Introduction to Cloud Modeling. Part VI: Types of Model

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Outline

» Introduction

» 0D ‘parcel models’

» 1D cloud models

» 2D cloud models

» 3D cloud models

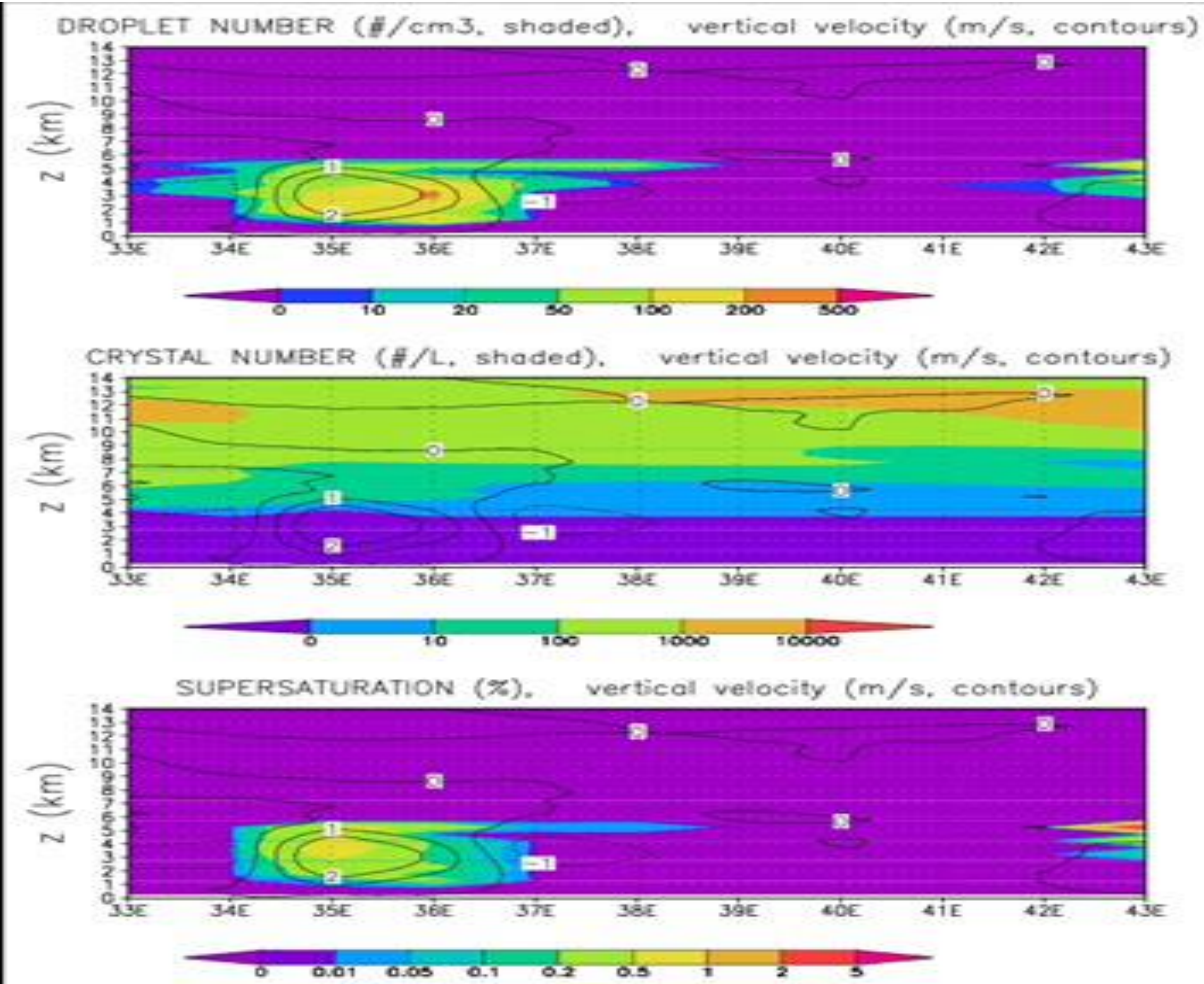
» Example of modeling system for research and forecasting

» Summary

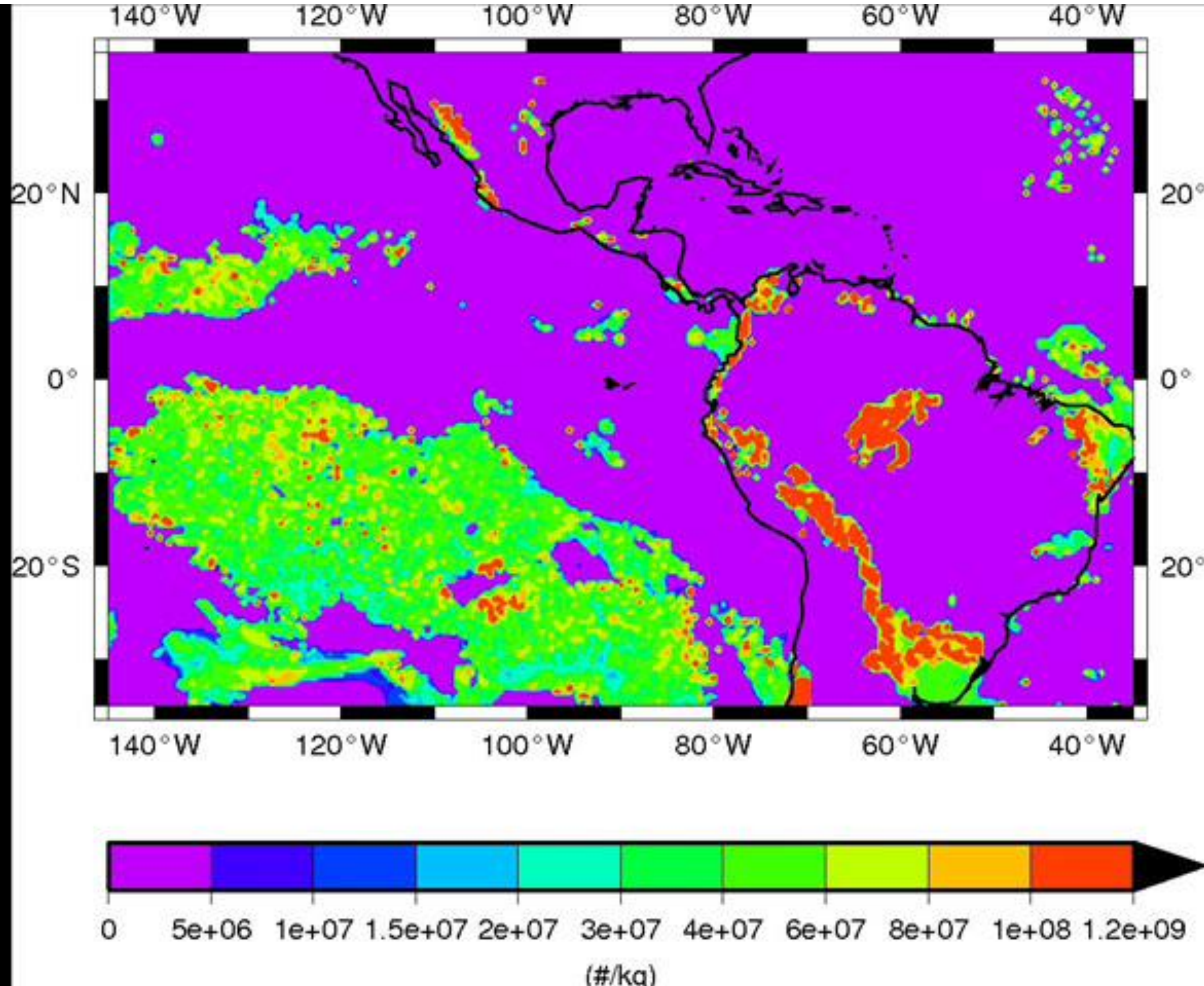
INTRODUCTION

Diversity of models that predict cloud properties, with wide range of resolutions and of levels of detail

