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, σ Coordinate System

- $p = p_o + p`(x,y,\sigma,t)$
- $\rho = \rho_o + \rho`(x,y,\sigma,t)$
- $T = T_o + T`(x,y,\sigma,t)$
- $\sigma = (p_o - p_t) / p^*$ 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 σ 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:

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

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:

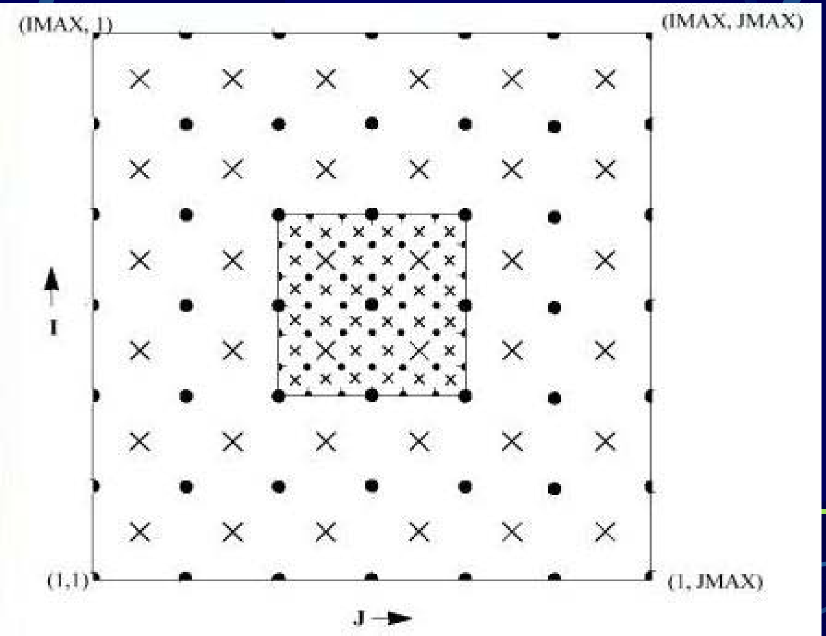
$$\frac{\partial T}{\partial t} = -\mathbf{V} \cdot \nabla T + \frac{1}{\rho c_p}\left(\frac{\partial p'}{\partial t} + \mathbf{V} \cdot \nabla p' - \rho_0 g w\right) + \frac{\dot{Q}}{c_p} + \frac{T_0}{\theta_0} D_\theta$$

