An Introduction to Scale-Aware Physics

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June 8, 2020

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.

The Grey Zone

- Questions to ask
  – What are you supposed to resolve at a given grid size?
  – What happens if you don't?
  – What can be done about it?
- Grey Zone Issues
  – Convective Parameterization → Resolved updrafts
  – PBL Parameterization → Resolved thermals
- Many similarities
  – Parameterizations assume scale separation – many cells per grid area
  – Problem when grid scale becomes comparable with individual cell
  – Problem goes away with high enough resolution to resolve the cell dynamics (and thermodynamics) properly
  – Sub-grid vertical fluxes often represented as a non-local transport

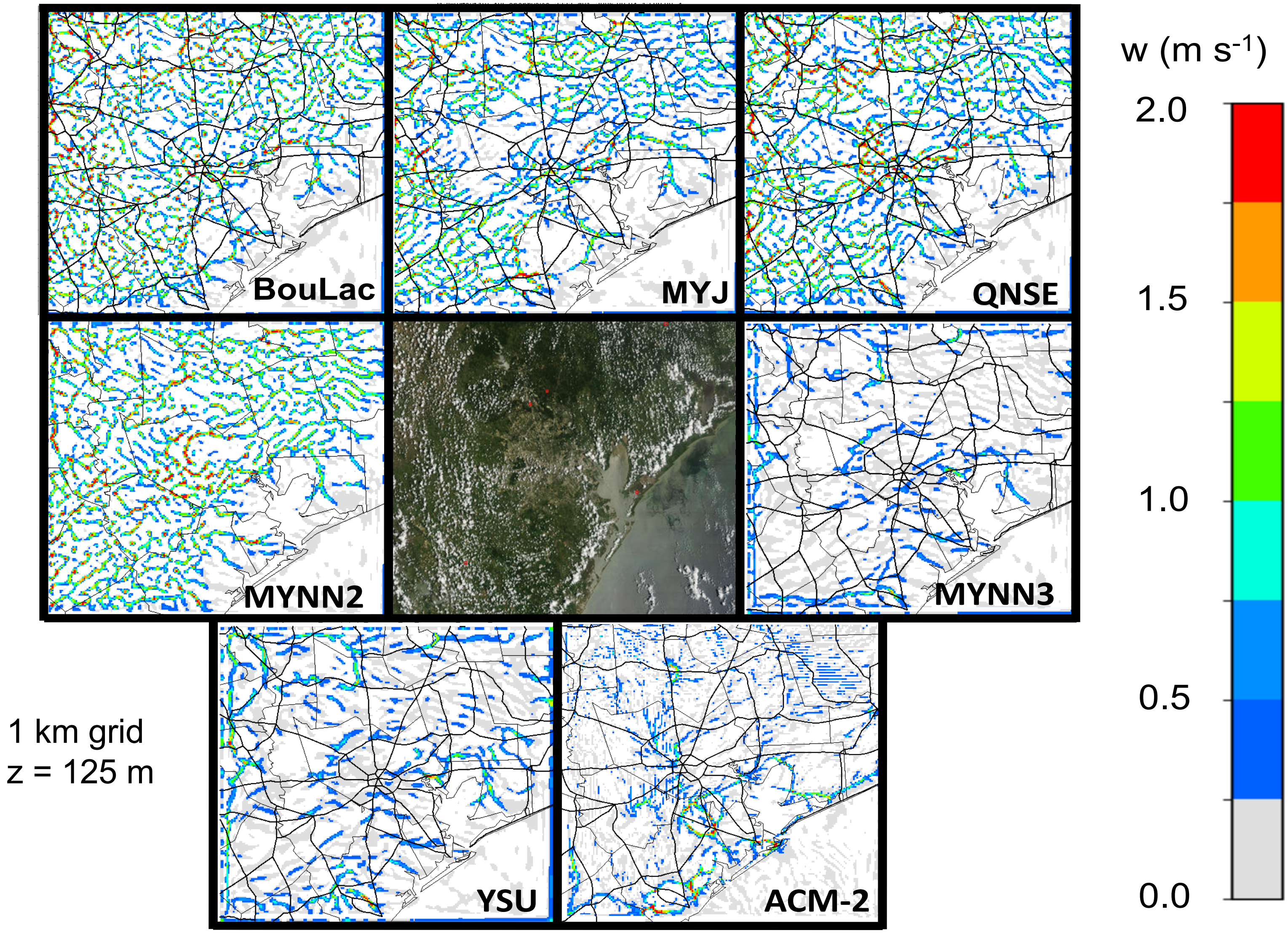
Non-Local Subgrid Schemes

