Overview of WRF Physics

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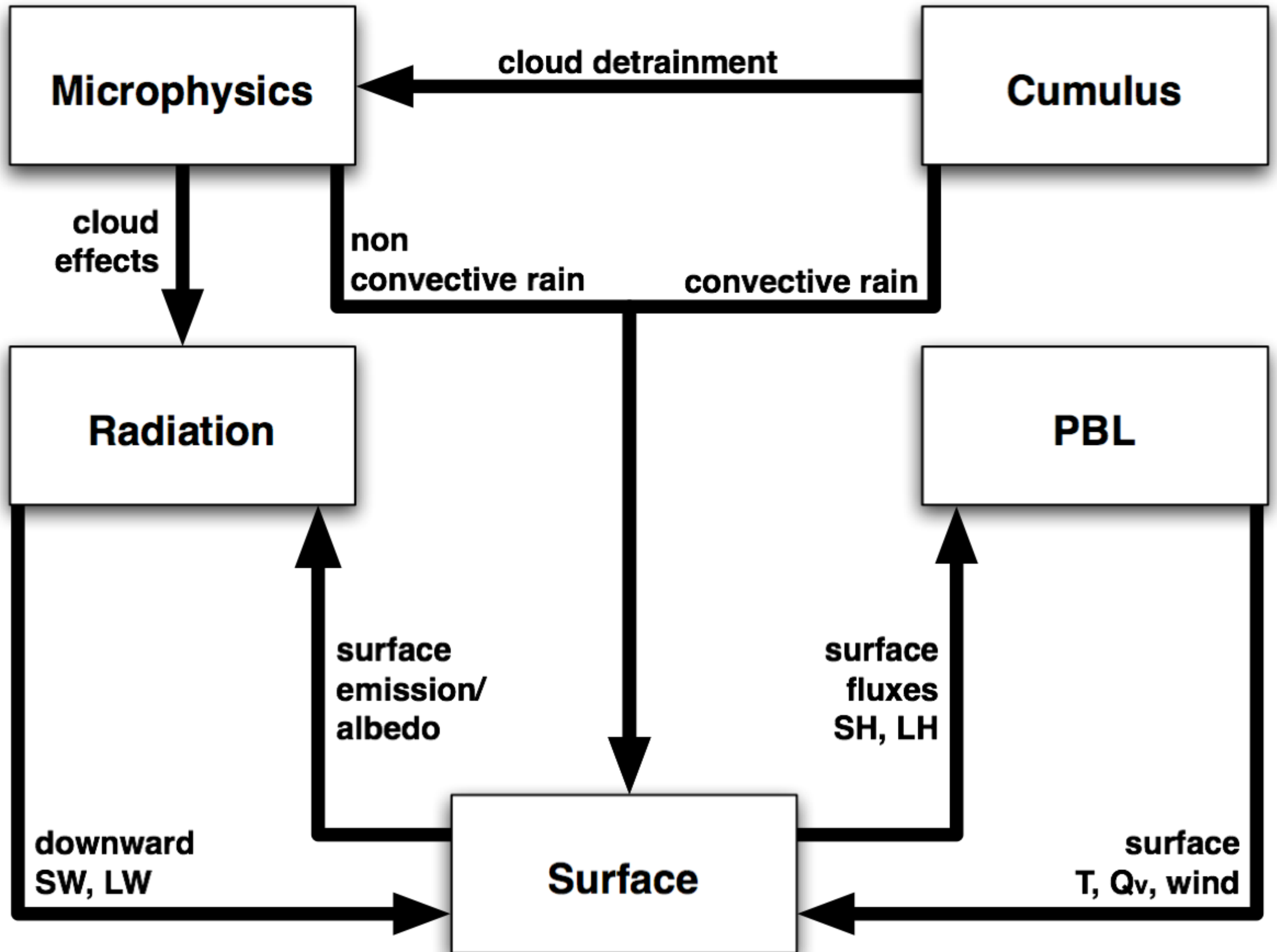
WRF Physics

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

Direct Interactions of Parameterizations



Radiation

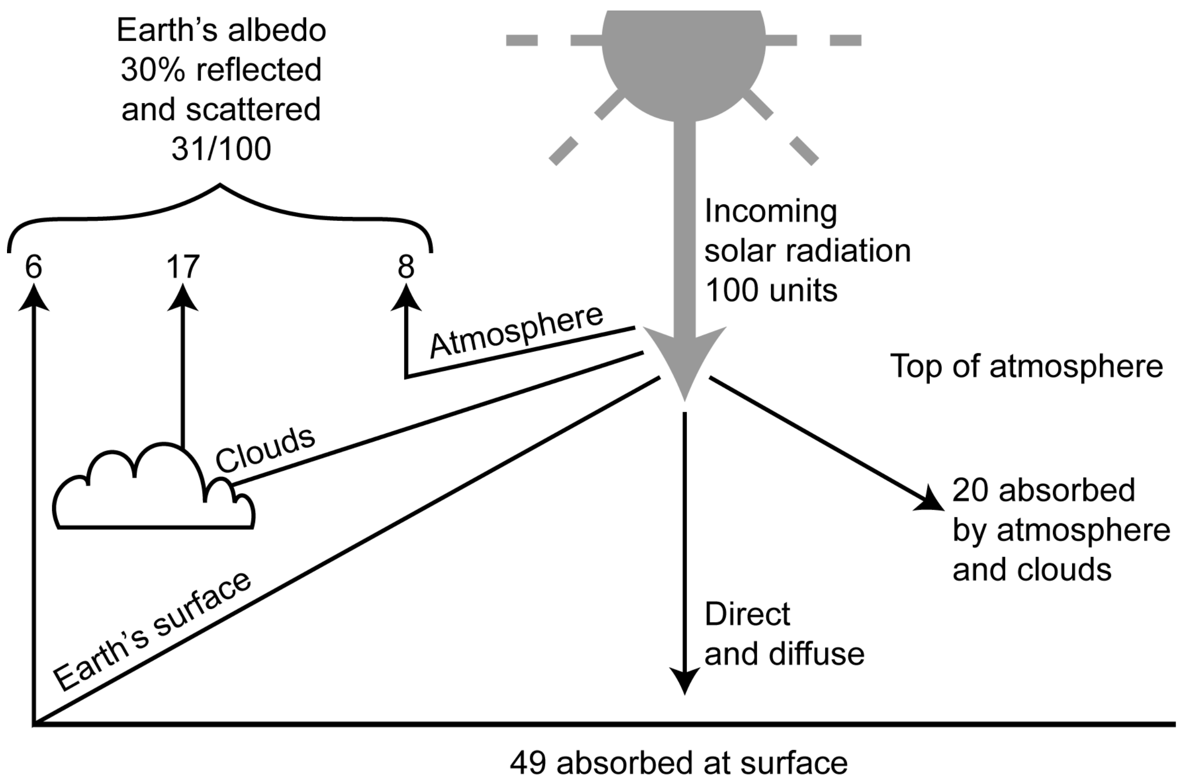
Provides

Atmospheric temperature tendency profile

Surface radiative fluxes

Radiation parameterizations

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



Radiation as part of the entire model energy budget

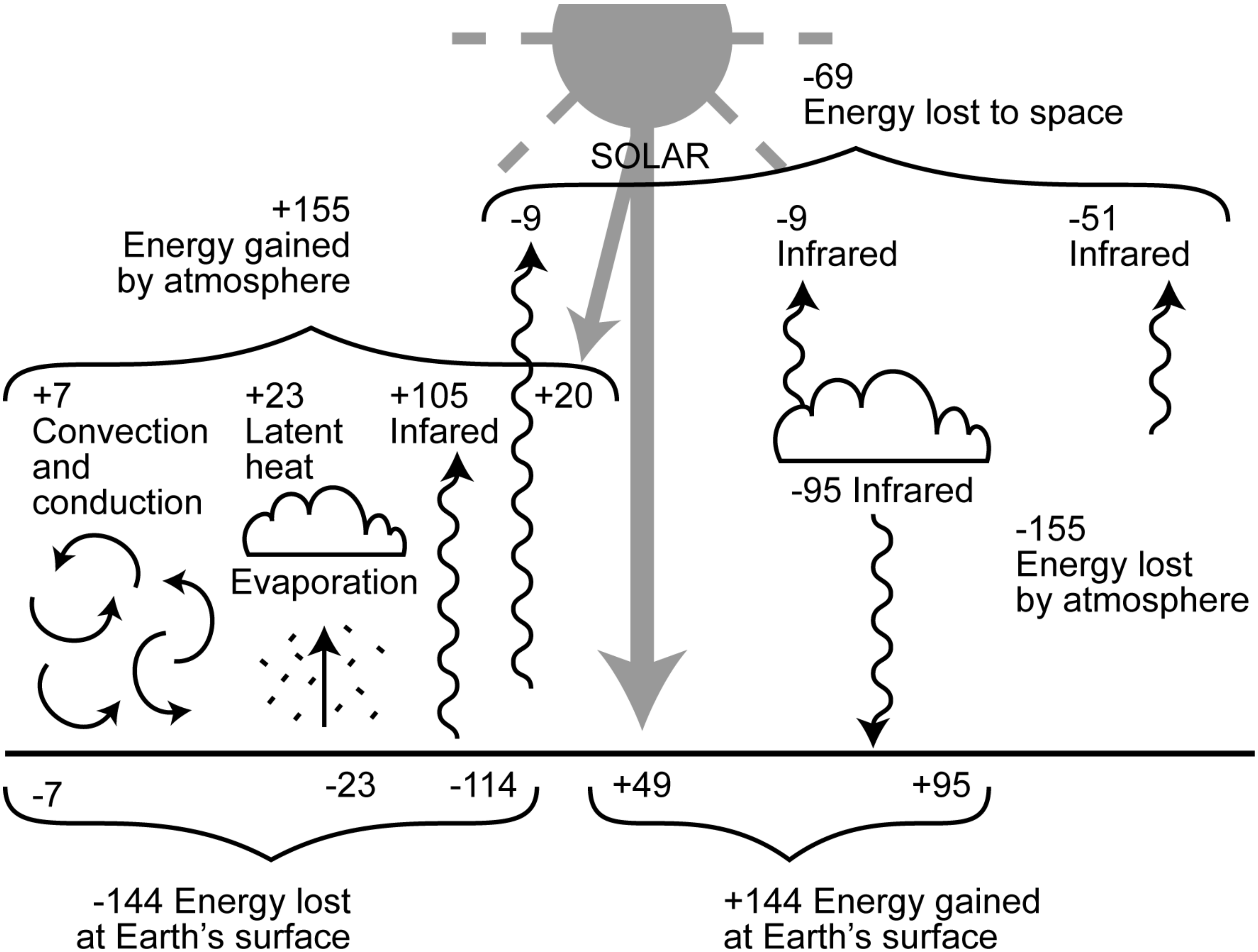
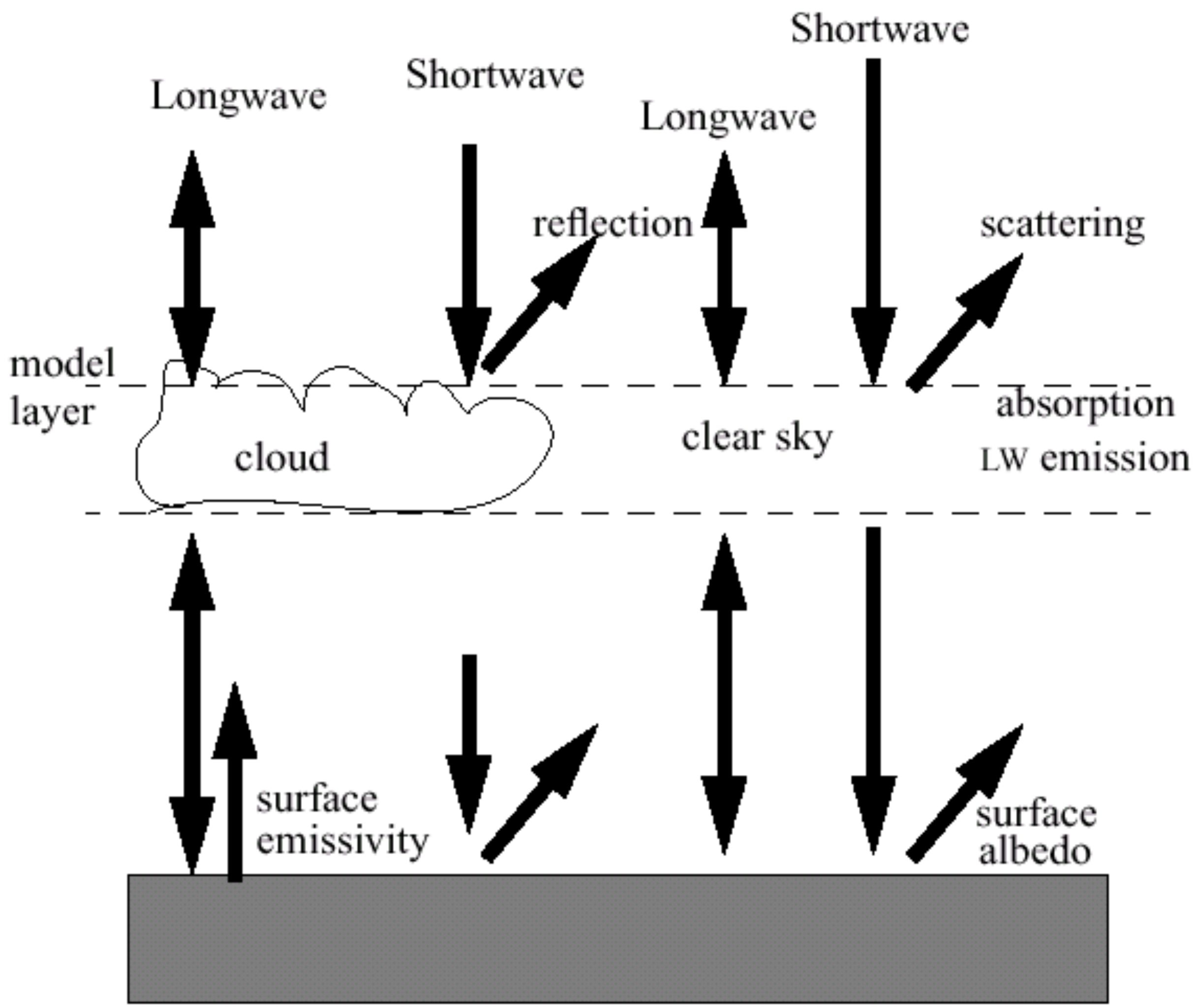


Illustration of Free Atmosphere Radiation Processes



WRF Longwave Radiation Schemes (ra_lw_physics)

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

Longwave Options

- RRTM
- CAM
- RRTMG
- Goddard
- Held-Suarez (idealized)
- GFDL

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		2000
99	GFDL	Fels and Schwarzkopf (1981, JGR)	2004

