



NCAR

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

# Overview of WRF Physics

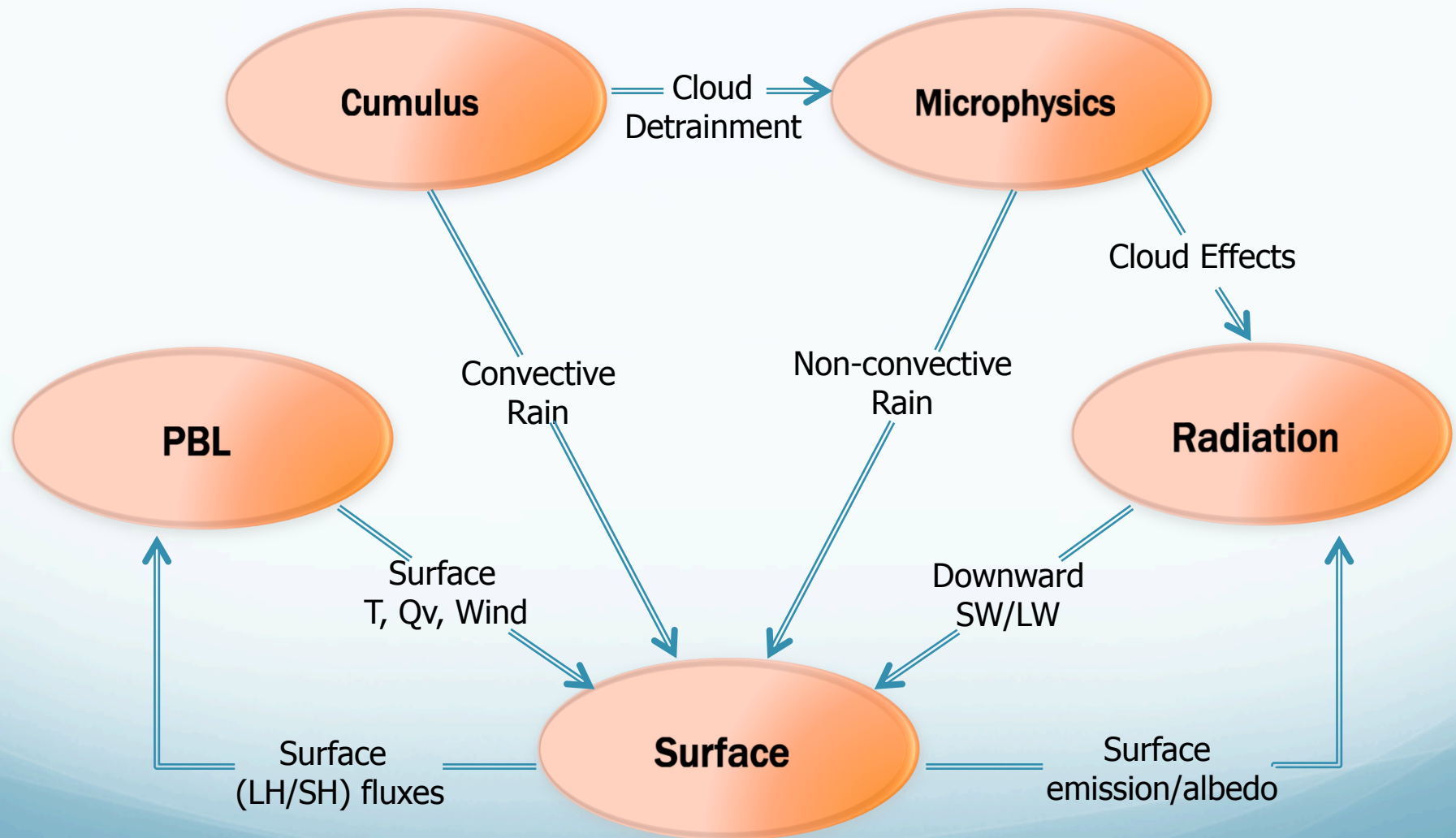
Jimmy Dudhia  
NCAR/MMM



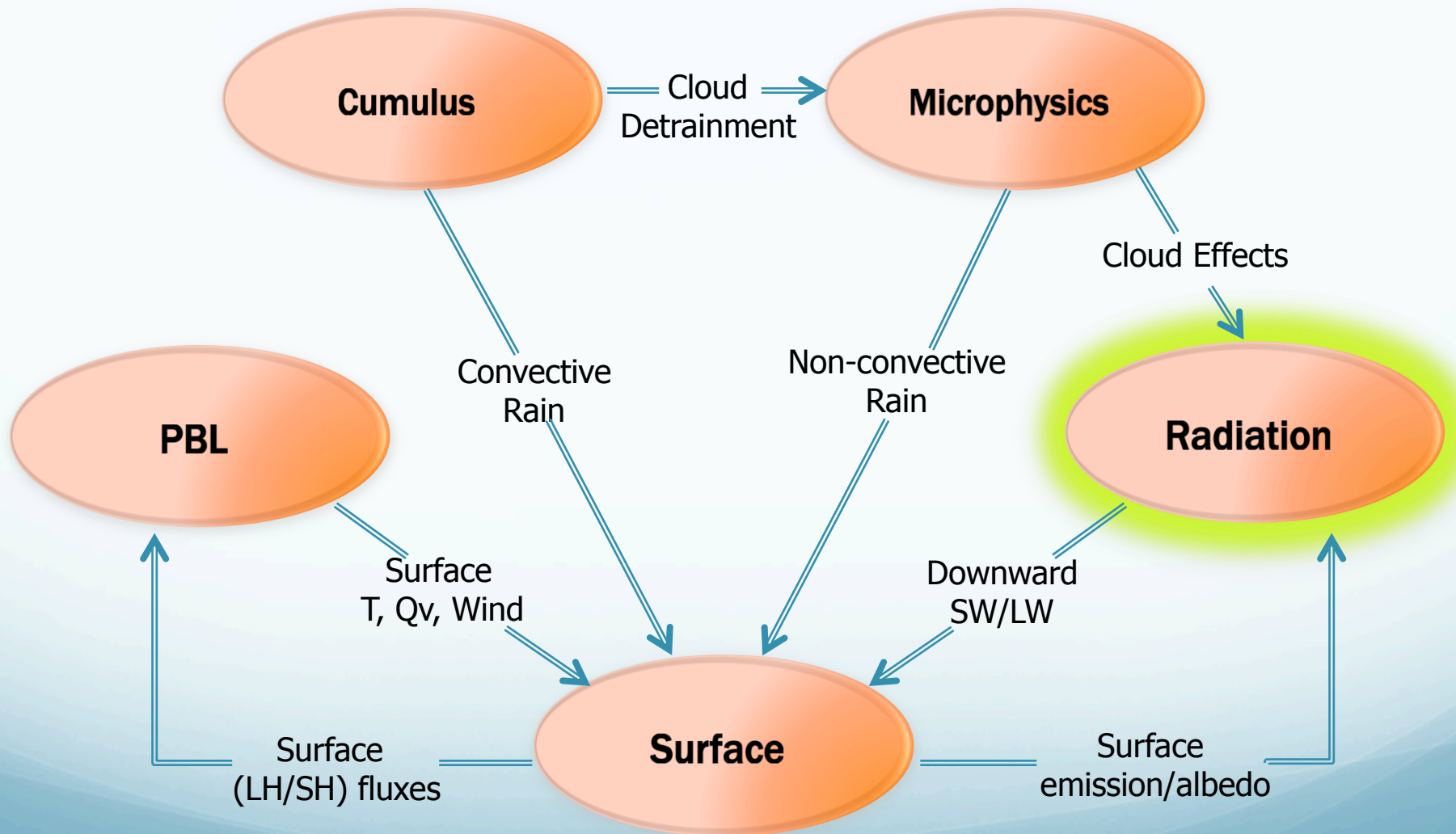
# WRF Physics

- 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



# Direct Interactions of Parameterizations





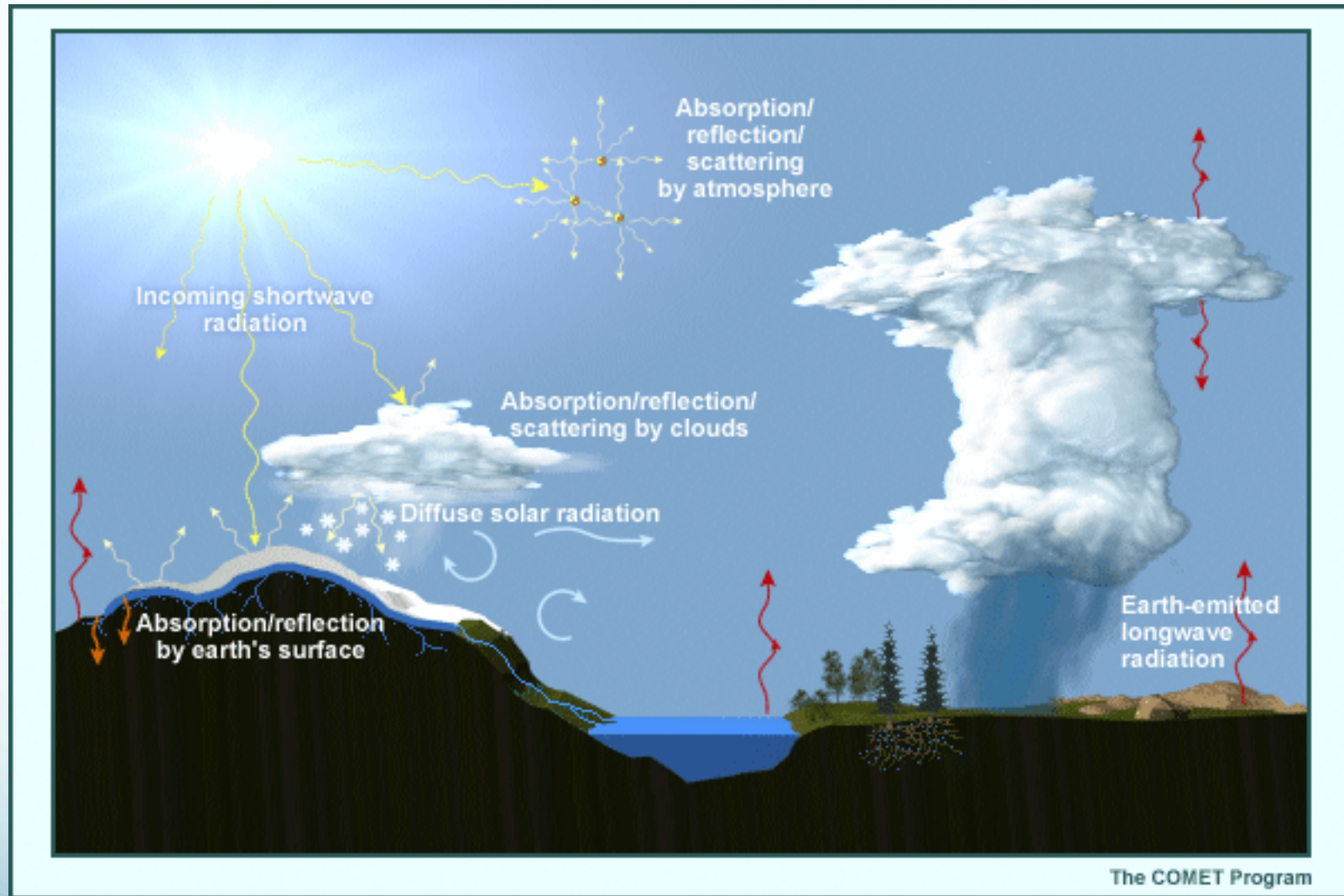
# Radiation

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  |
| 31            | Held-Suarez |                                                | 2008  |
| 99            | GFDL        | Fels and Schwarzkopf (1981, JGR)               | 2004  |

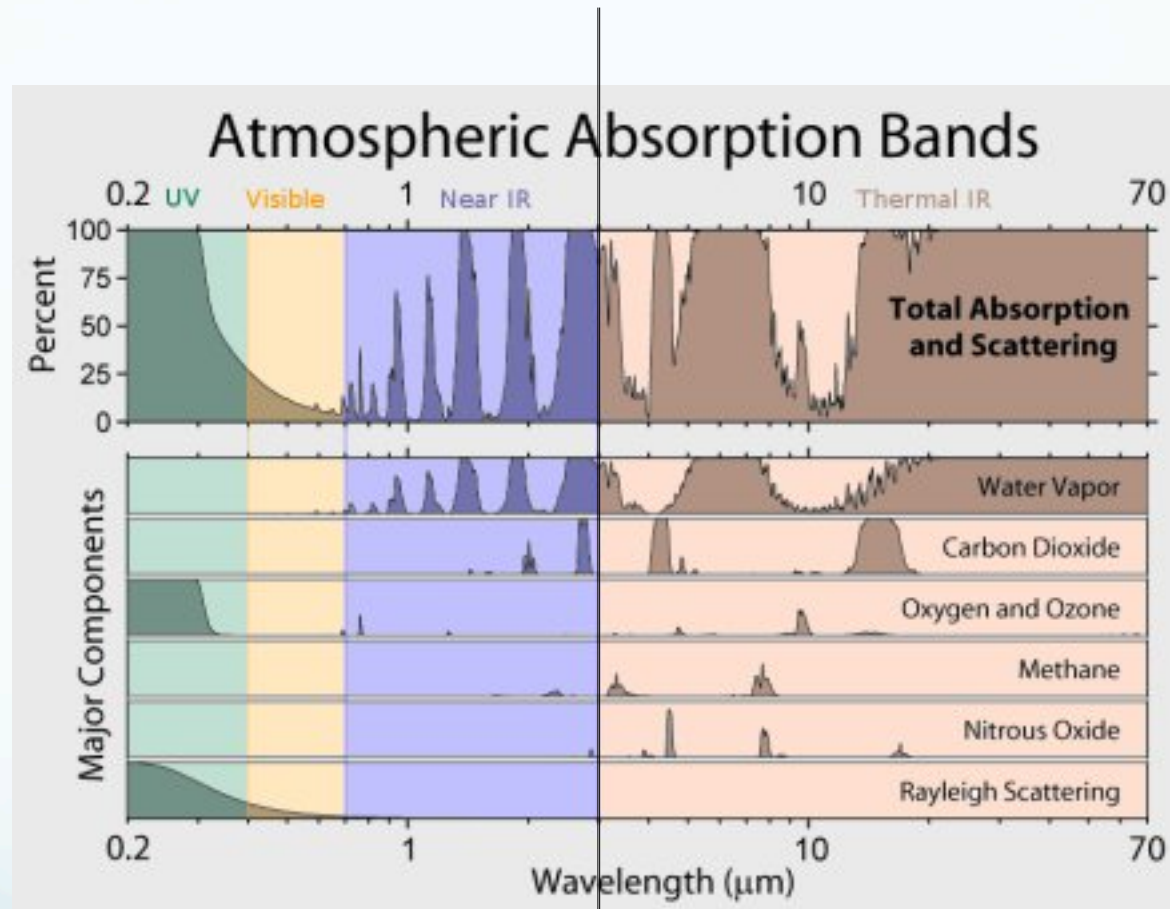
# Longwave Radiation schemes

| 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( $\tau$ ) | Qc Qr Qi Qs              | Max-rand overlap | constant or yearly GHG |
| 5             | New Goddard | ARW                 | Qc Qr Qi Qs Qg           | 1/0              | constant               |
| 7             | FLG (UCLA)  | ARW                 | Qc Qr Qi Qs Qg           | 1/0              | constant               |
| 31            | Held-Suarez | ARW                 | none                     | none             | none                   |
| 99            | GFDL        | ARW NMM             | Qc Qr Qi Qs              | Max-rand overlap | constant               |

