Overview of Physics

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Physics

- Radiation
  - Longwave
  - Shortwave
- Surface
  - Surface layer
  - Land/water surface
  - PBL
- Turbulence/Diffusion
- Cumulus parameterization
- Microphysics
- *Nudging/FDDA*

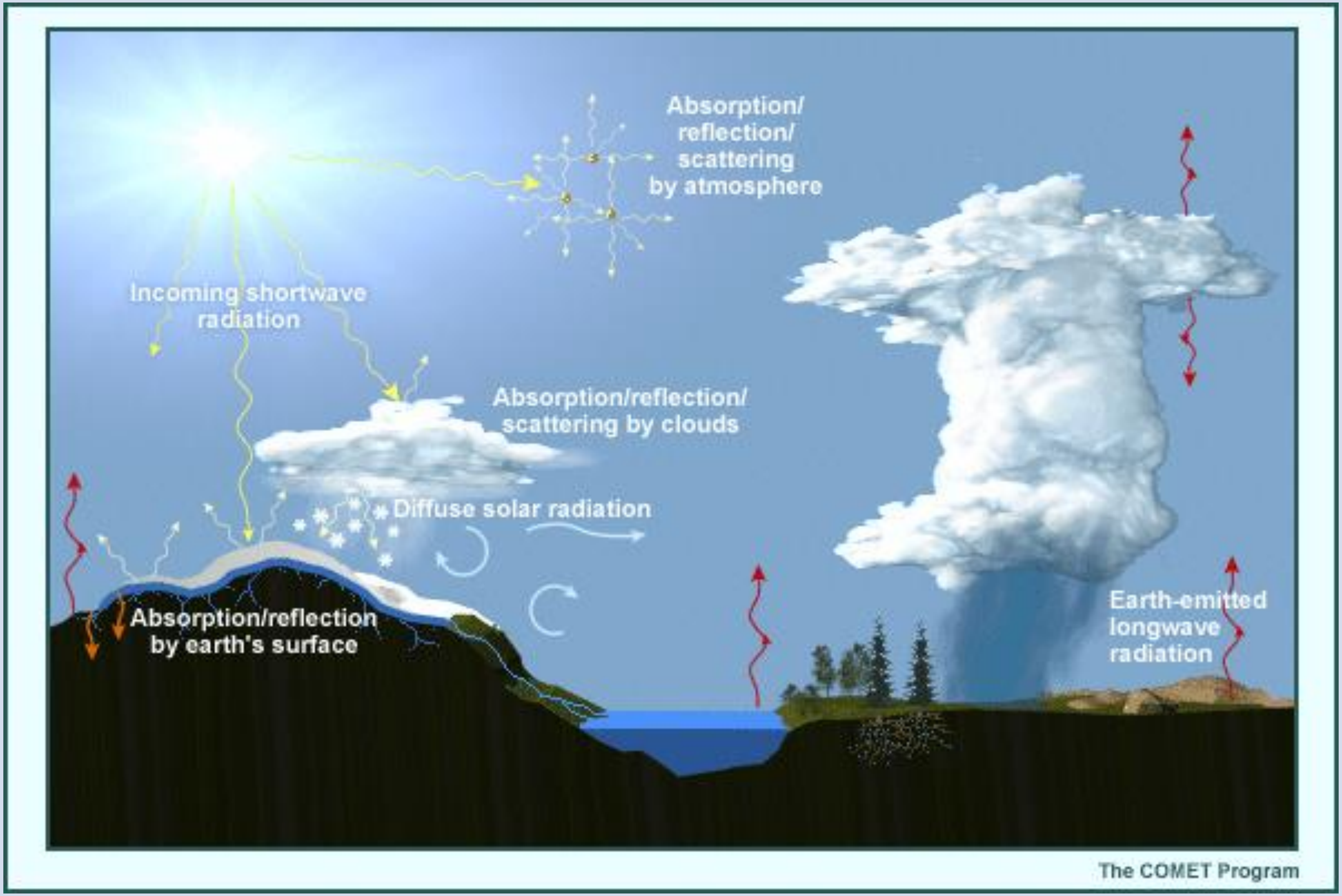
Radiation

Provides

Atmospheric temperature tendency profile

Surface radiative fluxes

Atmosphere Radiation Processes



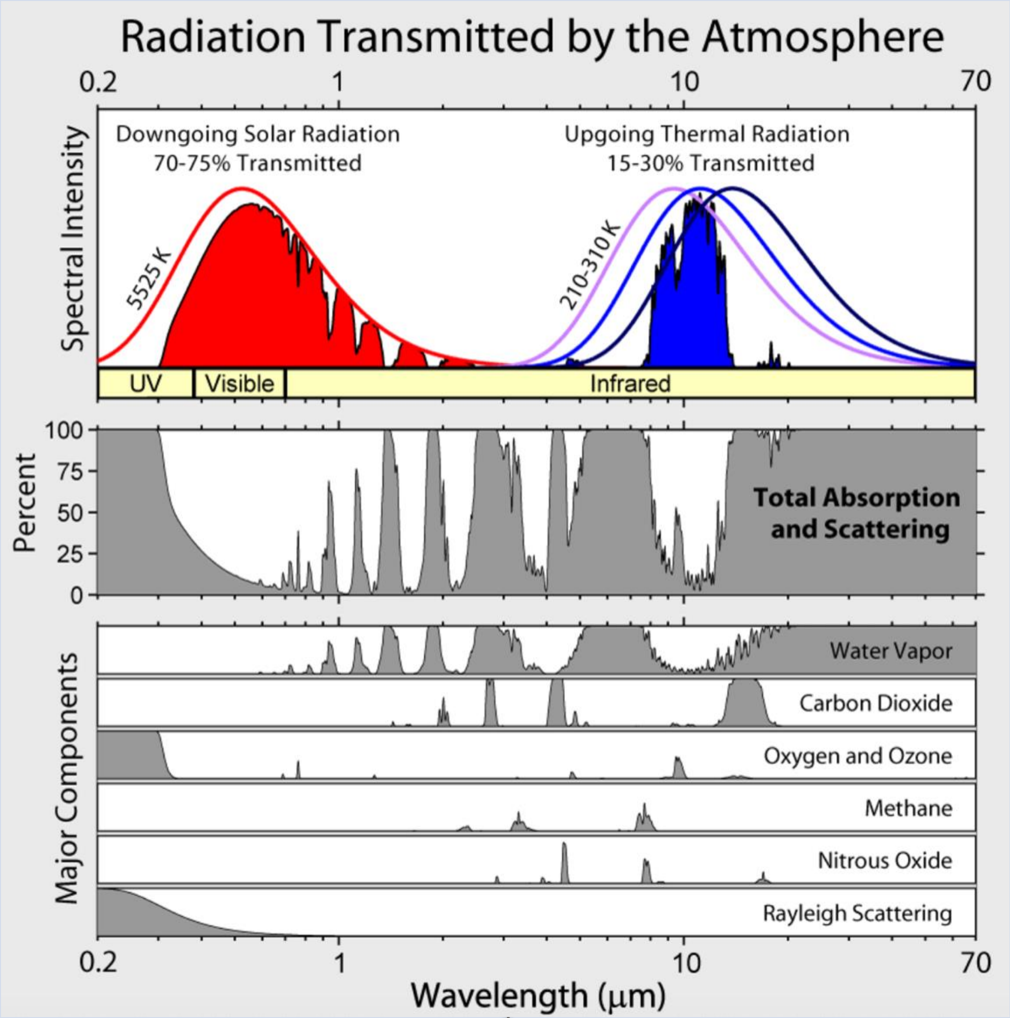
Longwave Radiation Schemes

- Compute clear-sky and cloud upward and downward radiation fluxes
  - Consider IR emission from layers
  - Surface emissivity based on land-type
  - Flux divergence leads to cooling in a layer
  - Downward flux at surface important in land energy budget
  - IR radiation generally leads to cooling in clear air (~2K/day), stronger cooling at cloud tops and warming at cloud base

Clear Sky: IR-active Gases

- H_2O – from model prognostic vapor
- CO_2 – well-mixed, specified constant in whole atmosphere
  - Since V4.2 CO_2 is calculated from year in RRTMG
  - For CAM, RRTM and RRTMG, GHG input file can update CO_2, N_2O and CH_4
- O_3 – schemes have own climatologies
  - CAM and RRTMG have monthly, zonal, pressure-level data
  - Others use single profiles (Goddard has 5 profiles to choose from)

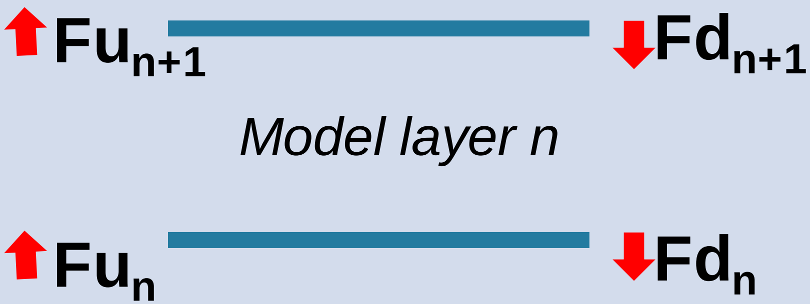
Radiation Effects in Clear Sky



shortwave | **longwave**

Longwave Radiative Transfer

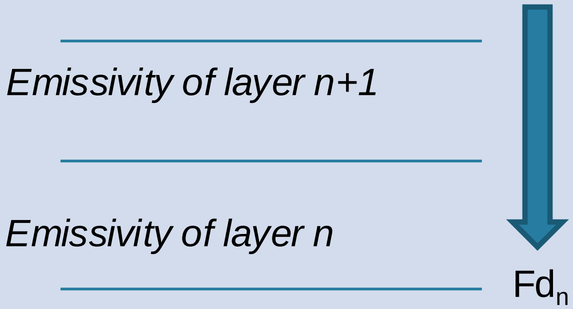
Upward and downward IR fluxes, $\mathbf{F_u}$ and $\mathbf{F_d}$ in W/m^2



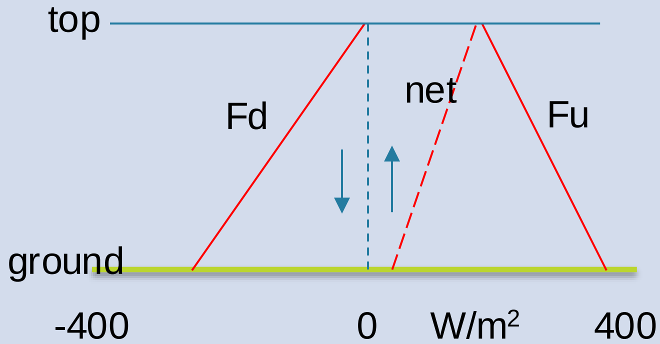
Temperature tendency is given by vertical flux convergence

$$\rho\, c_p\, dT_n/dt = d(F_u+F_d)/dz$$

Longwave Radiative Transfer



Flux Profiles



$$F = \int_0^1 B(T,\nu)\, d\varepsilon$$

B(T,ν) is Planck function of frequency

ε is layer emissivity

For Fd_n integrate upwards from each level n

Sum *B(T)*Δε from levels above

Emissivity ε depends on

gases, clouds, aerosols, pressure, T

For Fu integrate downwards from level n

Clouds

- All schemes interact with resolved model cloud fields allowing for ice and water clouds and precipitating species
  - Sensitive to particle sizes which can come from microphysics
  - Clouds strongly affect IR at all wavelengths (considered “grey bodies”) and are almost opaque to it
- Cloud fractions as a function of height also considered

Longwave Radiation schemes

ra_lw_physics	Scheme	Reference	Added
1	RRTM	Mlawer et al. (1997, JGR)	2000
3	CAM	Collins et al. (2004, NCAR Tech. Note)	2006
4	RRTMG	Iacono et al. (2008, JGR)	2009
5	New Goddard	Chou and Suarez (2001, NASA Tech Memo)	2011
7	FLG (UCLA)	Gu et al. (2011, JGR), Fu and Liou (1992, JAS)	2012
14	RRTMG-K	Baek (2017, JAMES)	2018
31	Held-Suarez		2008
99	GFDL	Fels and Schwarzkopf (1981, JGR)	2004

Longwave Radiation schemes

ra_lw_ physics	Scheme	Cores+Chem	Microphysics Interaction	Cloud Fraction	GHG
1	RRTM	ARW NMM	Qc Qr Qi Qs Qg	1/0	constant or yearly GHG
3	CAM	ARW	Qc Qi Qs	Max-rand overlap	yearly CO2 or GHG
4	RRTMG	ARW +Chem(τ)	Qc Qr Qi Qs	Max-rand overlap	constant or yearly GHG
5	New Goddard	ARW	Qc Qr Qi Qs Qg	Max-rand	constant
7	FLG (UCLA)	ARW	Qc Qr Qi Qs Qg	1/0	constant
14	RRTMG-K	ARW	Qc Qr Qi Qs	Max-rand overlap	constant
31	Held-Suarez	ARW	none	none	none
99	GFDL	ARW NMM	Qc Qr Qi Qs	Max-rand overlap	constant

Shortwave Radiation

- Compute clear-sky and cloudy solar fluxes
- Include annual and diurnal solar cycles
- Most schemes consider downward and upward (reflected) fluxes
- Primarily a warming effect in clear sky
- Important component of surface energy balance

