Overview of WRF Physics

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NCAR/MMM

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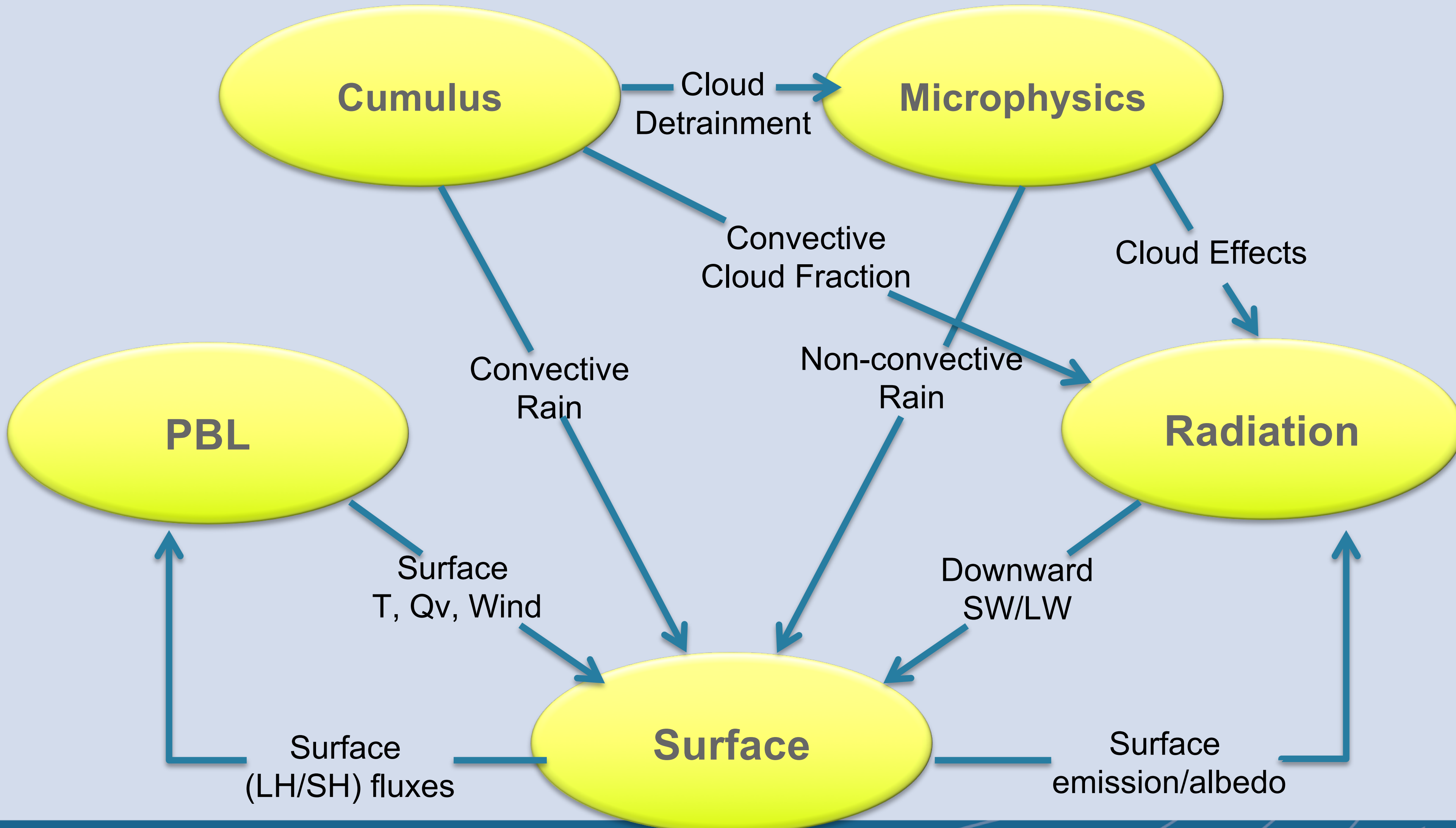
WRF Physics

- 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)
- Turbulence/Diffusion (diff_opt, km_opt)
- Cumulus parameterization (cu_physics)
- Microphysics (mp_physics)

Direct Interactions of Parameterizations



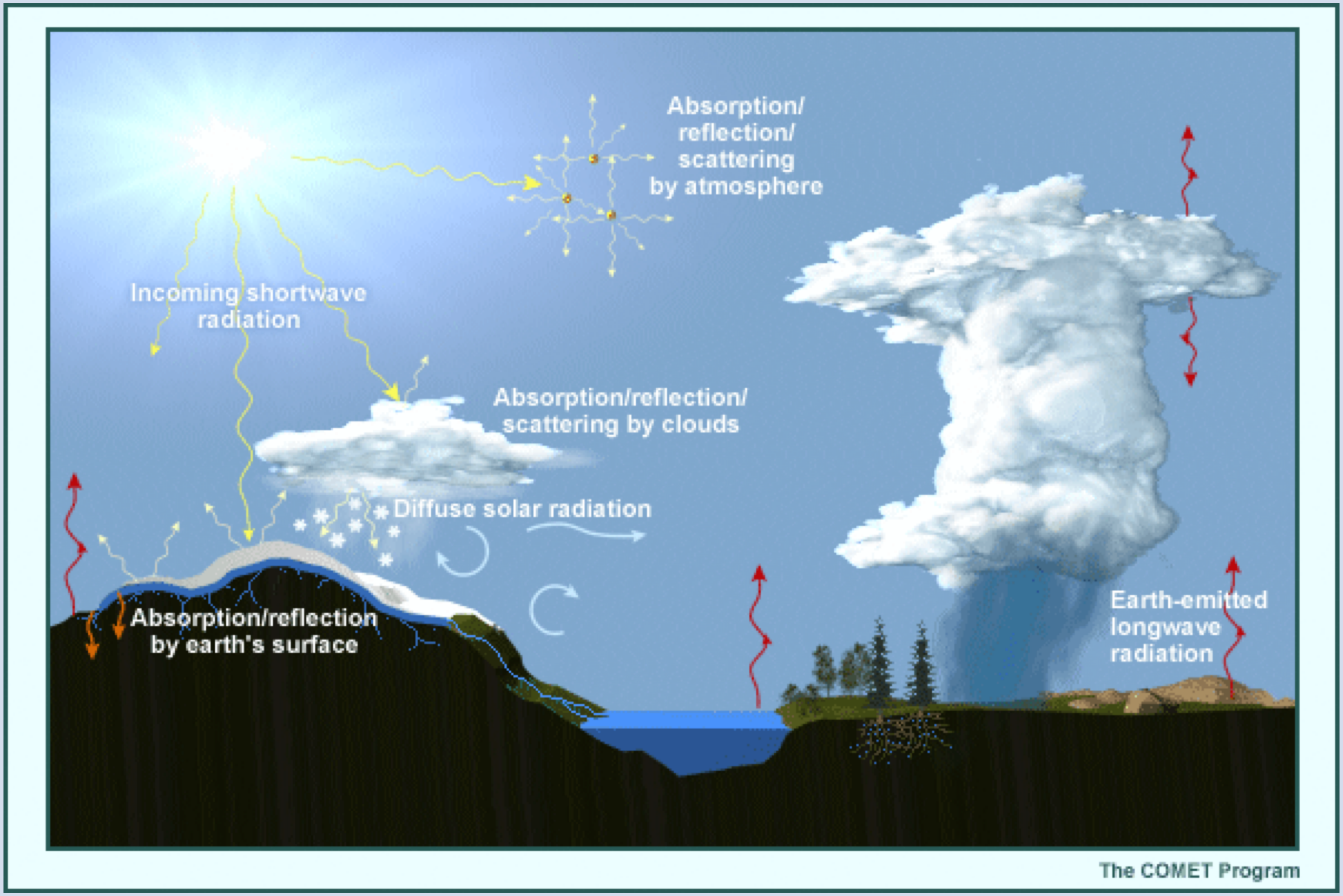
Radiation

Provides

Atmospheric temperature tendency profile

Surface radiative fluxes

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
7	FLG (UCLA)	Gu et al. (2011, JGR), Fu and Liou (1992, JAS)	2012
14	RRTMG-K	Baek et al. (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

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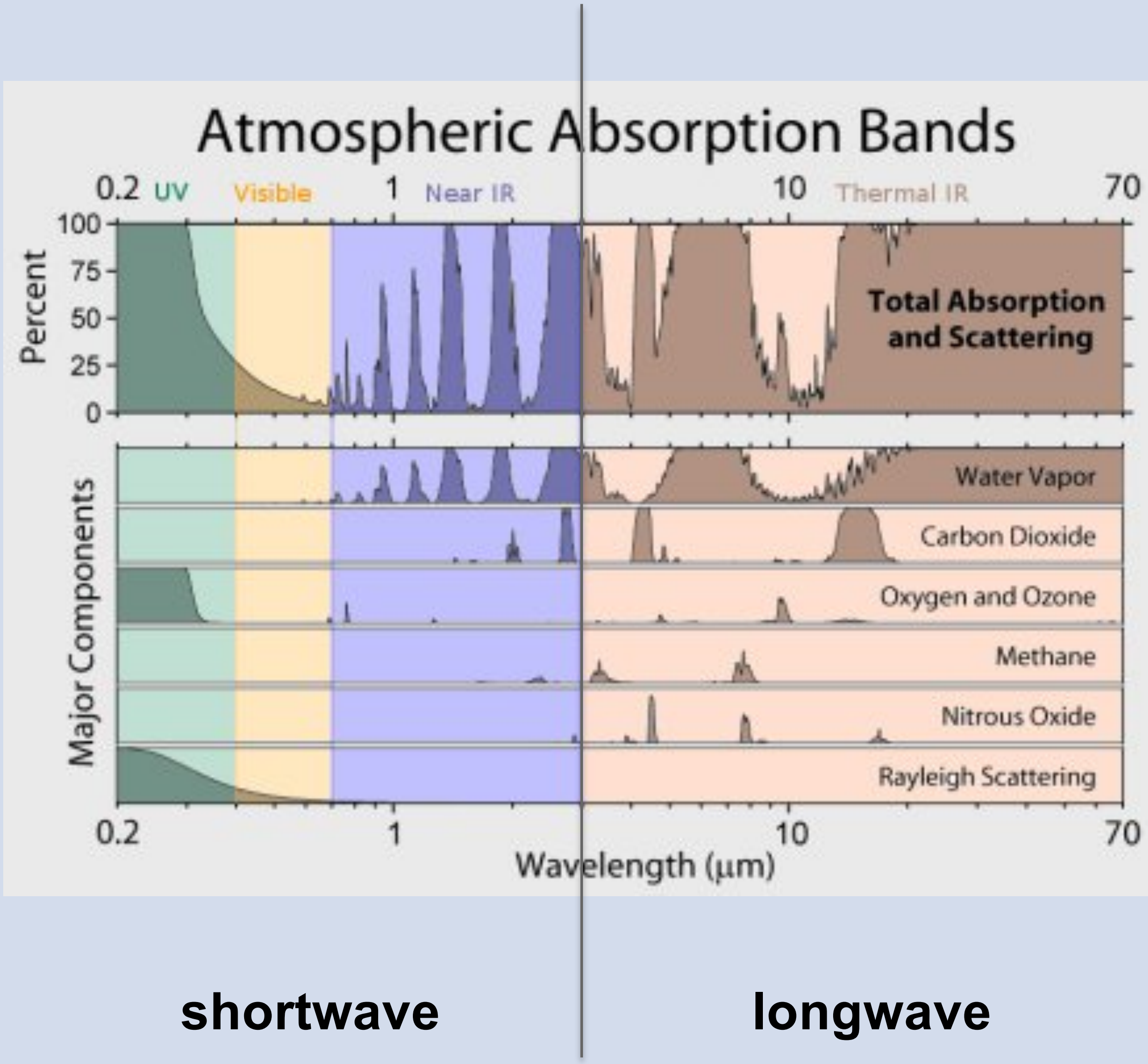
Clear Sky: IR-active Gases

- H_2O – from model prognostic vapor
- CO_2 – well-mixed, specified constant in whole atmosphere (CAM has yearly values)
  - For CAM, RRTM and RRTMG, GHG input file can update CO_2, N_2O and CH_4
- O_3 – schemes have own climatologies
  - CAM has monthly, zonal, pressure-level data and RRTMG has this as an option
  - 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
  - Some microphysics options pass own particle sizes to RRTMG radiation: other combinations only use mass info and assume effective sizes
- Clouds strongly affect IR at all wavelengths (considered “grey bodies”) and are almost opaque to it

Cloud Fractions

- Cloud fraction for microphysics clouds
  – icloud=1: Xu and Randall method
  – icloud=2: simple 1/0 method
  – Icloud=3: new Thompson option in V3.7 (improved in V3.8)
- Cloud fraction for unresolved convective clouds
  – cu_rad_feedback = .true.
  – Only works for GF, G3, GD and KF options
  – ZM separately provides cloud fraction to radiation

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)
- Different WRF schemes may use different cloud overlapping assumption. For example, RRTMG, CAM 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
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_lw_ 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/mont h
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

Clear Sky and Aerosols

- Main gas 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
  - RRTMG has climatological aerosol input options
    - aer_opt=1 Tegen (EC) global monthly climatology
    - aer_opt=2 user-specified properties and/or AOD map
    - aer_opt=3 Thompson microphysics nuclei (V3.8)

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 have zonal climatology
- CAM, RRTMG, Goddard can also handle trace gases mainly N2O and CH4 (set constant)

Spectral Bands

- Many schemes use multiple spectral bands
  - As with longwave, bands are ranges of wavelengths usually dominated by different gases
- Look-up tables
  - Also as with longwave

Clouds and Cloud Fraction

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

Slope effects on shortwave

- Available for all shortwave options
- Represents effect of slope on surface solar flux accounting for diffuse/direct effects
- Two levels of detail (namelist options):
  - slope_rad: activates slope effects - may be useful for complex topography and grid lengths < 2 km.
    - topo_shading: shading of neighboring grids by mountains - may be useful for grid lengths < 1 km.

