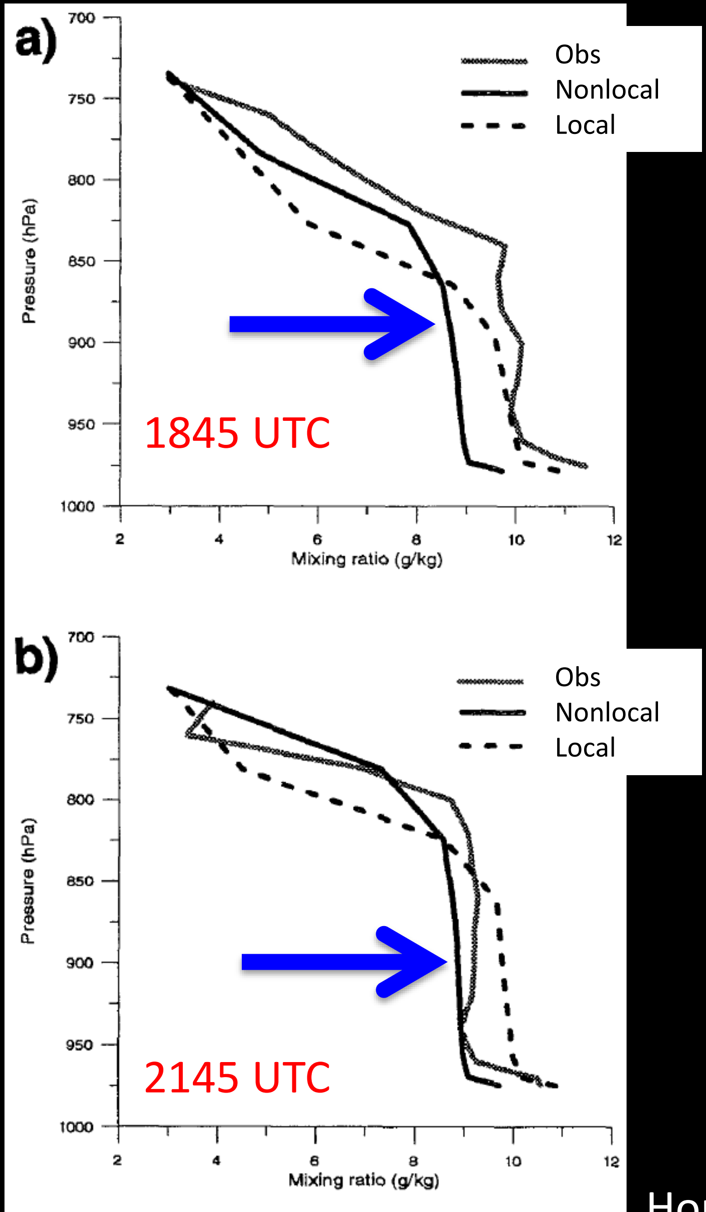


Fig. 4. As in Fig. 3 but for mixing ratio (g kg^{-1}).

- Due to efficiency of mixed-layer development, nonlocal schemes tend to overdeepen in convective environments
- Can result in reduction of CIN and underestimation of MLCAPE

Hong and Pan (1996)

Composite Soundings for Europe

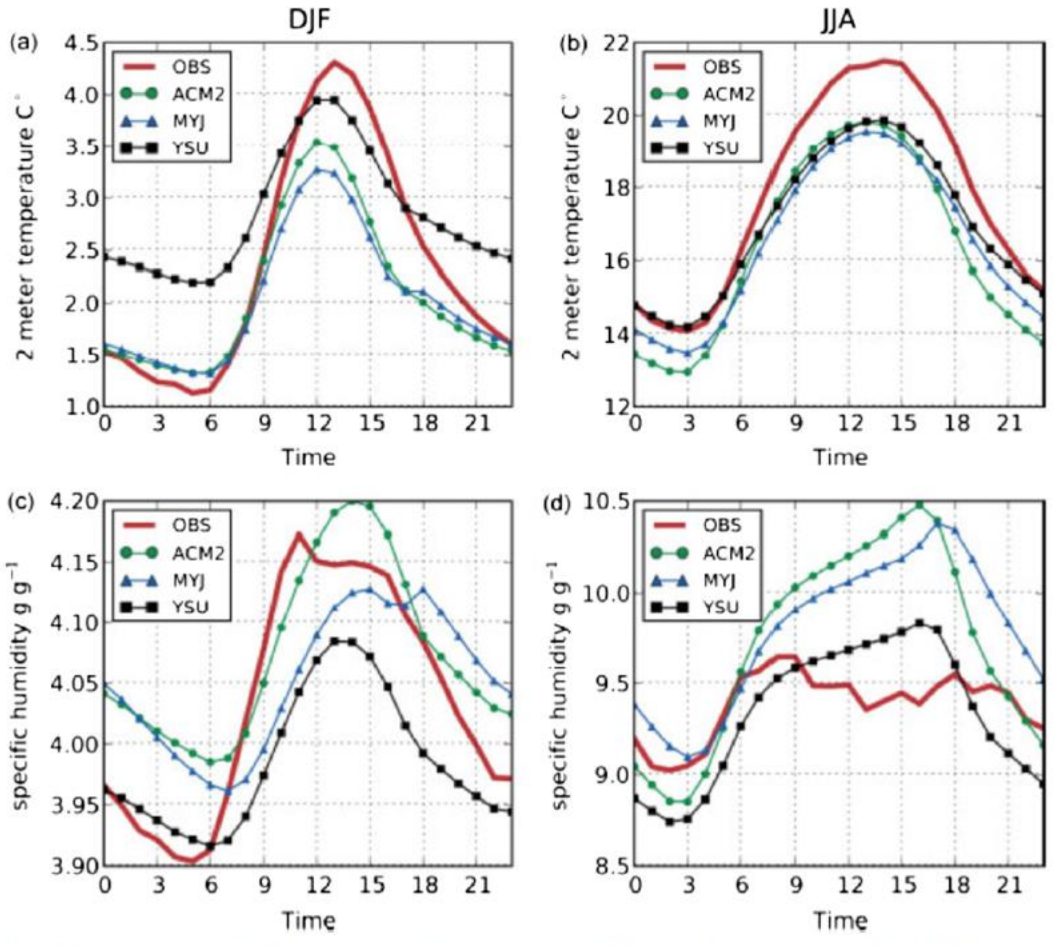
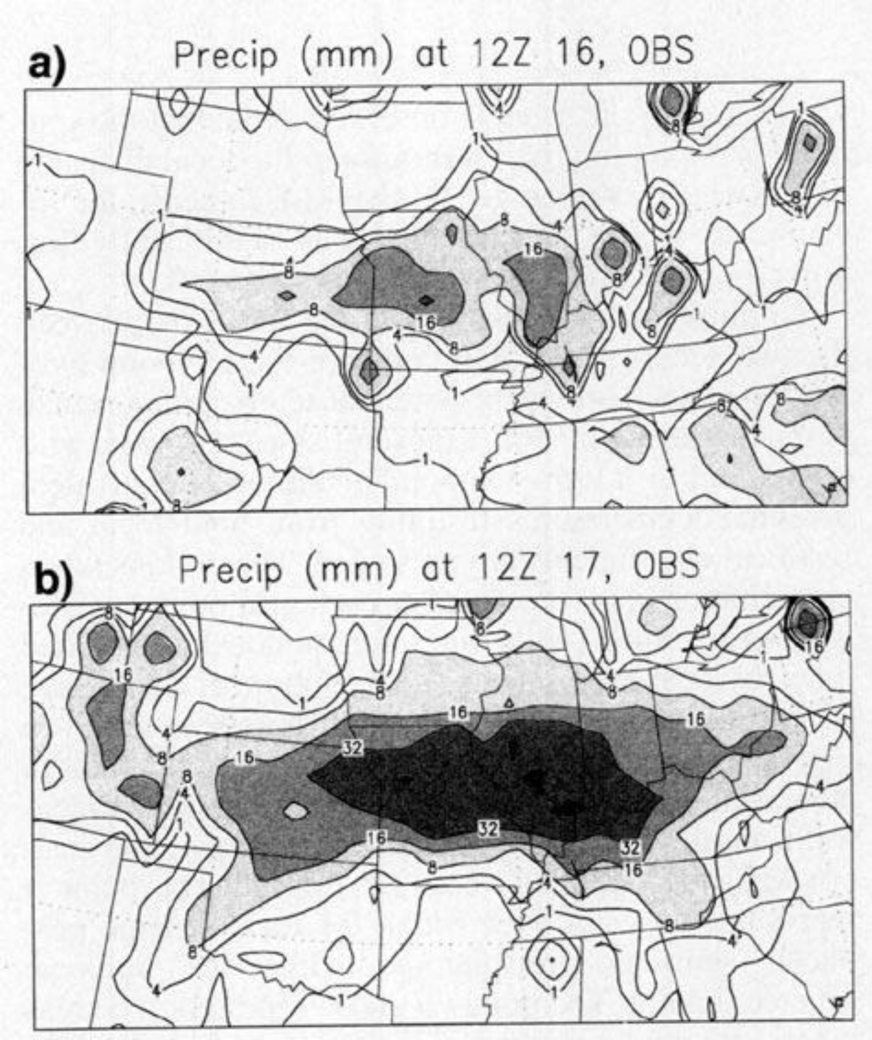


