Overview of WRF Physics
Boundary Layer and Turbulence

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NCAR/MMM

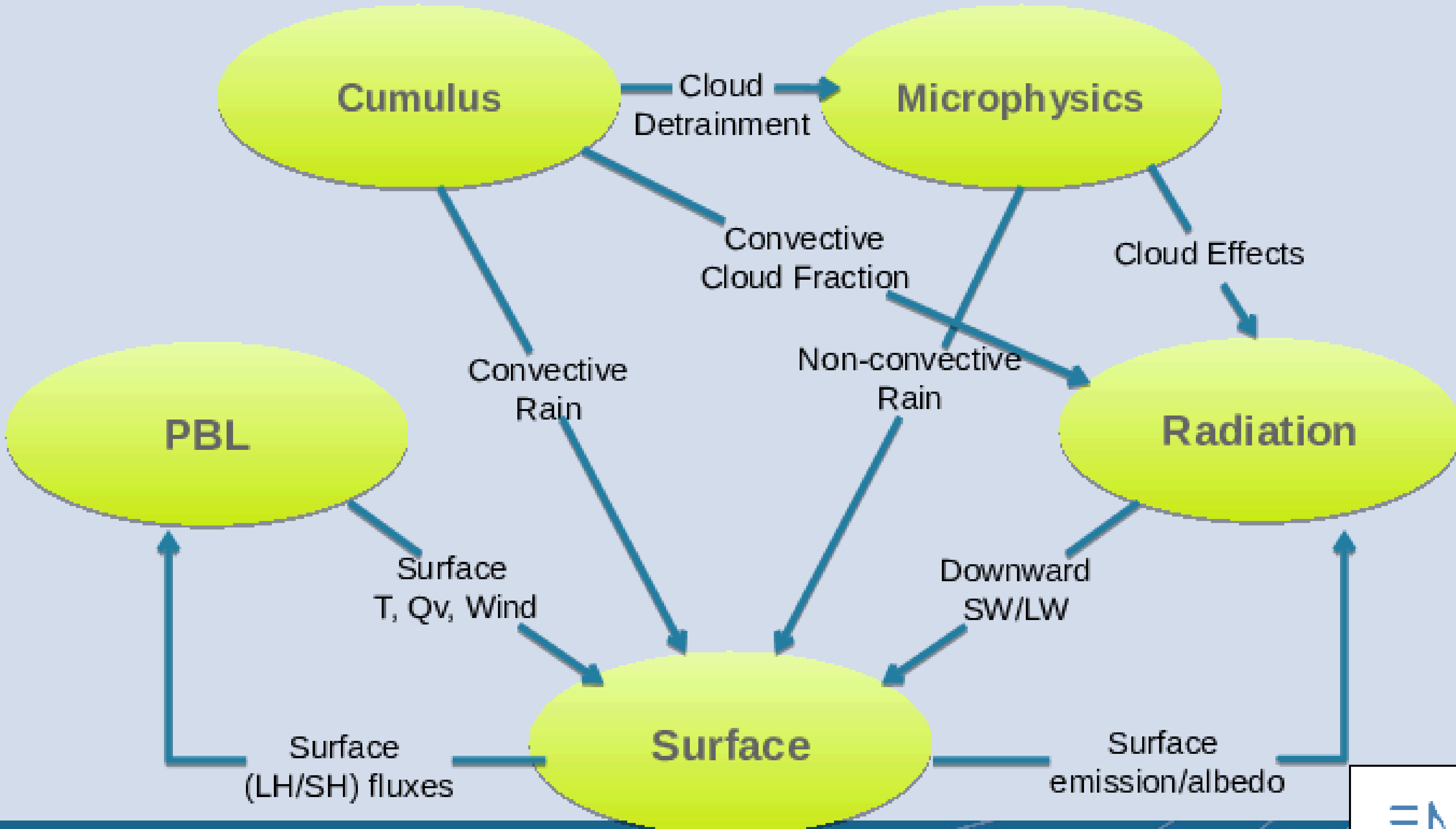
2023

This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977.

