Modeling Subgrid-Scale Transport

Jimy Dudhia
NCAR/MMM

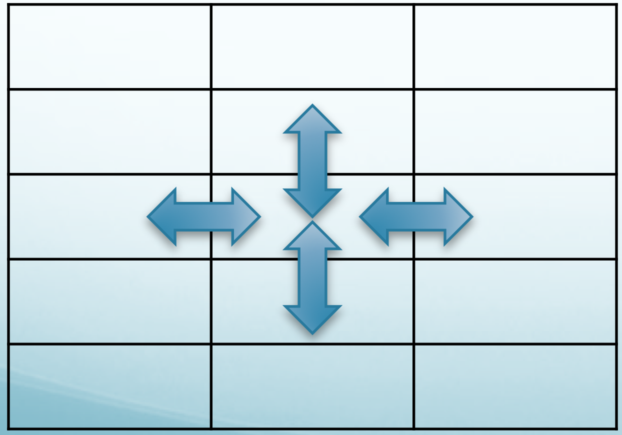
Subgrid Transport

- Model parameterizations that handle subgrid transport of scalars
  - Diffusion (horizontal and vertical)
    - Subgrid-scale eddies
  - PBL schemes (usually include/replace vertical diffusion)
    - Unresolved thermals
  - Cumulus parameterizations
    - Unresolved updrafts and downdrafts, also subsidence
  - Shallow convection schemes
    - May be included with PBL or cumulus schemes
    - Unresolved eddies or thermals (mixing or mass-flux types)

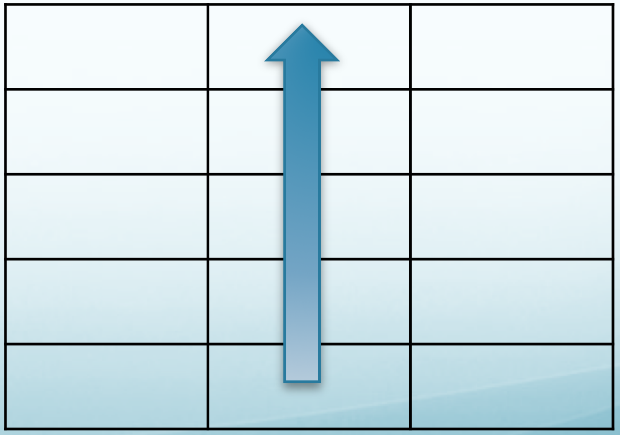
Subgrid Transport

- Two categories of sub-grid transport
  - Local (diffusion-like)
    - Eddy mixing with neighboring cells (horizontally or vertically)
  - Nonlocal (thermal-like)
    - Sub-grid mass fluxes to non-neighboring levels
    - Represented in most PBL and cumulus schemes

