The WRF NMM

Overview of PBL, Surface Layer, Moist Convection and Microphysics

Zavisa Janjic and Brad Ferrier
(Presented by Tom Black)

Mellor-Yamada-Janjic Turbulence

- TKE production due to shear and buoyancy
- TKE dissipation (Kolmogorov)
- Exchange coefficients (v. Heisenberg)

$$K \propto const\ l\ q$$

- Derivation from basic principles, proportionality factors in exchange coefficients for heat and moisture, l, empirical constants (Mellor and Yamada 1982)

$$K_M = S_M lq, K_H = S_H lq$$

- Removing singularity in TKE production/dissipation Eq in convectively driven growing turbulence, constraints on mixing length in stable & unstable ranges, revised constants, numerics (Janjic 1996, 2001), phase changes

$$d(q^2/2)/dt - (\partial/\partial z)[\ell\, q\, S_q\, (\partial/\partial z)(q^2/2)] = P_s + P_b - \varepsilon \qquad (2.1)$$

$$P_s = -\langle wu\rangle\, (\partial U/\partial z) - \langle wu\rangle\, (\partial V/\partial z),\; P_b = \beta\, g \langle w\theta_v\rangle,\; \varepsilon = q^3/(B1\, \ell) \qquad (2.2)$$

$$-\langle wu\rangle = K_M\, \partial U/\partial z,\; -\langle wv\rangle = K_M\, \partial V/\partial z,$$

$$-\langle w\theta_v\rangle = K_H\, \partial \Theta_v/\partial z,\; -\langle ws\rangle = K_H\, \partial S/\partial z, \qquad (2.3)$$

$$K_M = \ell\, q\, S_M,\; K_H = \ell\, q\, S_H, \qquad (2.4)$$

$$S_M\, (6\, A1\, A2\, G_M) + S_H\, (1 - 3\, A2\, B2\, G_H - 12\, A1\, A2\, G_H) = A2, \qquad (2.5)$$

$$S_M (1 + 6\, A1^2 G_M - 9\, A1 A2 G_H) - S_H\, (12\, A1^2\, G_H + 9\, A1\, A2\, G_H) = A1(1 - 3\, C1), \qquad (2.6)$$

$$G_M = (\ell^2/q^2)[(\partial U/\partial z)^2 + (\partial V/\partial z)^2],\;\; G_H = -\, (\ell^2/q^2)\, \beta\, g\, \partial \Theta_v/\partial z. \qquad (2.7)$$

Computation of ℓ

Constants

Singularity problem, limit on ℓ in unstable range (Janjic 2001)

- TKE production/dissipation Eq

$$\partial q/\partial t = (q^2/\ell)\ [S_M G_M + S_H\ G_H - 1/B1]$$

$$\ell\ d(1/q)/dt =$$
$$-\{[A(\ell/q)^4 + B(\ell/q)^2]/[C(\ell/q)^4 + D(\ell/q)^2 + 1] - 1/B1\},$$

A, B, C, D depend on large scale flow

- For given large scale flow TKE production/dissipation depends only on ℓ/q ratio, “return to isotropy time”

- Singularity occurs in case of growing turbulence in unstable regimes

- ℓ cannot be computed independently of q, upper limit on ℓ must be imposed

- Limit on ℓ in stable range, from internal relations

From limit of $<w^2>/q^2$ in case of vanishing turbulence

- Constants

$$Ri \leq 0.505$$

- Numerics
  - TKE production/dissipation Eq

$$\ell\, d(1/q)/dt =$$
$$-\{[A(\ell/q)^4+B(\ell/q)^2]/[C(\ell/q)^4+D(\ell/q)^2+1]-1/B1\}$$

  - Linearized around equilibrium solution and iterated to required accuracy (three iterations, unrolled loop)
- Phase changes
  - Liquid potential temperature (Bechtold et al., 1995), needed in cloud scale runs

Janjic Surface Layer Parameterization

- Turbulent fluxes constant with height, boundary conditions prescribed at two levels, z_1 and z_2

$$M=-<u'w'>=K_M\, dU/dz\,,\;\; H=-<\Theta'w'>=K_H\, d\Theta/dz\,,$$
$$H_v=-<\Theta_v'w'>=K_H\, d\Theta_v/dz\,,\;\; E=-<q'w'>=K_H\, dq/dz \qquad (1)$$