Clear Sky and Aerosols

- Main gas effect in troposphere is water vapor absorption (CO_2 minor effect)
- Aerosols can be considered in several ways
  - Specified optical depths
  - Aerosol monthly 3d climatology
  - Interaction with WRF-Chem

Ozone

- Ozone heating by ultraviolet maintains warm stratosphere
- Important for model tops above about 20 km (50 hPa)
- A climatology of month, latitude and pressure is used

Radiative Transfer

- In contrast to longwave, shortwave has no emission from the atmosphere but does have reflection from internal layers (aerosols and clouds) and as well as the surface
  - This requires a matrix solution rather than integrals

Surface Shortwave

- Slope effects for high resolution
  - South facing slopes have more solar radiation
  - Good for dx < 2 km
- Radiation can also be separated into diffuse and direct components for solar energy applications

Shortwave Radiation schemes

ra_sw_physics	Scheme	Reference	Added
1	Dudhia	Dudhia (1989, JAS)	2000
2	Goddard	Chou and Suarez (1994, NASA Tech Memo)	2000
3	CAM	Collins et a. (2004, NCAR Tech Note)	2006
4	RRTMG	Iacono et al. (2008, JGR)	2009
5	New Goddard	Chou and Suarez (1999, NASA TM)	2011
7	FLG (UCLA)	Gu et al. (2011, JGR), Fu and Liou (1992, JAS)	2012
14	RRTMG-K	Baek et al. (2017, JAMES)	2018
99	GFDL	Fels and Schwarzkopf (1981, JGR)	2004

Shortwave Radiation

ra_sw_physics	Scheme	Cores+Chem	Microphysics Interaction	Cloud Fraction	Ozone
1	Dudhia	ARW NMM + Chem(PM2.5)	Qc Qr Qi Qs Qg	1/0	none
2	GSFC	ARW +Chem(τ)	Qc Qi	1/0	5 profiles
3	CAM	ARW	Qc Qi Qs	Max-rand overlap	Lat/month
4	RRTMG	ARW +Chem(τ), NMM	Qc Qr Qi Qs	Max-rand overlap	1 profile or lat/month
5	New Goddard	ARW	Qc Qr Qi Qs Qg	Max-rand	5 profiles
7	FLG (UCLA)	ARW	Qc Qr Qi Qs Qg	1/0	5 profiles
14	RRTMG-K	ARW	Qc Qr Qi Qs	Max-rand overlap	1 profile or lat/month
99	GFDL	ARW NMM	Qc Qr Qi Qs	Max-rand overlap	Lat/date

Radiation Time Step

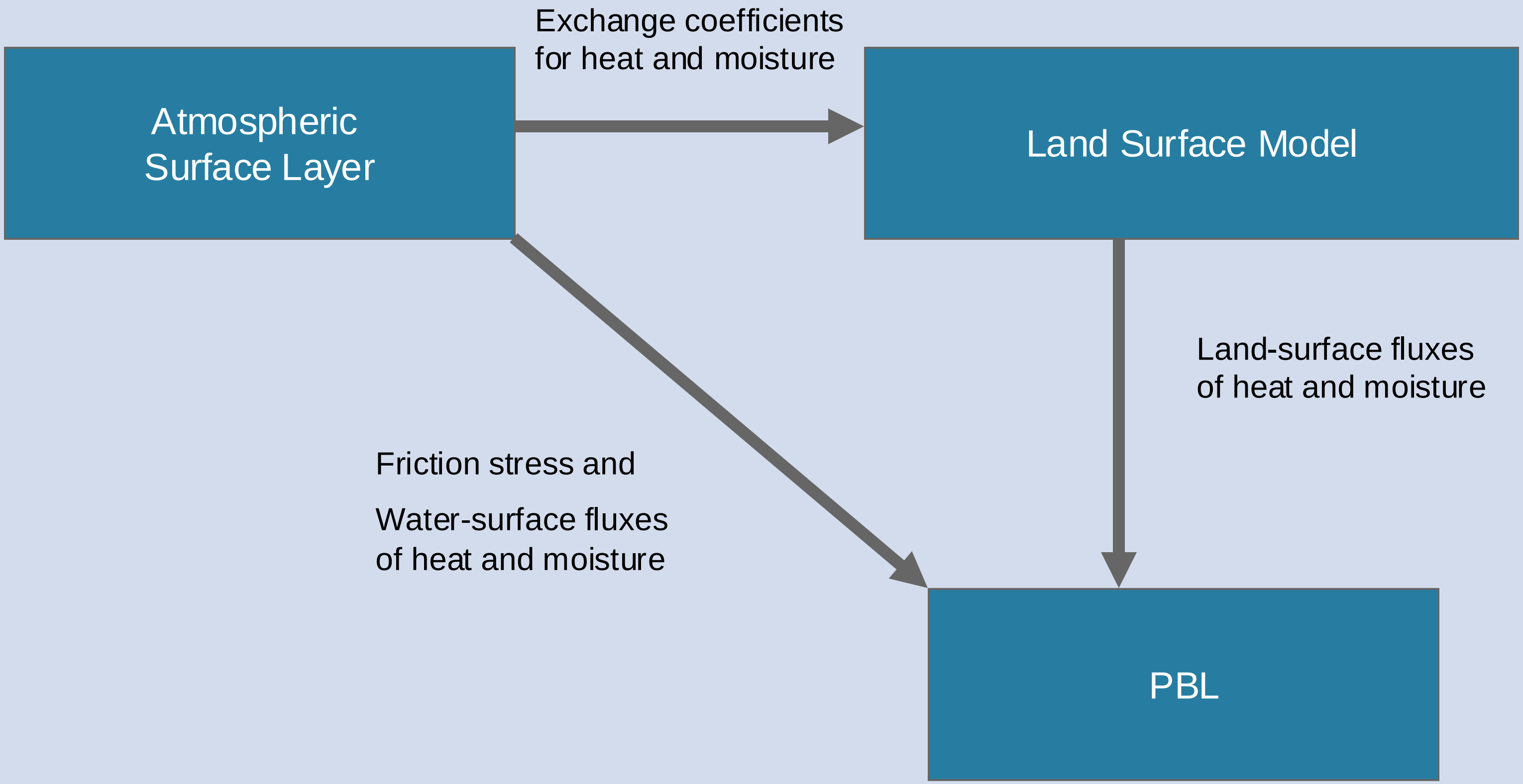
- Radiation is too expensive to call every step
- *radt* in minutes controls this
  - Needs to mostly resolve cloud motion on the grid
  - One minute per dx kilometer is about right (10 minutes for 10 km)
  - This gives about one radiation call every ten times steps when combined with the dx timestep rule

Surface schemes

Surface layer of atmosphere diagnostics (exchange/transfer coeffs)

Land Surface: Soil temperature /moisture /snow prediction /sea-ice temperature

Surface Physics Components

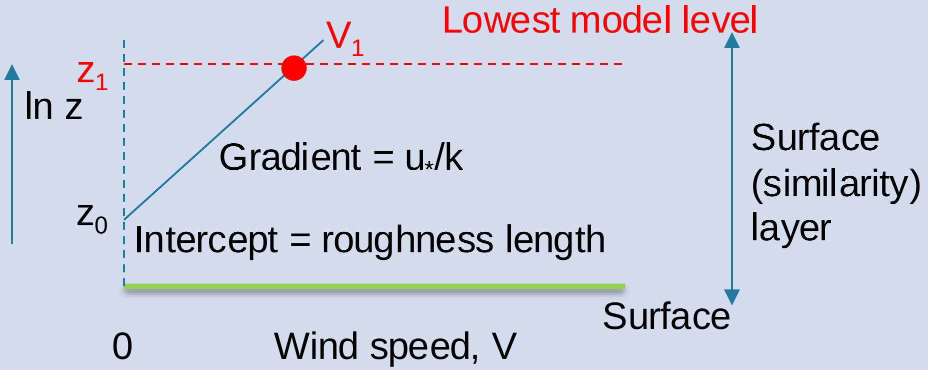


Surface Layer

- Constant flux layer is about 0.1 x PBL height (~100 m)
- Lowest model level is within this layer (typically 10-50 m)
- Therefore lowest level variables can be used to derive surface fluxes via **similarity theory**
- Example, heat flux

$$H = \rho c_p u_* \theta_*$$

- In similarity theory u_* and θ_* are constant in surface layer
- Roughness length z_0 is input dependent on surface



Neutral case:

$dV/d(\ln z) = u^* / k$

so

$u_* = kV_1 / \ln(z_1/z_0)$

k = 0.4 (von Karman constant)

Surface Fluxes

- Heat, moisture and momentum
- Similarity theory used to relate surface fluxes to lowest level

$$H = \rho c_p u_* \theta_* \qquad E = \rho u_* q_* \qquad \tau = \rho u_* u_*$$

$$u_* = \frac{kV_r}{\ln(z_r / z_0) - \psi_m} \qquad \theta_* = \frac{k\Delta\theta}{\ln(z_r / z_{0h}) - \psi_h} \qquad q_* = \frac{k\Delta q}{\ln(z_r / z_{0q}) - \psi_h}$$

Ψ (z/L) is the stability function (+ve for unstable) where z/L is related to sfc Ri
Subscript *r* is reference level (lowest model level, or 2 m or 10 m)
Δ refers to difference between surface and reference level value
z_0 are the roughness lengths
k is the von Karman constant (0.4)

Exchange Coefficient

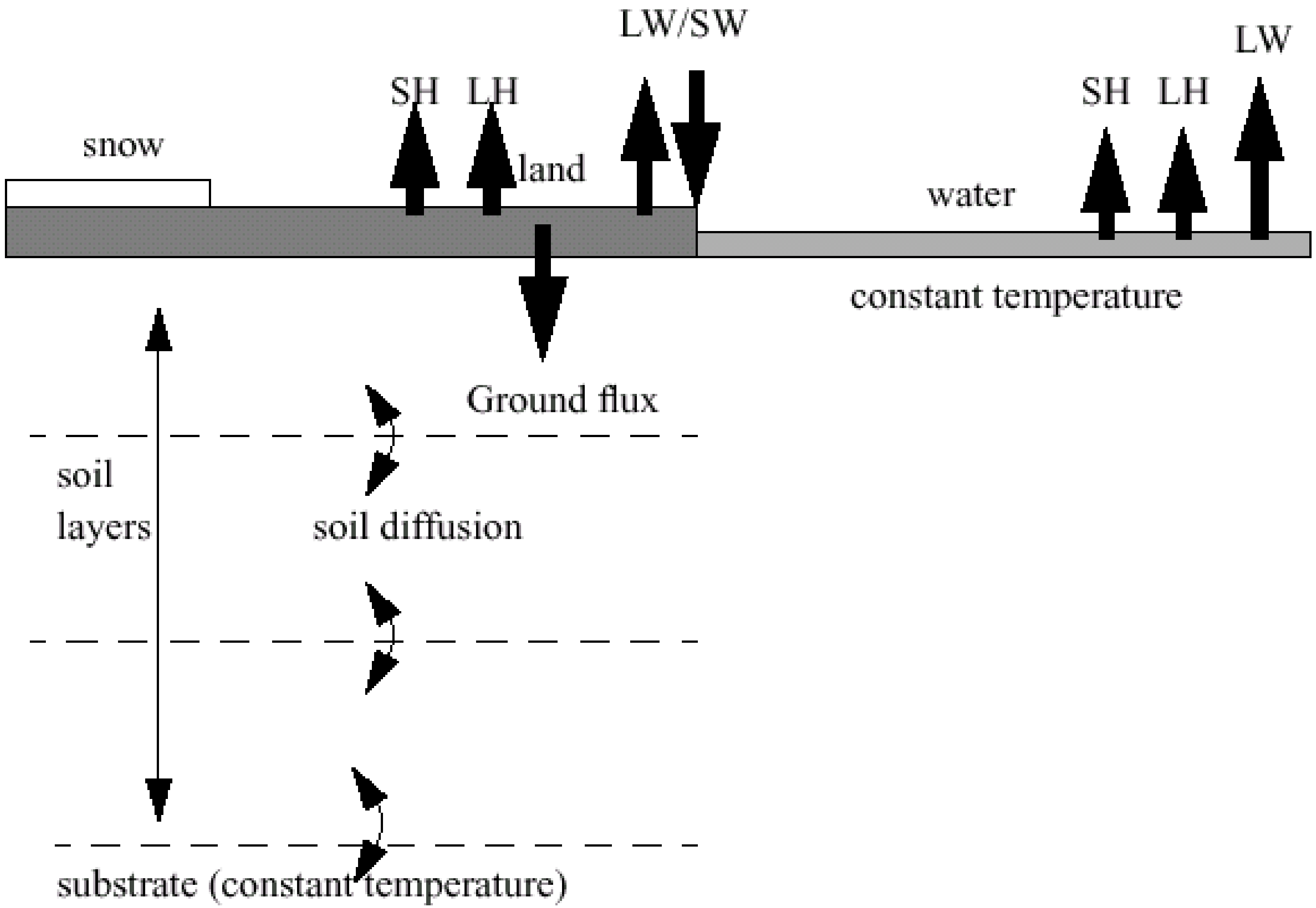
- C_{hs} is the exchange coefficient for heat, defined such that