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radt

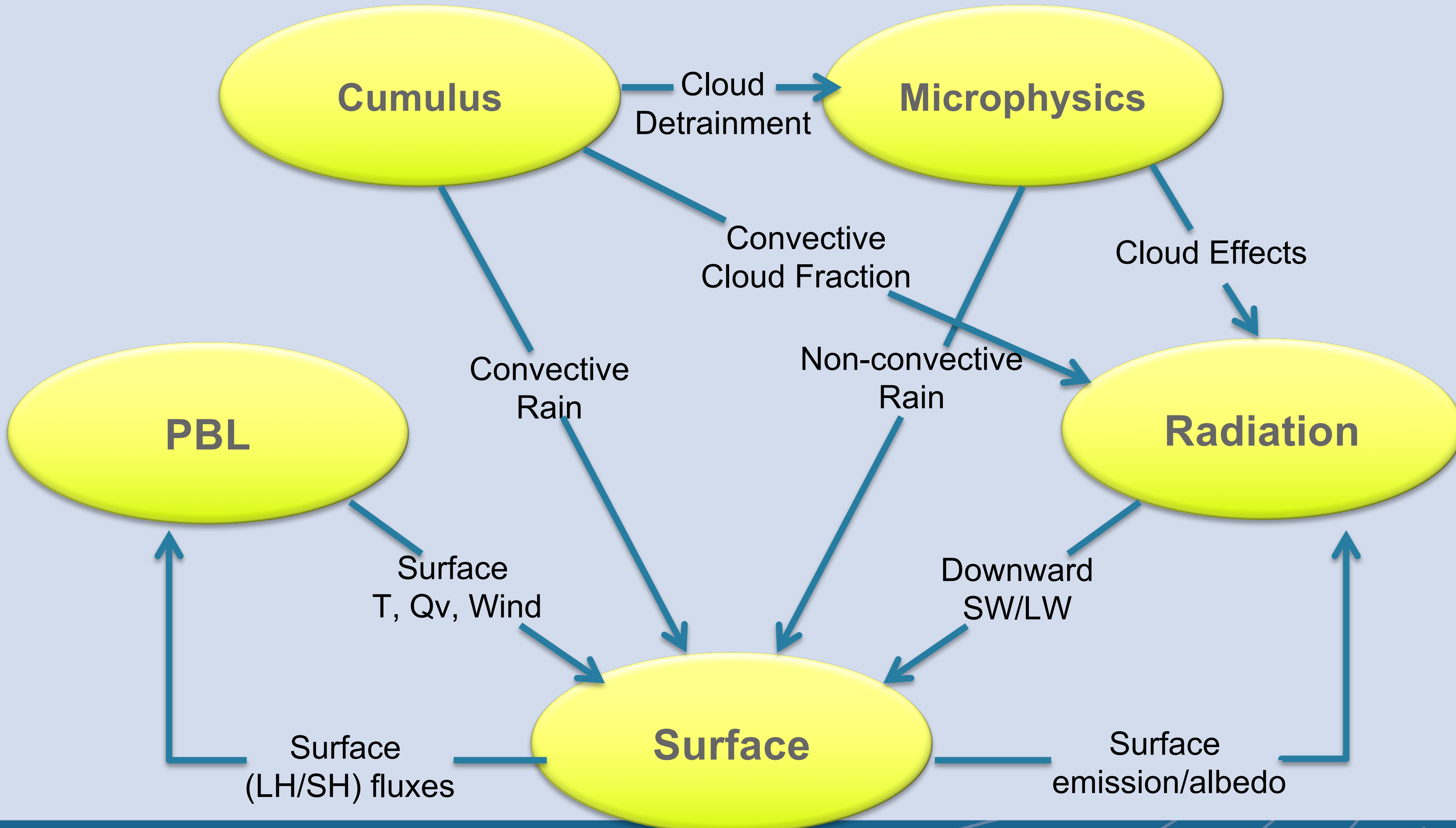
Radiation time-step recommendation

- 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 Shortwave Fluxes

- swint_opt=1
  - provides a smooth surface downward flux over time (interpolates between radiation steps using cosine zenith angle and clearness index)
  - This also allows smoother variation of ground variables and fluxes (eliminates steps in time series)
- Diffuse, direct, and direct normal shortwave components are output (swddir, swddif, swddni) – aerosols affect diffuse/direct ratio

Direct Interactions of Parameterizations



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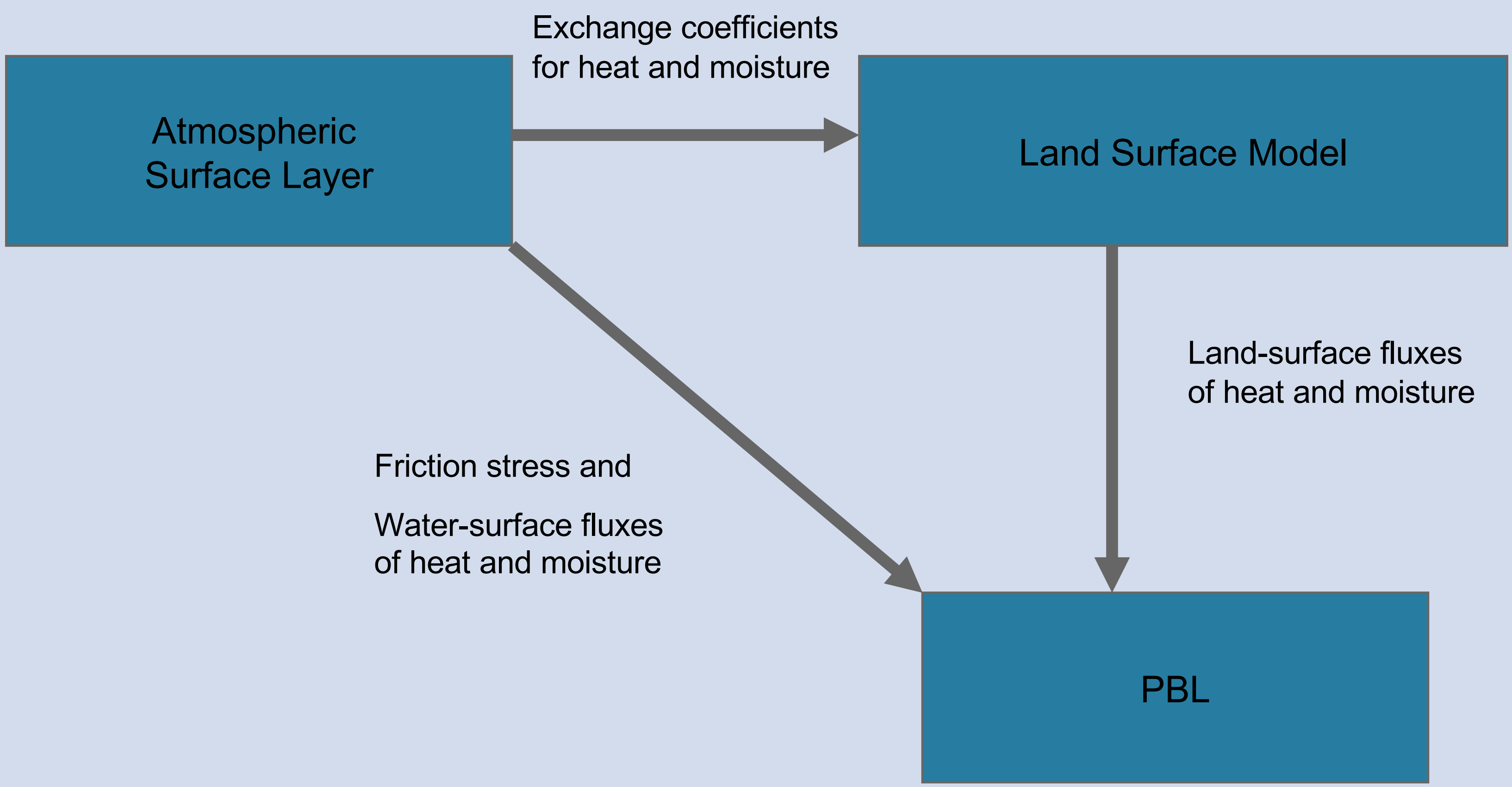
Surface schemes

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)
Δ refers to difference between surface and reference level value
z_0 are the roughness lengths
k is the von Karman constant (0.4)

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, stability function and u* by

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

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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

Hurricane Options

- Ocean Mixed Layer Model (sf_ocean_physics=1)
  - 1-d slab ocean mixed layer (specified initial depth)
  - Includes wind-driven ocean mixing for SST cooling feedback
- 3d PWP ocean (Price et al.) (sf_ocean_physics=2)
  - 3-d multi-layer (~100) ocean, salinity effects
  - Fixed depth
- 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)

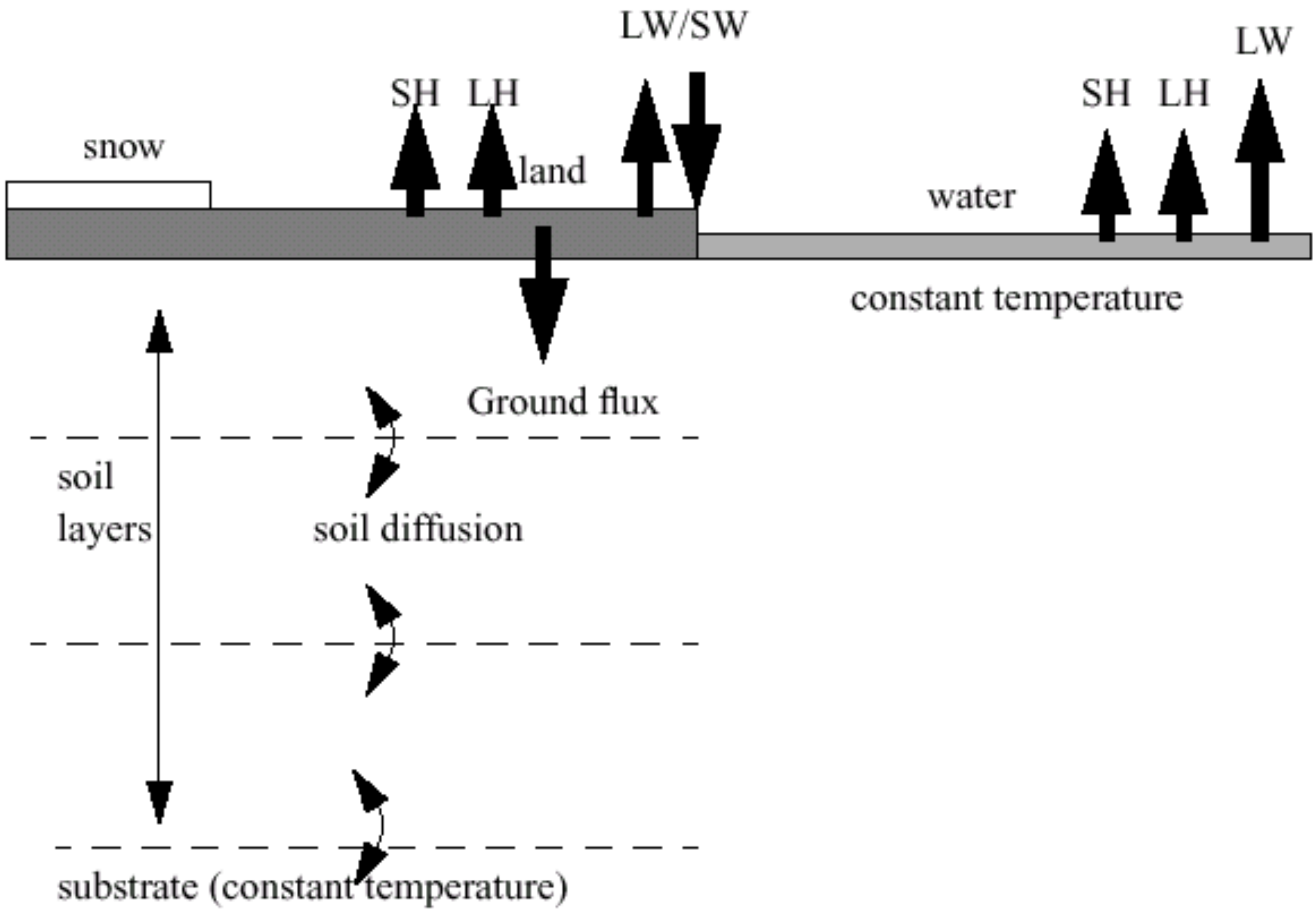
Fractional Sea Ice

- fractional_seaice=1 - with input sea-ice fraction data can partition land/water fluxes within a grid box
- Can be used with nearly all surface-layer schemes