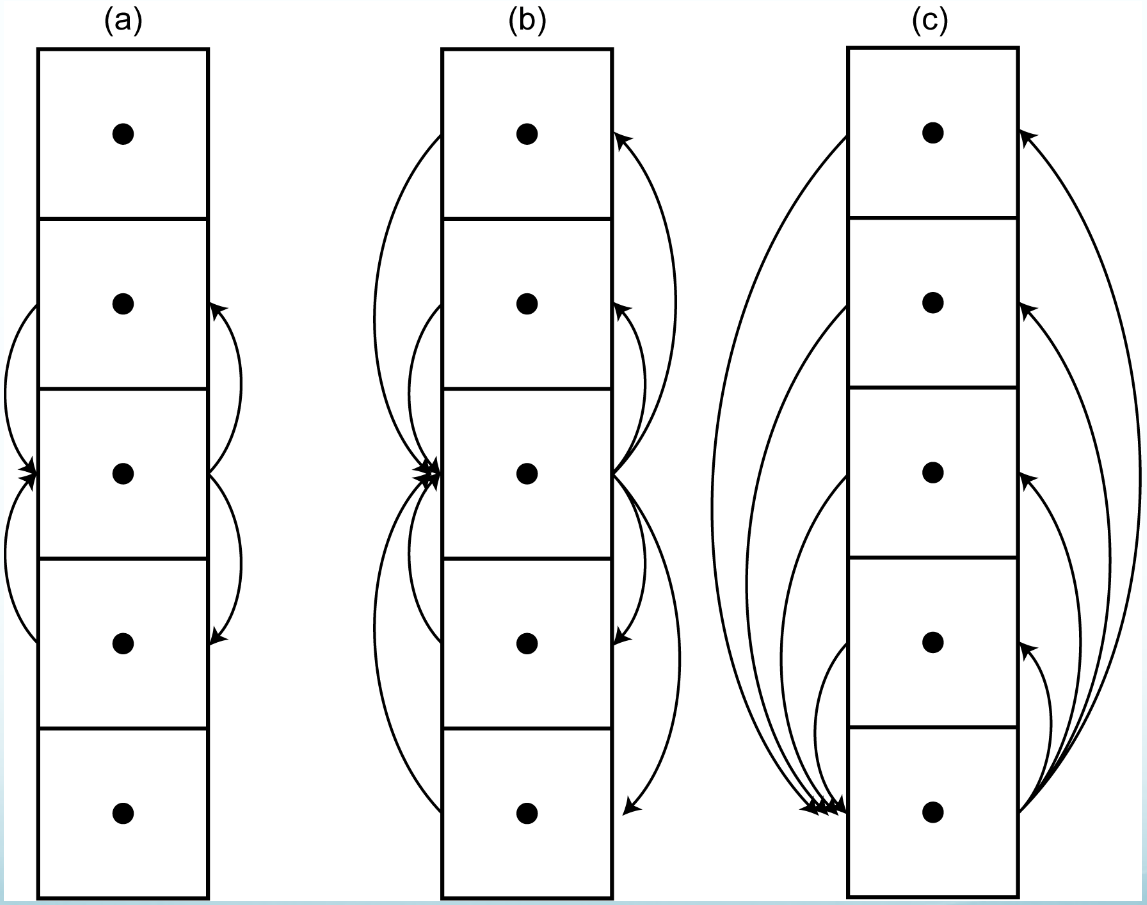
local



nonlocal



Different approaches



Local closure

Non-local closures

from Warner (2011)

Local Subgrid Transport

- For any model resolution there are always sub-grid local eddies to be represented
  - Some models may include diffusive terms for numerical purposes in addition to physical diffusion
  - Even at high enough resolution for the dynamics to resolve thermals (dx $\lesssim$100 m) and updrafts (dx $\lesssim$1 km) a model needs subgrid diffusion to represent local subgrid eddies
  - Local eddy mixing also needs to parameterize the strength of turbulence that depends on the local stability and shear
    - horizontal diffusion is treated separately from PBL/vertical mixing in coarse-grid models (dx $\gtrsim$ 1 km)
    - a more unified approach is typical as horizontal and vertical resolutions become comparable ($\lesssim$100 m LES 3d diffusion)
    - vertical diffusion in the free atmosphere may depend on Richardson number to represent clear-air turbulence or increased stratification

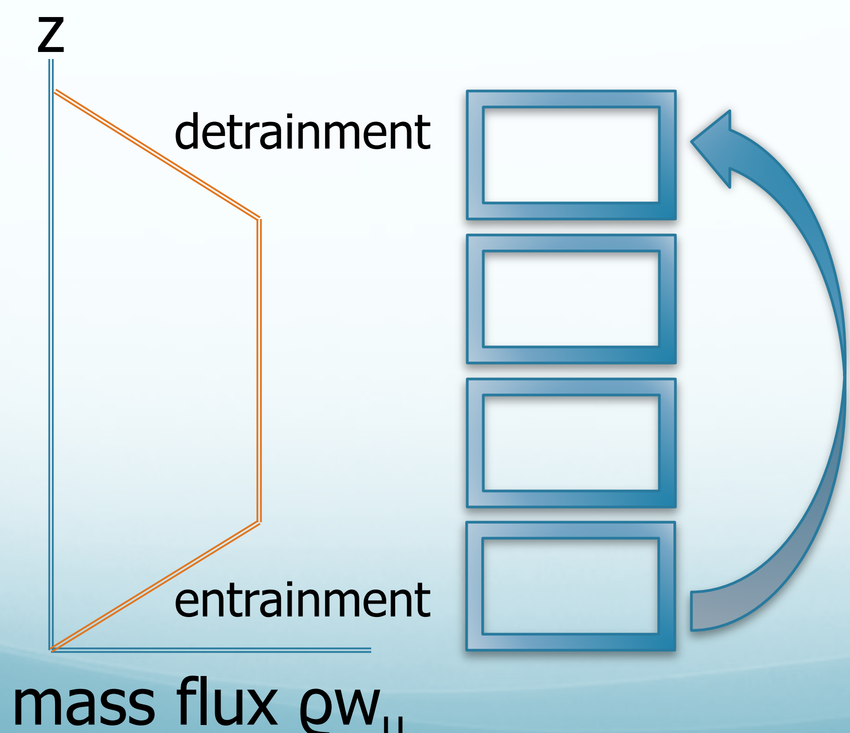
Local Subgrid Transport

- Horizontal diffusion of scalars including tracers and chemical species
  - Horizontal diffusion is typically applied to all advected variables including scalars
  - It will also apply the same diffusion coefficients to all scalars as to the meteorological variables and therefore handles numerical and physical diffusion processes for them consistently

Nonlocal Subgrid Transport

Used in

- EDMF type PBL schemes (thermals)
- mass-flux type cumulus schemes (updrafts)