Longwave Radiation in V3.4

3.4 new

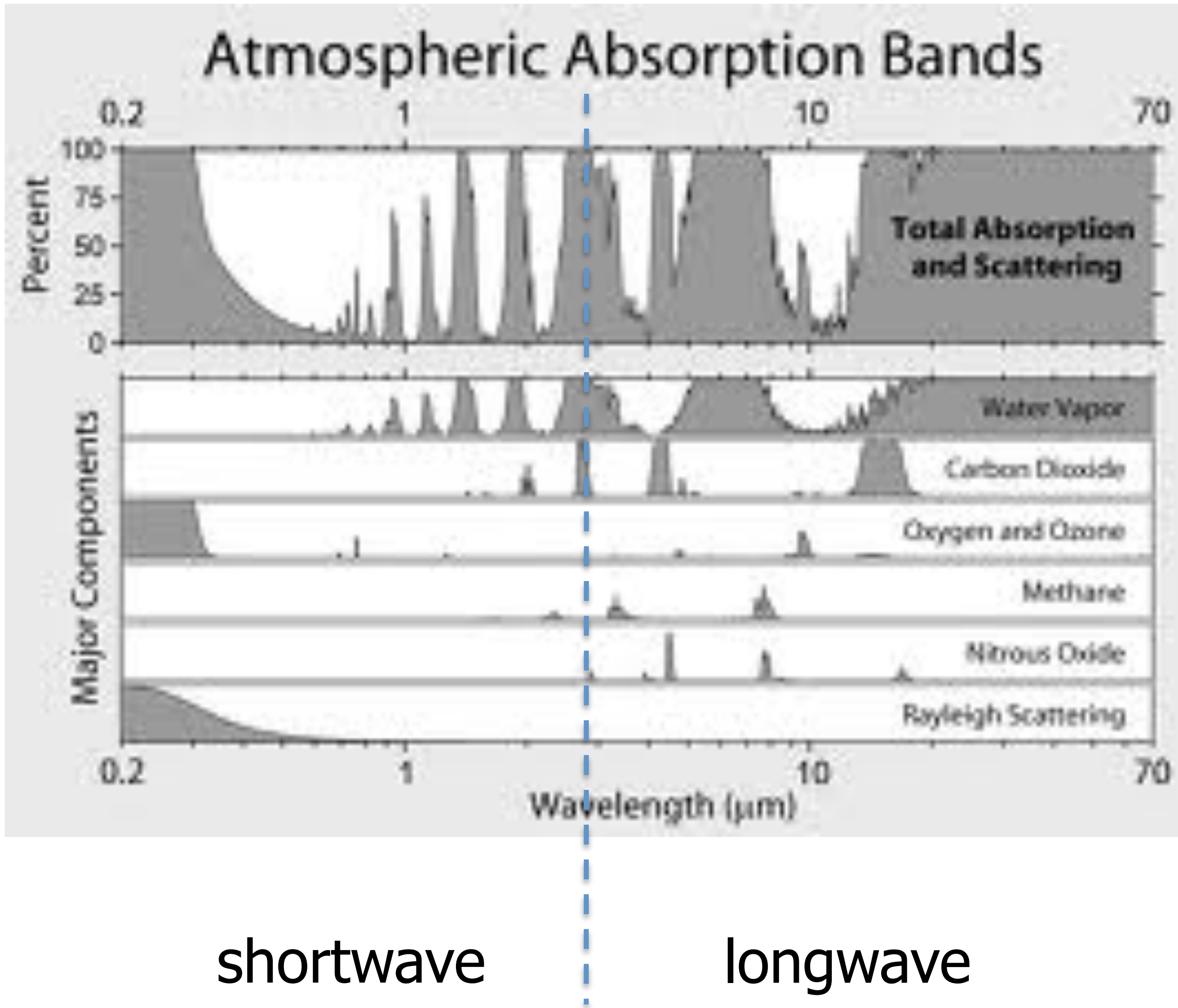
ra_lw_ physics	Scheme	Cores+Chem	Microphysics Interaction	Cloud Fraction	CO_2*
1	RRTM	ARW NMM	Qc Qr Qi Qs Qg	1/0	330
3	CAM	ARW	Qc Qi Qs	Max-rand overlap	yearly
4	RRTMG	ARW +Chem(τ)	Qc Qr Qi Qs	Max-rand overlap	379
5	New Goddard	ARW	Qc Qr Qi Qs Qg	1/0	337
7	FLG (UCLA)	ARW	Qc Qr Qi Qs Qg	1/0	345
31	Held-Suarez	ARW	none	none	none
99	GFDL	ARW NMM	Qc Qr Qi Qs	Max-rand overlap	fixed

* 2012 value = 392

Clear Sky: IR-active Gases

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

Radiation effects in clear sky



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
- Clouds strongly affect IR at all wavelengths (considered "grey bodies") and are almost opaque to it

Cloud Fractions

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

Cloud Fraction

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

ra_lw_physics=1

RRTM scheme

- Spectral scheme
- K-distribution
- Look-up table fit to accurate calculations
- Interacts with resolved clouds
- Ozone profile specified
- CO2 constant (well-mixed)

ARW only

ra_lw_physics=3

CAM3 scheme

- Spectral scheme
- 8 longwave bands
- Look-up table fit to accurate calculations
- Interacts with cloud fractions
- Can interact with trace gases and aerosols
- Ozone profile function of month, latitude
- CO2 changes based on year (since V3.1)
- Top-of-atmosphere (TOA) and surface diagnostics for climate

ARW only

ra_lw_physics=4

RRTMG longwave scheme (Since V3.1)

- Spectral scheme 16 longwave bands (K-distribution)
- Look-up table fit to accurate calculations
- Interacts with cloud fractions (MCICA, Monte Carlo Independent Cloud Approximation random overlap method)
- Ozone profile specified
- CO2 and trace gases specified
- WRF-Chem optical depth
- TOA and surface diagnostics for climate

ARW only

ra_lw_physics=5

New Goddard longwave scheme (Since V3.3)

- Spectral scheme
- 10 longwave bands
- Look-up table fit to accurate calculations
- Interacts with cloud fractions
- Can interact with trace gases and aerosols
- Ozone profile specified
- CO2 and trace gases specified
- TOA and surface diagnostics for climate

ARW only

ra_lw_physics=7

Fu-Liou-Gu (UCLA) longwave scheme (Since V3.4)

- Spectral scheme with correlated k-distribution method
- 12 longwave bands
- Look-up table fit to accurate calculations
- Cloud fraction 0/1 based on cloud presence
- Can interact with trace gases and aerosols
- Ozone profile specified similar to Goddard
- CO2 and trace gases specified

ARW only

ra_lw_physics=31

Held-Suarez relaxation term

- For Held-Suarez global idealized test
- Relaxation towards latitude and pressure-dependent temperature function
- Simple code - can be used as basis for other simplified radiation schemes, e.g relaxation or constant cooling functions

ra_lw_physics=99

GFDL longwave scheme

- used in Eta/NMM
- Default code is used with Ferrier microphysics
  - Remove #define to compile for use without Ferrier
- Spectral scheme from global model
- Also uses tables
- Interacts with clouds (cloud fraction)
- Ozone profile based on season, latitude
- CO_2 fixed
- ra_lw_physics=98 (nearly identical) for HWRF

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 Options

- Dudhia
- Goddard (original version)
- CAM
- RRTMG
- Goddard (new)
- GFDL

Shortwave Radiation schemes

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

Shortwave Radiation in V3.4

3.4 new

ra_lw_ physics	Scheme	Cores+Chem	Microphysics Interaction	Cloud Fraction	Ozone
1	Dudhia	ARW NMM + Chem(PM2.5)	Qc Qr Qi Qs Qg	1/0	none
2	GSFC	ARW +Chem(τ)	Qc Qi	1/0	5 profiles
3	CAM	ARW	Qc Qi Qs	Max-rand overlap	Lat/ month
4	RRTMG	ARW +Chem(τ)	Qc Qr Qi Qs	Max-rand overlap	1 profile
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

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

Ozone

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

Spectral Bands

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

Clouds and Cloud Fraction

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

Slope effects on shortwave

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

ARW only

radt

Radiation time-step recommendation

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

ra_sw_physics=1

MM5 shortwave (Dudhia)

- Simple downward calculation
- Clear-sky scattering
  - swrad_scat tuning parameter
    - 1.0 = 10% scattered, 0.5=5%, etc.
  - WRF-Chem aerosol effect (PM2.5)
- Water vapor absorption
- Cloud albedo and absorption
- No ozone effect (model top below 50 hPa OK)

ARW only

ra_sw_physics=2

Goddard shortwave

- Spectral method
- Interacts with resolved clouds
- Ozone profile (tropical, summer/winter, mid-lat, polar)
- CO2 fixed
- WRF-Chem optical depths

ARW only

ra_sw_physics=3

CAM3 shortwave

- Spectral method (19 bands)
- Interacts with cloud fractions
- Ozone/CO2 profile as in CAM longwave
- Can interact with aerosols and trace gases
- TOA and surface diagnostics for climate
- Note: CAM schemes need some extra namelist items (see README.namelist)

ARW only

ra_sw_physics=4

RRTMG shortwave (Since V3.1)

- Spectral method (14 bands)
- Interacts with cloud fractions (MCICA method)
- Ozone/CO2 profile as in RRTMG longwave
- Trace gases specified
- WRF-Chem optical depths
- TOA and surface diagnostics for climate

ARW only

ra_sw_physics=5

New Goddard shortwave scheme (Since V3.3)

- Spectral scheme
- 11 shortwave bands
- Look-up table fit to accurate calculations
- Interacts with cloud fractions
- Ozone profile specified
- CO2 and trace gases specified
- TOA and surface diagnostics for climate

ARW only

ra_sw_physics=7

Fu-Liou-Gu (UCLA) shortwave scheme (Since V3.4)

- Spectral scheme with correlated k-distribution method
- 6 shortwave bands
- Look-up table fit to accurate calculations
- Cloud fraction is 1/0 based on cloud presence
- Ozone profile specified similar to Goddard
- CO2 and trace gases specified
- Capability for aerosol effects

ra_sw_physics=99

GFDL shortwave

- Used in Eta/NMM model
- Default code is used with Ferrier microphysics (see GFDL longwave)
- Ozone/CO2 profile as in GFDL longwave
- Interacts with clouds (and cloud fraction)
- ra_lw_physics=98 (nearly identical) for HWRF

NMM only

nrads/nradl

Radiation time-step recommendation

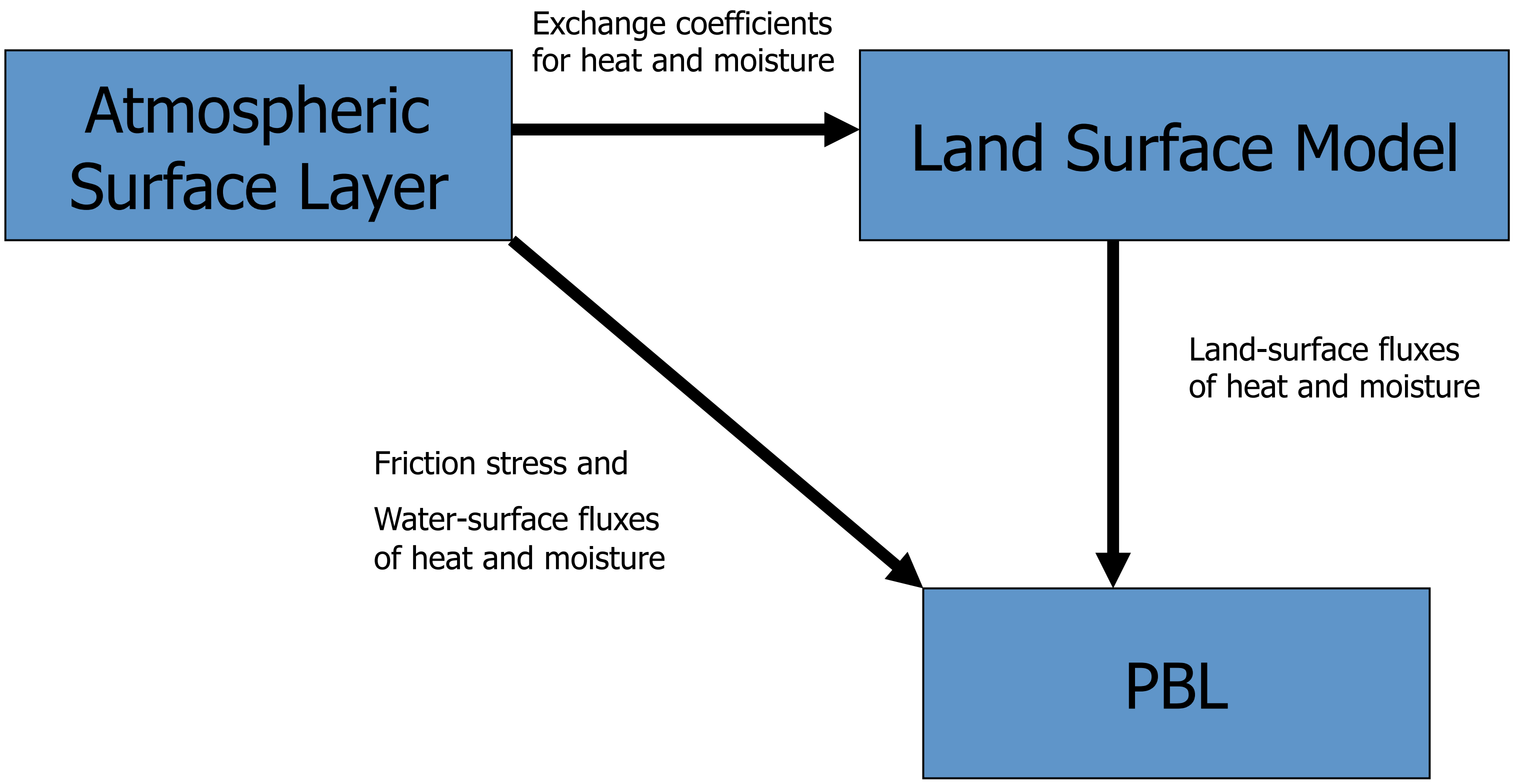
- Number of fundamental steps per radiation call
- Operational setting should be 3600/dt
- Higher resolution could be used, e.g. 1800/dt
- Recommend same value for all nested domains

Surface schemes

Surface layer of atmosphere diagnostics (exchange/transfer coeffs)

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

Surface Physics Components



Surface Fluxes

- Heat, moisture and momentum

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

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

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

Roughness Lengths

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

Exchange Coefficient

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

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

It is related to the roughness length and u* by

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

WRF Surface Layer Options (sf_sfclay_physics)

