



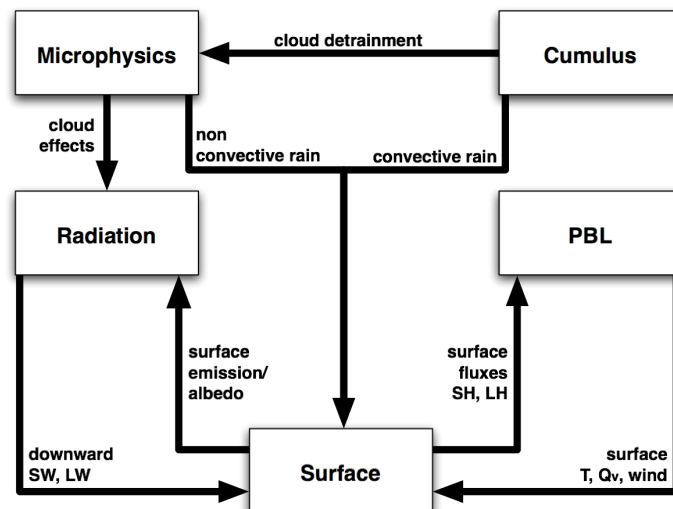
## Overview of WRF Physics

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## WRF Physics

- Radiation
  - Longwave (ra\_lw\_physics)
  - Shortwave (ra\_sw\_physics)
- Surface
  - Surface layer (sf\_sfclay\_physics)
  - Land/water surface (sf\_surface\_physics)
- PBL (bl\_pbl\_physics)
- Turbulence/Diffusion (diff\_opt, km\_opt)
- Cumulus parameterization (cu\_physics)
- Microphysics (mp\_physics)

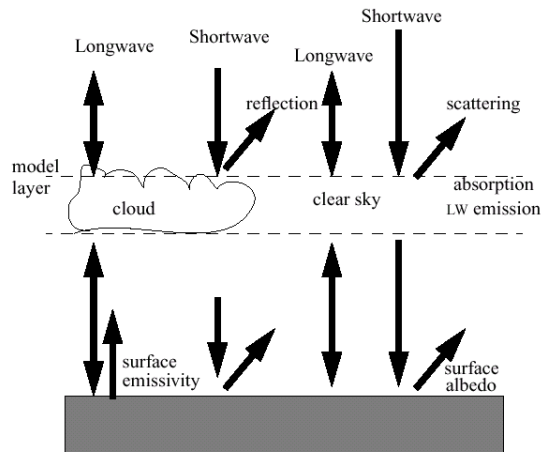
### Direct Interactions of Parameterizations



## Radiation

Provides  
Atmospheric temperature tendency  
profile  
Surface radiative fluxes

Illustration of Free Atmosphere Radiation Processes



## WRF Longwave Radiation Schemes (ra\_lw\_physics)

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

## Longwave Radiation schemes

ra_lw_physics	Scheme	Reference	Added
1	RRTM	Mlawer et al. (1997, JGR)	2000
3	CAM	Collins et al. (2004, NCAR Tech. Note)	2006
4	RRTMG	Iacono et al. (2008, JGR)	2009
5	New Goddard	Chou and Suarez (2001, NASA Tech Memo)	2011
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

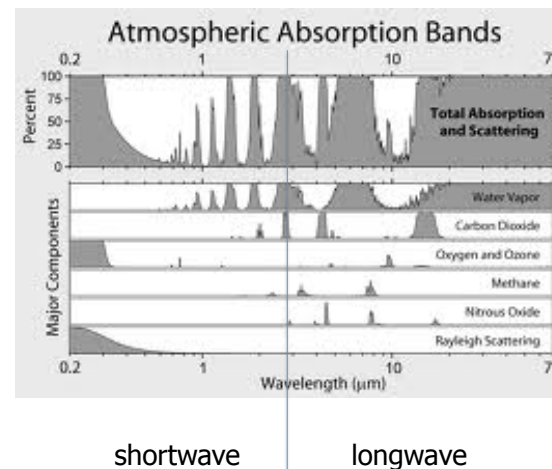
## Longwave Radiation schemes

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> (new in V3.5)
- O<sub>3</sub> – schemes have own climatologies
  - CAM has monthly, zonal, pressure-level data and RRTMG has this as an option (V3.5)
  - 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
  - Only Thompson passes its own particle sizes to RRTMG radiation (since 3.5.1): 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)
- WRF schemes use max-random overlap