FIG. 3. Comparisons of WRF PBL schemes with European synoptic observations for temperatures during the (a) winter and (b) summer and for specific humidity during the (c) winter and (d) summer [from García-Díez et al. (2013)].

PBL schemes for collection of European sites during winter (a) and summer (b). García-Díez (2013)

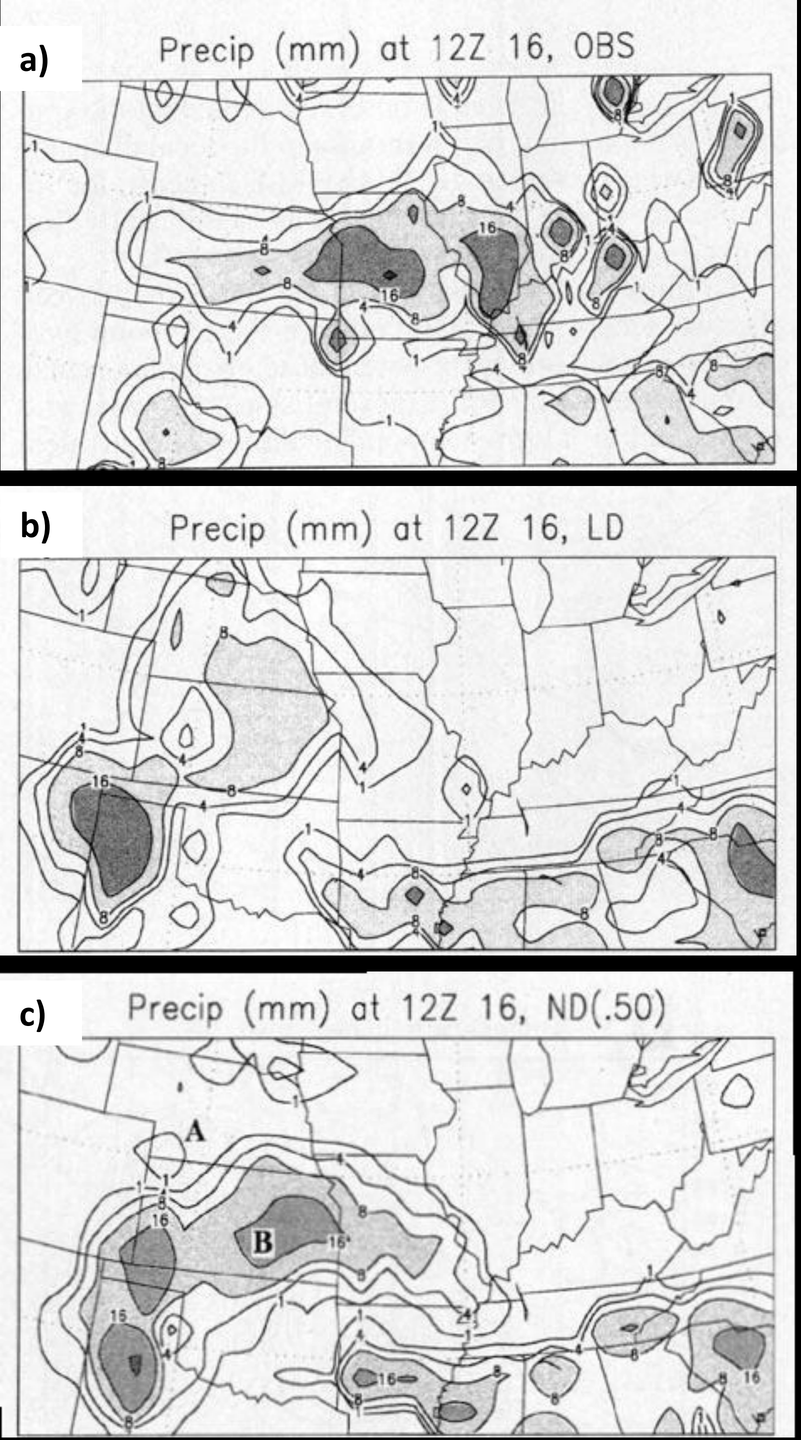
- Nonlocal (YSU) DJF warm bias at night
- Moisture overestimated during daytime JJA, less so with YSU.