# Clear Sky: IR-active Gases

- H<sub>2</sub>O – from model prognostic vapor
- CO<sub>2</sub> – well-mixed, specified constant in whole atmosphere (CAM has yearly values)
  - For CAM, RRTM and RRTMG, GHG input file can update CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub>
- O<sub>3</sub> – 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



**shortwave**

**longwave**



# 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
  - Only Thompson passes its 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 al. (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  |
| 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( $\tau$ )      | Qc Qi                    | 1/0              | 5 profiles             |
| 3             | CAM         | ARW                      | Qc Qi Qs                 | Max-rand overlap | Lat/month              |
| 4             | RRTMG       | ARW +Chem( $\tau$ ), NMM | Qc Qr Qi Qs              | Max-rand overlap | 1 profile or lat/month |
| 5             | New Goddard | ARW                      | Qc Qr Qi Qs Qg           | 1/0              | 5 profiles             |
| 7             | FLG (UCLA)  | ARW                      | Qc Qr Qi Qs Qg           | 1/0              | 5 profiles             |
| 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<sub>2</sub> 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 N<sub>2</sub>O and CH<sub>4</sub> (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.

# radt

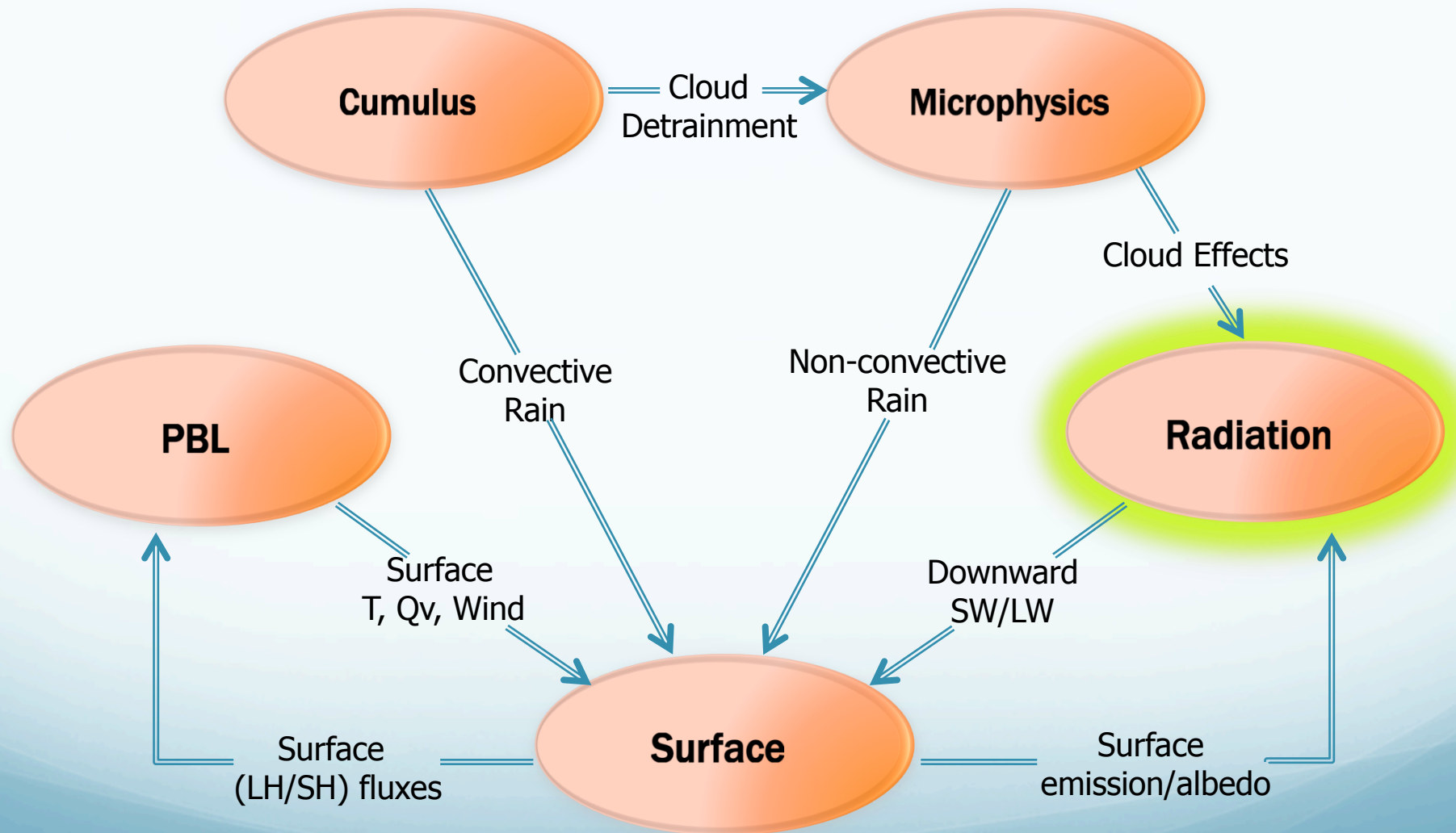
## Radiation time-step recommendation

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

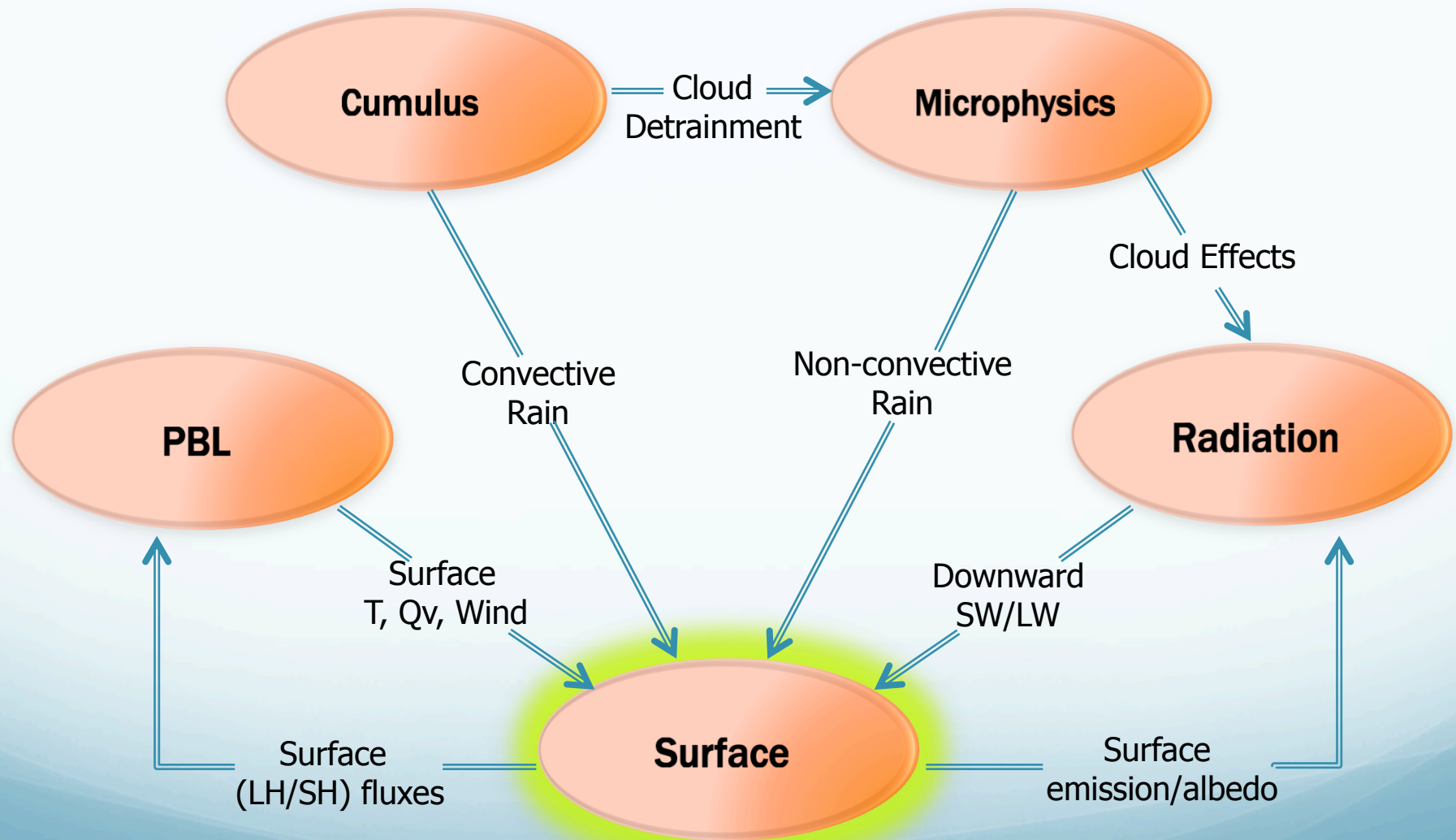
# Surface Shortwave Fluxes

- **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



# Direct Interactions of Parameterizations



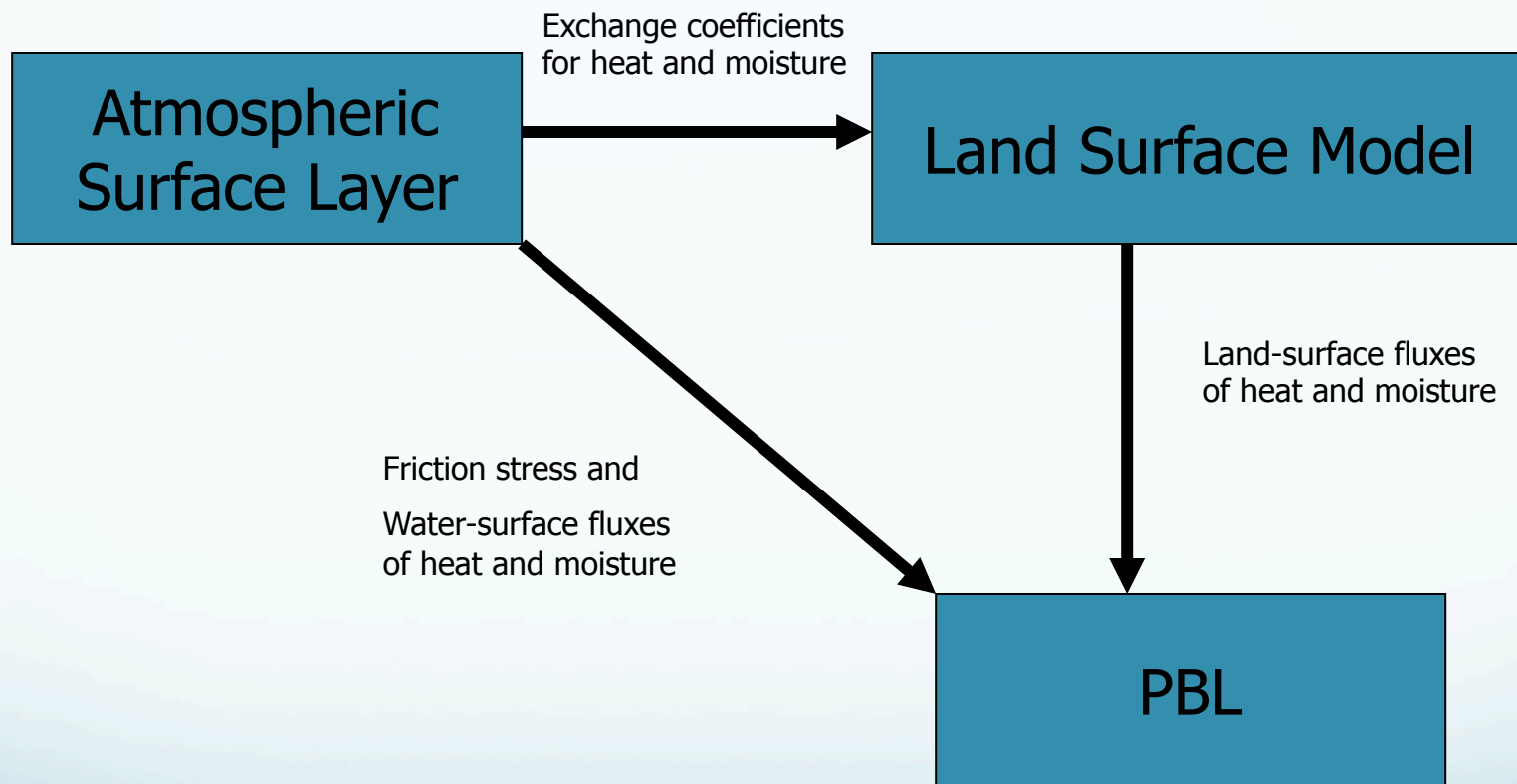


# Surface schemes

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

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

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

Subscript  $r$  is reference level (lowest model level, or 2 m or 10 m)  
D 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