## WRF Shortwave Radiation Options (ra\_sw\_physics)

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

## Shortwave Radiation schemes

ra_sw_physics	Scheme	Reference	Added
1	Dudhia	Dudhia (1989, JAS)	2000
2	Goddard	Chou and Suarez (1994, NASA Tech Memo)	2000
3	CAM	Collins et 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 (CO2 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

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

## Clouds and Cloud Fraction

- Similar considerations to longwave
- Interacts with model resolved clouds 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

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

## radt

ARW only

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

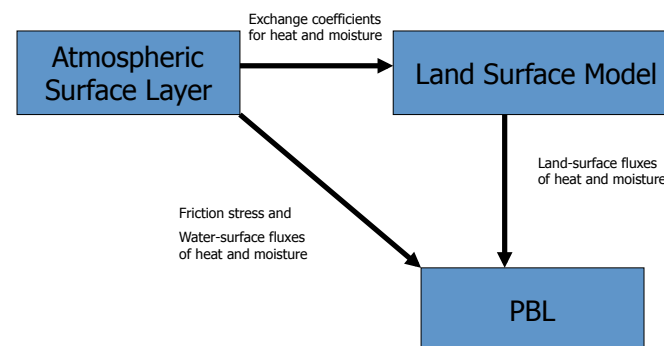
- swint\_opt=1
  - provides a smooth surface downward flux over time (interpolates between radiation steps using cosine zenith angle and clearness index)
  - This also allows smoother variation of ground variables and fluxes (eliminates steps in time series)
- Diffuse, direct, and direct normal shortwave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

## 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)  
 $\Delta$  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

ARW only

- 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)