Convective Case Study



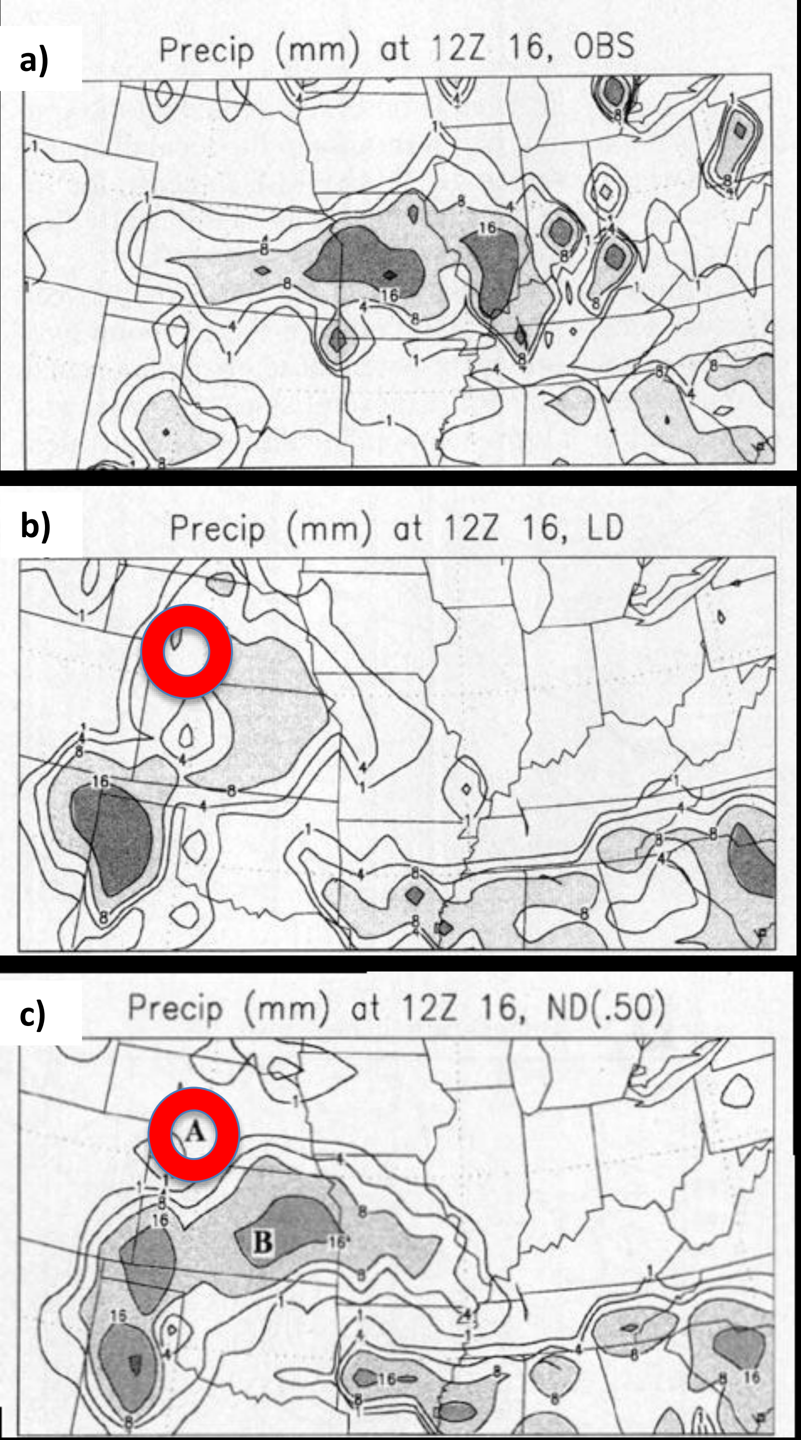
24-h accumulated precipitation (mm) ending at (a) 1200 UTC 16 May and (b) 1200 UTC 17 May 1995. (Hong and Pan 1996)

- Lighter precipitation in first period
- Widespread convective/large-scale rain within the warm sector in the second period



24-h accumulated precipitation (mm) ending at 1200 UTC 16 May from (a) observations, (b) local scheme, (c) nonlocal scheme. (Hong and Pan 1996)

- Some spurious convection in NE in local scheme



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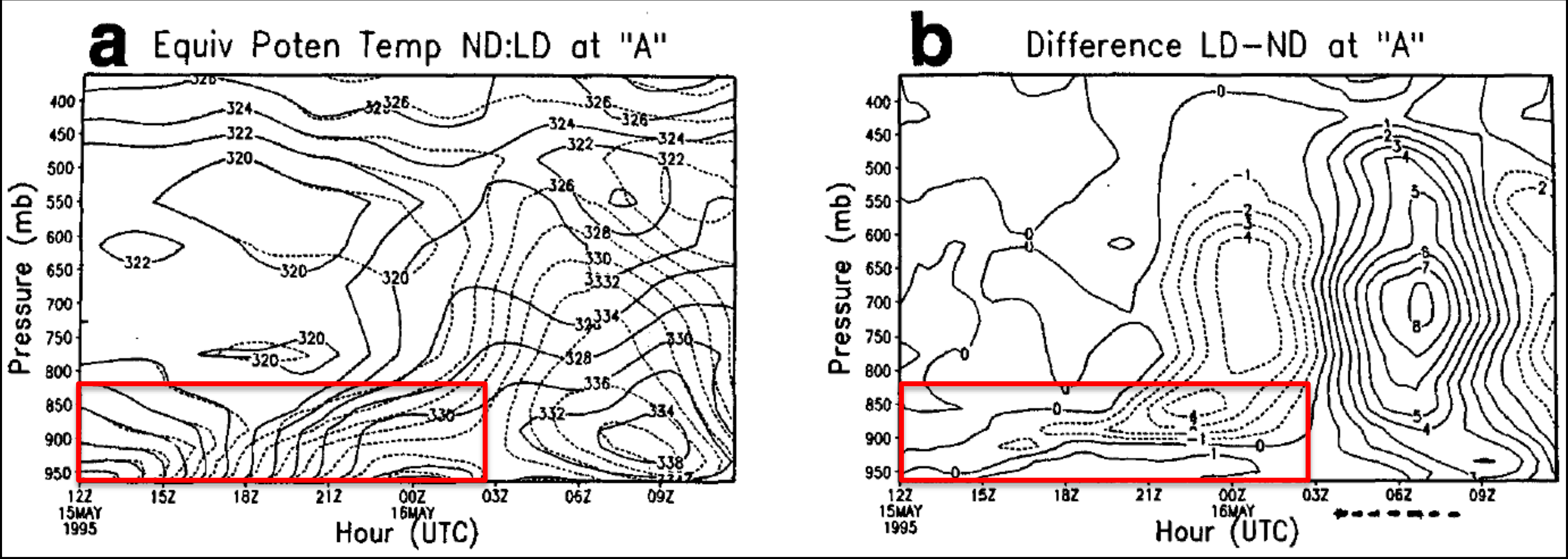
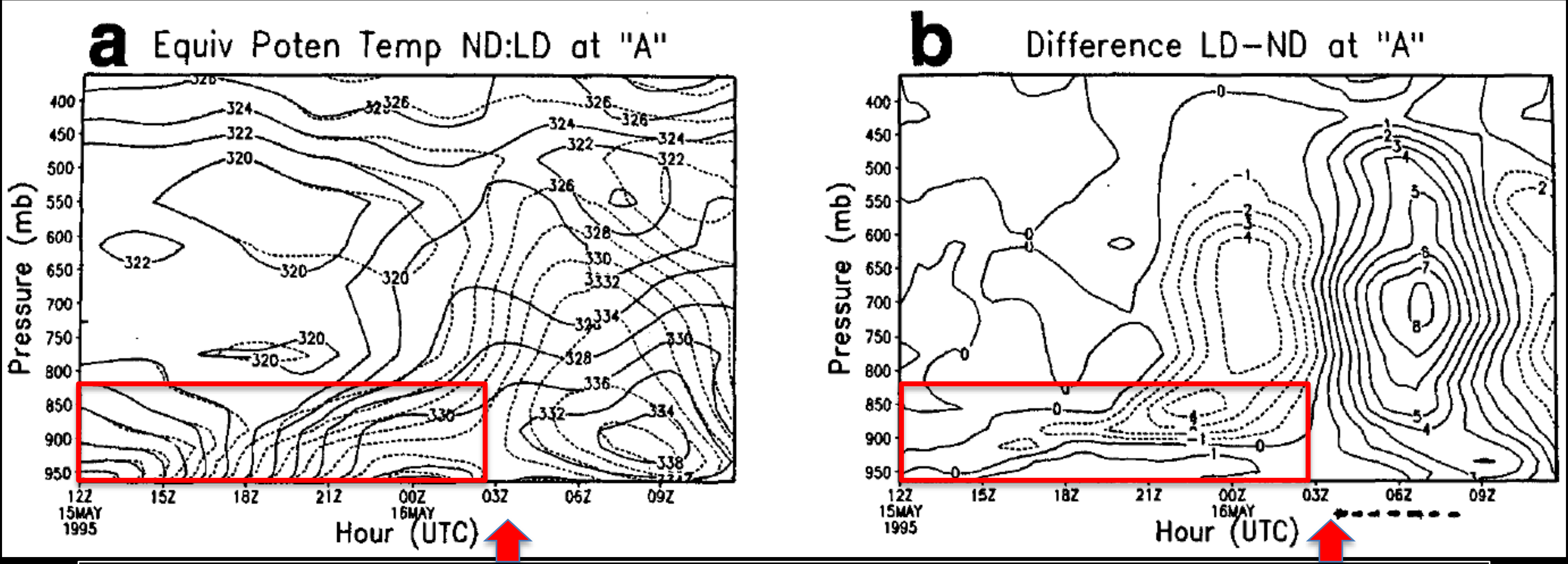
- Some spurious convection in NE in local scheme
- Investigate point A as to why