$$H = \rho c_p C_{hs} \Delta\theta$$

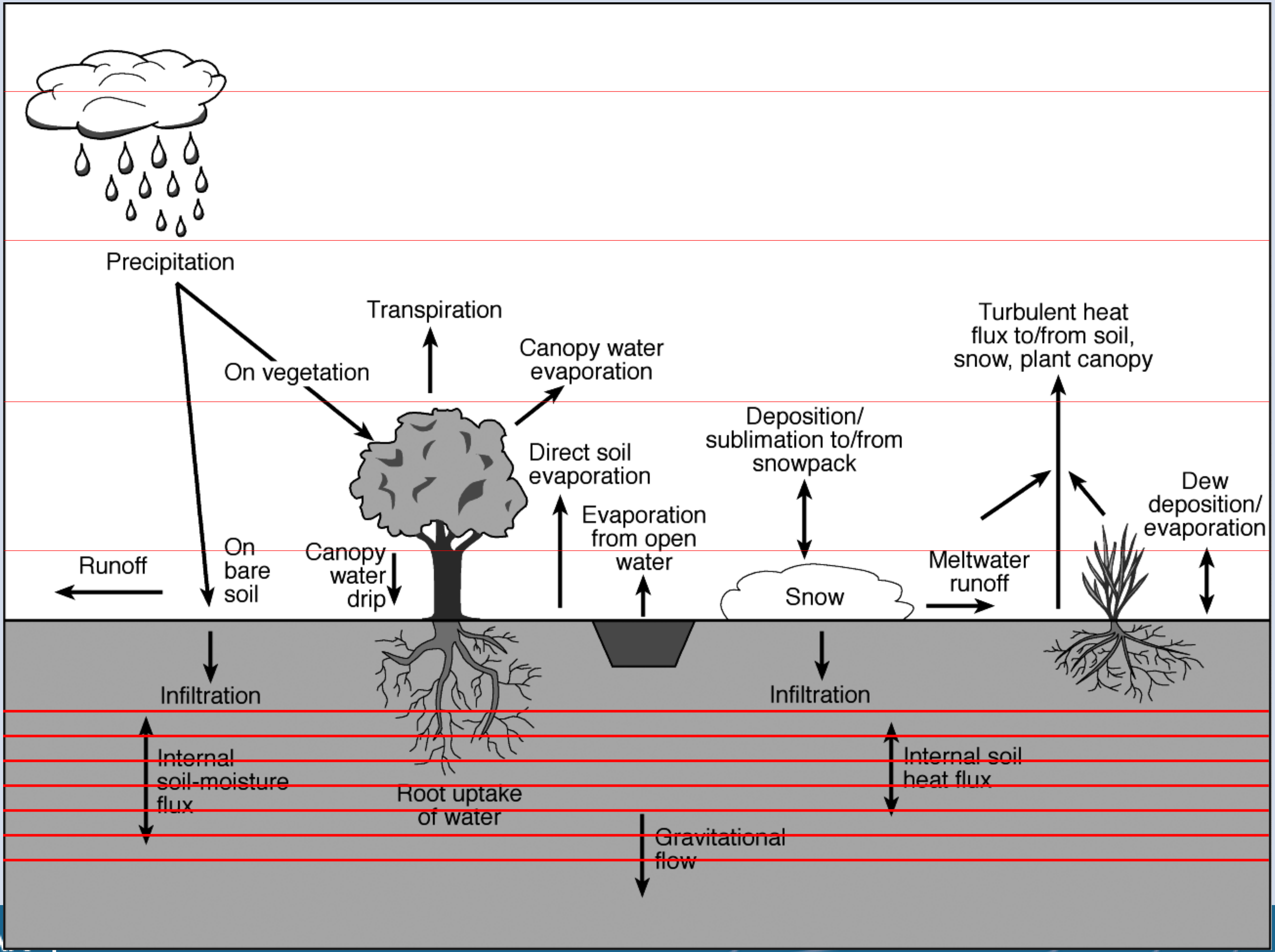
It is the ratio of surface θ flux $(w'\theta')_s$ to θ difference (units of velocity) required by the land model and is related to the roughness length, stability function and u* by

$$C_{hs} = \frac{k u_*}{\ln\left(\frac{z}{z_0}\right) - \psi_h}$$

Illustration of Surface Processes



Land-Surface Model Processes



Land-Surface Model

- Driven by surface energy and water fluxes
- Predicts soil temperature and soil moisture in layers
- Predicts snow water equivalent on ground. May have multi-layer snow model.
- May predict canopy moisture and temperature
- Vegetation effects (evapotranspiration, root zone, trees, etc.)
- Soil effects (drainage, thermal properties etc.)
- Urban models exist for more sophisticated representation of "urban canyon" effects and anthropogenic diurnal heat source

Land Surface Models

sf_surface_physics	Scheme	Reference
1	5-layer slab	Dudhia (1996)
2	Noah	Chen and Dudhia (MWR, 2001)
3	RUC	Benjamin et al. (MWR, 2004)
4	Noah-MP	Niu et al. (JGR, 2011), Yang et al. (JGR, 2011)
5	CLM4	Lawrence et al. (JAMES, 2011)
7	Pleim-Xiu	Pleim and Xiu (1995, 2003, JAM)
8	Simple SiB	Xue et al. (JClim, 1991)

Land Surface Models

sf_surface_physics	Scheme	Soil Temperature Layers	Soil Moisture Layers	Snow Layers
1	5-layer slab	5	0	0
2	Noah	4	4	1
3	RUC	6	6	1/2
4	Noah-MP	4	4	3
5	CLM4	10	10	5
7	Pleim-Xiu	2	2	1
8	Simple SiB	2	3	4

Water Surfaces

- There is a lake model (*sf_lake_physics*) for longer simulations
- Have to be careful with initializing unresolved lakes with SST
  - In WPS we recommend using TAVG for a previous period of at least a day to remove diurnal signal
- For long simulations (> 7 days) we recommend *sst_update=1* in which *real.exe* creates a *wrflowbdy* file containing varying SST, sea ice, vegetation fraction so that the model updates
- For hurricane simulations we have *sf_ocean_physics=1* which allows 1d ocean mixed layer response to strong winds (cool wake)
- We also have a simple 3d ocean model *sf_ocean_physics=2*

Planetary Boundary Layer

Provides

Boundary layer fluxes (heat, moisture, momentum)

Vertical diffusion in whole column

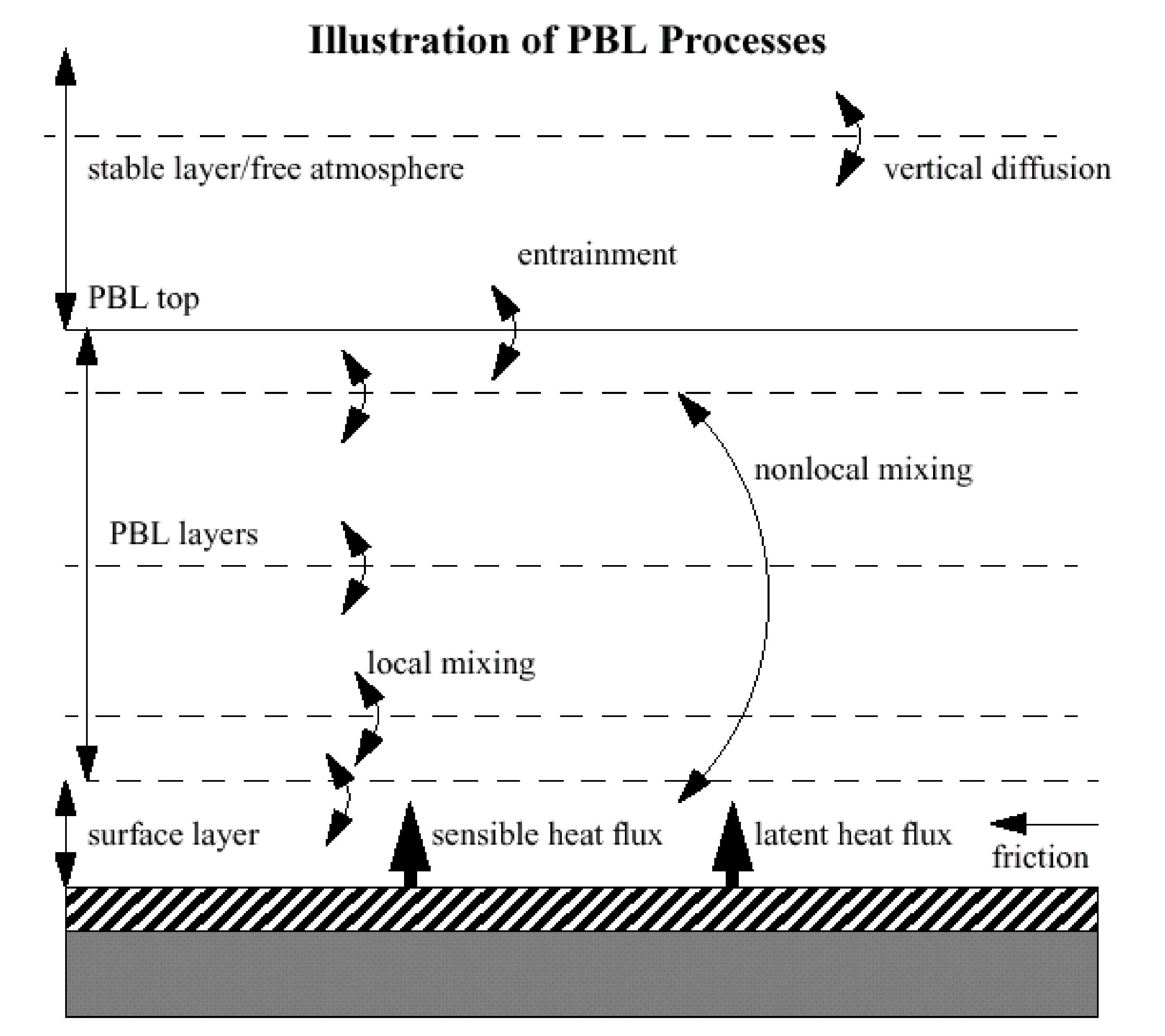
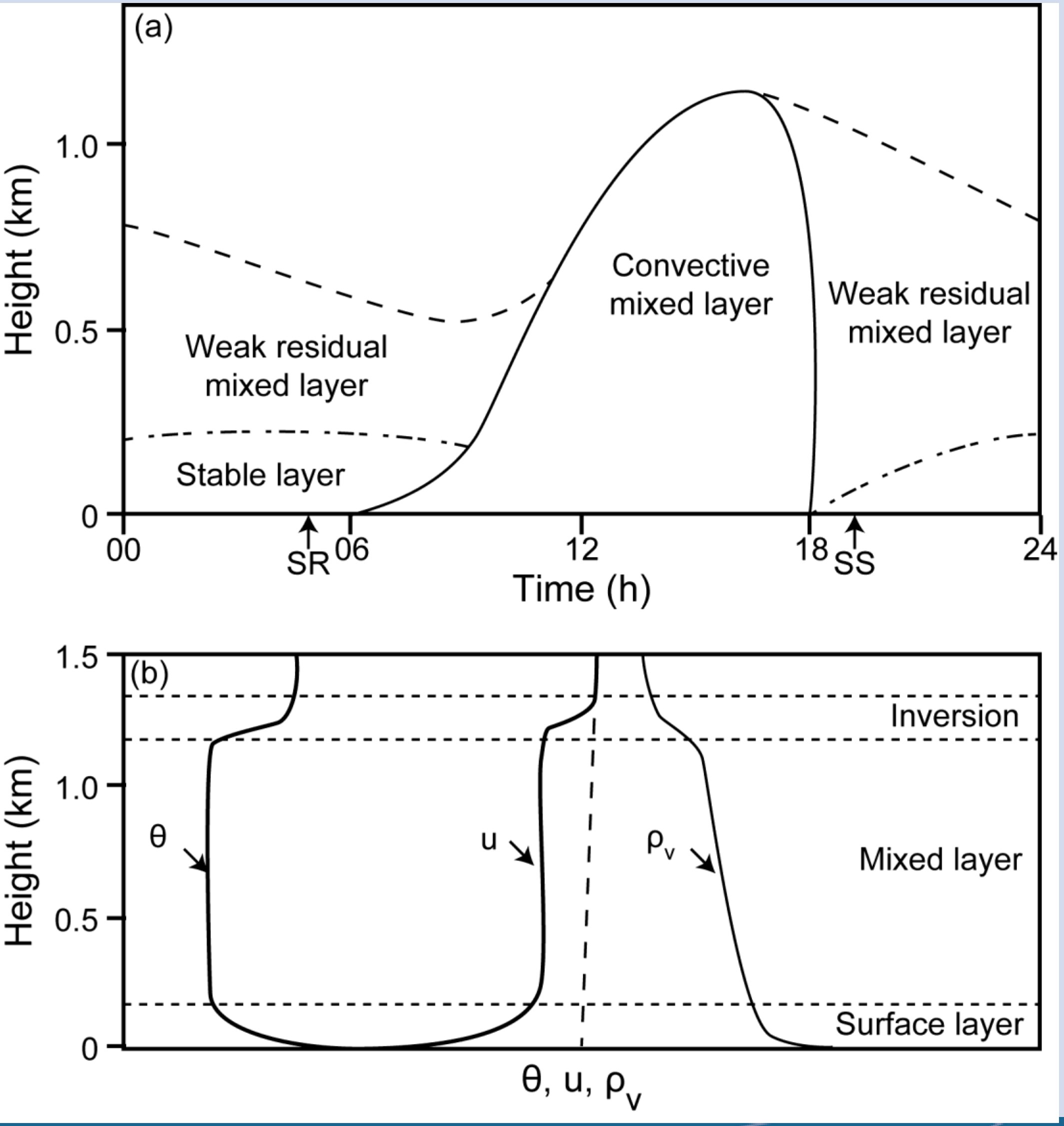