Non-local has two meanings in the context of vertical fluxes

1. The flux does not depend on the local vertical gradient like diffusive fluxes but instead may depend on surface heat flux and represent flux due to thermals even when potential temperature is well mixed
   – Example is Deardorff countergradient term in Troen-Mahrt method used in MRF and YSU PBL schemes.
2. An explicit mass flux that transports origin-layer air to higher levels
   – Mass flux used in EDMF PBL schemes with the origin layer in the surface layer
   – Mass flux used in deep convective transport with the origin in the PBL, and sometimes also a downdraft mass flux from mid levels

Results are sensitive to the PBL parameterization… Ching et al. (2014)

positive vertical velocity for 20 UTC August 4 over Houston-Galveston area using various PBL schemes



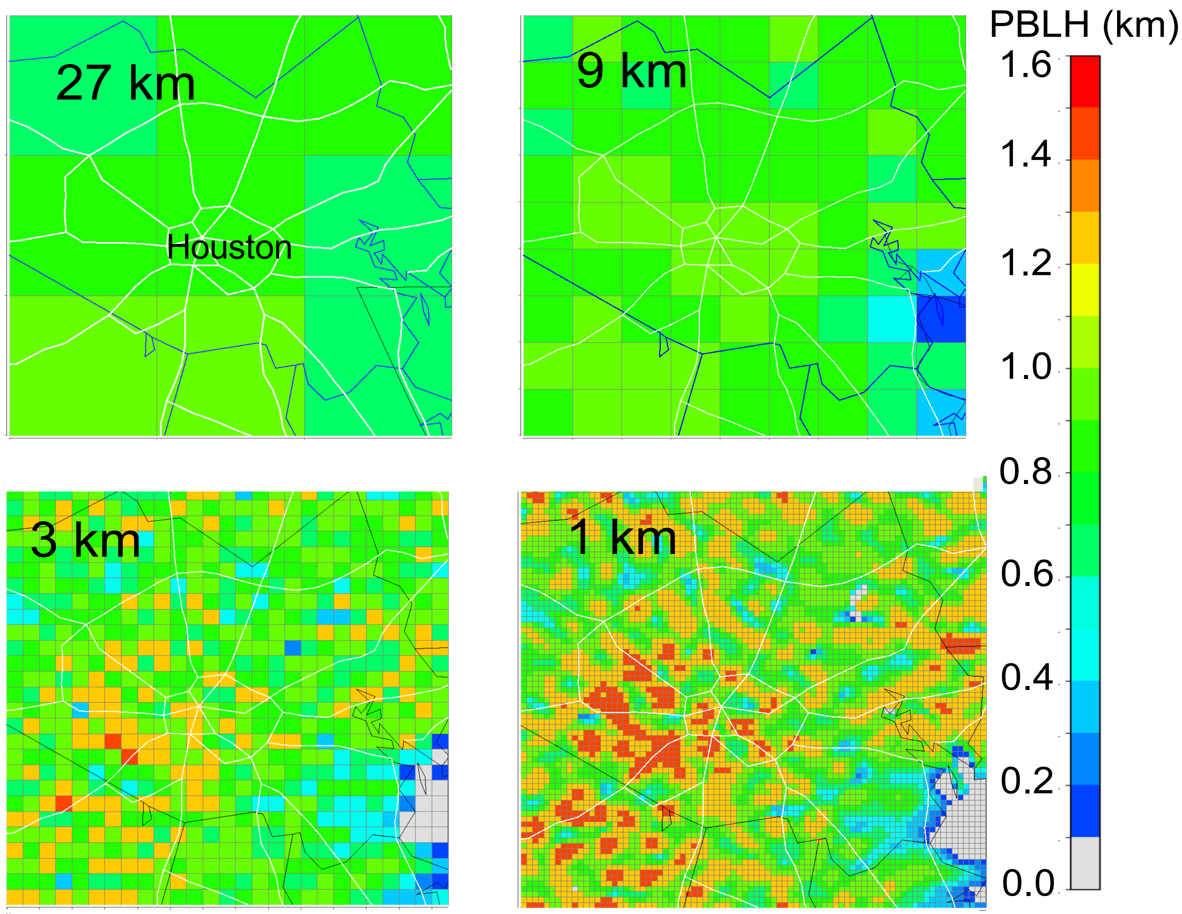
Ching et al. (2014)