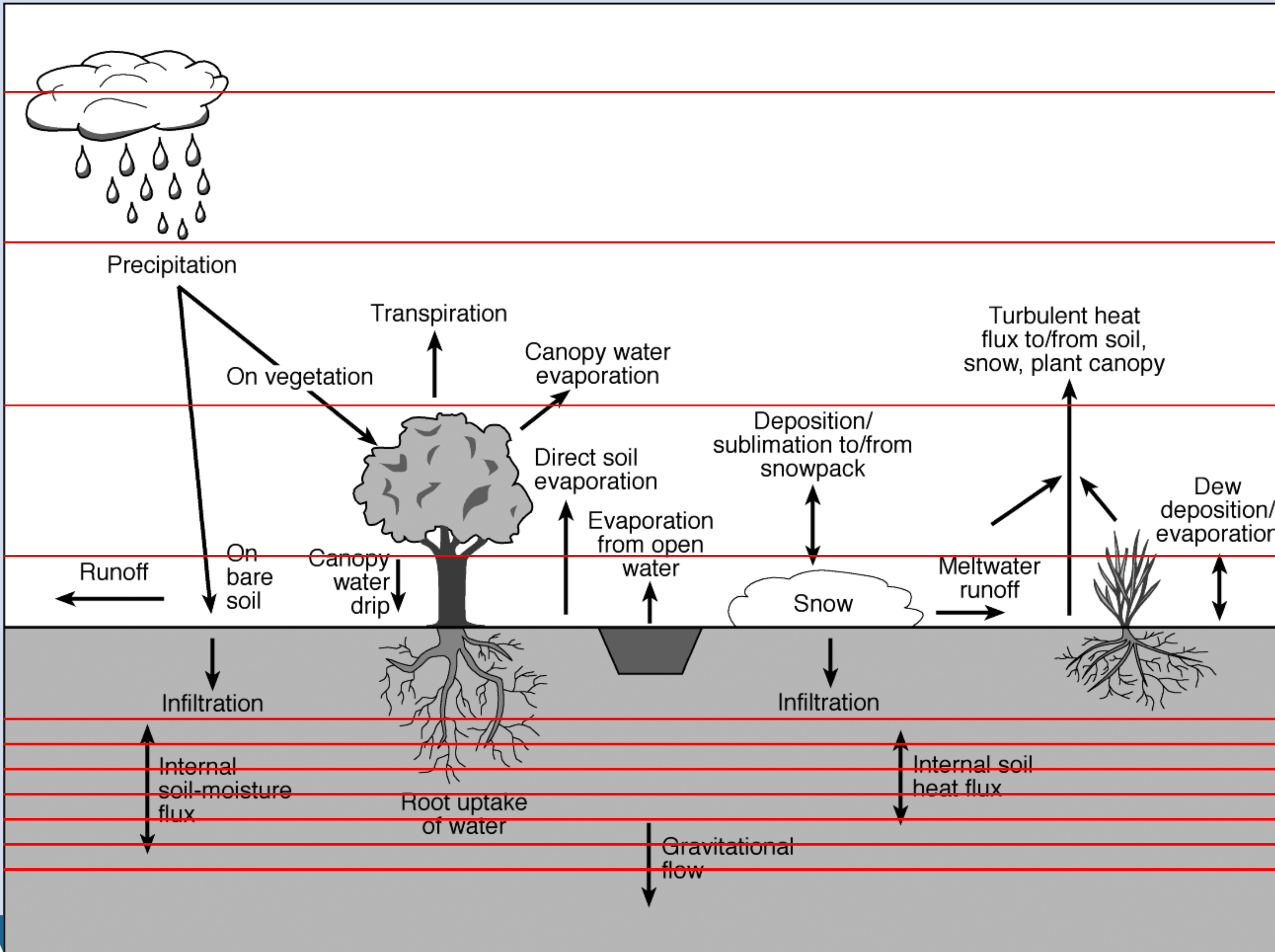
WRF Land-Surface Model Options (sf_surface_physics)

- Simple 5-layer soil model
  - No vegetation or snow cover prediction, just thermal diffusion in soil layers
- Noah LSM, NoahMP, RUC LSM, PX LSM, CLM4, SSiB land-surface models
  - Sophisticated vegetation model and snow cover prediction

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 (4 for Noah and NoahMP, 9 for RUC, 2 for PX and 3 for SSiB, 10 for CLM4)
- Predicts snow water equivalent on ground. May be in layers (NoahMP, RUC, SSiB,CLM4)
- May predict canopy moisture only (Noah, RUC) or temperature only (SSiB) or both (NoahMP, CLM4)

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

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

Snow Cover

- LSMs include fractional snow cover and predict snow water equivalent development based on precipitation, sublimation, melting and run-off
  - Single-layer snow (Noah, PX)
  - Multi-layer snow (RUC, NoahMP, SSiB,CLM4)
  - 5-layer option has no snow prediction
- Frozen soil water also predicted (Noah, NoahMP, RUC,CLM4)

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 to BEP)
  - NUDAPT detailed map data for 40+ US cities

LSM Tables

- Properties can be changed in text files (tables)
- VEGPARM.TBL used by Noah and RUC for vegetation category properties
  - Albedo, roughness length, emissivity, vegetation properties
- MPTABLE.TBL used by NoahMP
- 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)

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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
- The only adjustment for soil temperature (done in real.exe) is for elevation differences between the original elevation and model elevation (SOILHGT used)

Initializing LSMs

- Inconsistency leads to spin-up as adjustments occur in soil temperature and moisture at the beginning of the simulation
- This spin-up can only be avoided by running offline model on the same grid (e.g. HRLDAS for Noah) – may take months to spin up soil moisture
- Cycling land state between forecasts also helps, but may propagate errors (e.g in rainfall effect on soil moisture)

Sub-grid Mosaic

- Default behavior is one dominant vegetation and soil type per grid cell
- Noah (sf_surface_mosaic) and RUC (mosaic_lu and mosaic_soil) allow multiple categories within a grid cell
- PX averages properties of sub-grid categories

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
- 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 – ability to output max/min/mean/std of surface fields in a specified period

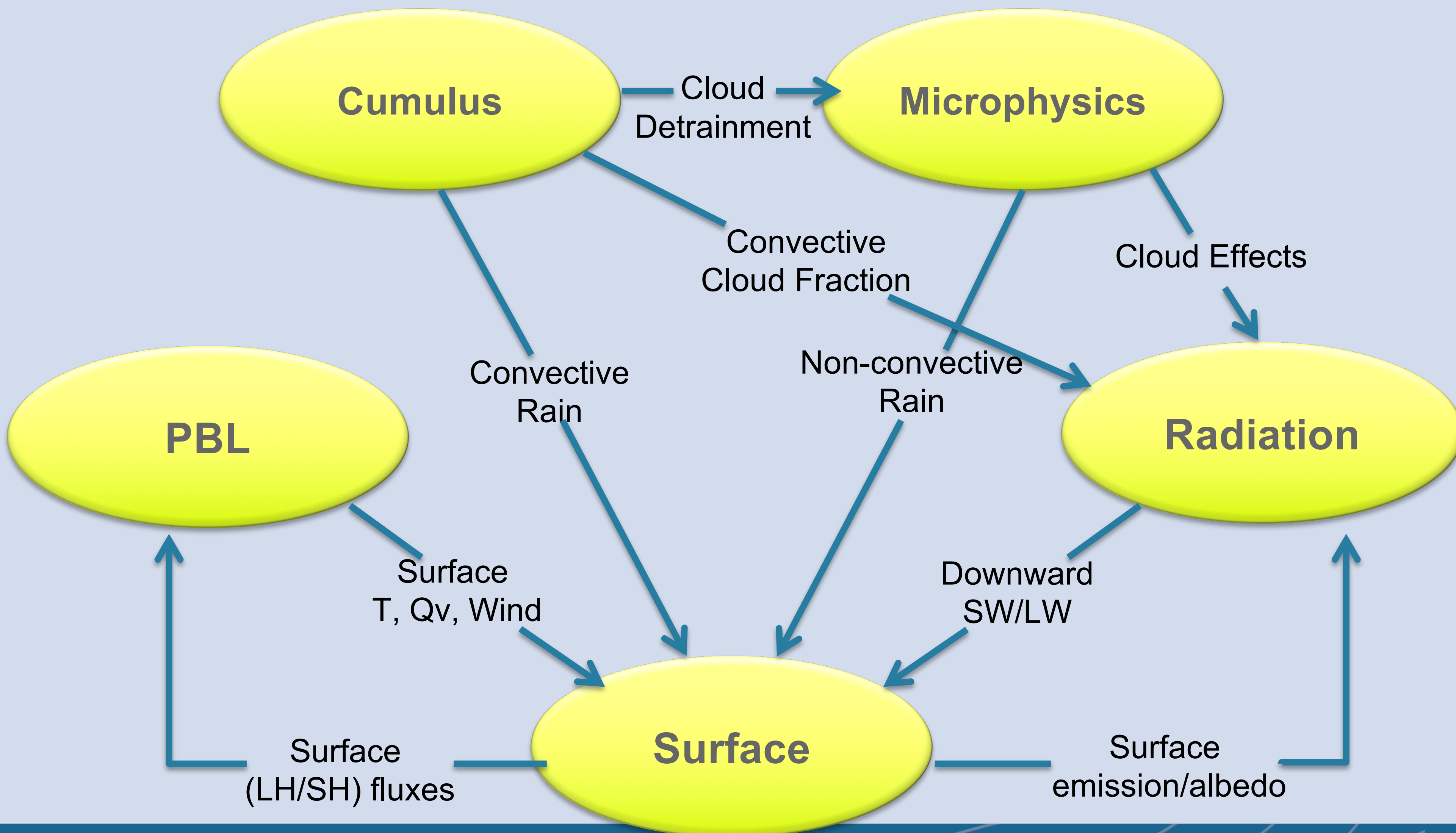
Lake Model

- 10-layer lake model from CLM (sf_lake_physics=1)
- We have global bathymetry data for most large lakes (added from geogrid)
- Also can predict lake ice
- Can be used with any LSM
- WPS preprocessing allows diurnal averaging methods to initialize lake temperatures where not resolved by SST analysis (TAVGSFC)

WRF-Hydro

- Coupling to hydrological model available
- Streamflow prediction, etc.
- Sub-grid tiling to ~100 m grid
- Requires special initialization for hydrological datasets

Direct Interactions of Parameterizations



Planetary Boundary Layer

Provides

Boundary layer fluxes (heat, moisture, momentum)

Vertical diffusion in whole column

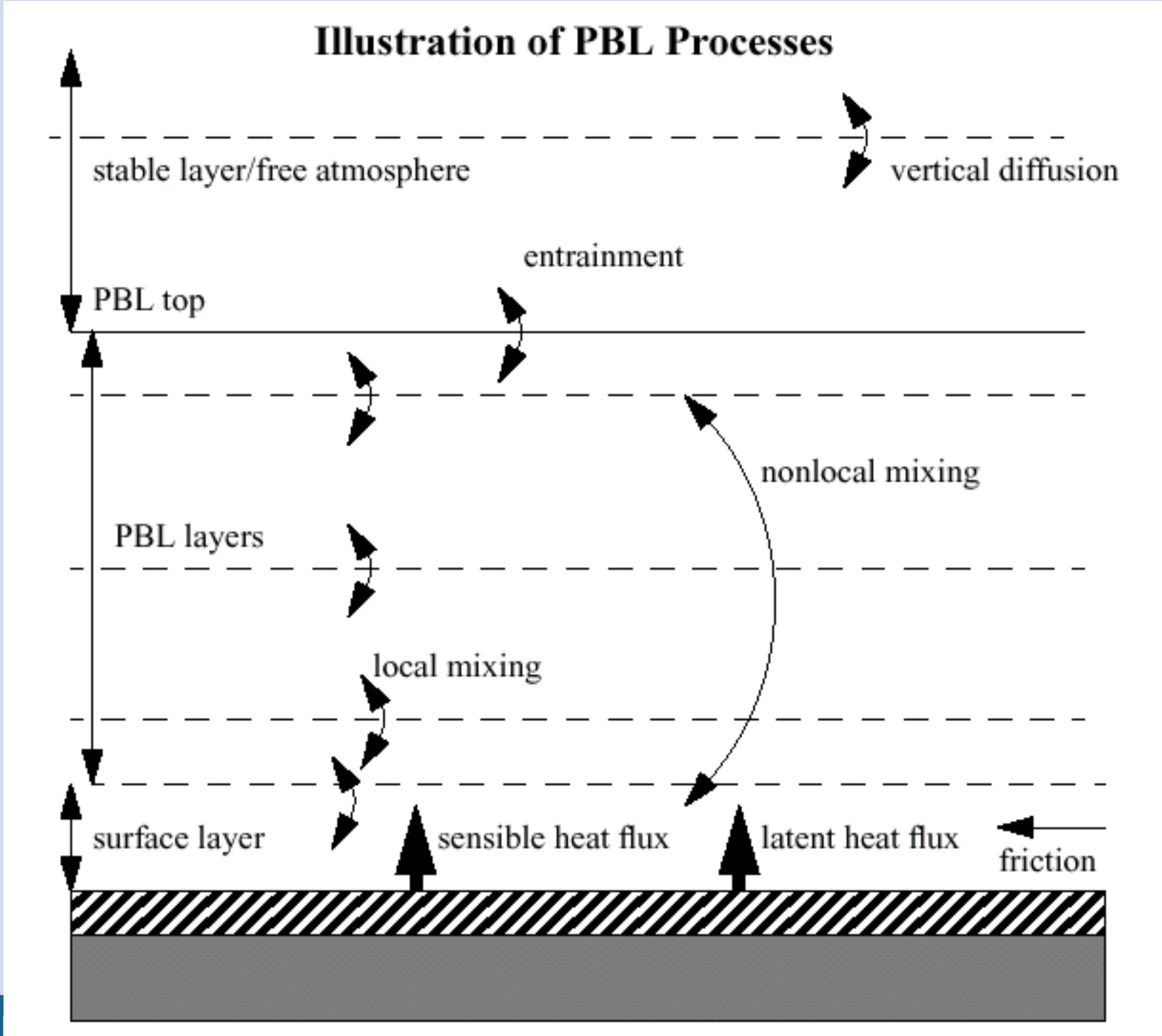
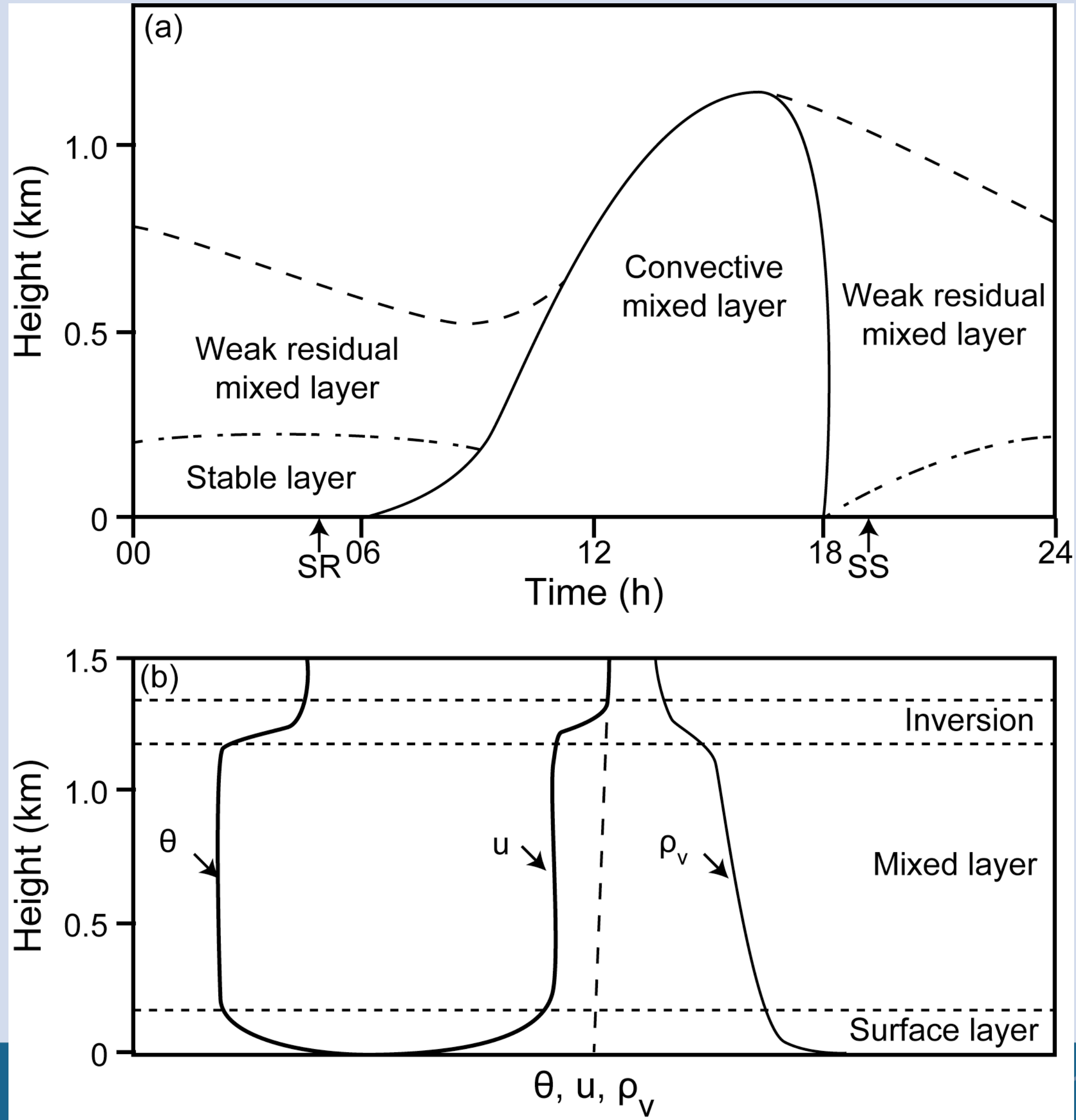