- Often used scales

$$u^*=M^{1/2}\,,\; \Theta^*=H/u^*\,,\; \Theta_v^*=H_v/u^*\,,\; E^*=E/u^* \qquad (3)$$

- F is a generic flux, constant with height, integrate

$$F = K_F \, dS/dz$$

$$S_2 - S_1 = F \int_{z_1}^{z_2} dz/K_F \qquad (4)$$

- Define bulk exchange coefficient

$$(z_2 - z_1)/K_{Fbulk} = \int_{z_1}^{z_2} dz/K_F \qquad (5)$$

- Fluxes in finite-difference form

$$F = K_{Fbulk} \, (S_2 - S_1)/(z_2 - z_1) \qquad (6)$$

- Similarity theory

$\partial S/\partial z=[S^*/(k\,z)]\ \varphi_F(\zeta)$ Highly implicit ! (7)

$S^*=F/M^{1/2}=F/u^*$ (8)

φ_F empirical functions

$\zeta=z/L$ nondimensional combination (9)

$L=M^{3/2}/(k\,\beta\,g\,H_v)$ Obukhov length scale (10)

$\beta=1/\Theta_0\approx 1/273°\,\mathrm{K}$

$z/L\rightarrow 0$ ($z\rightarrow 0$ or $L\rightarrow\infty$), $\varphi_F(0)=\mathrm{const}$ (typically close to 1)

Integrate the profiles

$$S_2 - S_1 = \int_{z_1}^{z_2} [S^*/(k\, z)]\ \varphi_F(\zeta) dz \qquad (11)$$

$$S_2 - S_1 = (S^*/k) \int_{z_1}^{z_2} (L/z)\ \varphi_F(\zeta)\ dz/L$$

$$S_2 - S_1 = F/(u^* k) \int_{\zeta_1}^{\zeta_2} \varphi_F(\zeta)\ d\zeta/\zeta$$

Singular point when L tends to infinity and ζ tends to zero

$$S_2\text{-}S_1=F/(u^*\,k)\int_{\zeta_1}^{\zeta_2}[\varphi_F(\zeta)-\varphi_F(0)]\,d\zeta/\zeta+\varphi_F(0)\,d\zeta/\zeta$$

$$S_2\text{-}S_1=F/(u^*k)\{\int_{\zeta_1}^{\zeta_2}[\varphi_F(\zeta)-\varphi_F(0)]d\zeta/\zeta+\varphi_F(0)\int_{z_1}^{z_2}dz/z\} \quad (12)$$

$\varphi_F(\zeta)$ known, integral on the rhs of (12) can be evaluated

$$\Phi_F=\Psi_F(\zeta_2)-\Psi_F(\zeta_1)+\varphi_F(0)\,ln(z_2/z_1) \quad (13)$$

$$S_2\text{-}S_1=[F/(u^*\,k)]\;\Phi_F \quad (14)$$

$F=M,\ S=U,\ \Phi_F=\Phi_M,$ from (14)

$U_2-U_1=[M/(u^*\,k)]\ \Phi_M$

and

$$U_2-U_1=(u^*/k)\,\Phi_M \qquad (15)$$

- If $z_1,\ z_2,\ U_1,\ U_2$ and L are known, u^* and consequently momentum flux M can be obtained from (15)

- After u^* , any other flux F can be computed from (14)

$$S_2-S_1=[F/(u^*\,k)]\ \Phi_F \qquad (14)$$

- L depends on fluxes, highly implicit equations
- Iterative approach
  - Accurate
  - Flexible
  - Allows different $z0$'s for different variables
- Integral functions Ψ_F
  - Paulson (1970) unstable range
  - Holtslag & DeBruin (1988) stable range

- Lower boundary condition
  - Independent of stratification, the profiles assume logarithmic form near lower boundary, singularity for $z=0$
  - Log profiles end at small but finite height $z0$ (roughness height or roughness length), variables take on their lower boundary values at this height
  - Variation of $z0$ significantly affects fluxes

- Viscous sublayer next to surface, no space for turbulent eddies, molecular transports limit fluxes
  - Implicit, through *z0* over land, Zilitinkevich (1995)
  - Explicit over water, Janjic (1994)