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

# 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

# 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  $C_d$ )
  - Modifies surface enthalpy ( $C_k$ , heat/moisture) either with constant  $z_{0q}$  (`isftcflx=1`), Garratt formulation (option 2)

# Fractional Sea Ice

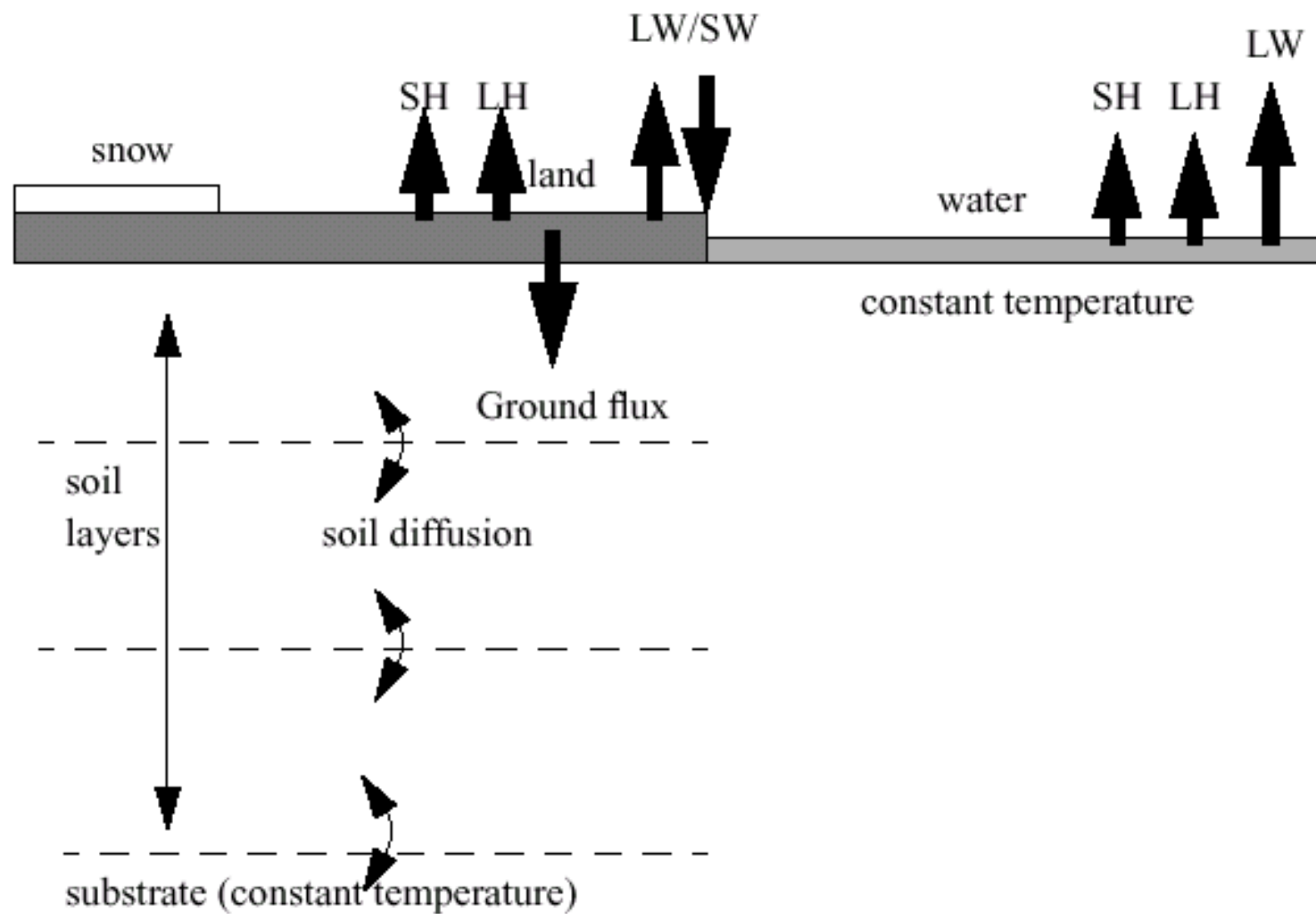
- `fractional_seaice=1` - with input sea-ice fraction data can partition land/water fluxes within a grid box
- Can be used with nearly all surface-layer schemes



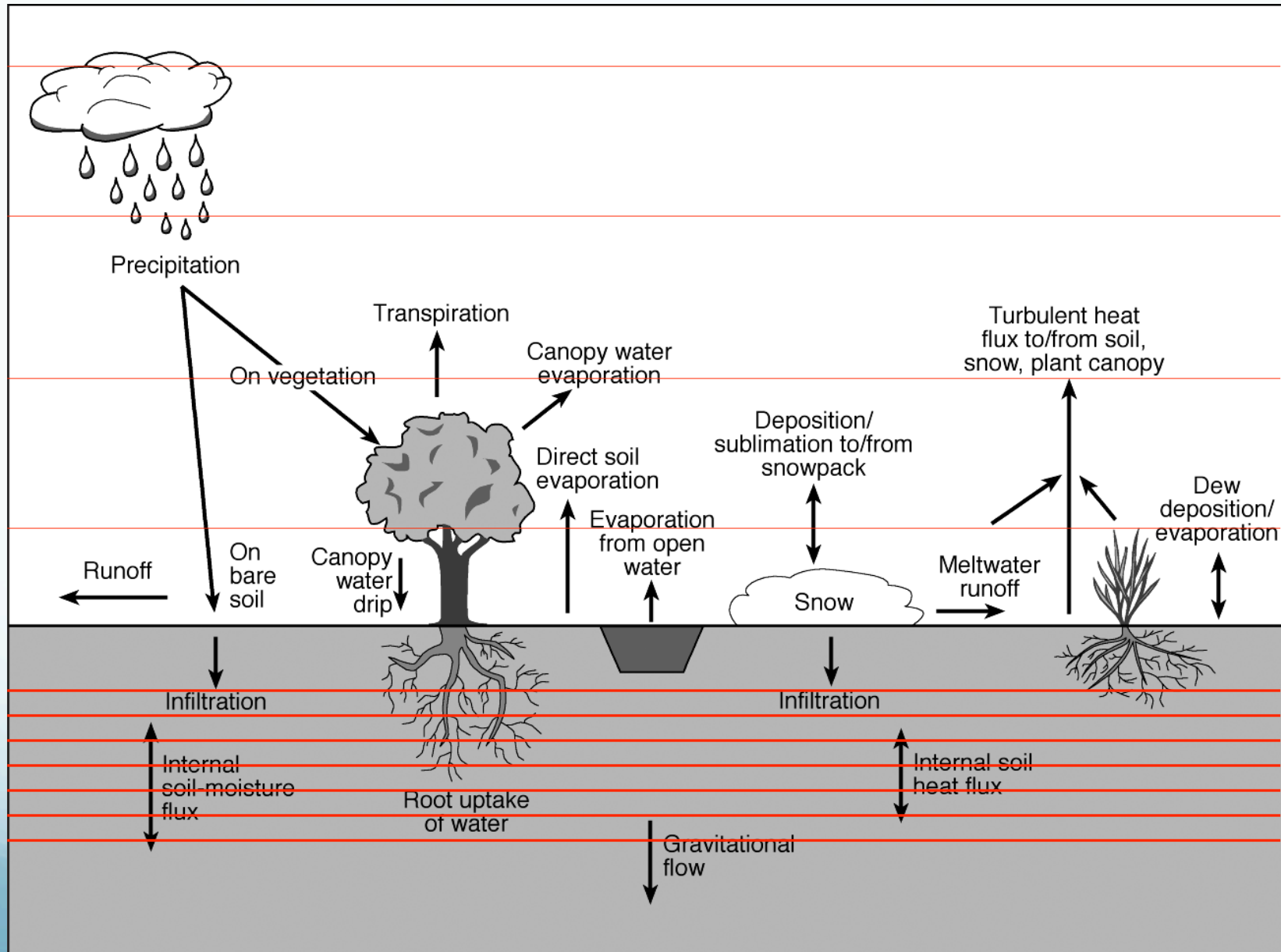
# WRF Land-Surface Model Options (sf\_surface\_physics)

- 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 Options

- 5-layer thermal diffusion
- Noah LSM (also with mosaic option in V3.6)
- RUC LSM
- Pleim-Xiu LSM
- NoahMP
- SSiB
- CLM4

# 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
- 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
- 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

# 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\_d0n 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

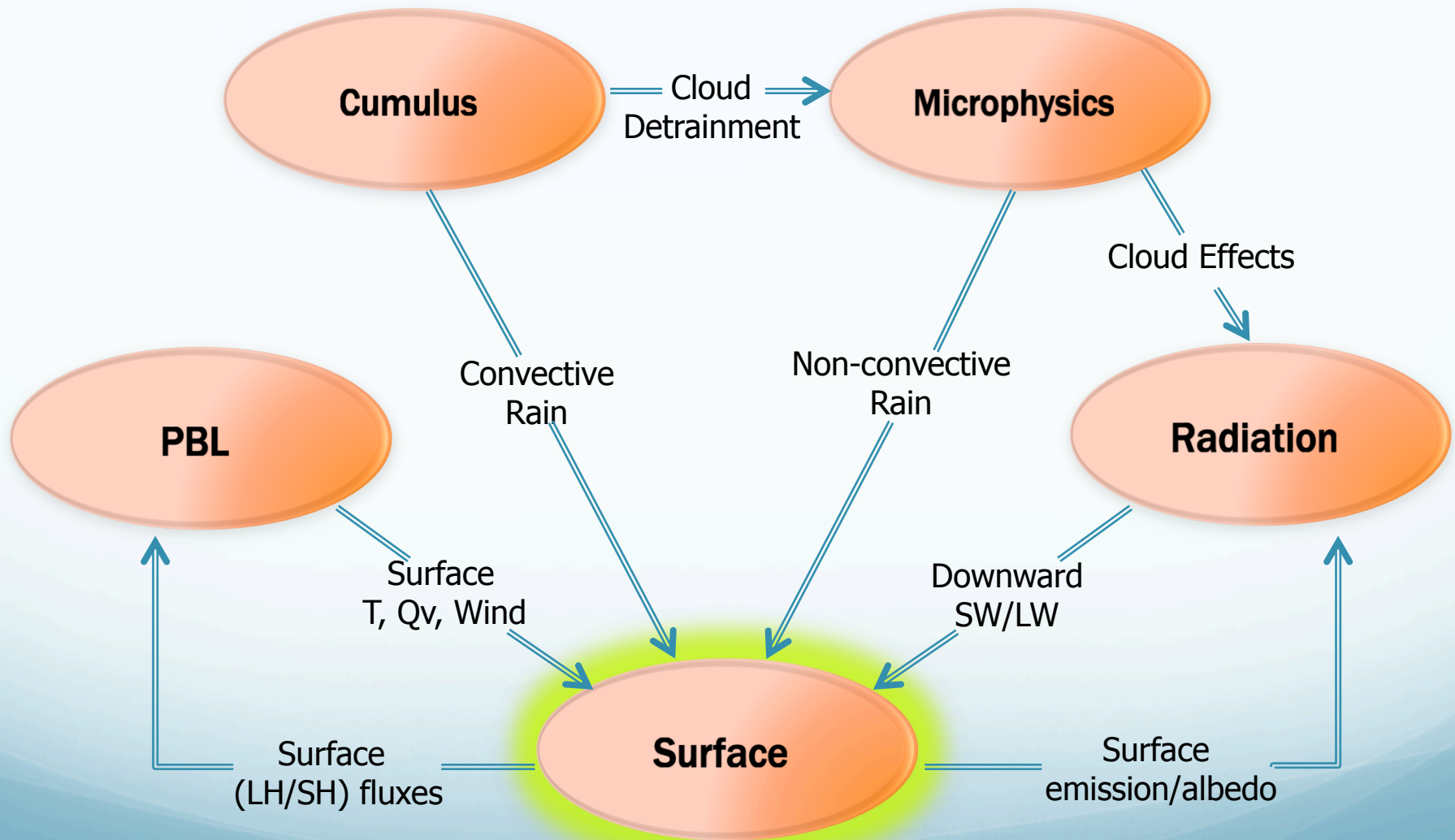
- 10-layer lake model from CLM (sf\_lake\_physics=1)
- We have global bathymetry data for most large lakes (added from geogrid)
- Also can predict lake ice
- Can be used with any LSM
- WPS preprocessing allows diurnal averaging methods to initialize lake temperatures where not resolved by SST analysis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