Illustration of PBL Processes
stable layer/free atmosphere
vertical diffusion
entrainment
PBL top
nonlocal mixing
PBL layers
local mixing
surface layer
sensible heat flux
latent heat flux
friction

Planetary Boundary Layer



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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)
    - some also include non-local mass-flux terms (QNSE, MYNN EDMF option, TEMF)
  - Diagnostic non-local (YSU, GFS, MRF, ACM2)
- Above PBL all these schemes also do vertical diffusion due to turbulence

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 (2014, MWR)	2015
12	GBM	Grenier and Brethertion (2001, MWR)	2013
99	MRF	Hong and Pan (1996, MWR)	2000

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

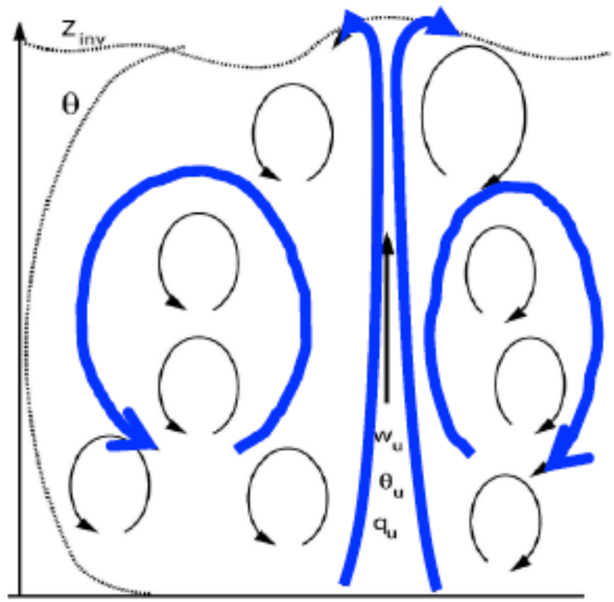

FIG. 1. Sketch of a convective updraft embedded in a turbulent eddy structure.

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

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

- 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
- YSU, MRF, GFS include a non-gradient term (Γ)
  - YSU also has explicit entrainment term
- ACM2, TEMF, EDMF include a mass-flux profile, M, which is an additional updraft flux

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

$$\frac{\partial}{\partial z} \left(K_v \frac{\partial}{\partial z} \theta + M(\theta_u - \theta) \right)$$

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Vertical Mixing Coefficient

- Several schemes also output exch_h which is Kv for scalars that is used by WRF-Chem
- WRF can do scalar and tracer vertical mixing with PBL K-coefficients
  - scalar_pblmix=1, tracer_pblmix=1
- PBL schemes themselves only mix limited variables: momentum, heat, vapor and some specific cloud variables

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PBL Schemes with Shallow Convection

- Some PBL schemes include shallow convection as part of their parameterization
- These use mass-flux approaches either
  - through the whole cloud-topped boundary layer (QNSE-EDMF and TEMF)
  - only from cloud base (GBM and UW PBL)
- Some schemes (YSU, MYNN, GBM) include capability of top-down mixing for turbulence driven by cloud-top radiative cooling which is separate from bottom-up surface-flux-driven mixing

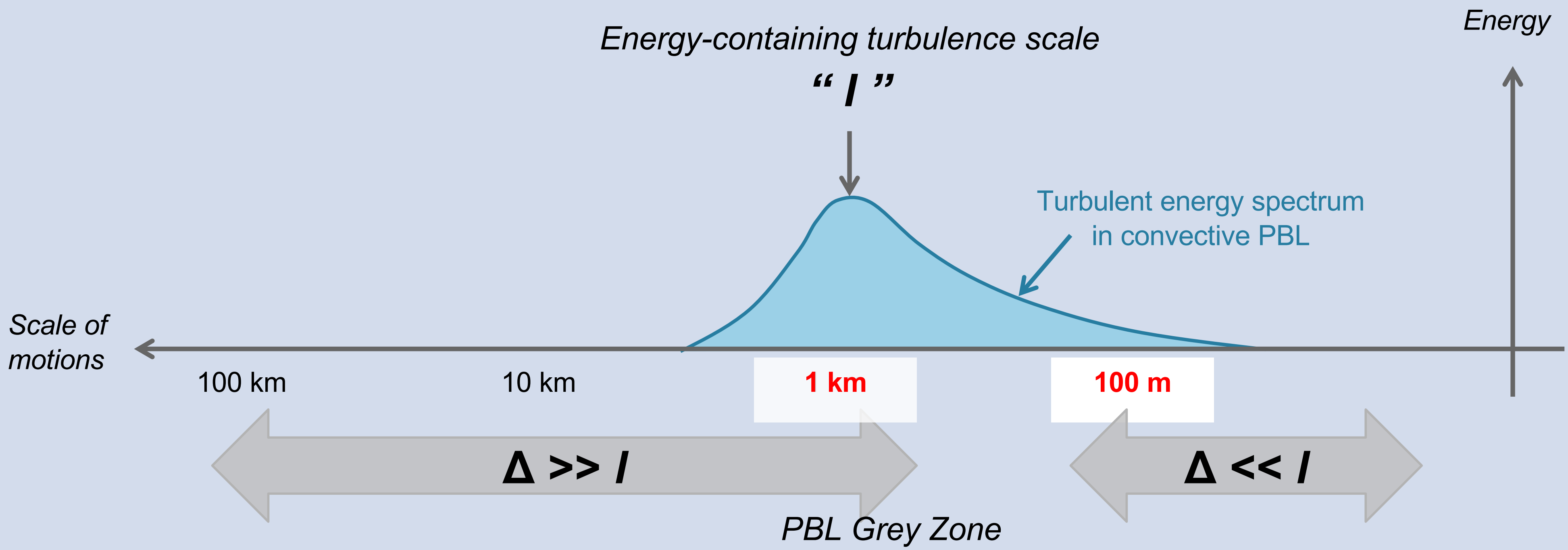
PBL schemes

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

PBL Scheme Options

- PBL schemes can be used for most grid sizes when surface fluxes are present
- Lowest level should be in the surface layer (0.1h)
  - Important for surface (2m, 10m) diagnostic interpolation
- With ACM2, GFS and MRF PBL schemes, lowest full level should be .99 or .995 (not too close to 1)
- TKE schemes and YSU 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 (coupled to surface physics)
  - Works best when dx and dz are comparable

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
- New Shin-Hong PBL based on YSU designed for sub-kilometer transition scales (200 m – 1 km)
  - Nonlocal mixing (gamma) term reduces in strength as grid size gets smaller and resolved mixing increases
- Other schemes may work in this range but will not have correctly partitioned resolved/sub-grid energy fractions

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
- TKE is also an advected variable in the LES option
  - Of the PBL schemes only MYNN has a TKE advection option

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

- For YSU
  - topo_wind=1,2: wind-bias correction methods for terrain effects
  - ysu_topdown_pblmix=1: cloud-top cooling-driven mixing
- For MYNN
  - Wind-farm model has been added to investigate wind-farm effects on the environment (extra stress and turbulence generation)

– Gravity-wave drag can be added for low resolution (> 5 km) runs to represent sub-grid orographic gravity-wave vertical momentum transport (gwd_opt=1)

– Fog: grav_settling=2 (Katata)

bldt

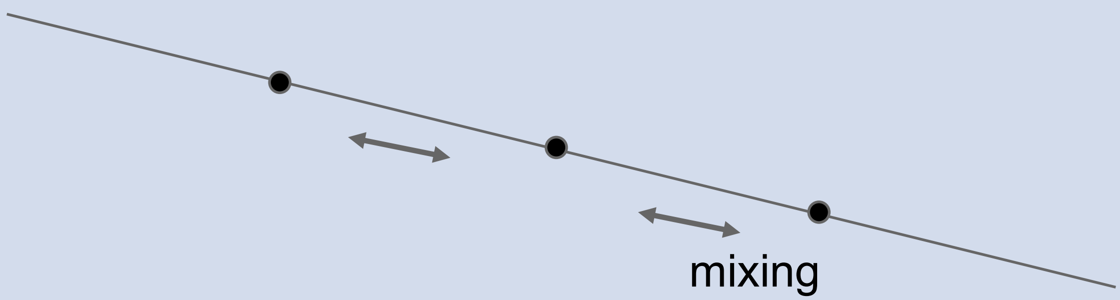
- Minutes between boundary layer/LSM calls
- Typical value is 0 (every step)
- CLM LSM is expensive, so may consider bldt in that case

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

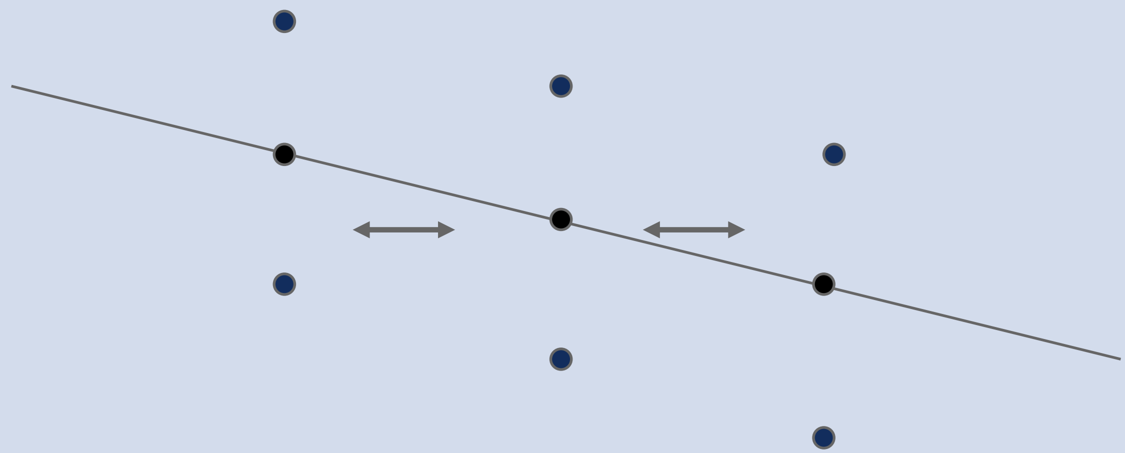


diff_opt=1

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

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 Smagorinsky diagnostic K (requires diff_opt=2)
  - km_opt=4: 2d Smagorinsky for horizontal K (to be used with PBL or kvdif for vertical K)