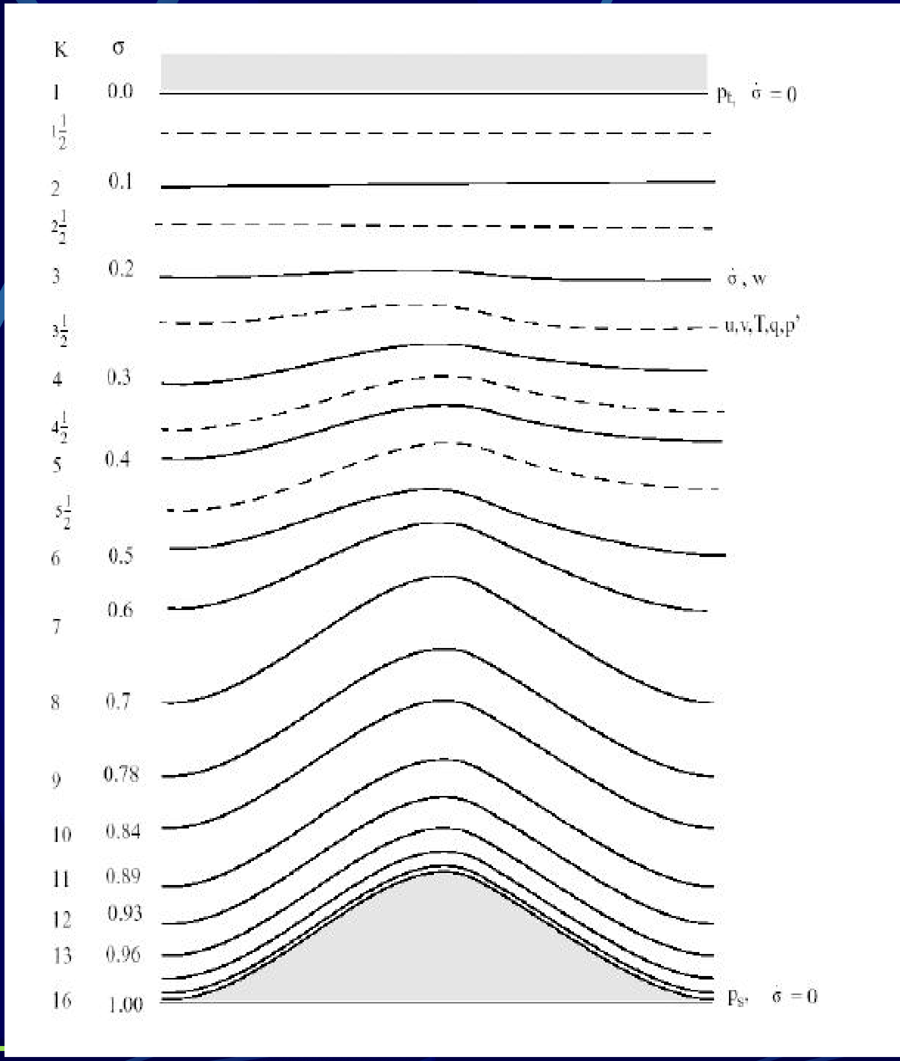
Ideal gas Law: $p = \rho R_d T_v$

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





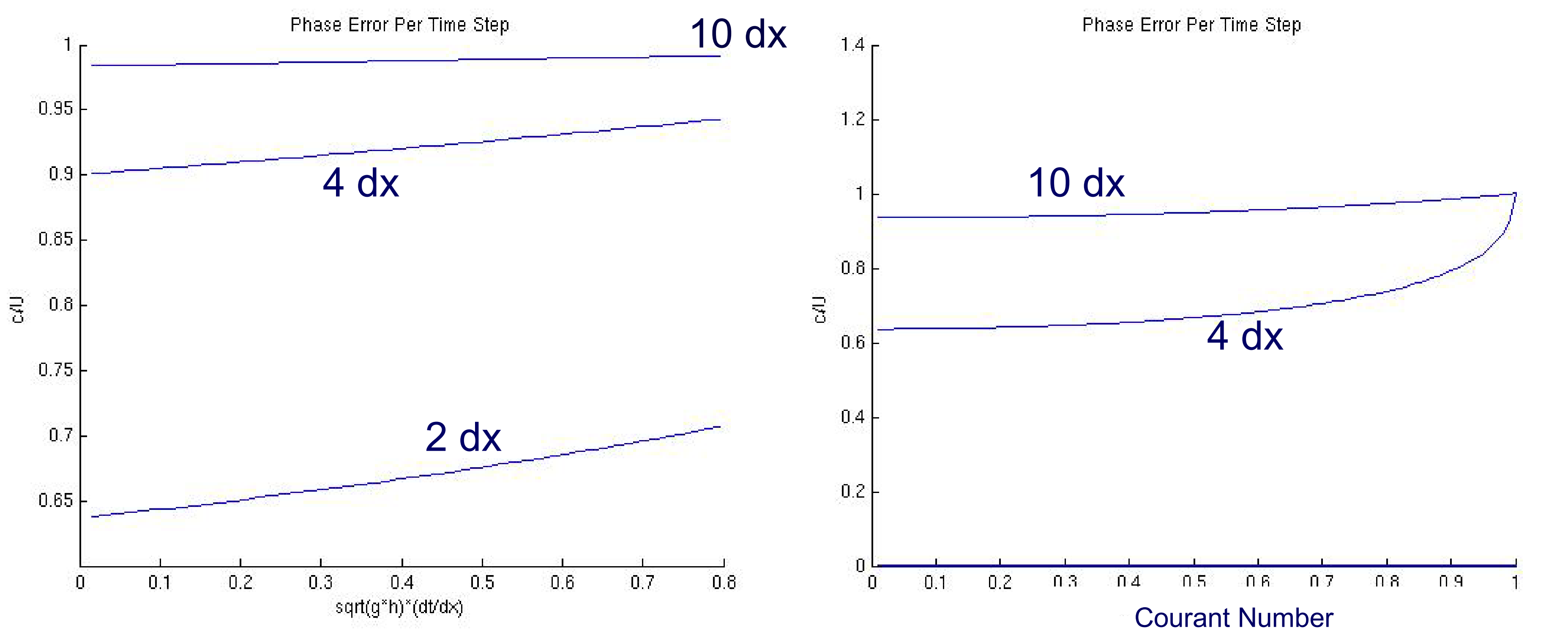
Equation Solution

- **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

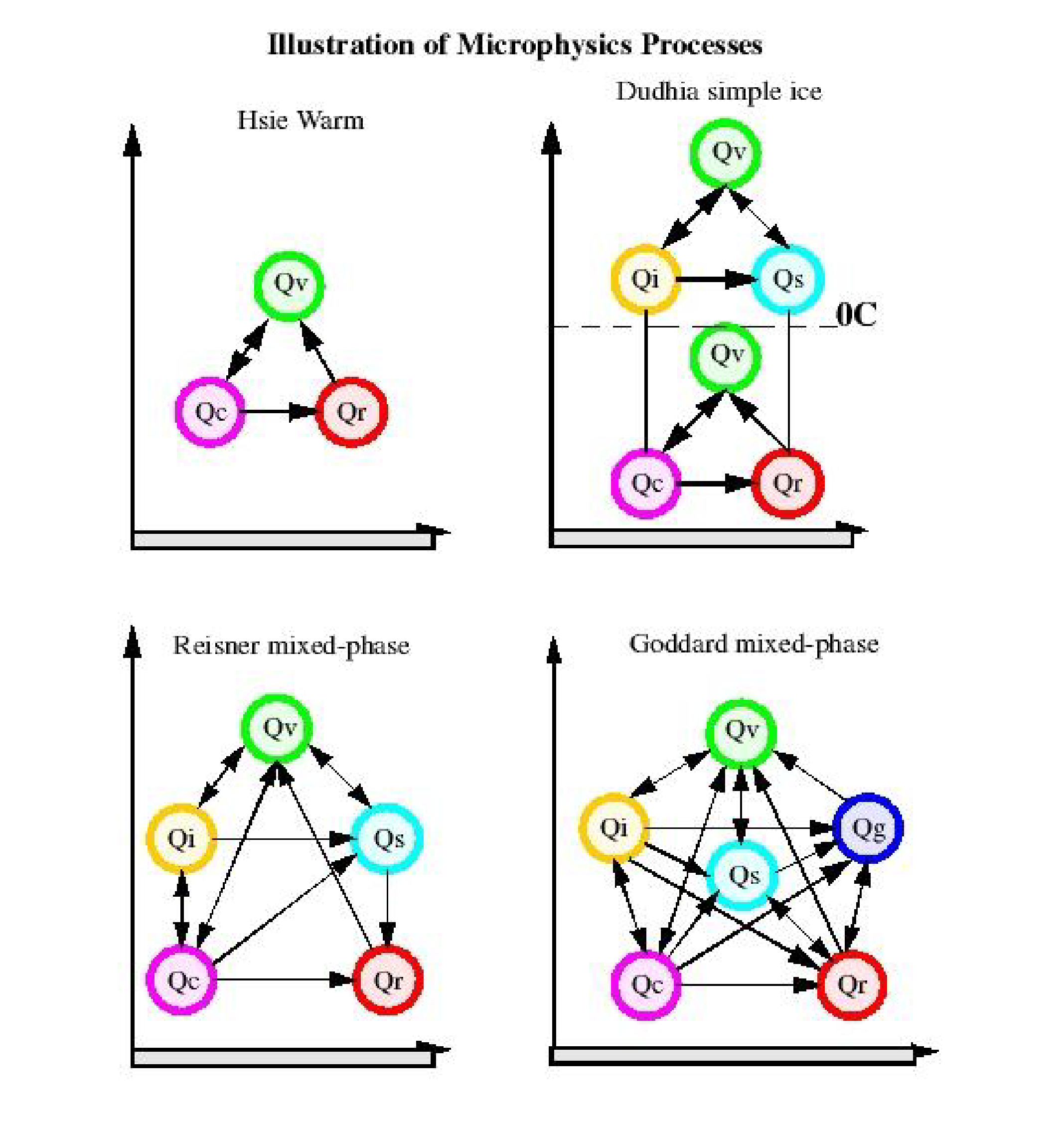
MM5 Physics

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

Cumulus Parameterizations

- None
  - Δx 5-10 km
- Anthes-Kuo
  - Δx > 30 km
  - Moiusture Convergence Closure
- Arakawa-Schubert
  - Entrainment into updrafts
  - Downdrafts
- Grell
  - Δx 10-30 km
  - Based on quasi equilibrium
  - Single cloud closure scheme
- Shallow Cumulus
  - Based on Grell
  - Non-precipitating clouds
- Fritsch-Chappell
  - Δx 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