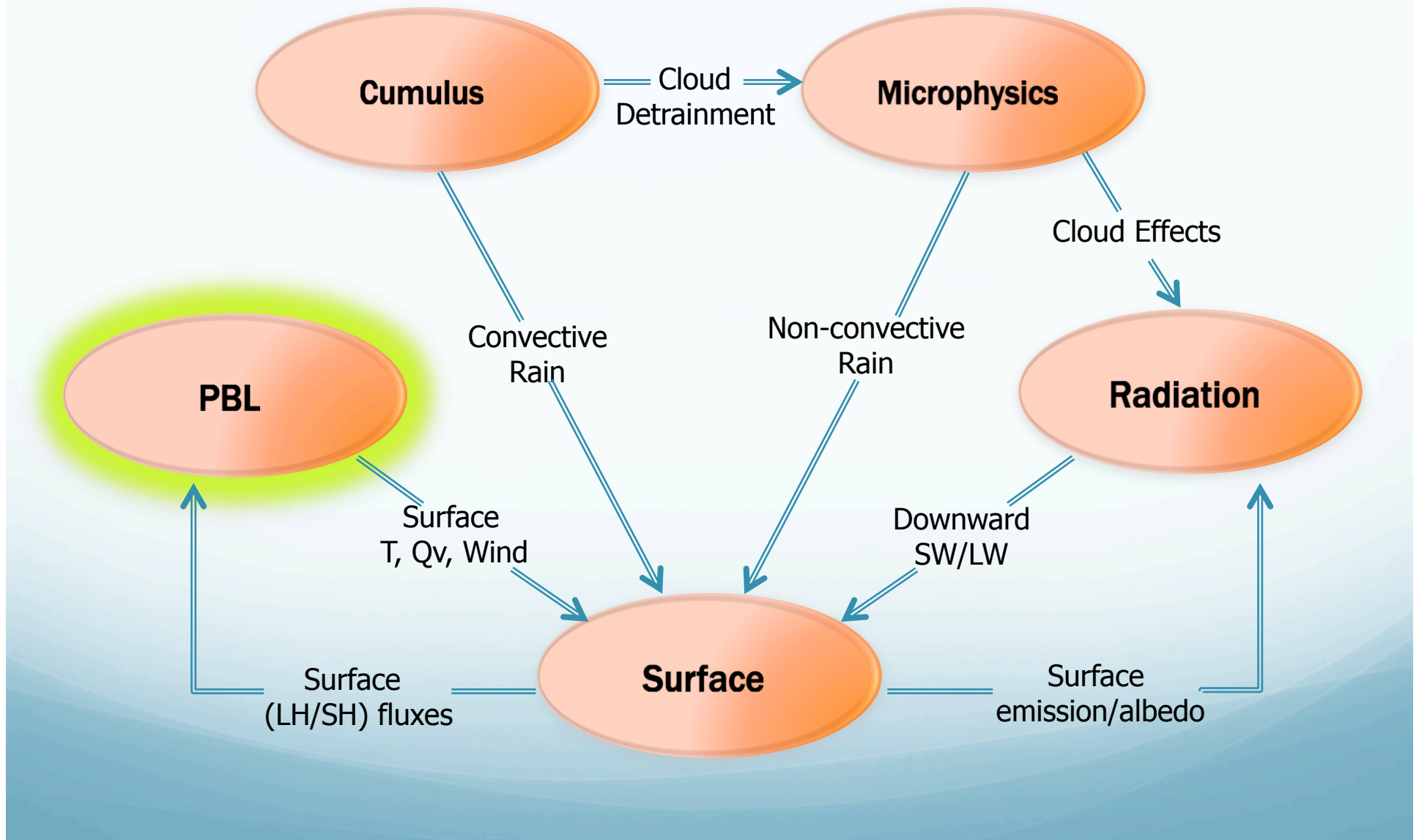
# WRF-Hydro

- 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



# Direct Interactions of Parameterizations



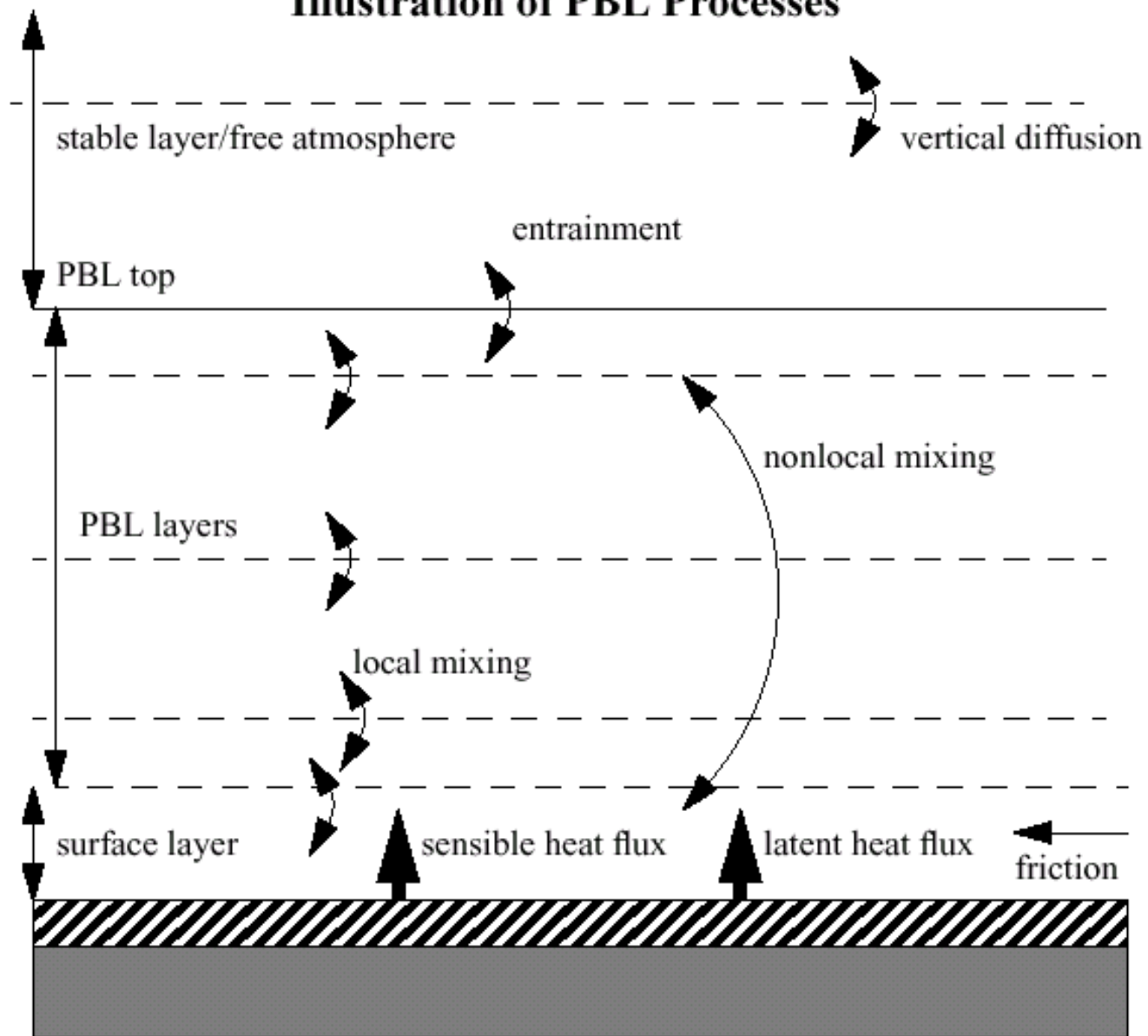
# Planetary Boundary Layer

Provides

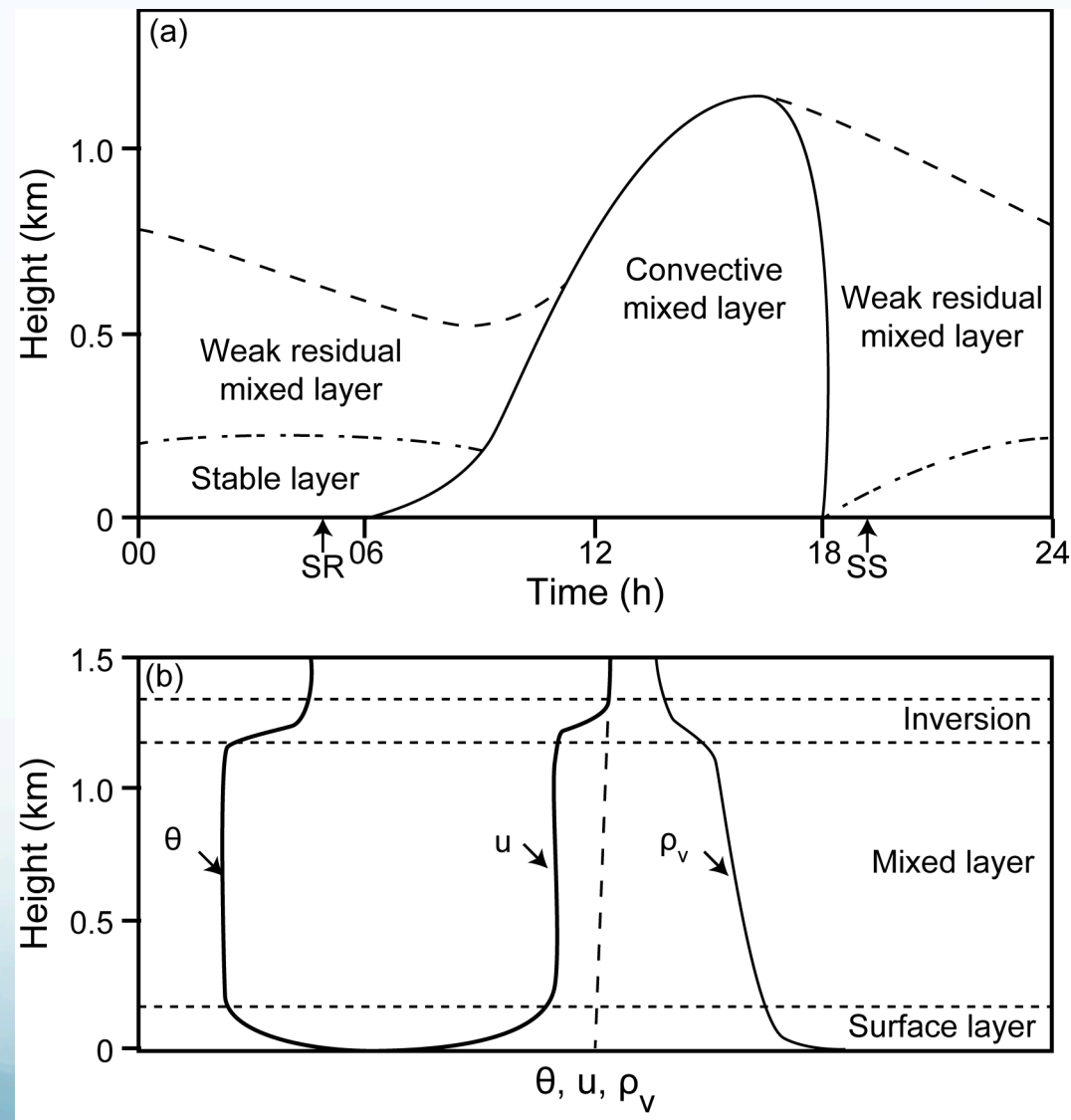
Boundary layer fluxes (heat, moisture, momentum)

Vertical diffusion in whole column

## Illustration of PBL Processes



# 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

| 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 Bretherton (2001, MWR)                                                        | 2013  |
| 99             | MRF       | Hong and Pan (1996, MWR)                                                                  | 2000  |



# Nonlocal PBL schemes

Non-local schemes have two main components

$$\overline{w'\phi'}^\Delta = -K_\phi \frac{\partial \bar{\phi}^\Delta}{\partial z} + F_{w\phi}^{NL}$$

(1) Term for local (L) transport by small eddies  
(2) **Term for nonlocal (NL) transport by large eddies**

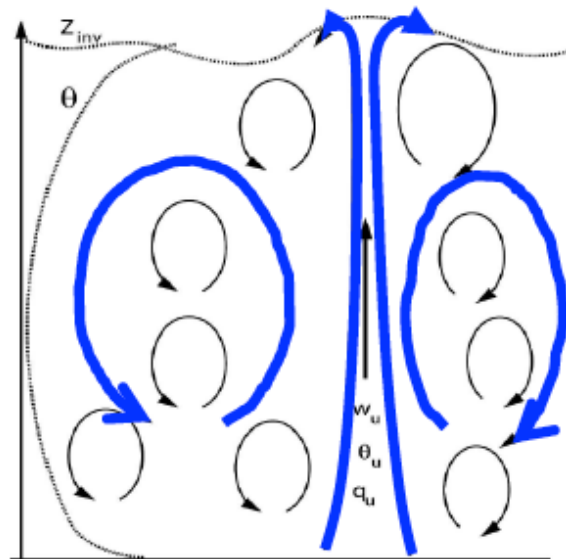


FIG. 1. Sketch of a convective updraft embedded in a turbulent eddy structure.

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
- TKE and length-scale are used to determine the  $K_v$  for local vertical mixing
- Schemes differ most in diagnostic length-scale computations

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

# Nonlocal Schemes

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

- Specify a K profile

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

- YSU, MRF, GFS include a non-gradient term ( $\Gamma$ )

- ACM2, TEMF, EDMF include a mass-flux profile,  $M$ , which is an additional updraft flux

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

# Vertical Mixing Coefficient

- Several schemes also output `exch_h` which is  $K_v$  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

# 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)
- YSU has top-down mixing option for turbulence driven by cloud-top radiative cooling which is separate from bottom-up surface-flux-driven mixing

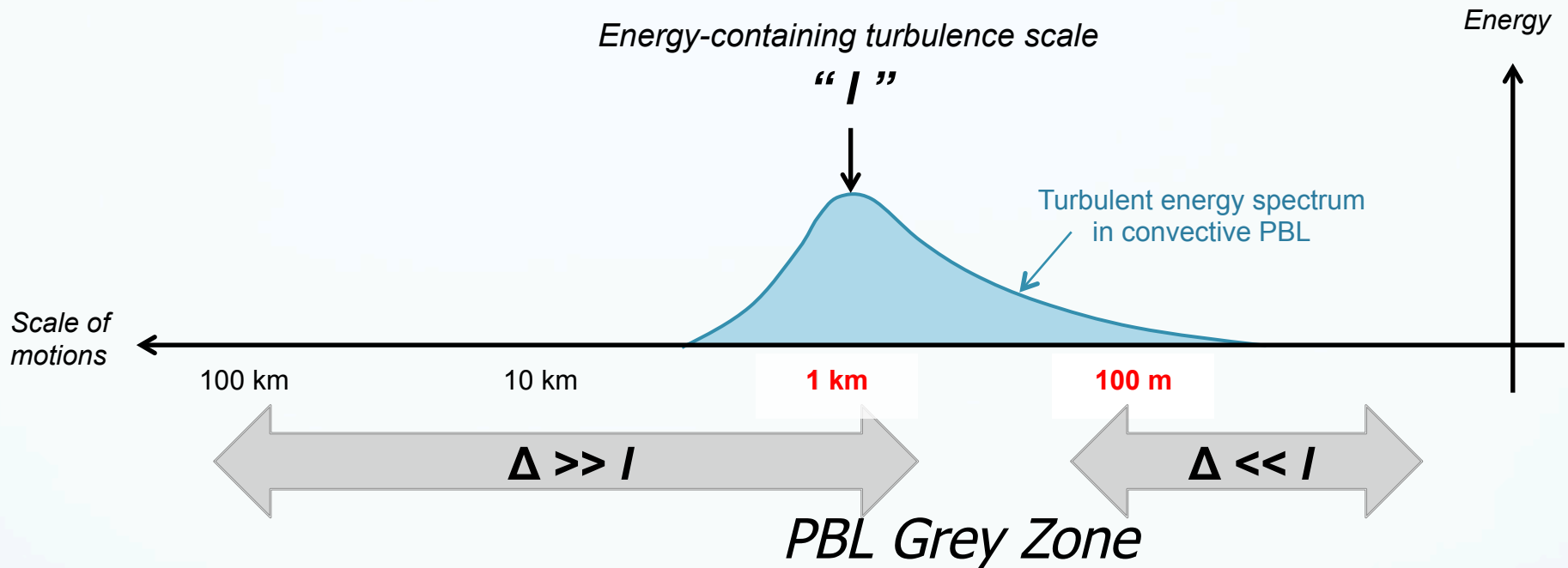
# PBL schemes

| 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 can use thinner surface layers
- Assumes that PBL eddies are not resolved
- At grid size  $dx \ll 1$  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  $\Delta \gg \lambda$
- ✓ All eddies are sub-grid
- ✓ 1d column schemes handle sub-grid vertical fluxes