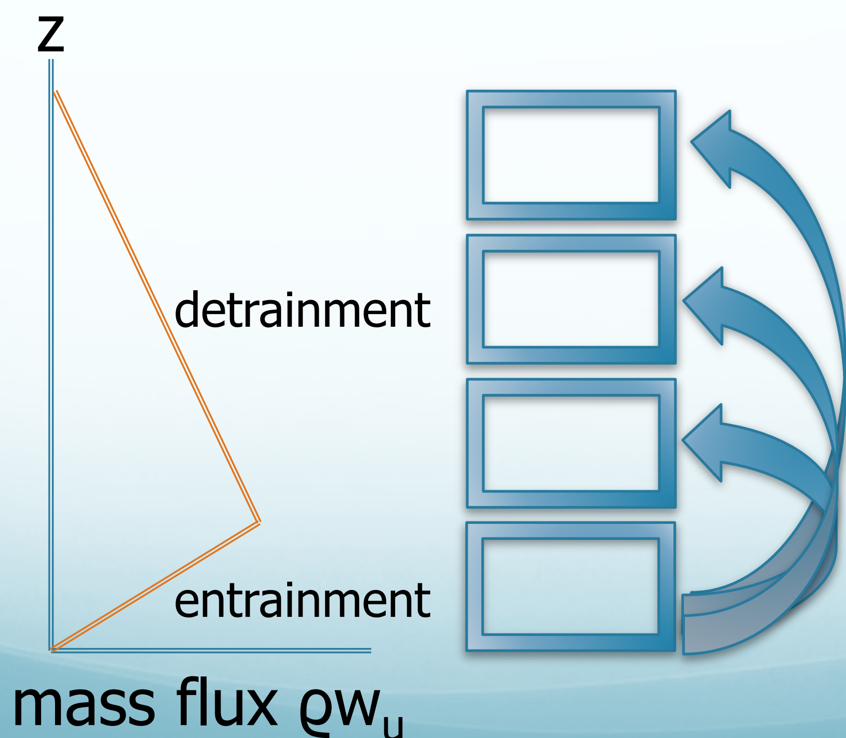


Species removed from entraining levels and added to detraining levels at rate that depends on subgrid mass flux of air (ρw_u kg m^{-2} s^{-1})

Nonlocal Subgrid Transport

Used in

- EDMF type PBL schemes (thermals)
- mass-flux type cumulus schemes (updrafts)



Species removed from entraining levels and added to detraining levels at rate that depends on subgrid mass flux of air (ϱw_u kg m^{-2} s^{-1})

Planetary Boundary Layer

Provides

Boundary layer fluxes (heat, moisture, momentum)