Time-pressure section of (a) equivalent potential temperature (K) for the local (dotted) and nonlocal (solid) experiments and (b) the differences (local minus nonlocal at the grid point A. Dotted line at the bottom of the difference field denotes the forecasted precipitation period for the local scheme (Hong and Pan 1996)

- Local scheme has shallower boundary layer
  - Traps moisture



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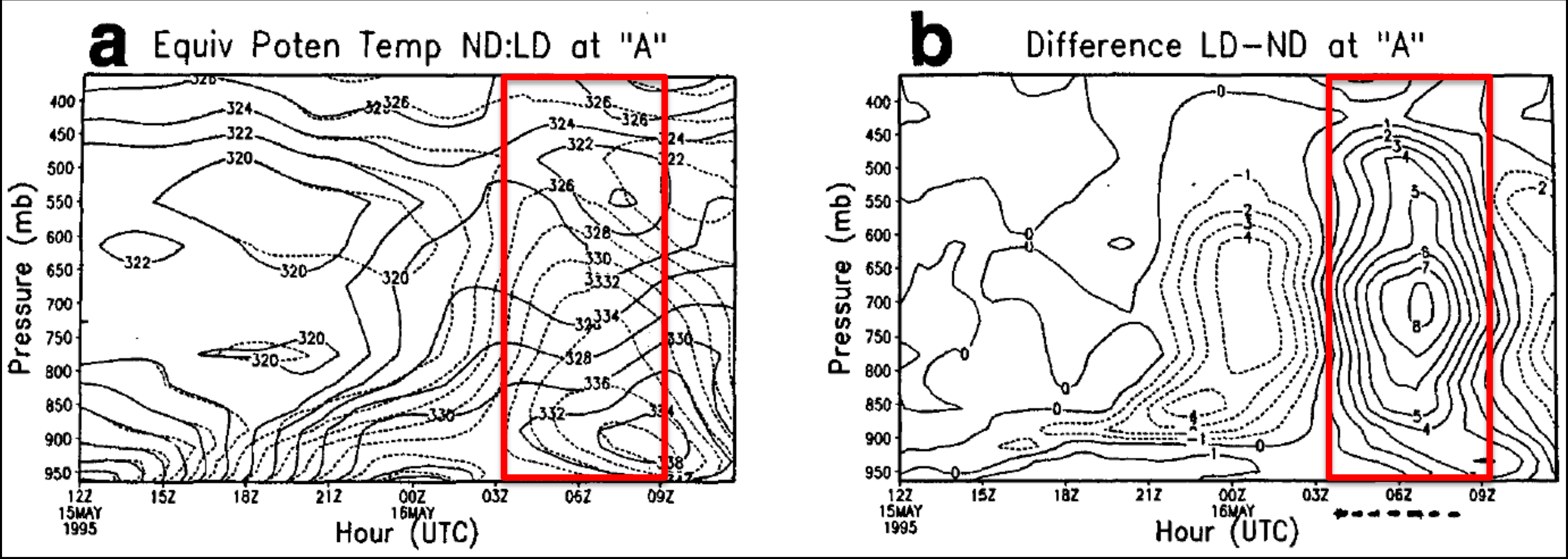
- Local PBL becomes sufficiently unstable
  - CAPE release around 0300 UTC