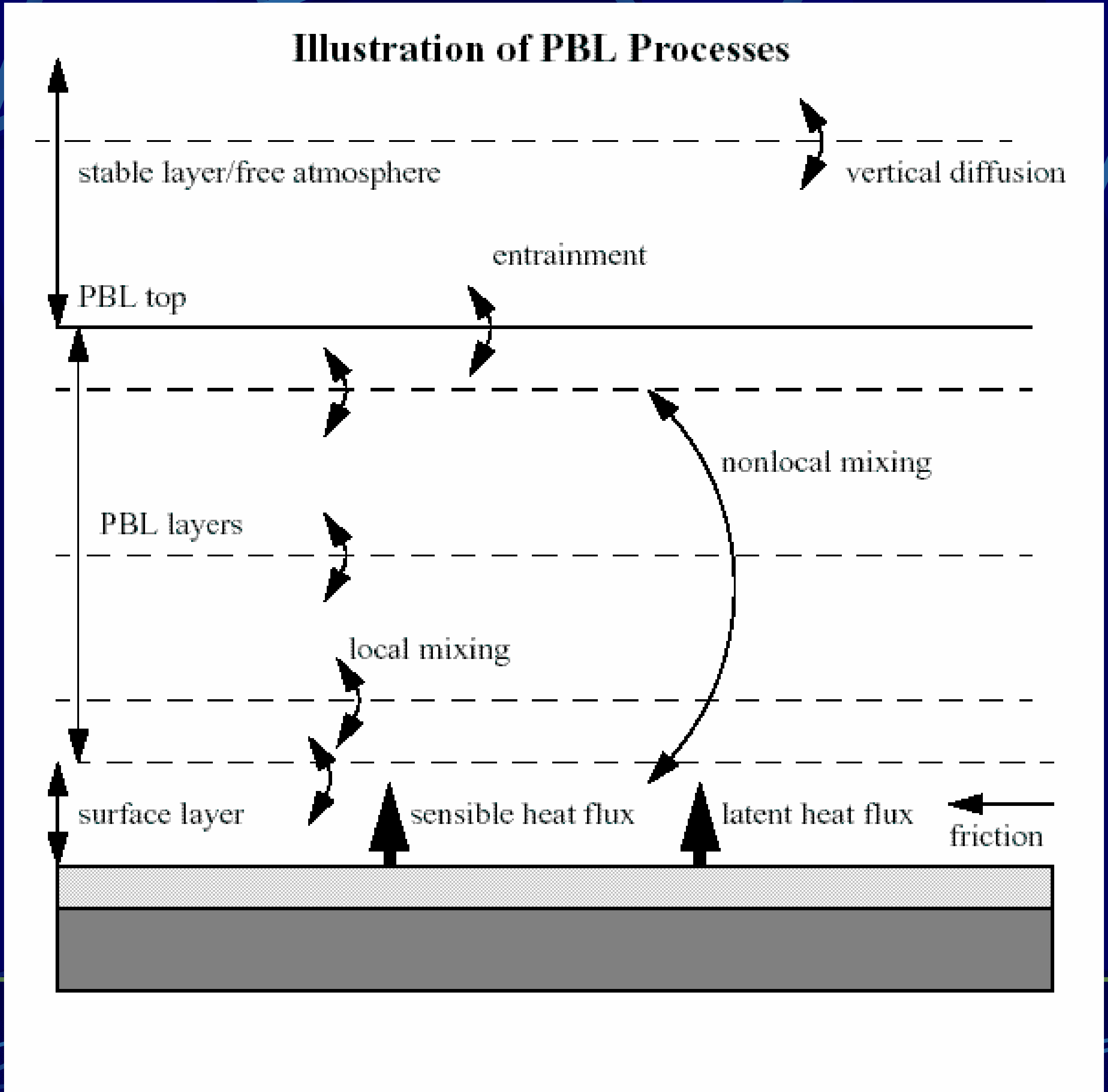
Illustration of Microphysics Processes



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^oC
  - 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

