Overview of WRF Physics

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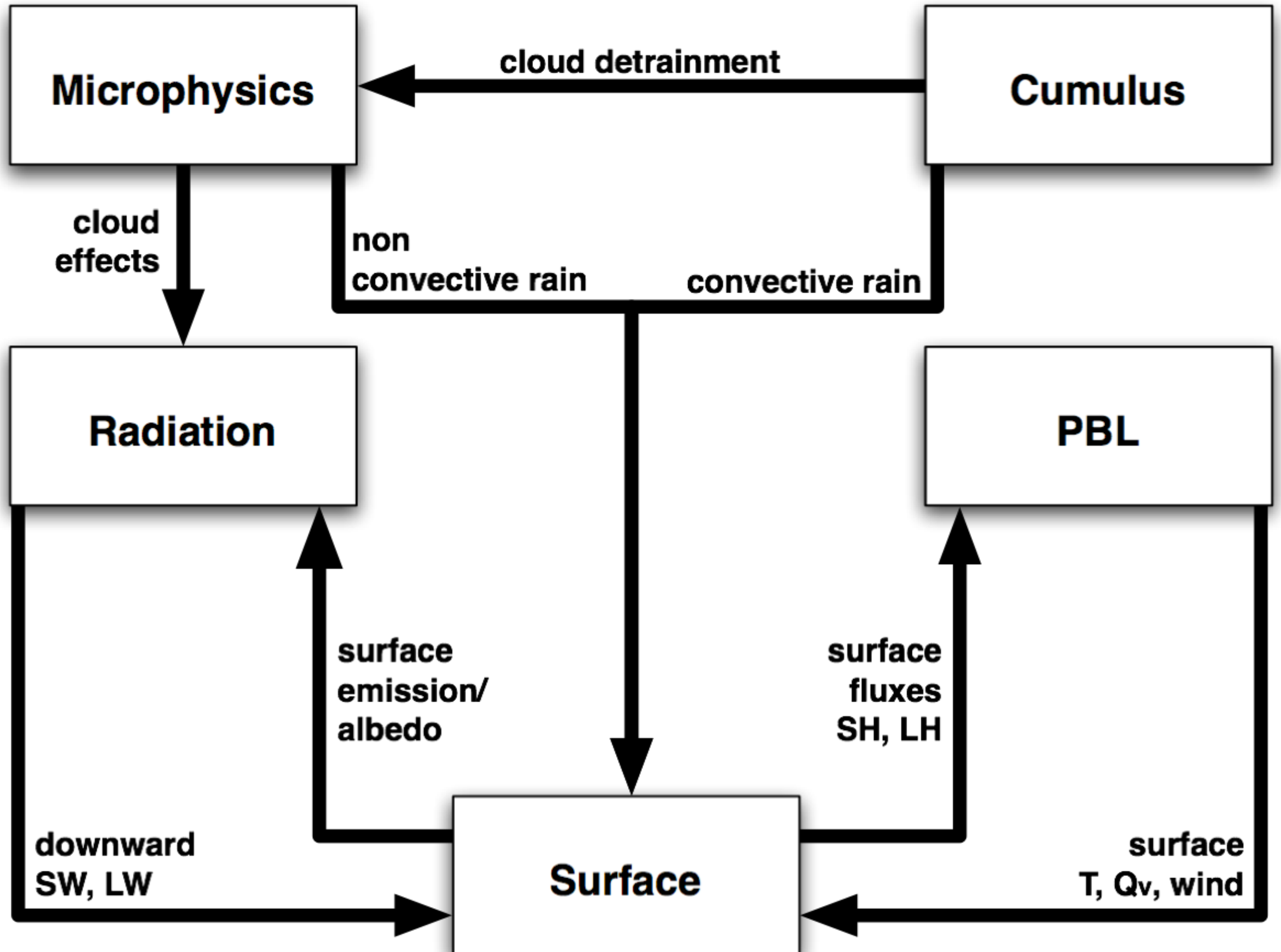
WRF Physics

- Radiation
  - Longwave (ra_lw_physics)
  - Shortwave (ra_sw_physics)
- Surface
  - Surface layer (sf_sfclay_physics)
  - Land/water surface (sf_surface_physics)
- PBL (bl_pbl_physics)
- Cumulus parameterization (cu_physics)
- Microphysics (mp_physics)
- Turbulence/Diffusion (diff_opt, km_opt)

Direct Interactions of Parameterizations



Radiation

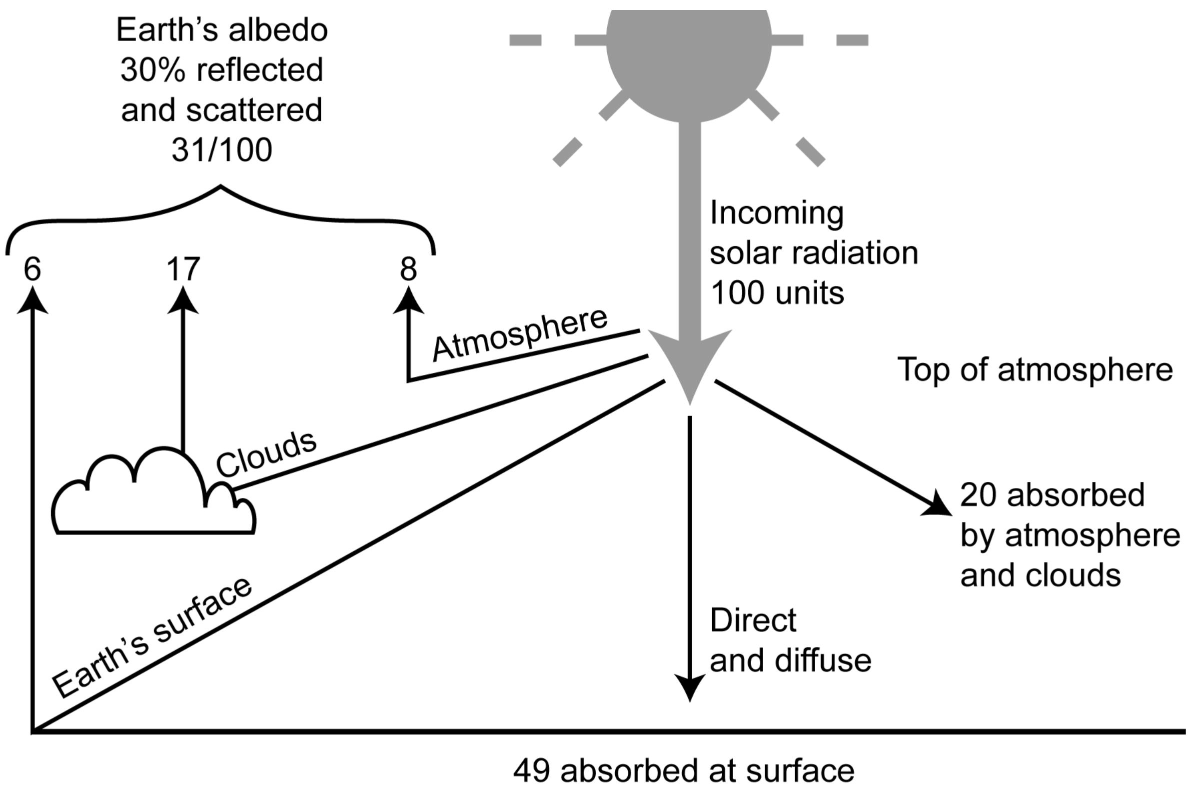
Provides

Atmospheric temperature tendency profile

Surface radiative fluxes

Radiation parameterizations

- Shortwave (solar) – use astronomical equations to calculate the sun's position as a function of time of day and day of the year.