PBL schemes

- Generally true that at high-resolution non-local PBL schemes (gamma-term or mass-flux type) suppress resolved eddies more than local (tke) PBL schemes
- Ching et al. (2014) refer to Model Convectively-Induced Secondary Circulations (M-CISCs)
- At a given grid size, what should a PBL scheme do?
  - Should you see resolved cells?
  - Should it be smooth with subgrid fluxes doing all the work?
  - Should it be between somehow?
  - What should happen if you use PBL schemes at small grid sizes

Ching et al. (2014)

For a given PBL parameterization, results are sensitive to grid size
WRF simulations of the fair-weather PBL over central Texas



PBL height based on MYJ PBL scheme (WRF v3.2 at 1500 CDT 4 August 2006)

Nonlocal PBL schemes

Non-local schemes have two main components

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

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

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

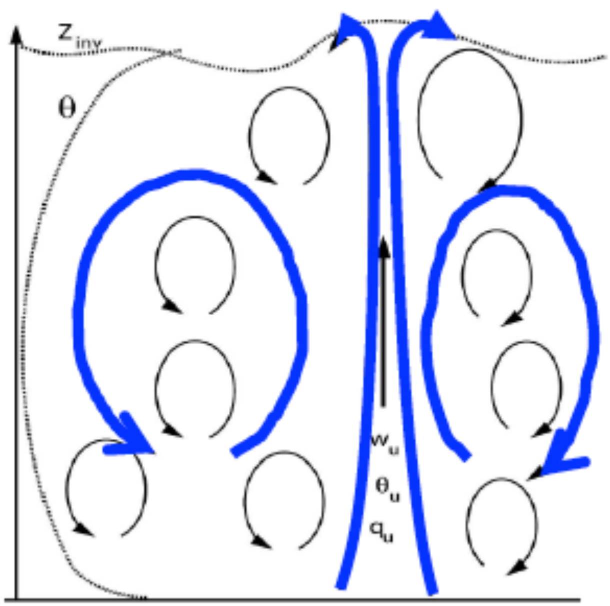


FIG. 1. Sketch of a convective updraft embedded in a turbulent eddy structure.

Explicitly included in **nonlocal PBL parameterizations**

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

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

An overview of PBL parameterizations in WRF

Representation of unresolved vertical transport

$$\overline{w'c'} = -K_c \frac{\partial \overline{c}}{\partial z} + C_{NL}$$

1st-order vs. 1.5-order (TKE)