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



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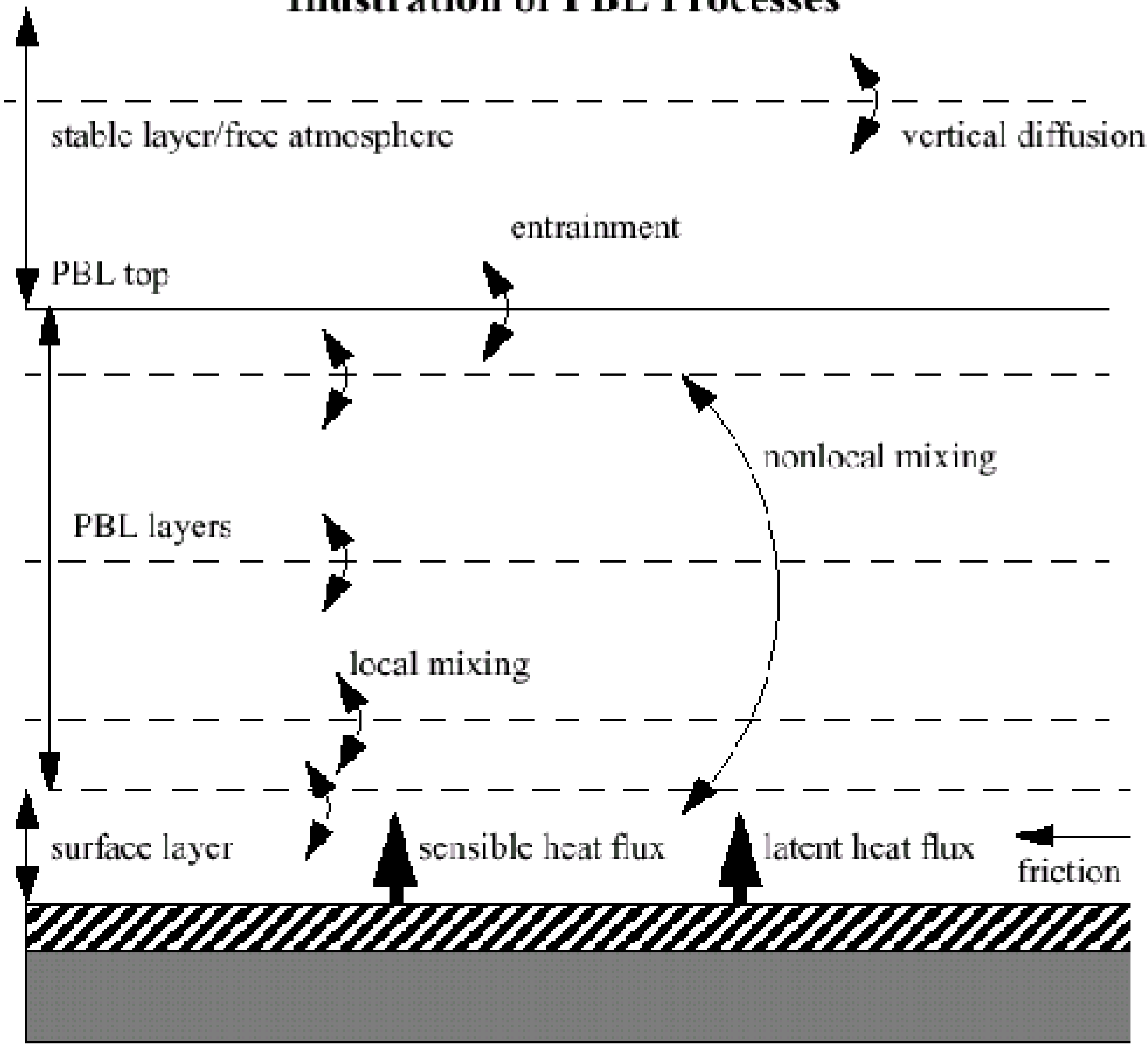
Planetary Boundary Layer

Provides

Boundary layer fluxes (heat, moisture, momentum)