Radiation as part of the entire model energy budget

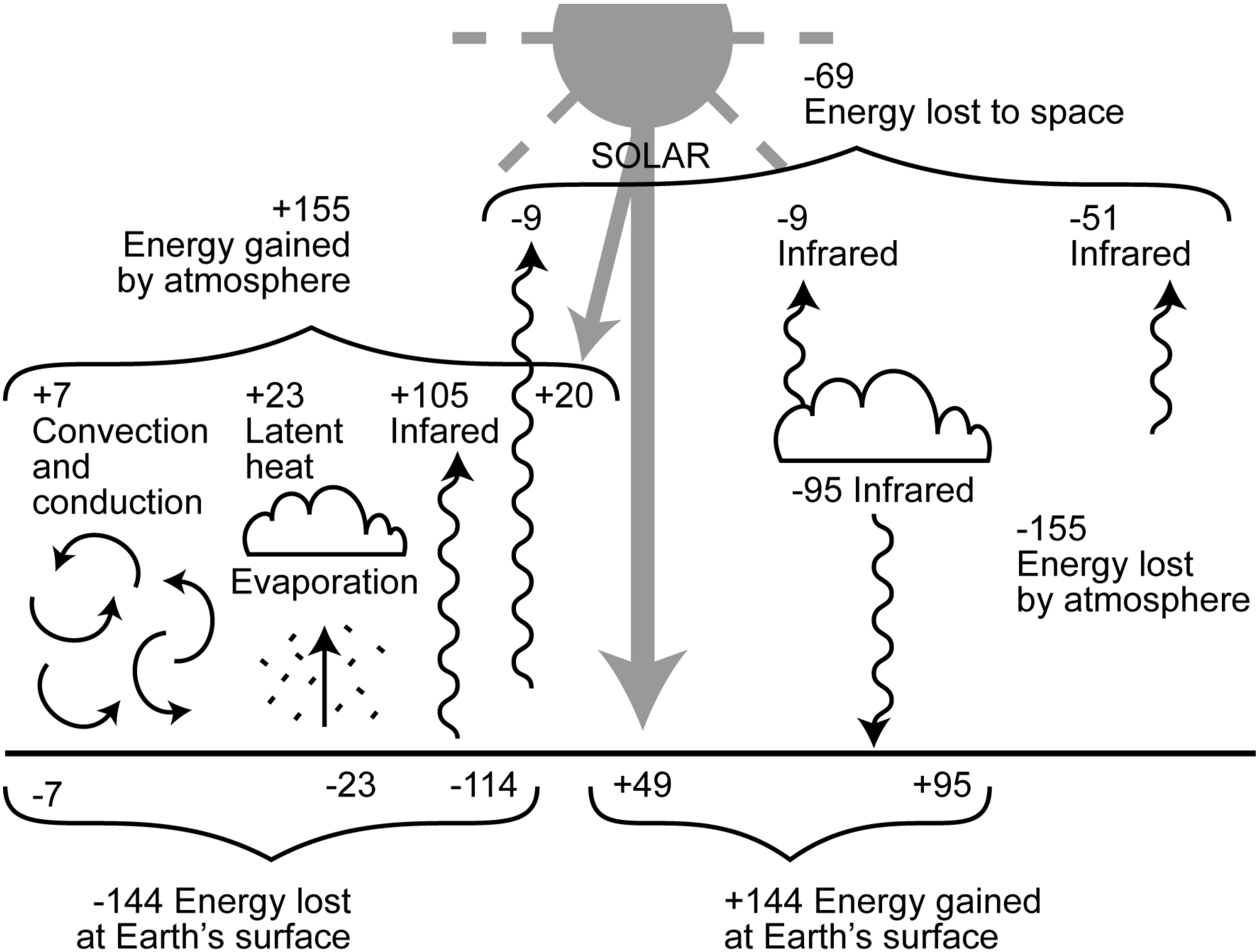
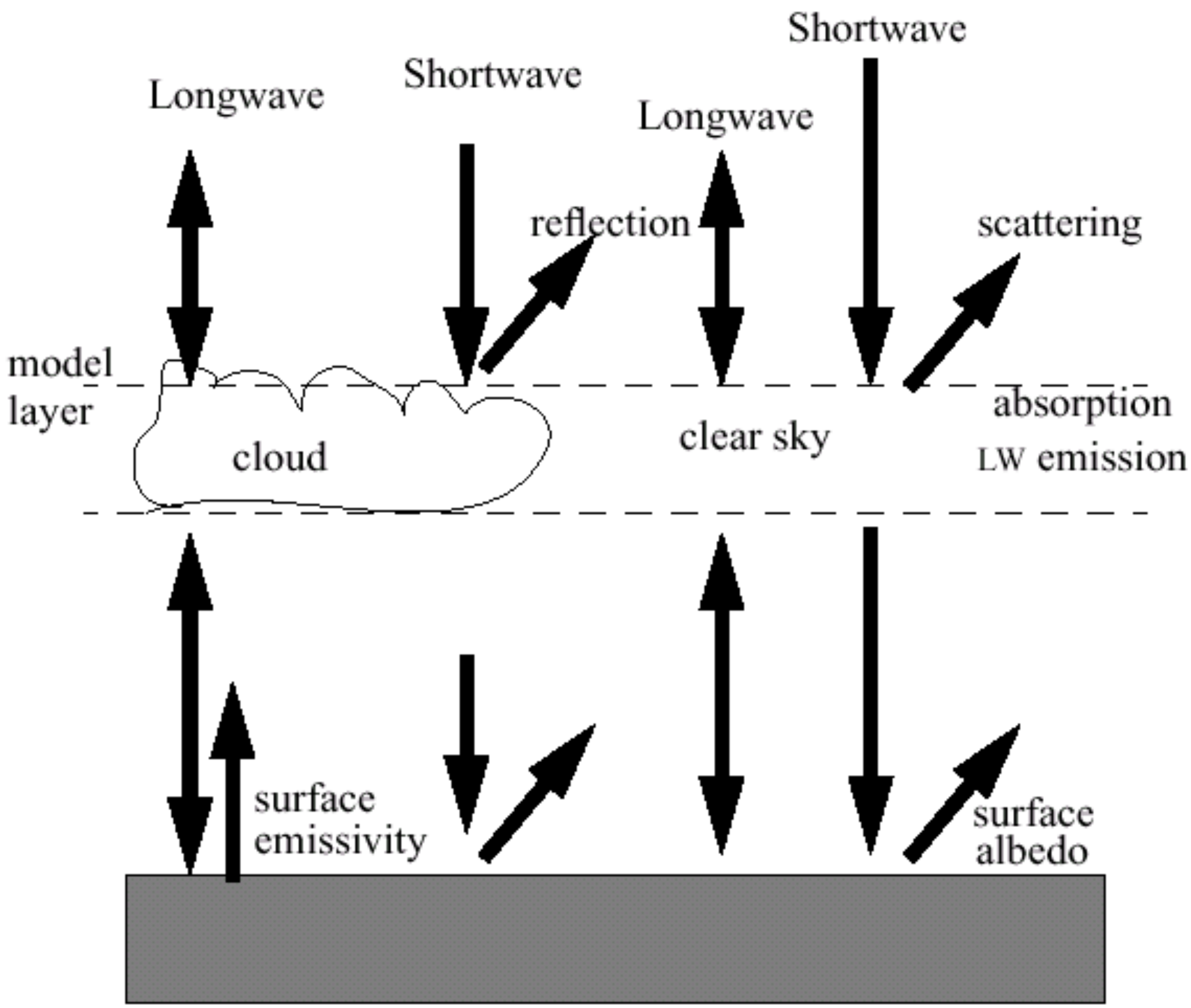


Illustration of Free Atmosphere Radiation Processes



WRF Longwave Radiation Schemes (ra_lw_physics)

- 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

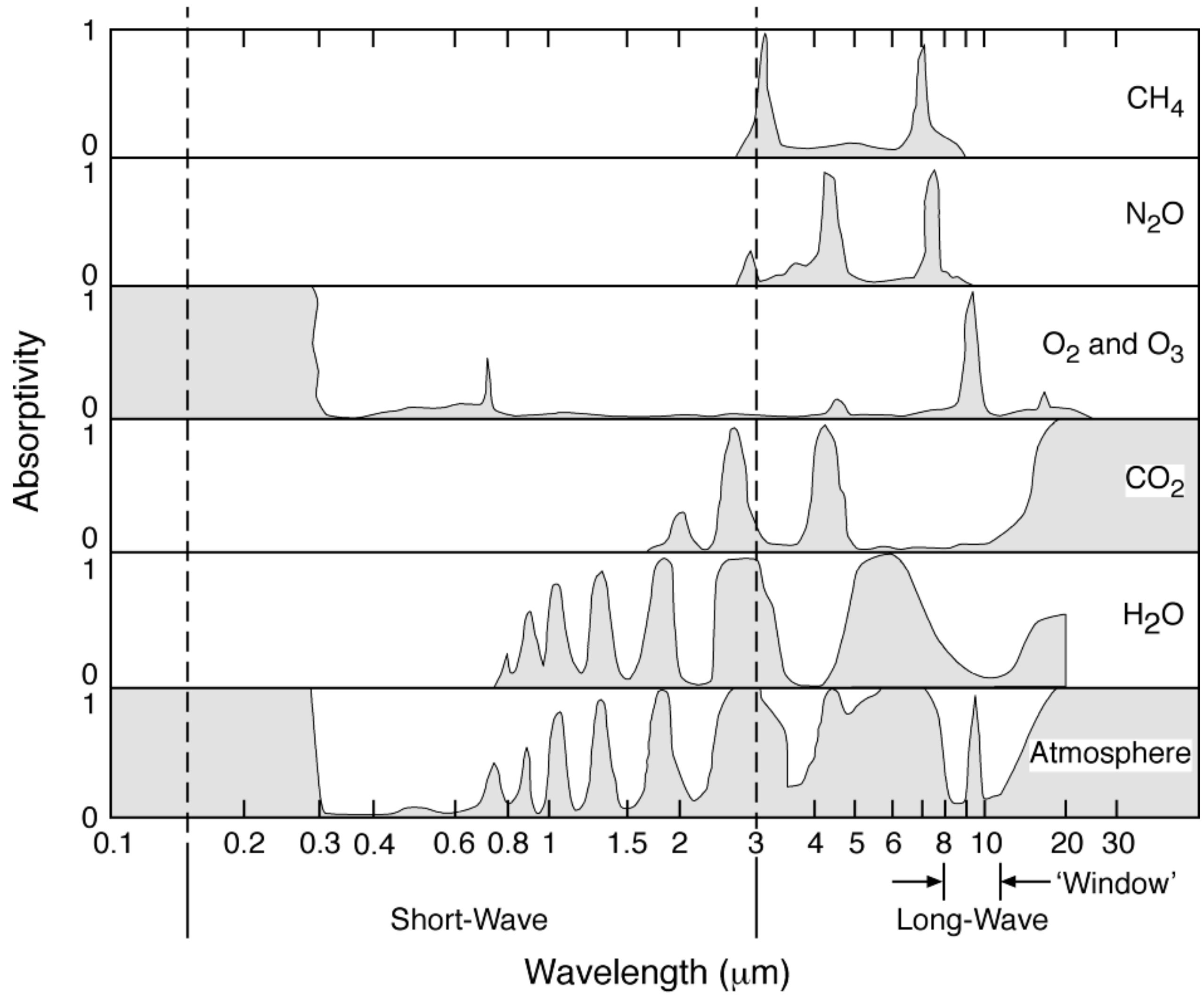
Longwave Radiation schemes

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
31	Held-Suarez		2000
99	GFDL	Fels and Schwarzkopf (1981, JGR)	2004

Clear Sky: IR-active Gases

- H_2O – from model prognostic vapor
- CO_2 – well-mixed, specified constant in whole atmosphere (CAM has year-dependent table of values)
- O_3 – schemes have own climatologies
  - CAM has monthly, zonal, pressure-level data
  - Others use single profiles (Goddard has 5 profiles to choose from)

Radiation effects in clear sky



Spectral Bands

- Schemes divide IR spectrum into bands dominated by different absorption gases
- Typically 8-16 bands are used
- Computations use look-up tables for each band
  - Tables were generated from results of line-by-line calculations (LBLRTM models)

Clouds

- All schemes interact with resolved model cloud fields allowing for ice and water clouds and precipitating species
- Clouds strongly affect IR at all wavelengths (considered "grey bodies") and are almost opaque to it

Cloud Fractions

- Schemes are capable of handling cloud fractions
- WRF can provide cloud fractions based on RH, but mostly the fraction is 0 or 1 in a grid box
- Cloud fraction methods
  – cldfra2 used by CAM and RRTMG
  – cldfra used by others except GFDL (computes its own)

Cloud Fraction

- Overlap assumptions needed with multiple layers of varying fraction
  - Random overlap
  - Maximum overlap (clouds stacked as much as possible)
  - Maximum-random overlap (maximum for neighboring cloudy layers, random for layers separated by clear air)
- WRF schemes use max-random overlap

WRF Shortwave Radiation Options (ra_sw_physics)

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

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
99	GFDL	Fels and Schwarzkopf (1981, JGR)	2004

Clear Sky

- Main effect in troposphere is water vapor absorption (CO_2 minor effect)
- Aerosols would be needed for additional scattering (WRF-Chem interacts with Goddard and RRTMG shortwave)
  - Dudhia scheme has tunable scattering

Ozone

- Ozone heating maintains warm stratosphere
- Important for model tops above about 20 km (50 hPa)
- Usually specified from profiles as with longwave options
  - Dudhia scheme has no ozone effect
- CAM, RRTMG, Goddard can also handle trace gases (set zero or constant)

Spectral Bands

- 11-19 spectral bands used by CAM, RRTMG and Goddard schemes
- Look-up tables

Clouds and Cloud Fraction

- Similar considerations to longwave
- Interacts with model resolved clouds
- Fraction and overlap assumptions
- Cloud albedo reflection
- Surface albedo reflection based on land-surface type and snow cover

Slope effects on shortwave

- In V3.2 available for all shortwave options
- Represents effect of slope on surface solar flux accounting for diffuse/direct effects
- slope_rad=1: activates slope effects - may be useful for complex topography and grid lengths < 2 km.
- topo_shading=1: shading of neighboring grids by mountains - may be useful for grid lengths < 1 km.

