

# **The Fifth-Generation NCAR / Penn State Mesoscale Model (MM5)**



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# Outline

- Basic Dynamical Equations
- Numerical Methods
- Initialization & Boundary Conditions
- MM5 Physics
- Data Assimilation
- Model Verification

# X, Y, $\sigma$ Coordinate System

- $p = p_0 + p'(x, y, \sigma, t)$
- $\rho = \rho_0 + \rho'(x, y, \sigma, t)$
- $T = T_0 + T'(x, y, \sigma, t)$
- $\sigma = (p_0 - p_t) / p^*$  where  $p^*(x, y) = (p_s - p_t)$ 
  - $p^*$  is a function of only topography

# Nonhydrostatic Momentum Equations

U:

$$\frac{\partial u}{\partial t} + \frac{m}{\rho} \left( \frac{\partial p'}{\partial x} - \frac{\sigma}{p^*} \frac{\partial p'}{\partial x} \frac{\partial p'}{\partial \sigma} \right) = -\mathbf{V} \cdot \nabla u + v \left( f + u \frac{\partial m}{\partial y} - v \frac{\partial m}{\partial x} \right) - ew \cos \alpha - \frac{uw}{r_{earth}} + D_u$$

Sloped  $\sigma$  terms

Subgrid scale eddy terms

V:

$$\frac{\partial v}{\partial t} + \frac{m}{\rho} \left( \frac{\partial p'}{\partial y} - \frac{\sigma}{p^*} \frac{\partial p'}{\partial y} \frac{\partial p'}{\partial \sigma} \right) = -\mathbf{V} \cdot \nabla v - u \left( f + u \frac{\partial m}{\partial y} - v \frac{\partial m}{\partial x} \right) + ew \sin \alpha - \frac{vw}{r_{earth}} + D_v$$

W:

$$\frac{\partial w}{\partial t} + \frac{\rho_0 g}{\rho p^*} \frac{\partial p'}{\partial \sigma} + \frac{g p'}{\gamma p} = -\mathbf{V} \cdot \nabla w + g \frac{p_0 T'}{p T_0} - \frac{g R_d p'}{c_p p} + e(u \cos \alpha - v \sin \alpha) + \frac{u^2 + v^2}{r_{earth}} + D_w$$

# Nonhydrostatic Pressure and Temperature Equations

Pressure:

$$\frac{\partial p'}{\partial t} - \rho_0 g w + \gamma p \nabla \cdot \mathbf{V} = -\mathbf{V} \cdot \nabla p'$$

Temperature:

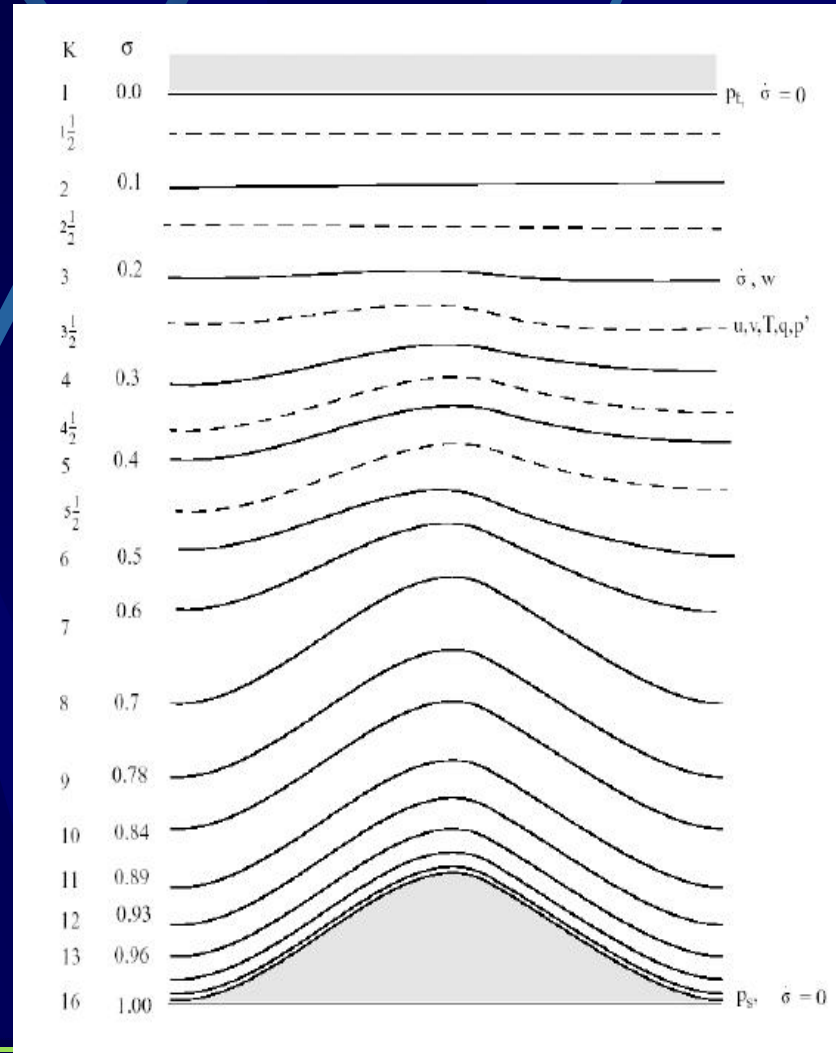
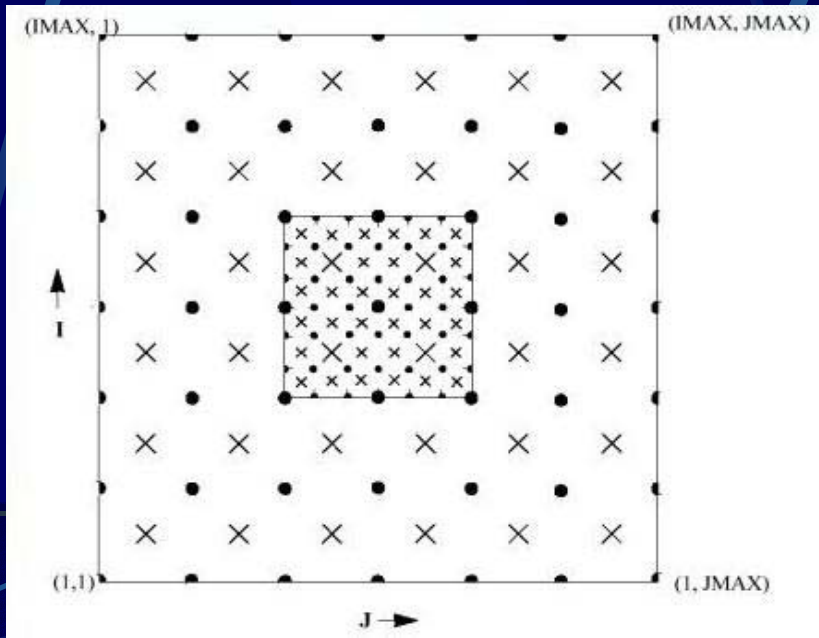
$$\frac{\partial T}{\partial t} = -\mathbf{V} \cdot \nabla T + \frac{1}{\rho c_p} \left( \frac{\partial p'}{\partial t} + \mathbf{V} \cdot \nabla p' - \rho_0 g w \right) + \frac{\dot{Q}}{c_p} + \frac{T_0}{\theta_0} D_\theta$$