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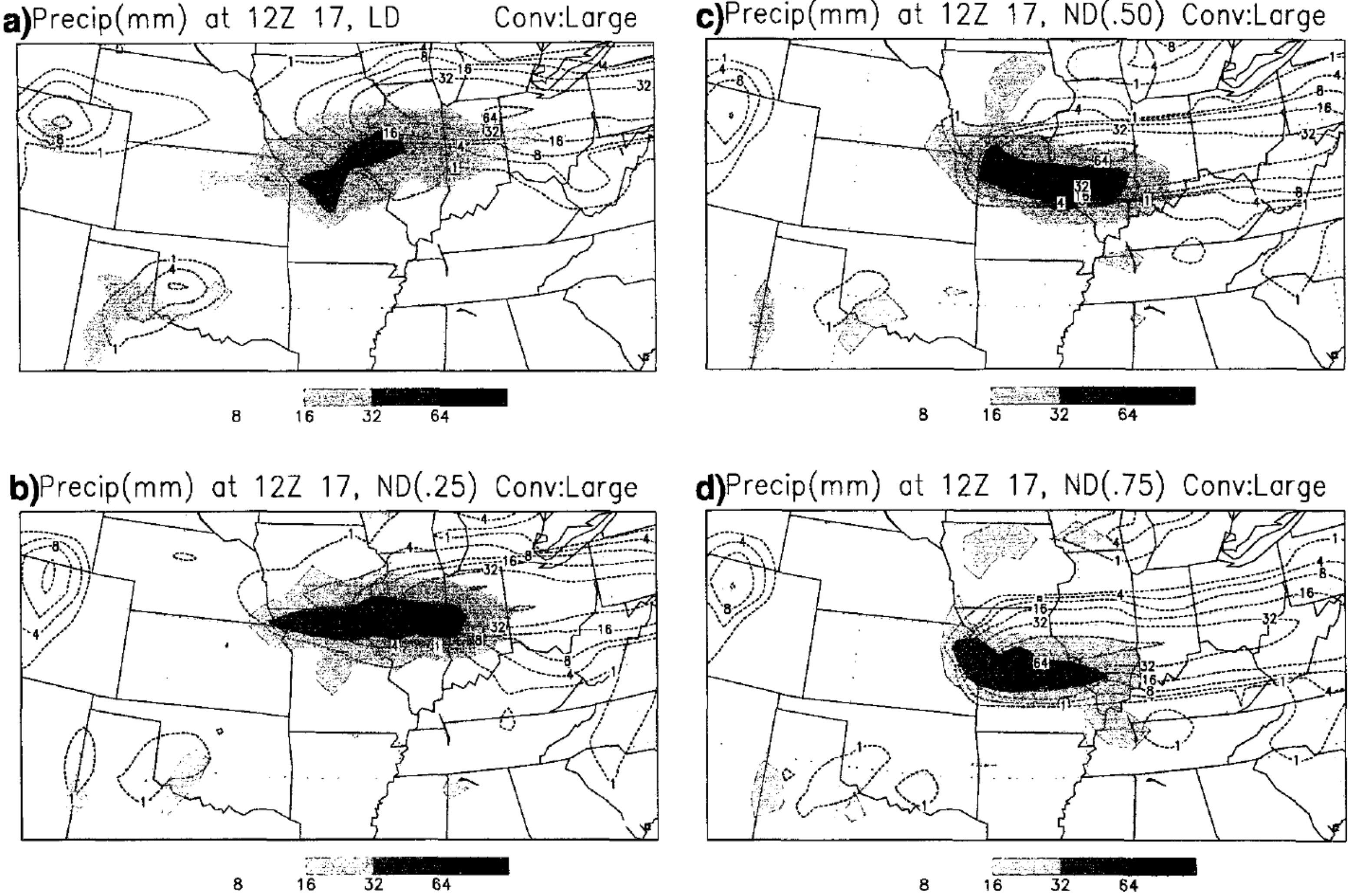
Hong and Pan (1996)



a)Precip(mm) at 12Z 17, LD Conv:Large

c)Precip(mm) at 12Z 17, ND(.50) Conv:Large

b)Precip(mm) at 12Z 17, ND(.25) Conv:Large

d)Precip(mm) at 12Z 17, ND(.75) Conv:Large

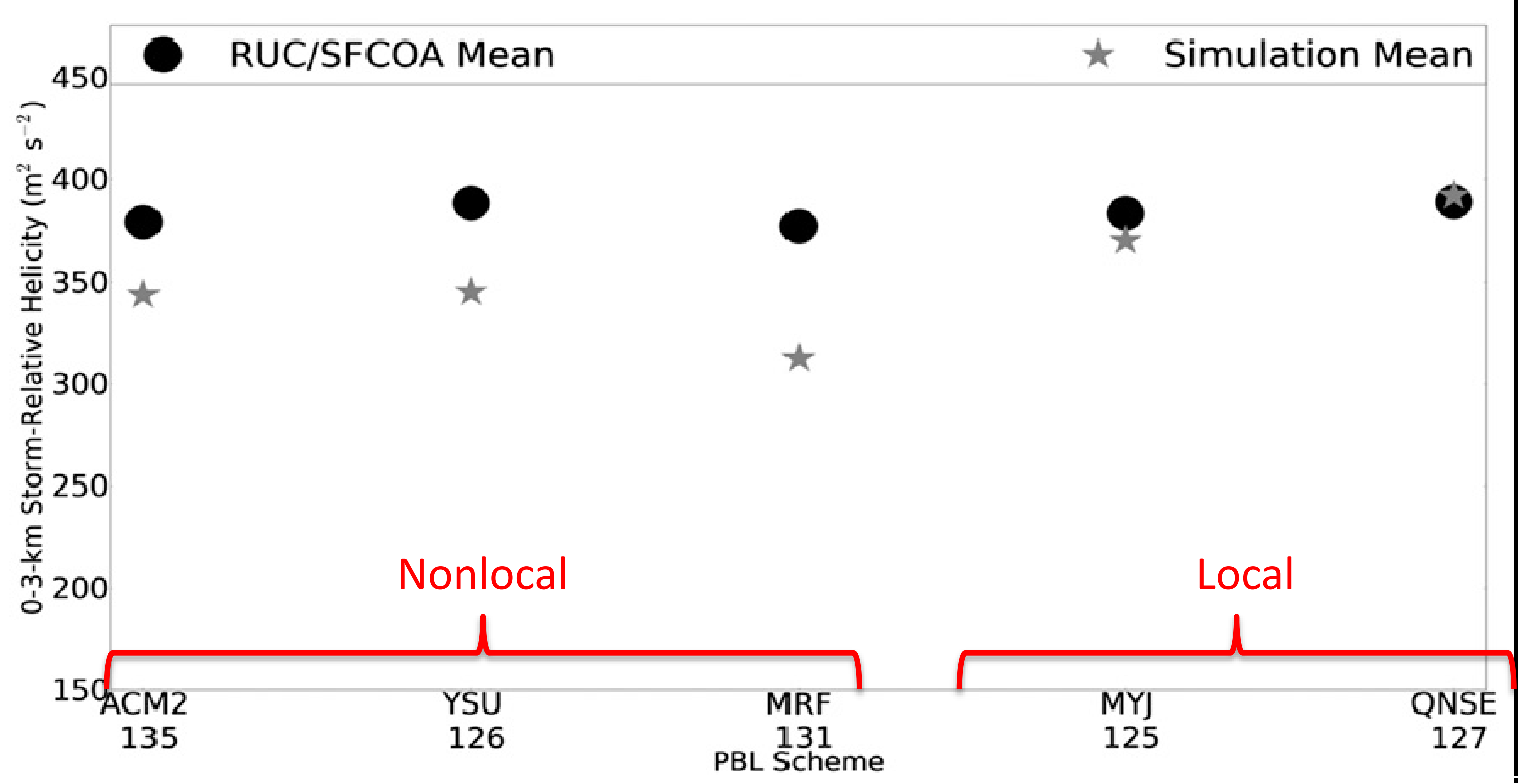
FIG. 14. Convective (shaded areas) and large-scale (dotted lines) rainfall (mm) ending at 1200 UTC 17 May 1995 for (a) the local and nonlocal experiments with (b) $\mathrm{Rib}_{cr} = 0.25$, (c) $\mathrm{Rib}_{cr} = 0.50$, and (d) $\mathrm{Rib}_{cr} = 0.75$.