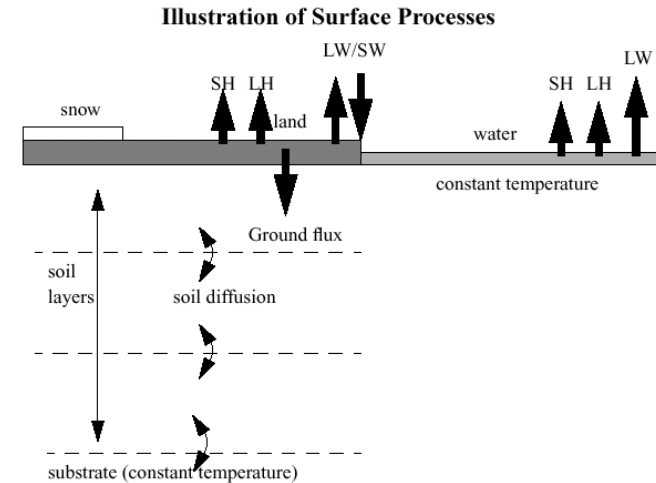
## Fractional Sea Ice

- 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

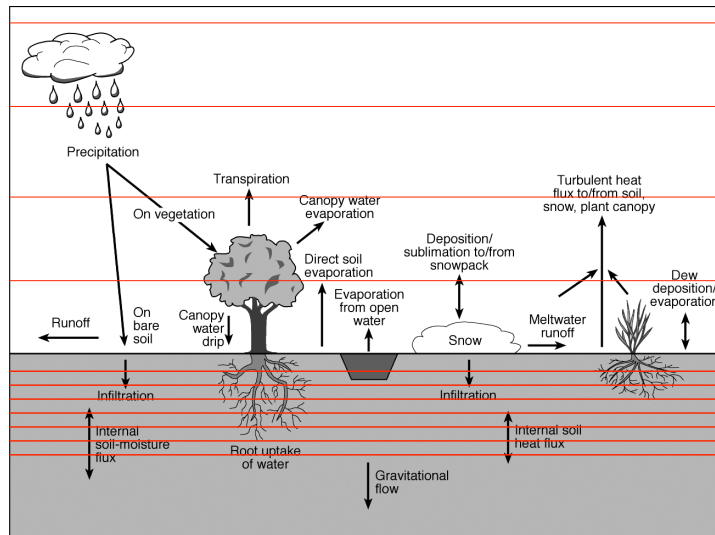


## WRF Land-Surface Model Options (sf\_surface\_physics)

- 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



## 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 (new in V3.4)
- SSiB (new in V3.4)
- CLM4 (new in V3.5)

## 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)
- 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

ARW only

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 since Version 3.0
- Vegetation fraction update is included
  - Allows seasonal change in albedo, emissivity, roughness length in Noah LSM
- usemonalb=.true. to use monthly albedo input

## Regional Climate Options

- tmn\_update=1 - updates deep-soil temperature for multi-year future-climate runs
- sst\_skin=1 - adds diurnal cycle to sea-surface temperature
- bucket\_mm and bucket\_J - a more accurate way to accumulate water and energy for long-run budgets (see later)
- output\_diagnostics=1 (added in 3.3.1) – ability to output max/min/mean/std of surface fields in a specified period

## Lake Model

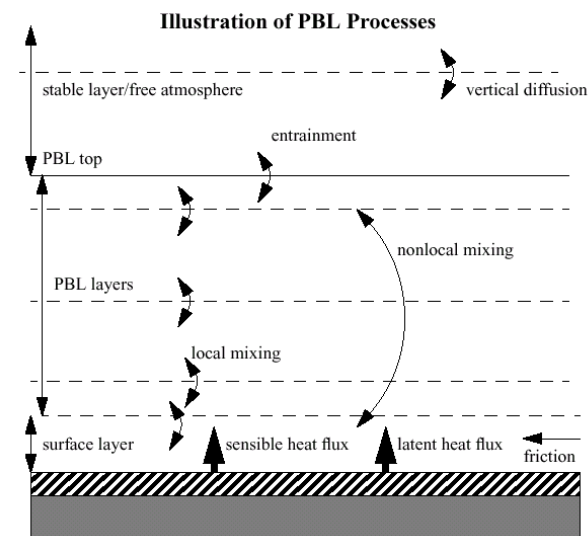
- Added in V3.6 (from CLM climate physics)
- 10-layer lake model (sf\_lake\_physics=1)
- We have global bathymetry data for most large lakes (added from geogrid)
- Also can predict lake ice
- Can be used with any LSM
- Preprocessing allows diurnal averaging methods to initialize lake temperatures where not resolved by SST analysis

## WRF-Hydro

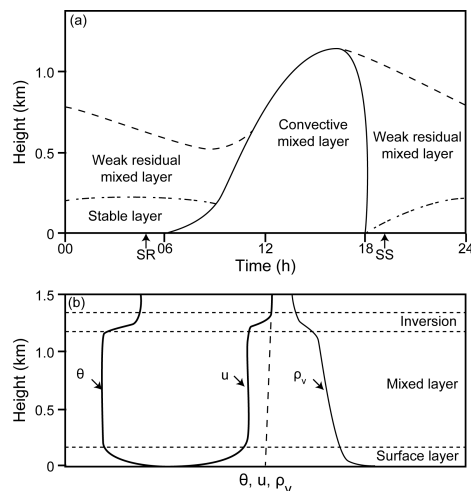
- New in V3.5
- Coupling to hydrological model available
- Streamflow prediction, etc.
- Sub-grid tiling to ~100 m grid

## Planetary Boundary Layer

Provides  
Boundary layer fluxes (heat, moisture,  
momentum)  
Vertical diffusion in whole column