## For fine grid spacing

- ✓ LES schemes have been designed for  $\Delta \ll \lambda$
- ✓ 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 term reduces in strength as grid size gets smaller and local 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

# 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  $dx \sim dz$ ).

Typically needed for  $dx < \sim 200$  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<br>tke_heat_flux        | From namelist<br>tke_drag_coefficient | Ideal      |
| 1      | 1,2               | From LSM/sfclay<br>physics (HFX, QFX) | From sfclay physics<br>(UST)          | Real       |
| 2      | 1,2               | From namelist<br>tke_heat_flux        | From sfclay physics<br>(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 (> 10 km) runs to represent sub-grid orographic gravity-wave vertical transport of horizontal momentum (gwd\_opt=1)
- Fog: grav\_settling=2 (Katata)

# bldt

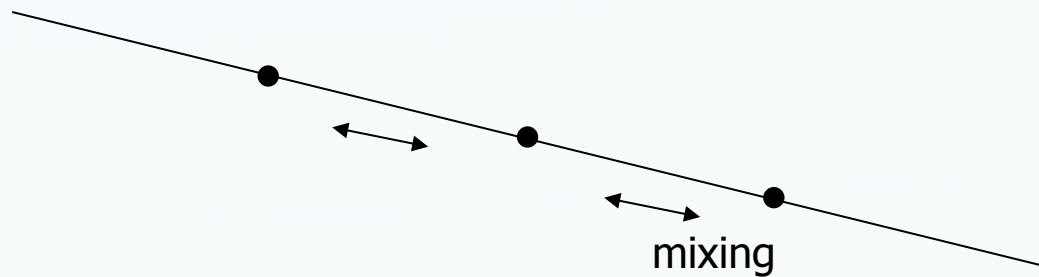
- Minutes between boundary layer/LSM calls
- Typical value is 0 (every step)
- CLM LSM is expensive, so may consider bldt in that case

# 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



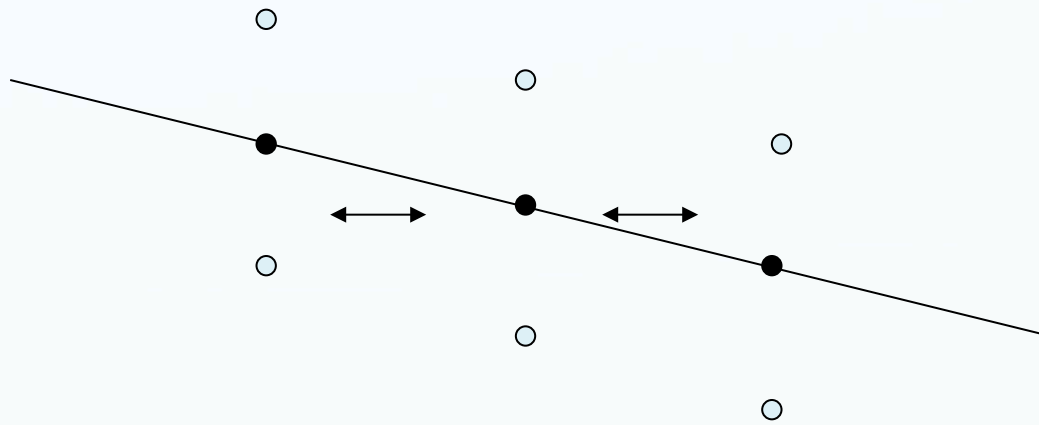
diff\_opt=1

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
- Note: WRF can run with no diffusion (`diff_opt=0`)

# diff\_6th\_opt

- 6<sup>th</sup> order optional added horizontal diffusion on model levels
  - Used as a numerical filter for  $2 \times dx$  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  $2 \times dx$  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.

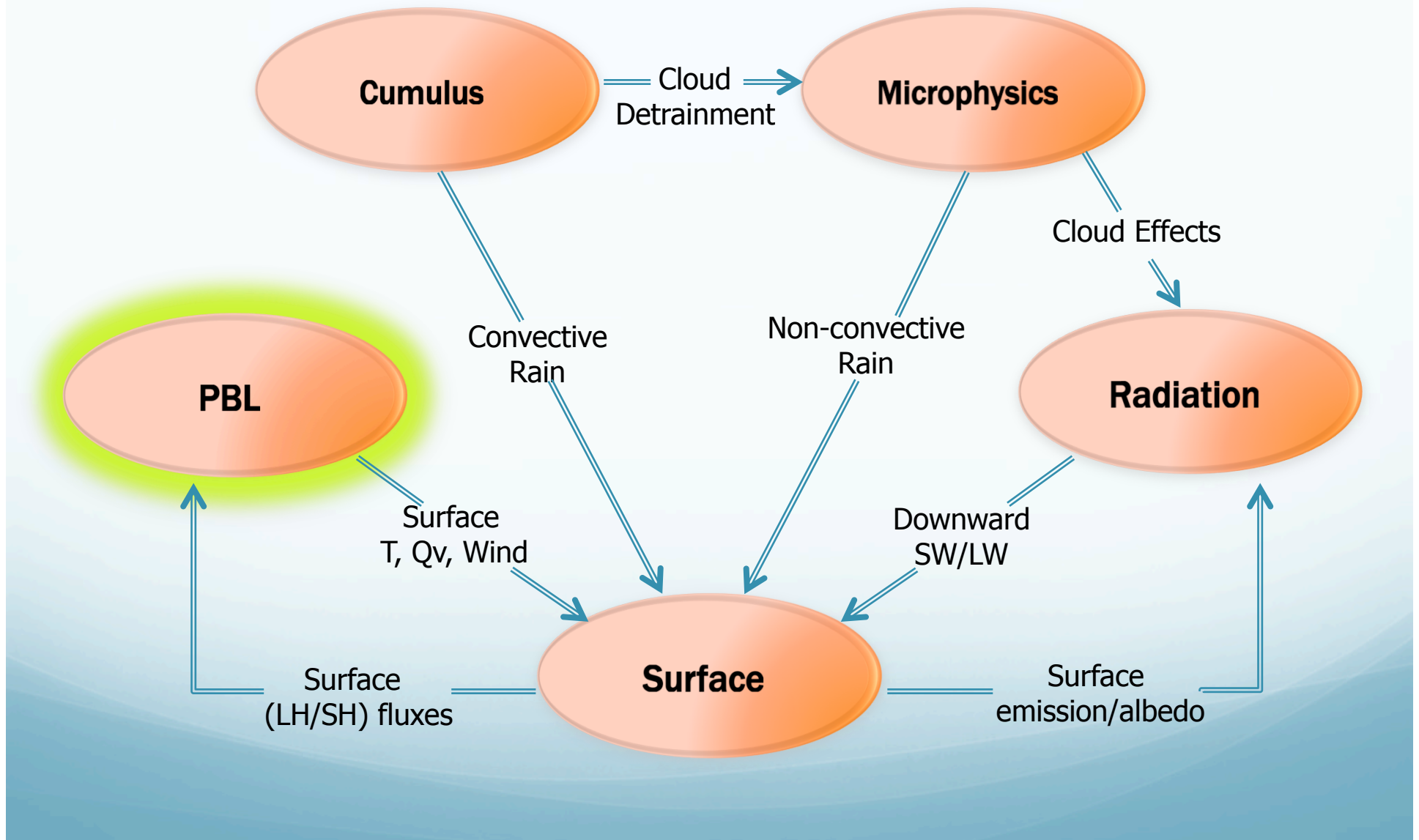
## Options

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

## All options use

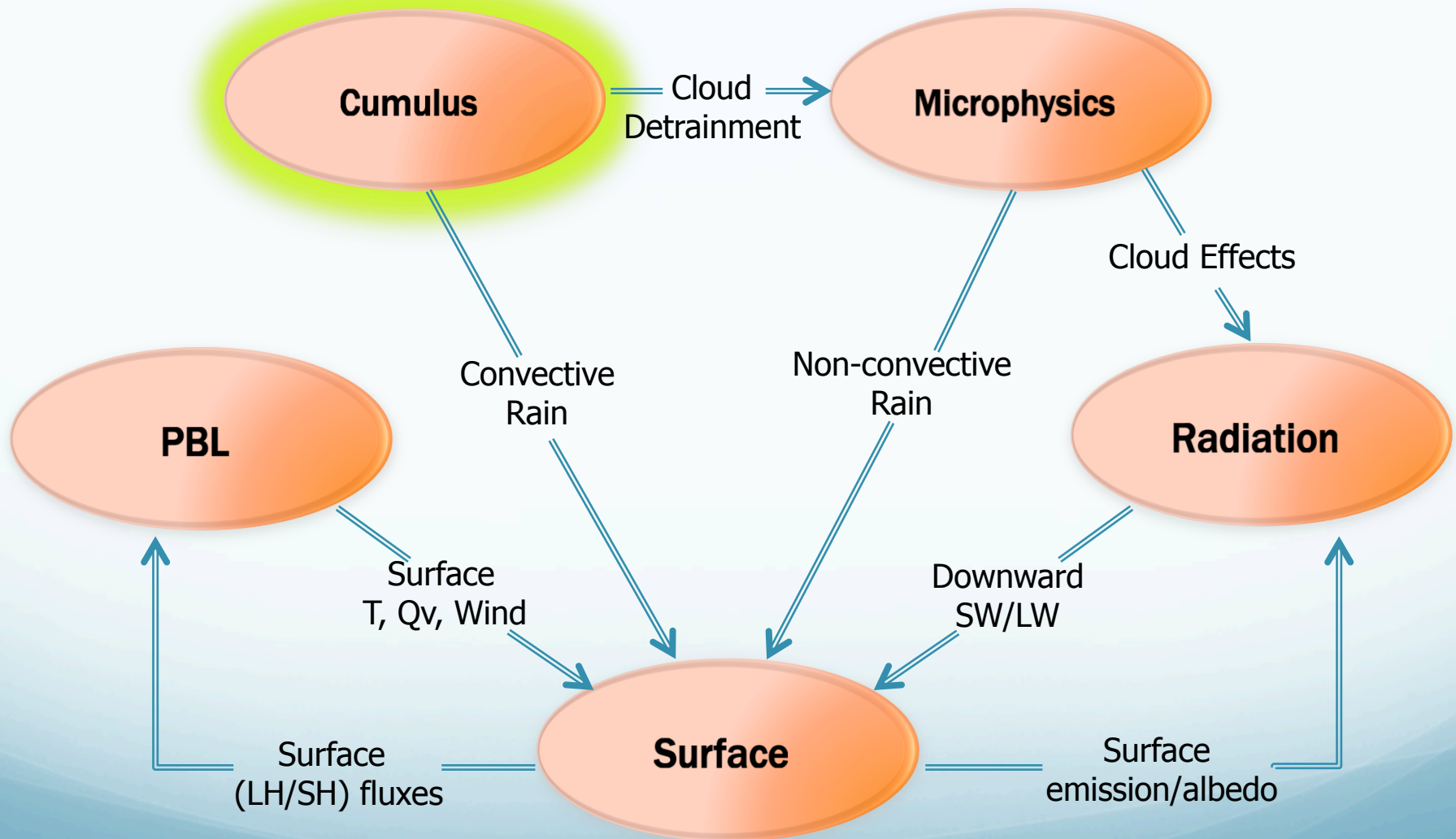
- Cosine function of height
- Additional parameters
  - zdamp: depth of damping layer
  - dampcoef: nondimensional maximum magnitude of damping