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

ARW only

Hurricane Options

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

Fractional Sea Ice

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

sf_sfclay_physics=1

Monin-Obukhov similarity theory

- Taken from standard relations used in MM5 MRF PBL
- Provides exchange coefficients to surface (land) scheme
- iz0tlnd thermal roughness length options for land points (0: Original Carlson-Boland, 1: Chen-Zhang)
  - Chen and Zhang (2009, JGR) modifies Zilitinkevich method with vegetation height
- Should be used with bl_pbl_physics=1 or 99

sf_sfclay_physics=11

Revised version of sf_sfclay_physics=1 (Jimenez et al. 2012)

- Reduces u* lower limit for land
- Uses new unlimited stability functions for unstable (Fairall et al. 1996) and stable (Cheng and Brutsaert 2005) conditions
- iz0tlnd thermal roughness length options for land points also available

sf_sfclay_physics=2

Monin-Obukhov similarity theory

- Modifications due to Janjic
- Taken from standard relations used in NMM model, including Zilitinkevich thermal roughness length
- iz0tlnd thermal roughness length options for land points (0: Original Zilitinkevich, 1: Chen-Zhang)
- Can be used with bl_pbl_physics=2, 9

NMM only

sf_sfclay_physics=3

GFS Monin-Obukhov similarity theory

- For use with NMM-LSM
- Should be used with bl_pbl_physics=3
- Option 88 is the HWRF version

sf_sfclay_physics=4

QNSE Monin-Obukhov similarity theory (New in V3.1)

- For use with QNSE-PBL
- Should be used with bl_pbl_physics=4
- Very similar to MYJ SFC
- New stability functions

ARW only

sf_sfclay_physics=5

MYNN Monin-Obukhov similarity theory (New in V3.1)

- For use with MYNN-PBL
- Should be used with bl_pbl_physics=5

ARW only

sf_sfclay_physics=7

Pleim-Xiu surface layer (EPA)

- For use with PX LSM and ACM PBL
  - Should be used with sf_surface_physics=7 and bl_pbl_physics=7
- New in Version 3

ARW only

sf_sfclay_physics=10

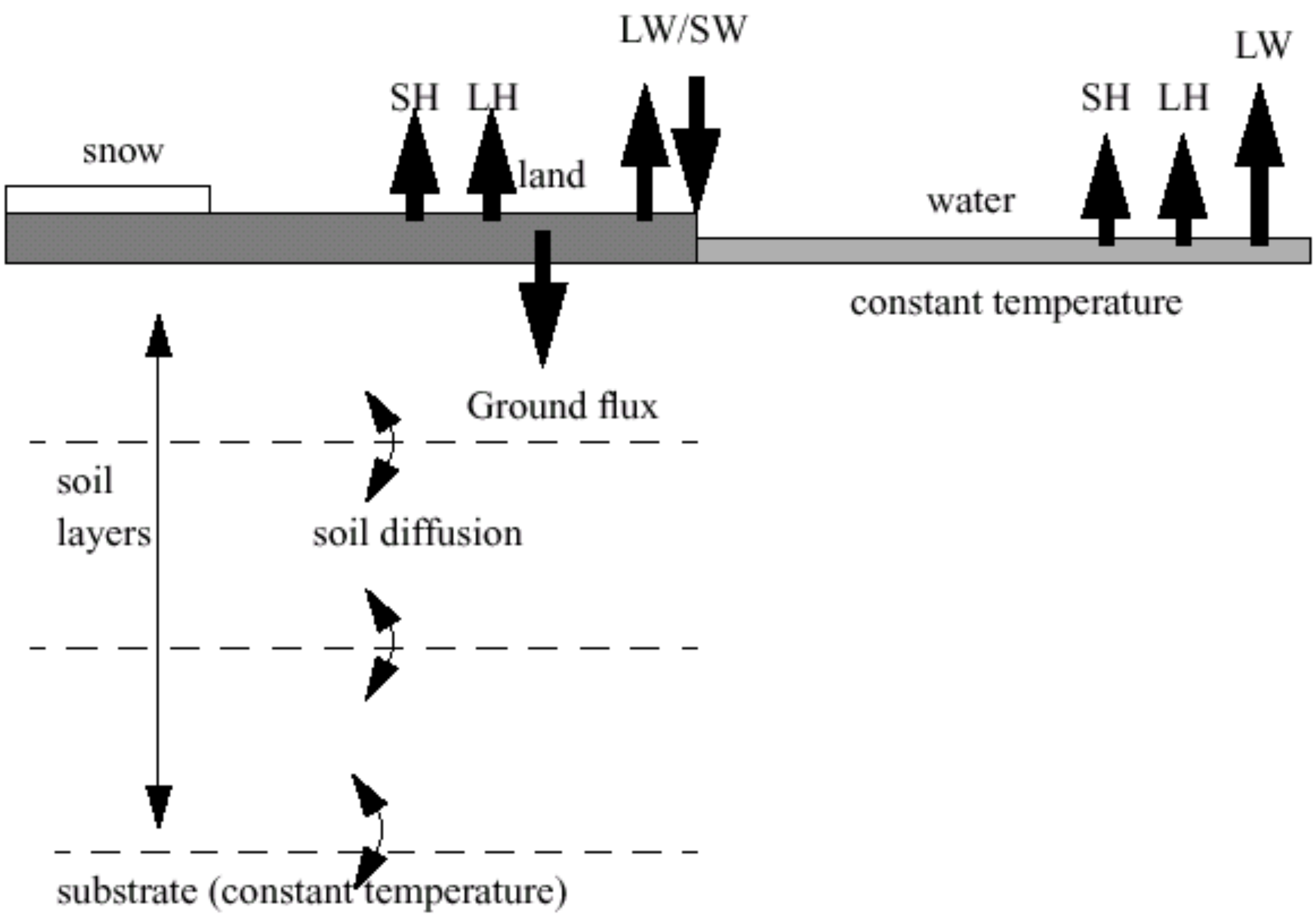
TEMF surface layer (Angevine et al.)

- For use with TEMF PBL
  - Should be used with bl_pbl_physics=10
- New in Version 3.3

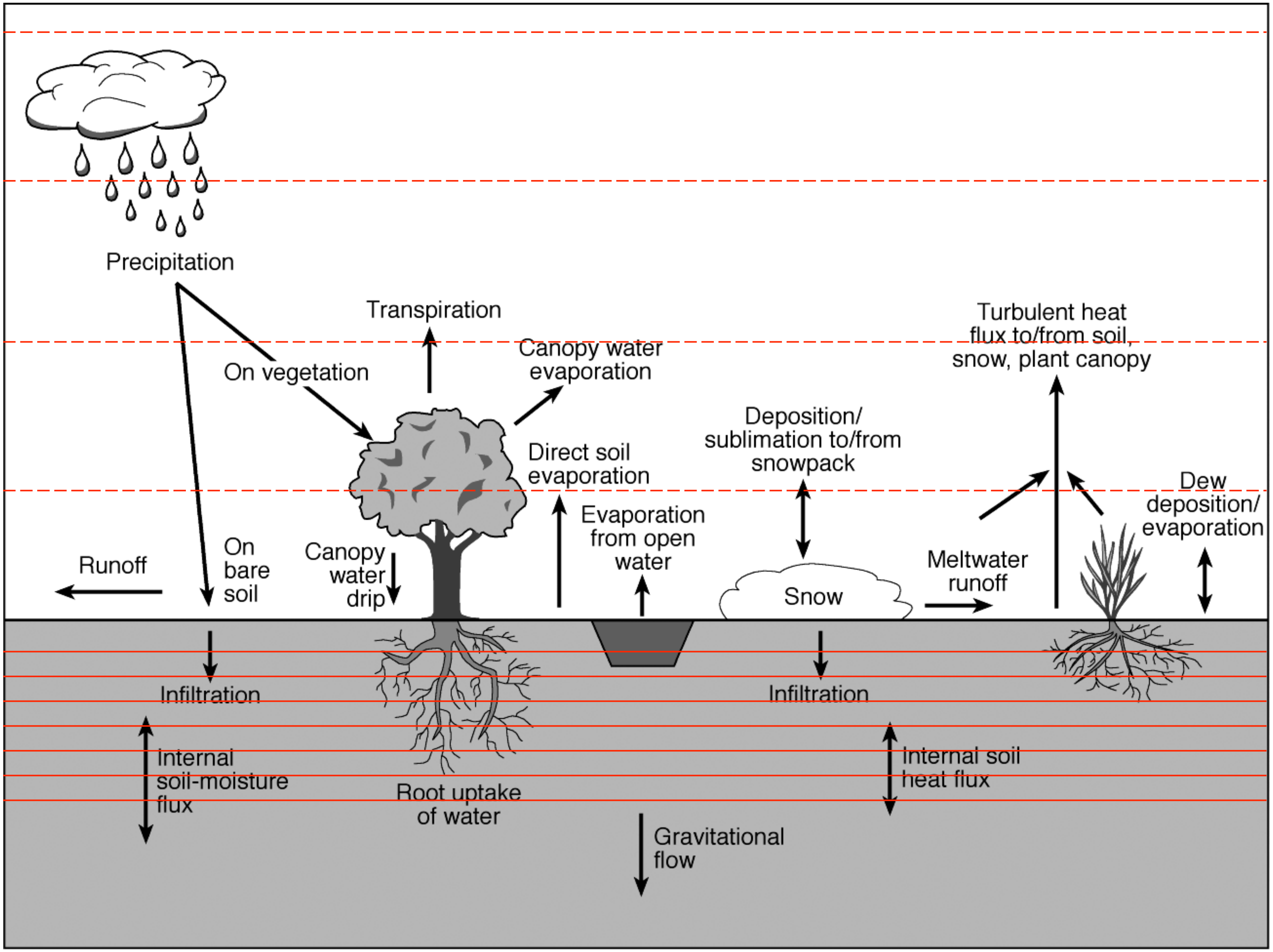
WRF Land-Surface Model Options (sf_surface_physics)

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

Illustration of Surface Processes



Land-Surface Model Processes



Land-Surface Model

- Predicts soil temperature and soil moisture in layers (4 for Noah and NoahMP, 6 for RUC, 2 for PX and 3 for SSiB)
- Predicts snow water equivalent on ground. May be in layers (NoahMP, RUC, SSiB)
- May predict canopy moisture only (Noah, NoahMP, RUC) or temperature only (SSiB)

Land-Surface Options

- 5-layer thermal diffusion
- Noah LSM
- RUC LSM
- Pleim-Xiu LSM
- NoahMP (new in V3.4)
- SSiB (new in V3.4)

Vegetation and Soil

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

Snow Cover

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

Urban Effects

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

LSM Tables

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

Initializing LSMs

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

Initializing LSMs

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

ARW only

sst_update=1

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

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

Regional Climate Options

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

ARW only

sf_surface_physics=1

5-layer thermal diffusion model from MM5

- Predict ground temp and soil temps
- Thermal properties depend on land use
- No soil moisture or snow-cover prediction
- Moisture availability based on land-use only
- Provides heat and moisture fluxes for PBL

sf_surface_physics=2

Noah Land Surface Model (Unified ARW/NMM version in Version 3)

- Vegetation effects included
- Predicts soil temperature and soil moisture in four layers and diagnoses skin temperature
- Predicts snow cover and canopy moisture
- Handles fractional snow cover and frozen soil
- New time-varying snow albedo (in V3.1)
- Provides heat and moisture fluxes for PBL
- Noah has three Urban Canopy Model options (sf_urban_physics, ARW only)

sf_urban_physics=1

Urban Canopy Model (UCM, Kusaka et al.)

- Sub-grid wall, roof, and road effects on radiation and fluxes
- Anthropogenic heat source can be specified
- Can use low, medium and high density urban categories

sf_urban_physics=2

Building Environment Parameterization (BEP, Martilli et al.)

- Sub-grid wall, roof, and road effects on radiation and fluxes
- Can be used with MYJ PBL or BouLac PBL to represent buildings higher than lowest model levels (Multi-layer urban model)
- Needs additional sub-grid building fractional area information

sf_urban_physics=3

Building Energy Model (BEM, Martilli and Salamanca)

- Includes anthropogenic building effects (heating, air-conditioning) in addition to BEP
- Can be used with MYJ PBL or BouLac PBL to represent buildings higher than lowest model levels (Multi-layer urban model)
- Needs additional sub-grid building fractional area information

sf_surface_physics=3

RUC Land Surface Model (Smirnova)

- Vegetation effects included
- Predicts soil temperature and soil moisture in six layers
- Multi-layer snow model
- Provides heat and moisture fluxes for PBL

sf_surface_physics=4

Noah MP (Noah Multi-Physics) added in V3.4

- Multiple physics options (namelist choice)
  - Default options are better tested
- Vegetation effects included
- Predicts soil temperature and soil moisture in four layers and diagnoses skin temperature
- Multi-layer snow
- Handles fractional snow cover and frozen soil
- Canopy model including radiative effects
- Provides heat and moisture fluxes for PBL

ARW only

sf_surface_physics=7

Pleim-Xiu Land Surface Model (EPA)

- New in Version 3
- Vegetation effects included
- Predicts soil temperature and soil moisture in two layers
- Simple snow-cover model
- Provides heat and moisture fluxes for PBL

ARW only

sf_surface_physics=8

Simplified SiB (UCLA)

- New in Version 3.4
- Vegetation effects included
- Predicts soil temperature in two layers and canopy temperature
- Predicts soil moisture in three layers
- Three-layer snow model
- Includes its own M-O surface layer scheme for land
  - sf_sfclay choice only affects water with this LSM
- Provides heat and moisture fluxes for PBL

NMM only

sf_surface_physics=88

GFDL slab model

- Simple land treatment for HWRF physics
- Force-restore 1-layer model with constant substrate

VEGPARM.TBL

Text (ASCII) file that has vegetation properties for Noah and RUC LSMs (separate sections in this table)

- 24 USGS categories or 20 MODIS categories (new) from 30” global dataset
- Each type is assigned min/max value of
  - Albedo
  - Leaf Area Index
  - Emissivity
  - Roughness length
- Other vegetation properties (stomatal resistance etc.)
- From 3.1, monthly vegetation fraction determines seasonal cycle between min and max values in Noah
- There is also a SOILPARM.TBL for soil properties in Noah and RUC

LANDUSE.TBL

Text (ASCII) file that has land-use properties for 5-layer slab model (vegetation, urban, water, etc.)