Ideal gas Law:  $p = \rho R_d T_v$

Diabatic Heating

# Grid

- Horizontal Spacing
  - 500 m through 200 km
- Arakawa B Grid
  - U,V (dot) staggered with P,T,q (cross)
- Vertical Velocity Staggered



# Equation Solution

## ● Spatial Differencing

- Centered In Space
- Precipitation Fall terms Use Forward Upstream
  - Prevent Negative Values

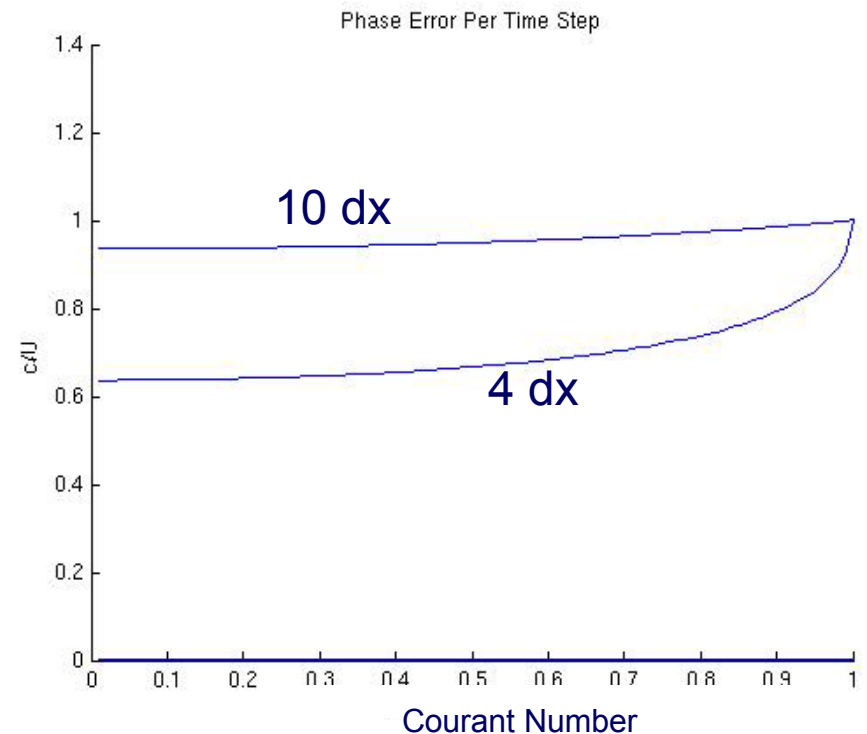
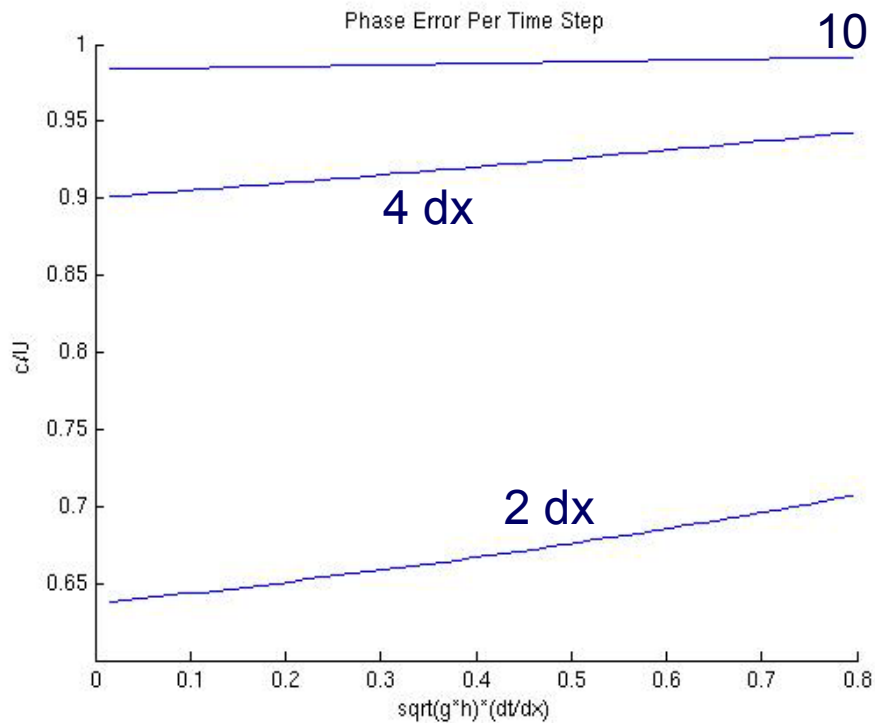
## ● Time Split Method