Illustration of PBL Processes
stable layer/free atmosphere
vertical diffusion
entrainment
PBL top
nonlocal mixing
PBL layers
local mixing
surface layer
sensible heat flux
latent heat flux
friction

Planetary Boundary Layer



Nonlocal PBL schemes

Non-local schemes have two main components

$$\overline{w'\phi'}^{\Delta} = \overset{(1)}{-K_\phi \frac{\partial \overline{\phi}^{\Delta}}{\partial z}} + \overset{(2)}{F_{w\phi}^{NL}}$$

(1) Term for local (L) transport by small eddies

(2) Term for nonlocal (NL) transport by large eddies

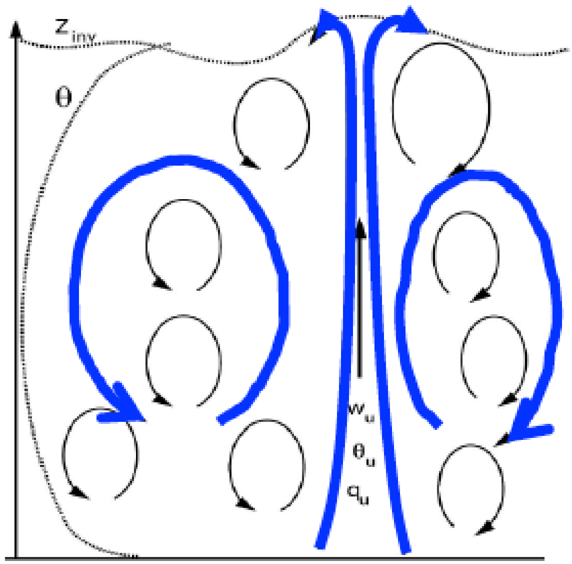


Fig. 1. Sketch of a convective updraft embedded in a turbulent eddy structure.

Explicitly included in **nonlocal PBL parameterizations**

(i.e., Mass-flux term or counter-gradient gamma)

Figure is taken from Siebesma et al. (2007, JAS)

TKE schemes

- Solve for TKE in each column
  - Buoyancy and shear production
  - Dissipation
  - Vertical mixing

$$\frac{\partial}{\partial z} K_v \frac{\partial}{\partial z} q$$

- TKE (*e*) and length-scale (*l*) are used to determine the Kv for local vertical mixing together with a stability function (S)

$$K_v = e^{1/2}\ l\ S$$

- Schemes differ most in diagnostic length-scale computations and how S is calculated

Nonlocal Schemes

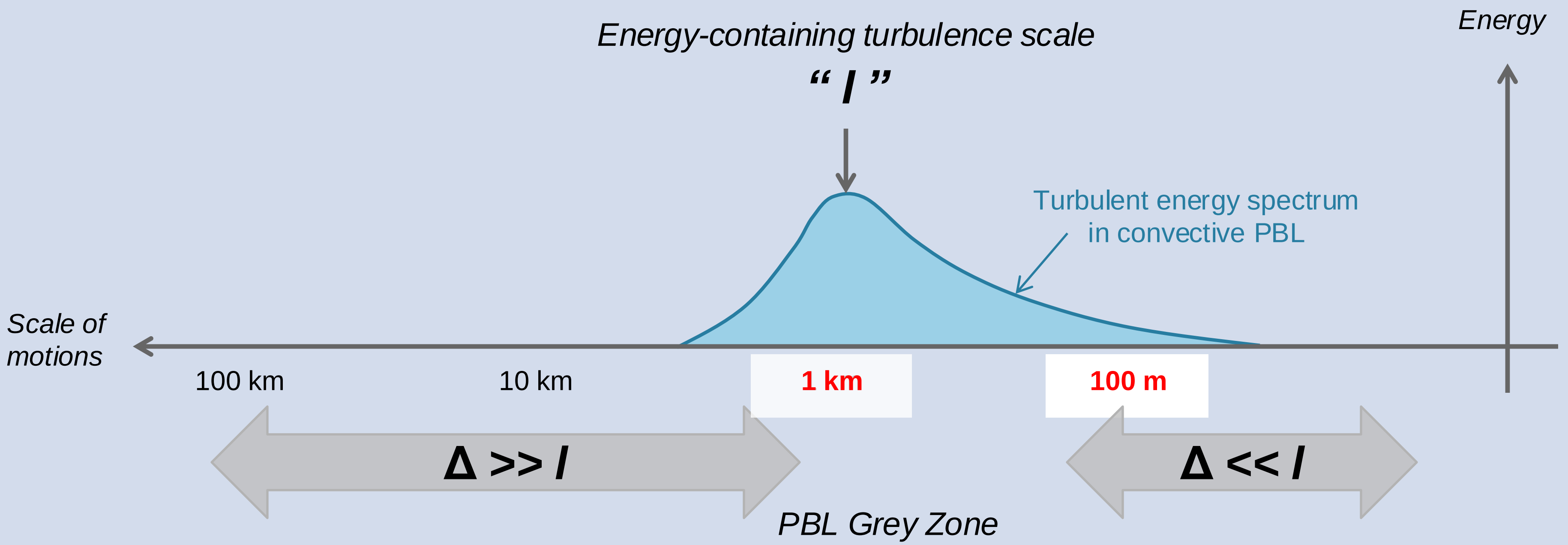
- Diagnose a PBL top
  - either stability profile or Richardson number
- Specify a K profile
  - E.g. cubic function of *z* with max in mid-PBL

$$\frac{\partial}{\partial z}K_v\left(\frac{\partial}{\partial z}q+\Gamma\right)$$

- Some nonlocal schemes include a non-gradient term (Γ)
- Others include a mass-flux profile, M, which is an additional updraft flux (EDMF or eddy-diffusivity mass-flux schemes)
  - Some EDMF schemes also include shallow convection
  - EDMF approach can also apply to tke schemes

$$\frac{\partial}{\partial z}\left(K_v\frac{\partial}{\partial z}q+M(q_u-q)\right)$$

Model Grid Spacing: PBL and LES



For coarse grid spacing

- ✓ **PBL schemes have been designed for Δ >> l**
- ✓ ***All eddies are sub-grid***
- ✓ ***1d column schemes handle sub-grid vertical fluxes***

For fine grid spacing

- ✓ **LES schemes have been designed for Δ << l**
- ✓ ***All major eddies are resolved***
- ✓ ***3d turbulence schemes handle sub-grid mixing***

Grey-Zone PBL

- “Grey Zone” is sub-kilometer grids
  - PBL and LES assumptions not perfect
- Some schemes are being designed for this range with scale-sensitive weighting functions (Shin-Hong PBL and 3d TKE turbulence options)
- Other PBL schemes work in this range but will not have correctly partitioned resolved/sub-grid energy fractions leading to either too much or too little resolved eddy activity

PBL schemes

bl_pbl_physics	Scheme	Reference	Added
1	YSU	Hong, Noh and Dudhia (2006, MWR)	2004
2	MYJ	Janjic (1994, MWR)	2000
3	GFS	Hong and Pan (1996, MWR)	2005
4	QNSE-EDMF	Sukoriansky, Galperin and Perov (2005, BLM), Pergaud, Masson, Malardel et al. (2009, BLM)	2012
5	MYNN2	Nakanishi and Niino (2006, BLM)	2009
6	MYNN3	Nakanishi and Niino (2006, BLM)	2009
7	ACM2	Pleim (2007, JAMC)	2008
8	BouLac	Bougeault and Lacarrere (1989, MWR)	2009
9	UW	Bretherton and Park (2009, JC)	2011
10	TEMF	Angevine, Jiang and Mauritsen (2010, MWR)	2011
11	SH	Shin and Hong (2015, MWR)	2015
12	GBM	Grenier and Brethertion (2001, MWR)	2013
99	MRF	Hong and Pan (1996, MWR)	2000

PBL schemes

Update needed: EEPS, KEPS

bl_pbl_ physics	Scheme	Cores	sf_sfclay_ physics	Prognostic variables	Diagnostic variables	Cloud mixing
1	YSU	ARW NMM	1,91		exch_h	QC,QI
2	MYJ	ARW NMM	2	TKE_PBL	EL_PBL, exch_h	QC,QI
3	GFS(hwrf)	NMM	3			QC,QI
4	QNSE-EDMF	ARW NMM	4	TKE_PBL	EL_PBL, exch_h, exch_m	QC,QI
5	MYNN2	ARW	1,2,5,91	QKE	Tsq, Qsq, Cov, exch_h, exch_m	QC
6	MYNN3	ARW	1,2,5,91	QKE, Tsq, Qsq, Cov	exch_h, exch_m	QC
7	ACM2	ARW	1,7,91			QC,QI
8	BouLac	ARW	1,2,91	TKE_PBL	EL_PBL, exch_h, exch_m	QC
9	UW	ARW	1,2,91	TKE_PBL	exch_h, exch_m	QC
10	TEMF	ARW	10	TE_TEMF	*_temf	QC, QI
11	SH	ARW	1,91		Exch_h	QC, QI
12	GBM	ARW	1,91	TKE_PBL	EL_PBL,exch_h, exch_m	QC, QI
99	MRF	ARW NMM	1,91			QC,QI

Turbulence/Diffusion

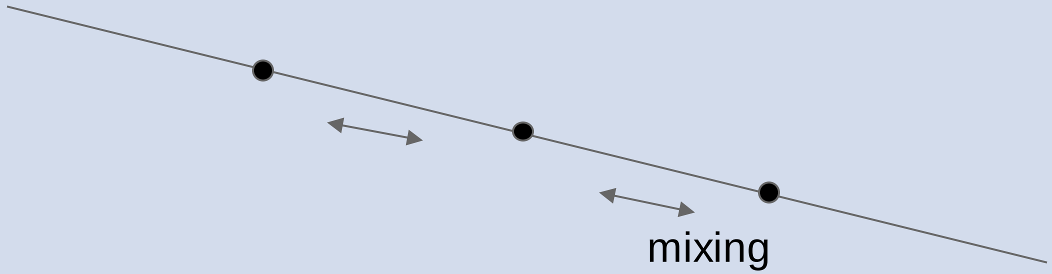
Sub-grid eddy mixing effects on all fields, e.g.

$$\frac{\partial}{\partial x} K_h \frac{\partial}{\partial x} \theta + \frac{\partial}{\partial y} K_h \frac{\partial}{\partial y} \theta + \frac{\partial}{\partial z} K_v \frac{\partial}{\partial z} \theta$$

Diffusion Option (diff_opt)

- Selects numerical method especially for horizontal diffusion (see next slides)
- When diffusion is used with a PBL scheme, vertical diffusion is deactivated, so *diff_opt* only affects horizontal diffusion
- Option *diff_opt=1* is limited to constant vertical diffusion coefficient (*kvdif*)
  - should not be used with calculated diffusion coefficient options (*km_opt=2,3*)
  - can be used with PBL schemes which include vertical diffusion internally
- Option *diff_opt=2* is strictly horizontal and better for complex terrain – avoids diffusion up and down slopes that *diff_opt=1* has

Difference between diff_opt 1 and 2

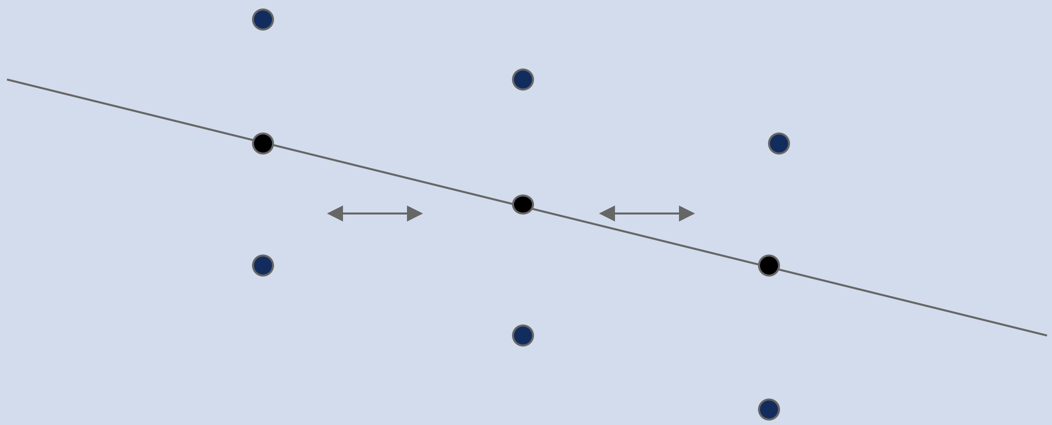


diff_opt=1

Horizontal diffusion acts along model levels

Simpler numerical method with only neighboring points on the same model level

Difference between diff_opt 1 and 2



diff_opt=2

Horizontal diffusion acts on strictly horizontal gradients

Numerical method includes vertical correction term using more grid points

For stability, diffusion strength is reduced in steep coordinate slopes ($\Delta z \sim \Delta x$)