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
  - From V3.6 diff_opt=2 can be used with km_opt=4 (was unstable with complex terrain before this version)
  - 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)

diff_6th_opt

- 6^{th} 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)

Upper damping (damp_opt)

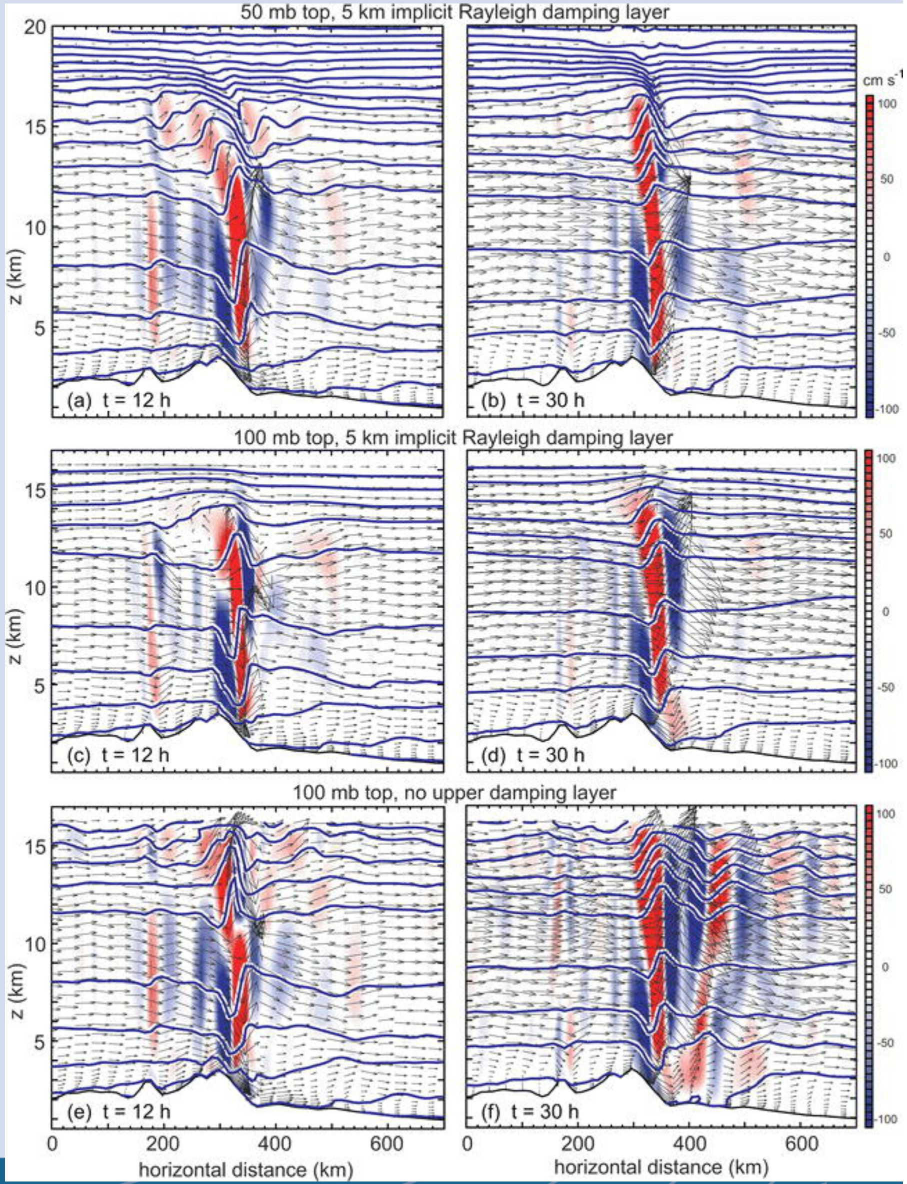
Purpose is to prevent unrealistic reflections of waves from model top. Can be important over high topography.

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



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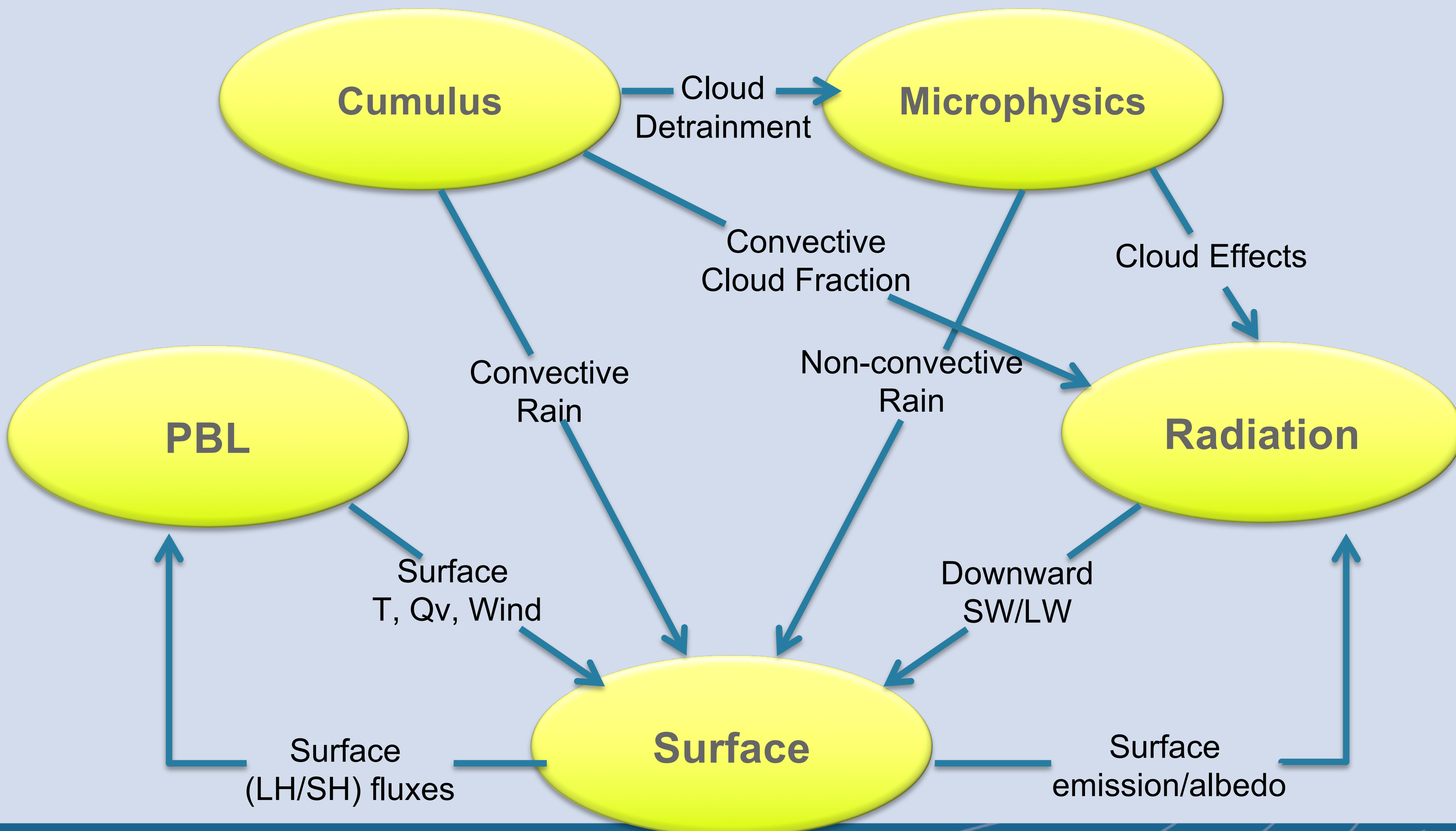
Direct Interactions of Parameterizations



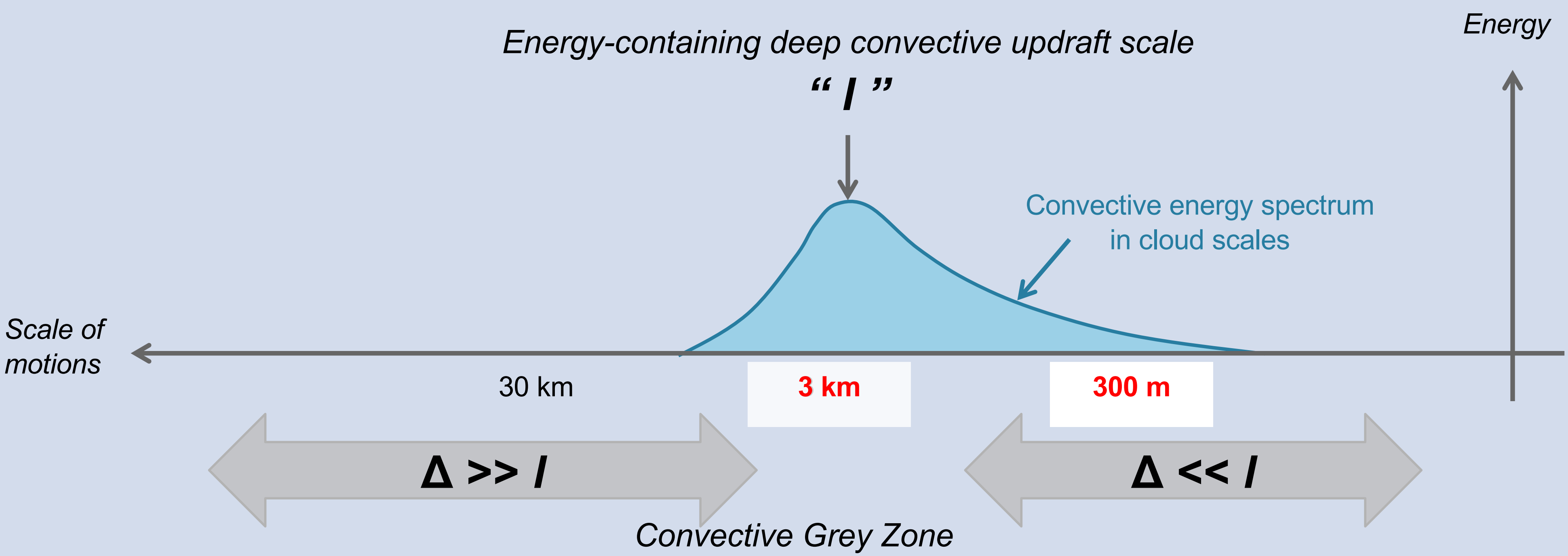
Cumulus Parameterization

Provides

Atmospheric heat and moisture/cloud tendency profiles

Surface sub-grid-scale (convective) rainfall

Model Grid Spacing: Cumulus Parameterization and Cloud-Resolving



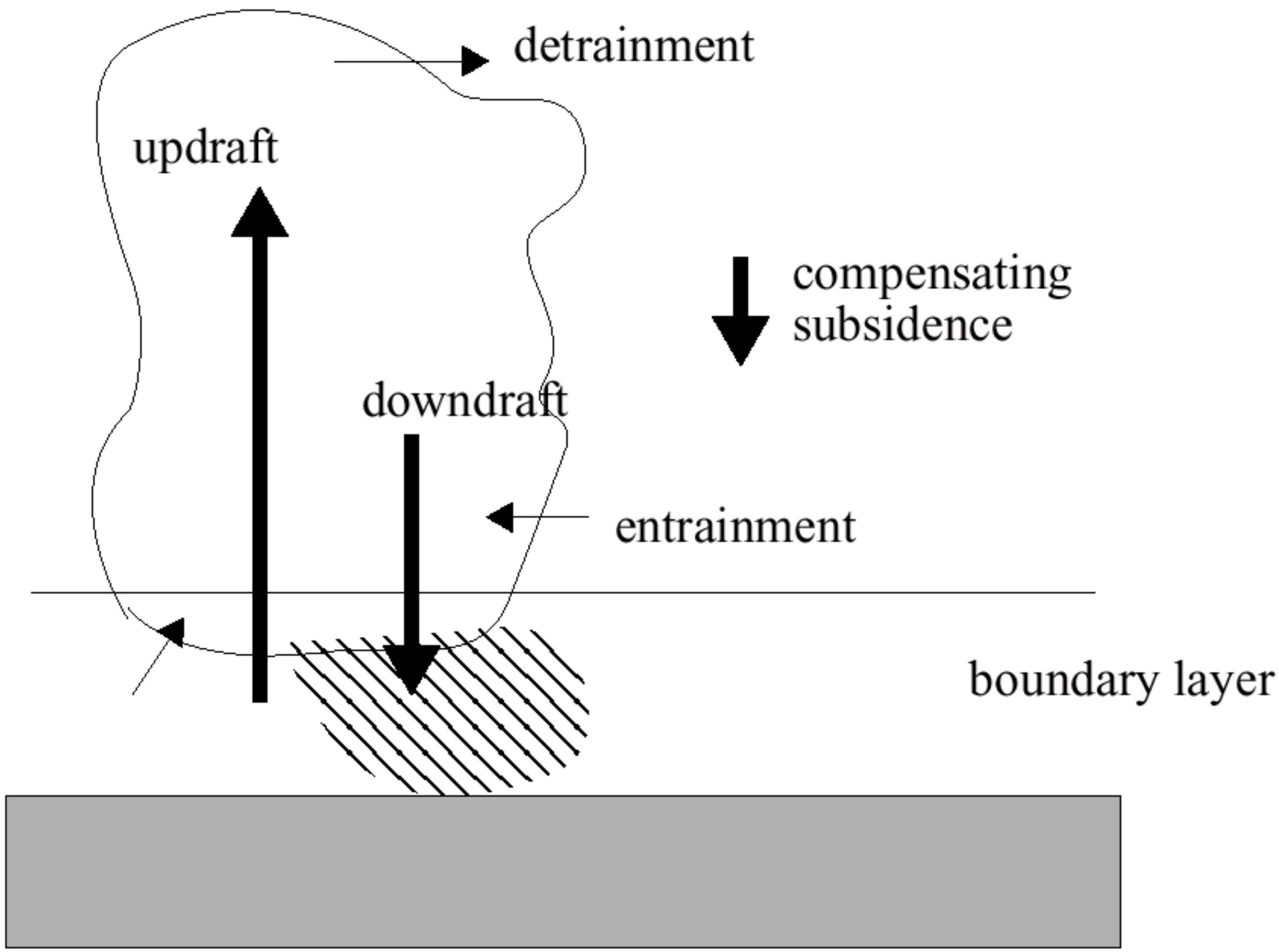
For coarse grid spacing

- ✓ **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***
- ✓ ***PBL and/or diffusion schemes handle local sub-grid mixing***