- Long Time Step Uses Leap Frog
  - Advection, Coriolis, Diffusion
- Short Time Step Uses Forward In Time
  - U,V Advanced First Explicitly
  - W,P` Advanced After
- Asselin Time Filter Applied every large time step
  - $T^{n-1} = T^{n-1} + 0.1*(T^{n-2} - 2T^{n-1} + T^n)$

# Error in Finite Difference Scheme

PGF: Forward in Time

Advection: Leap Frog



# Nesting

- 1 and 2 Way Nesting

- 2 Way Nesting

- Requires a 3:1 ratio

- 3 Methods

- Nest Interpolation

- Initialized by interpolating coarse-mesh grid

- Nest Analysis Input

- Initialized with a fine resolution topographic and initial condition file

- Nest Terrain Input

- Interpolate IC from coarse-mesh grid
- Terrain input from fine-mesh input file

# MM5 Initialization

- Objective analysis
- Dynamic initialization (Integrated divergence removal)
- Data Assimilation (FDDA or 3DVAR)

# Lateral Boundary Condition

- Fixed
- Time-dependent/Nest
- Relaxation/inflow-outflow

# Vertical Boundary Conditions

- Upper Boundary Condition

  - Rigid lid:  $w = 0$  at top

  - Radiative:  $w$  is a function of  $p'$  at top

- Lower Boundary Condition

  - Dataset (SST, substrate temperature, snow cover, sea-ice) (Fixed or Time-dependent)

  - Terrain-following flow conditions

# MM5 Physics

- Cumulus Parameterizations
- Explicit Moisture/Microphysics
- Planetary Boundary Layer/Vertical Diffusion
- Radiation
- Land Surface Model

# Cumulus Parameterizations

## None

- $\Delta x$  5-10 km

## Anthes-Kuo

- $\Delta x > 30$  km
- Moisture Convergence Closure

## Arakawa-Schubert

- Entrainment into updrafts
- Downdrafts

## Grell

- $\Delta x$  10-30 km
- Based on quasi equilibrium
- Single cloud closure scheme