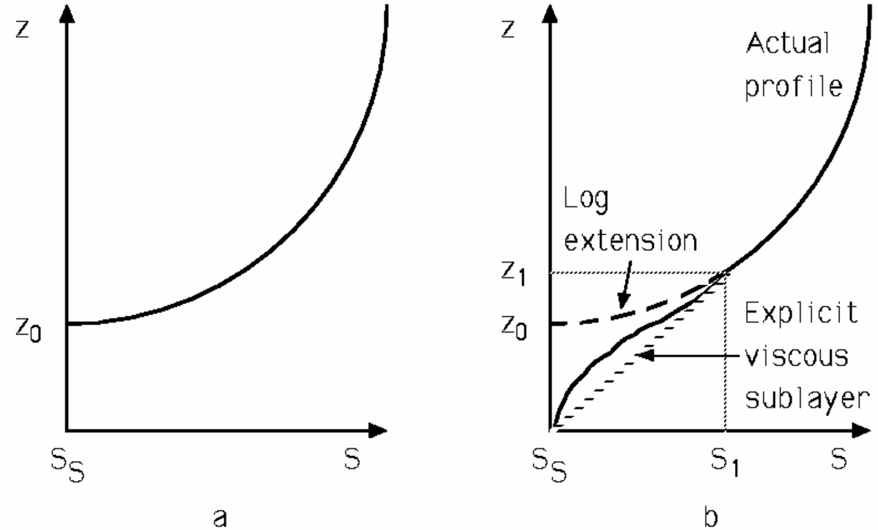


Fig. 1. Log profile ending (a), and log profile with viscous sublayer ending (b).

Betts-Miller-Janjic Convection Scheme

- Triggering mechanism
- Cloud model, blend of (i) Betts (1986) temperature profiles and (ii) Janjic (1994) moisture profiles and relaxation time scale

- Triggering mechanism
  - Find maximum buoyancy level in lower troposphere
  - Cloud base just below the lifting condensation level
  - Cloud top where the particle loses buoyancy

    In ascent without entrainment $fup=0$

    In ascent with entrainment $fup \neq 0$ *(for higher resolutions only)*

  - Check for positive work of buoyancy force EPSNTT *(for higher resolutions only)*

- *Abort if work of buoyancy force negative, and positive is required (for higher resolutions only)*

- Abort if cloud height does not reach the threshold for convection

- Deep convection, if cloud height exceeds the deep convection threshold

- Shallow convection, if cloud height exceeds the threshold for convection, but not the threshold for deep convection

Cloud model

- Reference profiles for temperature and humidity

- Relaxation toward reference profiles

- Deep convection reference profiles
  - 1st guess temperature (Betts, 1986)
    - Somewhat less stable than moist adiabat below freezing level
    - tends to the moist adiabat as the cloud top is approached
  - 1st guess moisture profile (Janjic, 1994)
    - Cloud efficiency=const x entropy change/precipitation
    - No single prescribed moisture reference profile, two envelope profiles
    - No single prescribed relaxation time
    - Moisture reference profile and relaxation time depend on cloud efficiency