## Planetary Boundary Layer



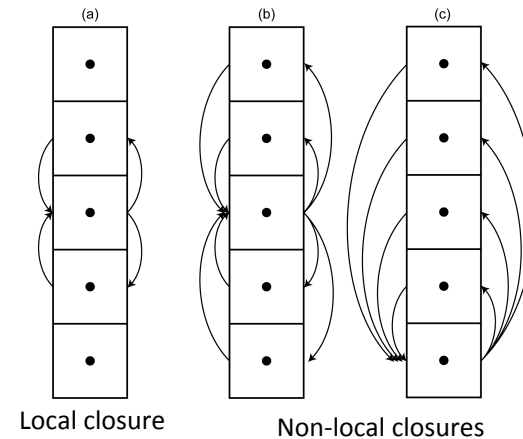
## WRF PBL Options (bl\_pbl\_physics)

- 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

## Different approaches



## 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
- 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 `Kv` for scalars that is used by WRF-Chem
- WRF can now (V3.6) 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

## 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

## PBL schemes

bl_pbl_physics	Scheme	Cores	sf_sfclay_physics	Prognostic variables	Diagnostic variables	Cloud mixing
1	YSU	ARW NMM	1,91		<code>exch_h</code>	QC,QI
2	MYJ	ARW NMM	2	TKE_PBL	<code>EL_PBL</code> , <code>exch_h</code>	QC,QI
3	GFS(hwrf)	NMM	3			QC,QI
4	QNSE-EDMF	ARW NMM	4	TKE_PBL	<code>EL_PBL</code> , <code>exch_h</code> , <code>exch_m</code>	QC,QI
5	MYNN2	ARW	1,2,5,91	QKE	<code>Tsq</code> , <code>Qsq</code> , <code>Cov</code> , <code>exch_h</code> , <code>exch_m</code>	QC
6	MYNN3	ARW	1,2,5,91	QKE, <code>Tsq</code> , <code>Qsq</code> , <code>Cov</code>	<code>exch_h</code> , <code>exch_m</code>	QC
7	ACM2	ARW	1,7,91			QC,QI
8	BouLac	ARW	1,2,91	TKE_PBL	<code>EL_PBL</code> , <code>exch_h</code> , <code>exch_m</code>	QC
9	UW	ARW	1,2,91	TKE_PBL	<code>exch_h</code> , <code>exch_m</code>	QC
10	TEMF	ARW	10	TE_TEMF	<code>*_temf</code>	QC, QI
11	SH	ARW	1,91		<code>Exch_h</code>	QC, QI
12	GBM	ARW	1,91	TKE_PBL	<code>EL_PBL</code> , <code>exch_h</code> , <code>exch_m</code>	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 in Version 3 (coupled to surface physics)
  - Works best when  $dx$  and  $dz$  are comparable

## Large-Eddy Simulation

- For grid sizes of up to about 100 m, LES is preferable
- LES treats turbulence three-dimensionally instead of separate vertical (PBL) and horizontal diffusion schemes
- TKE and 3d Smagorinsky options exist for the sub-grid turbulence

## Large-Eddy Simulation

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

## LES schemes

Unified horizontal and vertical mixing (for  $dx \sim dz$ ).

Typically needed for  $dx \ll 200$  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 <code>tke_heat_flux</code>	From namelist <code>tke_drag_coefficient</code>	Ideal
1	1,2	From LSM/sfclay physics (HFX, QFX)	From sfclay physics (UST)	Real
2	1,2	From namelist <code>tke_heat_flux</code>	From sfclay physics (UST)	Ideal



## Other Options

- For YSU
  - Gravity-wave drag can be added for low resolution (> 10 km) runs to represent sub-grid orographic gravity-wave vertical momentum transport (gwd\_opt=1)
  - 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)
  - Fog: grav\_settling=2 (Katata)

## Turbulence/Diffusion

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

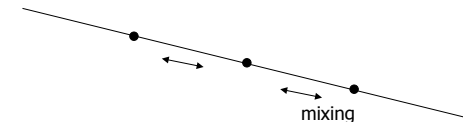
$$\frac{\partial}{\partial x} K_h \frac{\partial}{\partial x} \theta + \frac{\partial}{\partial y} K_h \frac{\partial}{\partial y} \theta + \frac{\partial}{\partial z} K_v \frac{\partial}{\partial z} \theta$$