Vertical diffusion in whole column

Illustration of PBL Processes



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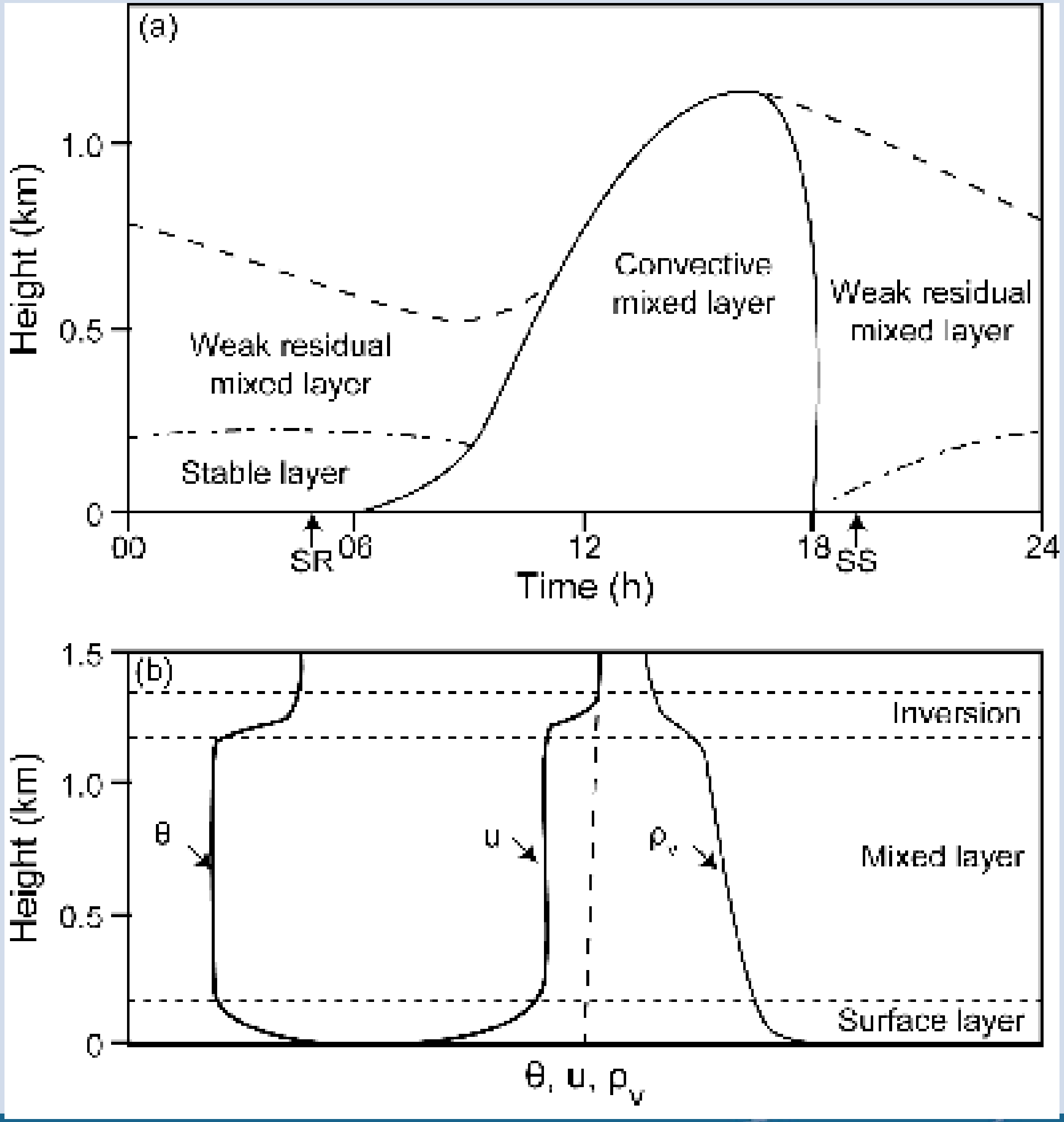
Planetary Boundary Layer



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

PBL schemes

bl_pbl_ physics	Scheme	Reference	Added
1	YSU	Hong, Noh and Dudhia (2006, MWR)	2004
2	MYJ	Janjic (1994, MWR)	2000
3	GFS	Hong and Pan (1996, MWR)	2005
4	QNSE-EDMF	Sukoriansky, Galperin and Perov (2005, BLM), Pergaud, Masson, Malardel et al. (2009, BLM)	2012
5	MYNN2	Nakanishi and Niino (2006, BLM)	2009
6	MYNN3	Nakanishi and Niino (2006, BLM)	2009
7	ACM2	Pleim (2007, JAMC)	2008
8	BouLac	Bougeault and Lacarrere (1989, MWR)	2009
9	UW	Bretherton and Park (2009, JC)	2011
10	TEMF	Angevine, Jiang and Mauritsen (2010, MWR)	2011
11	SH	Shin and Hong (2015, MWR)	2015
12	GBM	Grenier and Brethertion (2001, MWR)	2013
99	MRF	Hong and Pan (1996, MWR)	2000

Nonlocal PBL schemes

Non-local schemes have two main components

$$\overline{w'\phi'}^{\Delta} = \underbrace{-K_{\phi}\frac{\partial \overline{\phi}^{\Delta}}{\partial z}}_{(1)} + \underbrace{F^{NL}_{w\phi}}_{(2)}$$