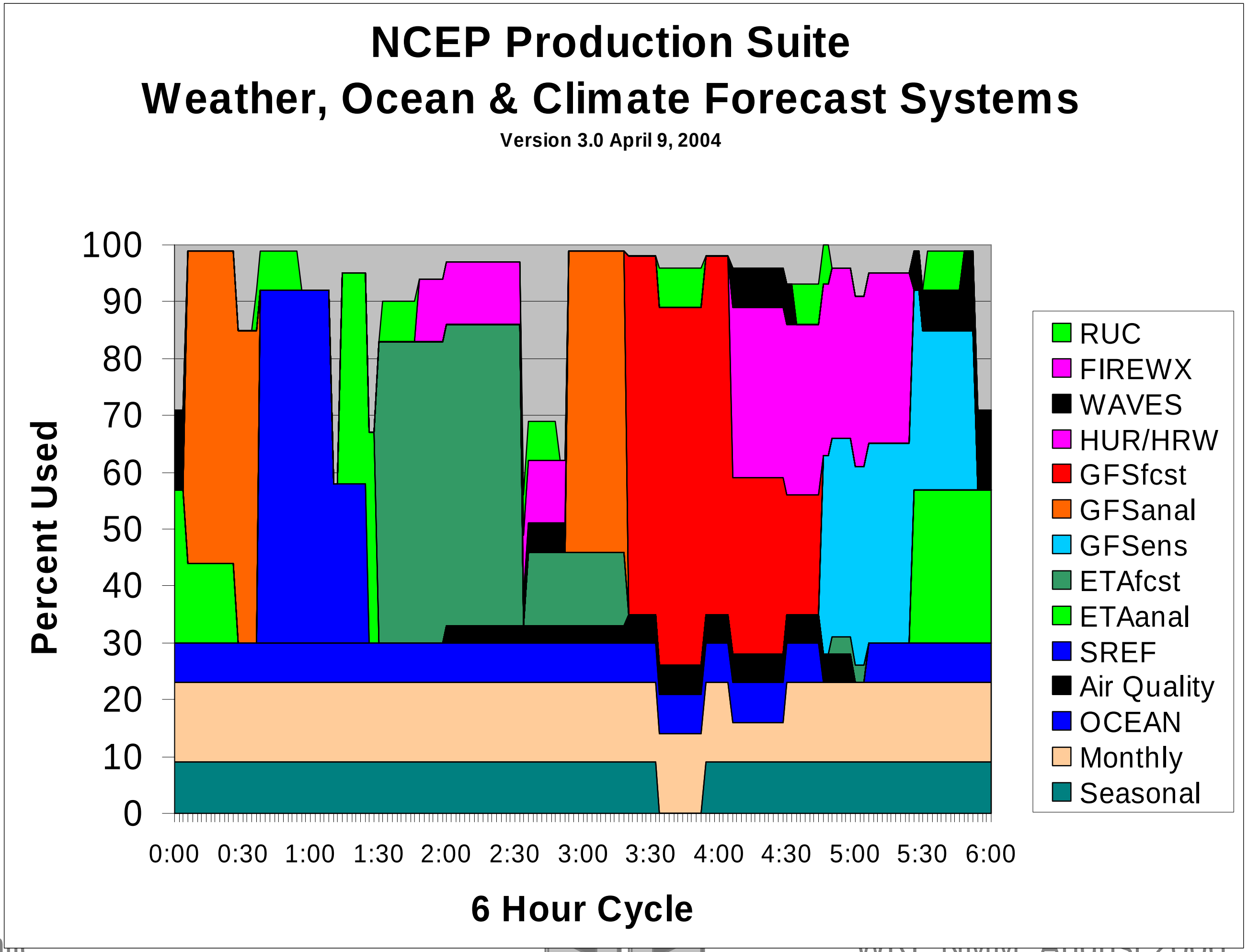
- Final reference profiles imposing enthalpy conservation
- If precipitation negative, or entropy change below threshold EPSNTP, abort deep convection and try shallow convection with lower cloud top
- Otherwise, relax toward deep reference profiles

- Shallow convection reference profiles
  - Temperature, mixing line (Betts, 1986)
  - Moisture, requirements for enthalpy conservation, small positive entropy change (Janjic, 1994)

- Problem, convection at single digit resolutions
  - Too much convection, spread out light precipitation
  - Too little convection, precipitation bulls-eyes (CICK)
- Trimming excessive convection
  - Moister reference profiles
  - Minimum entropy change required for onset of convection (EPSNTP)
  - Entrainment (FUP)
  - Positive work of buoyancy during ascent (EPSNTT)

NCEP Operational Model Suite

- “Jigsaw puzzle” from 2004 of NCO productions
- Lesson: Models must be efficient