## bldt

ARW only

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

## Difference between diff\_opt 1 and 2

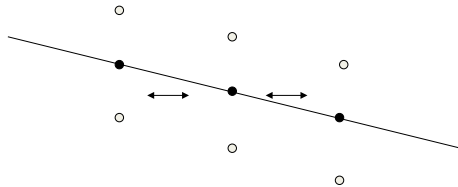


diff\_opt=1

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

ARW only

- 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

ARW only

- 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)
- 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

ARW only

- 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)

ARW only

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

Options

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

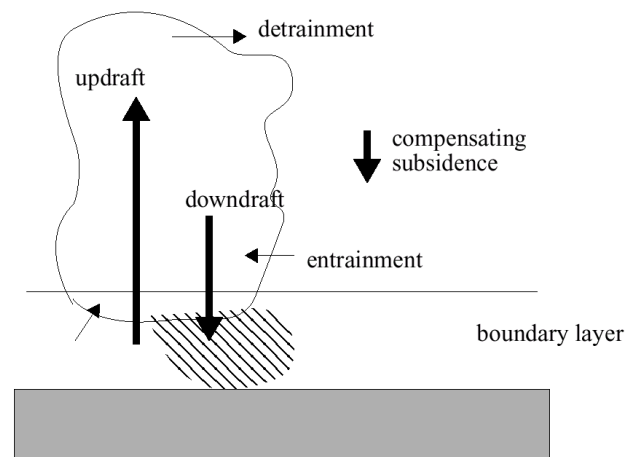
All options use

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

## Cumulus Parameterization

Provides  
Atmospheric heat and moisture/cloud  
tendency profiles  
Surface sub-grid-scale (convective) rainfall

Illustration of Cumulus Processes



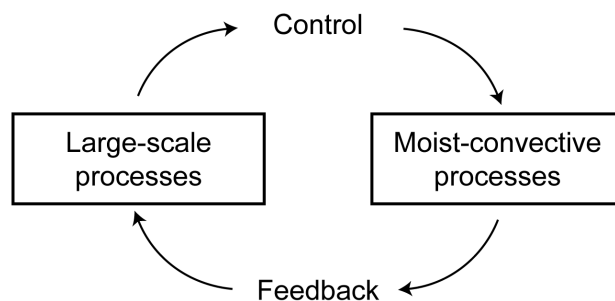
## Cumulus Schemes

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

## Deep Convection

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

## 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, MMS 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, 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 (mostly an NMM option) there is a Slingo method of cloud fraction from many schemes using precip rate, top and bottom, to compute a cloud fraction

## cudt

ARW only

- 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 about use

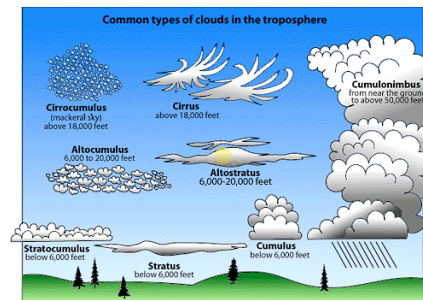
- For  $dx \geq 10$  km: probably need cumulus scheme
  - These release instability gradually (prevent grid-point storms)
- For  $dx \leq 3$  km: probably do not need scheme (resolved/ permitted by dynamics)
  - However, there are cases where the earlier triggering of convection by cumulus schemes help
- For  $dx=3-10$  km, scale separation is a question
  - Few schemes are specifically designed with this range of scales in mind
  - G3 has an option to spread subsidence in neighboring columns
  - GF 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