Large-Eddy Simulation

- For grid sizes of up to about 100 m, LES is preferable
- LES treats turbulence three-dimensionally instead of separate vertical (PBL) and horizontal diffusion schemes
- Explicit vertical diffusion replaces the PBL scheme and accepts surface fluxes from surface physics
- WRF has TKE and 3d Smagorinsky options for the sub-grid turbulence
- Use bl_pbl_physics =0
- Use diff_opt=2 and km_opt=2 or 3
- Can use PBL (e.g. YSU scheme) on outer domains and LES on inner domains

LES schemes

Unified horizontal and vertical mixing (for dx~dz).
Typically needed for dx<~200 m. Also use mix_isotropic=1

bl_pbl_ physics	diff_opt	km_opt	Scheme	sf_sfclay _physics	isfflx	Prognostic variables
0	2	2	tke	0,1,2	0,1,2	tke
0	2	3	3d Smagorinsky	0,1,2	0,1,2	

Namelist isfflx controls surface flux methods

isfflx	sf_sfclay_physics	Heat flux	Drag	Real/Ideal
0	0	From namelist tke_heat_flux	From namelist tke_drag_coefficient	Ideal
1	1,2	From LSM/sfclay physics (HFX, QFX)	From sfclay physics (UST)	Real
2	1,2	From namelist tke_heat_flux	From sfclay physics (UST)	Ideal

Diffusion Option Choice

- Real-data case with PBL physics on
  - Best is diff_opt=2, km_opt=4
    - Less diffusive in complex terrain while diff_opt=1 diffuses along slopes
  - This complements vertical diffusion done by PBL scheme
- High-resolution real-data cases (~100 m grid)
  - No PBL
  - diff_opt=2; km_opt=2,3 (tke or Smagorinsky scheme)

Diffusion Option Choice

- Idealized cloud-resolving (dx =1-3 km) modeling (smooth or no topography, no surface heat fluxes)
  - diff_opt=2; km_opt=2,3
- Complex topography with no PBL scheme
  - diff_opt=2 is more accurate for sloped coordinate surfaces, and prevents diffusion up/down valley sides but still sometimes unstable with complex terrain
  - WRF cannot generally handle slopes > 45 degrees
    - *epssm* is a sound-wave damping term that can be increased to help with steep slopes (e.g. 0.5-1.0)
- Note: WRF can run with no diffusion (diff_opt=0)

Upper damping (damp_opt)

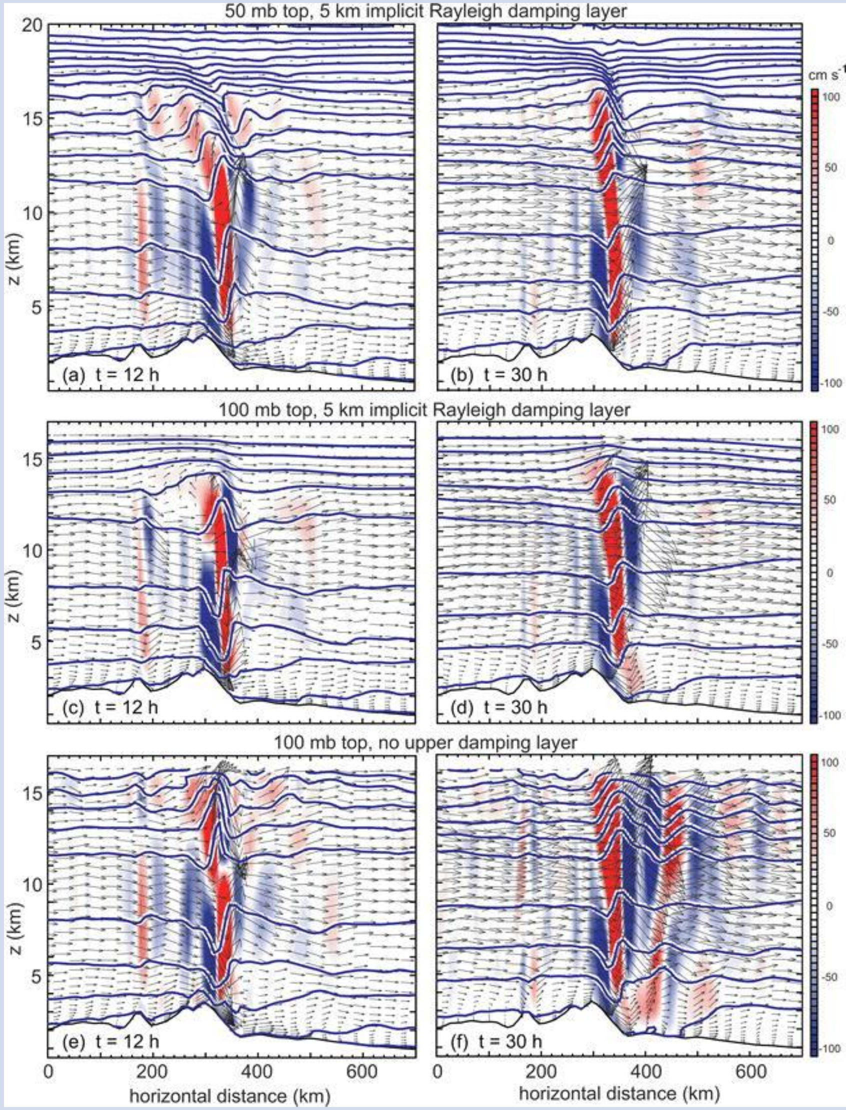
Purpose is to prevent unrealistic reflections of waves from model top. Can be important over high topography.

Options

- 1: Upper level diffusive layer
- 2: Rayleigh damping (idealized only – needs input sounding)
- 3: w-Rayleigh damping (damps w only)

All options use

- Cosine function of height
- Additional parameters
  - zdamp: depth of damping layer
  - dampcoef: nondimensional maximum magnitude of damping



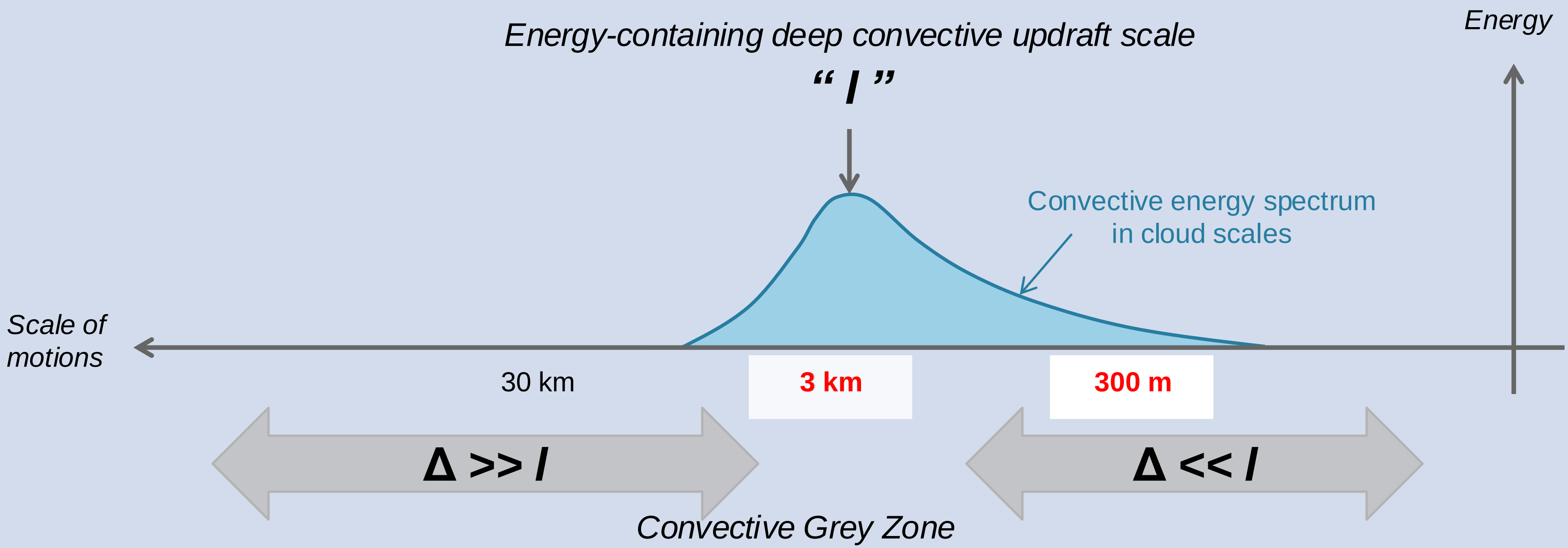
Cumulus Parameterization

Provides

Atmospheric heat and moisture/cloud and possibly momentum tendency profiles

Surface (sub-grid) convective rainfall

Cumulus Parameterization and Cloud-Resolving



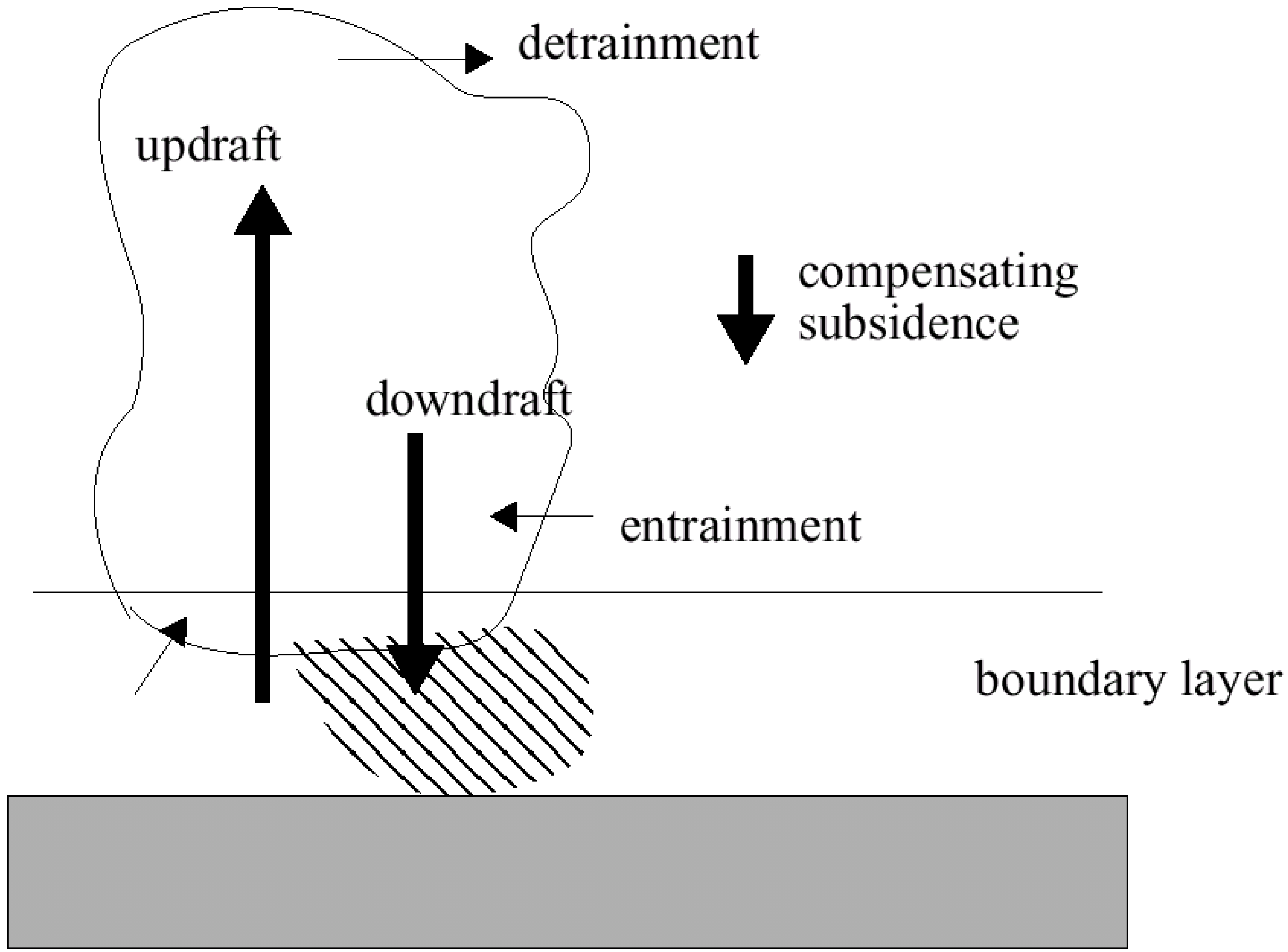
For coarse grid spacing

- ✓ **Cumulus parameterization schemes have been designed for Δ >> l**
- ✓ ***All updrafts and downdrafts are sub-grid***
- ✓ ***1d column schemes handle sub-grid vertical fluxes***

For fine grid spacing

- ✓ **Resolved dynamics and microphysics work for Δ << l**
- ✓ ***Updrafts and downdrafts are resolved***