ARW only

radt

Radiation time-step recommendation

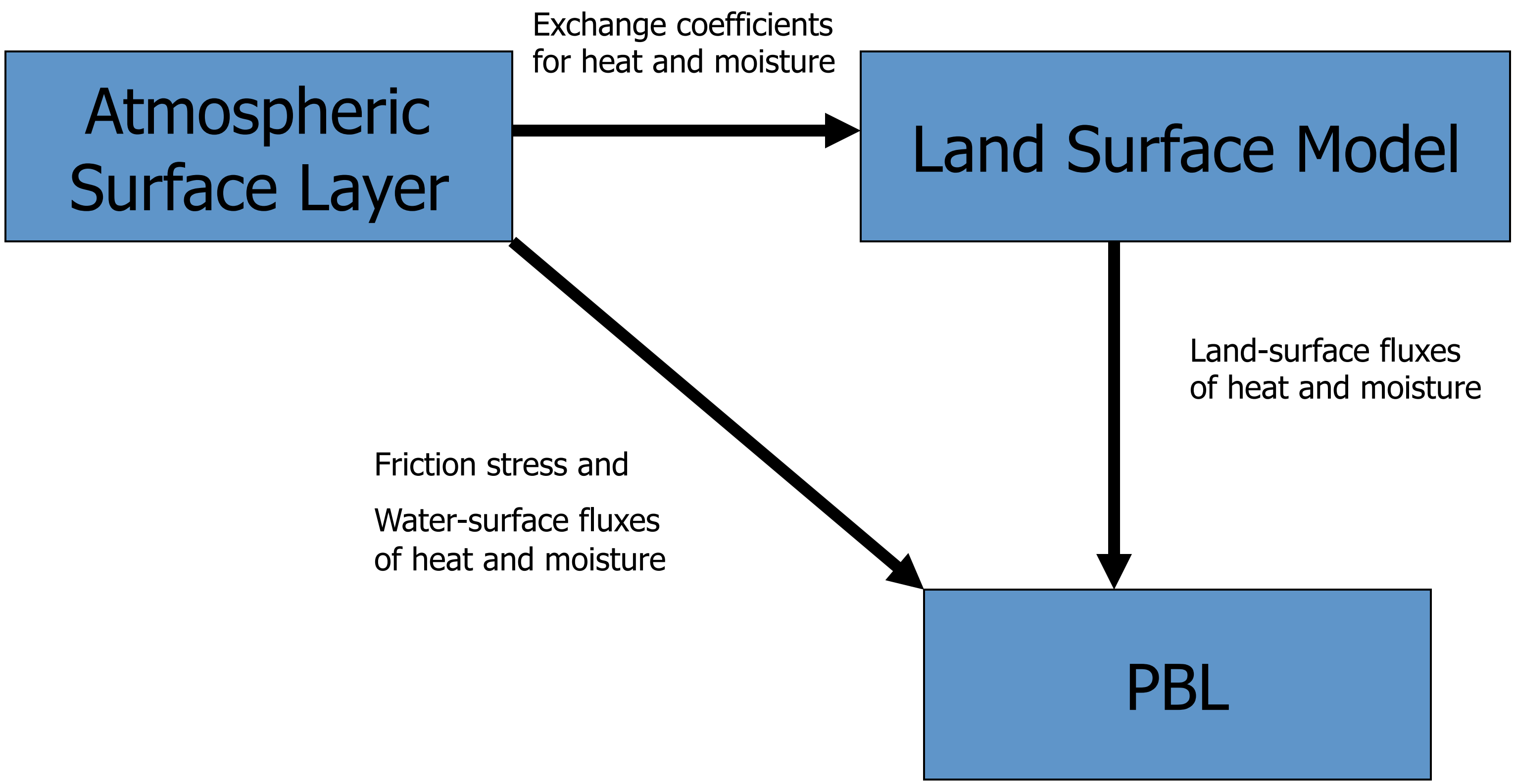
- Radiation is too expensive to call every step
- Frequency should resolve cloud-cover changes with time
- radt=1 minute per km grid size is about right (e.g. radt=10 for dx=10 km)
- Each domain can have its own value but recommend using same value on all 2-way nests

Surface schemes

Surface layer of atmosphere diagnostics (exchange/transfer coeffs)

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

Surface Physics Components



Surface Fluxes

- Heat, moisture and momentum

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

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

Subscript *r* is reference level (lowest model level, or 2 m or 10 m)
z_0 are the roughness lengths

Roughness Lengths

- Roughness lengths are a measure of the “initial” length scale of surface eddies, and generally differ for velocity and scalars
- Roughness length depends on land-use type
- Some schemes use smaller roughness length for heat than for momentum
- For water points roughness length is a function of surface wind speed

Exchange Coefficient

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

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

It is related to the roughness length and u* by

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

WRF Surface Layer Options (sf_sfclay_physics)

- Use similarity theory to determine exchange coefficients and diagnostics of 2m T and q and 10 m winds
- Provide exchange coefficient to land-surface models
- Provide friction velocity to PBL scheme
- Provide surface fluxes over water points
- Schemes have variations in stability functions, roughness lengths

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Hurricane Options

- Ocean Mixed Layer Model (omlcall=1)
  - 1-d slab ocean mixed layer (specified initial depth)
  - Includes wind-driven ocean mixing for SST cooling feedback
- Alternative surface-layer options for high-wind ocean surface (isftcflx=1,2)
  - Use with sf_sfclay_physics=1
  - Modifies Charnock relation to give less surface friction at high winds (lower Cd)
  - Modifies surface enthalpy (Ck, heat/moisture) either with constant z0q (isftcflx=1), Garratt formulation (option 2)

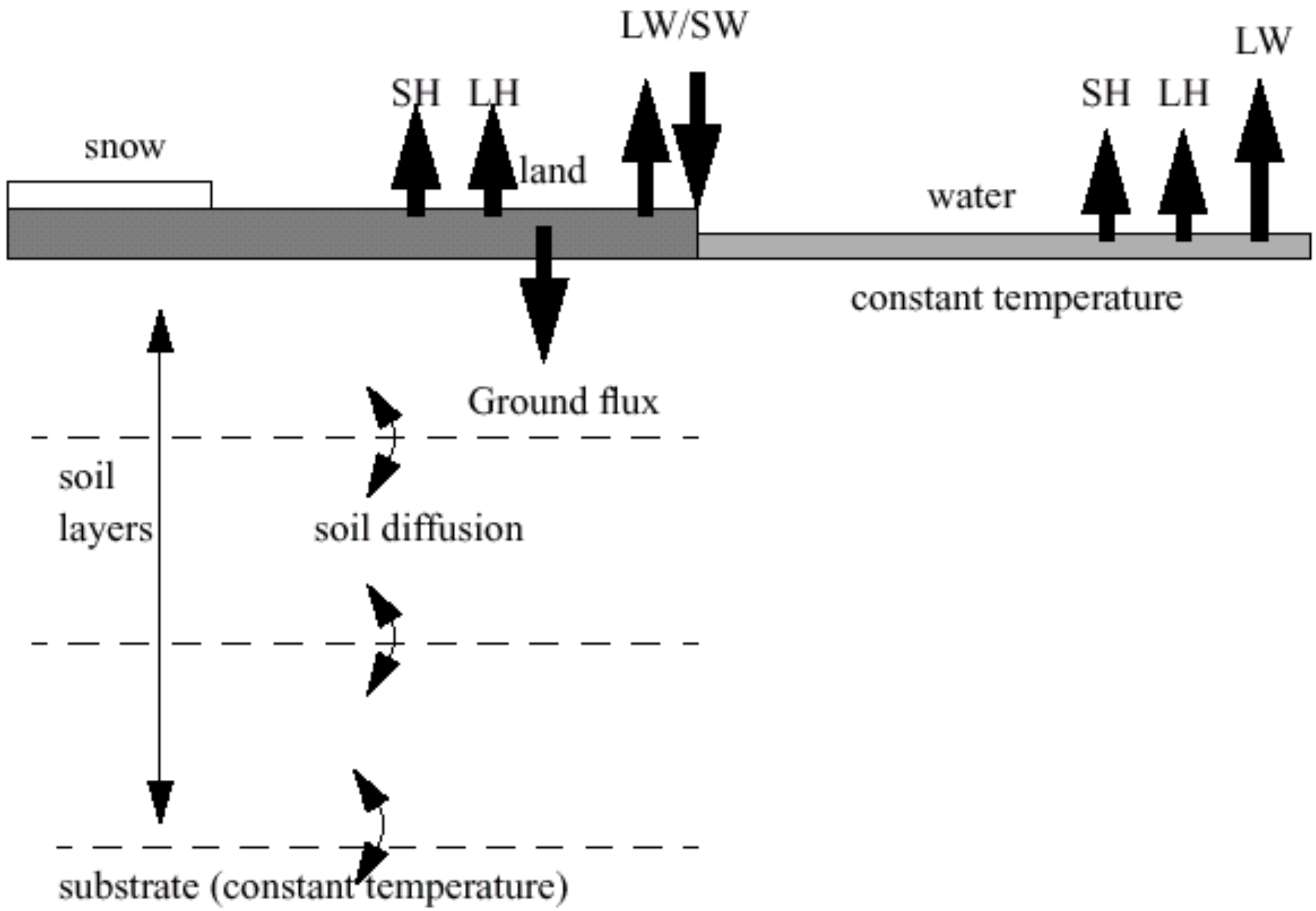
Fractional Sea Ice

- fractional_seaice=1 - with input sea-ice fraction data can partition land/water fluxes within a grid box