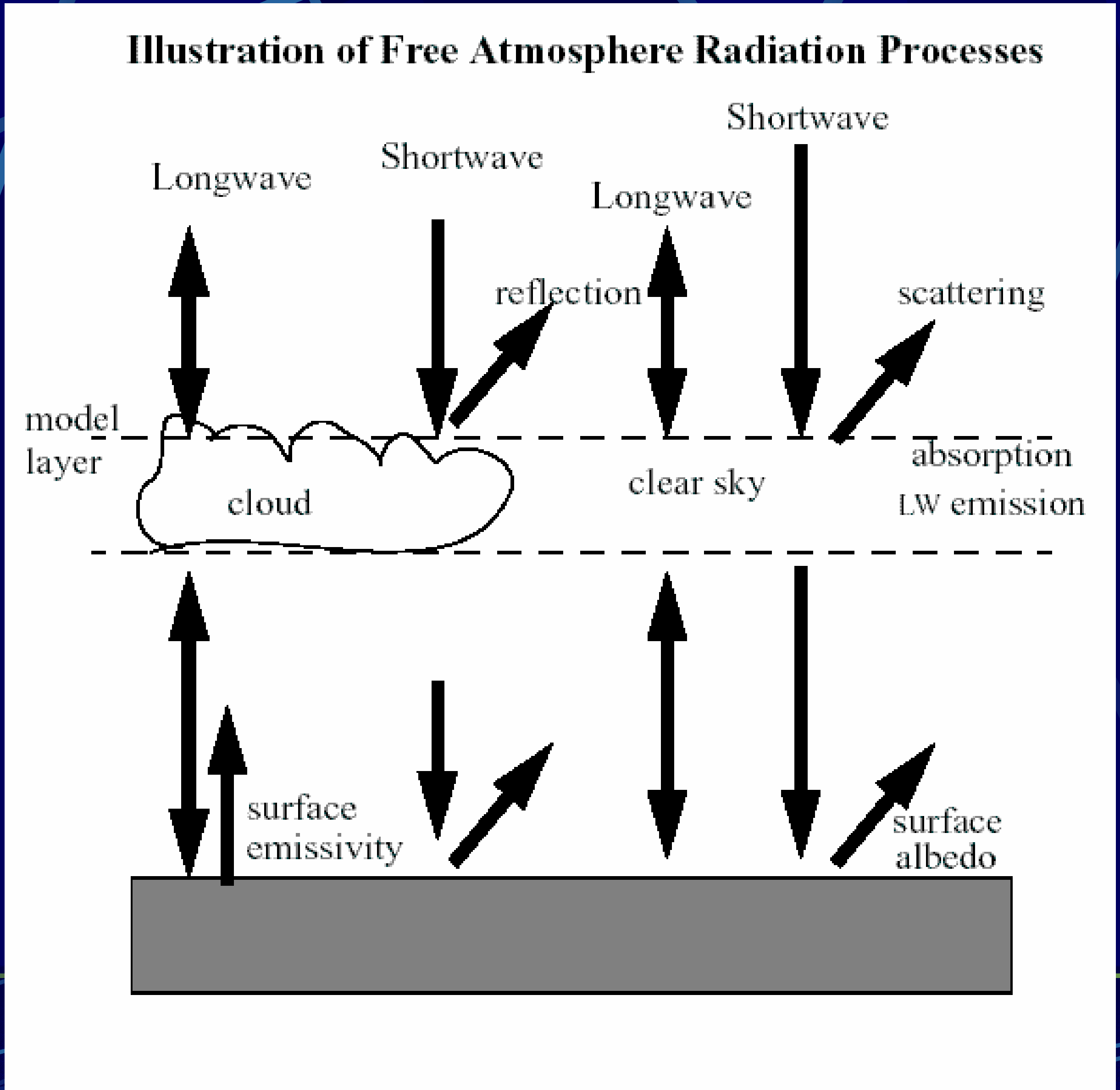
- Represent sub-grid vertical fluxes due to turbulence.
- Mostly distinguished by treatment of the unstable boundary layer.
- Generally provide column tendencies of heat, moisture and momentum and may provide cloud tendencies
- Interacts with fluxes from surface scheme
- Provides frictional effects on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

(Zhang and Anthes 1982; Hong and Pan 1996; Janjic,1990, 1994; Gayno 1994)