## Shallow Cumulus

- Based on Grell
- Non-precipitating clouds

## Fritsch-Chappell

- $\Delta x$  10-30 km
- Based on relaxation to a profile
- Fixed entrainment

## Kain-Fritsch

- Based on removal of buoyant energy over given time
- Variable entrainment

## Kain-Fritsch 2

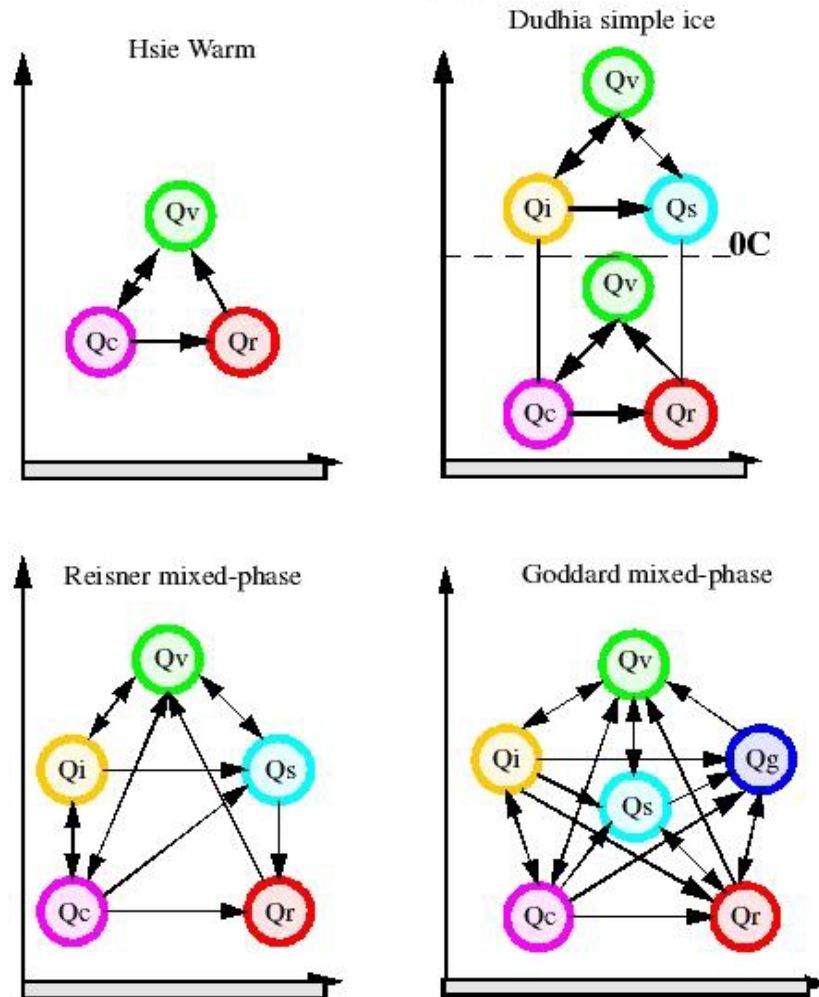
- Includes shallow convection

## Betts-Miller

- Relax to adjust to post-convective thermodynamic profile over given time
- No explicit downdrafts/updrafts