Example: High-resolution (dx = 2 km) cloud-resolving model of aerosol-cloud interaction with 6 species of aerosol and 2-moment bulk microphysics (Phillips et al. 2009)


DROPLET NUMBER (#/cm3, shaded), vertical velocity (m/s, contours)
z (km)
33E 34E 35E 36E 37E 38E 39E 40E 41E 42E 43E
0 10 20 50 100 200 500
CRYSTAL NUMBER (#/L, shaded), vertical velocity (m/s, contours)
z (km)
33E 34E 35E 36E 37E 38E 39E 40E 41E 42E 43E
0 10 100 1000 10000
SUPERSATURATION (%), vertical velocity (m/s, contours)
z (km)
33E 34E 35E 36E 37E 38E 39E 40E 41E 42E 43E
0 0.01 0.05 0.1 0.2 0.5 1 2 5

Example: Regional model (dx = 50 km) of Pacific and Americas, with similar Phillips scheme of aerosol-cloud interaction, for prediction of properties of large-scale clouds (Lauer et al. 2009)


140°W
120°W
100°W
80°W
60°W
40°W
20°N
0°
20°S
0
5e+06
1e+07
1.5e+07
2e+07
3e+07
4e+07
6e+07
8e+07
1e+08
1.2e+09
(#/kg)

0-D CLOUD MODELS

0D parcel models

» Parcel = buoyant element of air with size and shape unspecified

» Assumptions that parcel:

– maintains its identity in thermodynamic processes

– Does not disturb or interact with environment

– Has uniform properties

– Its pressure is always equal to that of ambient air

Adiabatic parcel model

» $\frac{d^2z}{dt^2} = F_B = \frac{gT'}{T_0}$

» $\frac{d\theta_e}{dt} = 0$

Example:

$$wdw = F_B \Longrightarrow w^2 = w_{cb}^2 + 2\int_{z_0}^{z} F_B\, dz$$

$$w_{max} = \sqrt{2\ CAPE}$$

$$CAPE = \int_{LFC}^{ct} F_B\, dz$$

» Optionally, moisture too:

» $\frac{dQ_v}{dt} = S_v$

» $\frac{dQ_w}{dt} = S_w$

» $\frac{dQ_r}{dt} = S_r - Q_r/\tau_{fall}$

Adiabatic parcel model

» $\frac{d^2z}{dt^2} = F_B = \frac{gT'}{T_0}$

» $\frac{d\theta_e}{dt} = 0$

» $\theta_e = \theta_e(T,p) \Longrightarrow T = \ \ldots$

Example:

$$wdw = F_B \Longrightarrow w^2 = w_{cb}^2 + 2\int_{z_0}^{z} F_B\, dz$$

$$w_{max} = \sqrt{2\ CAPE}$$

$$CAPE = \int_{LFC}^{ct} F_B\, dz$$

» Assuming water saturation (conserve $Q_T = Q_v + Q_w$):

» $\frac{dQ_T}{dt} = -S_r$

» $Q_w = Q_T - Q_{v,s}$

» $\frac{dQ_r}{dt} = S_r - Q_r/\tau_{fall}$

Entraining parcel model (e.g. Donner 1993)

- Entrainment rate $= E = \frac{1}{m}\frac{dm}{dt} \sim constant$
- $\frac{d^2z}{dt^2} = g\left(\frac{T_v{}'}{T_0} - Q_w - Q_r\right) - E\,w$
- $\frac{dQ_T}{dt} = -S_r - E\,Q_T{}'$
- $Q_w = Q_T - Q_{v,s}$
- $\frac{dQ_r}{dt} = S_r - EQ_r - \frac{Q_r}{\tau_{fall}}$
- $\frac{d\theta_e}{dt} = -E\theta_e{}'$

1-D CLOUD MODELS

Vertical 1-D draft

» Include interaction between dynamics and microphysics (e.g. Srivastava 1967)

» Approach: solve Boussinesq eqns for conservation of momentum, heat, and mass of moisture for vertical motion

$$\frac{D}{DT} \equiv \frac{\partial}{\partial t} + U\frac{\partial}{\partial z}$$

Evaporation (or condensation) $E_v = E_{v,1} + E_{v,2}$

$$\frac{DU}{Dt} = g\left(\frac{T_v{}'}{T_0} - Q_w - Q_r\right)$$

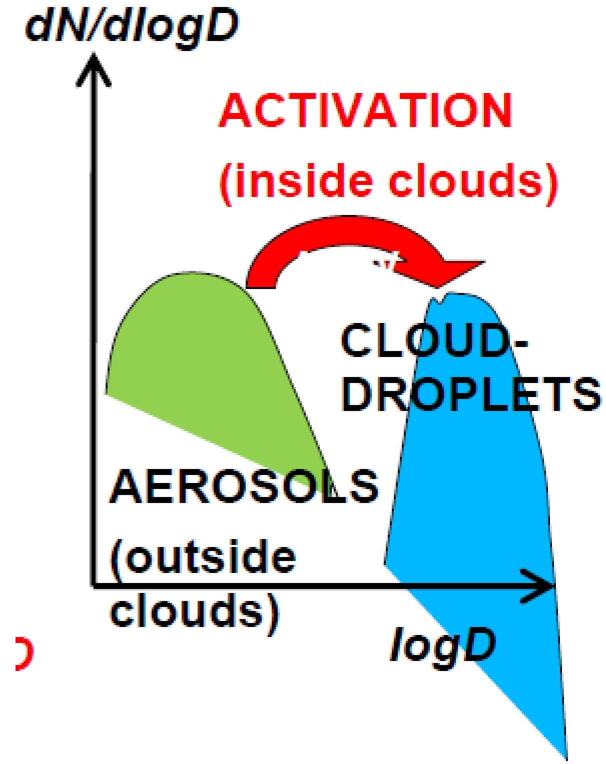
$$\frac{DQ_v}{Dt} = S_v = E_v$$

$$\frac{DQ_w}{Dt} = S_w = -E_{v,1} - P$$

$$\frac{DQ_r}{Dt} + \frac{1}{\rho_0}\frac{\partial}{\partial z}(\rho_0 Q_r V) = S_r = -E_{v,2} + P$$

$$\frac{DT}{Dt} = -U\,\Gamma_s - LE_v/c_p$$

Bulk microphysics



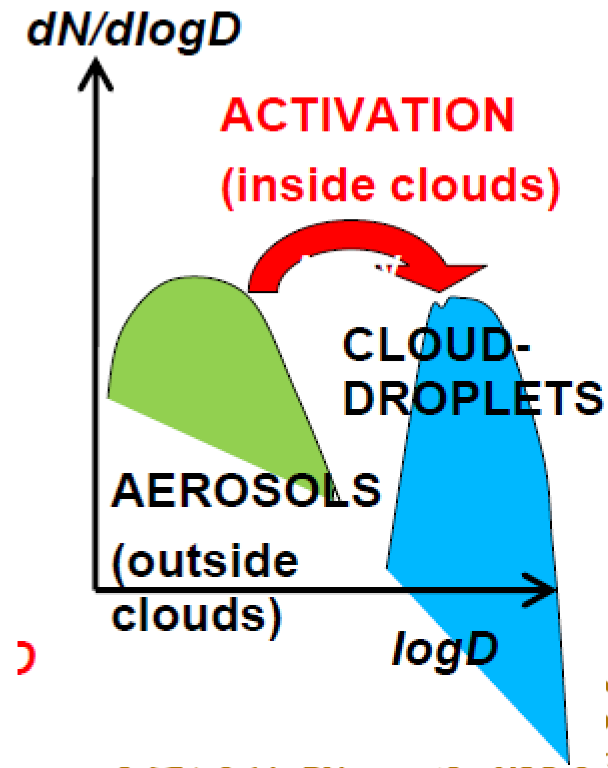
- Kessler (1969) analysed drop size distributions (DSDs)
- By approximating a mathematical form for DSDs (e.g. exponential), he derived:

$$E_v = E_{v,1} + E_{v,2}$$

  - Evaporation (or condensation)
  - Average fall-speed, *V*
  - Precipitation production, *P*,
    - Some cloud-water converts spontaneously to rain when a threshold on Q_w is exceeded