Overview of Ferrier microphysics

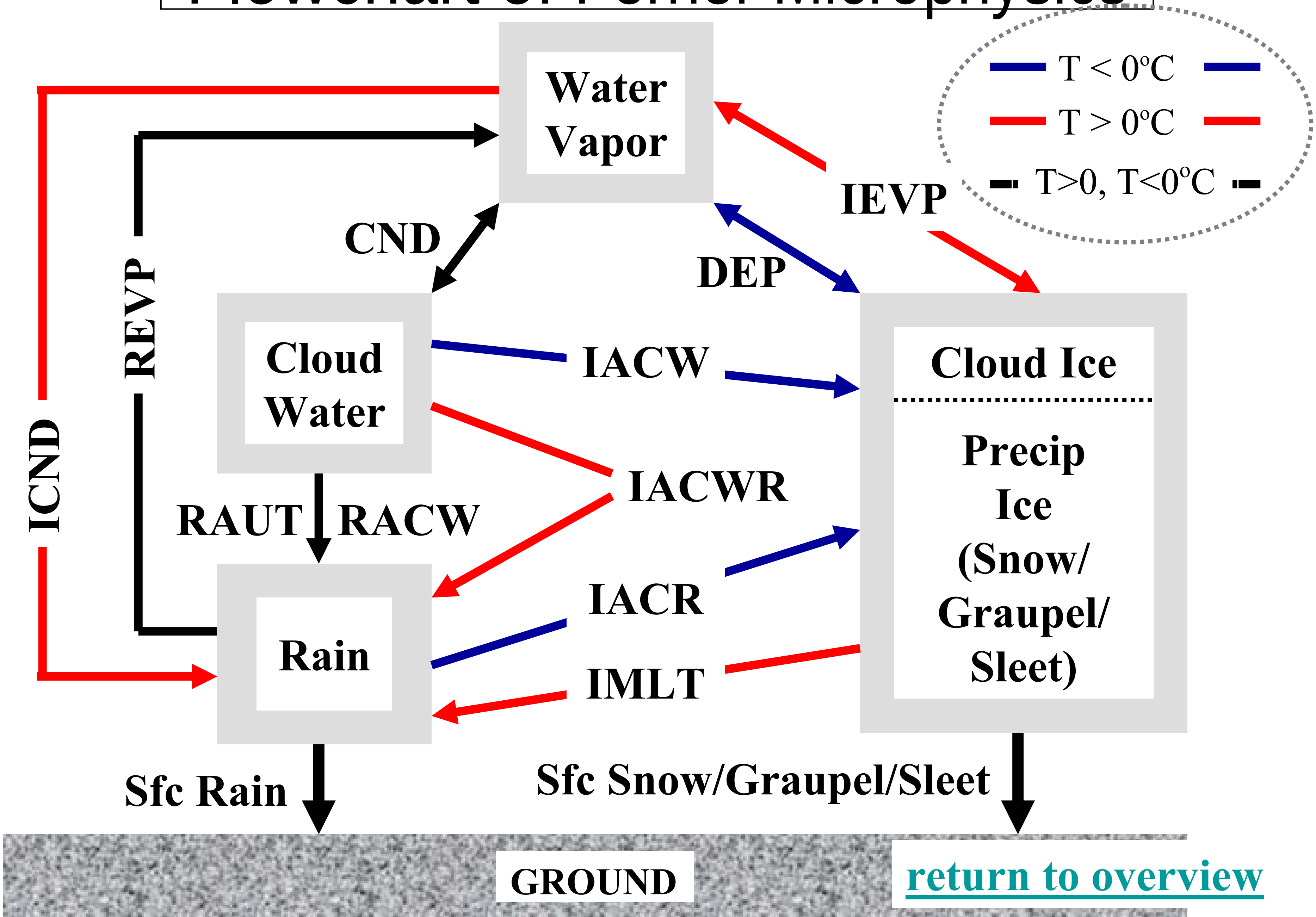
- Calculates mixing ratios of water vapor, cloud water, rain, and ice (“cloud ice” + “precipitation ice”)
  - Flowchart depicting microphysical sources & sinks
  - List of microphysical processes
- Precipitation sedimentation - partitioned between storage in grid box & fall out through bottom of box
- Only water vapor and total condensate are advected; an algorithm is used to derive hydrometeors from total condensate using storage arrays
- Supercooled liquid water allowed to T_{ice} (= -30°C)
- Assumed ice spectra based on global observations of stratiform layer clouds by Ryan (1996, 2000)
- Other features of scheme are summarized here
- More info at this ppt talk; also contact Brad.Ferrier@noaa.gov