Illustration of Cumulus Processes



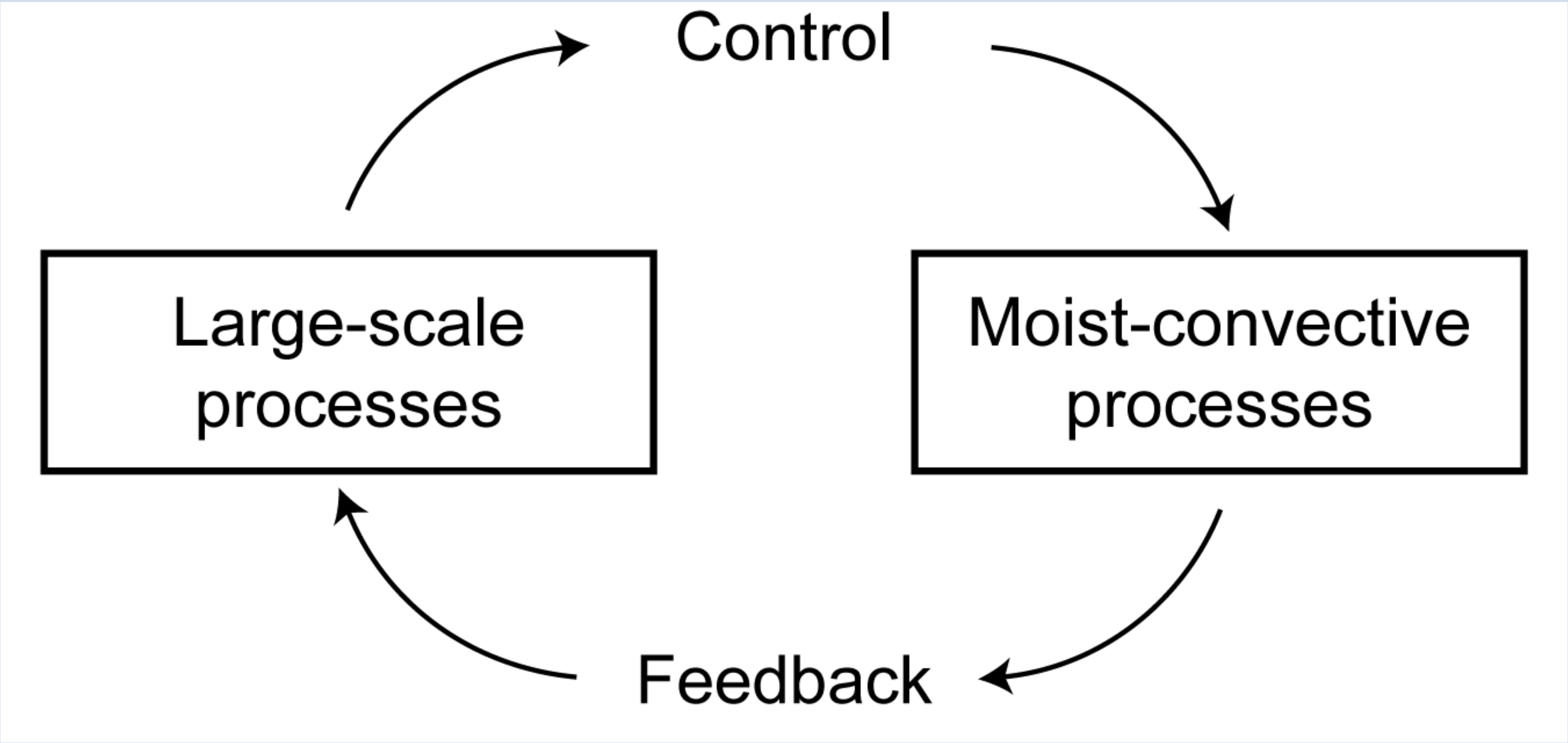
Cumulus Schemes

- 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

Deep Convection

- Schemes work in individual columns that are considered convectively unstable
- Mass-flux schemes transport surface air to top of cloud and include environmental subsidence around clouds
  - Note: schemes have no net mass flux – subsidence compensates cloud mass fluxes exactly
  - Environmental subsidence around cloud warms and dries troposphere removing instability over time
    - Dynamics may produce mean vertical motion in grid cell in response to scheme's heating profile
- Additionally downdrafts may cool PBL

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

cu_physics	Scheme	Reference	Added
1	Kain-Fritsch	Kain (2004, JAM)	2000
2	Betts-Miller-Janjic	Janjic (1994, MWR; 2000, JAS)	2002
3	Grell-Freitas	Grell and Freitas (2013, to be published)	2013
4	Old Simplified Arakawa-Schubert	Grell et al. (1994, MM5 NCAR Tech Note)	2002/ 2011
5	Grell-3	Grell and Devenyi (2002, GRL)	2008
6,16	Tiedtke	Tiedtke (1989, MWR), Zhang, Wang and Hamilton (2011, MWR)	2011, 2015
7	Zhang-McFarlane	Zhang and McFarlane (1995, AO)	2011
10	KF CuP	Berg and Stull (2004, 2005, JAS)	2016
11	Multi-Scale KF	Alapaty and Herwehe	2015
14	New SAS	Han and Pan (2010,…)	2011
84	New SAS (HWRF)	Han and Pan (2010,…)	2012
93	Grell-Devenyi	Grell and Devenyi (2002, GRL)	2002
99	Old Kain-Fritsch	Kain and Fritsch (1990, JAS; 1993 Meteo. Monogr.)	2000

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, ZM, Tiedtke, BMJ)
    - Quasi-equilibrium (Arakawa-Schubert) with large-scale destabilization d(CAPE)/dt (SAS, NSAS)
    - Moisture convergence
    - Low-level large-scale ascent (mass convergence)

Ensemble methods

- GF, G3 and GD use ensemble of triggers and closures possibly with varying parameters (up to 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, 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)

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

Radiation Interaction

- The Grell schemes, KF and MSKF interact using cu_rad_feedback=1 which allows them to provide a cloud fraction and amount in active grid columns
- Zhang-McFarlane is part of the CESM suite that also provides a part of the cloud fraction (used with CESM (or MG) microphysics and UW shallow scheme)
- If using the GFDL radiation scheme there is a Slingo method of cloud fraction from many schemes using precip rate, top and bottom, to compute a cloud fraction

cudt

- Time 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

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Cumulus schemes

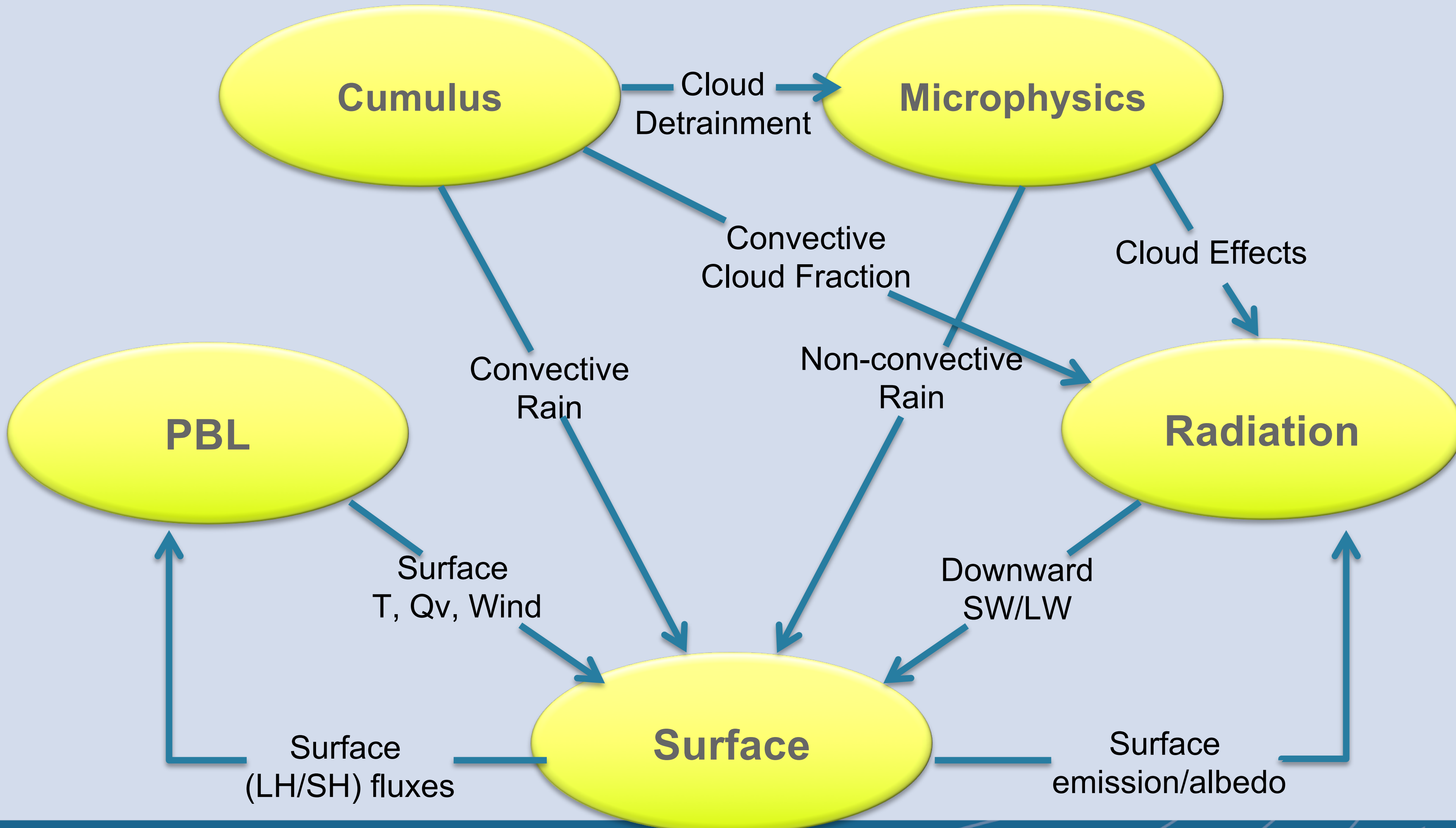
cu_physics	Scheme	Cores	Moisture Tendencies	Momentum Tendencies	Shallow Convection	Radiation Interactn
1	Kain-Fritsch Eta	ARW NMM	Qc Qr Qi Qs	no	yes	yes
2	Betts-Miller-Janjic	ARW NMM	-	no	yes	GFDL
3	Grell-Freitas	ARW	Qc Qi	no	yes	yes
4	Old Simplified Arakawa-Schubert	ARW NMM	Qc Qi	yes (NMM)	yes (ARW)	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 and MSKF automatically phases 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