nonlocal vs. local

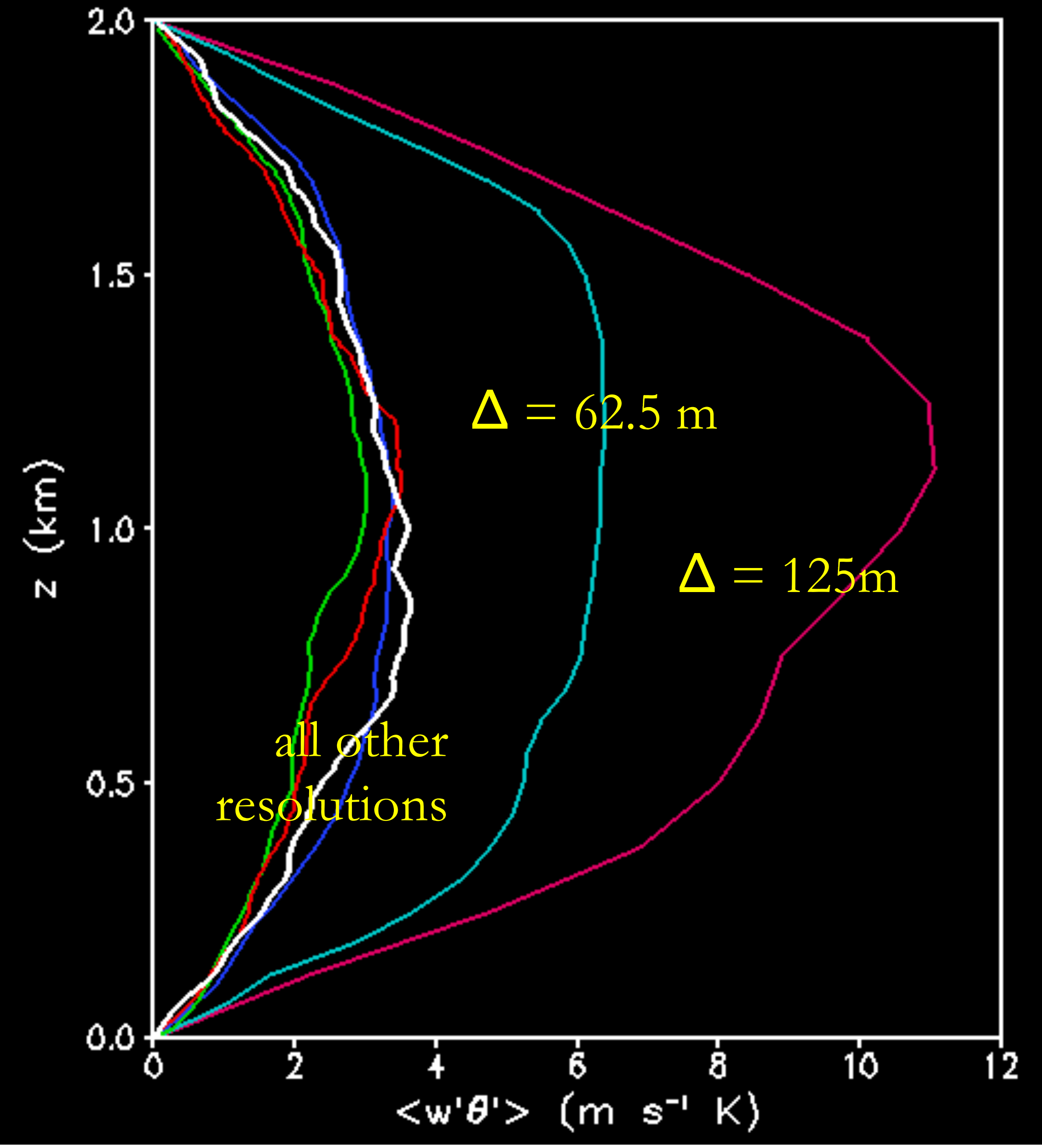
An important part that determines ***a scheme's performance at sub-kilometer grid spacing***

	K_c	C_{NL}
YSU	1st-order	$C_{NL} = K_c \gamma_c + \overline{w'c'}_h \left(\frac{z}{h}\right)^3$
ACM2	$K_{u,v} = k w_s z \left(1 - \frac{z}{h}\right)^2$	$C_{NL} = \mathrm{M2u}\overline{c}_1^{\Delta} - \mathrm{M2d}_k \overline{c}_k^{\Delta} + \mathrm{M2d}_{k+1} \overline{c}_{k+1}^{\Delta} \frac{\Delta z_{k+1}}{\Delta z_k}$
EDMF	1.5-order	$C_{NL} = \mathrm{M}_u \left(c_u - \overline{c}^{\Delta}\right) \quad \mathrm{M}_u = a_u w_u$
TEMF	$K_c = l\sqrt{e} S_c$	$C_{NL} = \mathrm{M}_u \left(c_u - \overline{c}^{\Delta}\right) \quad \mathrm{M}_u = a_u w_u$
MYNN		0

LES Models

- Large Eddy Simulation (LES) models can help
  - But these also don’t work in the grey zone
  - What is their mode of failure as grid size gets too large?
  - Two studies
    - Bryan and Rotunno (2005) and
    - Sullivan and Patton (2011)

Results: Vertical temperature flux at 20 min



Too much heat flux, because there is too much energy at large scales, overstabilizes PBL

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Bryan and Rotunno (2005)

Summary of LES Resolution Tests

- Above about 40 m grid size, thermals are
  - Too large due to underestimated energy cascade
  - Entrain/mix too little in PBL
  - Overshoot and over-entrain at PBL top
  - Therefore result in incorrect PBL growth and over-stabilization of thermal profile
- Need grey-zone scheme(s) to bridge 40 m to 1 km grid sizes
  - Have to parameterize unresolved non-local vertical transport like a PBL scheme
  - But only at grid sizes where such a term is needed

PBL Schemes

What about PBL schemes at dx > 1 km?