Vertical diffusion in whole column

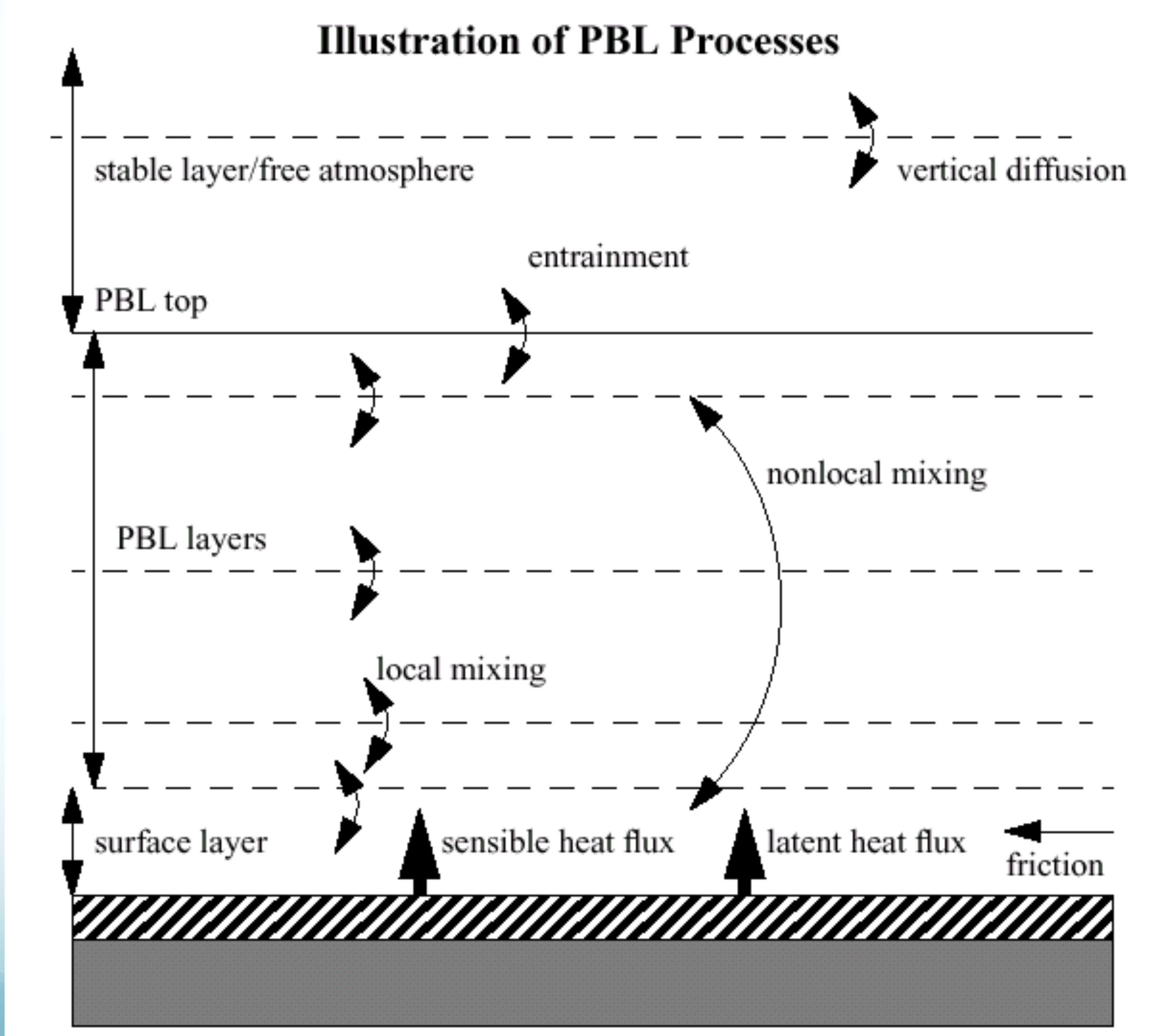
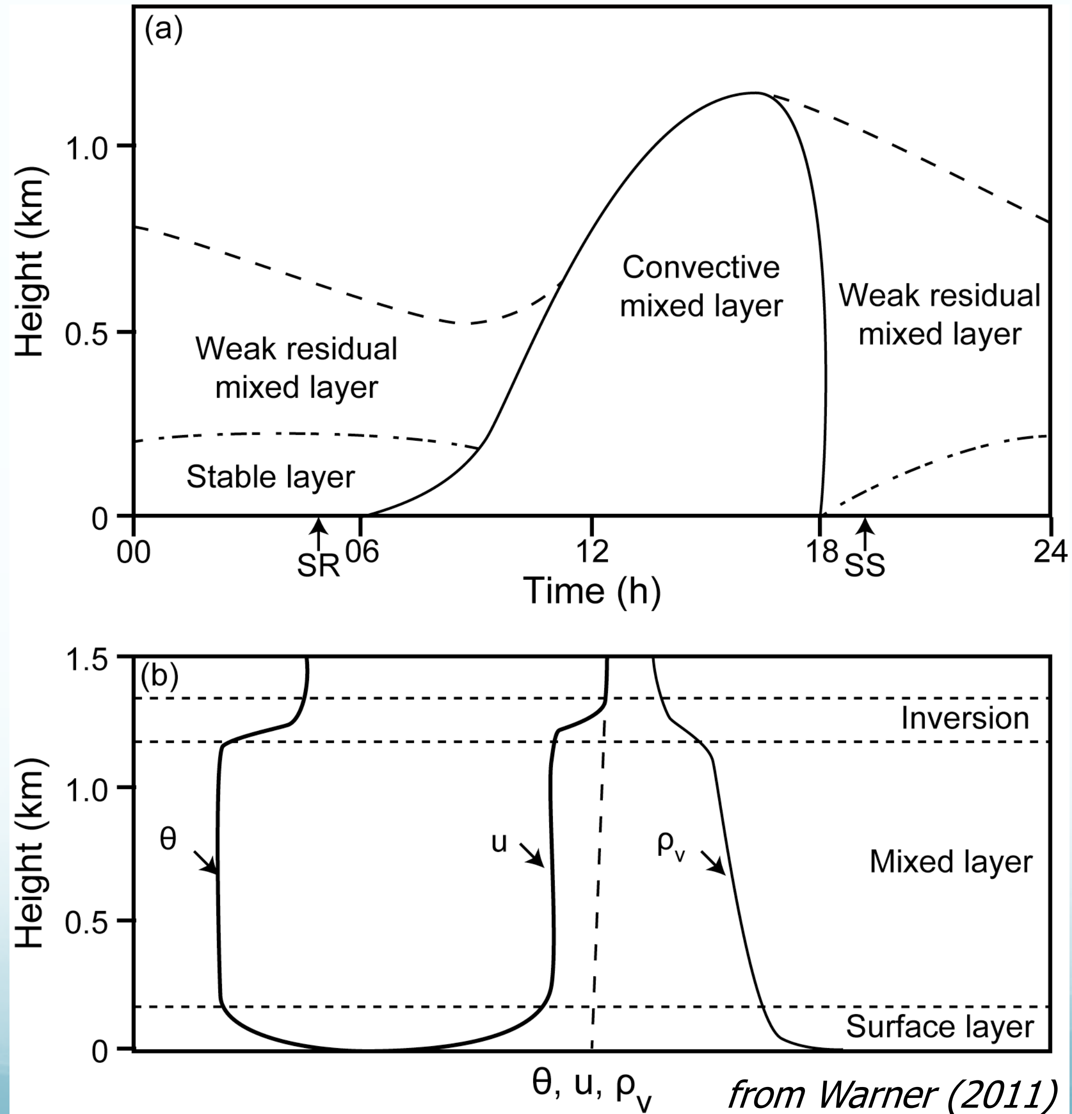
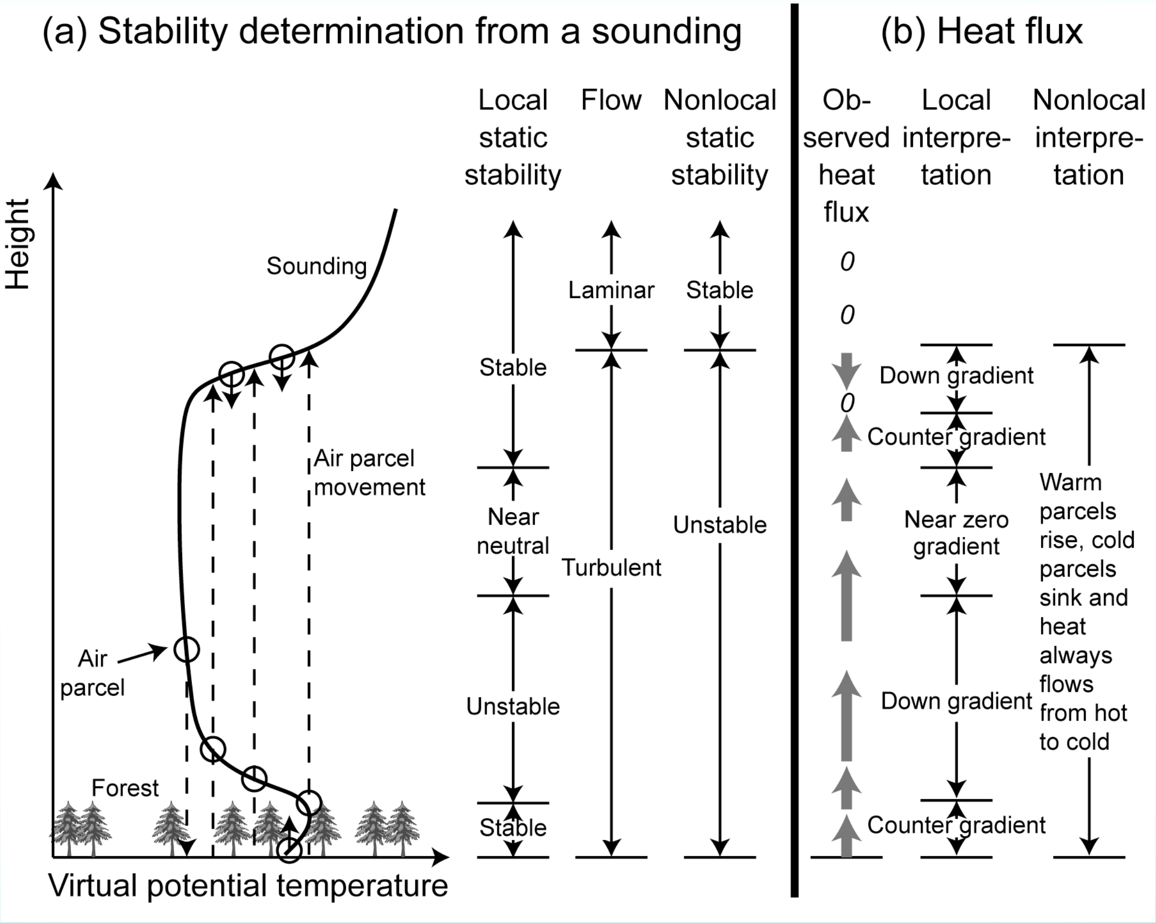