List of microphysical processes

Q_v = vapor, Q_c = cloud water, Q_r = rain, Q_i = ice

Acronym	Process Description	Source	Sink
CND	Cloud condensation (>0), evaporation (<0)	Q_c	Q_v
REVP	Rain evaporation	Q_v	Q_r
RAUT	Cloud water autoconversion to rain	Q_r	Q_c
RACW	Cloud water accretion by rain	Q_r	Q_c
DEP	Ice initiation and deposition (>0), sublimation (<0)	Q_i	Q_v
IMLT	Melting of ice	Q_r	Q_i
IACW	Cloud water accretion by ice (riming)	Q_i	Q_c
IACWR	Cloud water accretion by melting ice, shed to rain	Q_r	Q_c
IACR	Rain accretion by ice	Q_i	Q_r
IEVP	Evaporation of (wet) melting ice	Q_v	Q_i

Flowchart of Ferrier Microphysics



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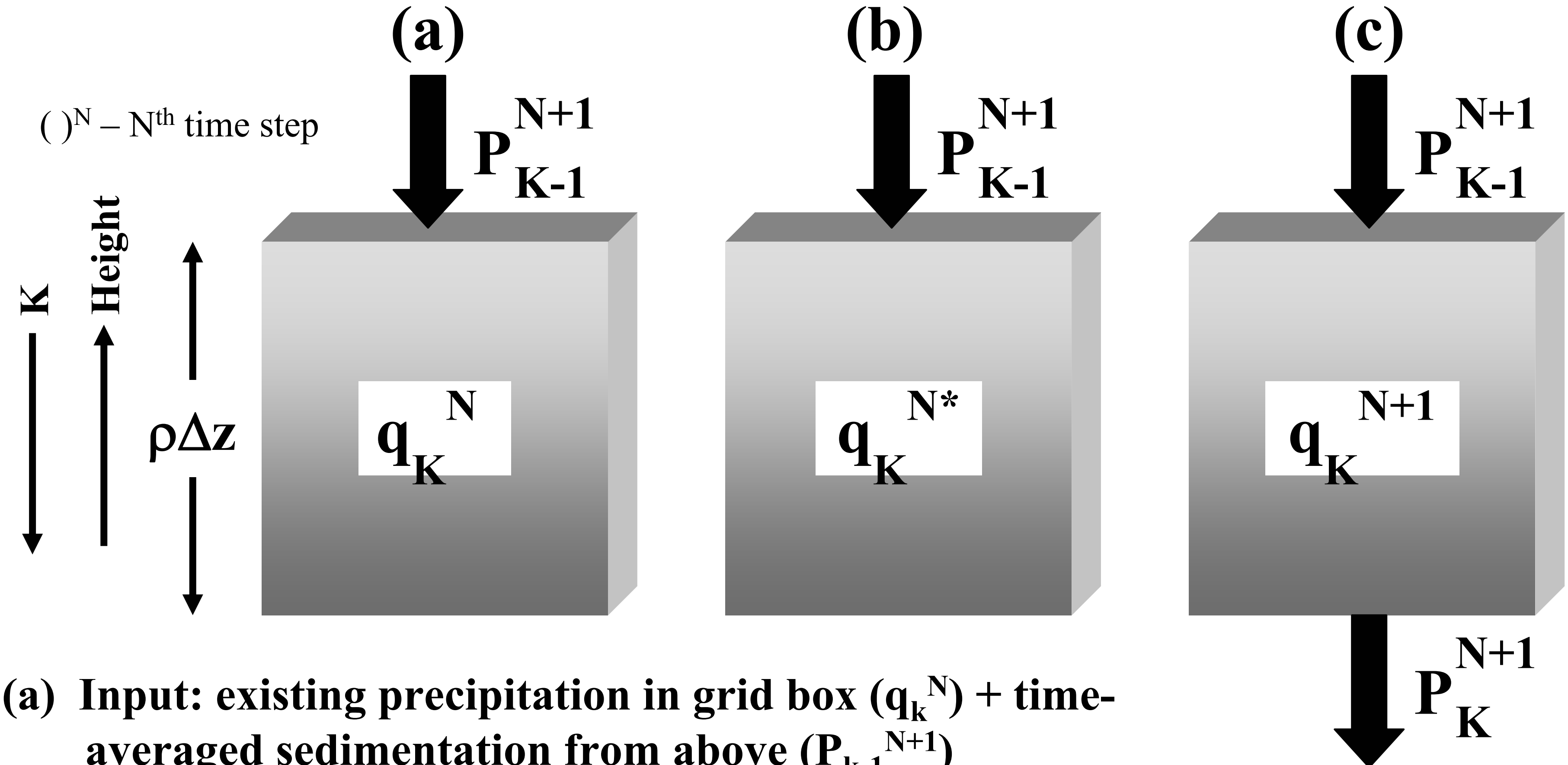
Precipitation Sedimentation