(1) Term for local (L) transport by small eddies

(2) Term for nonlocal (NL) transport by large eddies

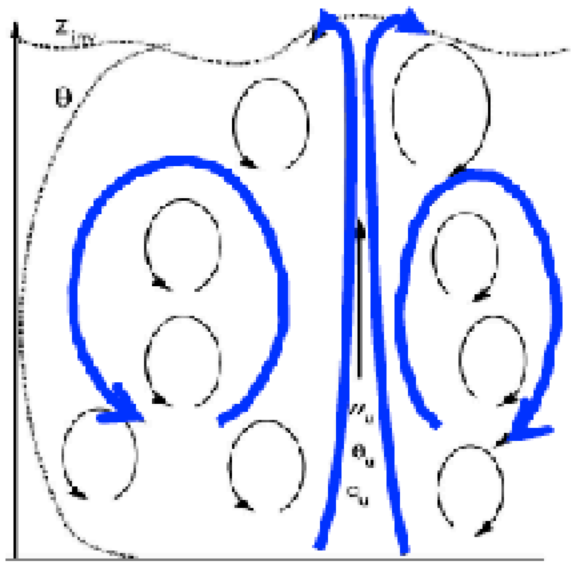


FIG. 1. Sketch of a convective updraft embedded in a turbulent eddy structure

Explicitly included in **nonlocal PBL parameterizations**

(i.e., Mass-flux term or counter-gradient gamma)

Figure is taken from Siebesma et al. (2007, JAS)

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TKE schemes

- Solve for TKE in each column
  - Buoyancy and shear production
  - Dissipation
  - Vertical mixing
- TKE (*e*) and length-scale (*l*) are used to determine the Kv for local vertical mixing together with a stability function (S)

$$K_v = e^{1/2}\ l\ S$$

- Schemes differ most in diagnostic length-scale computations and how S is calculated

Nonlocal Schemes

- Diagnose a PBL top (either stability profile or Richardson number)
- Specify a K profile
  - E.g. cubic function of *z* with max in mid-PBL
- YSU, MRF, GFS include a non-gradient term (Γ)
  - YSU also has explicit entrainment term
- ACM2, TEMF, QNSE-EDMF, MYNN-EDMF include a mass-flux profile, M, which is an additional updraft flux

Vertical Mixing Coefficient

- Several schemes also output exch_h which is Kv for scalars that is used by WRF-Chem
- WRF can do scalar and tracer vertical mixing with PBL K-coefficients
  - scalar_pblmix=1, tracer_pblmix=1
- PBL schemes themselves only mix limited variables: momentum, heat, vapor and some specific cloud variables
- Due to numerical time step constraints on large K values found in convective PBLs, vertical diffusion is done implicitly in PBL schemes which involves solving a tridiagonal matrix given the K profile and initial variable profile

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 (MYNN-EDMF, QNSE-EDMF and TEMF)
  - only from cloud base (GBM and UW PBL)
- Some schemes (YSU, MYNN, GBM) include capability of top-down mixing for turbulence driven by cloud-top radiative cooling which is separate from bottom-up surface-flux-driven mixing

PBL schemes

bl_pbl_physics	Scheme	Cores	sf_sfclay_physics	Prognostic variables	Diagnostic variables	Cloud mixing
1	YSU	ARW NMM	1,91		exch_h	QC,QI
2	MYJ	ARW NMM	2	TKE_PBL	EL_PBL, exch_h	QC,QI
3	GFS(hwrf)	NMM	3			QC,QI
4	QNSE-EDMF	ARW NMM	4	TKE_PBL	EL_PBL, exch_h, exch_m	QC,QI
5	MYNN2	ARW	1,2,5,91	QKE	Tsq, Qsq, Cov, exch_h, exch_m	QC
6	MYNN3	ARW	1,2,5,91	QKE, Tsq, Qsq, Cov	exch_h, exch_m	QC
7	ACM2	ARW	1,7,91			QC,QI
8	BouLac	ARW	1,2,91	TKE_PBL	EL_PBL, exch_h, exch_m	QC
9	UW	ARW	1,2,91	TKE_PBL	exch_h, exch_m	QC
10	TEMF	ARW	10	TE_TEMF	*_temf	QC, QI
11	SH	ARW	1,91		Exch_h	QC, QI
12	GBM	ARW	1,91	TKE_PBL	EL_PBL,exch_h, exch_m	QC, QI
99	MRF	ARW NMM	1,91			

PBL Scheme Options

- PBL schemes can be used for most grid sizes when surface fluxes are present
- Lowest level should be in the surface layer (0.1h)
  - Important for surface (2m, 10m) diagnostic interpolation
- With ACM2, GFS and MRF PBL schemes, lowest full level should be .99 or .995 (not too close to 1)
- TKE schemes and YSU can use thinner surface layers
- Assumes that PBL eddies are not resolved
- At grid size dx << 1 km, this assumption breaks down
  - Can use 3d diffusion instead of a PBL scheme (coupled to surface physics)
  - Works best when dx and dz are comparable

Other Options

- For YSU
  - topo_wind=1,2: surface stress correction for terrain effects (sub-grid and resolved, Jimenez and Dudhia, JAMC 2012)
  - ysu_topdown_pblmix=1: cloud-top cooling-driven mixing
- For MYNN
  - Wind-farm model has been added to investigate wind-farm effects on the environment (extra stress and turbulence generation)