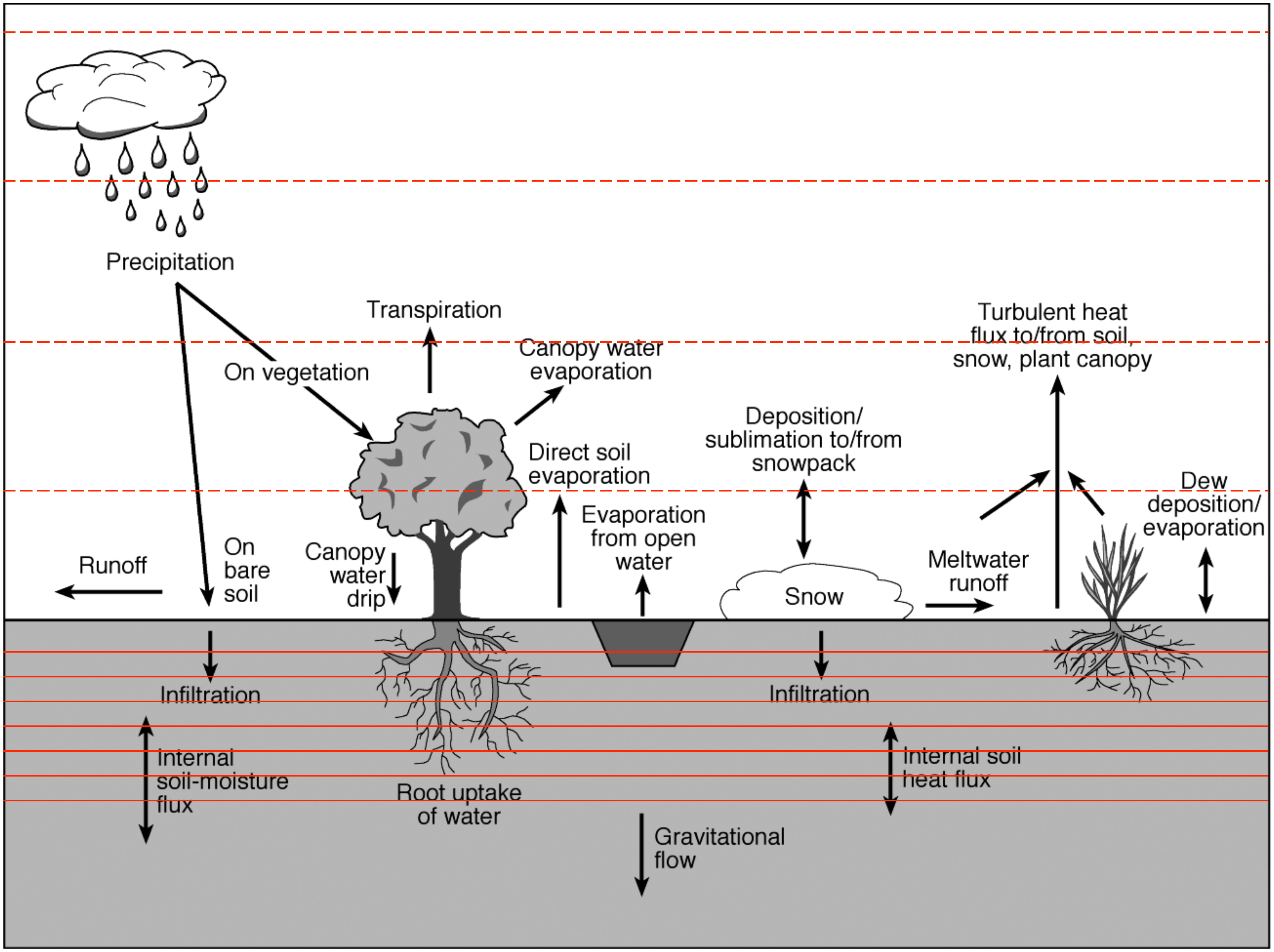
WRF Land-Surface Model Options (sf_surface_physics)

- Simple 5-layer soil model
  - No vegetation or snow cover prediction, just thermal diffusion in soil layers
- Noah LSM, RUC LSM, PX LSM land-surface models
  - Sophisticated vegetation model and snow cover prediction

Illustration of Surface Processes



Land-Surface Model Processes



Land-Surface Model

- Predicts soil temperature and soil moisture in layers (4 for Noah, 6 for RUC, 2 for PX)
- Predicts snow water equivalent on ground. May be in layers (RUC)
- May predict canopy moisture (Noah)

Land-Surface Options

- 5-layer thermal diffusion
- Noah LSM
- RUC LSM
- Pleim-Xiu LSM

Vegetation and Soil

- Processes include evapotranspiration, root zone and leaf effects
- Vegetation fraction varies seasonally
- Considers vegetation categories (e.g. cropland, forest types, etc.)
- Considers soil categories (e.g. sandy, clay, etc.) for drainage and thermal conductivity

Urban Effects

- Urban category in LSM is usually adequate for larger-scale studies
- Or can use an urban model (sf_urban_physics) with Noah LSM
  - Urban Canopy Model
  - Building Environment Parameterization (multi-layer model)
  - Building Energy Model (adds heating/AC effects to BEP)

LSM Tables

- Properties can be changed in text files (tables)
- VEGPARM.TBL used by Noah and RUC for vegetation category properties
- SOILPARM.TBL used by Noah and RUC for soil properties
- LANDUSE.TBL used by 5-layer model
- URBPARM.TBL used by urban models

Initializing LSMs

- Noah and RUC LSM require additional fields for initialization
  - Soil temperature
  - Soil moisture
  - Snow liquid equivalent
- These are in the Grib files, but are not from observations
- They come from “offline” models driven by observations (rainfall, radiation, surface temperature, humidity wind)

Initializing LSMs

- There are consistent model-derived datasets for Noah and RUC LSMs
  - Eta/GFS/AGRMET/NNRP for Noah (although some have limited soil levels available)
  - RUC for RUC
- But, resolution of mesoscale land-use means there will be inconsistency in elevation, soil type and vegetation
- This leads to spin-up as adjustments occur in soil temperature and moisture
- This spin-up can only be avoided by running offline model on the same grid (e.g. HRLDAS for Noah)
- Cycling land state between forecasts also helps, but may propagate errors (e.g in rainfall effect on soil moisture)

ARW only

sst_update=1

Reads lower boundary file periodically to update the sea-surface temperature (otherwise it is fixed with time)

- For long-period simulations (a week or more)
- wrflowinp_d0*n* created by *real*
- Sea-ice can be updated since Version 3.0
- Vegetation fraction update is included
  - Allows seasonal change in albedo, emissivity, roughness length in Noah LSM
- usemonalb=.true. to use monthly albedo input

Regional Climate Options

- tmn_update=1 - updates deep-soil temperature for multi-year future-climate runs
- sst_skin=1 - adds diurnal cycle to sea-surface temperature
- bucket_mm and bucket_J - a more accurate way to accumulate water and energy for long-run budgets (see later)
- output_diagnostics=1 (in 3.3.1) – ability to output max/min/mean/std of surface fields in a specified period

Planetary Boundary Layer

Provides

Boundary layer fluxes (heat, moisture, momentum)

Vertical diffusion in whole column

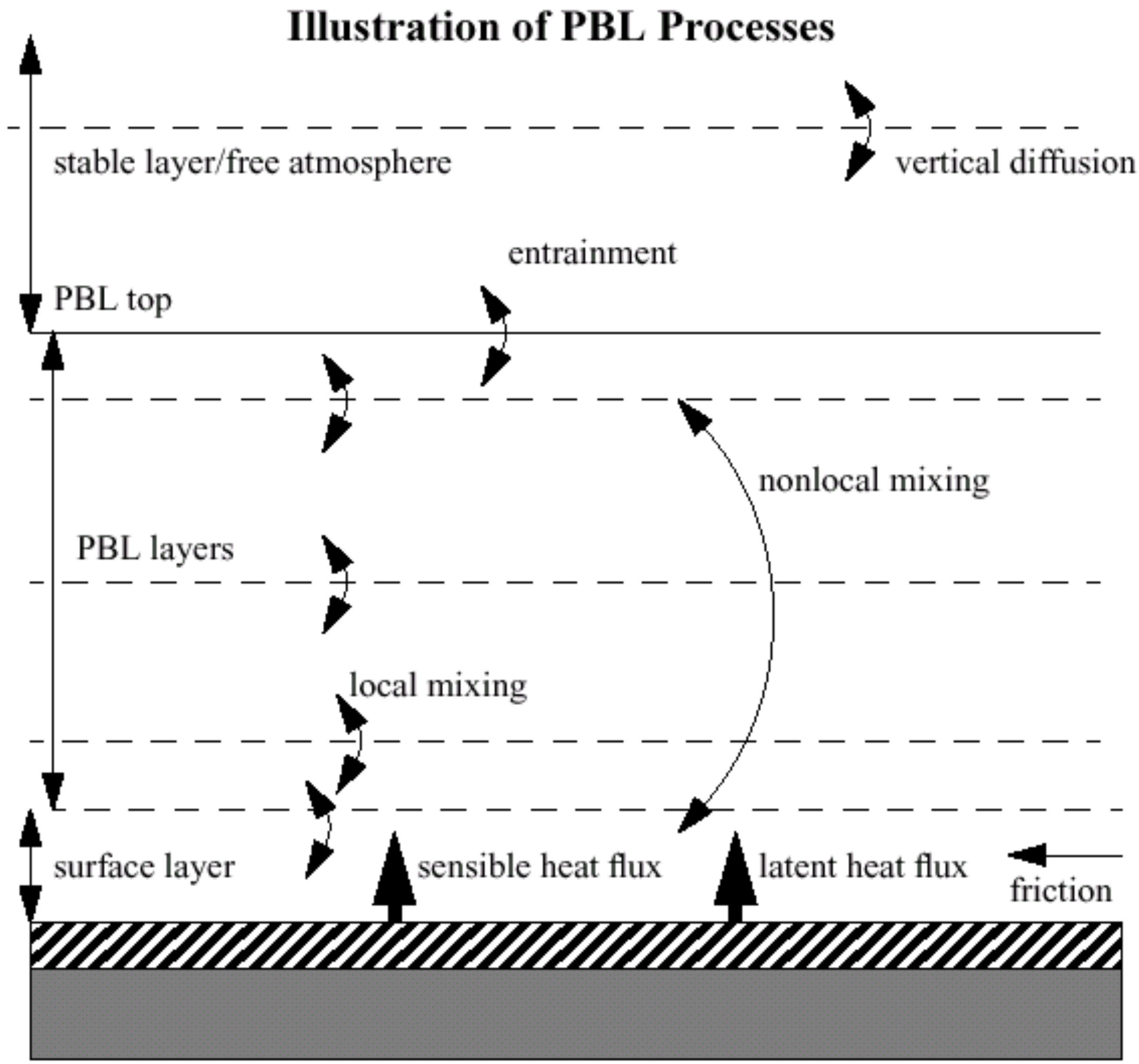
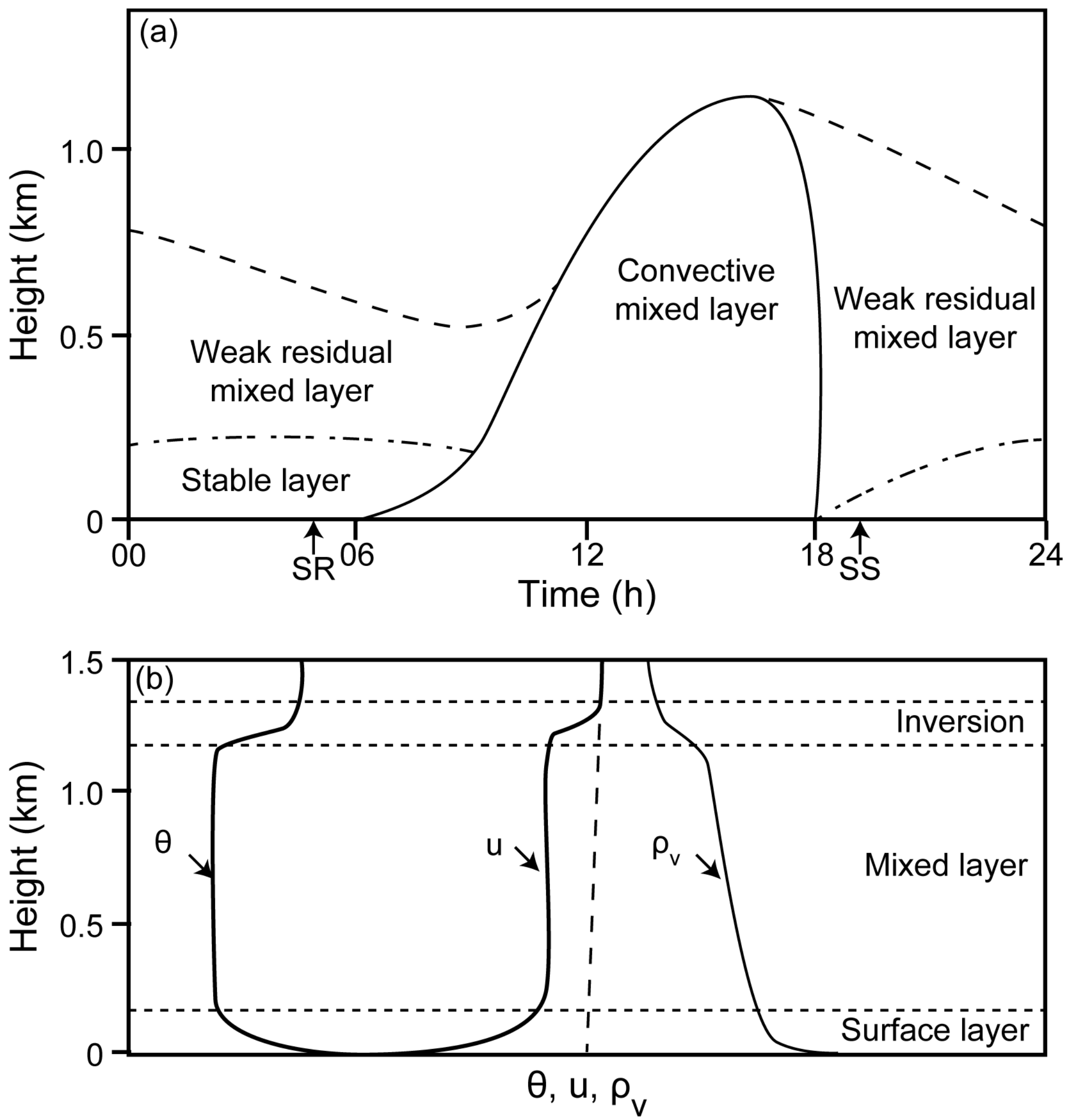