# Illustration of Microphysics Processes

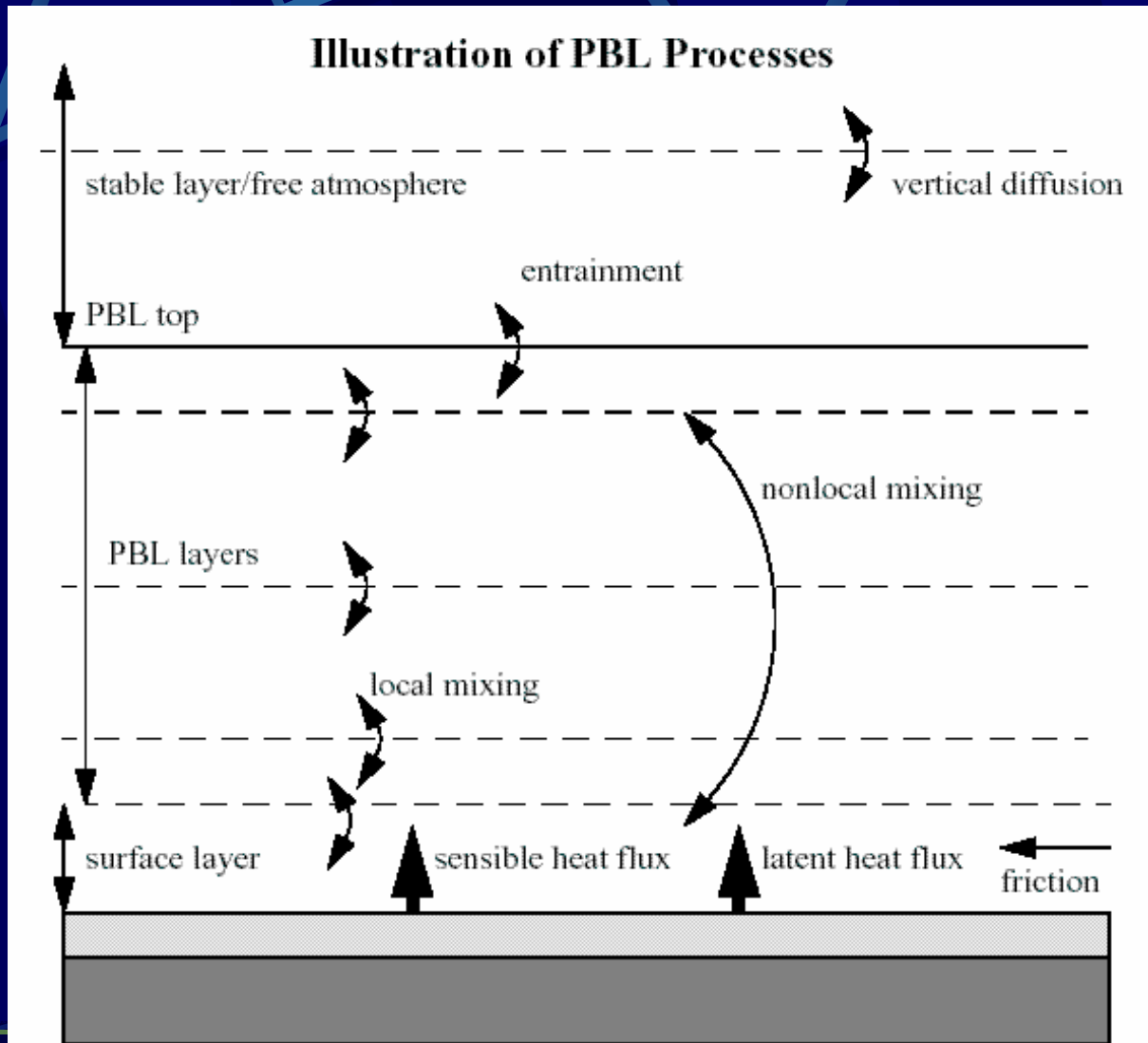
Illustration of Microphysics Processes



# Explicit Moisture/Microphysics

- Dry
  - No Moisture
- Stable
  - Removal of supersaturation
  - No explicit clouds
- Warm rain
  - No Ice phases
- Simple Ice
  - Immediately freeze/melt at 0°C
  - Look up table
- Reisner 1 Mixed Phase
  - Supercooled Liquid
  - Gradual Snow Melt
  - Look up table
- Goddard
  - Includes graupel and hail
- Reisner 2
  - Includes graupel
  - Predicts cloud ice number concentration
- Schultz
  - Simple tuneable equations
  - Includes graupel

# Illustration of PBL Processes



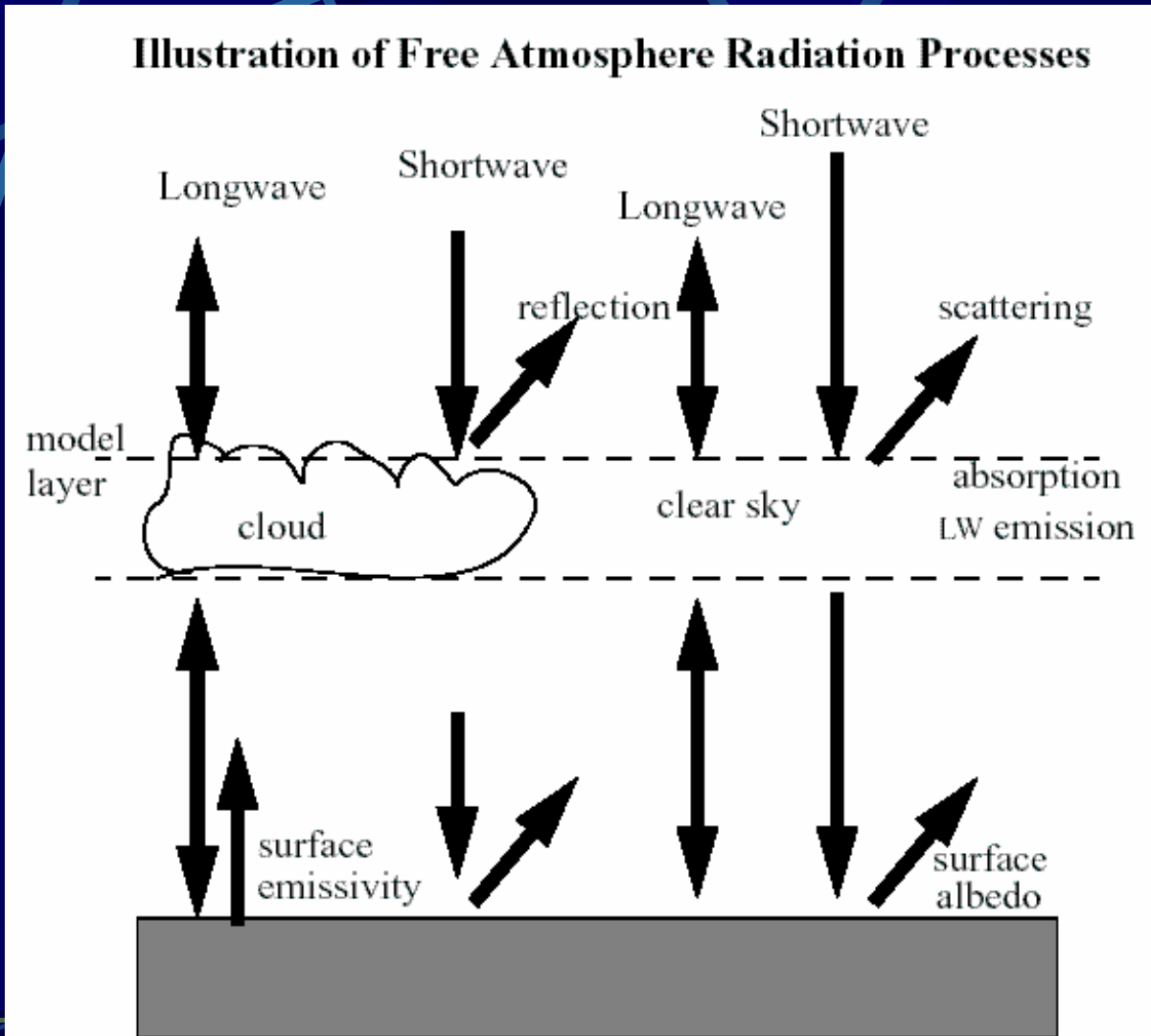
# PBL Process Parameterization

- Represent sub-grid vertical fluxes due to turbulence.
- Mostly distinguished by treatment of the unstable boundary layer.
- Generally provide column tendencies of heat, moisture and momentum and may provide cloud tendencies
- Interacts with fluxes from surface scheme
- Provides frictional effects on momentum