- From Version 3.1 Noah LSM does not use this table
- 24 USGS categories or 20 MODIS categories (new) from 30" global dataset
- Each type is assigned summer/winter value
  - Albedo
  - Emissivity
  - Roughness length
- Other table properties (thermal inertia, moisture availability, snow albedo effect) are used by 5-layer model
- Also note
  - Other tables (VEGPARM.TBL, etc.) are used by Noah
  - RUC LSM uses same table files after Version 3

Planetary Boundary Layer

Provides

Boundary layer fluxes (heat, moisture, momentum)

Vertical diffusion in whole column

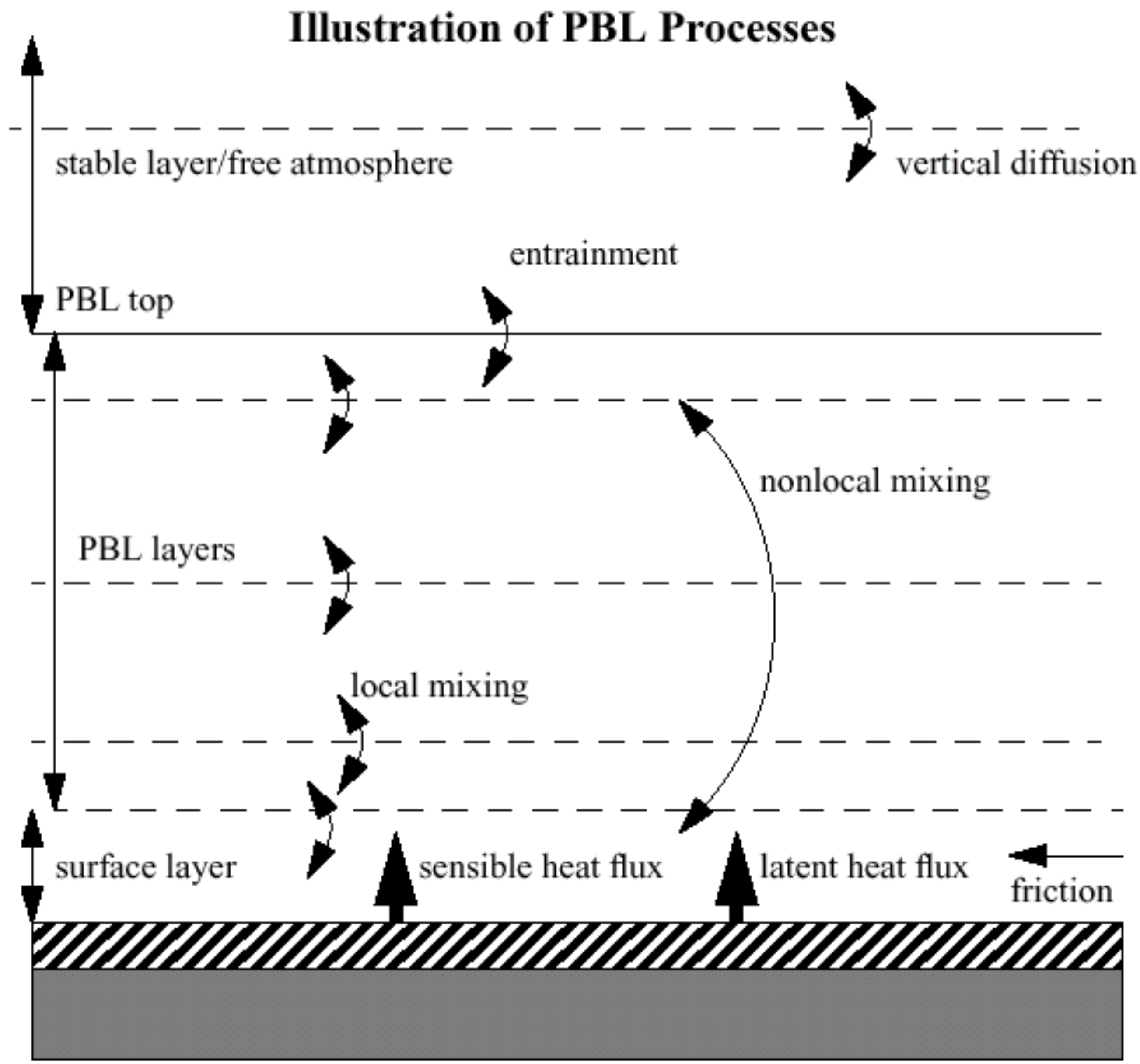
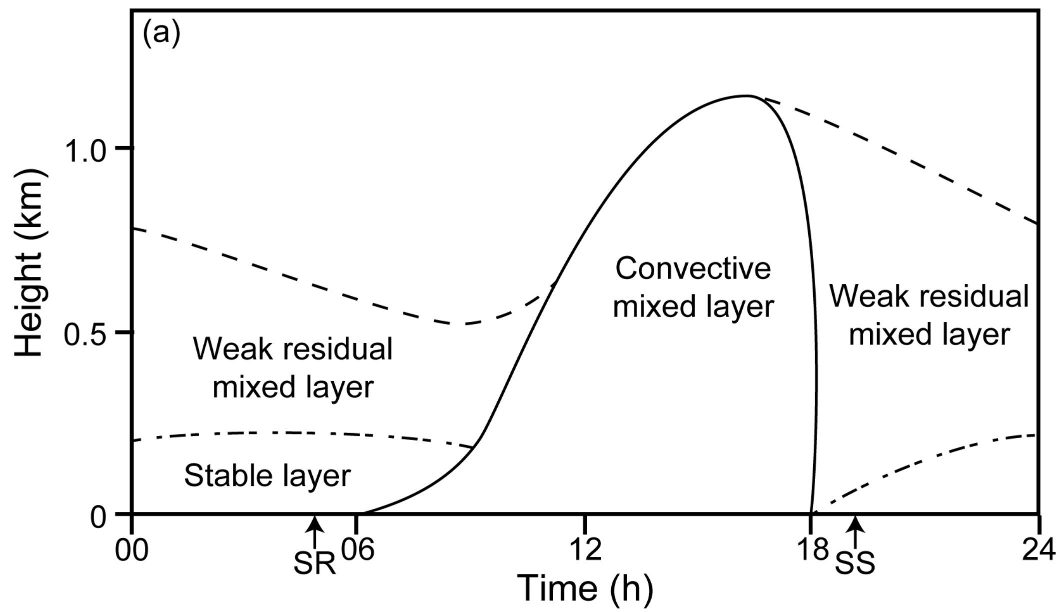
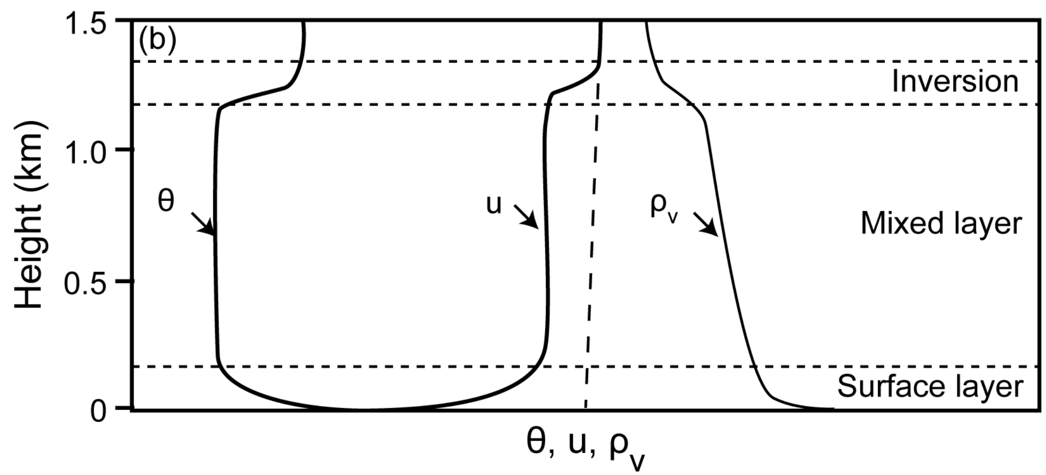


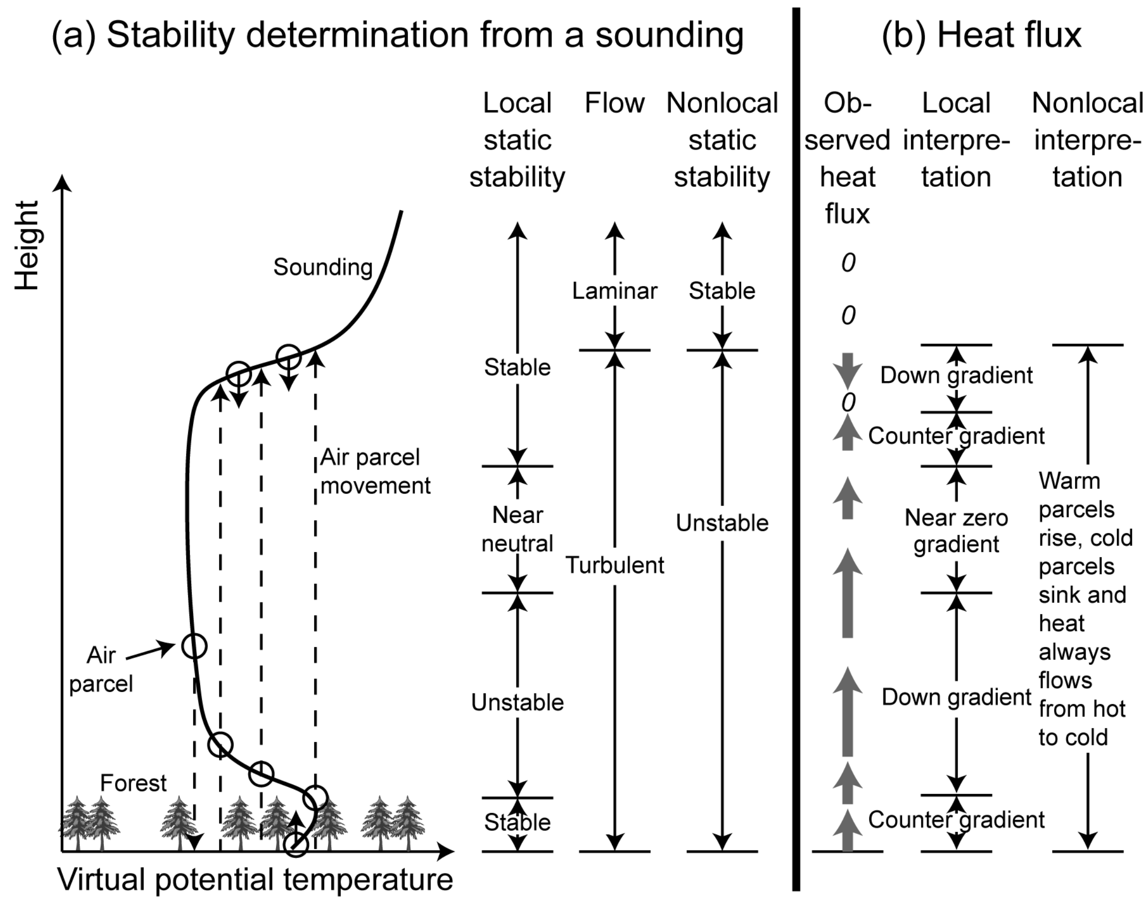
Illustration of PBL Processes
stable layer/free atmosphere
vertical diffusion
entrainment
PBL top
nonlocal mixing
PBL layers
local mixing
surface layer
sensible heat flux
latent heat flux
friction

Planetary Boundary Layer





PBL Structure and Fluxes



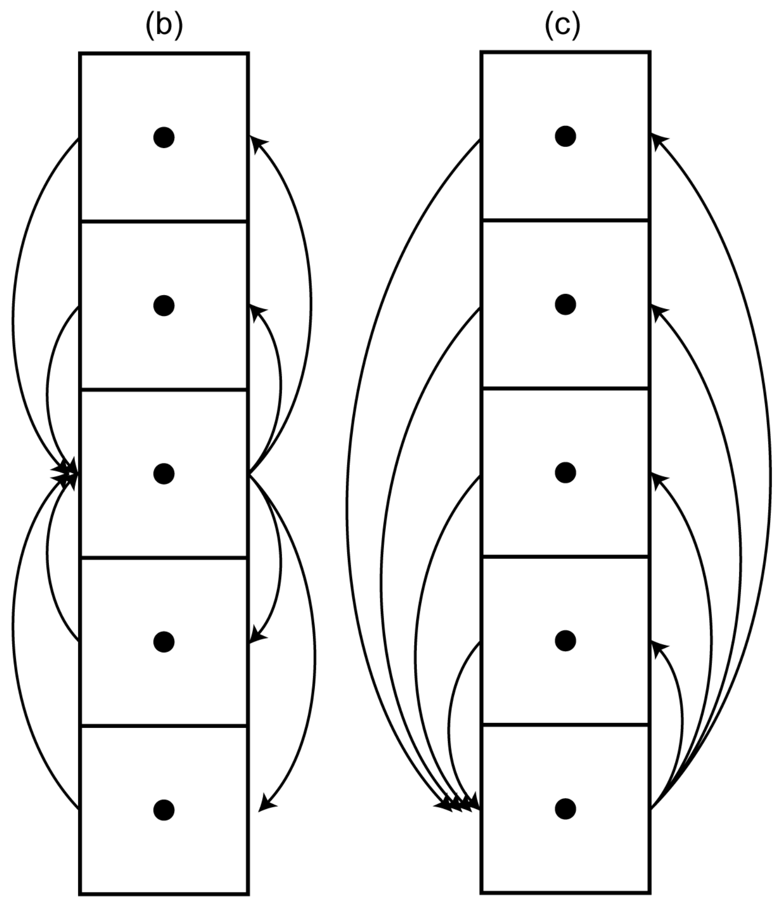
WRF PBL Options (bl_pbl_physics)

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

PBL schemes in V3.3

bl_pbl_ physics	Scheme	Reference	Added
1	YSU	Hong, Noh and Dudhia (2006, MWR)	2004
2	MYJ	Janjic (1994, MWR)	2000
3	GFS	Hong and Pan (1996, MWR)	2005
4	QNSE-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
94	QNSE	Sukoriansky, Galperin and Perov (2005, BLM)	2009
99	MRF	Hong and Pan (1996, MWR)	2000

Different approaches



Local closure

Non-local closures

TKE schemes

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

Nonlocal Schemes

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

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

- YSU, MRF, GFS include a non-gradient term (Γ)
- ACM2, TEMF 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 in the future will also use this for scalar and tracer vertical mixing outside the PBL scheme since these arrays are currently only advected and horizontally mixed when using a PBL scheme
- PBL schemes themselves only mix limited variables: momentum, heat, vapor and some specific cloud variables

PBL schemes in V3.4

3.4 changes

bl_pbl_ physics	Scheme	Cores	sf_sfclay_ physics	Prognostic variables	Diagnostic variables	Cloud mixing
1	YSU	ARW NMM	1,11		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	QKE	Tsq, Qsq, Cov, exch_h, exch_m	QC
6	MYNN3	ARW	1,2,5	QKE, Tsq, Qsq, Cov	exch_h, exch_m	QC
7	ACM2	ARW	1,7			QC,QI
8	BouLac	ARW	1,2	TKE_PBL	EL_PBL, exch_h, exch_m	QC
9	UW	ARW	1,2	TKE_PBL	exch_h, exch_m	QC
10	TEMF	ARW	10	TE_TEMF	*_temf	QC, QI
94	QNSE	ARW	4	TKE_PBL	EL_PBL, exch_h, exch_m	QC,QI
99	MRF	ARW NMM	1			QC,QI

PBL Scheme Options

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

- 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 << 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

ARW only

Large Eddy Simulation

- Explicit large-eddy simulation (LES) available for real-data cases (V3) or idealized cases
- For dx <~200 meters (dx~dz), horizontal and vertical mixing should be unified in the turbulence/diffusion parameterization
  - bl_pbl_physics = 0 (activates vertical diffusion routines)
    - isfflx = 0 (idealized drag and heat flux from namelist)
    - isfflx = 1 (drag and heat flux from physics)
      - sf_sfclay_physics=1
      - sf_surface_physics (choose non-zero option)
    - isfflx = 2 (drag from physics, heat flux from tke_heat_flux)
      - sf_sfclay_physics=1
  - diff_opt=2, km_opt = 2 or 3
  - mix_isotropic=1 (if dx and dz are of same order)

Large-Eddy Simulation

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

Large-Eddy Simulation

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

LES schemes

Unified horizontal and vertical mixing (for dx~dz).