Direct Interactions of Parameterizations



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

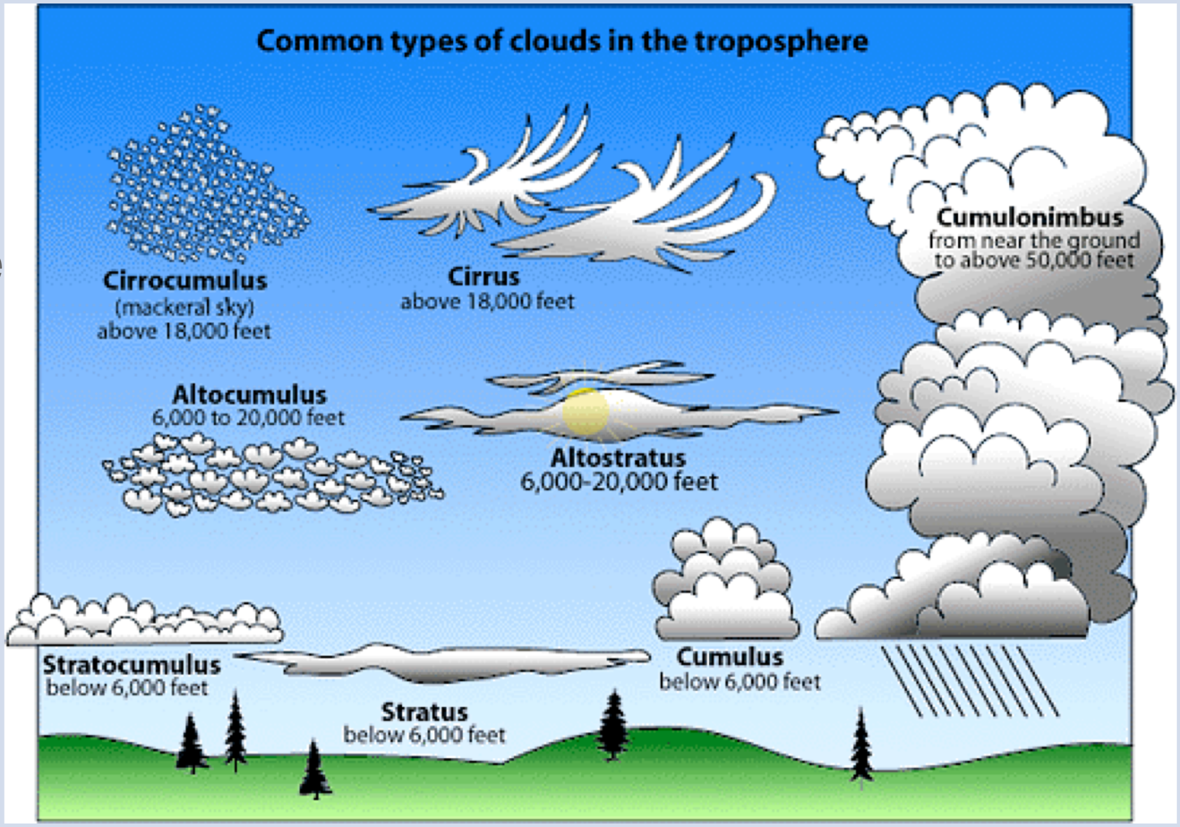


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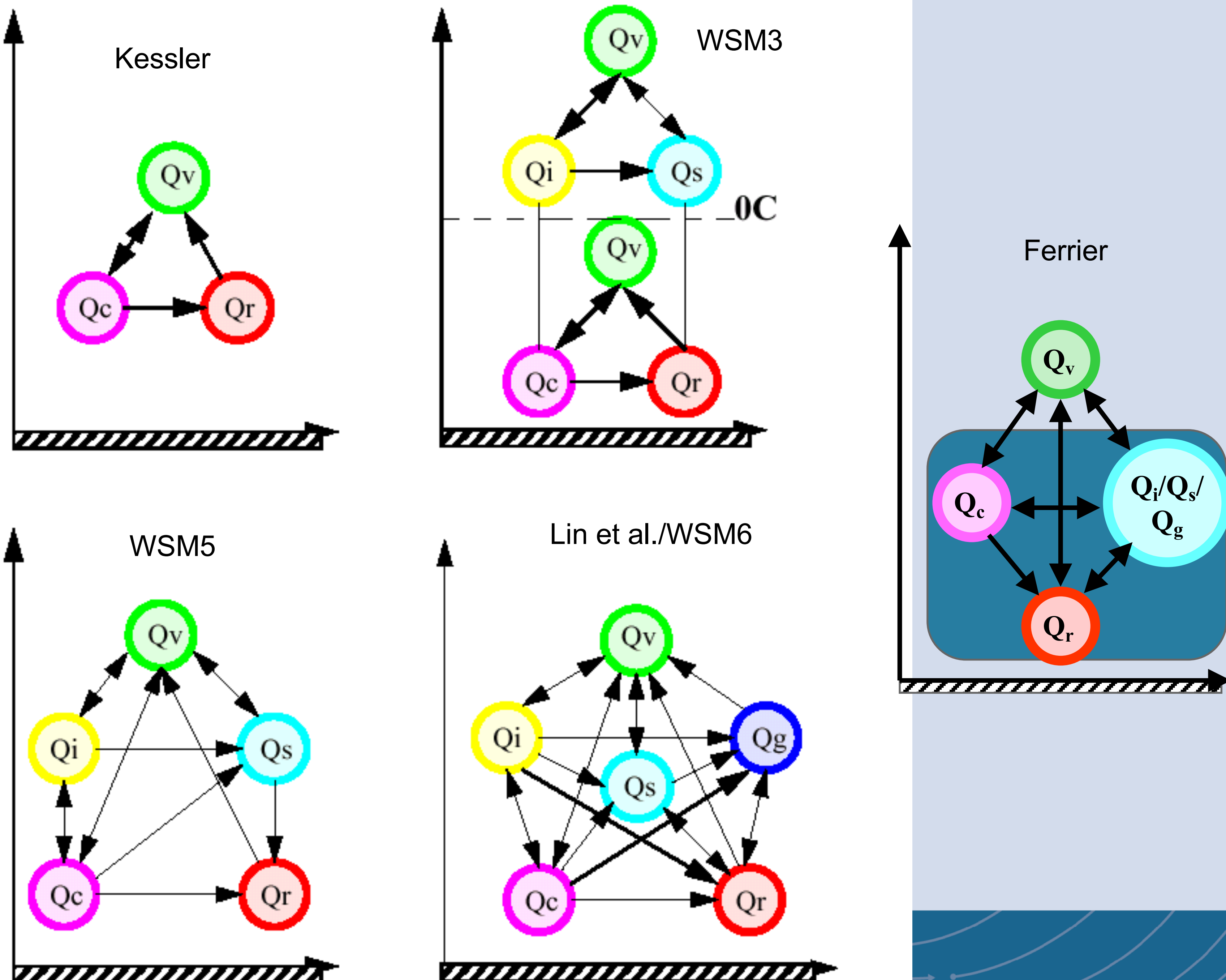
Illustration of Microphysics Processes



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
  - Spectral Bin (120-240 arrays)

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

- 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

Spectral Bin Schemes

- Hebrew University of Jerusalem (Khain and Lynn scheme)
- Size distribution resolved by doubling mass bins (typically 32 for each particle type)
- Many added advected arrays (expensive)
  - Options have 4x32 (fast scheme) or 8x32 (full scheme) arrays

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

Particle Densities and Shapes

- Some schemes allow variable densities especially for riming rather than discrete densities for snow, graupel and hail
  - WSM6/WDM6 schemes simply combine snow and graupel for purposes of computing fallspeed – rimed fraction is qg/(qs+qg)
  - NSSL schemes compute volume of graupel as a density variable
  - P3 computes growth by riming and deposition to compute density for ice/snow/graupel combined particles
- New ISHMAEL scheme predicts density and aspect ratio (shape)
- HUJI bin schemes have separate ice crystal habits (plates, columns, dendrites)

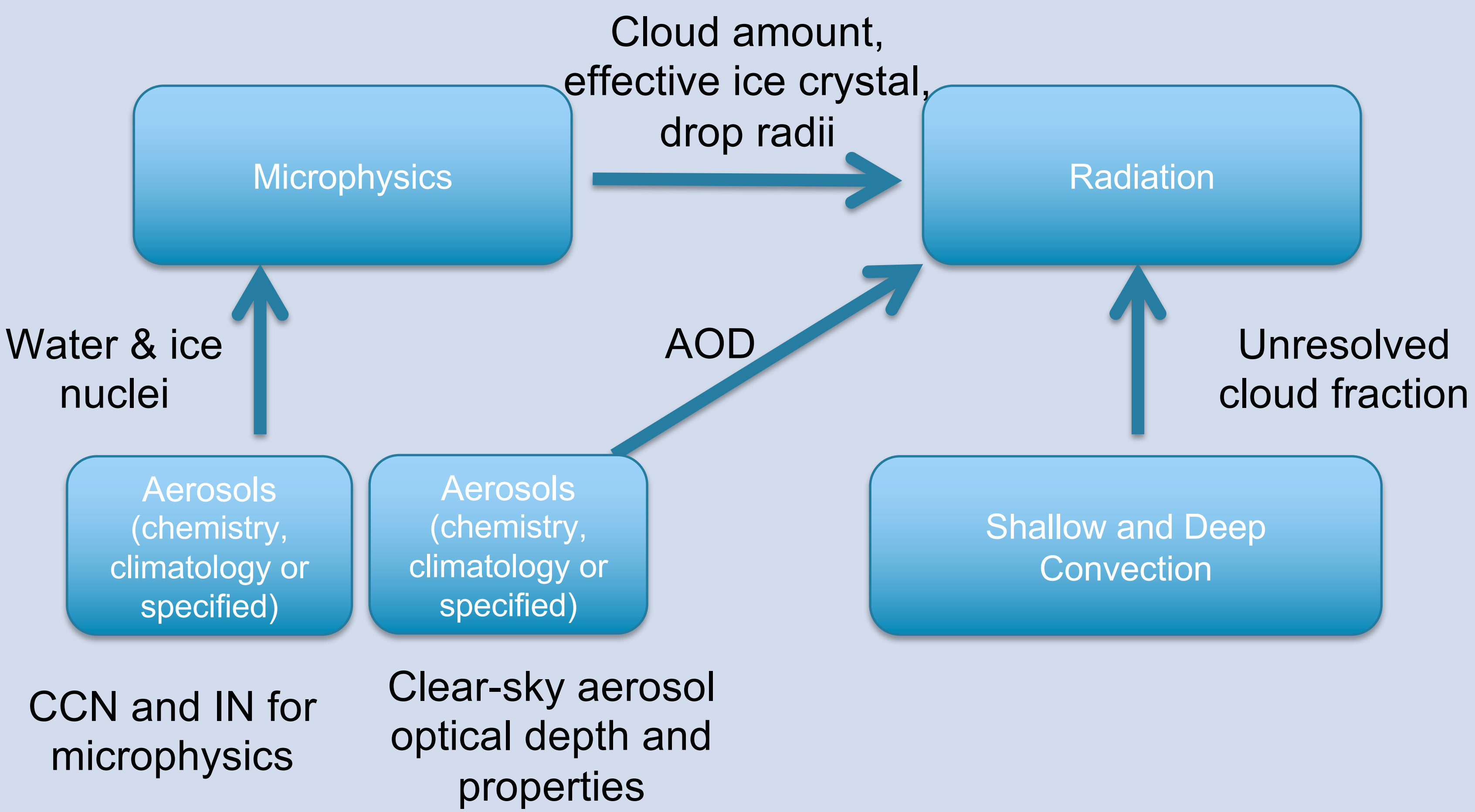
Interaction with Aerosols

- WRF-Chem can provide aerosols to some options (Lin, Morrison, CESM)
- WDM, an NSSL option, and spectral bin schemes can advect idealized CCNs which affect cloud droplet number
- Thompson “aerosol-aware” scheme can use its own aerosols (water and ice nuclei) initialized from climatology, advected
  - Since V4.0 also can do dust emission (*dust_emis=1*)
- Morrison aerosol version in V4.0 interacts with climatological aerosols

Interaction with Radiation

- Several schemes now pass their own ice, snow, cloud-water particle sizes to RRTMG radiation
  - Thompson, WSM, WDM, NSSL 2-mom schemes
  - This represents so-called indirect effect on radiation due to drop size variation
  - Other schemes do not and radiation uses internal assumptions about particle sizes

Cloud-Aerosol-Radiation Interaction



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

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

Microphysics Options: Recommendations

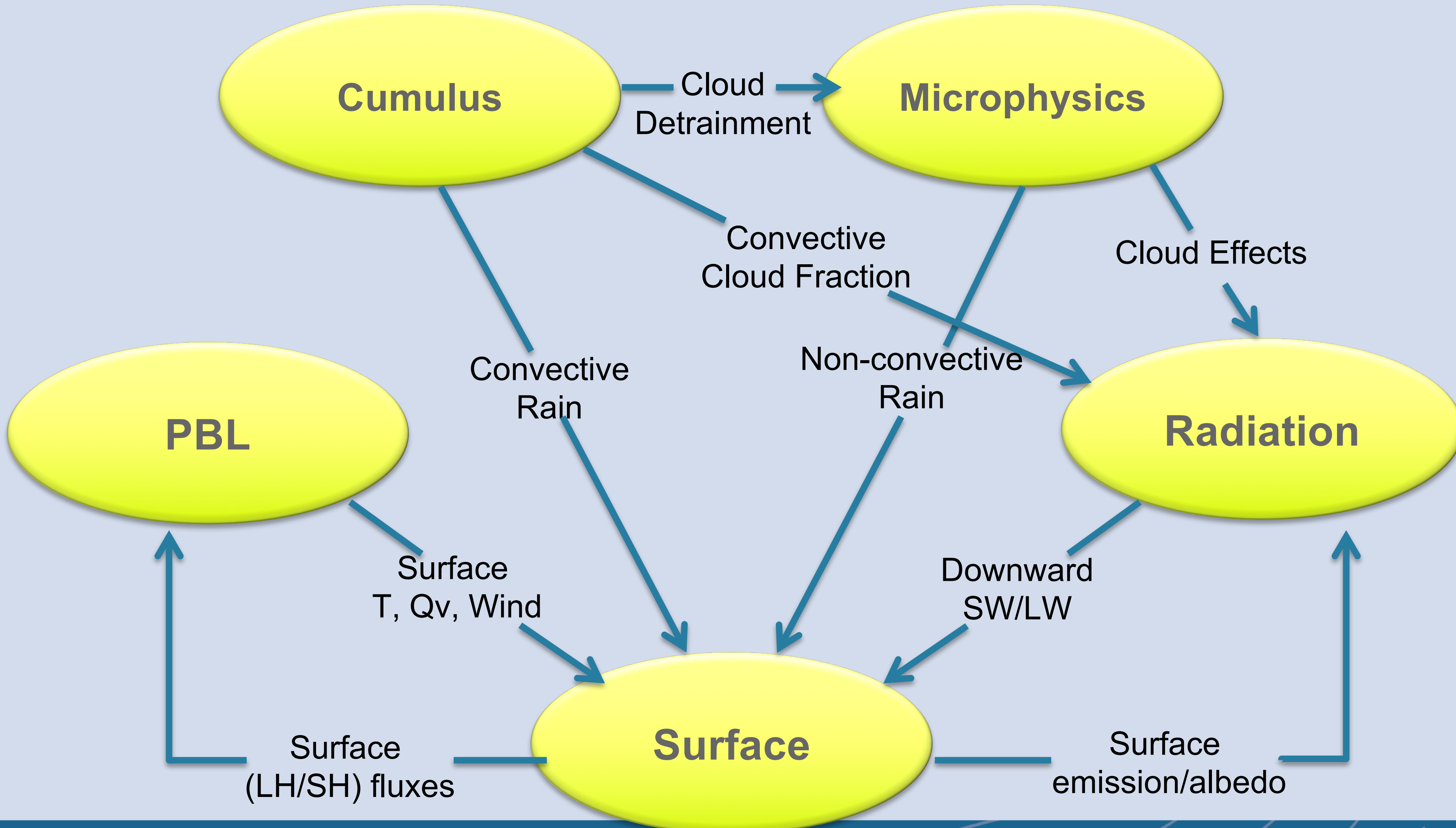
- Probably not necessary to use a graupel scheme for dx > 10 km
  - Updrafts producing graupel not resolved
  - Cheaper scheme may give similar results
- When resolving individual updrafts, graupel scheme should be used
- All domains use same option

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.)