# Direct Interactions of Parameterizations





# Direct Interactions of Parameterizations



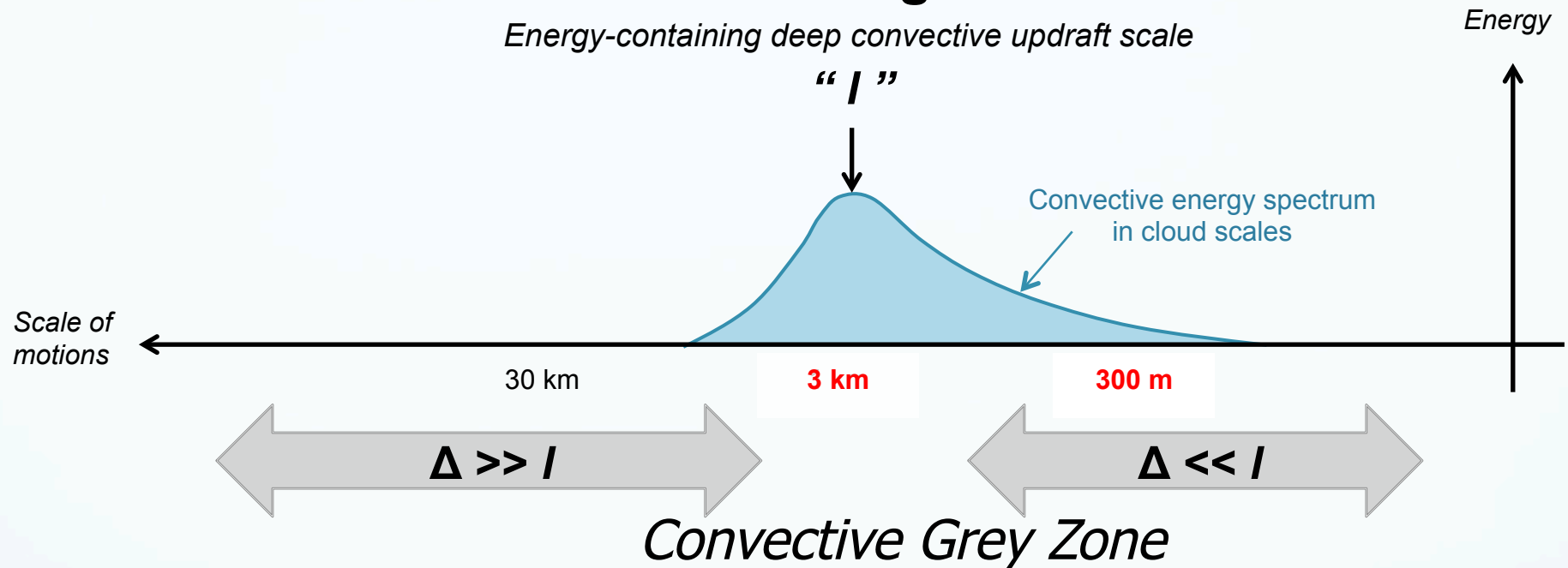
# Cumulus Parameterization

Provides

Atmospheric heat and moisture/cloud tendency profiles

Surface sub-grid-scale (convective) rainfall

# Model Grid Spacing: Cumulus Parameterization and Cloud-Resolving



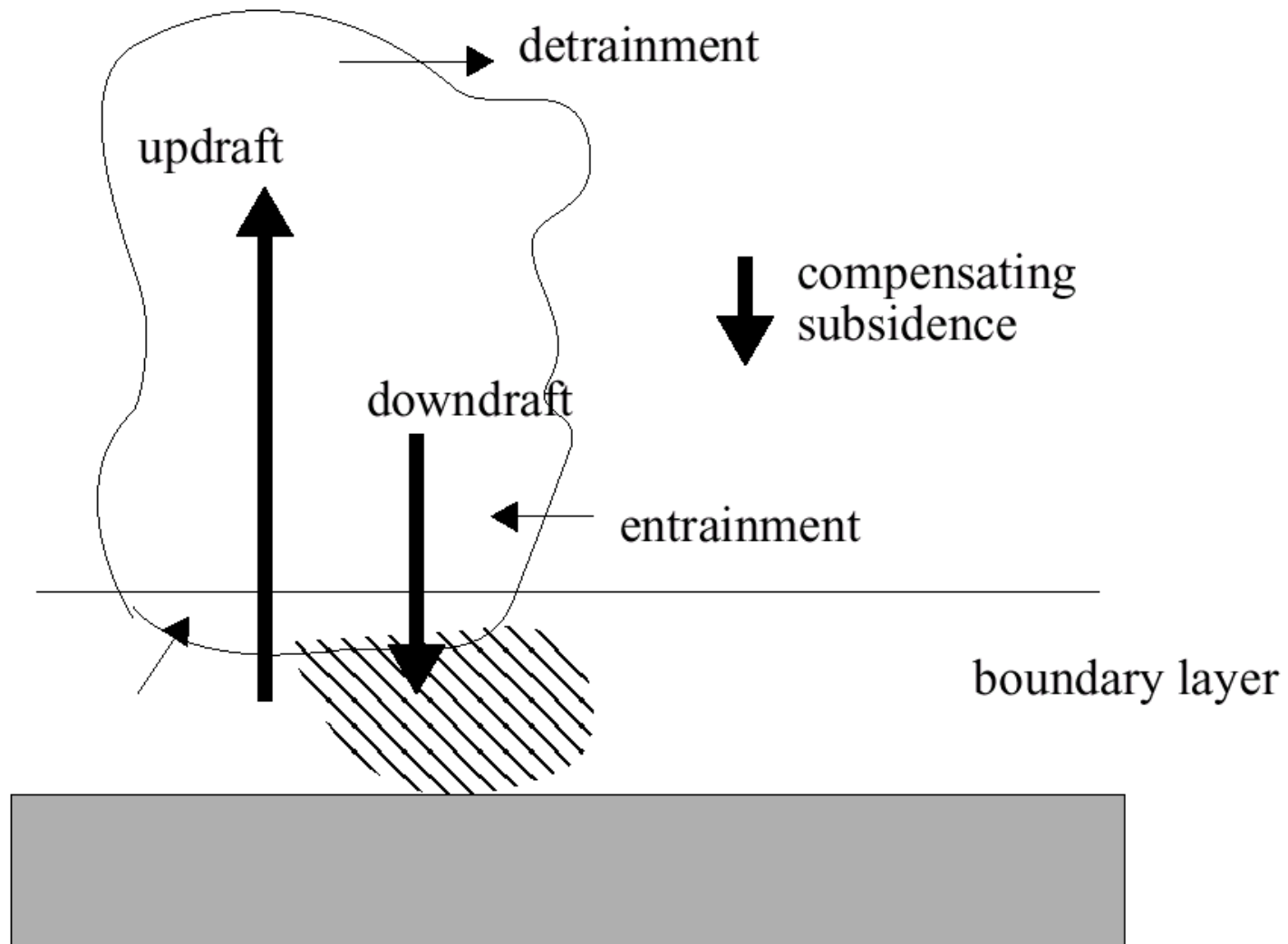
## For coarse grid spacing

- ✓ Cumulus parameterization schemes have been designed for  $\Delta \gg l$
- ✓ 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  $\Delta \ll l$
- ✓ Updrafts and downdrafts are resolved
- ✓ 3d turbulence schemes handle local sub-grid mixing

## Illustration of Cumulus Processes



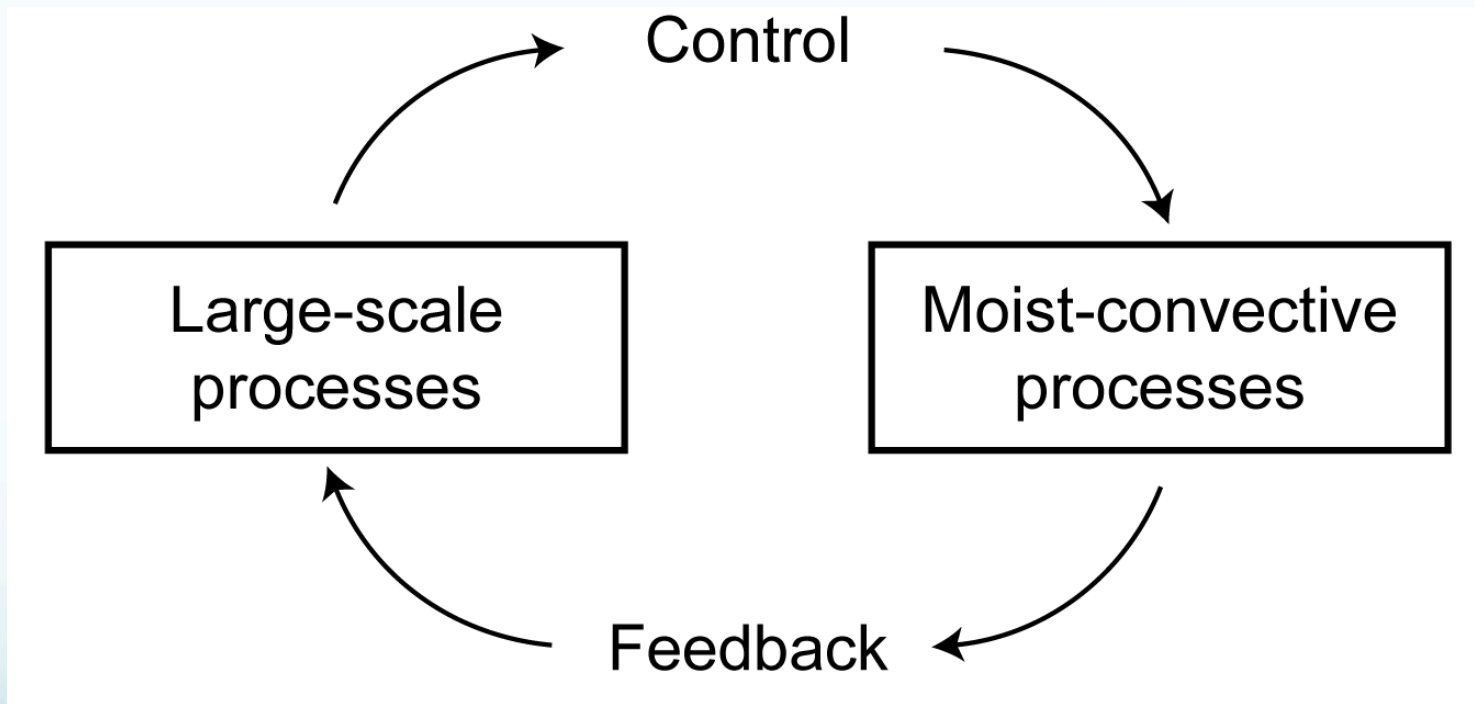
# Cumulus Schemes

- 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/<br>2011 |
| 5          | Grell-3                         | Grell and Devenyi (2002, GRL)                             | 2008          |
| 6,16       | Tiedtke                         | Tiedtke (1989, MWR), Zhang, Wang and Hamilton (2011, MWR) | 2011,<br>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, Tiedtke, ZM, BMJ)
    - Quasi-equilibrium (Arakawa-Schubert) with large-scale destabilization  $d(\text{CAPE})/dt$  (SAS, NSAS)
    - Column 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)
- 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)
- 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

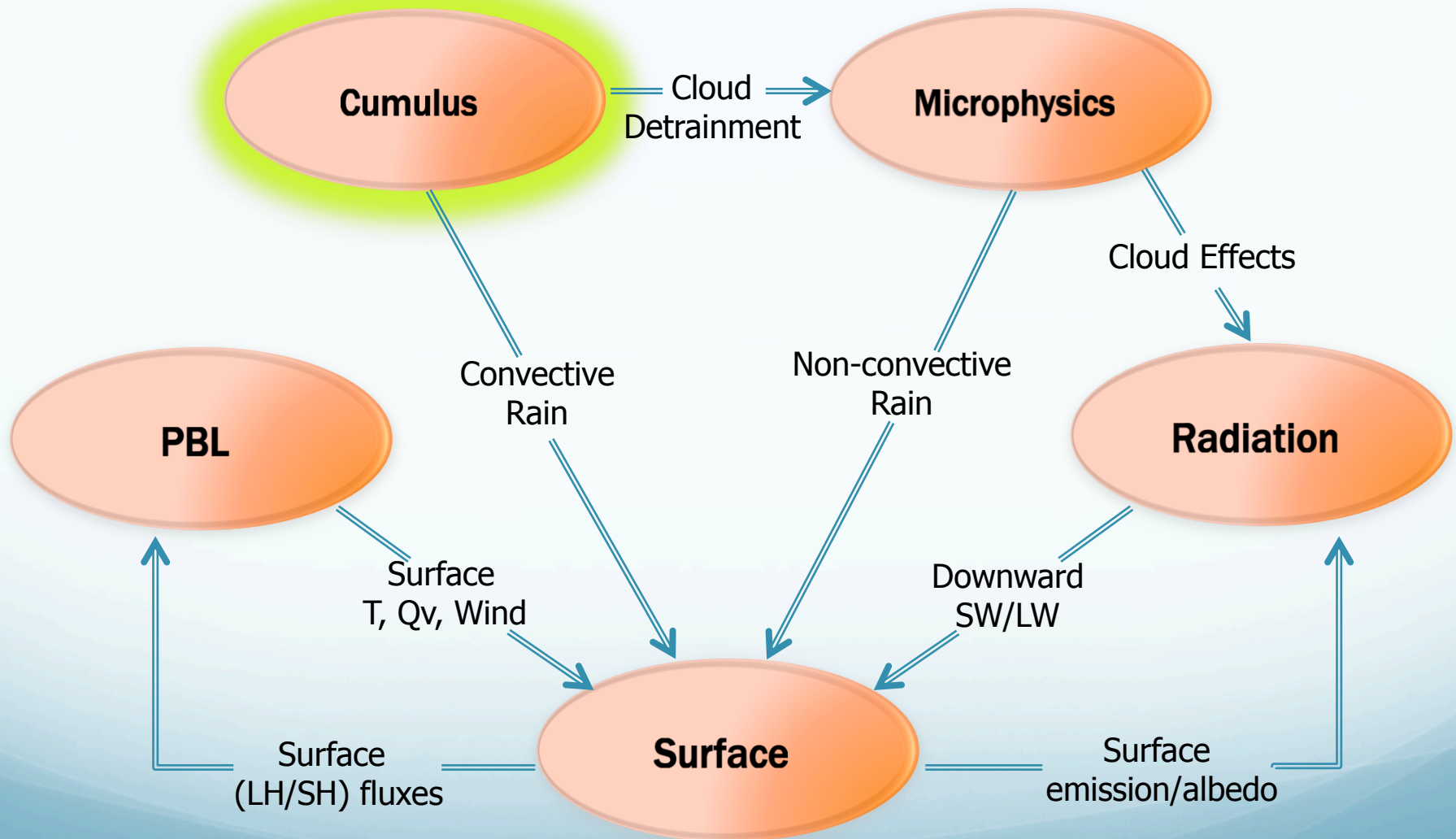
# Cumulus schemes

| 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         | New SAS                         | ARW     | Qc Qi               | yes                 | 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 yes=RRTMG       | GFDL                |