Hong and Pan (1996)

Thermodynamics isn’t the whole story

- Previous case from paper introducing nonlocal PBL scheme

- Shear also important to convective evolution
  - How do local and nonlocal schemes typically handle shear in a convective environment?



Mean values of simulated and RUC–SFCOA-derived 0–3-km Storm Relative Helicity among all PBL schemes. Sample sizes along abscissa. The black circles denote RUC–SFCOA values, whereas the gray stars denote simulation values. Note that minor differences in simulation means are explained by differences in analyzed times among corresponding PBLs (owing to variability in which soundings are convectively contaminated). (Cohen et al. 2013)

- Nonlocal schemes have a low shear bias relative to local schemes in convective boundary layers

Braun and Tao (2000)

- MRF nonlocal scheme produced wider, weaker storm than other local schemes
- “Braun and Tao (2009) did identify differences among the four schemes, with the MRF scheme identified as producing a weaker storm than the other three, with an unrealistically deep and dry boundary layer. This study led to a community-wide bias against using the MRF scheme for hurricane simulations. Early tests of WRF simulations using the MRF and then later the YSU schemes did show favorable results (Nolan and Tuleya 2002; Nolan et al. 2004). These discrepancies indicate the importance of evaluating PBL schemes and other parameterizations on a model-by-model basis.” –Nolan et al. (2009)

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- Land Surface Physics
  - Observational examples and relevance to NWP
  - Attributes of NCEP land-surface physics (NOAH model)
  - Milestones of land-surface physics upgrades
- PBL Physics
  - Attributes of PBL physics
- Recent Verification of Land-Surface / PBL schemes
- Future Work

Is the Land Surface Important to NWP?

"The atmosphere and the upper layers of soil or sea form together a united system. This is evident since the first few meters of ground has a thermal capacity comparable with 1/10 that of the entire atmospheric column standing upon it, and since buried thermometers show that its changes for temperature are considerable. Similar considerations apply to the sea, and to the capacity of the soil for water. "

L.F. Richardson, 1922
Weather Prediction by Numerical Processes

"Much improved understanding of land-atmosphere interaction and far better measurements of land-surface properties, especially soil moisture, would constitute a major intellectual advancement and may hold the key to dramatic improvements in a number of forecasting problems, including the location and timing of deep convection over land, quantitative precipitation forecasting in general, and seasonal climate prediction."

National Research Council, 1996

Goals of Improved Land-Surface Physics

Better diurnal cycle of surface heating and evaporation (2 meter TAIR and TDEW)

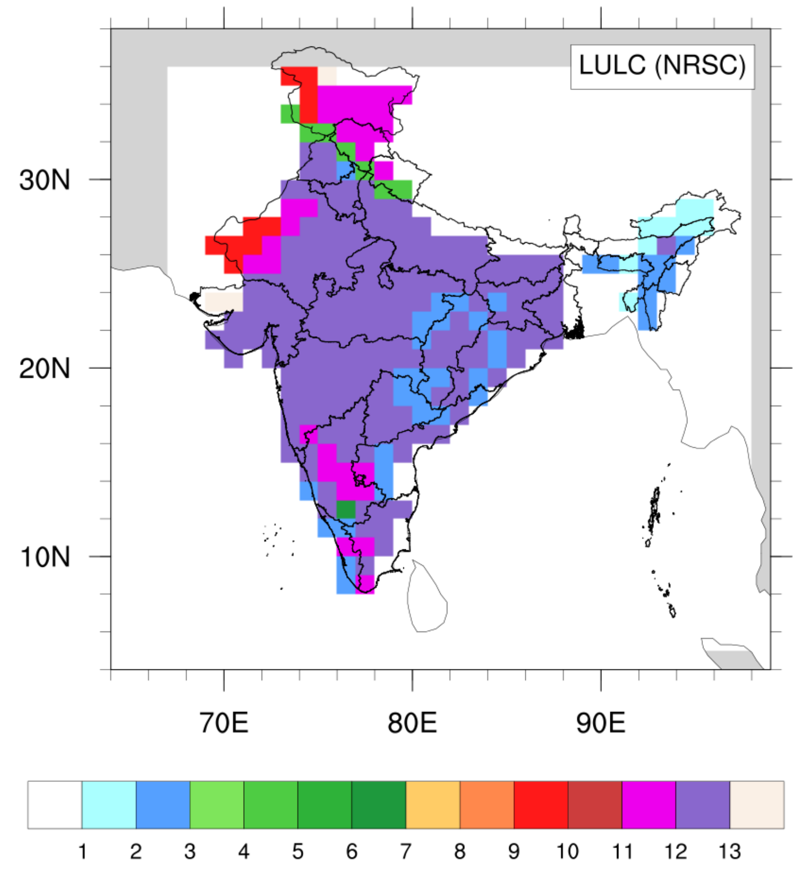
Reproduce diurnal growth and decay of PBL