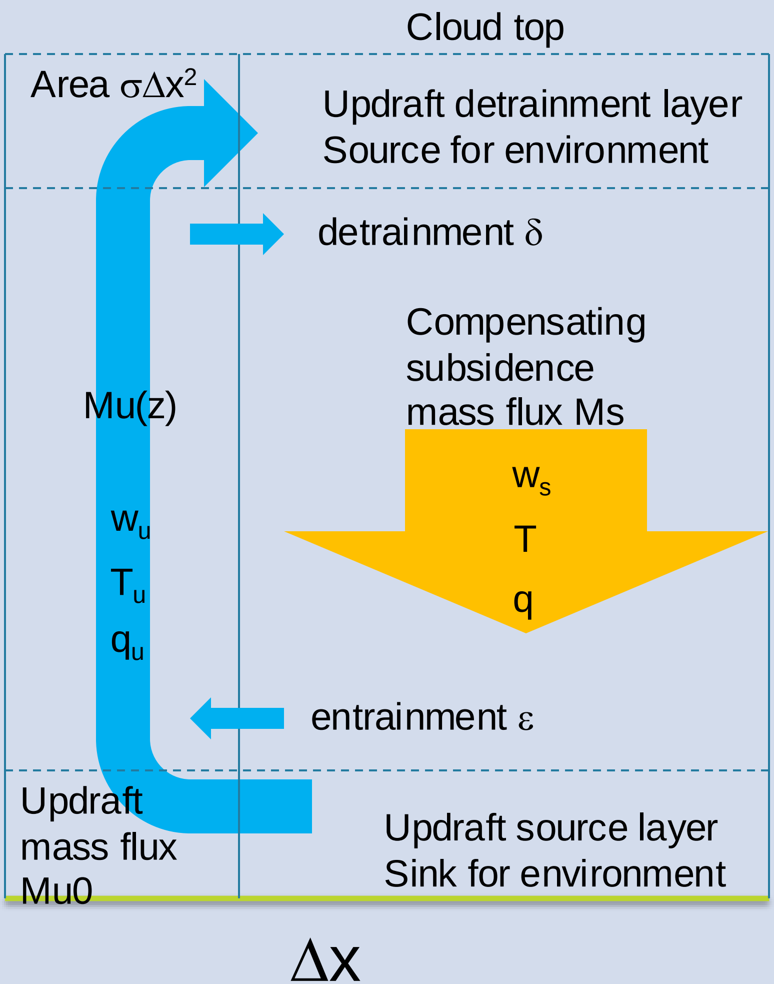
Illustration of Cumulus Processes



Cumulus Schemes

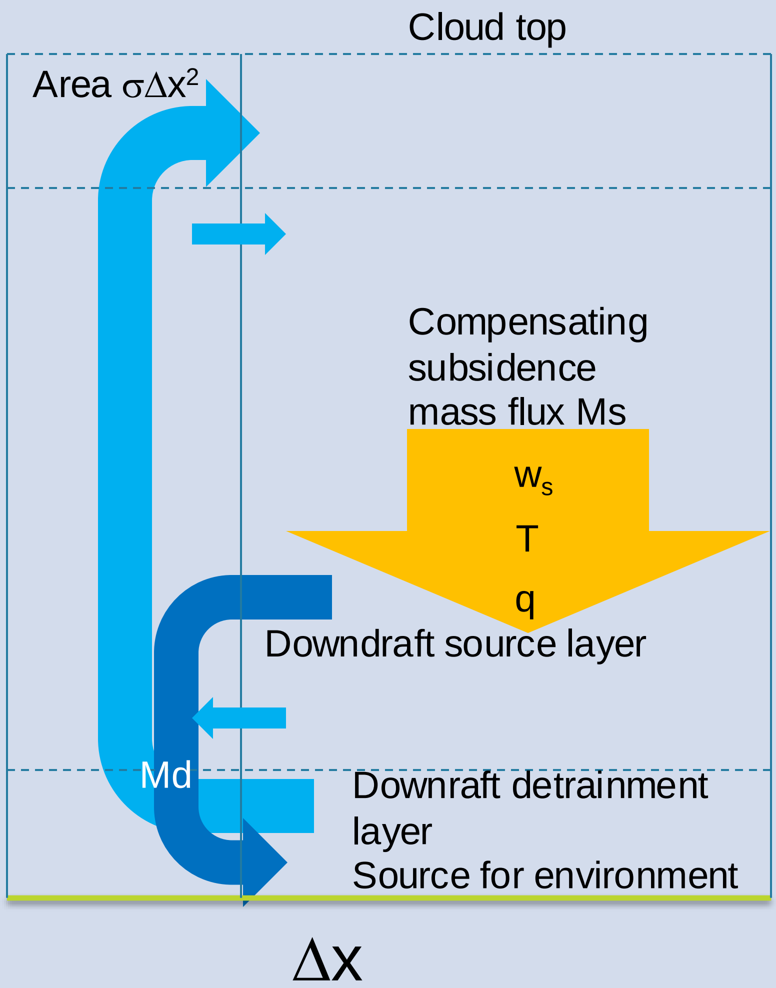
- Use for grid columns that completely contain convective clouds (typically dx > 10 km)
- Re-distribute air in column to account for vertical convective fluxes
  - Updrafts take boundary layer air upwards
  - Downdrafts take mid-level air downwards
- Schemes have to determine
  - When to trigger a convective column
  - How fast to make the convection act

Mass Flux Schemes



- Updraft mass changes with z
  - $d\,Mu / dz = Mu\,(\varepsilon \,□\, \delta)$
- Compensating subsidence balances
  - $Ms = -\,Mu \;:\; w_s = -\,\sigma\, w_u$
- Updraft transport of conserved moist static energy, h_u (J/kg)
  - $h_u = c_p T_u + L_v q_u + g z$
  - $\rho\, w_u\, h_u\, \sigma = Mu\, h_u$
  - $h_u(z)$ dilutes due to entrainment
- Subsidence
  - $d/dt(\rho\, \theta) = -\, d/dz(Ms\, \theta)$:warming
  - $d/dt(\rho\, q) = -\, d/dz(Ms\, q)$:drying

Mass Flux Schemes



- **Updrafts**
  - Driven by buoyancy
  - Moist air to upper troposphere
  - Condensation to convective rainfall
- **Downdrafts**
  - Driven by convective rain evaporation
  - Evaporatively cooled air to boundary layer
- **Subsidence**
  - Warms and dries troposphere
  - Main warming effect in column

Shallow Convection

- Non-precipitating shallow mixing dries PBL, moistens and cools above
- This can be done by an enhanced mixing approach (SAS, GRIMS) or mass-flux approach (KF, NSAS, Tiedtke, G3, GF, Deng)
- May be useful at grid sizes that do not resolve shallow cumulus clouds (> 1 km)

Shallow Convection

- Cumulus schemes may include shallow convection (KF, SAS schemes, G3, GF, BMJ, Tiedtke)
- Standalone shallow schemes
  - UW Park-Bretherton (shcu_physics=2)
  - GRIMS shallow scheme (shcu_physics=3)
  - NSAS shallow convection (shcu_physics=4) – to use with KSAS deep scheme
  - Deng shallow scheme (shcu_physics=5) – new in V4.1
- Part of PBL schemes with mass-flux method
  - TEMF PBL option (bl_bl_physics=10)
  - GBM PBL option (bl_bl_physics=12)
  - QNSE-EDMF PBL (bl_bl_physics=4)
  - MYNN (EDMF option) (bl_pbl_physics =5)

Convective Grey Zone

- Approximately dx = 3-10 km
- Updrafts not well resolved
- Grid column may not contain an entire updraft with compensating subsidence
- Some schemes have scale-sensitive parameters to reduce updraft effects at finer grid sizes
- At 3 km updrafts resolved well enough for no cumulus scheme
  - Dynamics and microphysics sufficient for representing individual convective cells and downdrafts
  - Full updraft dynamics resolving may require < 300 m grid

Cumulus schemes

cu_physics	Scheme	Cores	Moisture Tendencies	Momentum Tendencies	Shallow Convection	Radiation Interactn
1	Kain-Fritsch Eta	ARW NMM	Qc Qr Qi Qs	no	yes	yes
2	Betts-Miller-Janjic	ARW NMM	-	no	yes	GFDL
3	Grell-Freitas	ARW	Qc Qi	no	yes	yes
4	Old Simplified Arakawa-Schubert	ARW NMM	Qc Qi	yes (NMM)	yes (ARW)	GFDL
5	Grell-3	ARW	Qc Qi	no	yes	yes
6,16	Tiedtke	ARW	Qc Qi	yes	yes	no
7	Zhang-McFarlane	ARW	Qc Qi	yes	no	RRTMG
10	KF CuP	ARW	Qc Qi	no	yes	yes
14, 96	KSAS, NSAS	ARW	Qc Qi	yes	no/yes	GFDL
84	New SAS (HWRF)	ARW NMM	Qc Qi	yes (NMM)	yes	GFDL
93	Grell-Devenyi	ARW	Qc Qi	no	no	yes
99	Old Kain-Fritsch	ARW	Qc Qr Qi Qs	no	no	GFDL

yes=RRTMG and GFDL

Cumulus scheme: Recommendations

- dx ≥ 10 km:
  - Probably need cumulus scheme
  - These release instability gradually (prevent grid-point storms)
- dx ≤ 3 km:
  - Probably do not need scheme (resolved/permitted by dynamics)
  - However, there are cases where the earlier triggering of convection by cumulus schemes help
- dx=3-10 km:
  - Scale separation is a question
  - Few schemes are specifically designed with this range of scales in mind
  - G3 has an option to spread subsidence in neighboring columns
  - GF, MSKF, KSAS, newTiedtke automatically phase out deep convection at fine grid size
- Issues with 2-way nesting when physics differs across nest boundaries (seen in precip field on parent domain)
  - Best to use same physics in both domains or 1-way nesting or make nested domain large enough to keep parent effects away from interior

Microphysics

Provides

Atmospheric heat and moisture tendencies

Microphysical rates

Surface resolved-scale rainfall

Resolved clouds

- Formed by radiative, dynamical or convective processes
- Model only considers grid-scale average so will not resolve fine-scale structures

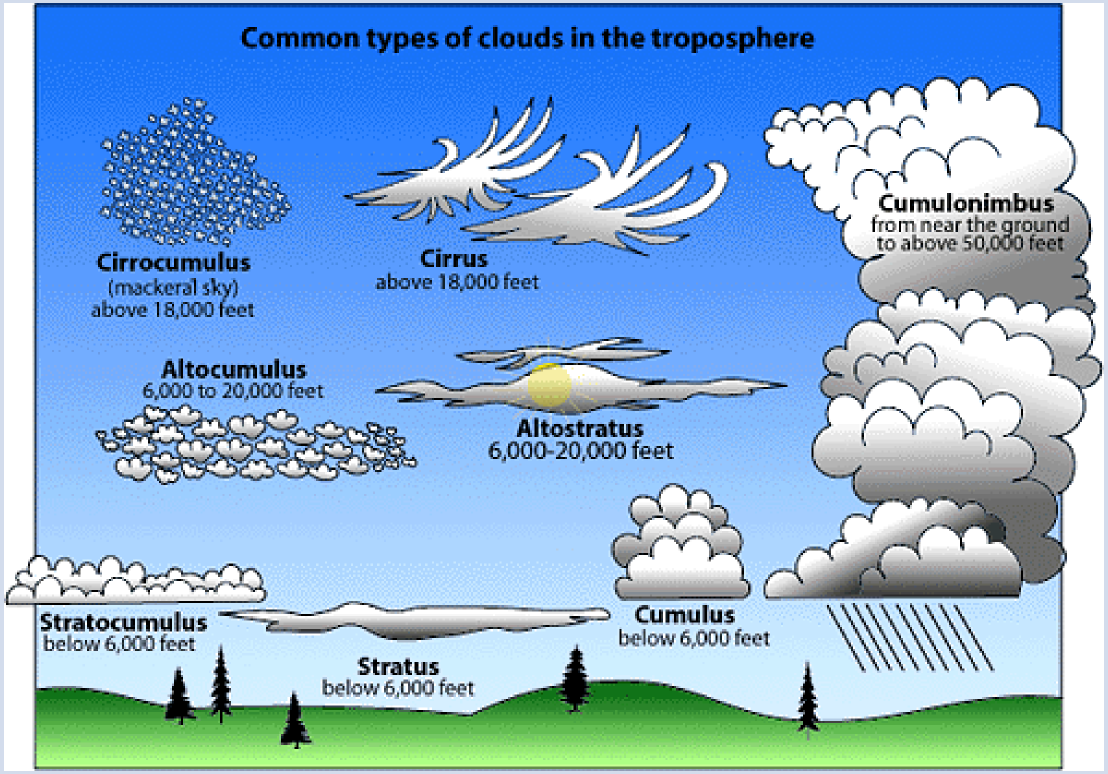
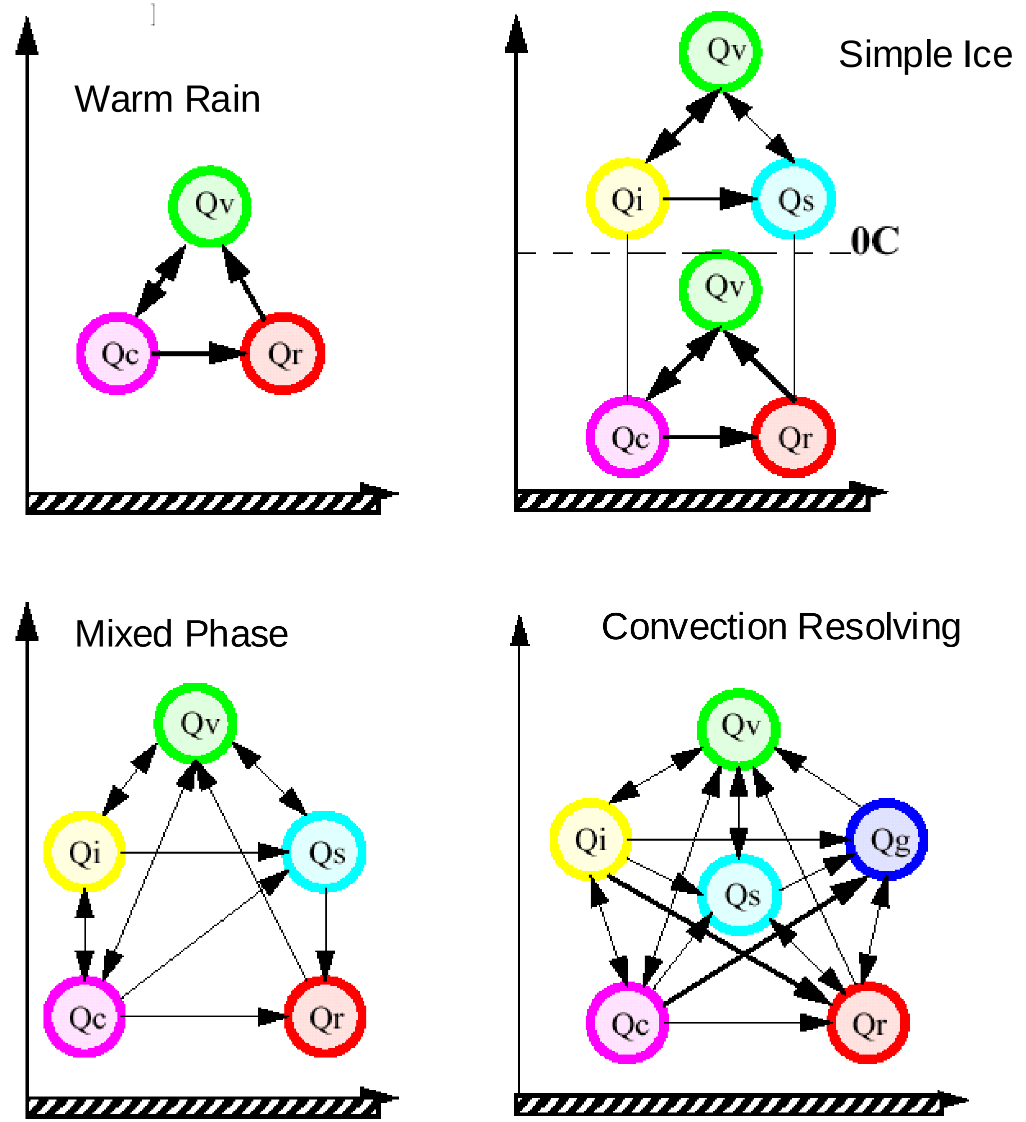
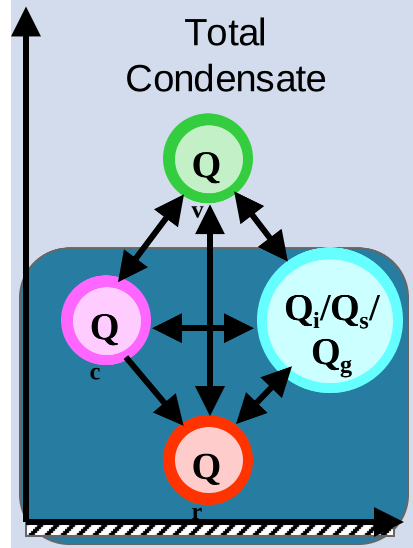