# PBL Schemes (Options)

- Bulk formula
- High-Resolution Blackadar scheme
- MRF scheme <OSU-LSM>
- Burk-Thompson (Mellor-Yamada 1.5-order/level-2.5 scheme)
- Eta TKE scheme <OSU-LSM (v3.5)>
- Gayno-Seaman scheme
- Pleim-Chang scheme <Pleim-Xiu LSM>

# Illustration of Radiation Processes



# Radiation Schemes

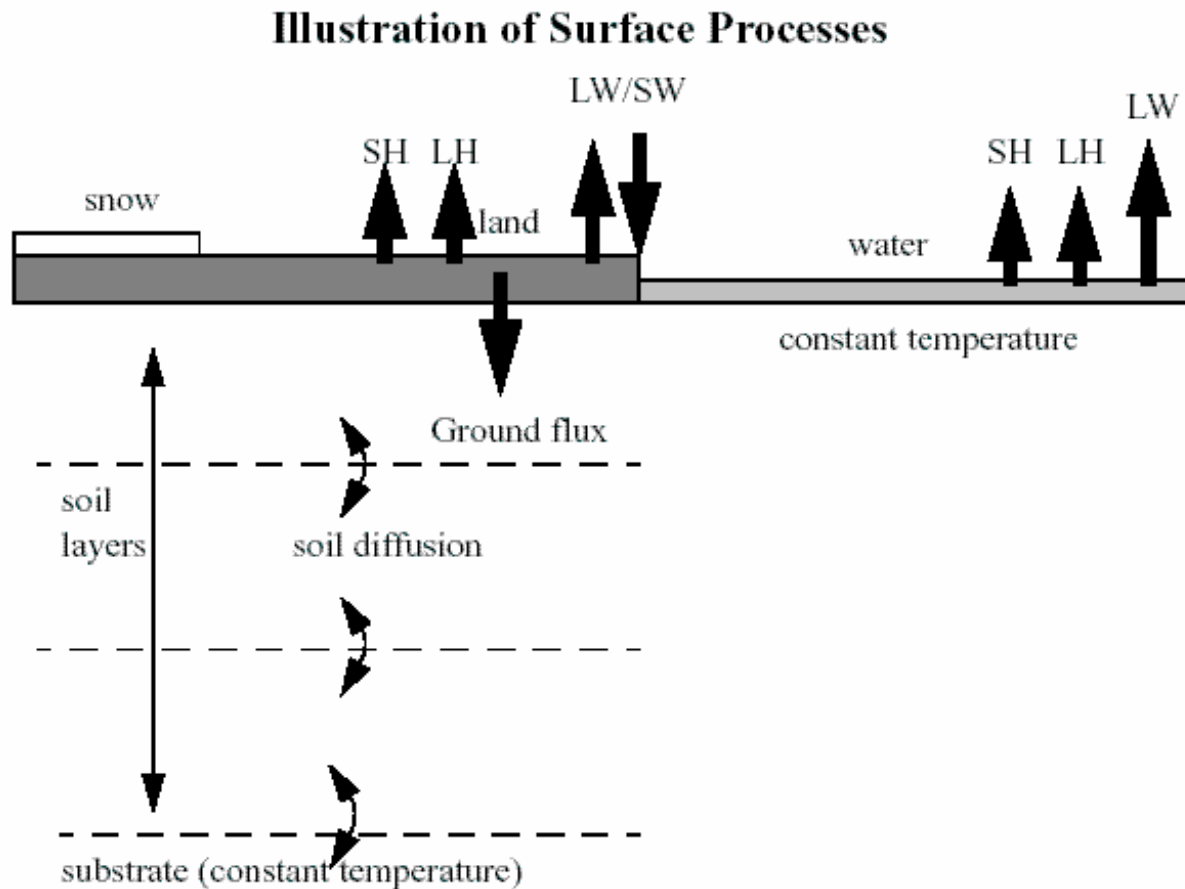
- Represent radiative effects in atmosphere and at surface
- Provides surface downwelling longwave and shortwave fluxes for surface scheme
- Provides column temperature tendencies due to vertical radiative flux divergence
- May interact with model clouds or relative humidity

# Radiation Schemes (Options)

- None (Surface radiation)
- Simple cooling (Surface radiation)
- Dudhia's long and short-wave radiation scheme (Cloud Radiation)
- NCAR/CCM2 radiation scheme
- RRTM long-wave radiation scheme (V3 only)

(Dudhia 1989; Hack et al. 1993; Mlawer et al., 1997)