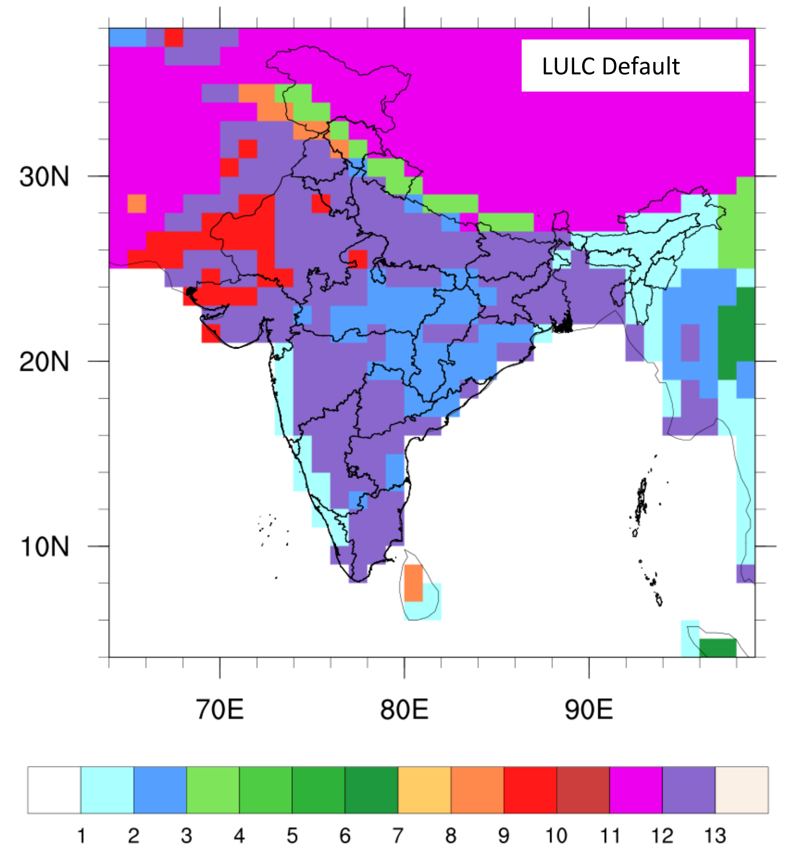
Improved convective index forecasts

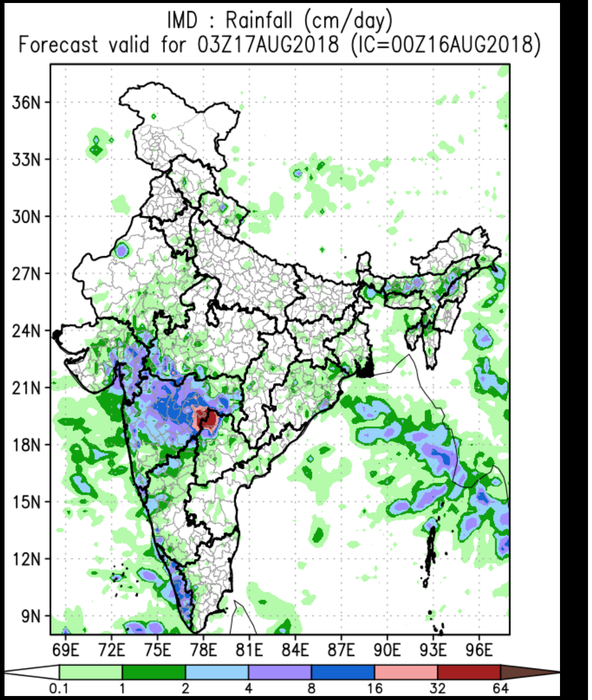
Better QPF

Expand use of model outputs for hydrologic and agricultural applications (runoff, snowmelt, soil moisture and temperature)

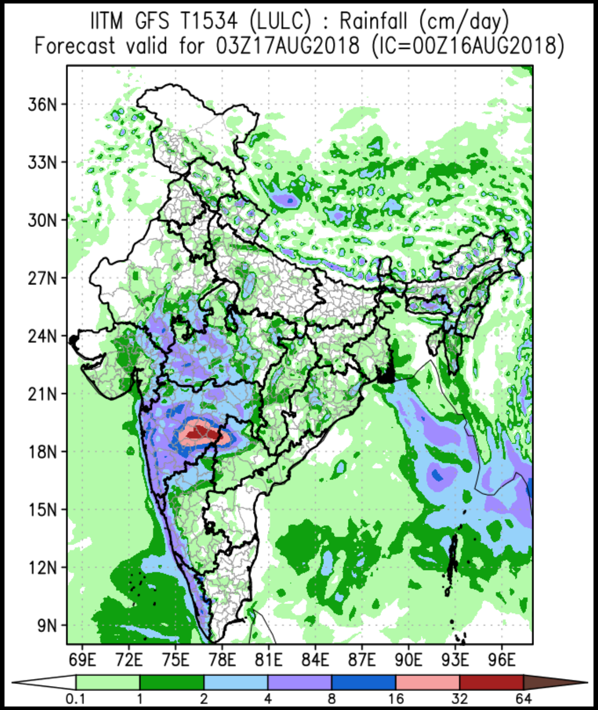
Examples of the influence of land-surface processes on the atmosphere in both models and observations



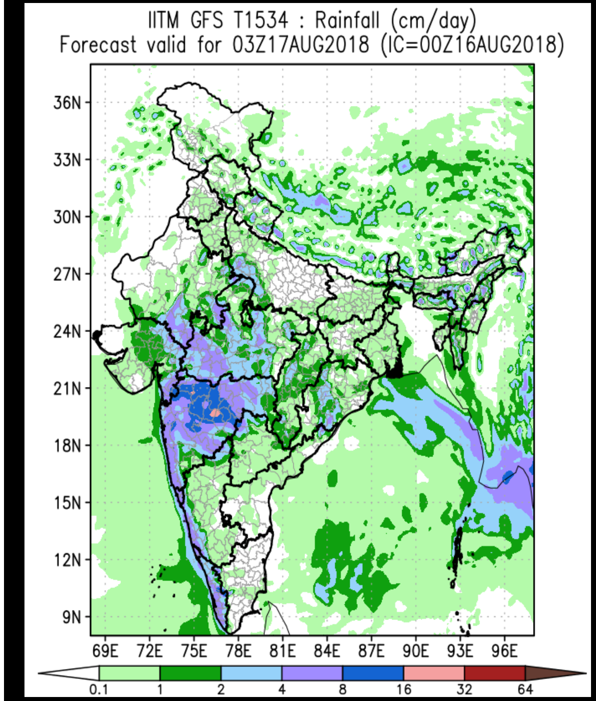




IMD OBS



GFS with Modified LULC



GFS with default LULC

So what does a land-surface scheme do?

- Provides albedo for calculating reflected shortwave radiation
- Calculates evapotranspiration (latent heat flux) from soil and vegetation canopy
- Provides ground surface (“skin”) temperature for determining surface sensible heat flux and upward longwave radiation
- Determine impact of snowpack on surface radiation and heat budgets