Typically needed for dx<~200 m. Also use mix_isotropic=1.

bl_pbl_physics	diff_opt	km_opt	Scheme	Cores	sf_sfclay_physics	isfflx	Prognostic variables
0	2	2	tke	ARW	0,1,2	0,1,2	tke
0	2	3	3d Smagorinsky	ARW	0,1,2	0,1,2	

Namelist isfflx controls surface flux methods

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

Other Options

- Gravity-wave drag can be added for low resolution (> 10 km) runs to represent sub-grid orographic gravity-wave vertical momentum transport (gwd_opt=1)
- Wind-farm model has been added to investigate wind-farm effects on the environment (extra stress and turbulence generation)
- topo_wind=1: Jimenez and Dudhia 10 m wind bias correction method for terrain effects

Gravity Wave Drag
(gwd_opt=1 for ARW, 2 for NMM)

- ARW scheme from Hong et al. New in V3.1
- Accounts for orographic gravity wave effect on momentum profile
- Extra sub-grid orographic information comes from geogrid
- Probably needed only if all below apply
  - dx > 10 km
  - Simulations longer than 5 days
  - Domains including mountains

Wind Farm Parameterization

- From A. Fitch (U. of Bergen, Norway)
- To be used with MYNN PBL
- Represents effect of specified turbines on wind and TKE in lower boundary-layer
- See README.windturbine file in WRF tar file for set-up information

topo_wind=1

- Jimenez and Dudhia (2012)
- Correction for effects on 10m wind of
  - Sub-grid topography (extra friction)
    - Uses sub-grid variance from geogrid (new)
  - Hill-tops (reduced friction)
    - Uses Laplacian of resolved elevation
- This reduces 10 m wind biases
- Designed for high resolution ~2 km
- Only implemented in YSU PBL (bl_pbl_physics=1)

bl_pbl_physics=1

YSU PBL scheme (Hong, Noh and Dudhia 2006)

- Parabolic K profile mixing in dry convective boundary layer
- Troen-Mahrt countergradient flux (non-local)

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

- Depth of PBL determined from thermal profile
- Explicit treatment of entrainment
- Vertical diffusion depends on Ri in free atmosphere
- New stable surface BL mixing using bulk Ri
- topo_wind = 1 option available only in this PBL

bl_pbl_physics=2

Mellor-Yamada-Janjic (Eta/NMM) PBL

- 1.5-order, level 2.5, TKE prediction
- Local TKE-based vertical mixing in boundary layer and free atmosphere
- TKE_MYJ is advected by NMM, not by ARW (yet)

NMM only

bl_pbl_physics=3

GFS PBL

- 1st order Troen-Mahrt
- Closely related to MRF PBL
- Non-local-K vertical mixing in boundary layer and free atmosphere

bl_pbl_physics=4

New QNSE (Quasi-Normal Scale Elimination) EDMF (Eddy Diffusivity Mass Flux) PBL

- 1.5-order, level 2.5, TKE prediction
- Local TKE-based vertical mixing in boundary layer and free atmosphere
- QNSE (Sukoriansky and Galperin) theory for stably stratified case
- New EDMF component in V3.4 for non-local convective boundary layer (Pergaud et al.)
  - mfshconv=1 (default) activates this component

bl_pbl_physics=94

Old QNSE (Quasi-Normal Scale Elimination) PBL from Galperin and Sukoriansky

- 1.5-order, level 2.5, TKE prediction
- Local TKE-based vertical mixing in boundary layer and free atmosphere
- New theory for stably stratified case
- Mixing length follows MYJ, TKE production simplified from MYJ

bl_pbl_physics=5 and 6

MYNN (Nakanishi and Niino) PBL

- (5)1.5-order, level 2.5, TKE prediction, OR
- (6)2nd-order, level 3, TKE, θ'^2,q'^2 and $\theta' q'$ prediction
- Local TKE-based vertical mixing in boundary layer and free atmosphere
- Since V3.1
- TKE advected since V3.3 (output name: QKE)

ARW only

bl_pbl_physics=7

Asymmetrical Convective Model, Version 2 (ACM2) PBL (Pleim and Chang)

- Blackadar-type thermal mixing upwards from surface layer
- Local mixing downwards
- PBL height from critical bulk Richardson number

ARW only

bl_pbl_physics=8

BouLac PBL (Bougeault and Lacarrère)

- TKE prediction scheme
- Designed to work with multi-layer urban model (BEP)
- Since V3.1

ARW only

bl_pbl_physics=9

CAM UW PBL (Bretherton and Park, U. Washington)

- TKE prediction scheme
- From current CESM climate model physics
- Use with sf_sfclay_physics=2
- New in V3.3

ARW only

bl_pbl_physics=10

Total Energy - Mass Flux (TEMF) PBL (Angevine et al.)

- Total Turbulent Energy (kinetic + potential) prediction scheme
- Includes mass-flux shallow convection
- New in V3.3

ARW only

bl_pbl_physics=99

MRF PBL scheme (Hong and Pan 1996)

- Non-local-K mixing in dry convective boundary layer
- Depth of PBL determined from critical Ri number
- Vertical diffusion depends on Ri in free atmosphere

ARW only

bldt

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

NMM only

nphs

- Time steps between PBL/turbulence/LSM calls
- Typical value is chosen to give a frequency of 1-3 minutes, i.e. 60/dt to 180/dt
- Also used for microphysics

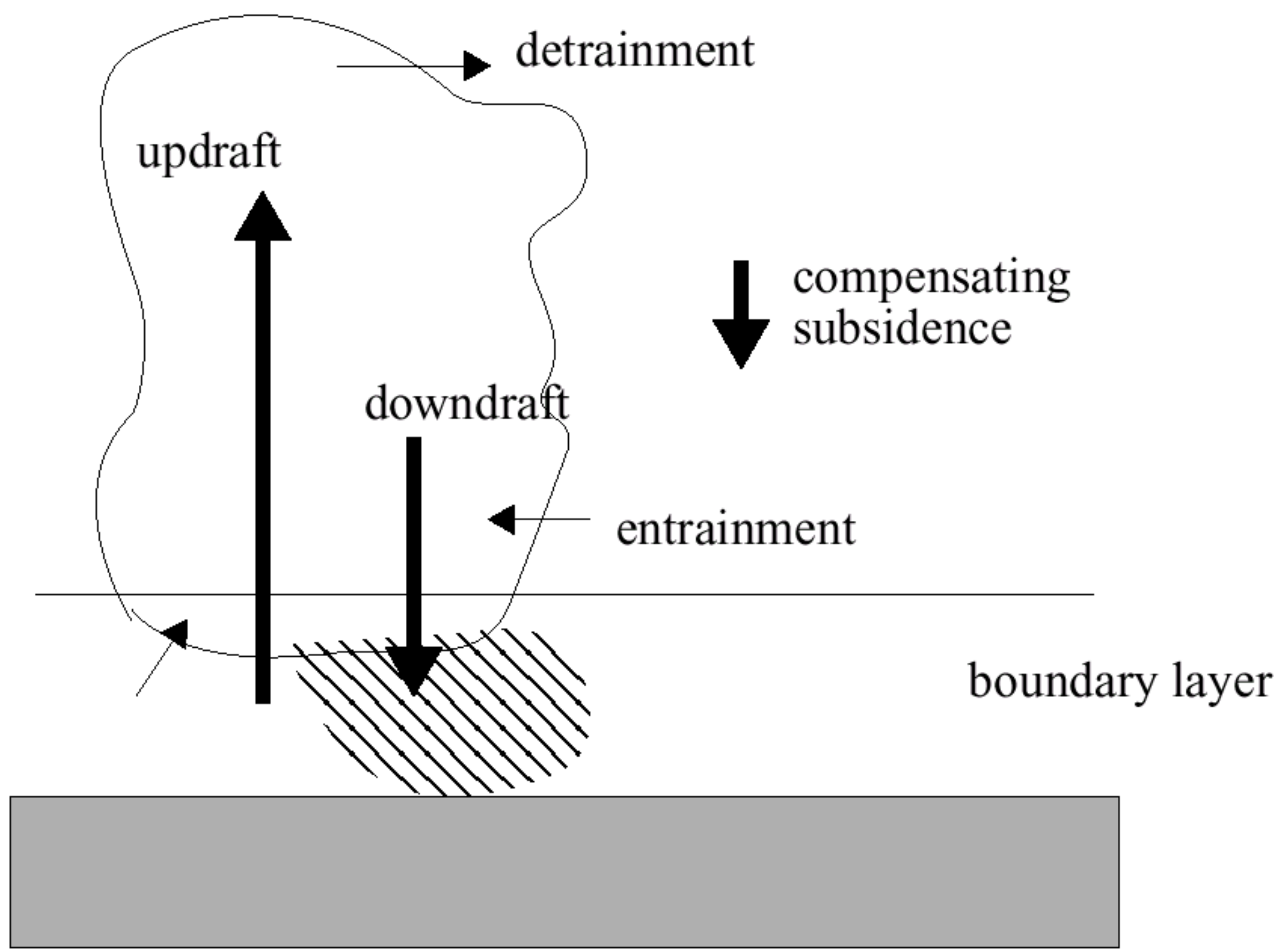
Cumulus Parameterization

Provides

Atmospheric heat and moisture/cloud tendency profiles

Surface sub-grid-scale (convective) rainfall

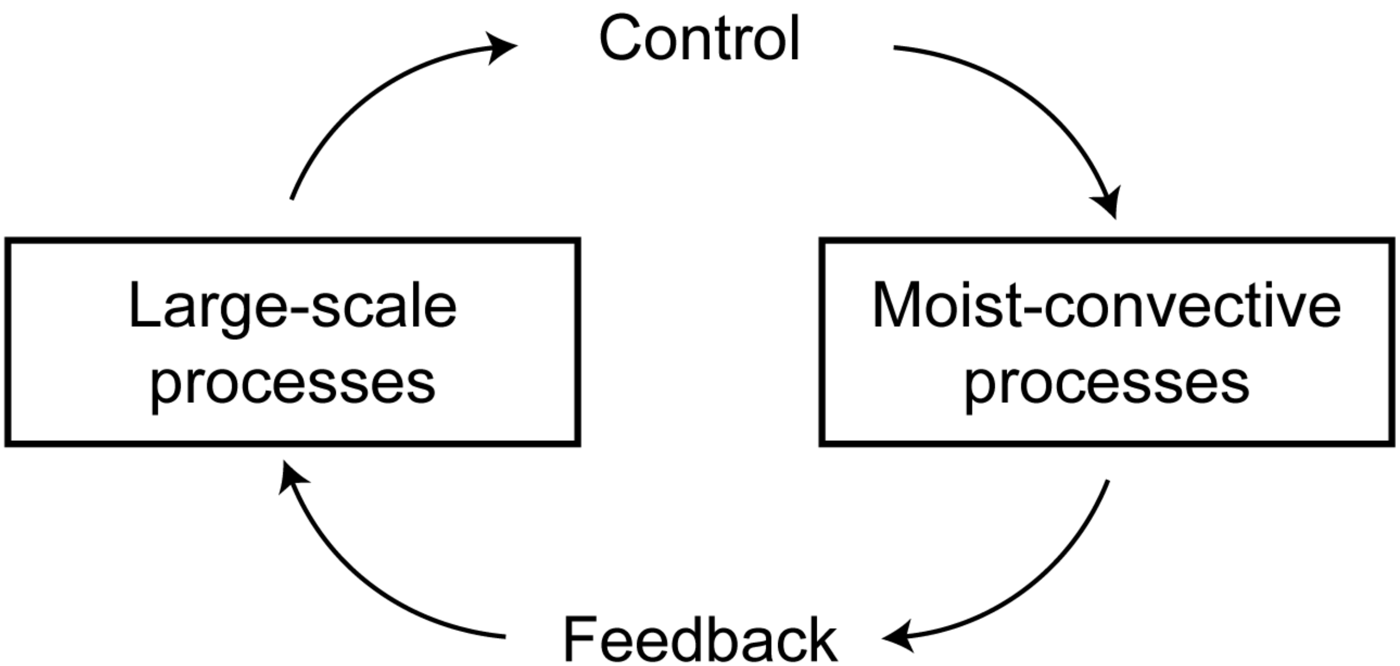
Illustration of Cumulus Processes



Cumulus Schemes

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

Parameterizations of cumulus convection



WRF Cumulus Parameterization Options

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

Cumulus schemes in V3.3

mp_physics	Scheme	Reference	Added
1	Kain-Fritsch	Kain (2004, JAM)	2000
2	Betts-Miller-Janjic	Janjic (1994, MWR; 2000, JAS)	2002
3	Grell-Devenyi	Grell and Devenyi (2002, GRL)	2002
4	Old Simplified Arakawa-Schubert	Grell et al. (1994, MM5 NCAR Tech Note)	2002/ 2011
5	Grell-3	Grell and Devenyi (2002, GRL)	2008
6	Tiedtke	Tiedtke (1989, MWR), Zhang, Wang and Hamilton (2011, MWR)	2011
7	Zhang-McFarlane	Zhang and McFarlane (1995, AO)	2011
14	New SAS	Han and Pan (2010,…)	2011
84	New SAS (HWRF)	Han and Pan (2010,…)	2012
99	Old Kain-Fritsch	Kain and Fritsch (1990, JAS; 1993 Meteo. Monogr.)	2000