# Microphysics

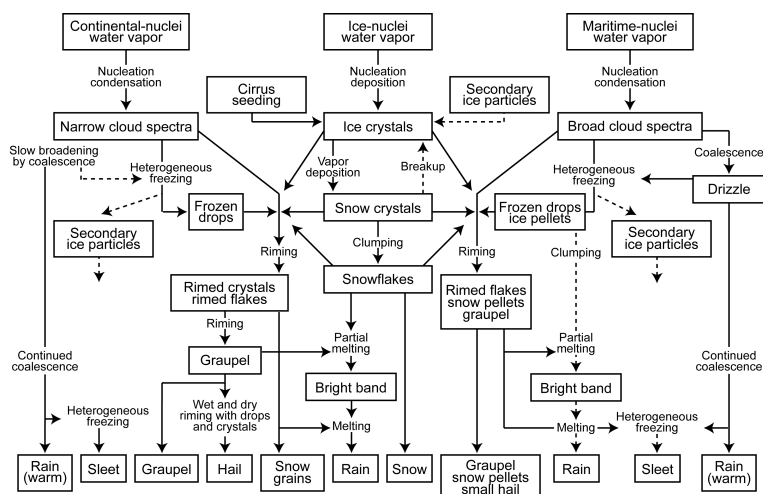
Provides  
Atmospheric heat and moisture tendencies  
Microphysical rates  
Surface resolved-scale rainfall

## Resolved clouds

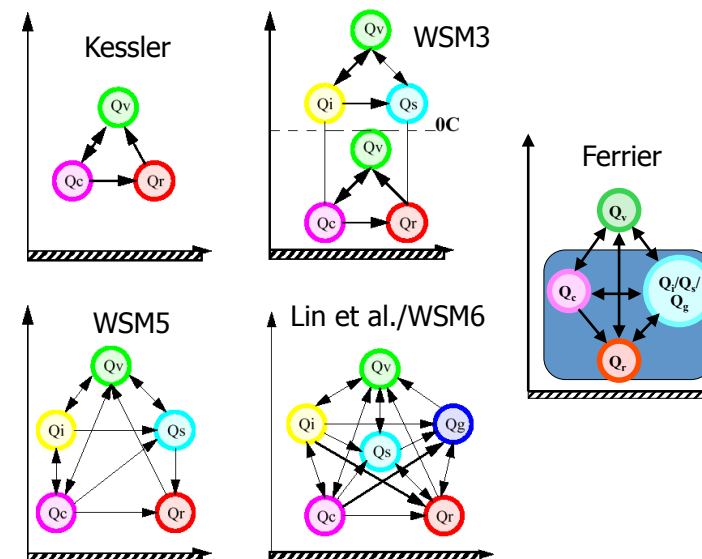
- Formed by radiative, dynamical or convective processes
- Model only considers grid-scale average so will not resolve fine-scale structures



## Microphysics Parameterization



## Illustration of Microphysics Processes





## WRF Microphysics Options (mp\_physics)

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

- New in V3.6 (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 or 8x32 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  $dt \sim 60$  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

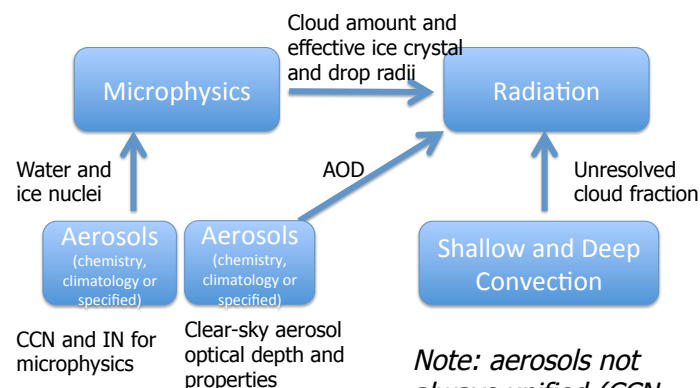
## Interaction with Aerosols

- 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 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 Qs Qg Qh (outputs aggregated from bins)	Nn Nc Nr Nic Nip Nid Ns Ng Nh