Physics Interactions

Direct Interactions of Parameterizations



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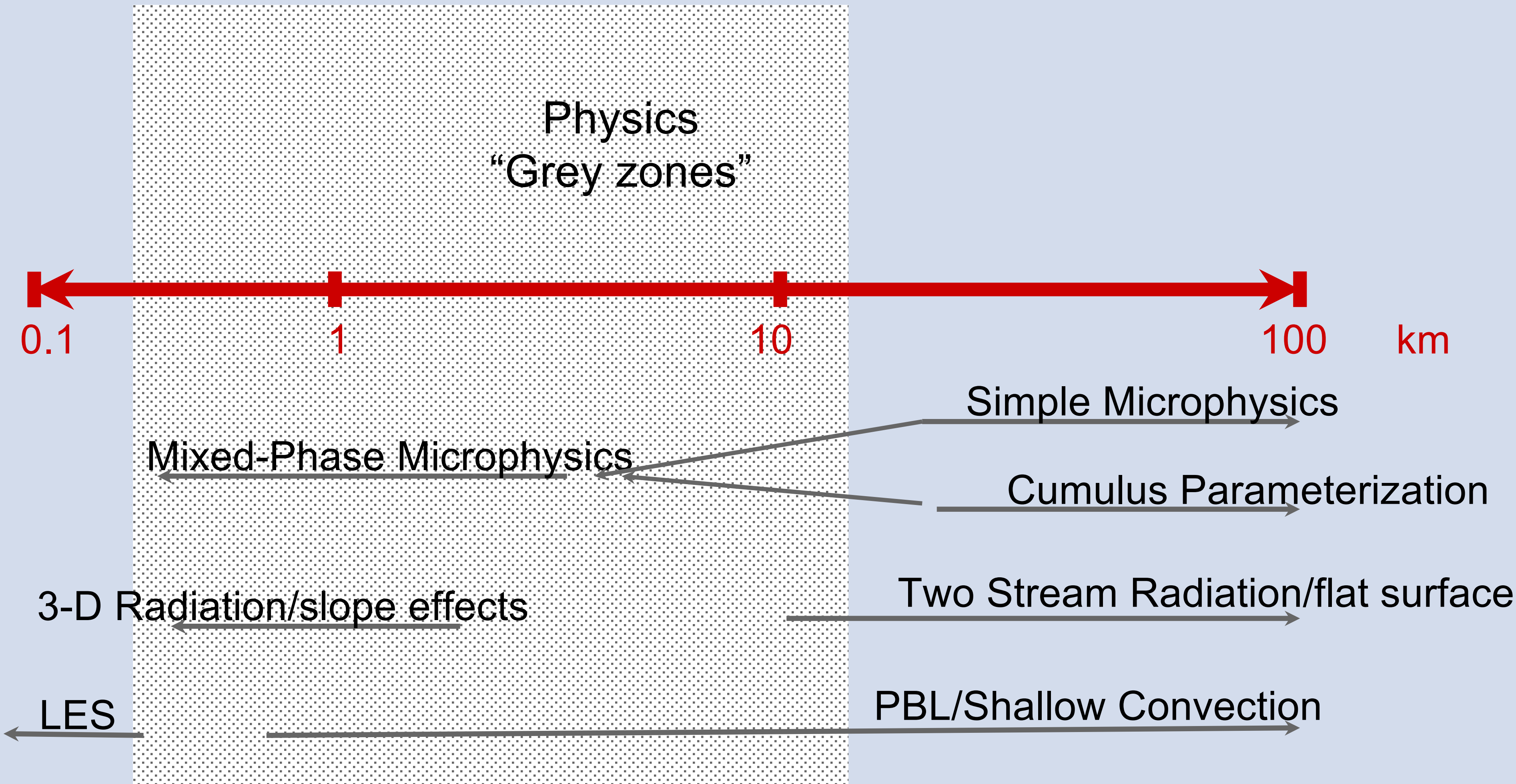
Physics in Multiscale NWP Model



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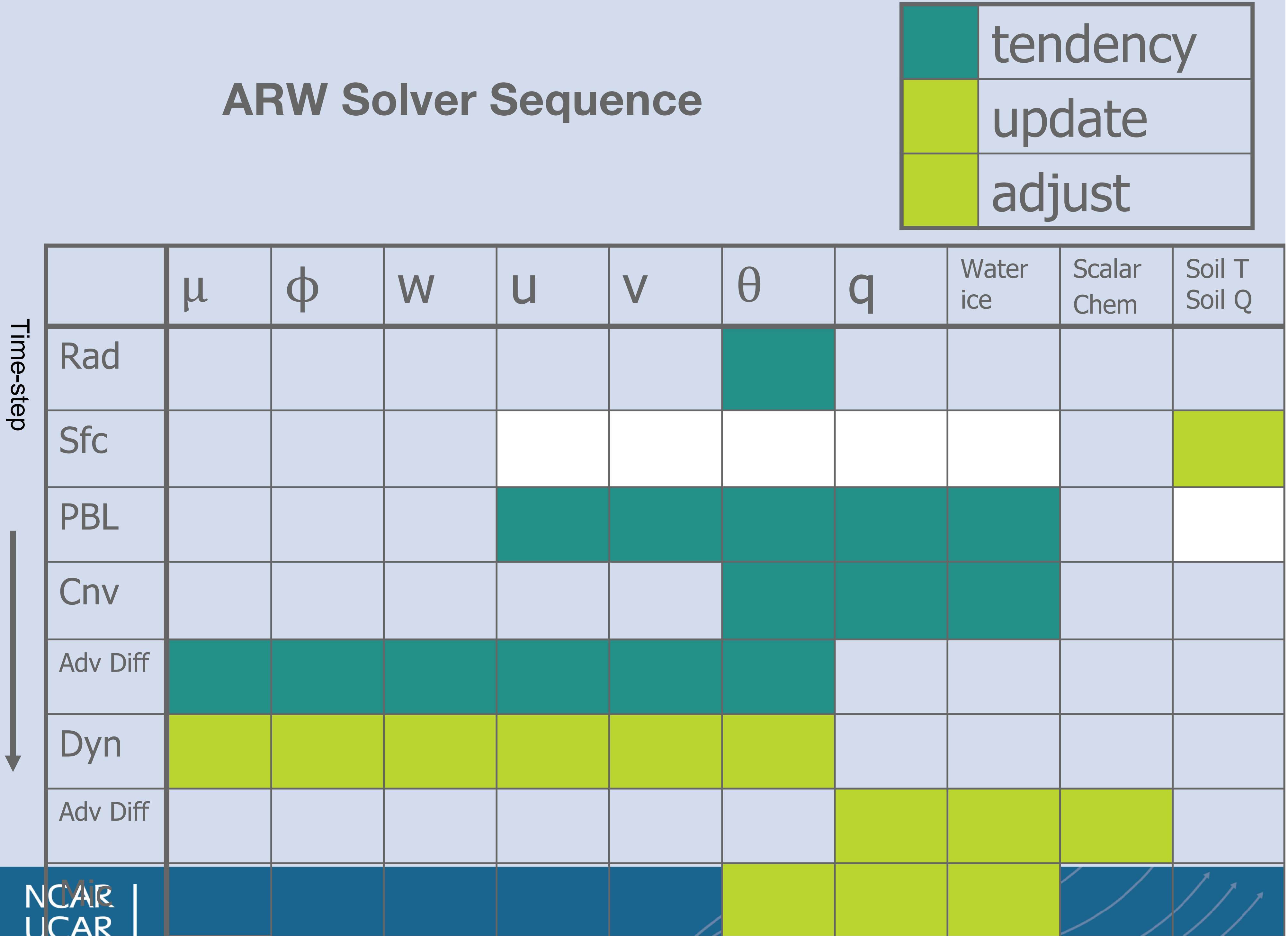
Solver Calling Sequence (ARW example)

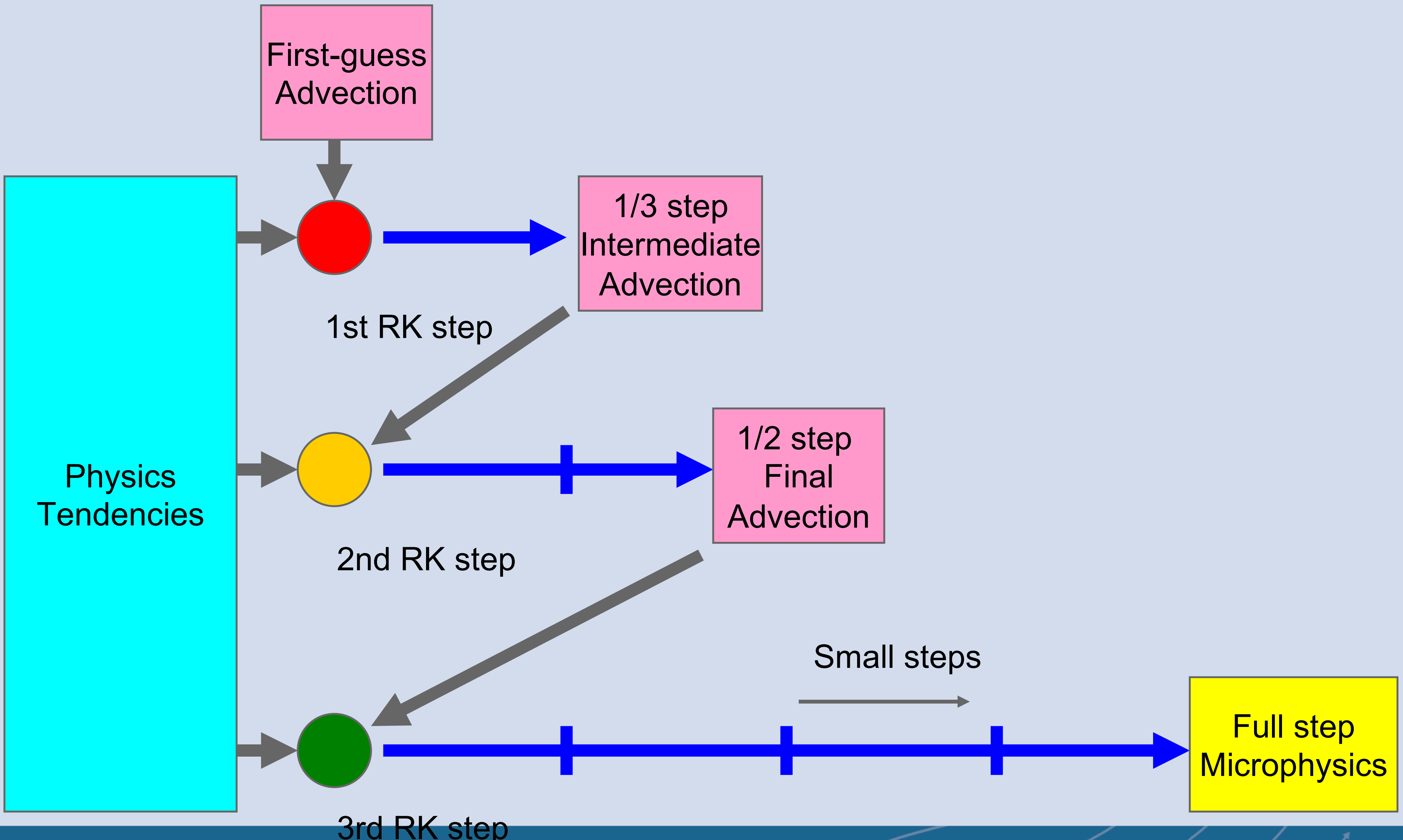
Call to solver advances one domain by one model time-step

- Physics tendencies
  - Radiation, surface, land-state update, PBL, cumulus, grid-fdda, obs-fdda
- Dynamics tendencies
  - Diffusion, advection, dynamics terms (for 3d momentum, theta, geopotential, surface pressure)
- Acoustic steps
  - Update 3d momentum, theta, surface pressure, height
- Scalar dynamics tendencies and update
  - Advection, diffusion of moist (qv,qc, etc.), scalar, tracer, tke, (and chemistry) variables
- Microphysics update

ARW Solver Sequence



ARW time-step schematic



&physics (namelist.input)

Seven major physics categories:

- **mp_physics**: 0,1,2,3,…
- **ra_lw_physics**: 0,1,3,…
- **ra_sw_physics**: 0,1,2,3,…
- **sf_sfclay_physics**: 0,1,2, …
- **sf_surface_physics**: 0,1,2,3,… (set before running **real** or **ideal**, need to match with **num_soil_layers** variable)
  - **sf_urban_physics**: 0, 1, 2, 3
- **bl_pbl_physics**: 0,1,2,…
- **cu_physics**: 0,1,2,3,…

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End