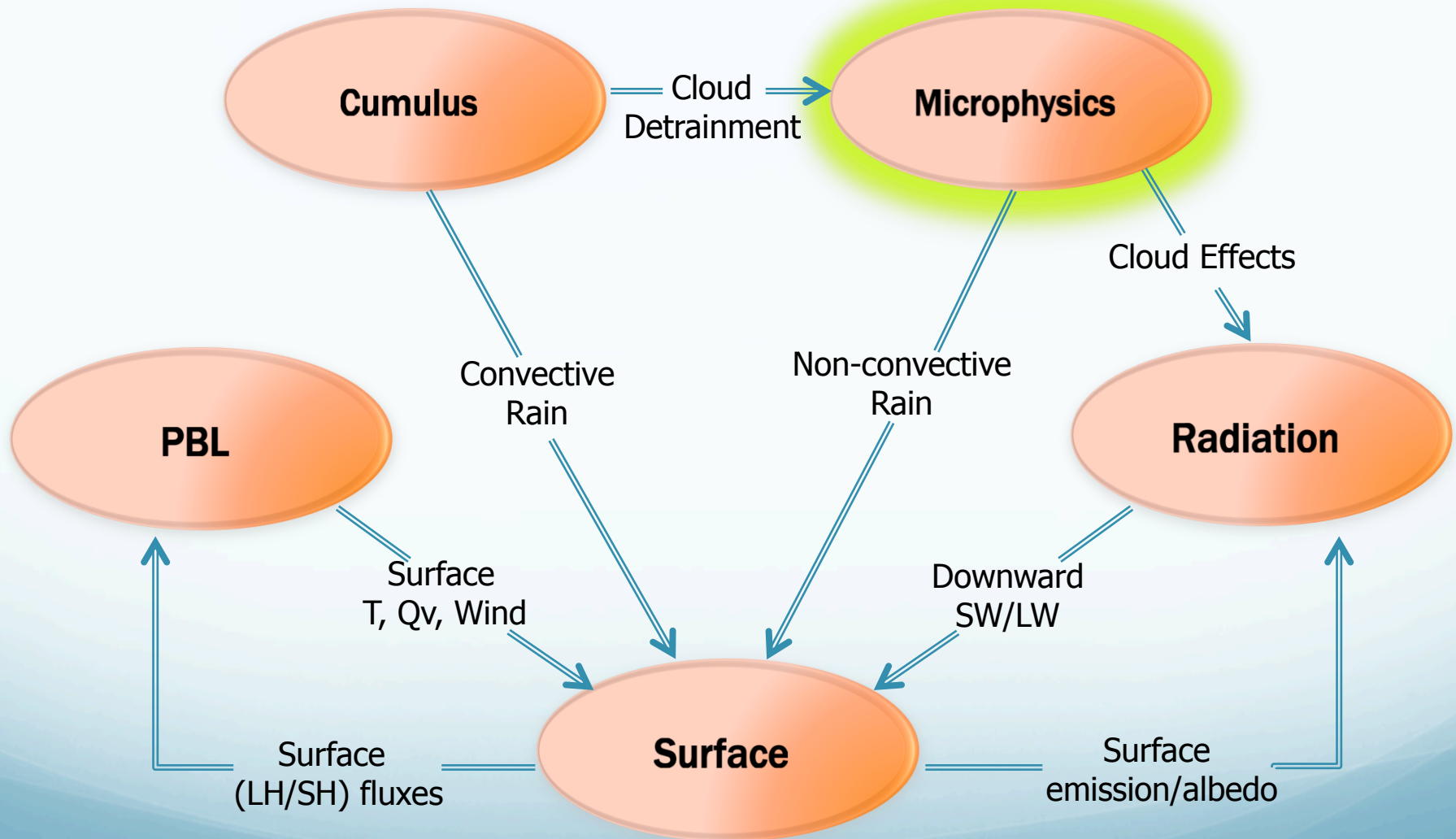
# Cumulus scheme: Recommendations

- $dx \geq 10$  km:
  - probably need cumulus scheme
  - These release instability gradually (prevent grid-point storms)
- $dx \leq 3$  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



# Direct Interactions of Parameterizations



# Microphysics

Provides

Atmospheric heat and moisture tendencies

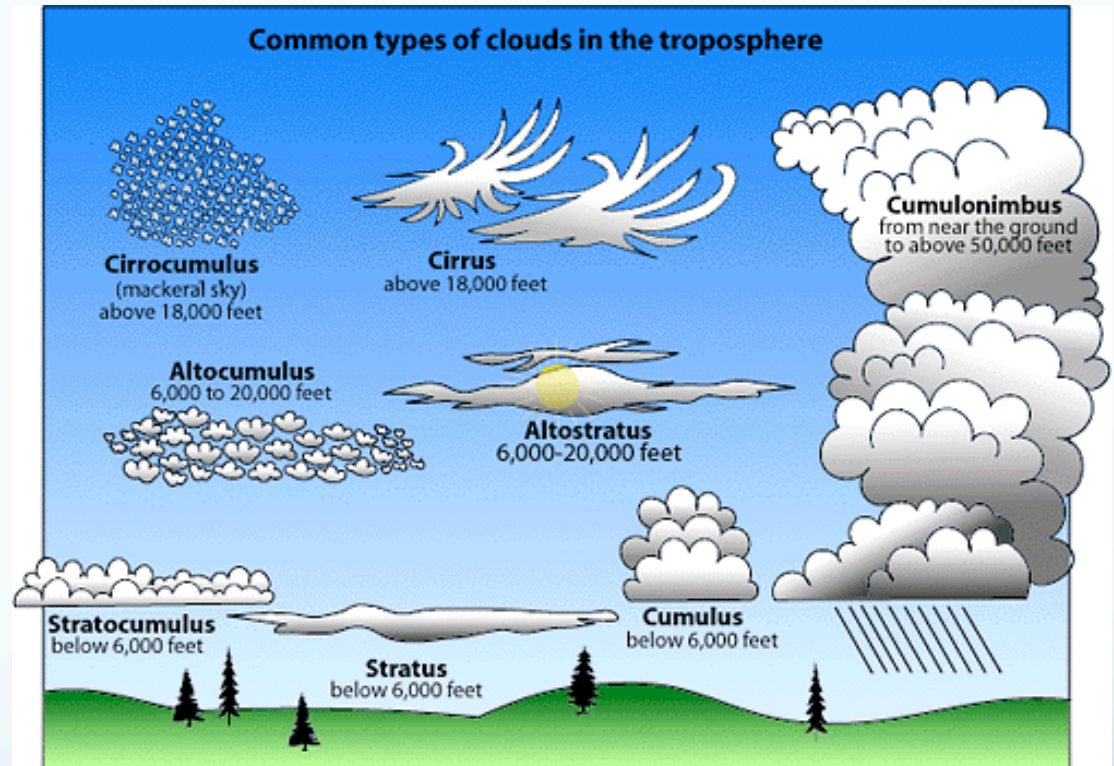
Microphysical rates

Surface resolved-scale rainfall



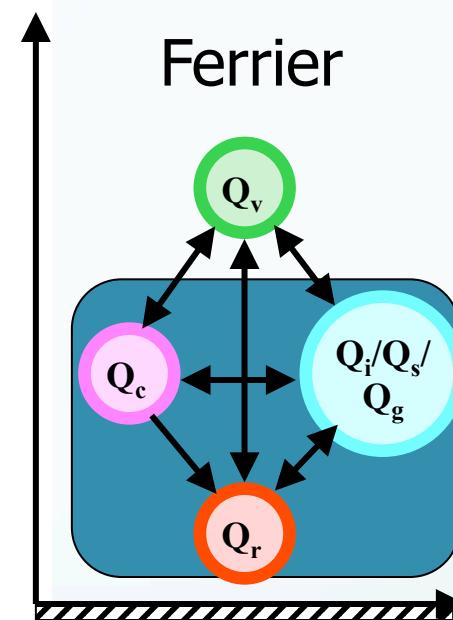
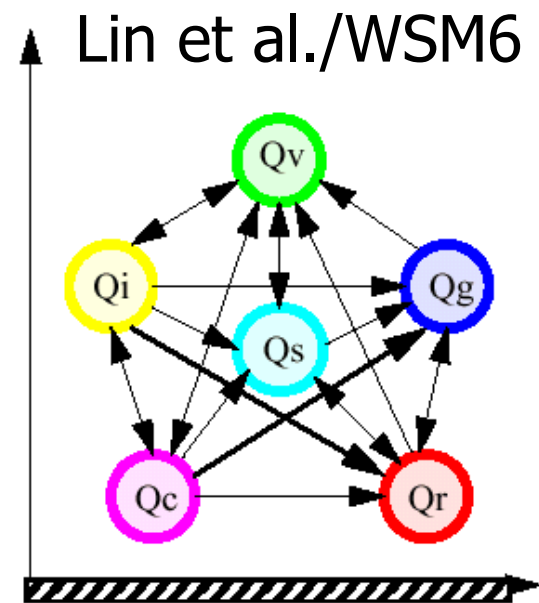
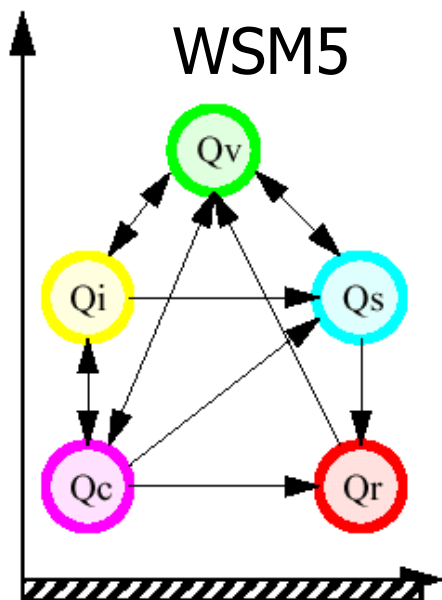
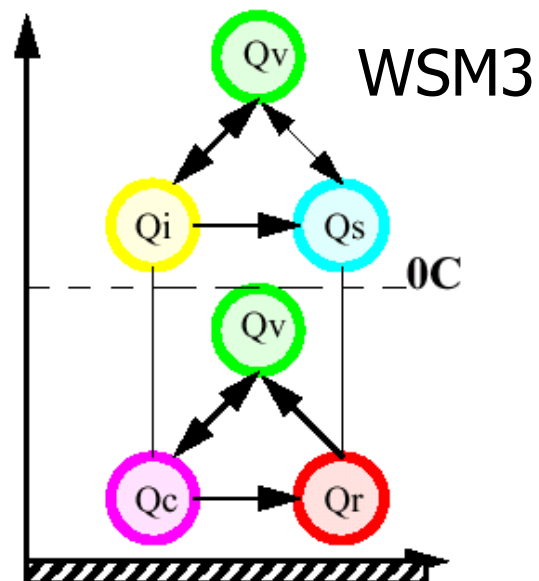
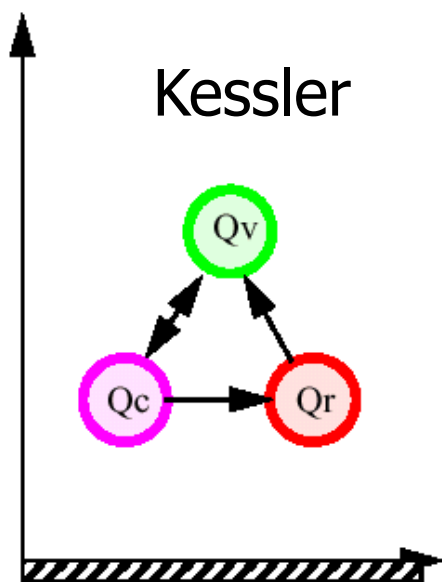
# Resolved clouds

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





## 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  |
| 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  |

# 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 ( $\text{kg/kg}$ ) per species ( $Q_r$ ,  $Q_s$ , etc.) with particle size distribution being derived from fixed parameters
- Double-moment (DM) schemes add a prediction equation for number concentration ( $\text{\#/kg}$ ) per DM species ( $N_r$ ,  $N_s$ , 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  $\Delta t \sim 60$  s,  $V_t = 5$  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



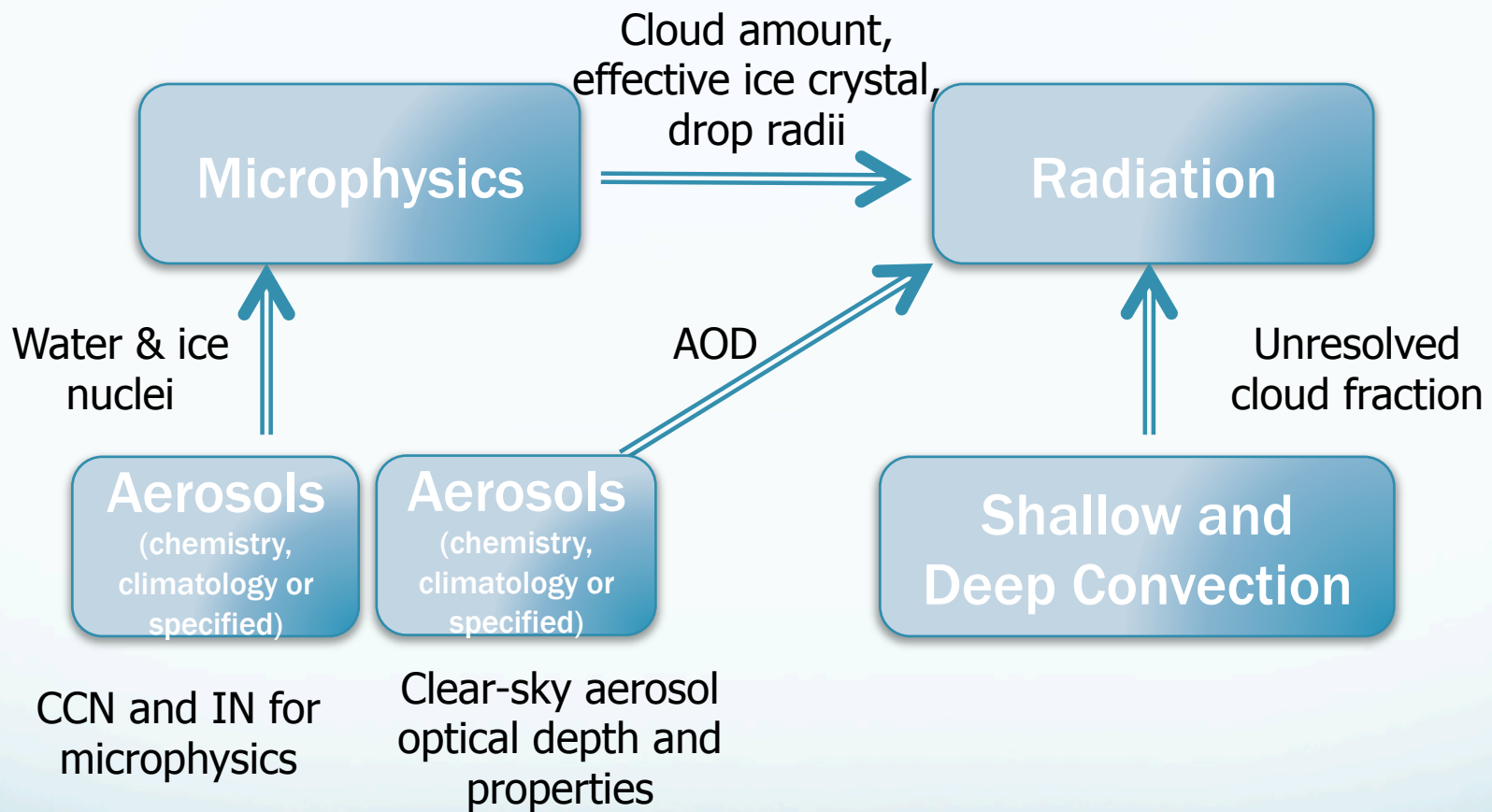
# Interaction with Aerosols

- 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

# 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         | 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          |
| 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             |
| 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 |