# Illustration of Surface Processes



# Land Surface Schemes

- Represent effects of land and water surfaces
- May also represent sub-soil temperature and moisture profiles
- Ground temperature based on heat budget using radiative fluxes and surface-layer atmospheric properties
- Provides sensible and latent heat flux
- May provide snow-cover tendencies and surface moisture availability variation

# Land Surface Schemes (Options)

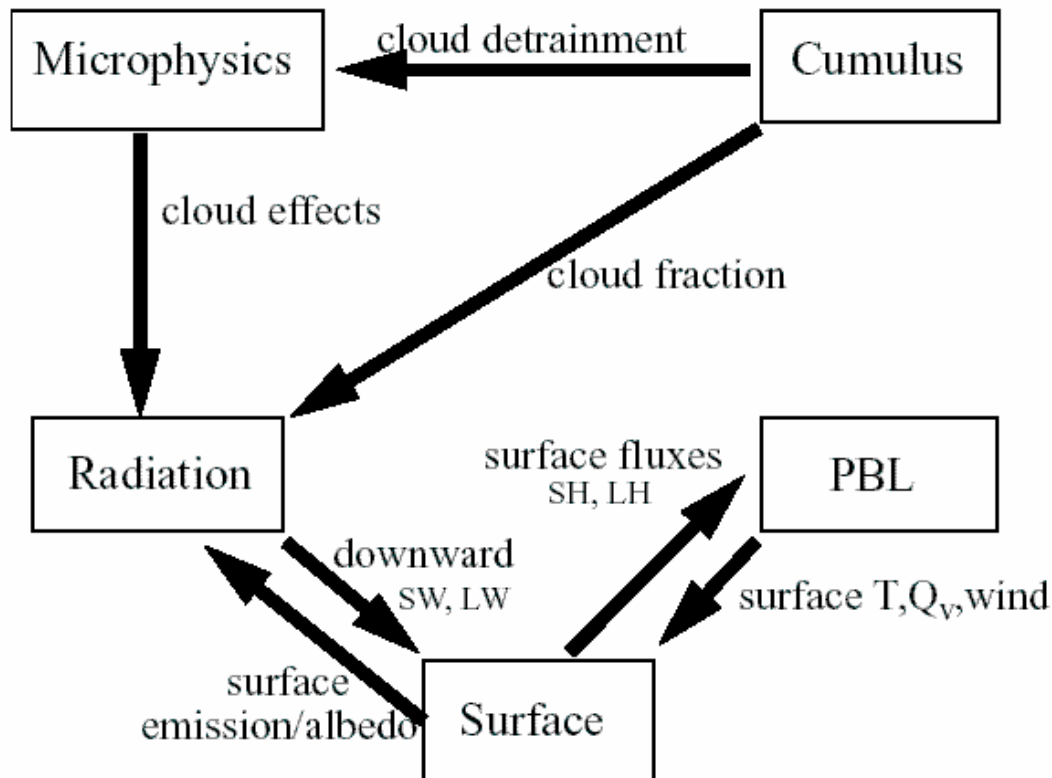
- Force-restore (Blackadar)
- Five-layer Soil Temperature
- Oregon State University/Eta LSM (V3.1 - V3.5)
- NOAA Land Surface Model (since V3.6)
- Pleim-Xiu LSM (V3 only)

# Four-Dimensional Data Assimilation (FDDA)

- Newtonian relaxation or “nudging”
- Three primary uses for FDDA:
  - Dynamical initialization
  - Four-dimensional dataset (e.g. for air quality model)
  - Boundary conditions (outer domain nudged towards analysis)
- Two methods of data assimilation:
  - Grid or analysis nudging
  - Observation or station nudging

# Interactions of Parameterizations

Direct Interactions of Parameterizations



# Verification

- IC and BC from NCEP model analysis and forecast grid
- $\Delta x = 27$  km, with 27  $\sigma$  levels