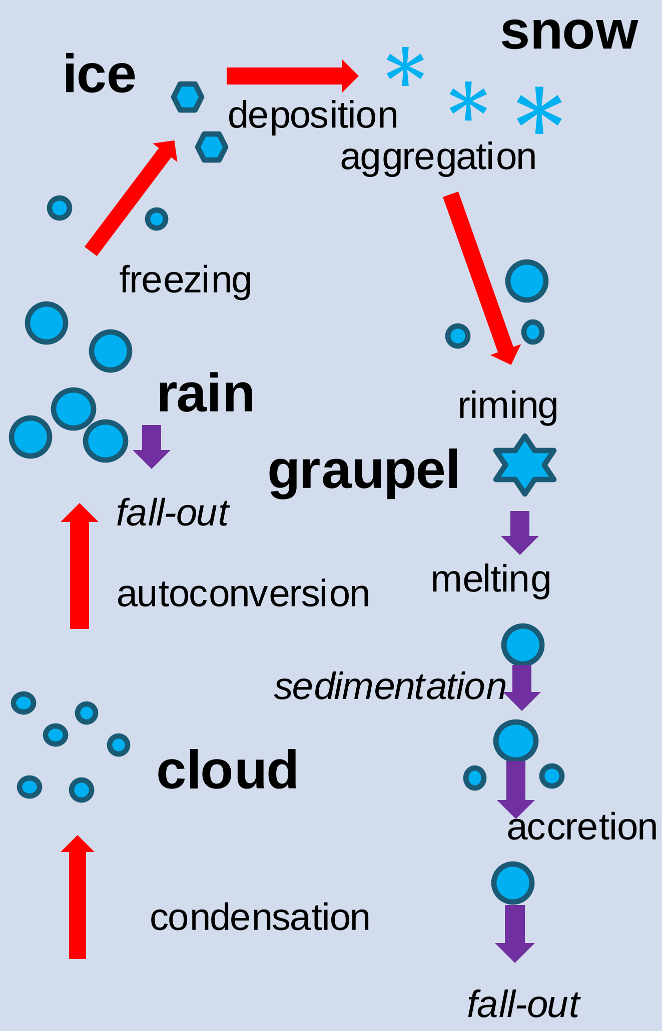
Illustration of Microphysics Processes





Microphysics Processes

- Latent heat release from
  - Condensation, evaporation, deposition, sublimation, freezing, melting
- Particle types
  - Cloud water, rain drops, ice crystals, snow, graupel/hail
    - Total mass contributes to liquid loading in *dynamics*
- Processes
  - Aggregation, accretion, autoconversion (growth), riming, sedimentation (fall term)
  - Water and ice saturation differ

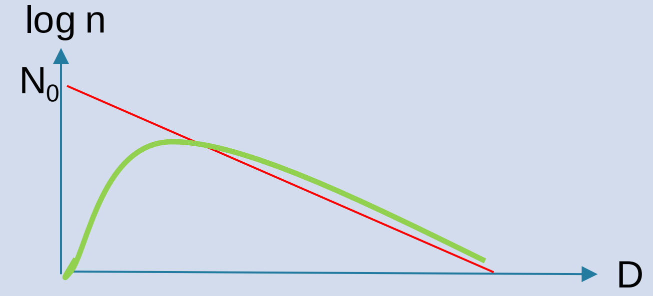


Particle Types

- Cloud droplets (10s of microns) condense from vapor at water saturation
  - Cloud condensation nuclei fixed or variable (specified or chemistry)
- Rain (~mm diameter) forms from cloud droplet growth
- Ice crystals (10s of microns) form from freezing of droplets or deposition on nuclei
  - Ice nuclei assumed or explicit (dust particles)
- Snow (100s of microns) forms from growth of ice crystals at ice supersaturation and their aggregation
- Graupel/hail (mm to cm) form and grow from mixed-phase interactions between water and ice particles
- Precipitating particles are typically assigned to an observationally based **size distribution**

Size Distribution

- Log-normal (red), n is number per size range, D is diameter
  - $n(D)\, dD = N_0 \exp(-\lambda D)\, dD$
- Gamma (green) with exponent α
  - $n(D)\, dD = N_0 D^{\alpha} \exp(-\lambda D)\, dD$
- Mass and fall speed depend on D
  - $M = \frac{1}{6} \pi \rho_r D^3$
  - $V = a D^b$
- Gamma function is integrated to relate mixing ratio Q_r to λ
  - $\lambda = (\pi \rho_r N_0 / \rho Q_r)^{1/4}$ for log-normal distribution
  - where ρ_r is rain density and ρ is air density
- Integration also gives a mass-weighted fall speed
  - $V_f = a\, [\, \Gamma(4+b)/6\,]\, \lambda^{-b}$



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Microphysics: Single and Double Moment Schemes

- Single-moment schemes have one prediction equation for mass (kg/kg) per species (Qr, Qs, etc.) with particle size distribution being derived from fixed parameters (e.g. N_0)
- Double-moment (DM) schemes add a prediction equation for number concentration (#/kg) per DM species (Nr, Ns, etc.)
  - This allows for incorporation of enhanced aerosol effects (pollution) for example

Microphysics: Fall terms

- Microphysics schemes handle fall terms for particles (usually everything except cloud water has a fall term)
  - Rain ~5 m/s
  - Graupel ~2 m/s
  - Hail ~5-10 m/s
  - Snow ~1-2 m/s
  - Ice crystals ~0.5 m/s
- For long time-steps (such as mesoscale applications dt ~ 60 s, Vt= 5 m/s), drops may fall more than a grid level in a time-step
- This requires either splitting the microphysics time-step (most schemes) or lagrangian numerical methods (WSM and WDM schemes) to keep the scheme numerically stable

Microphysics schemes

mp_physics	Scheme	Reference	Added
1	Kessler	Kessler (1969)	2000
2	Lin (Purdue)	Lin, Farley and Orville (1983, JCAM)	2000
3	WSM3	Hong, Dudhia and Chen (2004, MWR)	2004
4	WSM5	Hong, Dudhia and Chen (2004, MWR)	2004
5	Eta (Ferrier)	Rogers, Black, Ferrier et al. (2001)	2000
6	WSM6	Hong and Lim (2006, JKMS)	2004
7	Goddard	Tao, Simpson and McCumber (1989, MWR)	2008
8	Thompson (+old)	Thompson et al. (2008, MWR)	2009
9	Milbrandt 2-mom	Milbrandt and Yau (2005, JAS)	2010
10	Morrison 2-mom	Morrison et al. (2009, MWR)	2008
11	CESM 1.0	Morrison and Gettelman (2008, JC)	2013
13	SBU-Ylin	Lin and Colle (2011, MWR)	2011
14	WDM5	Lim and Hong (2010, MWR)	2009
16	WDM6	Lim and Hong (2010, MWR)	2009
17	NSSL 2-mom	Mansell, Ziegler and Bruning (2010, JAS)	2012
18	NSSL 2-mom + ccn	Mansell, Ziegler and Bruning (2010, JAS)	2012

Microphysics schemes

mp_physics	Scheme	Reference	Added
19	NSSL 7-class	Mansell, Ziegler and Bruning (2010, JAS)	2013
21	NSSL 6-class	Gilmore, Straka and Rasmussen (2004, MWR)	2013
22	NSSL 6-class 2-mom	Mansell, Ziegler and Bruning (2010, JAS)	2015
24	WSM7	Bae, Hong and Tao (2018, APJAS)	2019
26	WDM7	Bae, Hong and Tao (2018, APJAS)	2019
28	Thompson aero	Thompson and Eidhammer (2014, JAS)	2014
30	SBM fast	Khain, Lynn and Dudhia (2010, JAS)	2014
32	SBM full	Khain et al. (2004, JAS)	2014
50	P3	Morrison and Milbrandt (2015, JAS)	2017
51	P3-nc	Morrison and Milbrandt (2015, JAS)	2017
52	P3-2nd	Morrison and Milbrandt (2015, JAS)	2018
55	ISHMAEL	Jensen et al. (2017, JAS)	2019

Microphysics schemes

* Advects only total condensate   Nn= CCN number

mp_physics	Scheme	Cores	Mass Variables	Number Variables
1	Kessler	ARW	Qc Qr	
2	Lin (Purdue)	ARW (Chem)	Qc Qr Qi Qs Qg	
3	WSM3	ARW	Qc Qr	
4	WSM5	ARW NMM	Qc Qr Qi Qs	
5	Eta (Ferrier)	ARW NMM	Qc Qr Qs (Qt*)	
6	WSM6	ARW NMM	Qc Qr Qi Qs Qg	
7	Goddard 4-ice	ARW	Qc Qr Qi Qs Qg Qh	
8	Thompson	ARW NMM	Qc Qr Qi Qs Qg	Ni Nr
9	Milbrandt 2-mom	ARW	Qc Qr Qi Qs Qg Qh	Nc Nr Ni Ns Ng Nh
10, 40	Morrison 2-mom	ARW (Chem)	Qc Qr Qi Qs Qg	Nr Ni Ns Ng
11	CESM 1.0	ARW (Chem)	Qc Qr Qi Qs	Nc Nr Ni Ns
13	SBU-YLin	ARW	Qc Qr Qi Qs	
14	WDM5	ARW	Qc Qr Qi Qs	Nn Nc Nr
16	WDM6	ARW	Qc Qr Qi Qs Qg	Nn Nc Nr

Microphysics schemes

mp_physics	Scheme	Cores	Mass Variables	Number Variables
17	NSSL 2-mom	ARW	Qc Qr Qi Qs Qg Qh	Nc Nr Ni Ns Ng Nh
18	NSSL2-mom+ccn	ARW	Qc Qr Qi Qs Qg Qh	Nc Nr Ni Ns Ng Nh Nn
19	NSSL 7-class	ARW	Qc Qr Qi Qs Qg Qh	VOLg
21	NSSL 6-class	ARW	Qc Qr Qi Qs Qg	
22	NSSL 6-class 2-mom	ARW	Qc Qr Qi Qs Qg	Nn Nc Nr Ni Ns Ng VOLg
24	WSM7	ARW	Qc Qr Qi Qs Qg Qh	
26	WDM7	ARW	Qc Qr Qi Qs Qg Qh	Nc Nr
28	Thompson aero	ARW	Qc Qr Qi Qs Qg	Nc Ni Nr Nn Nni