Bin microphysics: more accuracy in treatment of coagulation and sedimentation

- » Danielson et al. (1972) explicitly accounts for DSDs and for ice size distributions
  - – Stochastic coalescence predicted bin by bin
  - – Concentration is explicitly predicted in each of many categories arranged logarithmically over size
    - » water drops: from 2 microns to 2.5 mm
    - » Ice: up to 20 mm



Results: Case Study

- Example: shower, a convective cell, warm climate (Srivastava 1967)
- In first 10 mins, rain develops at expense of cloud-liquid, forming first near cloud-top
  - Updraft starts weakening, due to burden of rain
- After about 20 mins, rain has descended, forming downdraft at low levels
  - updraft strenthens again

Overview of 1D models

» Advantages:

- Interaction of dynamics and microphysics treated
- Computationally cheap
- Good for analysis of microphysical processes

» Disadvantages

- Crude treatment of dynamics (no shear)
- In reality, vertical shear controls storm structure, and there are downdrafts flanking updraft

2D CLOUD MODELS

- Approach: solve Boussinesq equations for conservation of momentum, heat, and mass of air and moisture on a vertical grid (*x,z*)
  - Density constant, $\rho_0(z)$, except for F_B (Boussinesq)
  - Include convergence of turbulent fluxes, *F*
  - Treat pressure and temperature as sum of basic state ($p_0(z)$, $T_0(z)$) and a perturbation ($p'(x, z, t)$, $T'(x, z, t)$)
  - Convection started by warm bubble initially

$$\frac{D}{DT} \equiv \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + w\frac{\partial}{\partial z}$$

$$\frac{Du}{Dt} = F_u - \frac{1}{\rho_0}\frac{\partial p'}{\partial x}$$

$$\frac{Dw}{Dt} = g\left(\frac{T_v{}'}{T_0} - Q_w - Q_r\right) + F_w - \frac{1}{\rho_0}\frac{\partial p'}{\partial z}$$

$$0 = \frac{\partial(\rho_0 u)}{\partial x} + \frac{\partial(\rho_0 w)}{\partial z}$$

$$\frac{DT}{Dt} = -\Gamma_s w + F_T + S_T$$

$$\frac{DQ_v}{Dt} = S_v + F_v$$

$$\frac{DQ_w}{Dt} = S_w + F_w$$

$$\frac{DQ_r}{Dt} + \frac{1}{\rho_0}\frac{\partial}{\partial z}(\rho_0 Q_r V) = S_r + F_r$$

Results: Case Study

- Takeda (1971) used above 2D model but with bin microphysics, treating stochastic coalescence and breakup
- Type 1: weak vertical shear, moderate instability
  - Clouds develop in-cloud downdraft due to precipitation burden and evaporative cooling
  - Cold pool near surface spreads and triggers new cell
  - New clouds develop around dissipating cloud
- Type 2: strong shear, moderate instability
  - Downdraft forms on downshear side
  - No new cells triggered, cloud is short-lived

Overview of 2D model

» Advantages:

- Effects from vertical shear on longevity and intensity of storm simulated
- Cheaper than 3D

» Disadvantages:

- Vertical motions grossly distorted
- Vertical pressure pertubation forces grossly overestimated
- Turbulence ?
- Forecasting ?

3D CLOUD MODELS

Need for 3D model for realism

» In reality,

- wind speed and direction change with height:
- Vortices are advected, tilted and stretched in 3D (e.g. tornadoes), updrafts rotate
- Outflow in downdrafts can interact with ambient flow, foming multicell storms
- PPGF and updraft speeds differ between 2D and 3D
- Clouds act as barriers to ambient flow at some (near steering) levels, move with the wind at other levels

» Approach: solve numerically 3D version of Boussinesq equations for 2D models

$$\frac{D}{DT} \equiv \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z}$$

Results:

- Splitting of supercells simulated by Wilhelmson and Klemp (1978)
  - Sensitivity test shows splitting is due to rain
  - Right-moving storms are more common after splitting (than left-moving ones) because ambient flow turns clockwise with height usually
    - Low-level convergence due to downdrafts sustains the storm and the downdrafts are promoted by mid-level inflow from south, which is linked to such a sounding
- Tornadoes simulated and explained in terms of intensification of mesovortex (Klemp *et al*. 1981)

EXAMPLE OF MODELING SYSTEM FOR RESEARCH AND FORECASTING

Example of 3D model: Weather, Research and Forecasting (WRF)

Outline of WRF

- Two forms of WRF:
  - Advanced Research WRF (ARW)
  - Non-hydrostatic Mesoscale Model (NMM)
- Both are Eulerian mass dynamical cores
  - terrain-following vertical co-ordinates
  - non-hydrostatic (sound and gravity waves may be included by high-resolution solution of ODEs)
- Pressure closely related to their vertical co-ordinate
- Pre-processing, main model running and post-processing elements in both

Components of WRF modeling system

Initialisation of WRF simulation

- WRF Pre-processing System (WPS) prepares data for a run
  - Real observational data interpolated by WPS onto model grid, if numerical weather prediction (NWP) runs are to be done

- WRF Model also prepares the data for a run ("real.exe" and "ideal.exe") :
  - Hydrostatic balance of data on model grid
  - Creates data-files for lateral and initial boundary conditions