Illustration of PBL Processes
stable layer/free atmosphere
vertical diffusion
entrainment
PBL top
nonlocal mixing
PBL layers
local mixing
surface layer
sensible heat flux
latent heat flux
friction

Planetary Boundary Layer



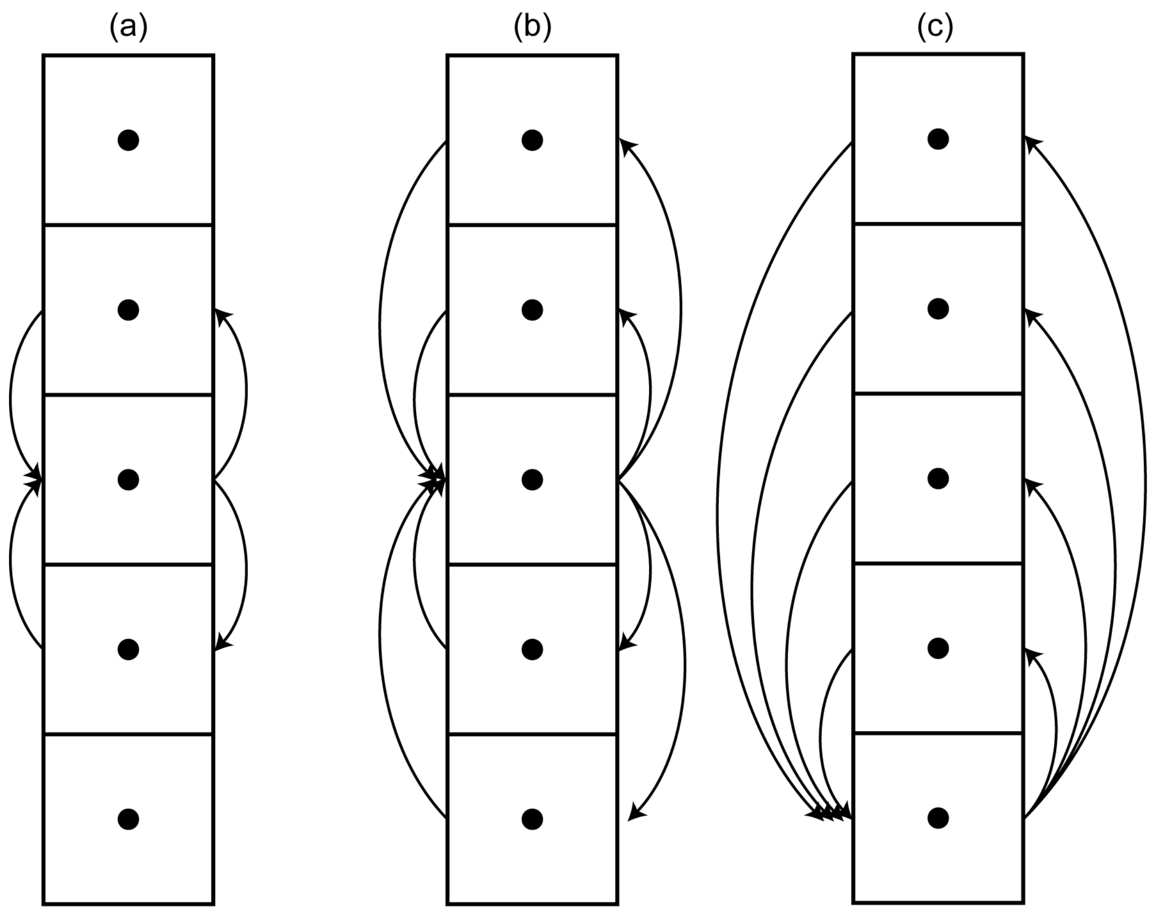
WRF PBL Options (bl_pbl_physics)

- Purpose is to distribute surface fluxes with boundary layer eddy fluxes and allow for PBL growth by entrainment
- Classes of PBL scheme
  - Turbulent kinetic energy prediction (Mellor-Yamada Janjic, MYNN, Bougeault-Lacarrere, TEMF, QNSE, CAM UW)
  - Diagnostic non-local (YSU, GFS, MRF, ACM2)
- Above PBL all these schemes also do vertical diffusion due to turbulence

PBL schemes in V3.3

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	Sukoriansky, Galperin and Perov (2005, BLM)	2009
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
99	MRF	Hong and Pan (1996, MWR)	2000

Different approaches



Local closure

Non-local closures

TKE schemes

- Solve for TKE in each column
  - Buoyancy and shear production
  - Dissipation
  - Vertical mixing $\frac{\partial}{\partial z} K_v \frac{\partial}{\partial z} \theta$
- TKE and length-scale are used to determine the Kv for local vertical mixing
- Schemes differ most in diagnostic length-scale computations

Nonlocal Schemes

- Diagnose a PBL top (either stability profile or Richardson number)
- Specify a K profile

$$\frac{\partial}{\partial z}(K_v \frac{\partial}{\partial z}\theta + \Gamma)$$

- YSU, MRF, GFS include a non-local term (Γ)
- ACM2, TEMF include a mass-flux term which is a flux between non-neighboring layers

Vertical Mixing Coefficient

- Several schemes also output exch_h which is Kv for scalars that is used by WRF-Chem
- WRF in the future will also use this for scalar and tracer vertical mixing outside the PBL scheme since these arrays are currently only advected and horizontally mixed when using a PBL scheme
- PBL schemes themselves only mix limited variables: momentum, heat, vapor and some specific cloud variables

PBL schemes in V3.3

3.3 changes

bl_pbl_ physics	Scheme	Cores	sf_sfclay_ physics	Prognostic variables	Diagnostic variables	Cloud mixing
1	YSU	ARW NMM	1		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	ARW NMM	4	TKE_PBL	EL_PBL, exch_h, exch_m	QC,QI
5	MYNN2	ARW	1,2,5	QKE	Tsq, Qsq, Cov, exch_h, exch_m	QC
6	MYNN3	ARW	1,2,5	QKE, Tsq, Qsq, Cov	exch_h, exch_m	QC
7	ACM2	ARW	1,7			QC,QI
8	BouLac	ARW	1,2	TKE_PBL	EL_PBL, exch_h, exch_m	QC
9	UW	ARW	2	TKE_PBL	exch_h, exch_m	QC
10	TEMF	ARW	10	TE_TEMF	*_temf	QC, QI
99	MRF	ARW NMM	1			QC,QI

PBL Scheme Options

PBL schemes can be used for most grid sizes when surface fluxes are present

- With ACM2, GFS and MRF PBL schemes, lowest full level should be .99 or .995 not too close to 1 (YSU can now handle thin layers)
- TKE schemes can use thinner surface layers
- Assumes that PBL eddies are not resolved
- At grid size dx << 1 km, this assumption breaks down
  - Can use 3d diffusion instead of a PBL scheme in Version 3 (coupled to surface physics)
  - Works best when dx and dz are comparable

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
- TKE and 3d Smagorinsky options exist for the sub-grid turbulence

Large-Eddy Simulation

- To run LES mode
  - Use bl_pbl_physics=0 and diff_opt=2 with km_opt=2 or 3
  - This scheme can also use real surface fluxes from the surface physics (heat, moisture, momentum stress) or idealized constant values

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	Cores	sf_sfclay_physics	isfflx	Prognostic variables
0	2	2	tke	ARW	0,1,2	0,1,2	tke
0	2	3	3d Smagorinsky	ARW	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

Other Options

- Gravity-wave drag can be added for low resolution (> 10 km) runs to represent sub-grid orographic gravity-wave vertical momentum transport (gwd_opt=1)
- A wind-farm model has been added to investigate wind-farm effects on the environment (extra stress and turbulence generation)

ARW only

bldt

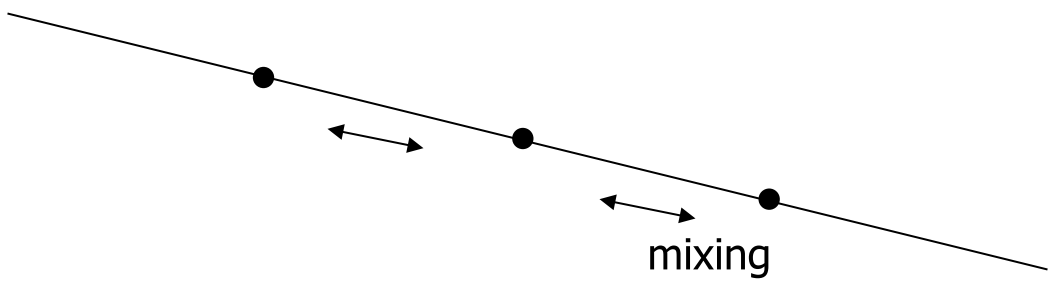
- Minutes between boundary layer/LSM calls
- Typical value is 0 (every step)