Illustration of PBL Processes
stable layer/free atmosphere
vertical diffusion
entrainment
PBL top
nonlocal mixing
PBL layers
local mixing
surface layer
sensible heat flux
latent heat flux
friction

Planetary Boundary Layer



PBL Structure and Fluxes



from Warner (2011)

WRF PBL Options

- 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

Nonlocal PBL schemes

Non-local schemes have two main components

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

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

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

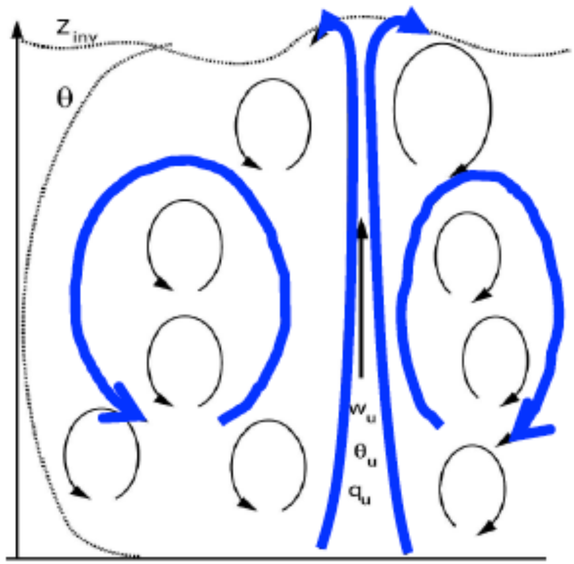


FIG. 1. Sketch of a convective updraft embedded in a turbulent eddy structure.

Explicitly included in **nonlocal PBL parameterizations**

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

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

TKE schemes

- Solve for TKE in each column
  - Buoyancy and shear production
  - Dissipation
  - Vertical mixing

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

- TKE (e) and length-scale (l) are used to determine the Kv for local vertical mixing

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

- Schemes differ most in diagnostic length-scale computations
- TKE schemes are mostly local, but some have been coupled with mass-flux schemes for thermals

Nonlocal Schemes

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

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

- 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

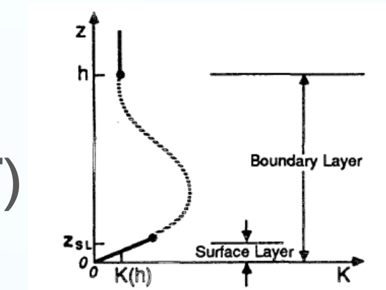


FIG. 1. Typical variation of eddy viscosity K with height in the boundary layer proposed by O'Brien (1970). Adopted from Stull (1988).