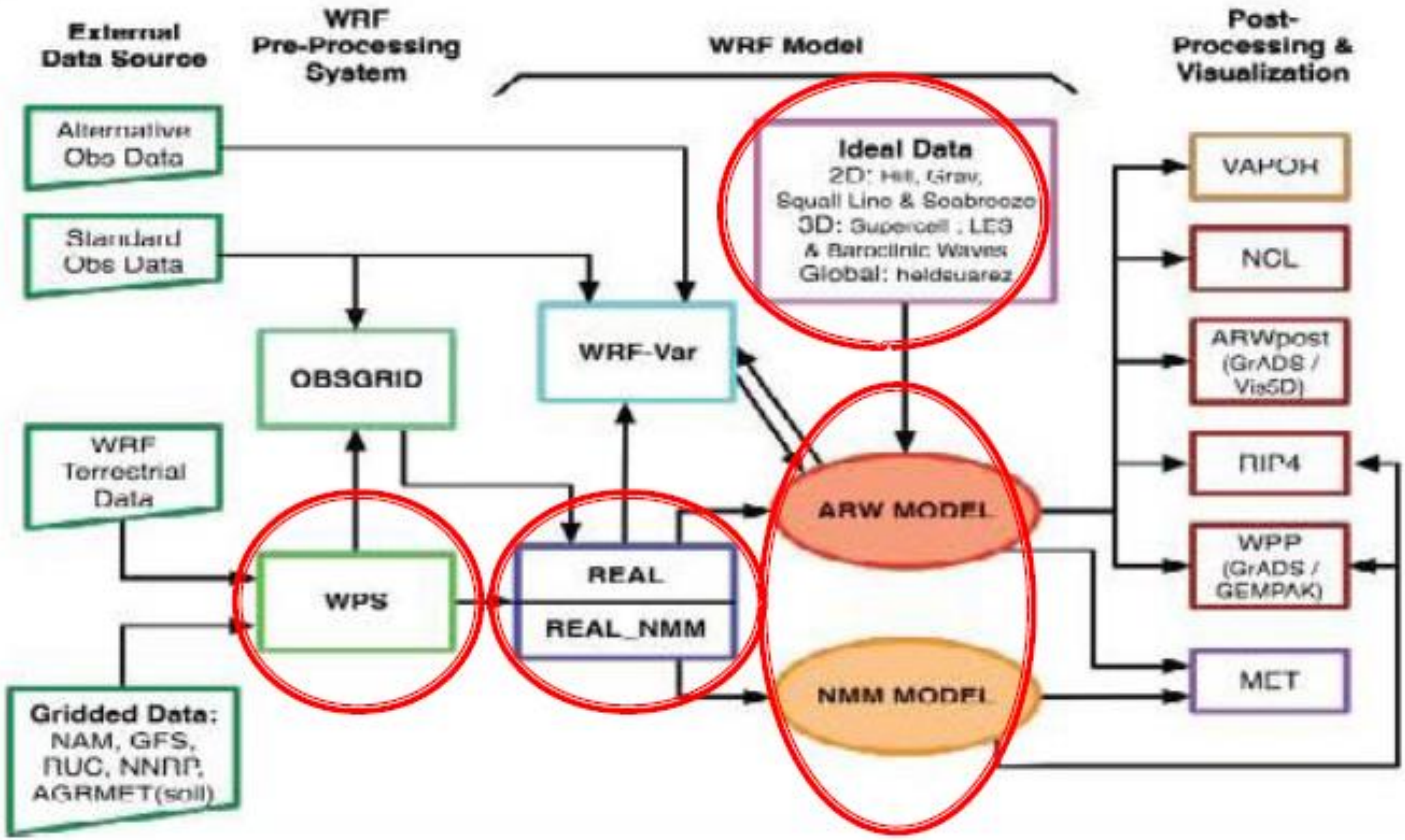
Components of WRF modeling system

WRF Model run and post-processing:

- WRF Model(ARW or NMM) solves ODEs of physical and dynamical laws so as to simulate the atmosphere ("wrf.exe")
  - reads in input data (processed previously), and initialises variables/arrays
  - Integrates ODES, creating output

- Graphics and Verification tools
  - (e.g. RIP4, WPP, NCL)

Map of WRF modeling system

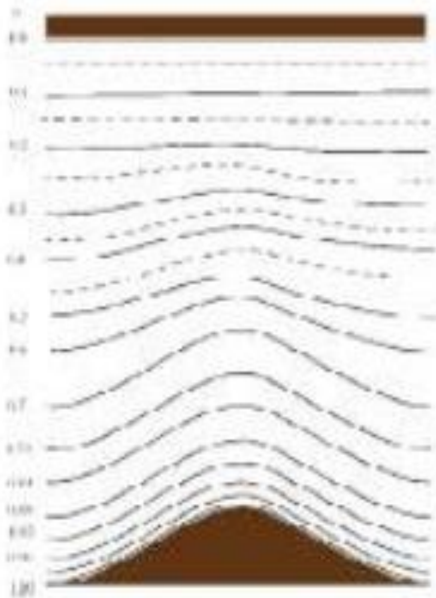


Dynamics of ARW WRF Model

Key features:

- Fully compressible, non-hydrostatic (with hydrostatic option)
- Mass-based terrain following coordinate, η

$$\eta = \frac{(\pi - \pi_t)}{\mu}, \qquad \mu = \pi_s - \pi_t$$



where π is hydrostatic pressure,
μ is column mass

- Arakawa C-grid staggering

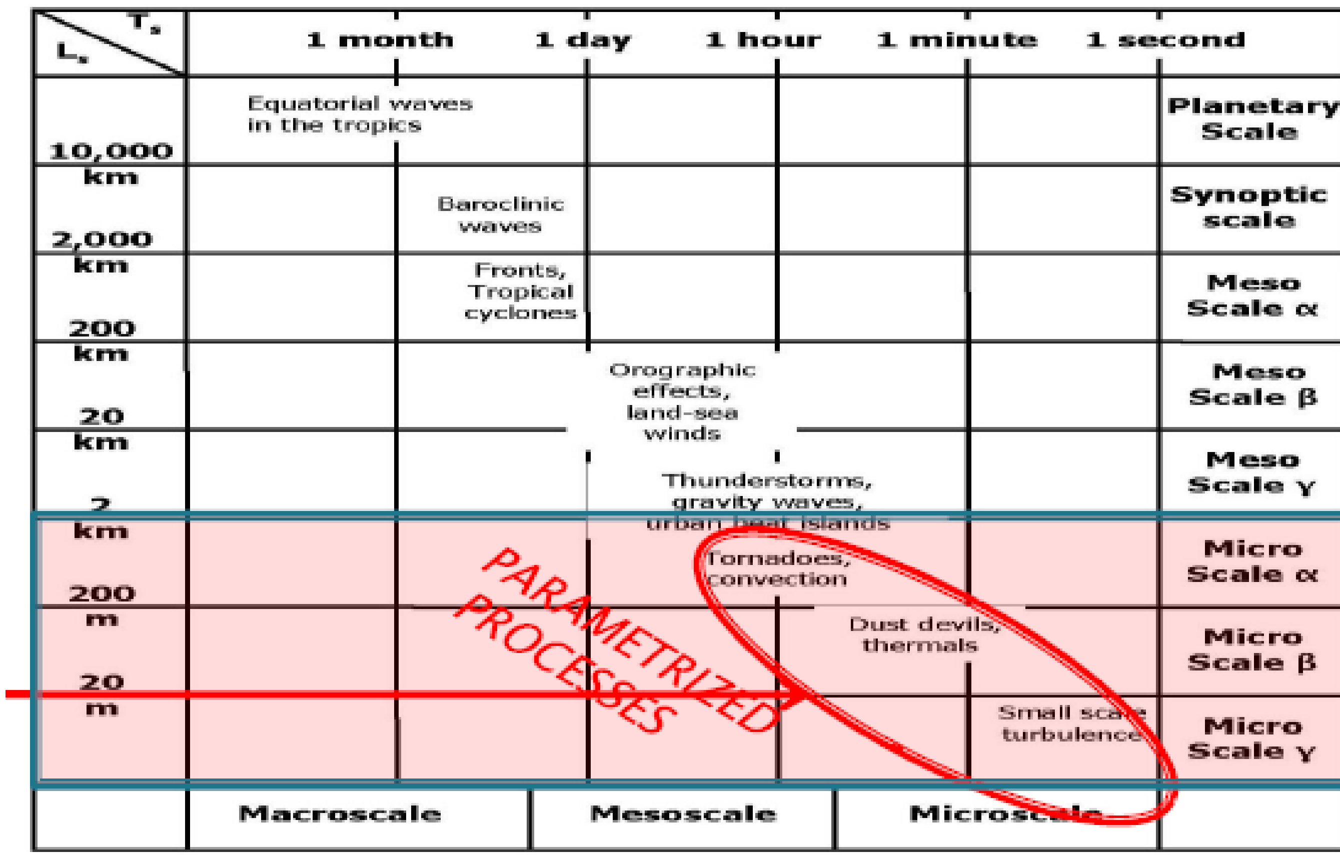
```
     v
u    T    u
     v
```

WRF as cloud model

Phenomena occur on many scales, some too small to resolve on model grid

WRF AS CLOUD-SYSTEM RESOLVING MODEL (CSRM)