Deep Convection

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

Triggers

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

Closures

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

Ensemble methods

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

Shallow Convection

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

Shallow Convection

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

Momentum Transport

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

Cloud Detrainment

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

cu_physics=1

New Kain-Fritsch

- As in MM5 and Eta/NMM SREF ensemble
- Includes shallow convection
- Low-level vertical motion in trigger function
  - New moisture advection perturbation trigger option (kfeta_trigger=2)
- CAPE removal time scale closure
- Mass flux type with updrafts and downdrafts, entrainment and detrainment
- Includes cloud, rain, ice, snow detrainment
- Clouds persist over convective time scale (recalculated every convective step in NMM)

cu_physics=2

Betts-Miller-Janjic

- As in NMM model (Janjic 1994)
- Adjustment type scheme
- Deep and shallow profiles
- BM saturated profile modified by cloud efficiency, so post-convective profile can be unsaturated in BMJ
- No explicit updraft or downdraft
- No cloud detrainment

cu_physics=3

Grell-Devenyi Ensemble

- Multiple-closure (CAPE removal, quasi-equilibrium, moisture convergence, cloud-base ascent) - 16 mass flux closures
- Multi-parameter (maximum cap, precipitation efficiency) - e.g. 3 cap strengths, 3 efficiencies
- Explicit updrafts/downdrafts
- Includes cloud and ice detrainment
- Mean feedback of ensemble is applied
- Weights can be tuned (spatially, temporally) to optimize scheme (training)

cu_physics=4

Old Simpified Arakawa-Schubert (OSAS) scheme

- Quasi-equilibrium scheme
- Related to Grell scheme in MM5
- Includes cloud and ice detrainment
- Downdrafts and single, simple cloud
- Shallow convective mixing in ARW only
- Part of HWRF physics in NMM
- Momentum transport in NMM only

cu_physics=5

Grell-3d

- As GD, but slightly different ensemble
- Includes cloud and ice detrainment
- Subsidence is spread to neighboring columns
  - This makes it more suitable for < 10 km grid size than other options
  - cugd_avgdx=1 (default), 3(spread subsidence)
- ishallow=1 option for shallow convection
- Mean feedback of ensemble is applied
- Weights can be tuned (spatially, temporally) to optimize scheme (training)

cu_physics=6

Tiedtke scheme (U. Hawaii version)

- Mass-flux scheme (updrafts, downdrafts)
- CAPE-removal time scale closure
- Includes cloud and ice detrainment
- Includes shallow convection
- Includes momentum transport
- New in V3.3
- V3.4 changes entrainment/detrainment adds internal trigger choice (moisture convergence or dilute parcel testing)

cu_physics=7

CAM Zhang-McFarlane scheme

- Mass-flux scheme (updrafts, downdrafts)
- CAPE-removal time-scale closure
- From current CESM climate model physics
- Includes cloud and ice detrainment
- Includes momentum transport with pressure term
- New in V3.3

cu_physics=14

- New Simpified Arakawa-Schubert (NSAS) scheme
- Quasi-equilibrium scheme
- Updated from SAS for current NCEP GFS global model
- Includes cloud and ice detrainment
- Downdrafts and single, simple cloud
- New mass-flux type shallow convection (changed from OSAS)
- Momentum transport with pressure term
- New in V3.3

cu_physics=84

- HWRF version of new Simpified Arakawa-Schubert (SAS) scheme (similar to NSAS)
- Quasi-equilibrium scheme
- Updated from SAS for current NCEP GFS global model
- Includes cloud and ice detrainment
- Downdrafts and single, simple cloud
- New mass-flux type shallow convection (changed from OSAS)
- Momentum transport with pressure term
- New in V3.4

ARW only

shcu_physics=2

CAM UW shallow convection (Bretherton and Park, U. Washington)

- To be used with a TKE PBL scheme and a deep scheme with no shallow convection (e.g. CESM Zhang-McFarlane)
- From current CESM climate model physics
- New shallow convection driver in V3.3
- Other options such as Grell ishallow to be moved here in the future

ARW only

cudt

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

NMM only

ncnvc

- Time steps between cumulus parameterization calls
- Typically 10 - same as NPHS

Cumulus schemes in V3.4

3.4 new

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

Cumulus scheme

Recommendations about use

- For dx ≥ 10 km: probably need cumulus scheme
- For dx ≤ 3 km: probably do not need scheme
  - However, there are cases where the earlier triggering of convection by cumulus schemes help
- For dx=3-10 km, scale separation is a question
  - Few schemes are specifically designed with this range of scales in mind
  - G3 has an option to spread subsidence in neighboring columns
- Issues with 2-way nesting when physics differs across nest boundaries (seen in precip field on parent domain)
  - best to use same physics in both domains or 1-way nesting

Microphysics

Provides

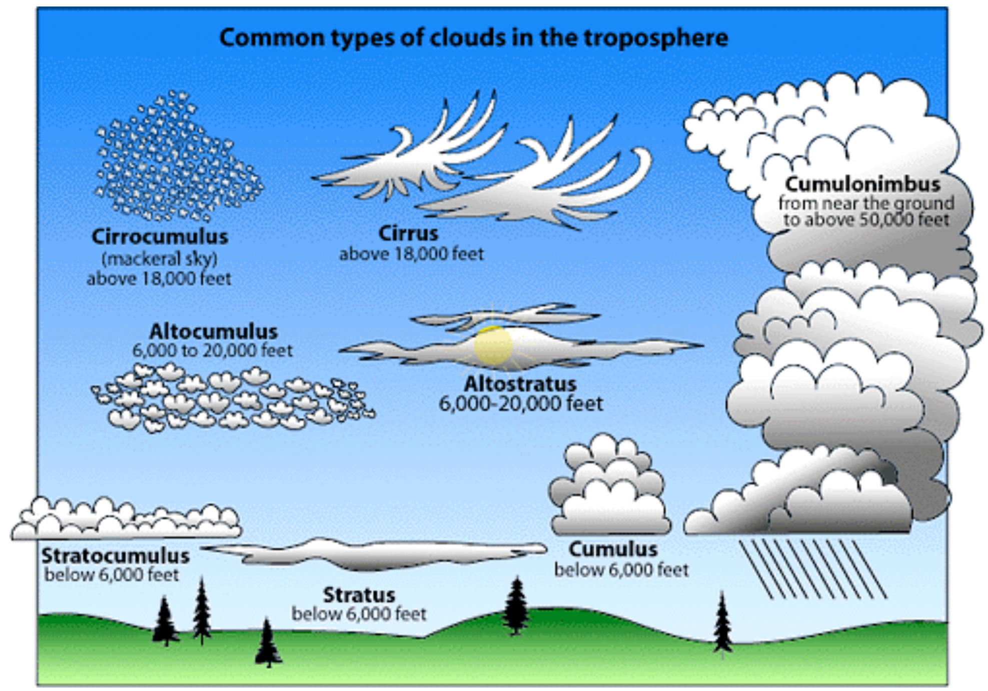
Atmospheric heat and moisture tendencies

Microphysical rates

Surface resolved-scale rainfall

Resolved clouds

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



Microphysics Parameterization

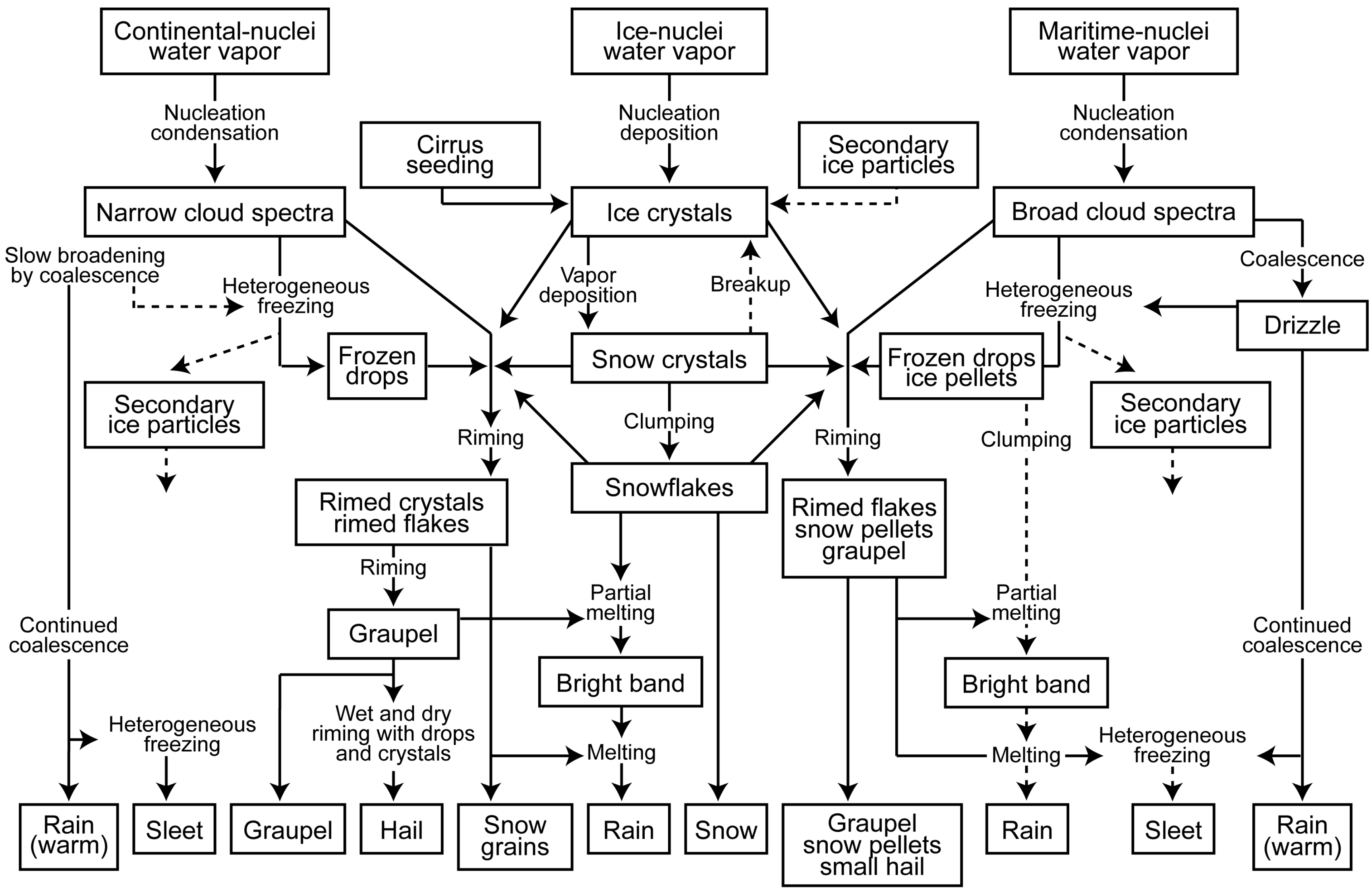
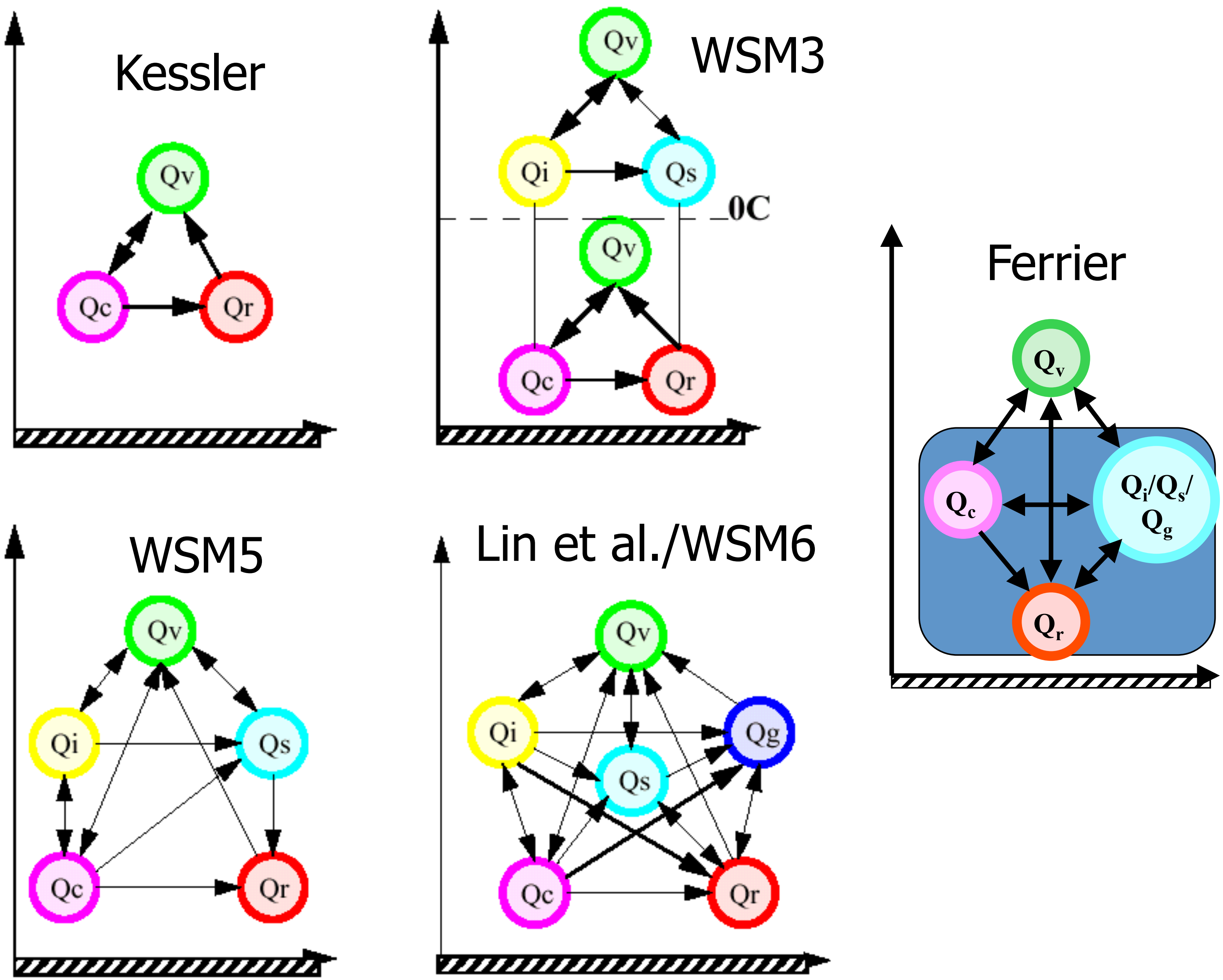


Illustration of Microphysics Processes



WRF Microphysics Options (mp_physics)

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

Microphysics schemes in V3.4

mp_physics	Scheme	Reference	Added
1	Kessler	Kessler (1969)	2000
2	Lin (Purdue)	Lin, Farley and Orville (1983, JCAM)	2000
3	WSM3	Hong, Dudhia and Chen (2004, MWR)	2004
4	WSM5	Hong, Dudhia and Chen (2004, MWR)	2004
5	Eta (Ferrier)	Rogers, Black, Ferrier et al. (2001)	2000
6	WSM6	Hong and Lim (2006, JKMS)	2004
7	Goddard	Tao, Simpson and McCumber (1989, MWR)	2008
8	Thompson (+old)	Thompson et al. (2008, MWR)	2009
9	Milbrandt 2-mom	Milbrandt and Yau (2005, JAS)	2010
10	Morrison 2-mom	Hong and Pan (1996, MWR)	2008
13	SBU-Ylin	Lin and Colle (2011, MWR)	2011
14	WDM5	Lim and Hong (2010, 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