Turbulence/Diffusion

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

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

Difference between diff_opt 1 and 2

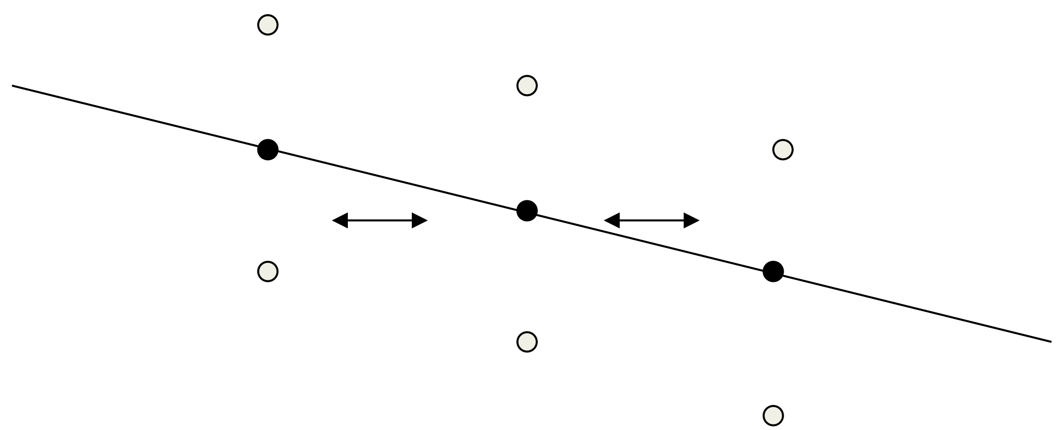


diff_opt=1

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 horizontal gradients
Numerical method includes vertical correction term using more grid points

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km_opt

- km_opt selects method for computing K coefficient
  - km_opt=1: constant (use khdif and kvdif to specify – idealized)
  - km_opt=2: 3d tke prediction used to compute K (requires diff_opt=2)
  - km_opt=3: 3d Smagorisnky diagnostic K (requires diff_opt=2)
  - km_opt=4: 2d Smagorinsky for horizontal K (to be used with PBL or kvdif for vertical K)

ARW only

sfs_opt

- Sub-filter-scale stress model for LES applications impacting momentum mixing (Kosovic, Mirocha)
  - sfs_opt=0 (default) off
  - sfs_opt=1 Nonlinear Backscatter and Anisotropy (NBA) option 1: using diagnostic stress terms (km_opt=2,3)
  - sfs_opt=2 NBA option 2: using tke-based stress terms (km_opt=2 only)
  - Also m_opt=1 for added outputs of SGS stresses

Diffusion Option Choice

- Real-data case with PBL physics on
  - Best is diff_opt=1, km_opt=4
  - 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)
- idealized cloud-resolving modeling (smooth or no topography)
  - 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
- Note: WRF can run with no diffusion (diff_opt=0)

ARW only

diff_6th_opt

- 6th order optional added horizontal diffusion on model levels
  - Used as a numerical filter for 2*dx noise
  - Suitable for idealized and real-data cases
  - Affects all advected variables including scalars
- diff_6th_opt
  - 0: none (default)
  - 1: on (can produce negative water)
  - 2: on and prohibit up-gradient diffusion (better for water conservation)
- diff_6th_factor
  - Non-dimensional strength (typical value 0.12, 1.0 corresponds to complete removal of 2*dx wave in a time-step)

ARW only

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

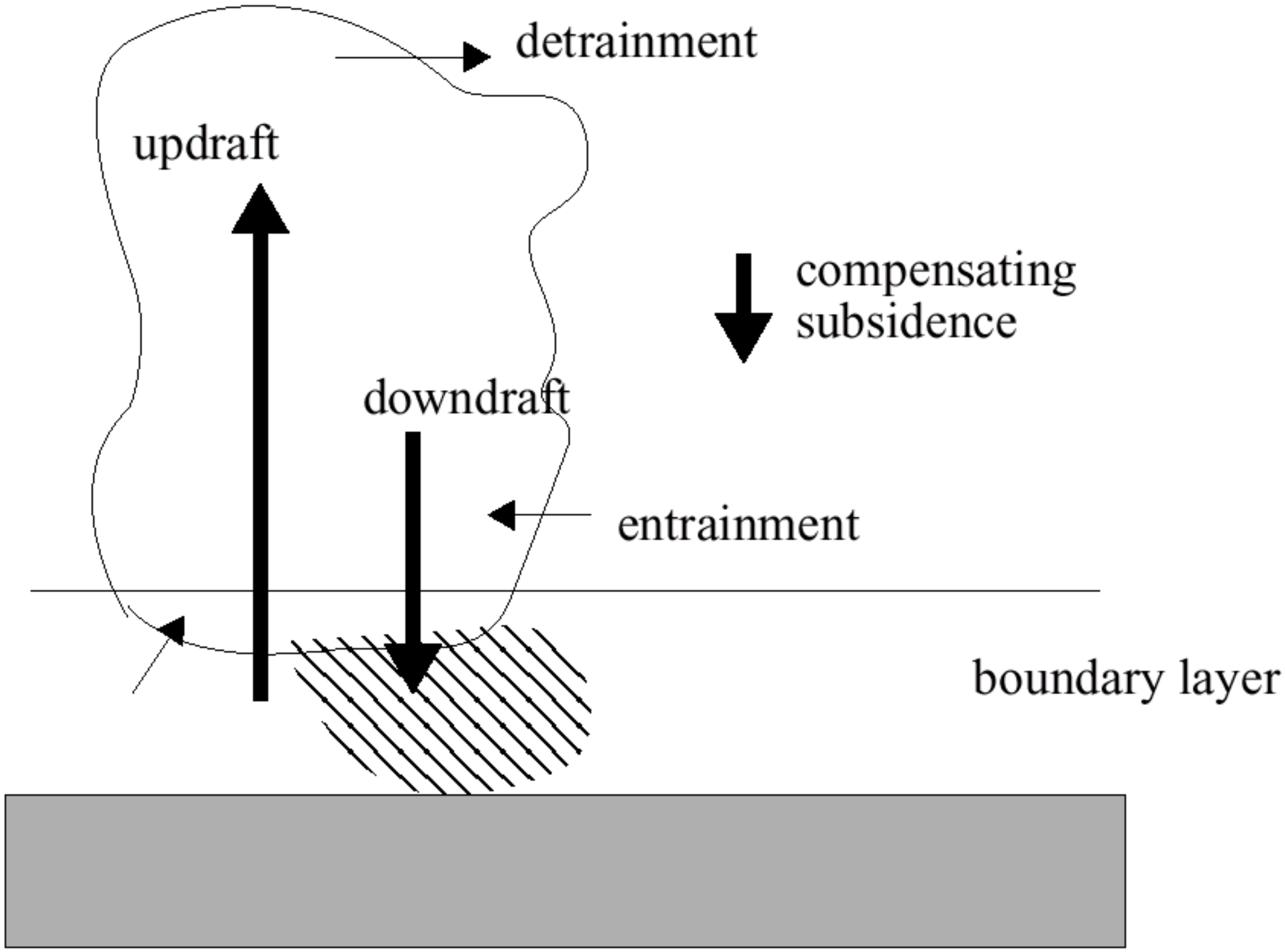
Cumulus Parameterization

Provides

Atmospheric heat and moisture/cloud tendency profiles

Surface sub-grid-scale (convective) rainfall

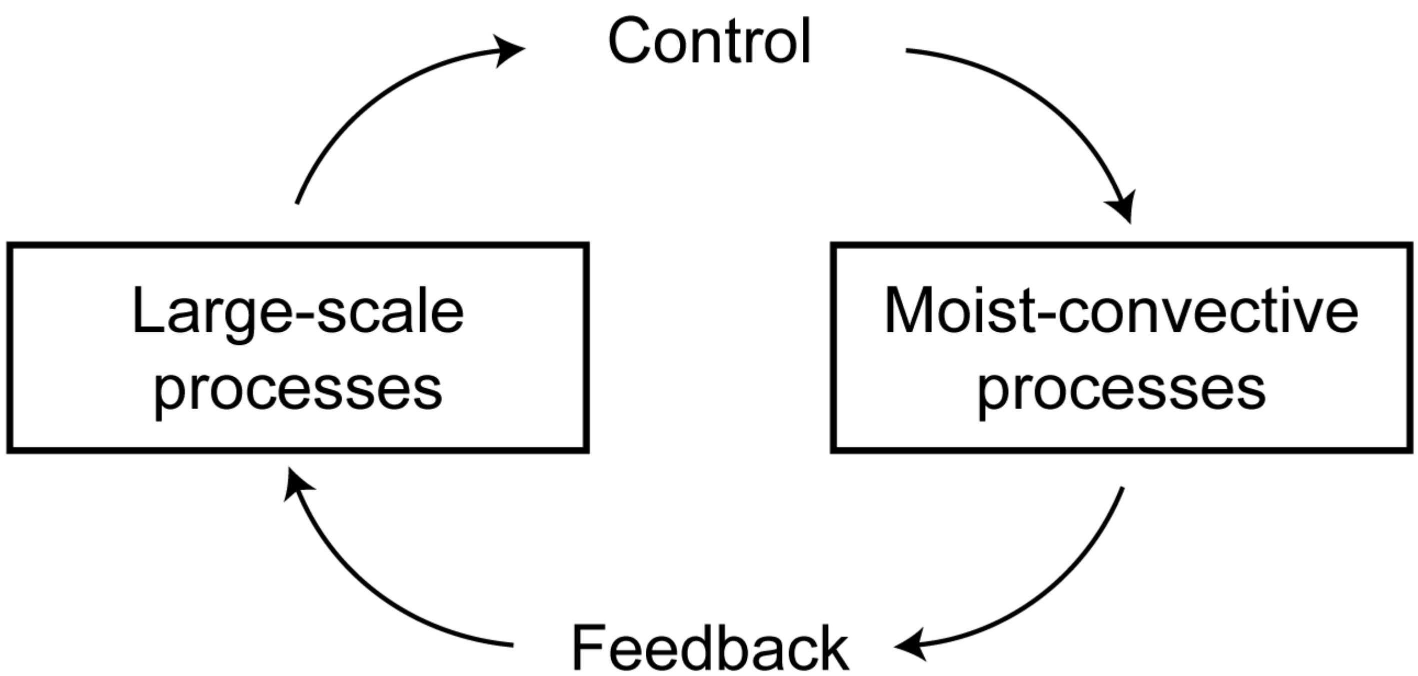
Illustration of Cumulus Processes



Cumulus Schemes

- Use for grid columns that completely contain convective clouds
- 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

Parameterizations of cumulus convection



WRF Cumulus Parameterization Options

- Cumulus schemes fall into two main classes
  - Adjustment type (Betts-Miller-Janjic)
    - Relaxes towards a post-convective (mixed) sounding
  - Mass-flux type (all others in WRF)
    - Determines updraft (and often downdraft) mass flux and other fluxes (sometimes including momentum transport)