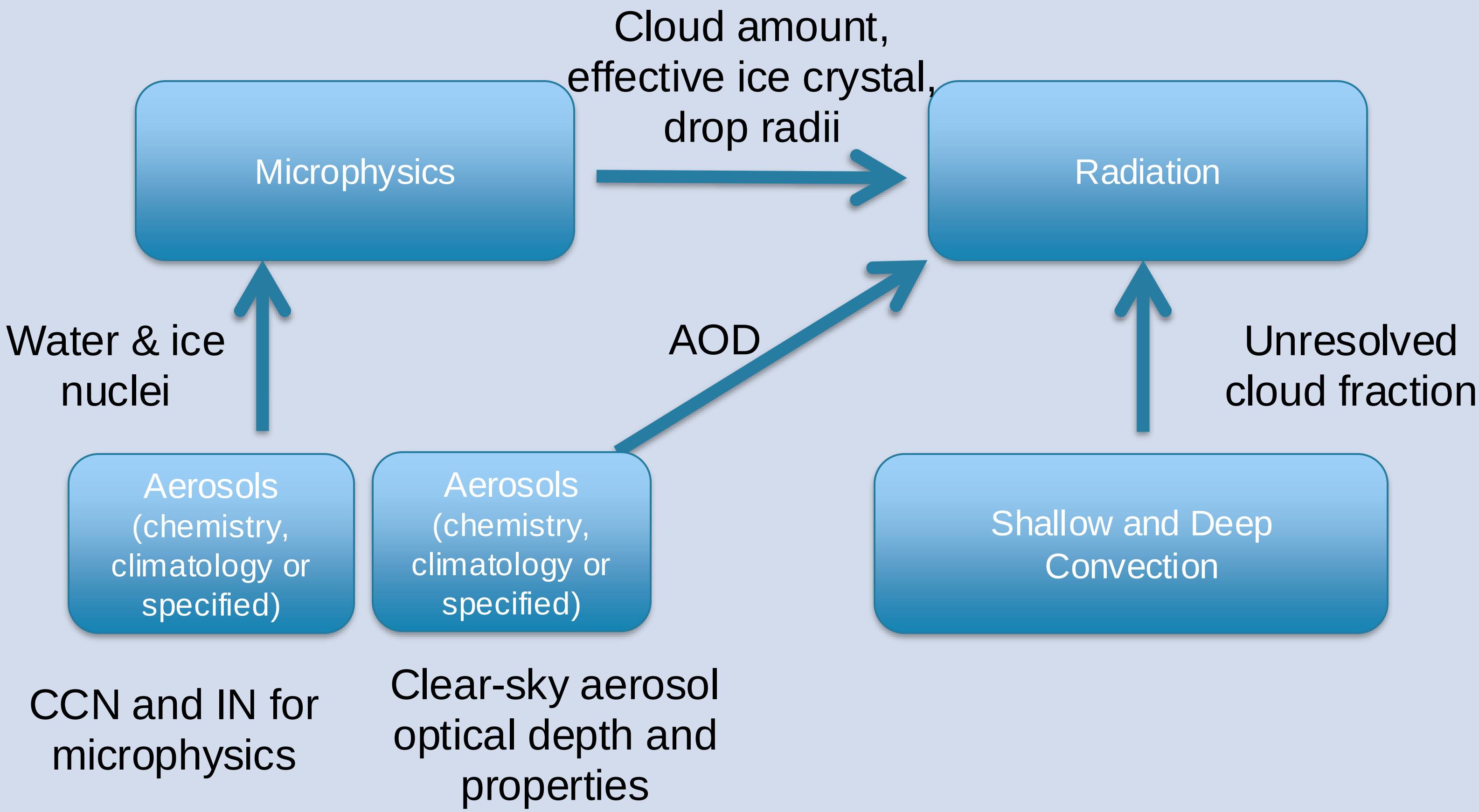
- Nn = CCN number
- VOLg = graupel volume

Microphysics schemes

mp_physics	Scheme	Cores	Mass Variables	Number Variables
30	HUJI fast SBM	ARW	Qc Qr Qi Qs Qg	Nn Nc Nr Ni Ns Ng
32	HUJI full SBM	ARW	Qc Qr Qic Qip Qid Qs Qg Qh (outputs aggregated from bins)	Nn Nc Nr Nic Nip Nid Ns Ng Nh
50	P3	ARW	Qc Qr Qi	Nr Ni Ri Bi
51	P3-nc	ARW	Qc Qr Qi	Nc Nr Ni Ri Bi
52	P3-2nd	ARW	Qc Qr Qi2	Nc Nr Ni Ni2 Ri Ri2 Bi Bi2
55	ISHMAEL	ARW	Qc Qr Qi Qi2 Qi3	Nr Ni Ni2 Ni3 Vi Vi2 Vi3 Ai Ai2 Ai3

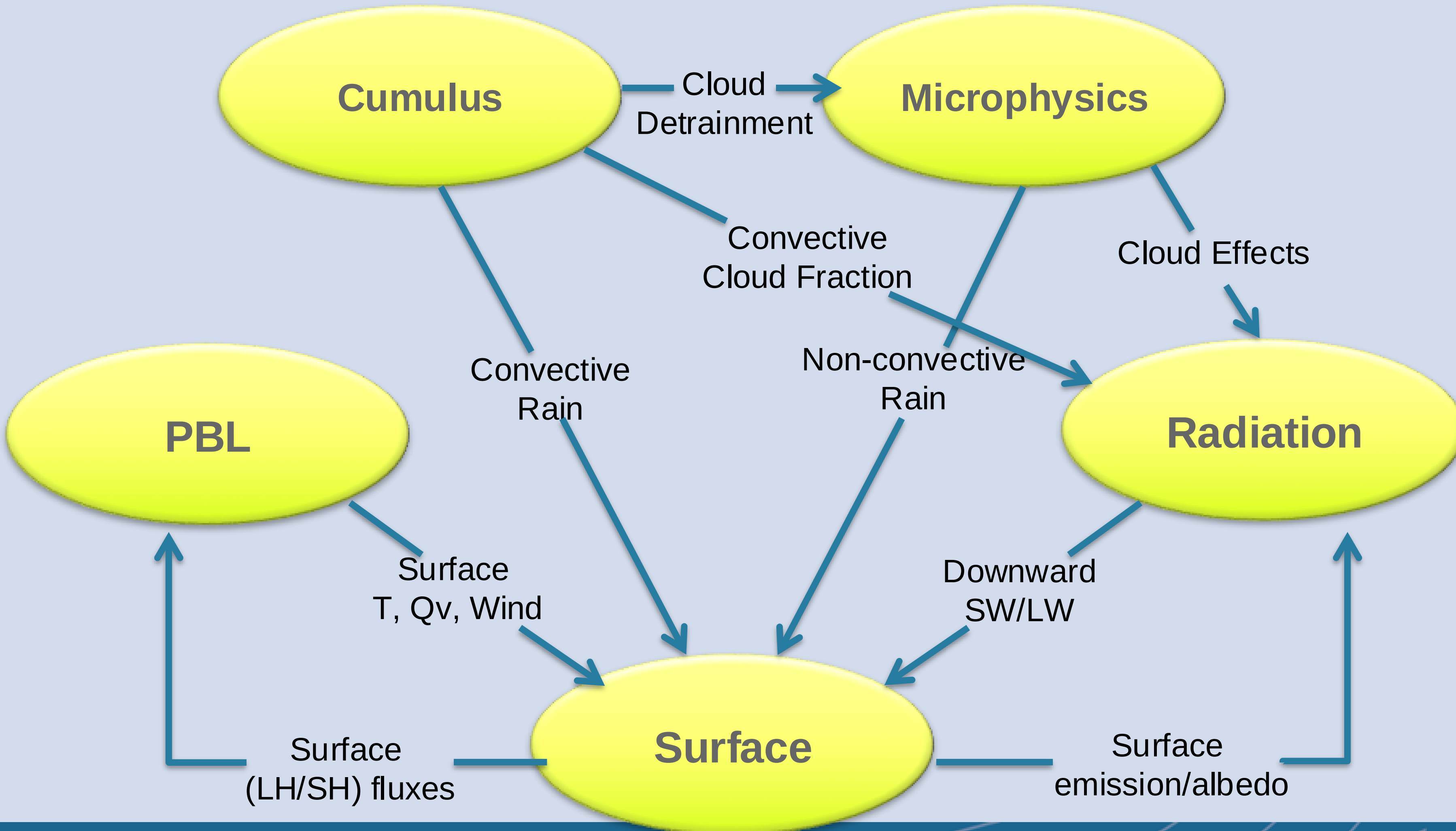
- Nn = CCN number
- Ri = rimed ice mass   Bi = rimed ice volume
- Vi = volume   Ai = vol*aspect ratio

Cloud-Aerosol-Radiation Interaction

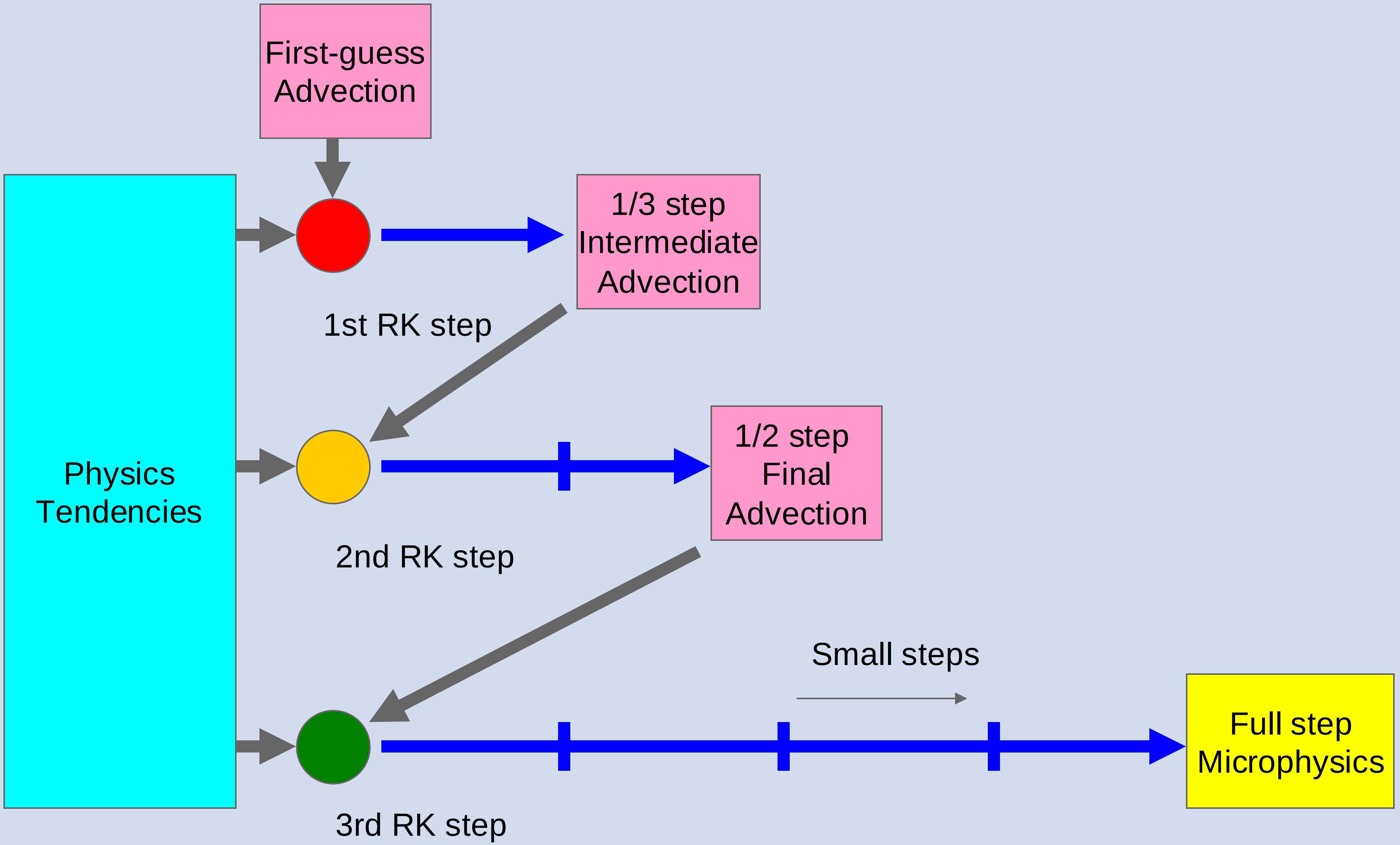


Note: aerosols not always unified (CCN and AOD may come from different sources)

Direct Interactions of Parameterizations



ARW time-step schematic



Nudging Summary

- WRF Four-Dimensional Data Assimilation (see Nudging presentation)
- Uses
  - dynamic initialization, 4-D meteorological analysis, boundary conditions, selective large-scale nudging
- Methods
  - Analysis nudging, surface analysis nudging
    - wrffdda and wrfsfdda inputs
  - Spectral nudging
  - Observational nudging
    - Input text file, radius of influence, vertical weighting function