Land-Surface Physics

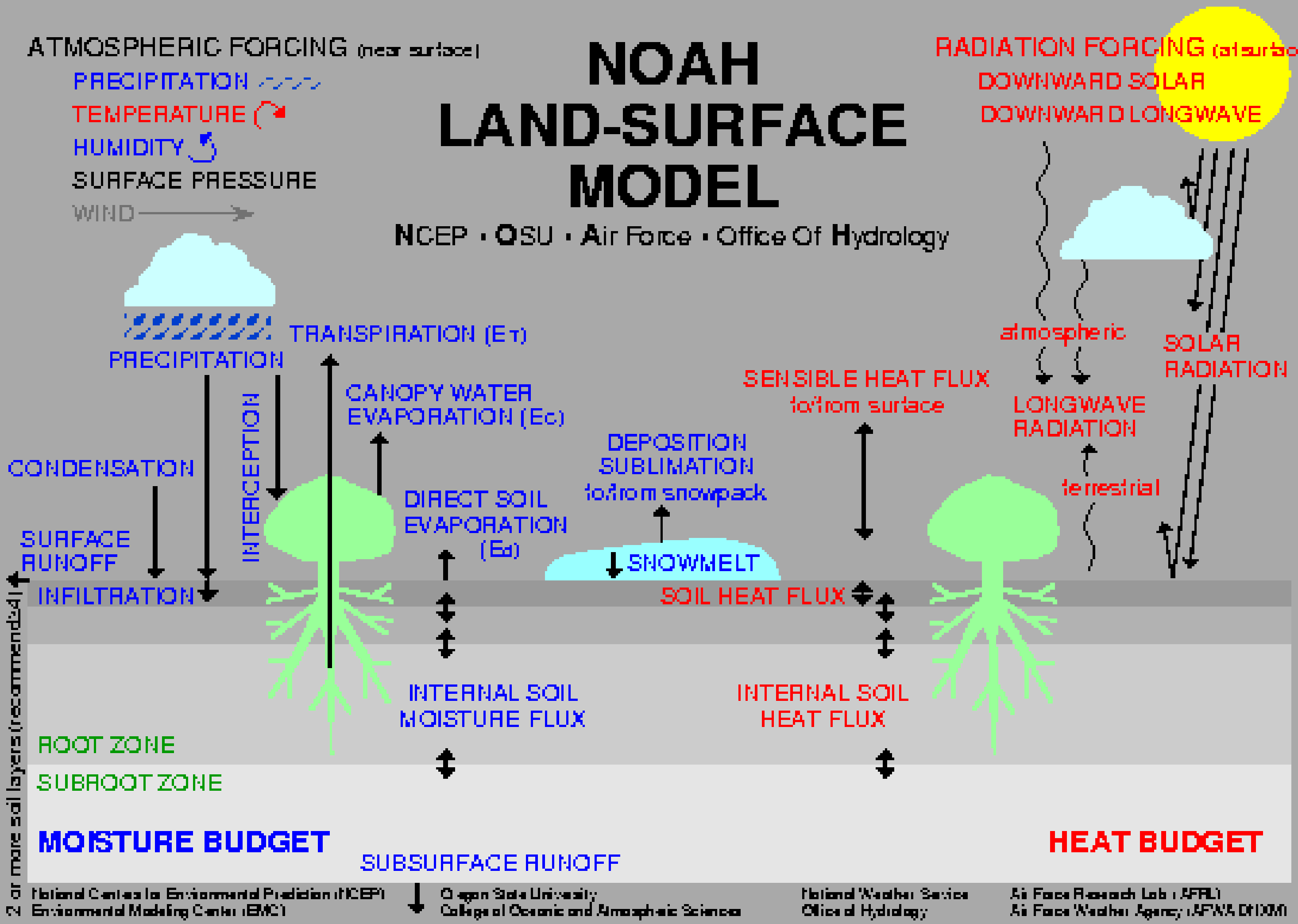
- 4 soil layers (10, 30, 60, 100 cm thick)
  - predict soil moisture/temperature
  - Continuous 3-hour update in fully cycled EDAS
- Explicit vegetation physics
  - 12 vegetation classes over Eta domain
  - annual cycle of vegetation greenness
- Explicit snowpack physics
  - prognostic treatment of snowmelt
  - explicit streamflow routing

NOAH LAND-SURFACE MODEL

NCEP • **O**SU • **A**ir Force • Office Of **H**ydrology

ATMOSPHERIC FORCING (near surface)
- PRECIPITATION
- TEMPERATURE
- HUMIDITY
- SURFACE PRESSURE
- WIND

RADIATION FORCING (at surface)
- DOWNWARD SOLAR
- DOWNWARD LONGWAVE



PRECIPITATION

TRANSPIRATION (E_T)

CONDENSATION

INTERCEPTION

CANOPY WATER EVAPORATION (E_C)

SURFACE RUNOFF

INFILTRATION

DIRECT SOIL EVAPORATION (E_d)

DEPOSITION SUBLIMATION to/from snowpack

SNOWMELT

SENSIBLE HEAT FLUX to/from surface

atmospheric

LONGWAVE RADIATION

terrestrial

SOLAR RADIATION

SOIL HEAT FLUX

INTERNAL SOIL MOISTURE FLUX

INTERNAL SOIL HEAT FLUX

ROOT ZONE

SUBROOT ZONE

2 or more soil layers (recommend 4)

MOISTURE BUDGET

SUBSURFACE RUNOFF

HEAT BUDGET

National Centers for Environmental Prediction (NCEP)
Environmental Modeling Center (EMC)

Oregon State University
College of Oceanic and Atmospheric Sciences

National Weather Service
Office of Hydrology

Air Force Research Lab (AFRL)
Air Force Weather Agency (AFWA DNXM)

STATE VARIABLES

- SKIN TEMPERATURE
- SOIL TEMPERATURE
- SOIL WATER
- SOIL ICE
- CANOPY WATER
- SNOW WATER
- SNOW DENSITY

SURFACE PARAMETERS

- VEGETATION TYPE
- GREEN VEGETATION FRACTION
- SOIL TEXTURE
- ROUGHNESS
- ALBEDO
- SLOPE FACTOR

Key Assumption: Surface Energy Balance:

$$Rn = H + LE + G$$

Rn = Net Radiation

H = Surface Sensible Heat Flux

LE = Surface Latent Heat Flux

G = Soil (Ground) Heat Flux

$$Rn - G = H + LE$$

"Available Energy" for Turbulent Fluxes

Prognostic Equations

Soil Moisture:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(D \frac{\partial \theta}{\partial z} \right) + \frac{\partial K}{\partial z} + F_{\theta}$$

– “Richard’s Equation” for soil water movement

– D, K functions (soil texture)

– F_{θ} represents sources (rainfall) and sinks (evaporation)

Soil Temperature

$$C(\theta)\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(K_t(\theta) \frac{\partial T}{\partial z} \right)$$

– C, Kt functions (soil texture, soil moisture)

– Soil temperature information used to compute ground heat flux

Evapotranspiration Treatment

$$E = E_{dir} + E_t + E_c$$

WHERE:

E = total evapotranspiration from combined soil/vegetation

E_{dir} = direct evaporation from soil

E_t = transpiration through plant canopy

E_c = evaporation from canopy-intercepted rainfall

Evapotranspiration (continued)

- These terms represent a flux of moisture, that can be parameterized in terms of “resistances” to the “potential” flux. Borrowing from electrical physics (Ohm’s Law):

FLUX = POTENTIAL/RESISTANCE

- Potential ET can roughly be thought of as the rate of ET from an open pan of water. In the soil/vegetation medium, what are some resistances to this?
  - Available amount of soil moisture
  - Canopy (stomatal) resistance: function of vegetation type and amount of green vegetation)
  - atmospheric stability, wind speed

Canopy Resistance Issues

Canopy transpiration determined by:

- – Amount of photosynthetically active (green) vegetation. Green vegetation fraction (σf) partitions direct (bare soil) evaporation from canopy transpiration:

$$Et/Edir \approx f(\sigma f)$$

- – Green vegetation in Eta based on 5 year NDVI climatology of monthly values
- – Not only the amount, but the TYPE of vegetation determines canopy resistance (Rc):

$$R_c = \frac{R_{c\,\min}}{LAI\, F_1 F_2 F_3 F_4}$$

Canopy Resistance (continued)

- Where:

Rcmin ≈ f(vegetation type)

F1 ≈ drying power of the sun

F2, F3 ≈ drying power of the air mass

F4 ≈ soil moisture stress

- Thus: hot air, dry soil, and strong insolation lead to stressed vegetation!
- Eta model uses database of 12 separate vegetation classes

Thank you