Illustration of Radiation Processes



Radiation Schemes

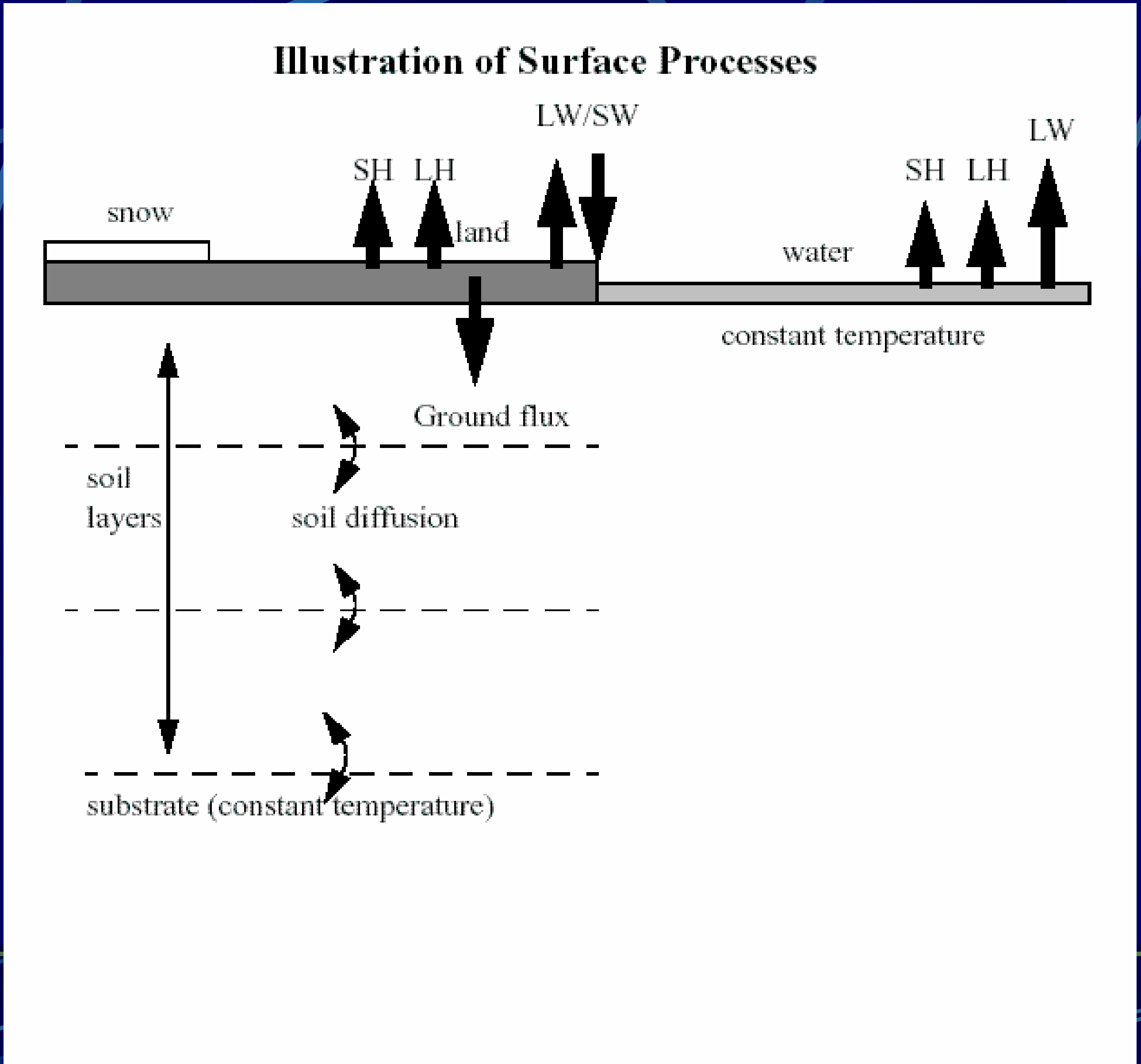
- Represent radiative effects in atmosphere and at surface
- Provides surface downwelling longwave and shortwave fluxes for surface scheme
- Provides column temperature tendencies due to vertical radiative flux divergence
- May interact with model clouds or relative humidity

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)
- NOAH Land Surface Model (since V3.6)
- Pleim-Xiu LSM (V3 only)