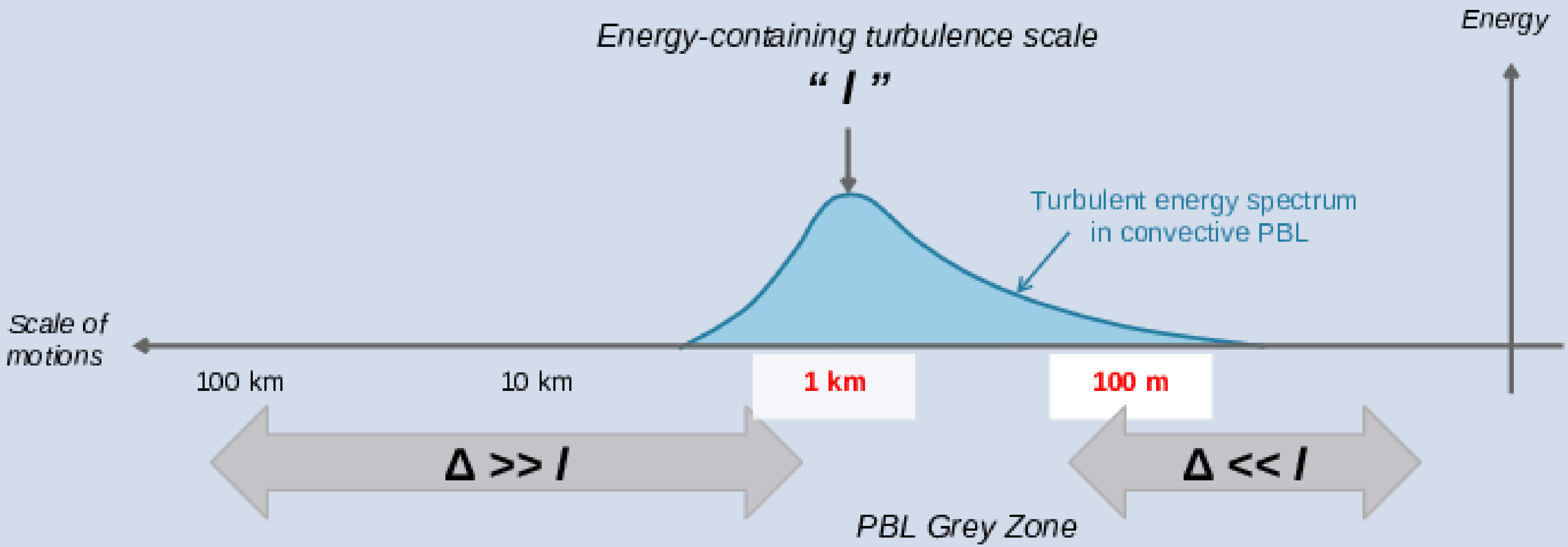
– Gravity-wave drag can be added for low resolution (> 5 km) runs to represent sub-grid orographic gravity-wave vertical momentum transport (gwd_opt=1)

– Fog: grav_settling=2 (Katata)

PBL and Land Surface Time Step (bldt)

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

Model Grid Spacing: PBL and LES



For coarse grid spacing

- ✓ **PBL schemes have been designed for Δ >> *l***
- ✓ ***All eddies are sub-grid***
- ✓ ***1d column schemes handle sub-grid vertical fluxes***

For fine grid spacing

- ✓ **LES schemes have been designed for Δ << *l***
- ✓ ***All major eddies are resolved***
- ✓ ***3d turbulence schemes handle sub-grid mixing***

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Grey-Zone PBL

- "Grey Zone" is sub-kilometer grids
  - PBL and LES assumptions not perfect
- Shin-Hong PBL based on YSU designed for sub-kilometer transition scales (200 m – 1 km)
  - Nonlocal mass-flux and Kv term reduce in strength as grid size gets smaller and resolved mixing increases
- New 3d tke option (km_opt=5) in V4.2
  - Becomes 3d LES at fine scale, adds scale-dependent Shin-Hong nonlocal mass flux and implicit vertical diffusion at coarse grid sizes
- Other schemes may work in this range but will not have correctly partitioned resolved/sub-grid energy fractions