# Microphysics schemes

\* Advects only total condensate Nn= CCN number

| mp_physics | Scheme             | Cores | Mass Variables                                                     | Number Variables                 |
|------------|--------------------|-------|--------------------------------------------------------------------|----------------------------------|
| 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<br>VOLg        |
| 28         | Thompson aero      | ARW   | Qc Qr Qi Qs Qg                                                     | Nc Ni Nr Nn Nni                  |
| 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<br>Qs Qg Qh (outputs<br>aggregated from<br>bins) | Nn Nc Nr Nic Nip Nid<br>Ns Ng Nh |

# 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

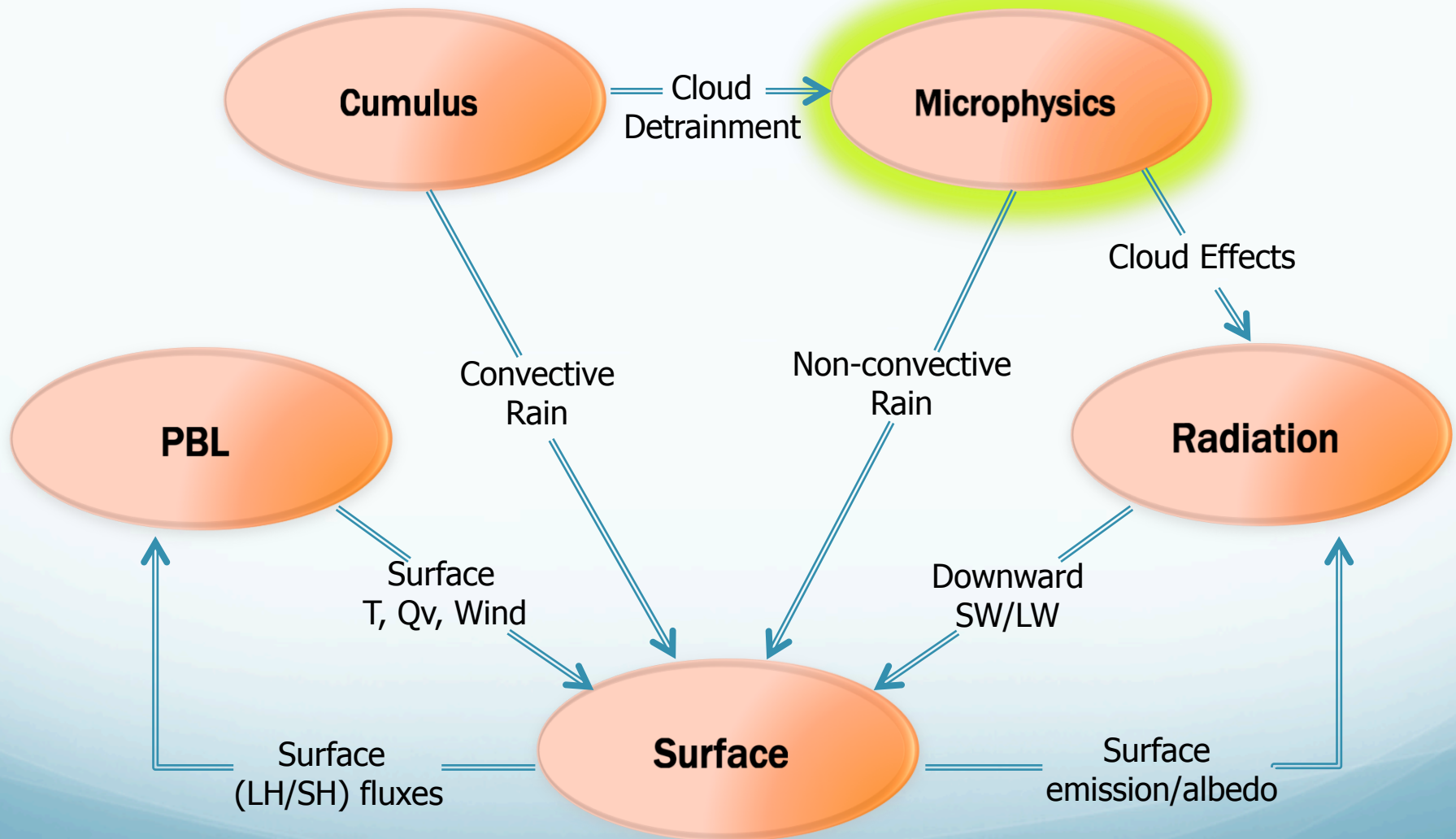
# Rainfall Output

- 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.)

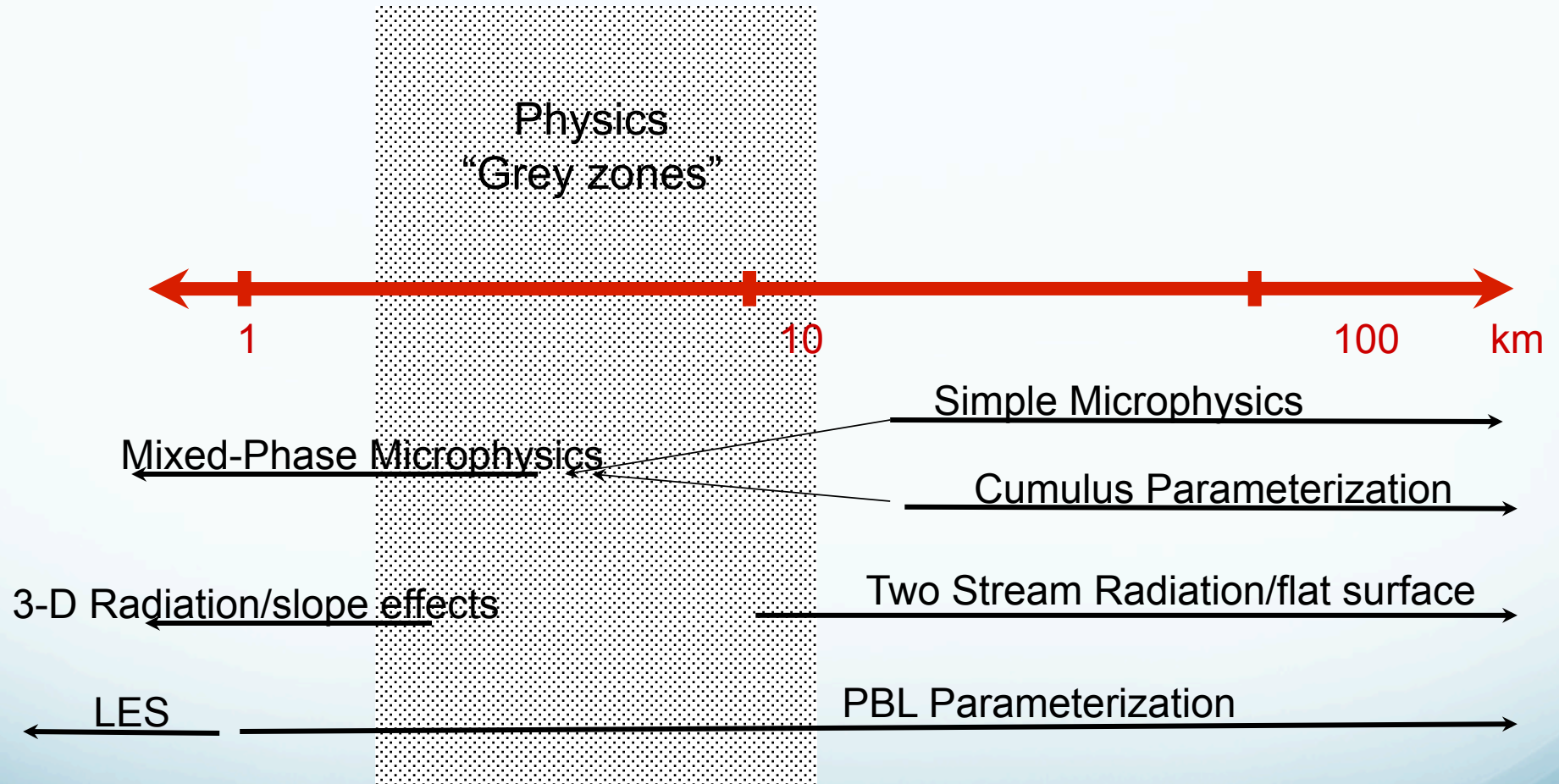
# Physics Interactions



# Direct Interactions of Parameterizations



# Physics in Multiscale NWP Model



# Solver Calling Sequence (ARW example)

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

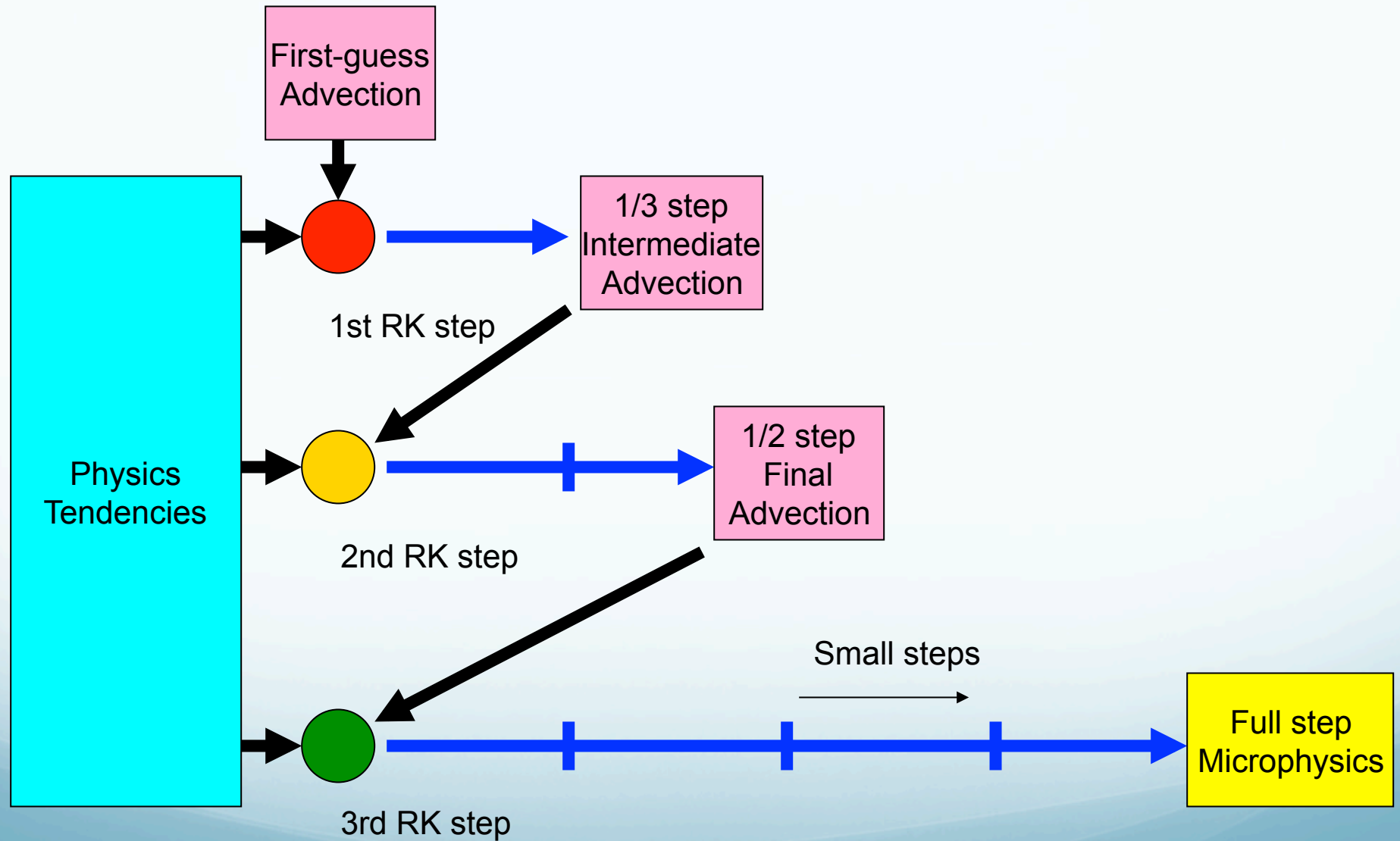
- **Physics tendencies**
  - Radiation, surface, land-state update, PBL, cumulus, grid-fdda, obs-fdda
- **Dynamics tendencies**
  - Diffusion, advection, dynamics terms (for 3d momentum, theta, geopotential, surface pressure)
- **Acoustic steps**
  - Update 3d momentum, theta, surface pressure, height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

# ARW Solver Sequence

|  |          |
|--|----------|
|  | tendency |
|  | update   |
|  | adjust   |

|          | $\mu$ | $\phi$ | w | u | v | $\theta$ | q | Water ice | Scalar Chem | Soil T<br>Soil Q |
|----------|-------|--------|---|---|---|----------|---|-----------|-------------|------------------|
| Rad      |       |        |   |   |   |          |   |           |             |                  |
| Sfc      |       |        |   |   |   |          |   |           |             |                  |
| PBL      |       |        |   |   |   |          |   |           |             |                  |
| Cnv      |       |        |   |   |   |          |   |           |             |                  |
| Adv Diff |       |        |   |   |   |          |   |           |             |                  |
| Dyn      |       |        |   |   |   |          |   |           |             |                  |
| Adv Diff |       |        |   |   |   |          |   |           |             |                  |
| Mic      |       |        |   |   |   |          |   |           |             |                  |

# 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,...

**End**