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

Microphysics: Single and Double Moment Schemes

- Single-moment schemes have one prediction equation for mass (kg/kg) per species (Qr, Qs, etc.) with particle size distribution being derived from fixed parameters
- Double-moment (DM) schemes add a prediction equation for number concentration (#/kg) per DM species (Nr, Ns, etc.)
- DM schemes may only be double-moment for a few species
- DM schemes allow for additional processes such as size-sorting during fall-out and sometimes aerosol (CCN) effects

Microphysics: Fall terms

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

ARW only

mp_physics=1

Kessler scheme

- Warm rain – no ice
- Idealized microphysics
- Time-split rainfall

ARW only

mp_physics=2

Purdue Lin et al. scheme

- 5-class microphysics including graupel
- Includes ice sedimentation and time-split fall terms
- Can be used with WRF-Chem aerosols

ARW only

mp_physics=3

WSM 3-class scheme

- From Hong, Dudhia and Chen (2004)
- Replaces NCEP3 scheme
- 3-class microphysics with ice
- Ice processes below 0 deg C
- Ice number is function of ice content
- Ice sedimentation
- Semi-lagrangian fall terms in V3.2

mp_physics=4

WSM 5-class scheme

- Also from Hong, Dudhia and Chen (2004)
- Replaces NCEP5 scheme
- 5-class microphysics with ice
- Supercooled water and snow melt
- Ice sedimentation
- Semi-lagrangian fall terms in V3.2

ARW only

mp_physics=14

WDM 5-class scheme

- Version of WSM5 that is double-moment for warm rain processes
- 5-class microphysics with ice
- CCN, and number concentrations of cloud and rain also predicted

mp_physics=5

Ferrier (current NAM) scheme

- Designed for efficiency
  - Advection only of total condensate and vapor
  - Diagnostic cloud water, rain, & ice (cloud ice, snow/graupel) from storage arrays – assumes fractions of water & ice within the column are fixed during advection
- Supercooled liquid water & ice melt
- Variable density for precipitation ice (snow/graupel/sleet) – "rime factor"
- mp_physics=85 (nearly identical) for HWRF

mp_physics=6

WSM 6-class scheme

- From Hong and Lim (2006, JKMS)
- 6-class microphysics with graupel
- Ice number concentration as in WSM3 and WSM5
- New combined snow/graupel fall speed
- Semi-lagrangian fall terms

ARW only

mp_physics=16

WDM 6-class scheme

- Version of WSM6 that is double-moment for warm rain processes
- 6-class microphysics with graupel
- CCN, and number concentrations of cloud and rain also predicted

mp_physics=7

ARW only

Goddard 6-class scheme

- From Tao et al.
- 6-class microphysics with graupel
- Based on Lin et al. with modifications for ice/water saturation
- gsfcgce_hail switch for hail/graupel properties
- gsfcgce_2ice switch for removing graupel or snow processes
- Time-split fall terms with melting

mp_physics=8

New Thompson et al. scheme in V3.1

- Replacement of Thompson et al. (2007) scheme that was option 8 in V3.0
- 6-class microphysics with graupel
- Ice and rain number concentrations also predicted (double-moment ice)
- Time-split fall terms

mp_physics=9

ARW only

Milbrandt-Yau 2-moment scheme

- New in Version 3.2
- 7-class microphysics with separate graupel and hail
- Number concentrations predicted for all six water/ice species (double-moment) - 12 variables
- Time-split fall terms

mp_physics=10

ARW only

Morrison 2-moment scheme

- Since Version 3.0
- 6-class microphysics with graupel
- Number concentrations also predicted for ice, snow, rain, and graupel (double-moment)
- Time-split fall terms
- Can be used with WRF-Chem aerosols (V3.3)

mp_physics=13

Stonybrook University (Y. Lin, SBU) scheme

- From Lin and Colle (2010)
- 5-class microphysics (no separate graupel array)
- Riming intensity factor for mixed-phase growth
- Time-split fall terms
- New in V3.3

mp_physics=17

NSSL 2-moment scheme (Mansell et al.)

- 7-class, includes graupel and hail and all number concentrations
- Also predicts graupel volume (density)
- Time-split fall terms
- New in V3.4

mp_physics=18

NSSL 2-moment scheme with CCN (Mansell et al.)

- 7-class, includes graupel and hail and all number concentrations
- Also predicts graupel volume (density)
- Time-split fall terms
- Adds cloud condensation nuclei number prognostic variable (currently initialized to constant)
- New in V3.4

ARW only

no_mp_heating=1

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

ARW only

mp_zero_out

Microphysics switch (also mp_zero_out_thresh)

- 1: all values less than threshold set to zero (except vapor)
- 2: as 1 but vapor also limited ≥ 0
- Note: this option will not conserve total water
- Not needed when using positive definite advection
- NMM: Recommend mp_zero_out=0

NMM only

nphs

- Time steps between microphysics calls
- Same as parameter for turbulence/PBL/LSM
- Typical value is chosen to give a frequency of 1-3 minutes, i.e. 60/dt to 180/dt

* Advects only total condensate Nn= CCN number

Microphysics schemes in V3.4

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

Microphysics Options

Recommendations about choice

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

ARW only

Rainfall Output

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

ARW only

Rainfall Output

Options for "buckets"

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

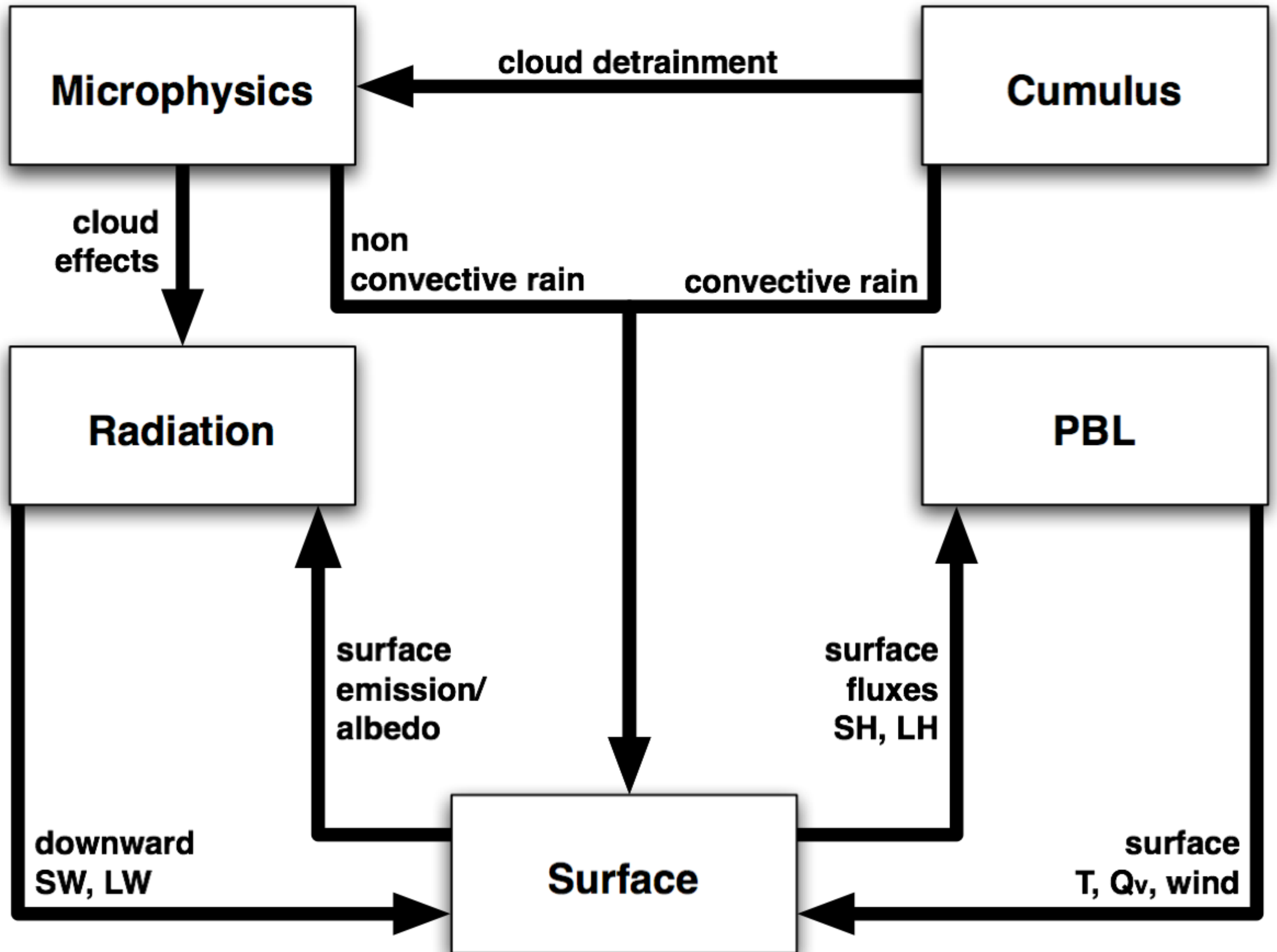
NMM only

Rainfall Output

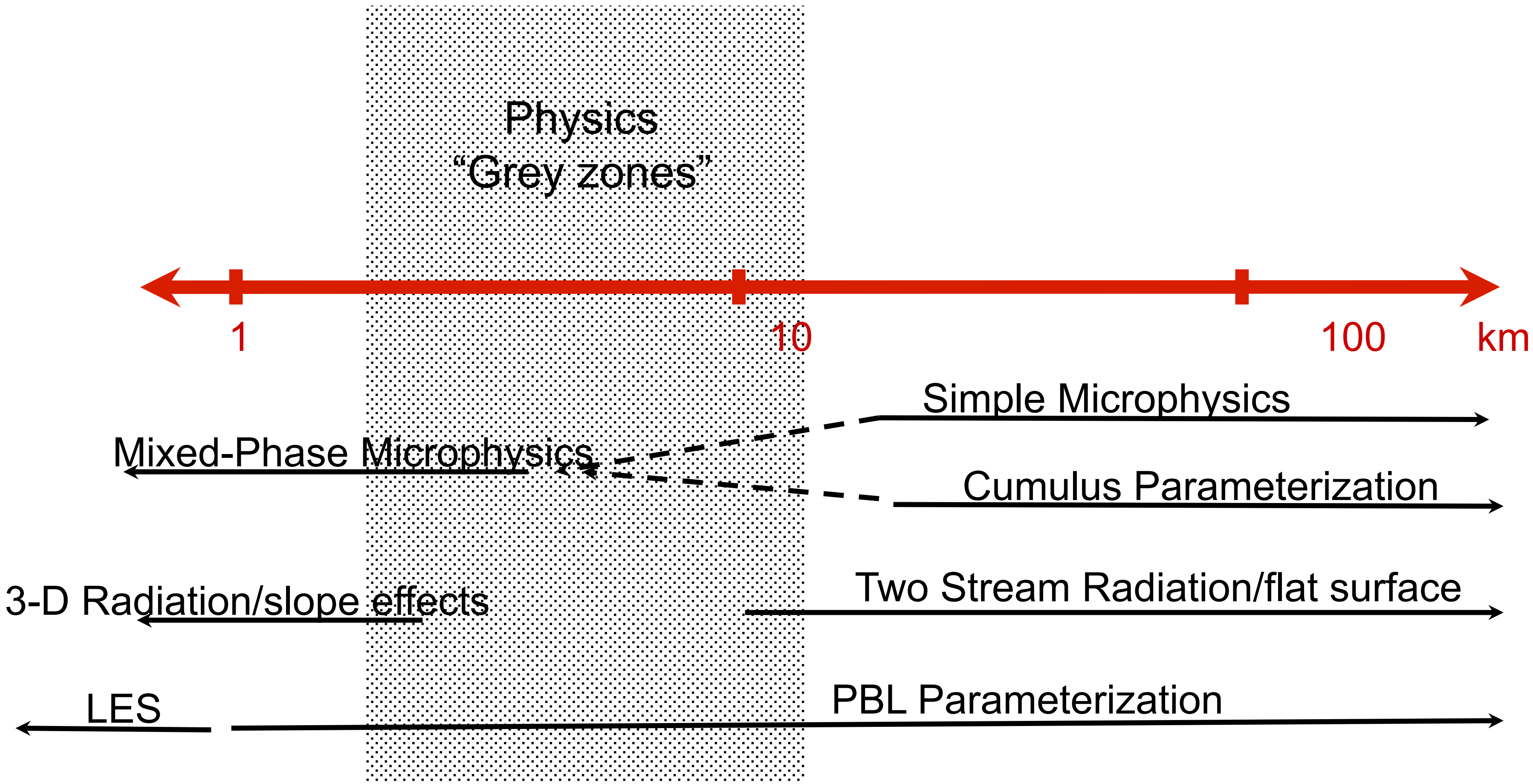
- Cumulus and microphysics can be run at the same time
- NMM outputs rainfall accumulations in mm
- TPREC controls zeroing out frequency
- ACPREC is the total precipitation
- CUPREC is the part that comes from the cumulus scheme
- The microphysics part is ACPREC-CUPREC

Physics Interactions

Direct Interactions of Parameterizations



Physics in Multiscale NWP Model



Turbulence/Diffusion

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

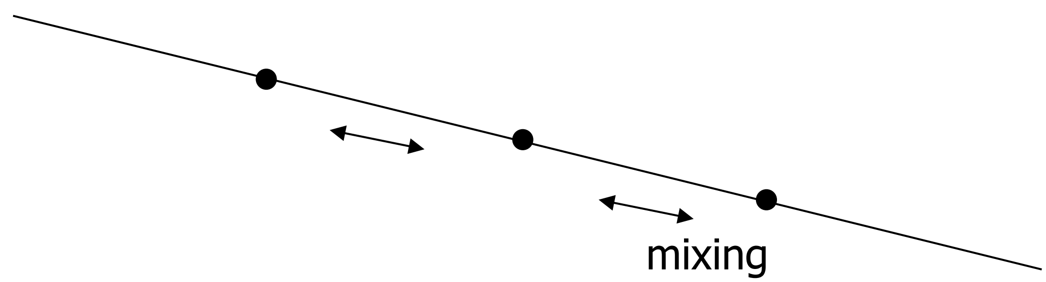
$$\frac{\partial}{\partial x} K_h \frac{\partial}{\partial x}\theta + \frac{\partial}{\partial y} K_h \frac{\partial}{\partial y}\theta + \frac{\partial}{\partial z} K_v \frac{\partial}{\partial z}\theta$$

ARW only

diff_opt=1

- 2nd order diffusion on model levels
  - Constant vertical coefficient (kvdif) or use with PBL
  - For theta, only perturbation from base state is diffused
- km_opt selects method to compute K
  - 1: constant (khdif and kvdif used)
  - 4: 2D Smagorinsky (deformation based on horizontal wind for horizontal diffusion only)