Cumulus schemes in V3.3

mp_physics	Scheme	Reference	Added
1	Kain-Fritsch	Kain (2004, JAM)	2000
2	Betts-Miller-Janjic	Janjic (1994, MWR; 2000, JAS)	2002
3	Grell-Devenyi	Grell and Devenyi (2002, GRL)	2002
4	Simplified Arakawa-Schubert	Grell et al. (1994, MM5 NCAR Tech Note)	2002/ 2011
5	Grell-3	Grell and Devenyi (2002, GRL)	2008
6	Tiedtke	Tiedtke (1989, MWR), Zhang, Wang and Hamilton (2011, MWR)	2011
7	Zhang-McFarlane	Zhang and McFarlane (1995, AO)	2011
14	New SAS	Han and Pan (2010,…)	2011
99	Old Kain-Fritsch	Kain and Fritsch (1990, JAS; 1993 Meteo. Monogr.)	2000

Deep Convection

- Schemes work in individual columns that are considered convectively unstable
- Mass-flux schemes transport surface air to top of cloud and include subsidence
- Subsidence around cloud warms and dries troposphere removing instability over time
- Additionally downdrafts may cool PBL

Triggers

- Clouds only activate in columns that meet certain criteria
  - Presence of some convective available potential energy (CAPE) in sounding
  - Not too much convective inhibition (CIN) in sounding (cap strength)
  - Minimum cloud depth from parcel ascent

Closures

- Closure determine cloud strength (mass-flux) based on various methods
  - Clouds remove CAPE over time
    - Specified CAPE-removal time scale (KF, Tiedtke, ZM, BMJ)
    - Quasi-equilibrium (Arakawa-Schubert) with large-scale destabilization d(CAPE)/dt (SAS, NSAS)
    - Column moisture convergence
    - Low-level large-scale ascent (mass convergence)

Ensemble methods

- G3 and GD use ensemble of triggers and closures with varying parameters (effectively 144 members)
- Take mean of ensemble to feed back to model
- In principle, can be tuned to emphasize various members under different conditions

Shallow Convection

- Non-precipitating shallow mixing dries PBL, moistens and cools above
- This can be done by an enhanced mixing approach (SAS) or mass-flux approach (KF, NSAS, Tiedtke, G3)

Shallow Convection

- Several schemes include shallow convection (KF, SAS schemes, G3, BMJ, Tiedtke)
  - WRF also has UW Park-Bretherton stand-alone scheme (shcu_physics=2)
  - Note: TEMF PBL option (bl_bl_physics=10) also includes a mass-flux shallow convection component and some future PBL schemes may add it
    - This development will require making shallow convectional independent of deep schemes in a future WRF version

Momentum Transport

- Some cumulus parameterizations also have momentum transport (SAS, NSAS, Tiedtke, ZM)
- Most schemes transport momentum as a passive scalar but ZM and NSAS include a convective pressure gradient term

Cloud Detrainment

- Most schemes detrain cloud and ice at cloud top (except BMJ)
- KF schemes also detrain snow and rain
- These are then used by the microphysics

ARW only

cudt

- Time steps between cumulus scheme calls
- Typical value is 5 minutes
  - Note: for KF scheme this is also used for averaging time for vertical velocity trigger
  - Not used by G3 or GD schemes

Cumulus schemes in V3.3

cu_physics	Scheme	Cores	Moisture Tendencies	Momentum Tendencies	Shallow Convection
1	Kain-Fritsch Eta	ARW NMM	Qc Qr Qi Qs	no	yes
2	Betts-Miller-Janjic	ARW NMM	-	no	yes
3	Grell-Devenyi	ARW	Qc Qi	no	no
4	Simplified Arakawa-Schubert	ARW NMM	Qc Qi	yes (NMM)	yes (ARW)
5	Grell-3	ARW	Qc Qi	no	yes
6	Tiedtke	ARW	Qc Qi	yes	yes
7	Zhang-McFarlane	ARW	Qc Qi	yes	no
14	New SAS	ARW	Qc Qi	yes	yes
99	Old Kain-Fritsch	ARW	Qc Qr Qi Qs	no	no

Cumulus scheme

Recommendations about use

- For dx ≥ 10 km: probably need cumulus scheme
- For dx ≤ 3 km: probably do not need scheme
  - However, there are cases where the earlier triggering of convection by cumulus schemes help
- For 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
- 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

Microphysics

Provides

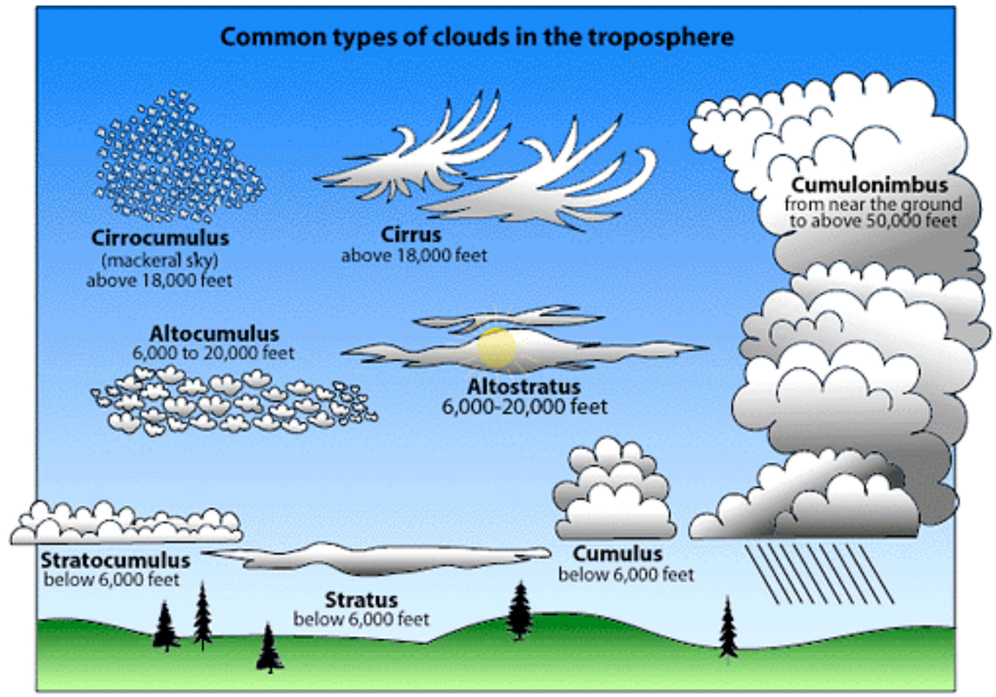
Atmospheric heat and moisture tendencies

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



Microphysics Parameterization

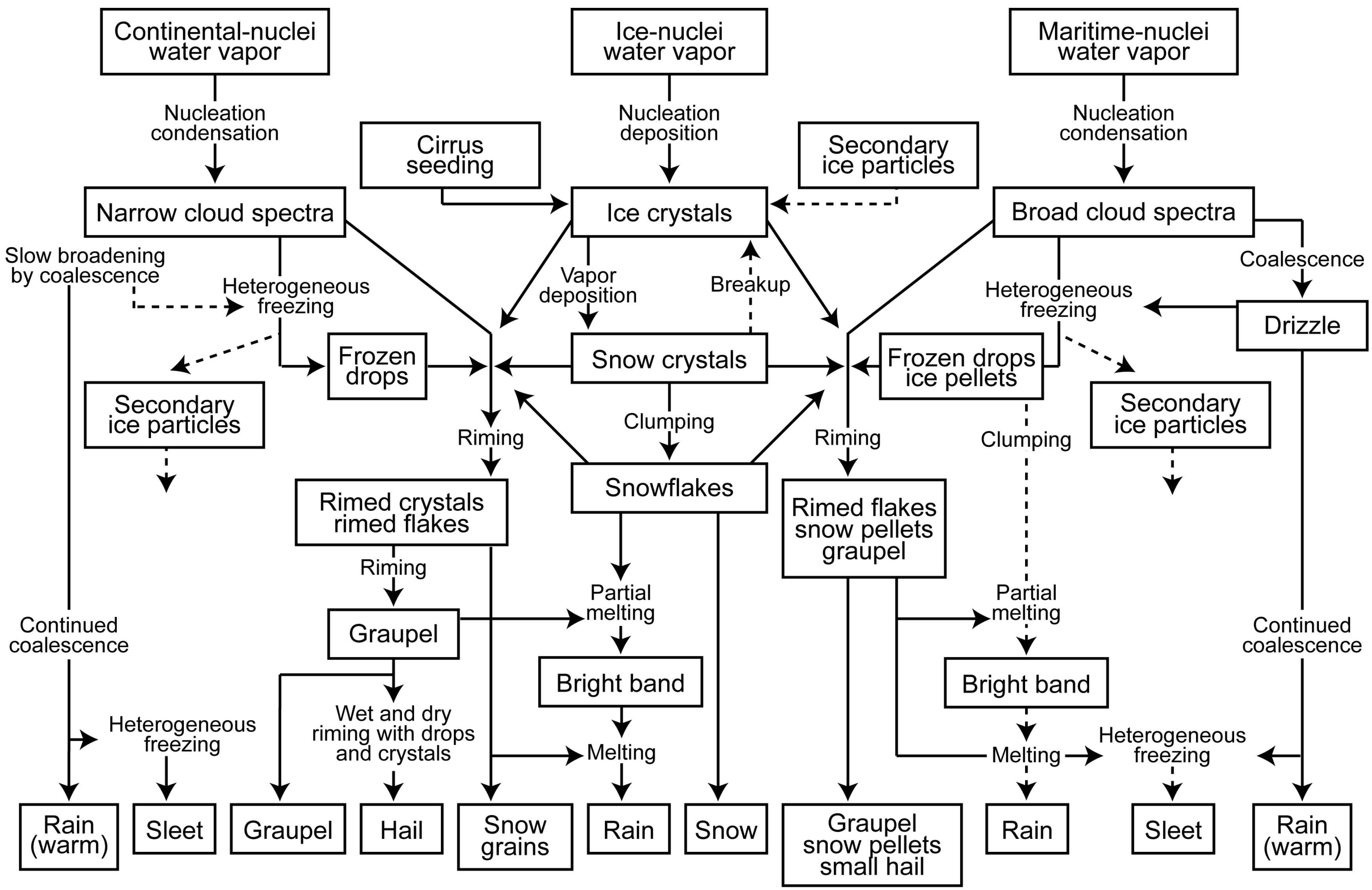
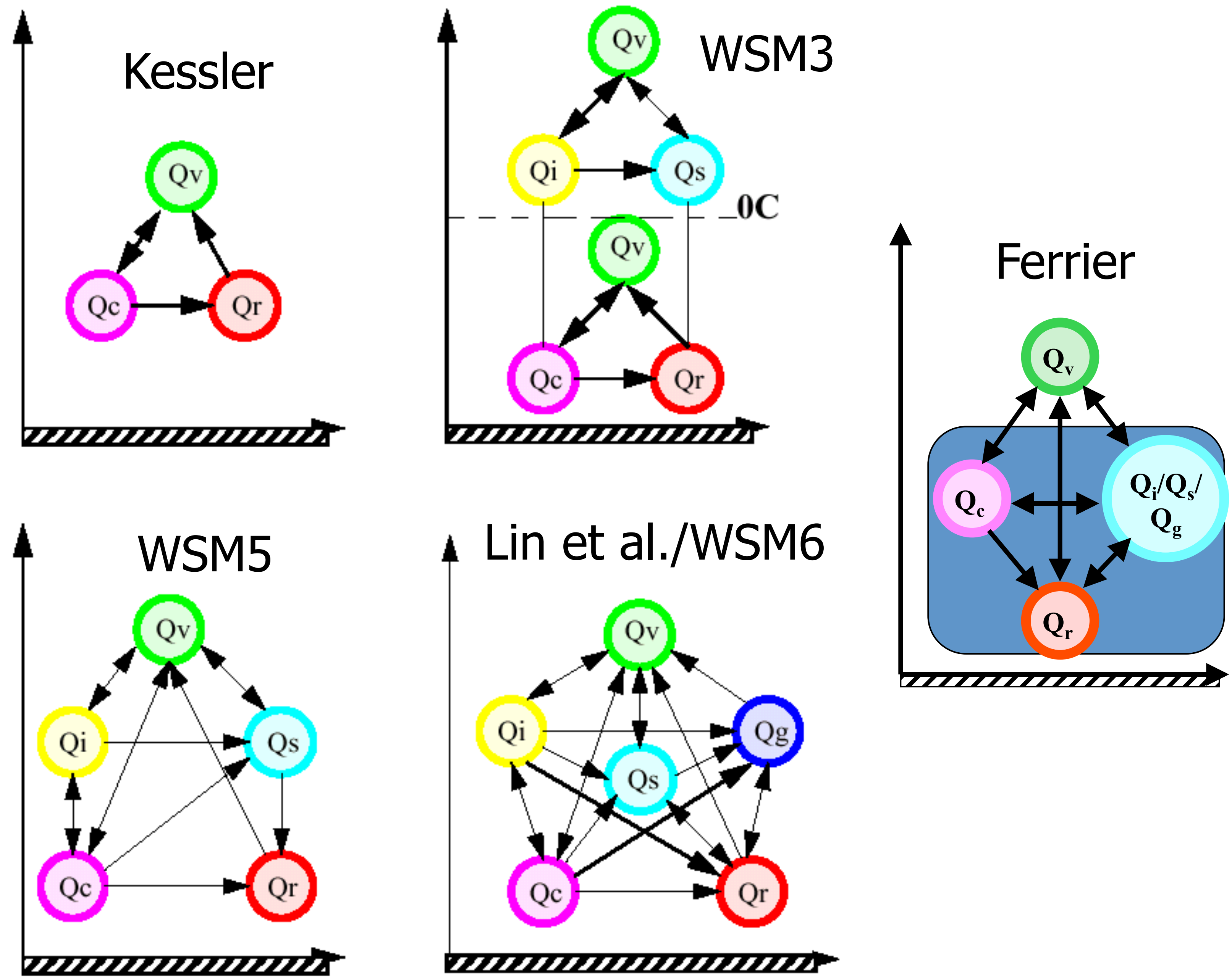