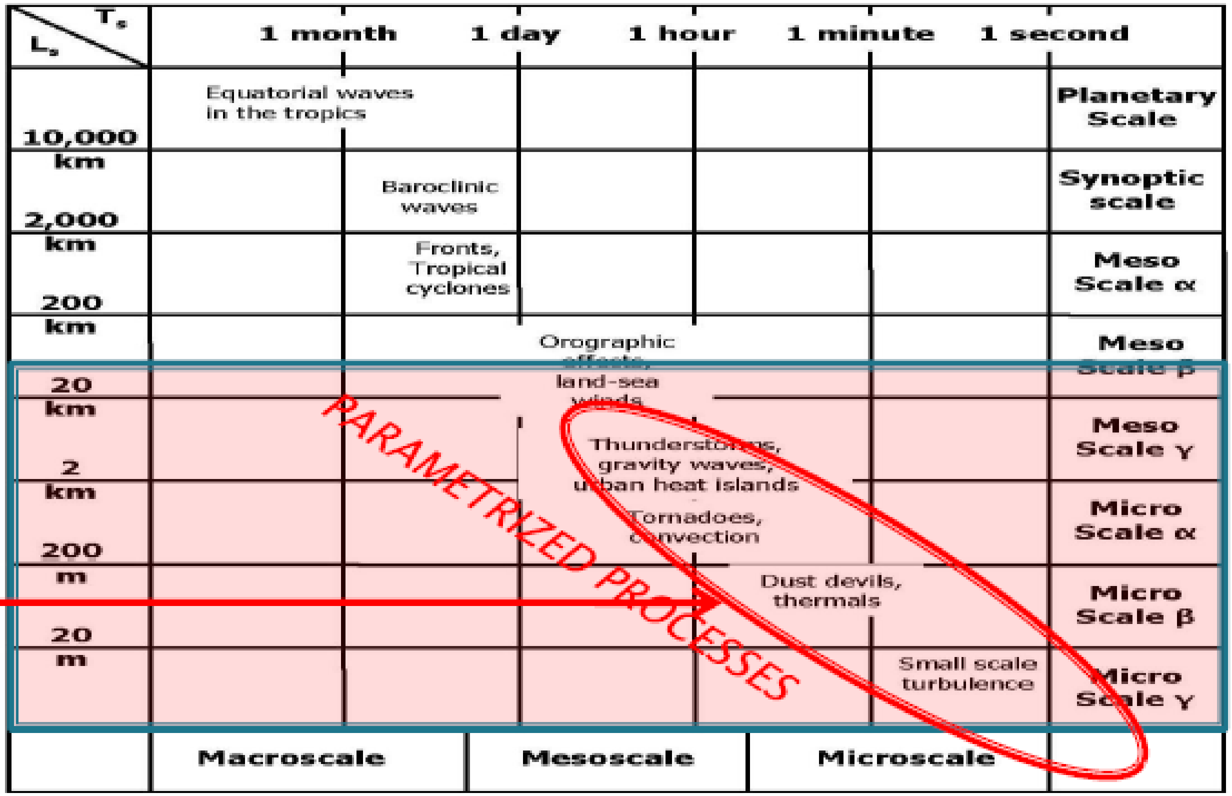
NOT RESOLVED BY WRF 's RESOLUTION OF $\Delta X = 2$ km



WRF as regional model

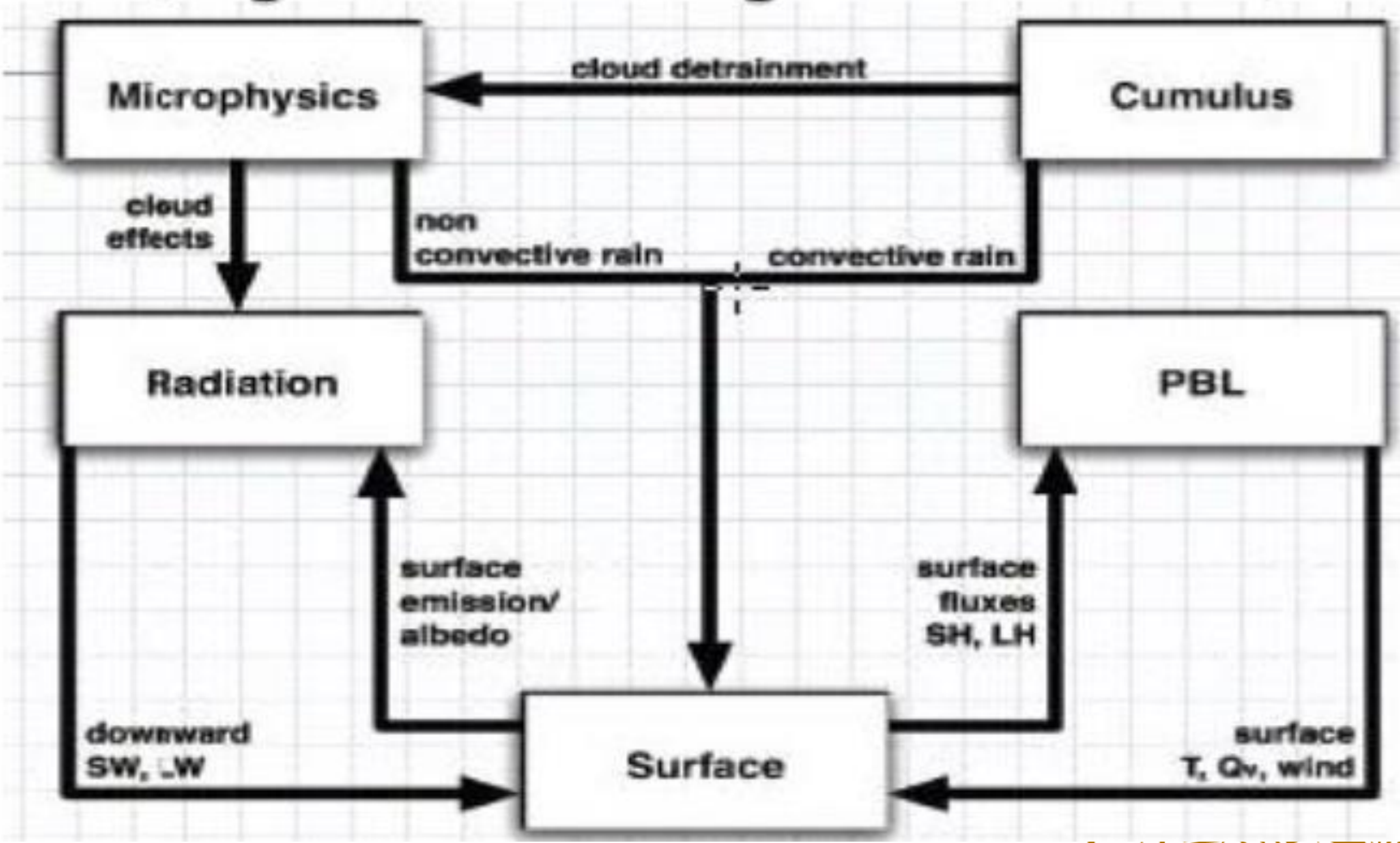
Phenomena occur on many scales, some too small to resolve on model grid