Difference between diff_opt 1 and 2

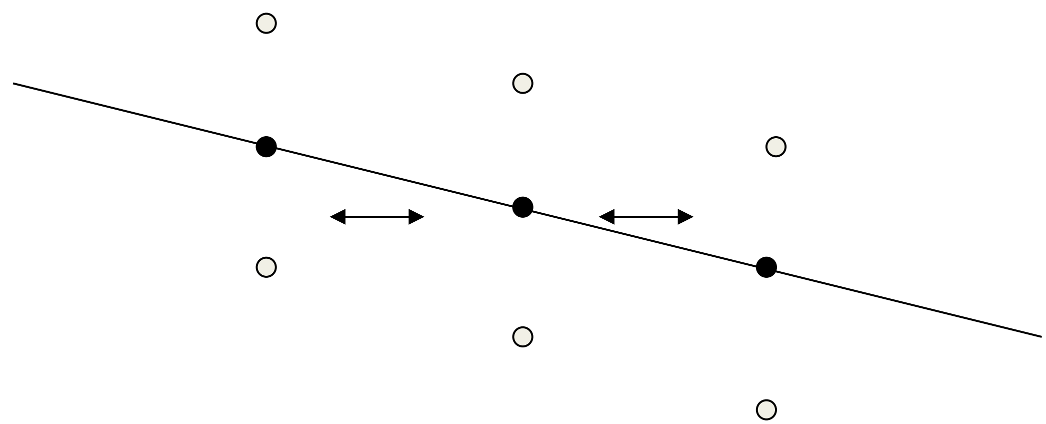


diff_opt=1

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

ARW only

diff_opt=2

- 2nd order horizontal diffusion
- Allows for terrain-following coordinate
- km_opt selects method to compute K
  - 1: constant (khdif and kvdif used)
  - 2: 1.5-order TKE prediction
  - 3: Smagorinsky (deformation/stability based K)
  - 4: 2D Smagorinsky (deformation based on horizontal wind for horizontal diffusion only)

ARW only

diff_opt=2 (continued)

- mix_full_fields=.true.: vertical diffusion acts on full (not perturbation) fields (recommended, but default = .false.)
- mix_isotropic=1: same length scale used for horizontal and vertical diffusion (for dx≈dz)
- Idealized constant surface fluxes can be added in diff_opt=2 using namelist (dynamics section). Not available for diff_opt=1.
  - tke_drag_coefficient (C_D)
  - tke_heat_flux (=$H/\rho c_p$)
  - Must use isfflx=0 to use these switches

ARW only

diff_opt=2 (continued)

- Explicit large-eddy simulation (LES) PBL in real-data cases (V3) or idealized cases
  - bl_pbl_physics = 0
    - isfflx = 0 (idealized drag and heat flux from namelist)
    - isfflx = 1 (drag and heat flux from physics)
      - sf_sfclay_physics=1
      - sf_surface_physics (choose non-zero option)
    - isfflx = 2 (drag from physics, heat flux from tke_heat_flux)
      - sf_sfclay_physics=1
  - km_opt = 2 or 3
  - mix_isotropic=1 (if dx and dz are of same order)
- Not available for diff_opt=1.

ARW only

km_opt

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

ARW only

sfs_opt

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

Diffusion Option Choice

- Real-data case with PBL physics on
  - Best is diff_opt=1, km_opt=4
  - This complements vertical diffusion done by PBL scheme
- High-resolution real-data cases (~100 m grid)
  - No PBL
  - diff_opt=2; km_opt=2,3 (tke or Smagorinsky scheme)
- Idealized cloud-resolving (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
- Note: WRF can run with no diffusion (diff_opt=0)

ARW only

diff_6th_opt

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

ARW only

Upper damping (damp_opt)

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

Options

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

All options use

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

ARW only

damp_opt=1

- Upper level diffusive layer
- Enhanced horizontal diffusion at top
- Also enhanced vertical diffusion at top for diff_opt=2
- Cosine function of height
- Uses additional parameters
  - zdamp: depth of damping layer
  - dampcoef: nondimensional maximum magnitude of damping
- Works for idealized cases and real-data since 2.2 release

ARW only

damp_opt=2

- Upper level relaxation towards 1-d profile
- Rayleigh (relaxation) layer
- Cosine function of height
- Uses additional parameters
  - zdamp: depth of damping layer
  - dampcoef: inverse time scale (s^{-1})
- Works for idealized cases only

ARW only

damp_opt=3

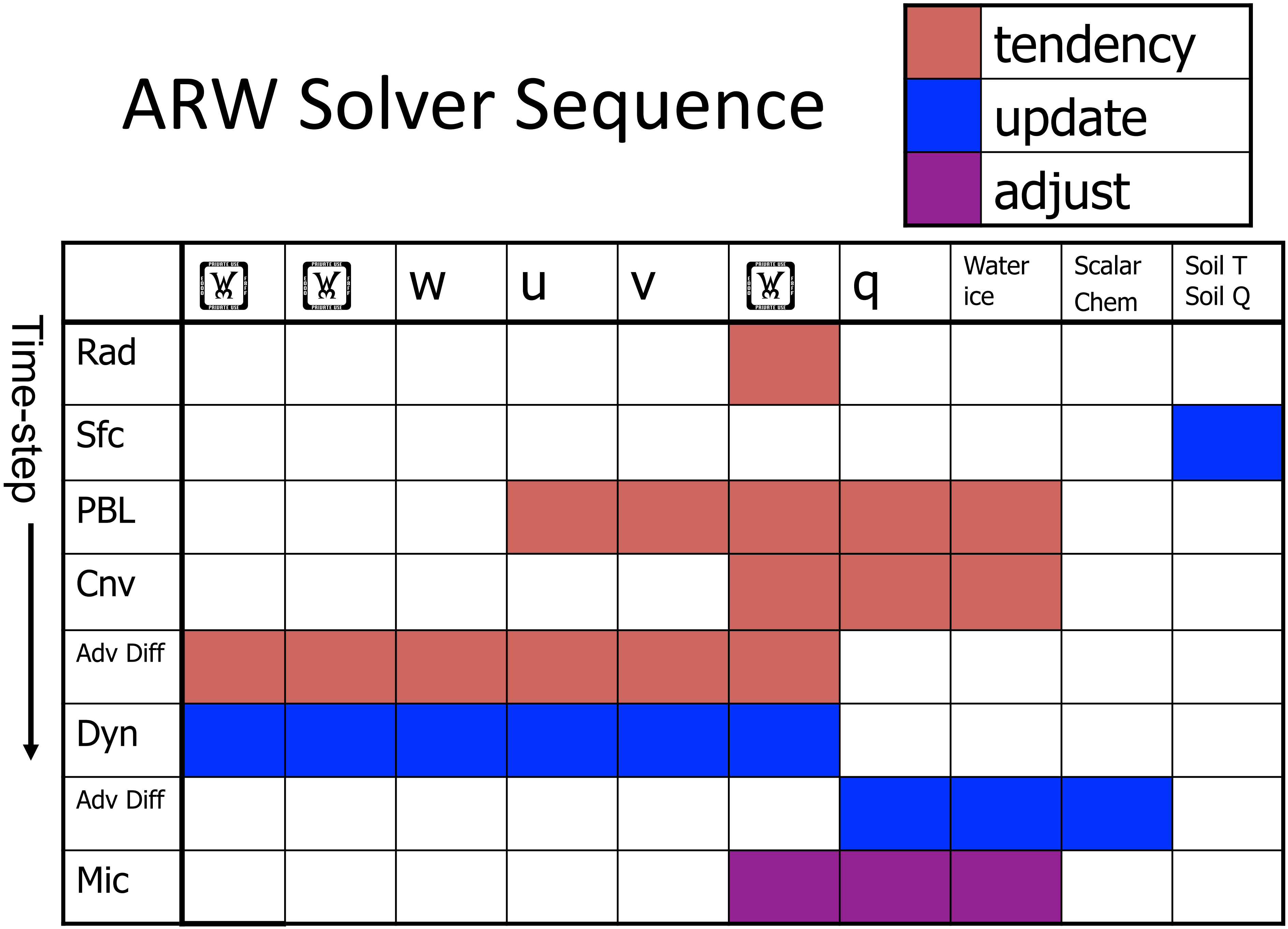
- “W-Rayleigh” (relaxation) layer
- Upper level relaxation towards zero vertical motion
- Cosine function of height
- Uses additional parameters
  - zdamp: depth of damping layer
  - dampcoef: inverse time scale (s^{-1})
- Works for idealized and real-data cases
- Applied in small time-steps (dampcoef=0.2 is stable)

Solver Calling Sequence (ARW example)

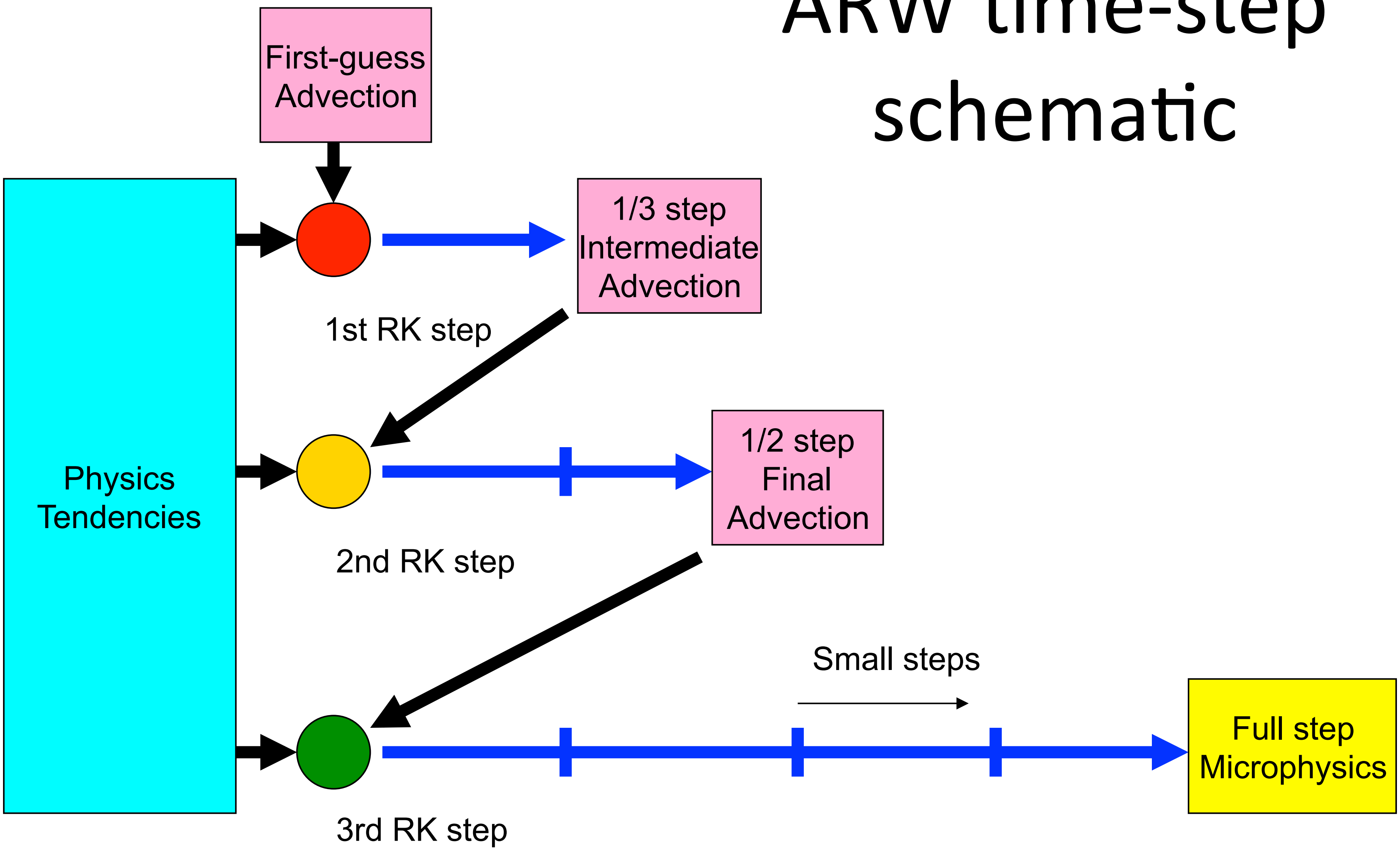
Call to solver advances one domain by one model time-step

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

ARW Solver Sequence



ARW time-step schematic



&physics

Seven major physics categories:

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

End

Summary of Boundary Layer, Microphysics and Cumulus Options

Jimy Dudhia
NCAR/MMM

PBL schemes in V3.3

bl_pbl_ physics	Scheme	Reference	Added
1	YSU	Hong, Noh and Dudhia (2006, MWR)	2004
2	MYJ	Janjic (1994, MWR)	2000
3	GFS	Hong and Pan (1996, MWR)	2005
4	QNSE	Sukoriansky, Galperin and Perov (2005, BLM)	2009
5	MYNN2	Nakanishi and Niino (2006, BLM)	2009
6	MYNN3	Nakanishi and Niino (2006, BLM)	2009
7	ACM2	Pleim (2007, JAMC)	2008
8	BouLac	Bougeault and Lacarrere (1989, MWR)	2009
9	UW	Bretherton and Park (2009, JC)	2011
10	TEMF	Angevine, Jiang and Mauritsen (2010, MWR)	2011
99	MRF	Hong and Pan (1996, MWR)	2000

PBL schemes in V3.3

3.3 changes

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

LES schemes

Unified horizontal and vertical mixing (for dx~dz).

Typically needed for dx<~200 m. Also use mix_isotropic=1.

bl_pbl_physics	diff_opt	km_opt	Scheme	Cores	sf_sfclay_physics	isfflx	Prognostic variables
0	2	2	tke	ARW	0,1,2	0,1,2	tke
0	2	3	3d Smagorinsky	ARW	0,1,2	0,1,2	

Namelist isfflx controls surface flux methods

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

Microphysics schemes in V3.3

mp_physics	Scheme	Reference	Added
1	Kessler	Kessler (1969)	2000
2	Lin (Purdue)	Lin, Farley and Orville (1983, JCAM)	2000
3	WSM3	Hong, Dudhia and Chen (2004, MWR)	2004
4	WSM5	Hong, Dudhia and Chen (2004, MWR)	2004
5	Eta (Ferrier)	Rogers, Black, Ferrier et al. (2001)	2000
6	WSM6	Hong and Lim (2006, JKMS)	2004
7	Goddard	Tao, Simpson and McCumber (1989,MWR)	2008
8	Thompson (+old)	Thompson et al. (2008, MWR)	2009
9	Milbrandt 2-mom	Milbrandt and Yau (2005, JAS)	2010
10	Morrison 2-mom	Hong and Pan (1996, MWR)	2008
13	SBU-Ylin	Lin and Colle (2011, MWR)	2011
14	WDM5	Lim and Hong (2010,...)	2009
16	WDM6	Lim and Hong (2010,…)	2009

* Advects only total condensate ** Nn= CCN number

Microphysics schemes in V3.3

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

Cumulus schemes in V3.3

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

Cumulus schemes in V3.3

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