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

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

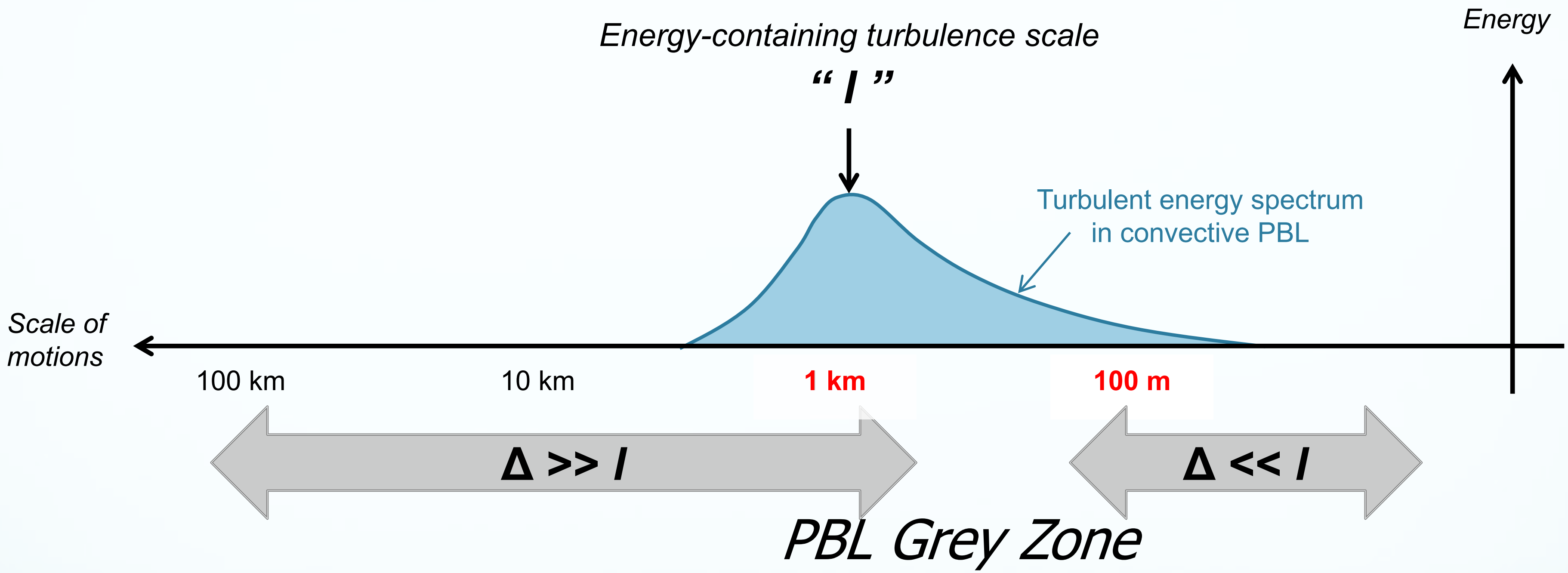
Vertical Mixing Coefficient

- Most PBL schemes in WRF also output exch_h which is Kv for scalars that is used by WRF-Chem
- 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 and adds to the K profile

Model Grid Spacing: PBL and LES



For coarse grid spacing

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

For fine grid spacing

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

Grey-Zone PBL

- “Grey Zone” is sub-kilometer grids
  - PBL and LES assumptions not perfect
- Some newer schemes are being designed for sub-kilometer transition scales (200 m – 1 km), e.g.
  - Nonlocal mixing (gamma) term reduces in strength as grid size gets smaller and resolved mixing increases (Shin and Hong 2014)
  - or turbulence/diffusion transitions from vertical 1d to 3d
- Other PBL schemes may work in this range but will not have correctly partitioned resolved/sub-grid energy fractions

Large-Eddy Simulation

- For grid sizes of up to about 100 m, LES is preferable
- LES treats turbulence three-dimensionally instead of separate vertical (PBL) and horizontal diffusion schemes
- Prognostic TKE and diagnostic (e.g. Smagorinsky) options exist for the sub-grid turbulence
- At these scales, nonlocal mixing is not needed because thermals are resolved well enough for explicit transport by the dynamics (advection)