WRF AS REGIONAL (e.g. HURRICANE) MODEL



NOT RESOLVED BY WRF's RESOLUTION OF $\Delta X = 50$ km

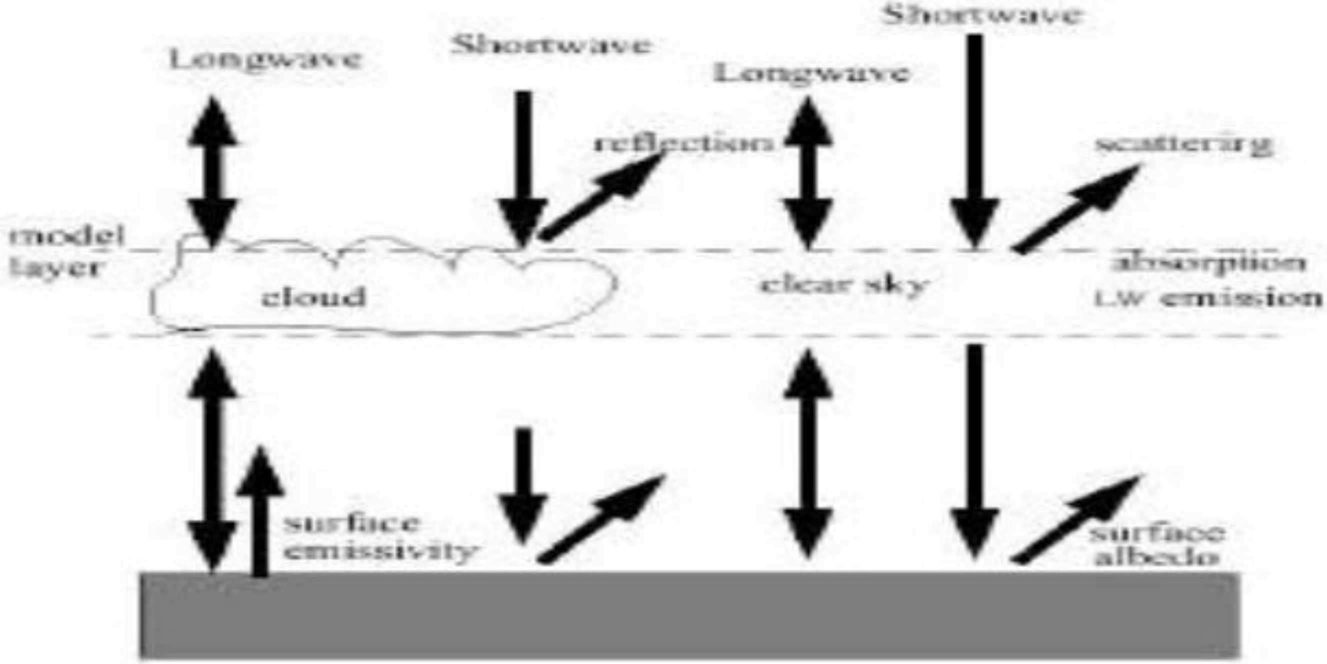
Map of parameterizations when all are used (e.g. WRF as regional model)



WRF Parametrisations: Radiation

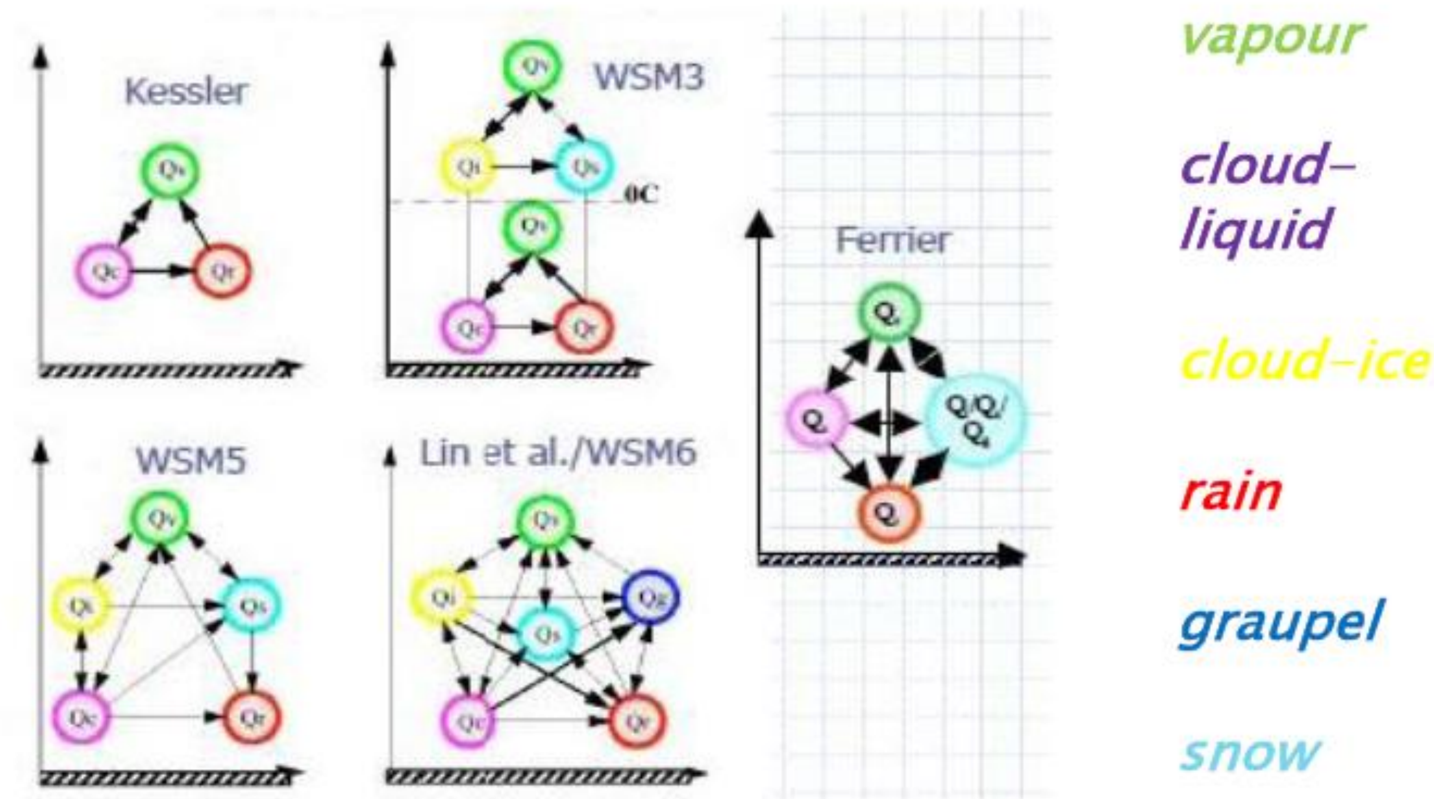
Radiative Transfer in Atmosphere:

- Models always treat solar (shortwave [SW]) and terrestrial (longwave [LW]) radiation from Sun and Earth separately, since there is no overlap