## Microphysics Options

Recommendations about choice

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

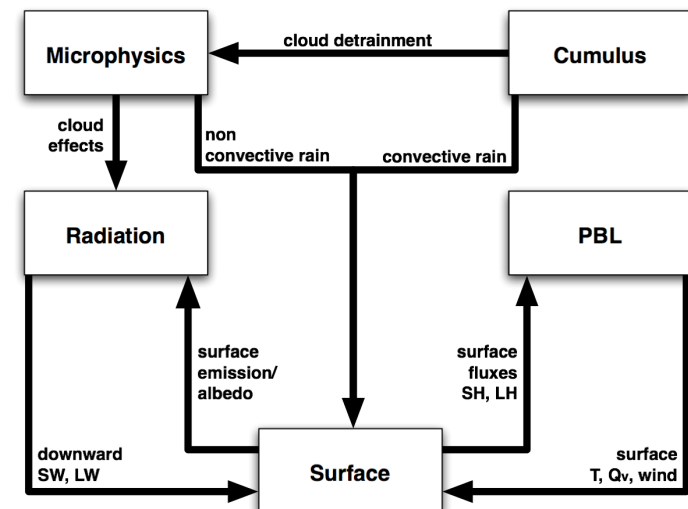
## Rainfall Output

ARW only

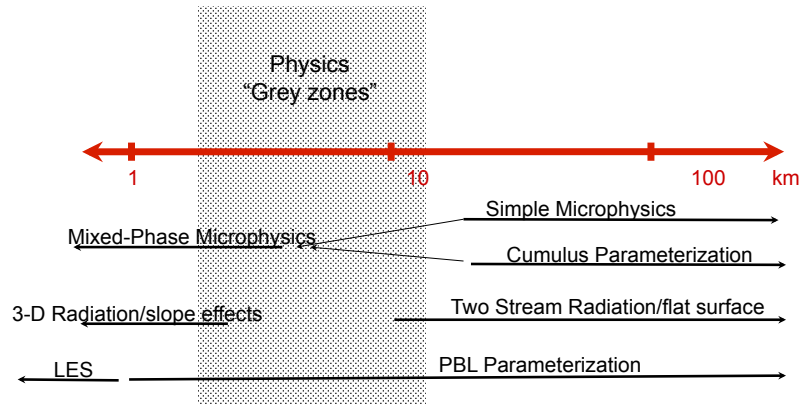
- Cumulus and microphysics can be run at the same time
- ARW outputs rainfall accumulations since simulation start time (0 hr) in mm
- RAINC comes from cumulus scheme
- RAINNC comes from microphysics scheme
- Total is RAINC+RAINNC
  - RAINNCV is time-step value
  - SNOWNC/SNOWNCV are snow sub-set of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

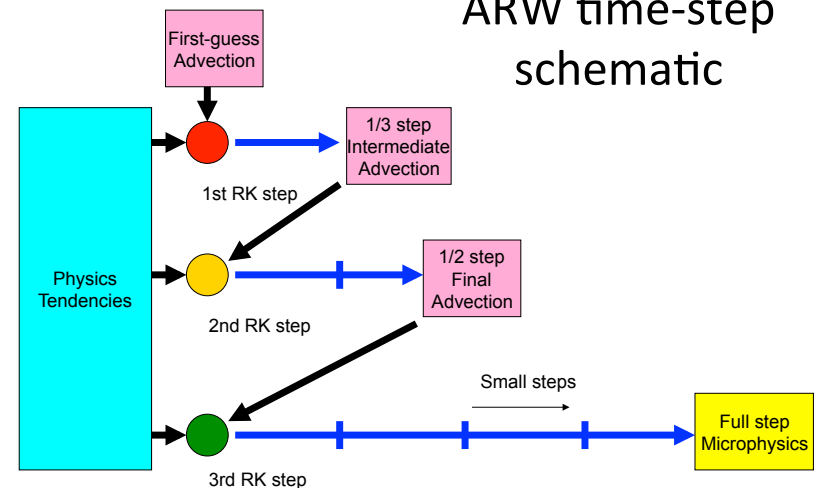
- Physics tendencies
  - Radiation, surface, land-state update, PBL, cumulus, grid-fdda, obs-fdda
- Dynamics tendencies
  - Diffusion, advection, dynamics terms (for 3d momentum, theta, geopotential, surface pressure)
- Acoustic steps
  - Update 3d momentum, theta, surface pressure, height
- Scalar dynamics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

## ARW Solver Sequence

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

tendency
update
adjust

## ARW time-step schematic



## &physics

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