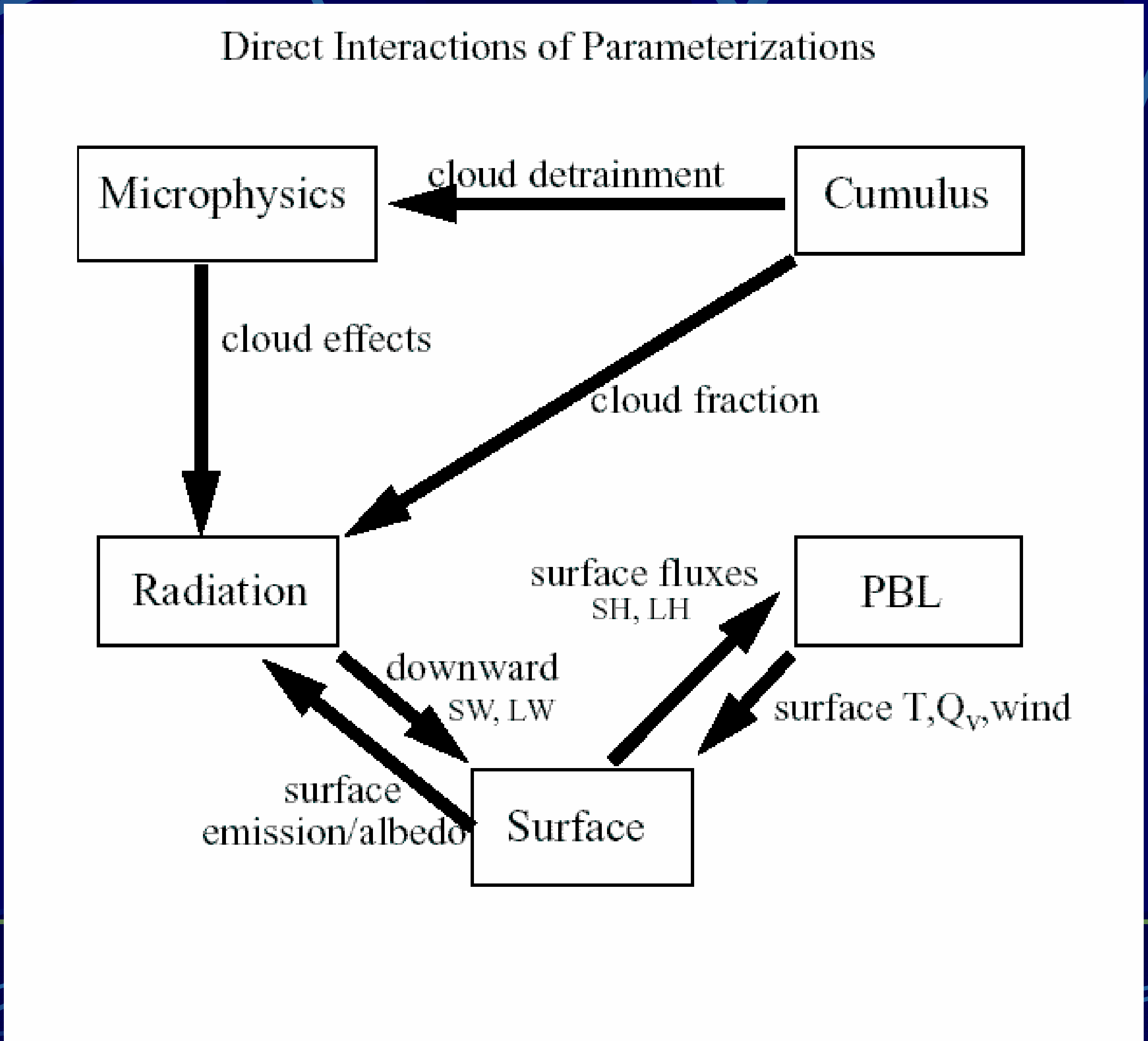
(Pan and Mahrt 1987; Chen and Dudhia 2001)

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

(Stauffer and Seaman 1990)

Interactions of Parameterizations



Verification

- IC and BC from NCEP model analysis and forcast grid
- Δx = 27 km, with 27 σ levels