(a) Input: existing precipitation in grid box (q_k^N) + time-averaged sedimentation from above (P_{k-1}^{N+1})

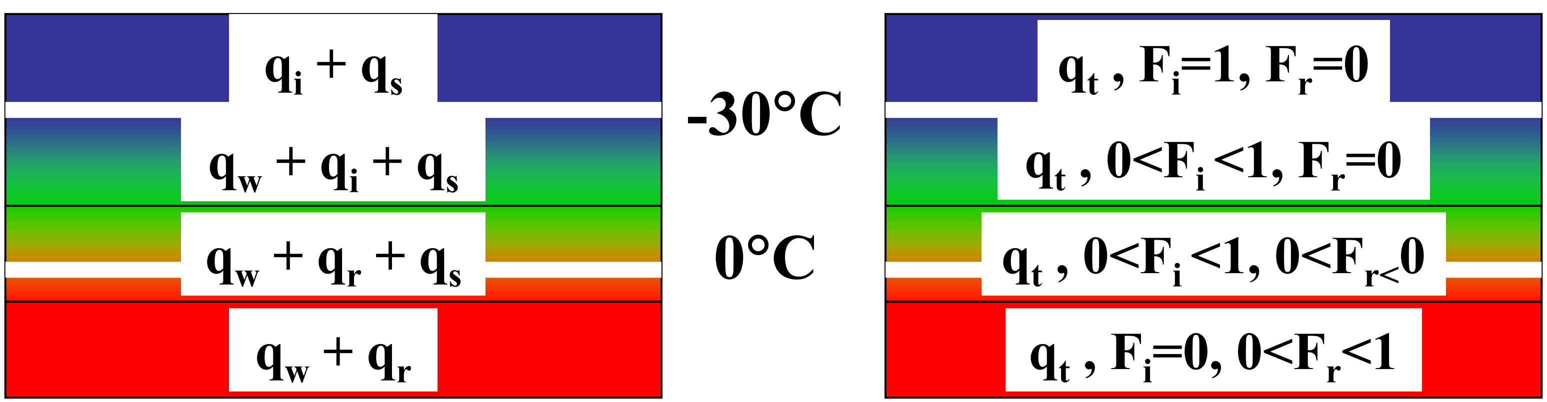
(b) Microphysical sources/sinks based on time-averaged mixing ratio, q_K^{N*}

(c) Partition storage (q_k^{N+1}) and precipitation through bottom of box (P_k^{N+1}) based on thickness of model layer ($\rho\Delta z$) & estimated fall distance ($\Delta t \cdot V_k$)