Options: microphysics schemes

Multiple species of hydrometeor



Example: Morrison scheme

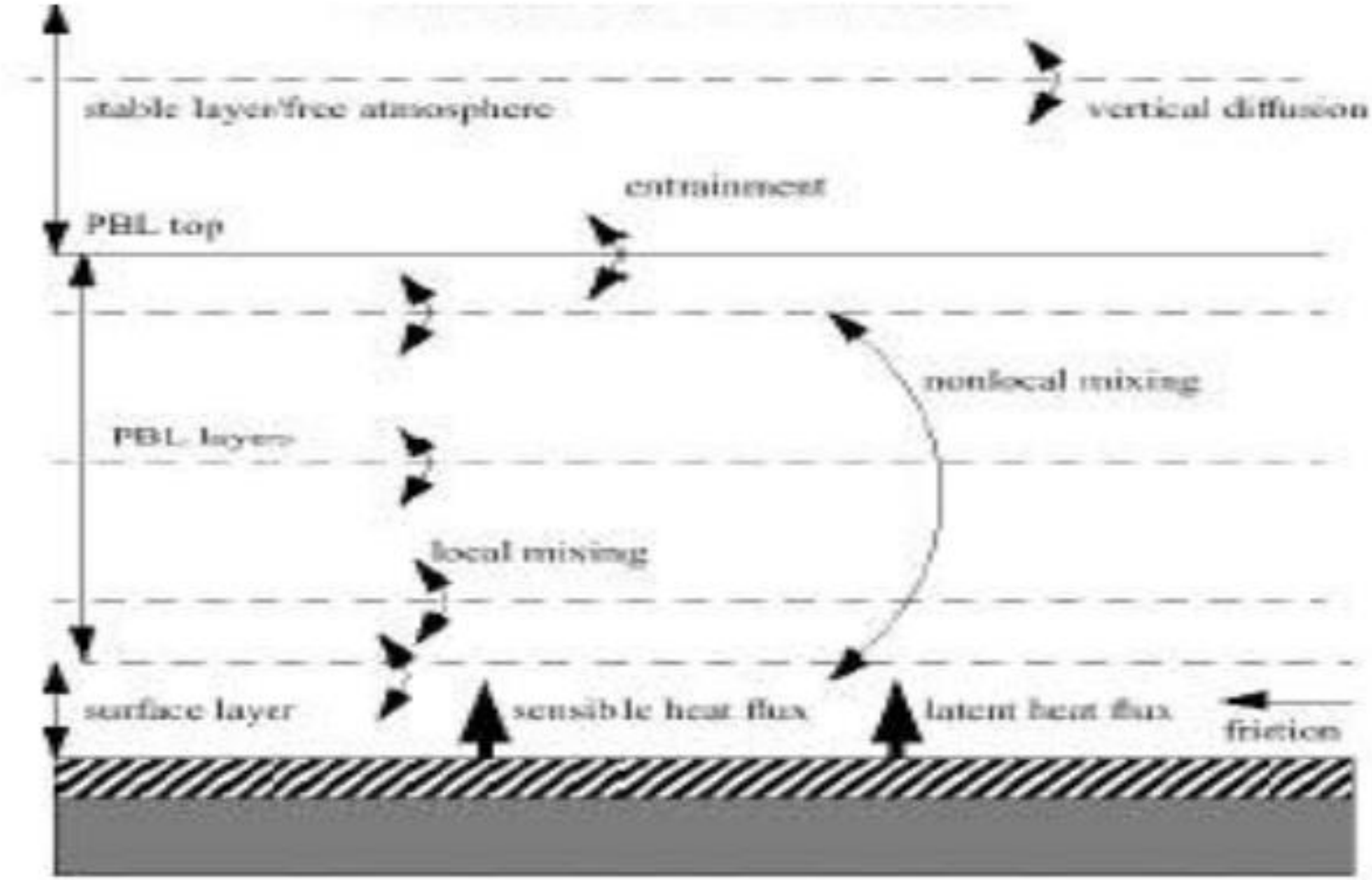
- **Usual 5 species of hydrometeor:**
  - Cloud-ice, snow, graupel, cloud-liquid, rain

- **2-moment treatment of some species**
  - x-th species has a size distribution, dN_x (#/m3) = $n_x(D)\, dD$

  - both total mass and number of particles, per m^3, are predicted
    - $N_x = \int n_x \, dD$ *(0-th moment)*
    - $Q_x \propto \int D^3 n_x \, dD$ *(3rd moment)*
    - Prediction of N_x and Q_x ⇒ mean size of particles and n_x predicted

- **Advantage of 2-moment approach**: in nature, cloud properties determined by mean size of cloud-particles
  - Cloud properties are predicted

PBL scheme (e.g. *bl_pbl_physics* =1): vertical turbulent fluxes of heat and moisture



SUMMARY

» Complex mechanisms elucidated by models

» Parcel models can elucidate microphysical processes

» 1D, 2D and 3D models include an increasing range of mechanisms

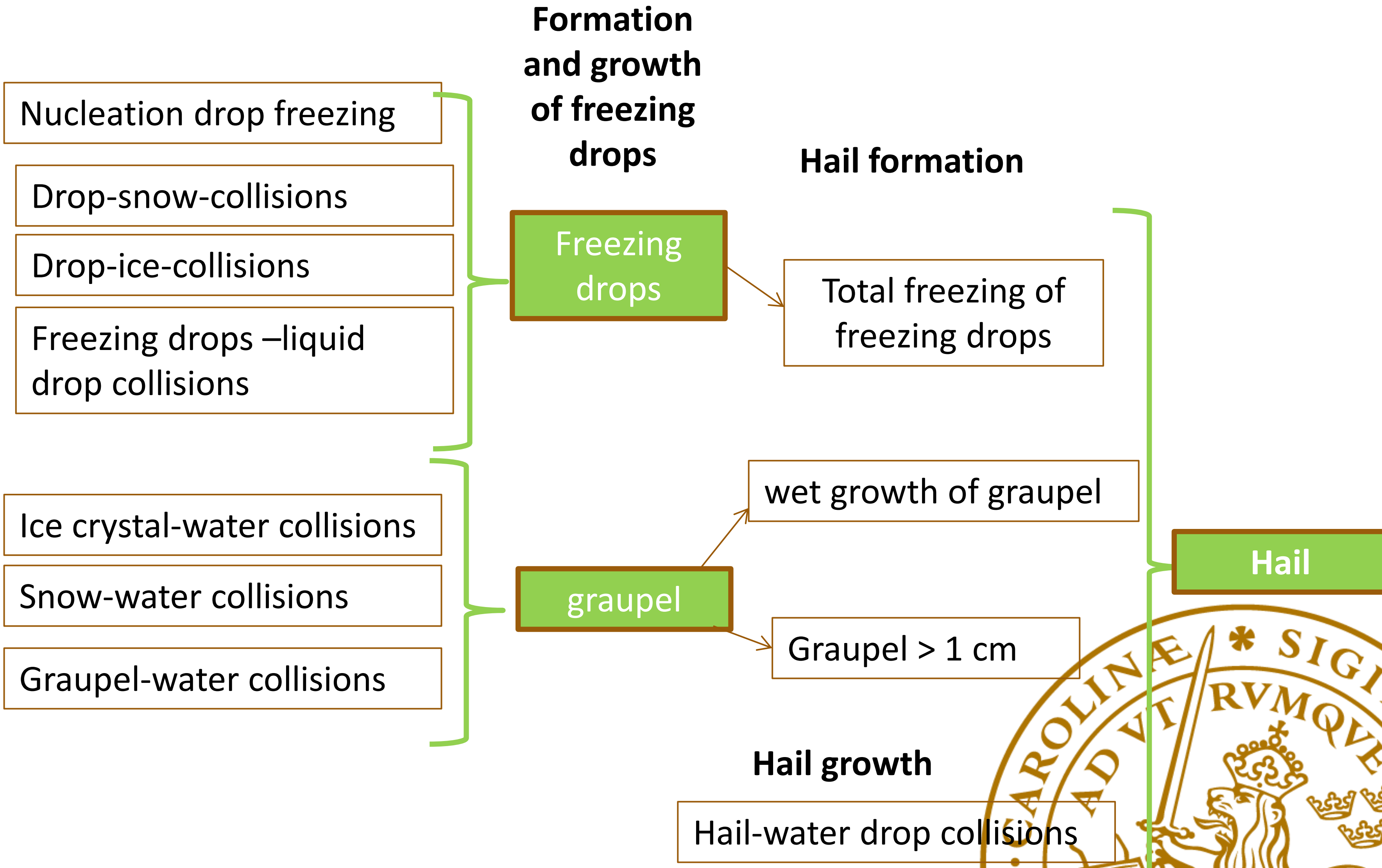
» Modeling systems (e.g. WRF) have flexibility for choice of any resolution and of corresponding parameterizations