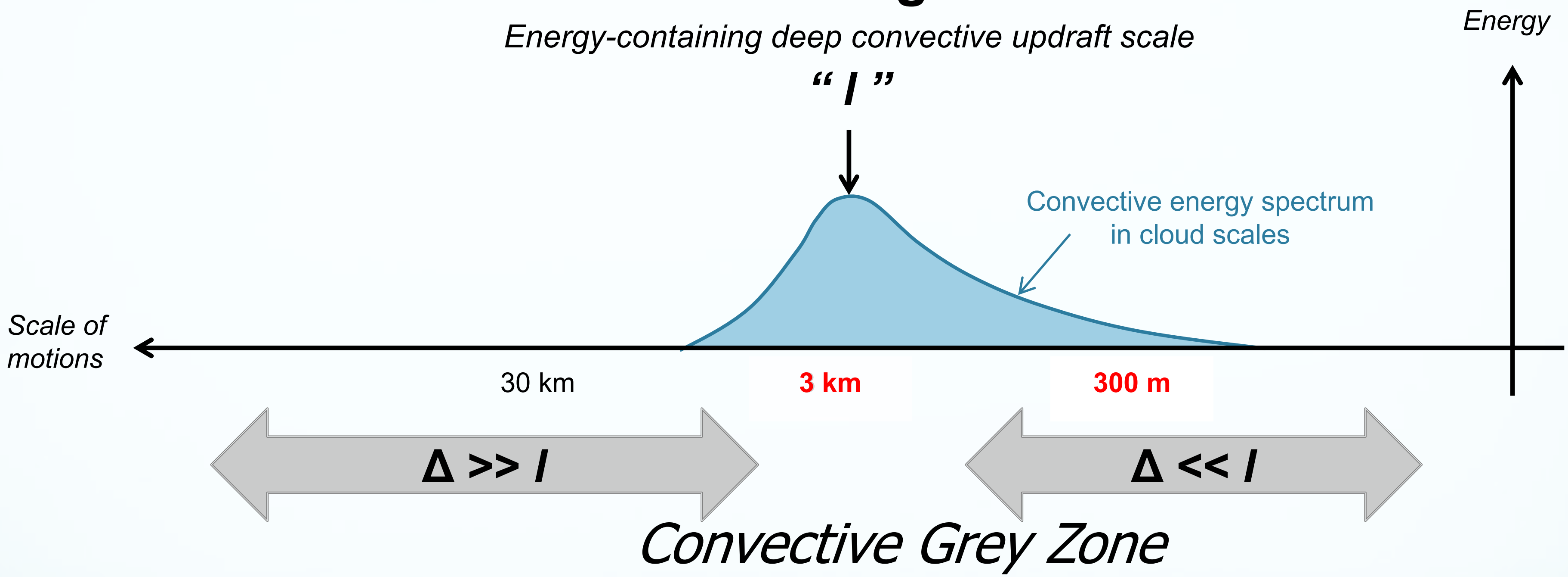
Cumulus Parameterization

Provides

Atmospheric heat and moisture/cloud tendency profiles

Surface sub-grid-scale (convective) rainfall

Model Grid Spacing: Cumulus Parameterization and Cloud-Resolving



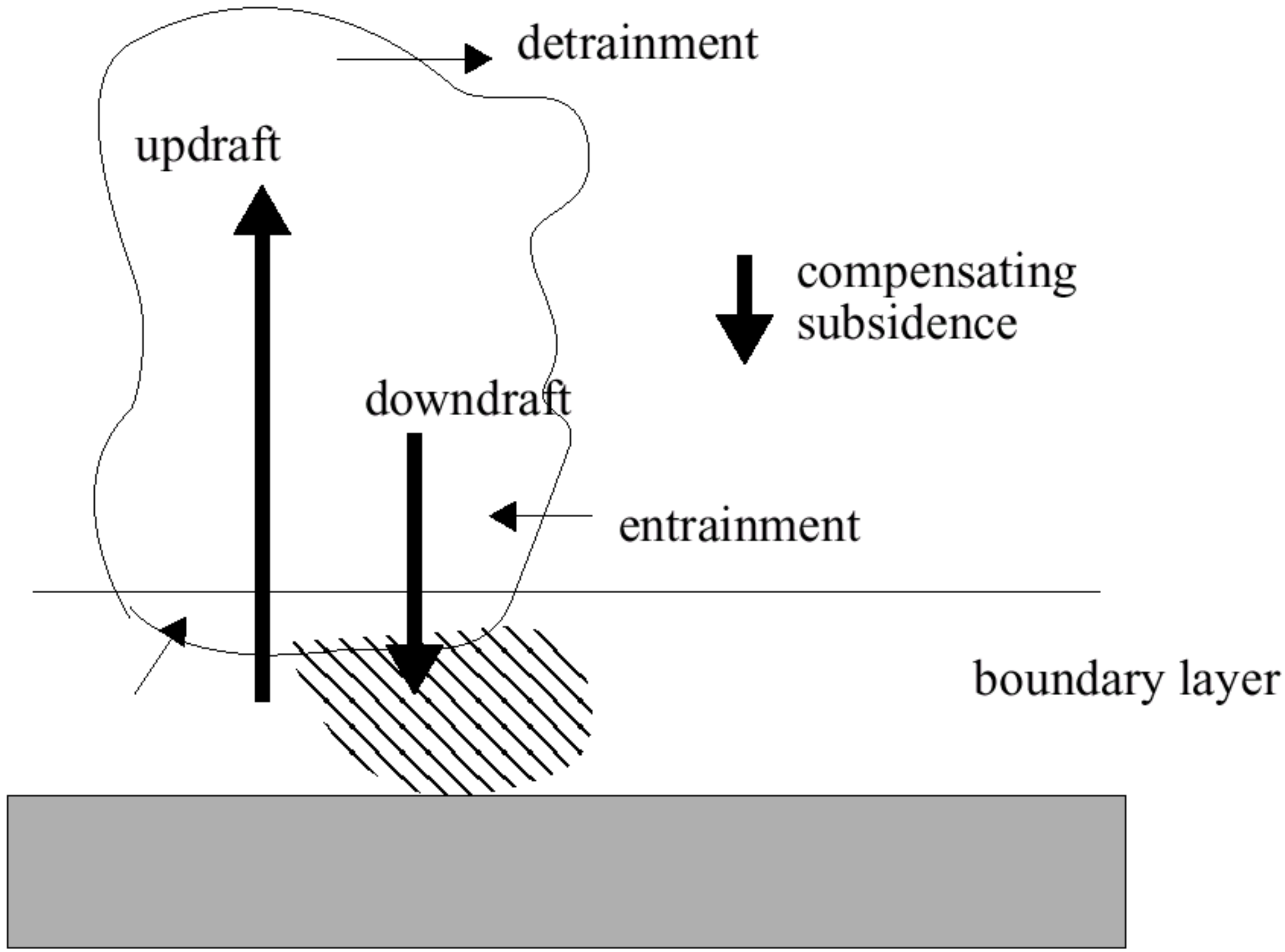
For coarse grid spacing

- ✓ **Cumulus parameterization schemes have been designed for Δ >> *l***
- ✓ ***All updrafts and downdrafts are sub-grid***
- ✓ ***1d column schemes handle sub-grid vertical fluxes***