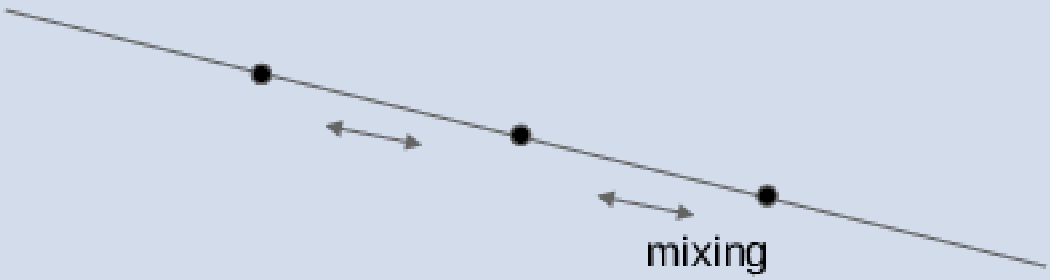
Turbulence/Diffusion

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

Diffusion Option (diff_opt)

- Selects numerical method especially for horizontal diffusion (see next slides)
- When diffusion is used with a PBL scheme, vertical diffusion is deactivated, so *diff_opt* only affects horizontal diffusion
- Option *diff_opt=1* is limited to constant vertical diffusion coefficient (*kvdif*)
  - should not be used with calculated diffusion coefficient options (*km_opt=2,3*)
  - can be used with PBL schemes which include vertical diffusion internally
- Option *diff_opt=2* is strictly horizontal and better for complex terrain – avoids diffusion up and down slopes that *diff_opt=1* has

Difference between diff_opt 1 and 2

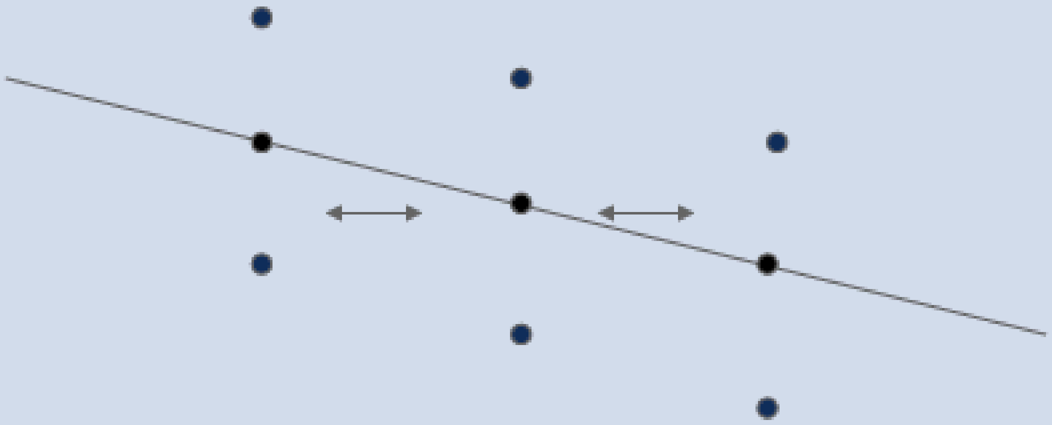


diff_opt=1

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 strictly horizontal gradients

Numerical method includes vertical correction term using more grid points

For stability, diffusion strength is reduced in steep coordinate slopes (Δz ~ Δx)

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
- Explicit vertical diffusion in diff_opt=2 replaces the PBL scheme and can accept surface fluxes from surface physics as input (can be run with full physics real-data cases)
- TKE and 3d Smagorinsky options exist for the sub-grid turbulence
- TKE is also an advected variable in the LES option
  - Of the PBL schemes only MYNN has a TKE advection option

Large-Eddy Simulation

- To run LES mode
  - Use bl_pbl_physics=0 and diff_opt=2 with km_opt=2 or 3
  - This scheme can also use real surface fluxes from the surface physics (heat, moisture, momentum stress) or idealized constant values
  - Best to use dx~dz especially in boundary layer and avoid stretching to very large dz/dx aspect ratios at upper levels
    - Note: seems to work better with continuous stretching to top than with fixed upper level dz when dz >> dx

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

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Turbulent Kinetic Energy Option (km_opt=2)

- Prognostic tke with advection, diffusion (not shown), sources and sinks

$$K_{h,v} = C_k l_{h,v} \sqrt{e},$$

$$\partial_t(\mu_d e) + \nabla \cdot \mathbf{V} e = \mu_d(\text{ shear production } + \text{ buoyancy } + \text{ dissipation }).$$

$$\text{shear production} = K_h D_{11}^2 + K_h D_{22}^2 + K_v D_{33}^2 + K_h {D_{12}^2}^{xy} + K_v {D_{13}^2}^{x\eta} + K_v {D_{23}^2}^{y\eta}.$$

$$\text{buoyancy} = -K_v N^2,$$

$$\text{dissipation} = -\frac{C e^{3/2}}{l},$$

ARW Tech Note for details

3d Smagorinsky Option (km_opt=3)