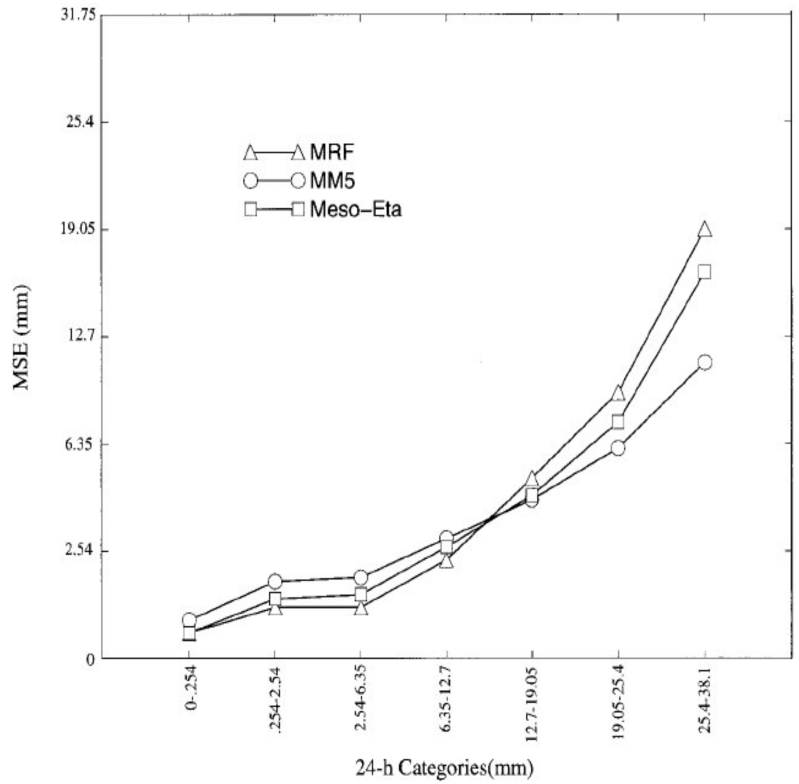


FIG. 8. Precipitation mse analysis for 24-h period ending at the 36-h forecast during the months of Oct, Nov, and Dec, 1997. Models verified are the MRF, Meso Eta, and MM5.

(White et al 1998)

Verification

- Initialized from satellite measurements
- SST updated daily

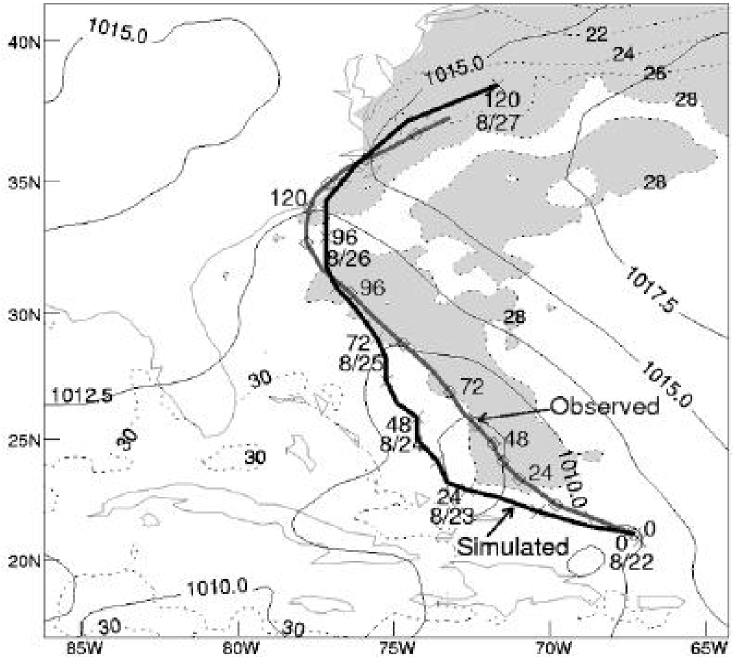


FIG. 2. Tracks (6 h) of Bonnie from the best analyses (light thick lines) and the model simulation (dark thick lines), superposed with the 5-day (0000 UTC 22–0000 UTC 27 Aug) averaged sea level pressure (solid lines) and SST (dotted, with its value of less than 28°C shaded).

(Zhu et al. 2004)

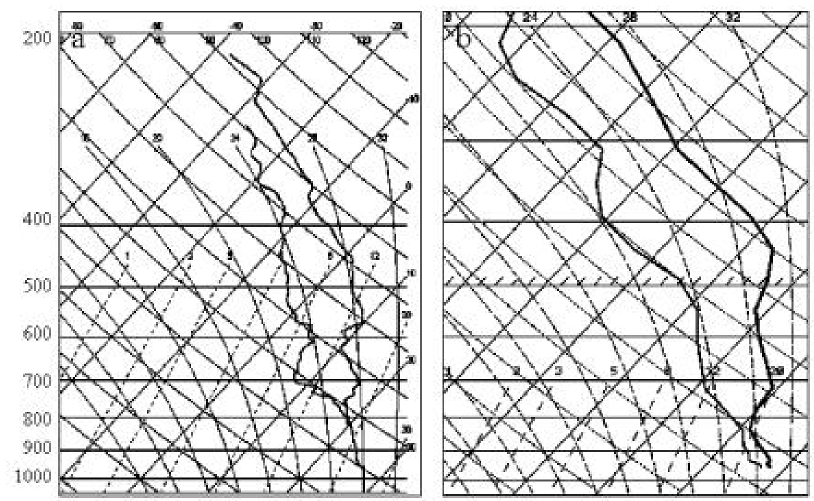


FIG. 4. (a) Dropsonde released by DC-8 aircraft in the eye of Hurricane Bonnie at 2126 UTC 23 Aug (see Fig. 7a for its location) and (b) a simulated sounding at the eye center at 2130 UTC 23 Aug 1998 (see Fig. 7b later for its location).

- 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.