For fine grid spacing

- ✓ **Resolved dynamics and microphysics work for Δ << *l***
- ✓ ***Updrafts and downdrafts are resolved***
- ✓ ***PBL and/or diffusion schemes handle local sub-grid mixing***

Illustration of Cumulus Processes



Cumulus Schemes

- Use for grid columns that completely contain convective clouds (typically dx > 10 km)
- Re-distribute air in column to account for vertical convective fluxes – inherently nonlocal transports
  - Updrafts take boundary layer air upwards
  - Downdrafts take mid-level air downwards
- Schemes have to determine
  - When to trigger a convective column
  - How fast to make the convection act

Deep Convection

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

Shallow Convection

- Non-precipitating shallow mixing dries PBL, moistens and cools above
- This can be done by an enhanced mixing approach or mass-flux approach
- May be useful at grid sizes that do not resolve shallow cumulus clouds (> 1 km)

Shallow Convection

- Cumulus schemes may include shallow scheme
- Standalone shallow schemes exist
- Part of PBL schemes with mass-flux method

Chemistry and Subgrid Transport

- Chemistry model uses
  - Local: K coefficient from PBL/diffusion schemes in model
    - Note this is a local mixing with some assumptions (see next slide)
  - Nonlocal Γ term when used by PBL for heat and moisture is *not* applied to chemistry – only enhanced K profile
    - Justifiable if species is not correlated with surface buoyancy
  - Nonlocal: Mass flux profiles from cumulus schemes (deep or shallow) when provided
    - EDMF type PBL schemes could also provide mass flux profiles

Chemistry and Local Subgrid Transport

- K-theory assumes flux is proportional to local gradient and that the quantity is conserved during diffusion

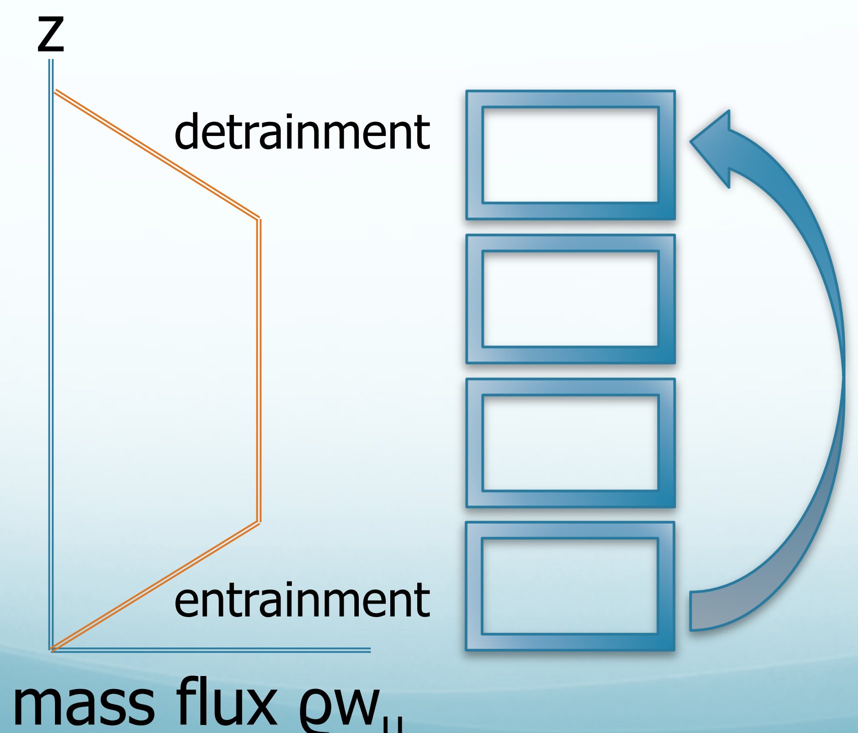
$$\overline{w'\phi'} = \mathrm{K}\,\frac{\partial\phi}{\partial z}$$

  - However in presence of fast chemical reactions, gradients may be partially due to chemical reactions near emission sources
  - Ideally diffusion should not act fully on chemistry-produced gradients because part of gradient is due to sources and sinks
    - Either modify flux calculation (e.g. reactive K) or only apply diffusion to conserved totals for fast reacting species
    - There may be similar considerations for advection (better to advect conserved quantities)

Chemistry and Nonlocal Subgrid Transport

Extract mass flux profile from cumulus (or EDMF) scheme to be used in chemical species transport (insoluble trace gases and aerosols)

- This assumes some conservation during transport
- May need to account for processes happening during transport (~1000 seconds)



Summary

- Subgrid-scale transport terms need to be provided by the physics to consistently transport chemical species
- PBL schemes can provide at least K profiles not just in PBL but through model column free atmosphere
  - and in the case of EDMF schemes mass-flux profiles but this is not often done yet
- Cumulus schemes should also provide mass-flux profiles to account for entrainment, transport, and detrainment by updrafts (maybe downdrafts)
  - make sure cumulus scheme has this option for chemistry applications

References

- Shin, H. H., and S.-Y. Hong, 2014: Representation of the subgrid-scale turbulent transport in convective boundary layers at gray-zone resolutions. Mon. Wea. Rev., 143, 250—271.
- Siebesma, A. P., P. M. Soares, and J. Teixeira, 2007: A combined eddy-diffusivity mass-flux approach for the convective boundary layer. J. Atmos. Sci., 64, 1230–1248.
- Warner, T. T. , 2011: Numerical Weather and Climate Prediction, Cambridge University Press, 526pp.