- K computed directly from deformation components (velocity gradients, D terms) and stability N.

$$K_{h,v} = C_s^2 \, l_{h,v}^2 \max\left[0., \left(D^2 - P_r^{-1} N^2\right)^{\frac{1}{2}}\right],$$

$$D^2 = \frac{1}{2}\left[D_{11}^2 + D_{22}^2 + D_{33}^2\right] + \left(\overline{D_{12}}^{xy}\right)^2 + \left(\overline{D_{13}}^{x\eta}\right)^2 + \left(\overline{D_{23}}^{y\eta}\right)^2,$$

ARW Tech Note for details

km_opt

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

sfs_opt

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

Diffusion Option Choice

- Real-data case with PBL physics on
  - Best is diff_opt=2, km_opt=4
    - Less diffusive in complex terrain while diff_opt=1 diffuses along slopes
  - This complements vertical diffusion done by PBL scheme
- High-resolution real-data cases (~100 m grid)
  - No PBL
  - diff_opt=2; km_opt=2,3 (tke or Smagorinsky scheme)

Diffusion Option Choice

- Idealized cloud-resolving (dx =1-3 km) modeling (smooth or no topography, no surface heat fluxes)
  - diff_opt=2; km_opt=2,3
- Complex topography with no PBL scheme
  - diff_opt=2 is more accurate for sloped coordinate surfaces, and prevents diffusion up/down valley sides but still sometimes unstable with complex terrain
  - WRF cannot generally handle slopes > 45 degrees
    - *epssm* is a sound-wave damping term that can be increased to help with steep slopes (e.g. 0.5-1.0)
- Note: WRF can run with no diffusion (diff_opt=0)

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diff_6th_opt

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

Upper damping (damp_opt)

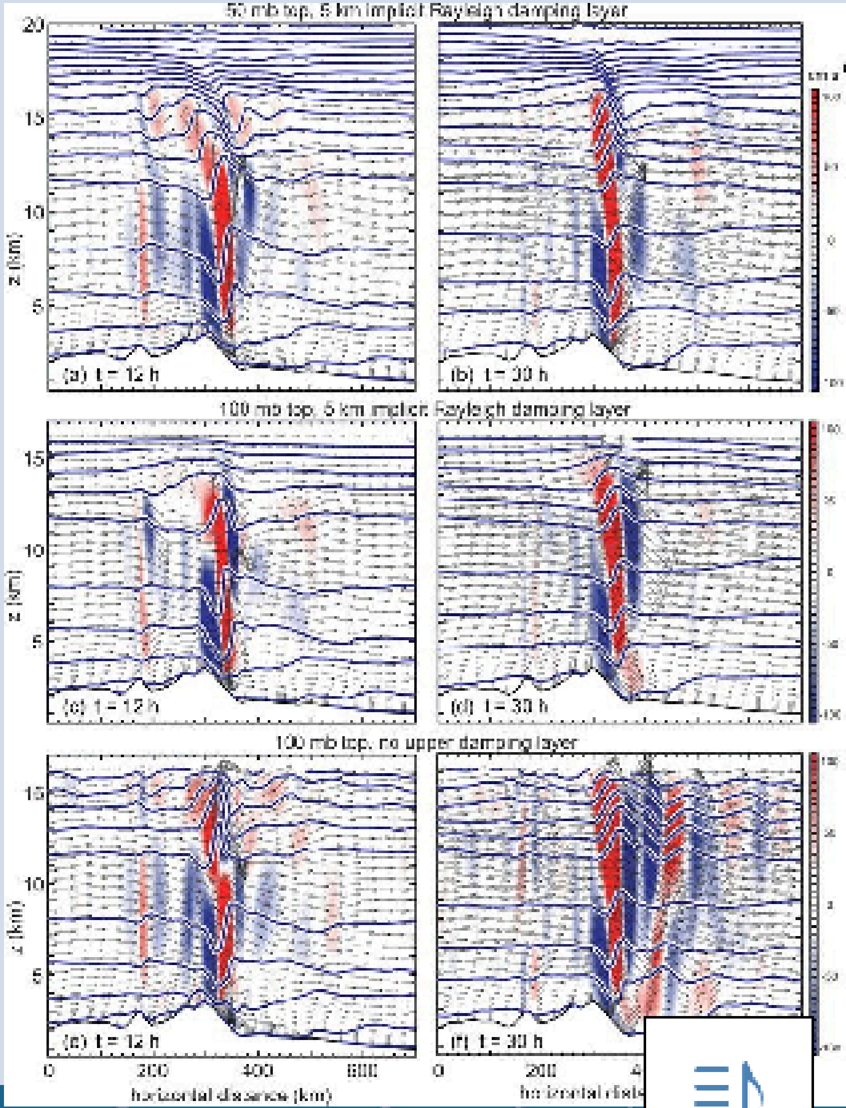
Purpose is to prevent unrealistic reflections of waves from model top. Can be important over high topography.