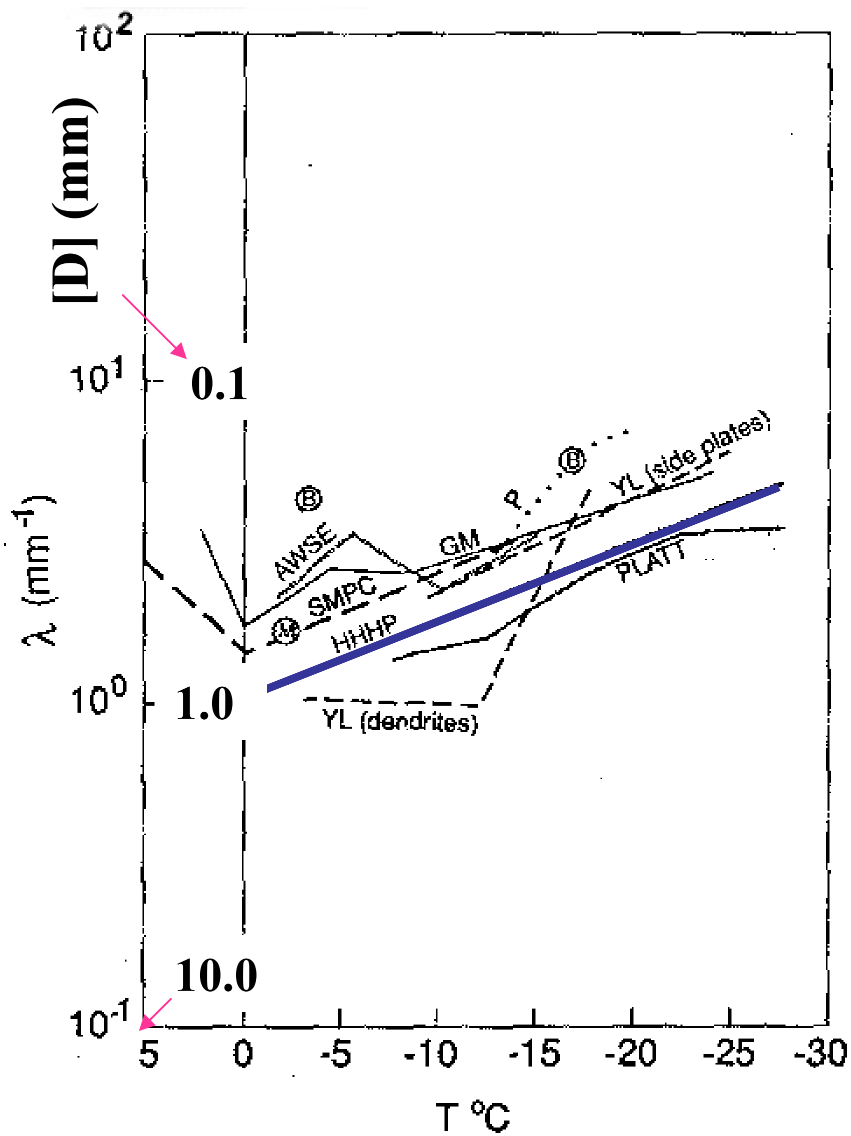
Deriving hydrometeors from total condensate

- **Water vapor (q_v), total condensate (q_t) advected in model (efficient)**
- **Cloud water (q_w), rain (q_r), cloud ice (q_i), precip ice ("snow", q_s) calculated in microphysics**
- **Local, saved arrays store fraction of condensate in form of ice (F_i), fraction of liquid in form of rain (F_r). Assumed fixed with time in column between microphysics calls. Note that $0 \le F_i , F_r \le 1$.**
- $q_t = q_w + q_r + q_i + q_s$, $q_{ice} = q_i + q_s \Rightarrow F_i = q_{ice}/q_t$, $F_r = q_r/(q_w + q_r)$

Internal to microphysics ***Rest of model***



Size of “snow” a function of temperature



Observed size distributions of ice as functions of temperature, fit to (M-P) exponential spectra as

$$N(D)=N_o \exp(-\lambda \cdot D),$$

N_o is the intercept, λ is the slope, & $[D] = \lambda^{-1}$ is the mean diameter

- **HHHP (Washington state)**
  SMPC (California)
  GM (California)
  PLATT (multiple locations)
  AWSE (Australia)
  YL (China)
  B, M (Europe)

Adjust [D] so that $0.1L^{-1} \le N_s \le 20L^{-1}$

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Other Features of Microphysics

- Discrimination between cloud ice and "snow"
  - Assume 50 μm size cloud ice, no fall speeds
  - No cloud ice if T>0°C (melting) $\Rightarrow$ only "snow"
  - $N_s = 0.2 \cdot N_i$ (N_s=snow # conc, N_i=cloud ice # conc)
  - $N_s = 0.1 \cdot N_i$ if above ice saturation & $-8°C < T < -3°C$
- Variable rime density $\Rightarrow$ assumes accreted liquid water fills air holes of ice lattice w/o changing volume
  - "Rime Factor" (3D array) $\Rightarrow$ $RF = \frac{TotalGrowth}{DepositionalGrowth}$
- Efficient look-up tables store solutions for:
  - Various particle moments (ventilation, accretion, mass, precipitation rate) at 1 μm resolution
  - Composite rain & ice fall speed relationships
  - Increase in fall speed of rimed ice (Böhm, 1989)