Obrigado

Example: Very high resolution (about 0.5 km) 2D model with bin microphysics

- explicit prediction of size distributions and cloud-processes

New transformation of hydrometeors during hail formation in HUCM:



Dynamics of ARW WRF Model

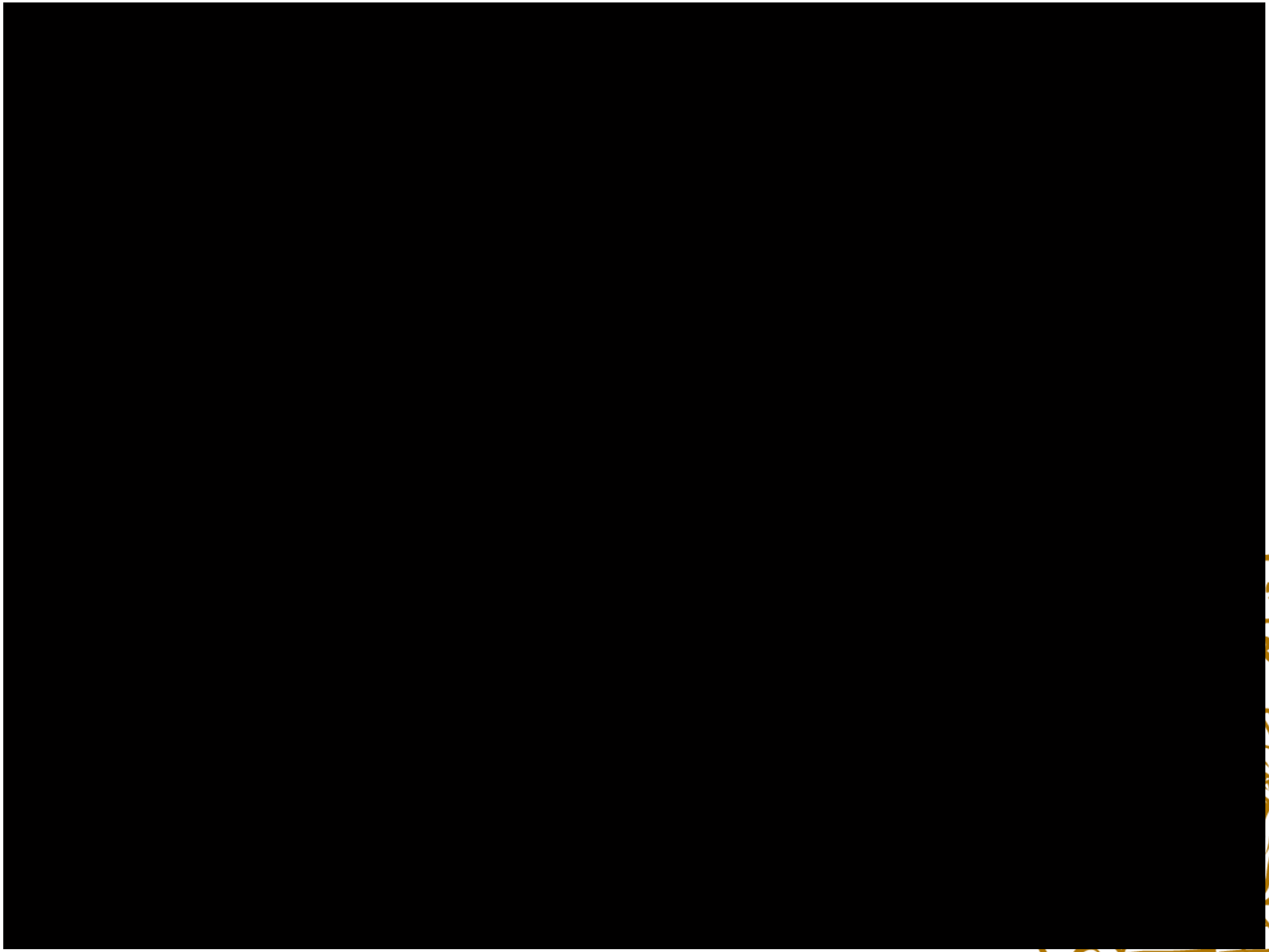
Key features:

- 3rd-order Runge-Kutta time integration scheme
- High-order advection scheme
- Scalar-conserving (positive definite option)
- Complete Coriolis, curvature and mapping terms
- Two-way and one-way nesting

Dynamics of ARW WRF Model

Key features:

- Choices of lateral boundary conditions suitable for real-data and idealized simulations
  - Specified, Periodic, Open, Symmetric, Nested
- Full physics options to represent atmospheric radiation, surface and boundary layer, and cloud and precipitation processes
- Grid-nudging and obs-nudging (FDDA)
- New Digital Filter Initialization option



- Type 3: low-level jet, with strong opposite shears above and below it
  - Precipitation and updraft are both inclined in direction of low-level shear at low levels,
  - Updraft has opposite tilt aloft
  - Cold pool from downdraft spreads out, triggering ascent near base of original updraft
  - Long-lived cloud
- Other 2D models: Farley and Orville (1986), Khain et al. (2004)

Turbulence

- When fluid flow is turbulent, its elements move irregularly and do not follow the direction of the mean flow

- Turbulent eddies cause random fluctuations of advected quantities around their mean (< >) values

  $$X \quad = \quad \langle X \rangle \quad + \quad X'$$

  MEAN (e.g. RESOLVED ON GRID) — EDDY (e.g. SUB-GRIDSCALE)

- Turbulence involves interactions and exchange of energy between motions of different scales

- Momentum equation, $Dv_H/Dt = \Sigma_i F_i$ can be modified for grid-box average quantities, with an extra eddy stress term:
  - $$D\langle v_H \rangle/Dt = \Sigma_i \langle F_i \rangle \;+\; (1/\rho)\; \partial\,[\,\rho \langle w' v_H' \rangle\,] / \partial z$$

    RESOLVED ON GRID — EFFECT FROM SUB-GRIDSCALE TURBULENCE (PARAMETERIZATION)

- Similarly, the (1st Law) energy eqn, $D\theta/Dt = \Sigma_i S_i$, becomes
  - $D\langle\theta\rangle/Dt = \Sigma_i \langle S_i\rangle + (1/\rho)\,\partial[\rho \langle w'\theta'\rangle]/\partial z$

    RESOLVED ON GRID — EFFECT FROM SUB-GRIDSCALE TURBULENCE (PARAMETERIZATION)
- Vertical turbulent fluxes of heat and momentum are $\rho \langle w' \mathbf{v}_H' \rangle$ and $\rho \langle w' \theta' \rangle$
- *Turbulent mixing transports heat and momentum down the gradient of mean temperature and mean momentum*
  - $\rho \langle w' \mathbf{v}_H' \rangle \sim -\rho K_m \partial \langle \mathbf{v}_H \rangle / \partial z$
  - $\rho \langle w' \theta' \rangle \sim -\rho K_h \partial \langle \theta \rangle / \partial z$
- PBL/turbulent mixing parameterizations predict $K_{m/h}(z)$ and the turbulent fluxes of heat, moisture and momentum
  - K varies strongly with z in surface layer (lowest 10% of PBL)
  - In surface layer: $K_m \propto \partial \langle \mathbf{v}_H \rangle / \partial z$ and $K_h \propto \partial \langle \theta \rangle / \partial z$