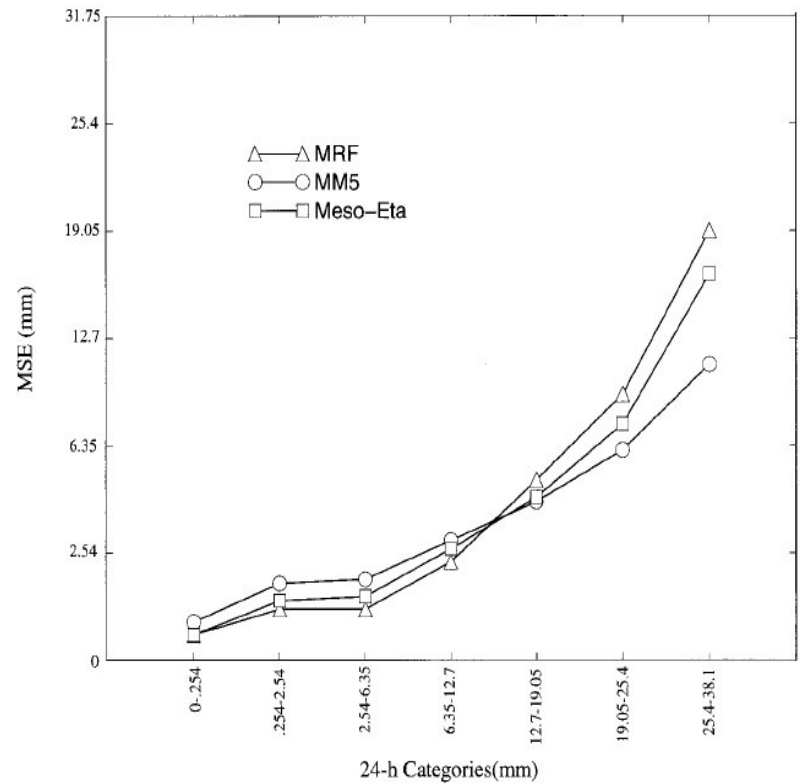


FIG. 8. Precipitation mse analysis for 24-h period ending at the 36-h forecast during the months of Oct, Nov, and Dec, 1997. Models verified are the MRF, Meso Eta, and MM5.

# Verification

- Initialized from satellite measurements
- SST updated daily

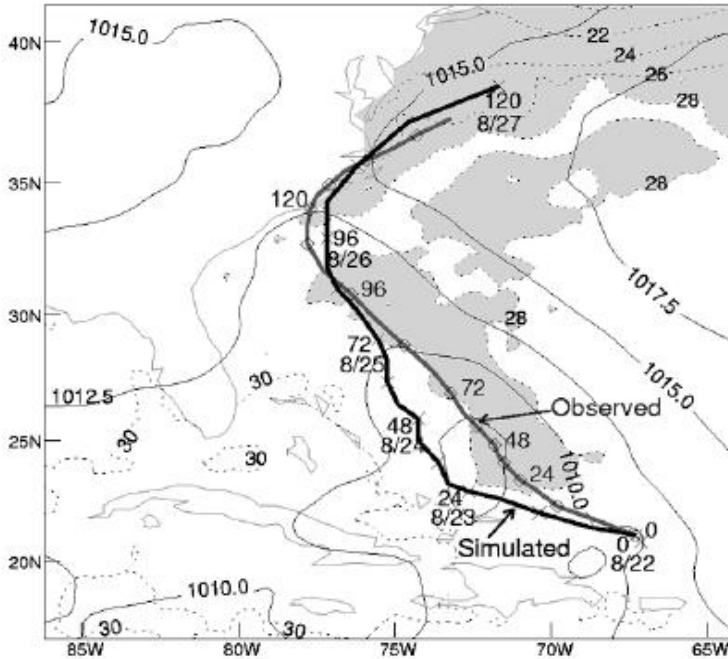


FIG. 2. Tracks (6 h) of Bonnie from the best analyses (light thick lines) and the model simulation (dark thick lines), superposed with the 5-day (0000 UTC 22–0000 UTC 27 Aug) averaged sea level pressure (solid lines) and SST (dotted, with its value of less than 28°C shaded).

(Zhu et al. 2004)

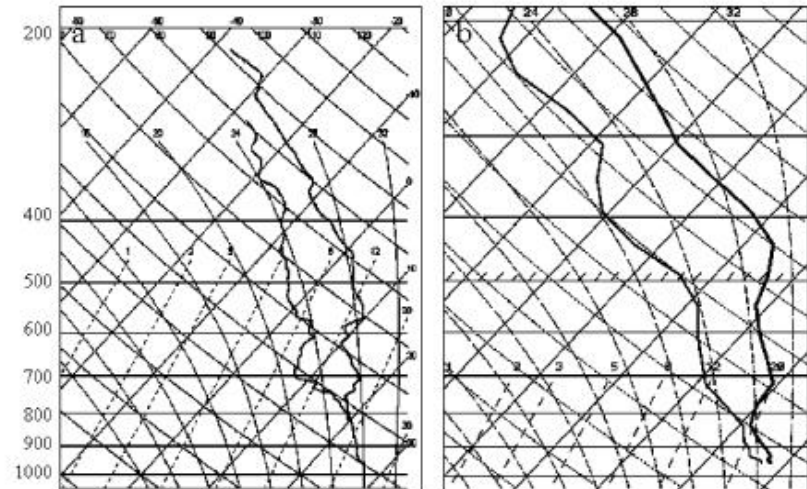


FIG. 4. (a) Dropsonde released by DC-8 aircraft in the eye of Hurricane Bonnie at 2126 UTC 23 Aug (see Fig. 7a for its location) and (b) a simulated sounding at the eye center at 2130 UTC 23 Aug 1998 (see Fig. 7b later for its location).

- MM5 model users website:  
<http://www.mmm.ucar.edu/mm5/>
- White, B.G., J. Paegle, W.J. Steenburgh, J.D. Horel, R.T. Swanson, L.K. Cook, D.J. Onton, J.G. Miles, 1998: Short Term Forecast Validation of Six Models. *Weather and Forecasting*, 14, 84-108.
- Zhu, T., D. Zhang, F. Weng, 2004: Numerical Simulation of Hurricane Bonnie (1998). Part 1: Eyewall Evolution and Intensity Changes. *Monthly Weather Review*, 132, 225-242.