Illustration of Microphysics Processes



WRF Microphysics Options (mp_physics)

- Range of levels of sophistication
  - Warm rain (i.e. no ice) – Kessler (idealized)
  - Simple ice (3 arrays) – WSM3
  - Mesoscale (5 arrays, no graupel) – WSM5
  - Cloud-scale single-moment (6 arrays, graupel) – WSM6, Lin, Goddard, SBU, Eta-Ferrier
  - Double-moment (8-13 arrays) – Thompson, Morrison, Milbrandt-Yau, WDM5, WDM6

Microphysics schemes in V3.3

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	Hong and Pan (1996, MWR)	2008
13	SBU-Ylin	Lin and Colle (2011, MWR)	2011
14	WDM5	Lim and Hong (2010,...)	2009
16	WDM6	Lim and Hong (2010,…)	2009

Microphysics

- Latent heat release from
  - Condensation, evaporation, deposition, sublimation, freezing, melting
- Particle types
  - Cloud water, rain drops, ice crystals, snow, graupel (also hail in some)
    - Total mass contributes to liquid loading in dynamics
- Processes
  - Aggregation, accretion, growth, fall-out

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
- Double-moment (DM) schemes add a prediction equation for number concentration (#/kg) per DM species (Nr, Ns, etc.)
- DM schemes may only be double-moment for a few species
- DM schemes allow for additional processes such as size-sorting during fall-out and sometimes aerosol (CCN) effects

Microphysics: Fall terms

- Microphysics schemes handle fall terms for particles (usually everything except cloud water has a fall term)
- 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 splitting the time-step (most schemes) or lagrangian numerical methods (WSM and WDM schemes) to keep the scheme numerically stable

ARW only

no_mp_heating=1

- Turn off heating effect of microphysics
  - Zeroes out the temperature tendency
  - Equivalent to no latent heat
  - Other microphysics processes not affected
  - Since Version 3.0

Microphysics schemes in V3.3

* 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	ARW	Qc Qr Qi Qs Qg	
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	Morrison 2-mom	ARW (Chem)	Qc Qr Qi Qs Qg	Nr Ni Ns Ng
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 Options

Recommendations about choice

- Probably not necessary to use a graupel scheme for dx > 10 km
  - Updrafts producing graupel not resolved
  - Cheaper scheme may give similar results
- When resolving individual updrafts, graupel scheme should be used
- All domains use same option

ARW only

Rainfall Output

- Cumulus and microphysics can be run at the same time
- ARW outputs rainfall accumulations since simulation start time (0 hr) in mm
- RAINC comes from cumulus scheme
- RAINNC comes from microphysics scheme
- Total is RAINC+RAINNC
  - RAINNCV is time-step value
  - SNOWNC/SNOWNCV are snow sub-set of RAINC/RAINNCV (also GRAUPELNC, etc.)

ARW only

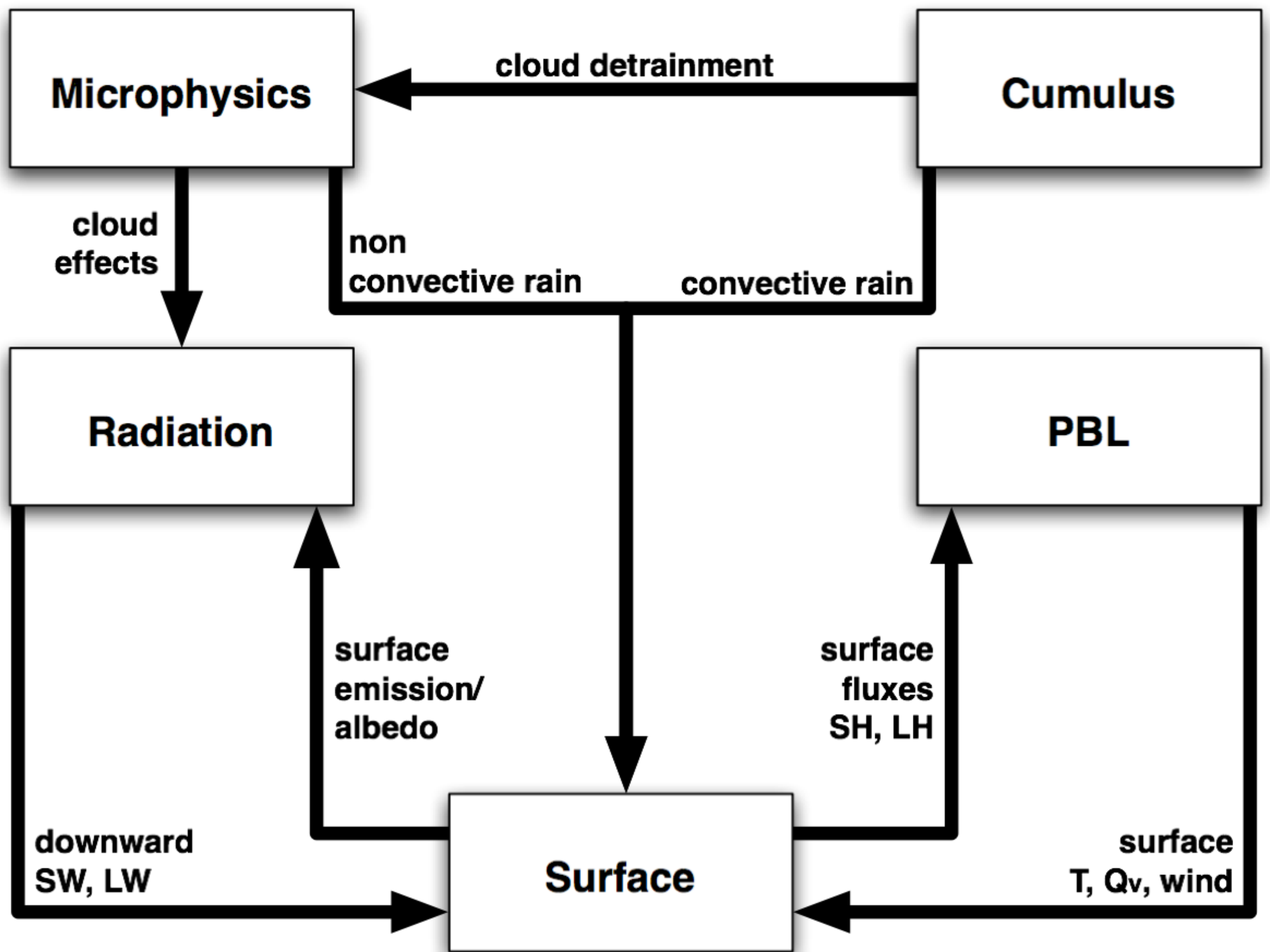
Rainfall Output

Options for "buckets"

- prec_acc_dt (minutes) - accumulates separate prec_acc_c, prec_acc_nc, snow_acc_nc in each time window (we recommend prec_acc_dt is equal to the wrf output frequency to avoid confusion)
- bucket_mm - separates RAIN(N)C into RAIN(N)C and I_RAIN (N)C to allow accuracy with large totals such as in multi-year accumulations
  - Rain = I_RAIN(N)C*bucket_mm + RAIN(N)C
  - bucket_mm = 100 mm is a reasonable bucket value
  - bucket_J also for CAM and RRTMG radiation budget terms (1.e9 J/m^2 recommended)

Physics Interactions

Direct Interactions of Parameterizations



&physics

Seven major physics categories:

- **mp_physics**: **0,1,2,3,4,5,6,8,10**
- **ra_lw_physics**: **0,1,3,99**
- **ra_sw_physics**: **0,1,2,3,99**
- **sf_sfclay_physics**: **0,1,2**
- **sf_surface_physics**: **0,1,2,3,99** (set before running **real** or **ideal**, need to match with **num_soil_layers** variable)
  - **ucm_call = 0,1**
- **bl_pbl_physics**: **0,1,2,99**
- **cu_physics**: **0,1,2,3,99**

End