Options

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

All options use

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



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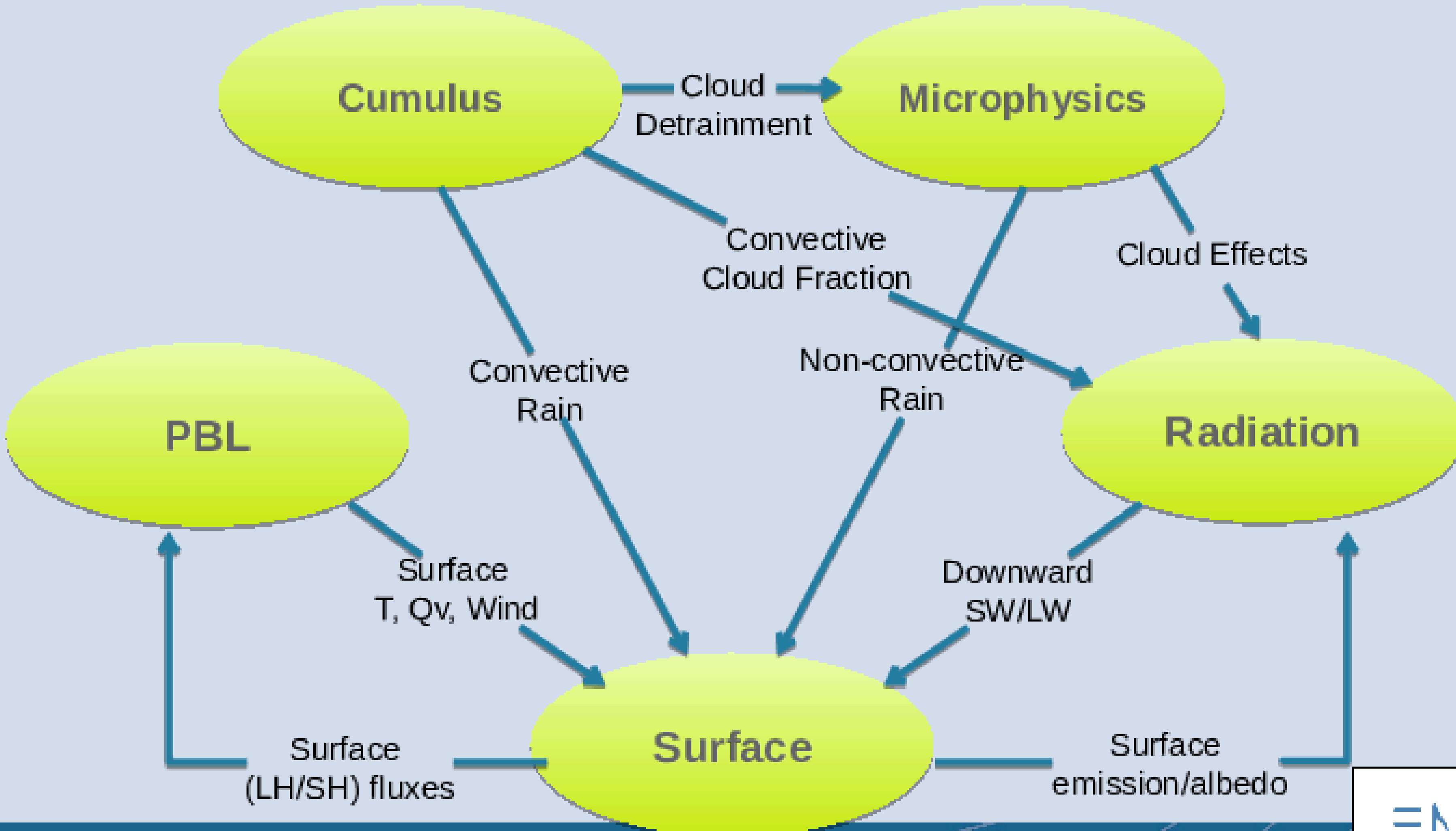

PBL/Turbulence Summary

- Planetary Boundary Layer
  - Nonlocal PBL schemes, TKE schemes, Nonlocal flux, vertical mixing coefficient, shallow convection
- Grey Zone PBL/LES
  - Shin-Hong (1d), 3d tke
- Turbulence and Diffusion
  - diff_opt=1,2
- Large-Eddy Simulation
  - tke option, Smagorinsky option
- Filtering
  - diff_6th_opt
- Upper damping
  - damp_opt