(1) Temperature profile

Examples of previous studies

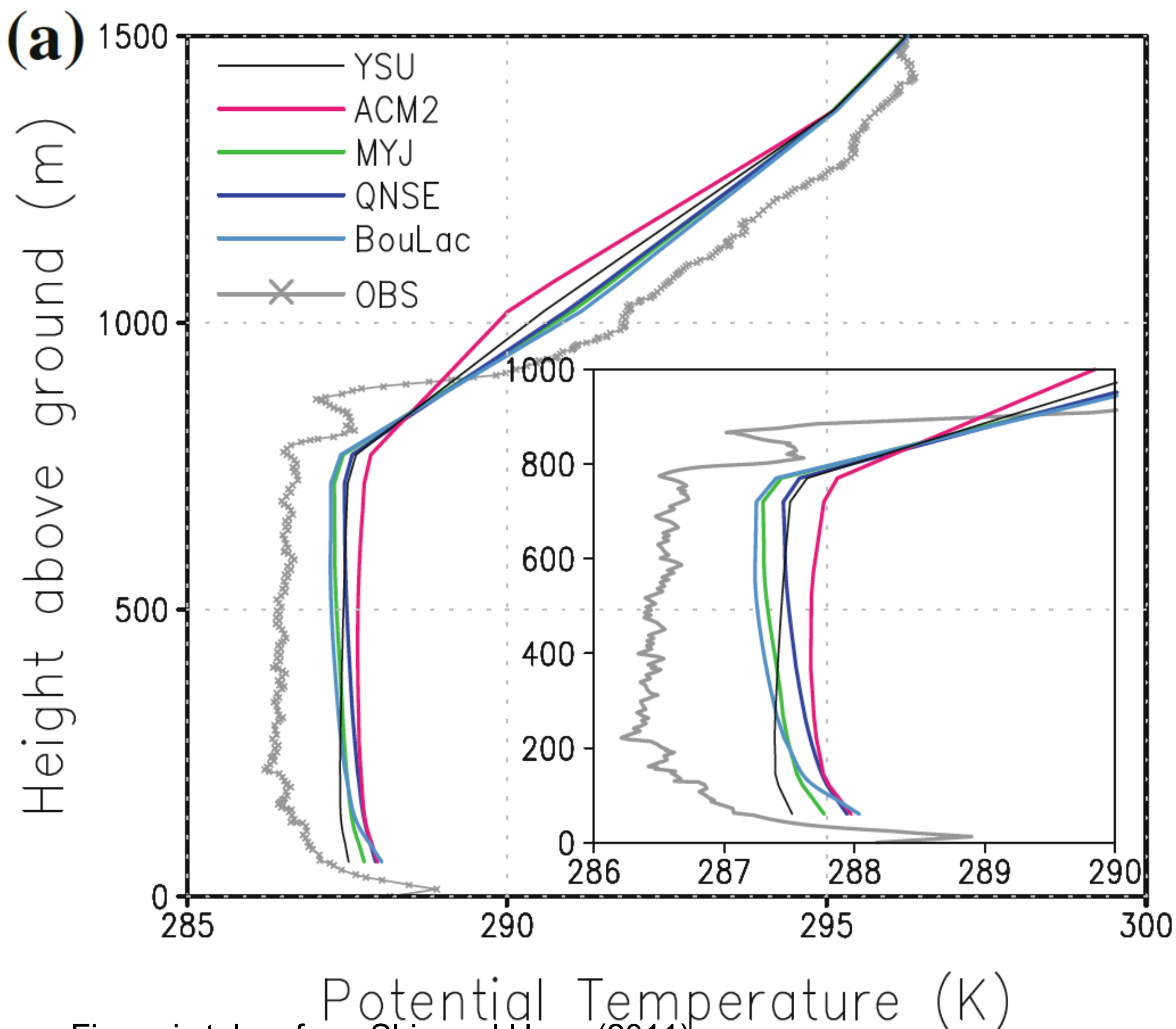


Figure is taken from Shin and Hong (2011)

Coarse grid spacing (Δ >> *l*)

Observed profile
: weakly stable

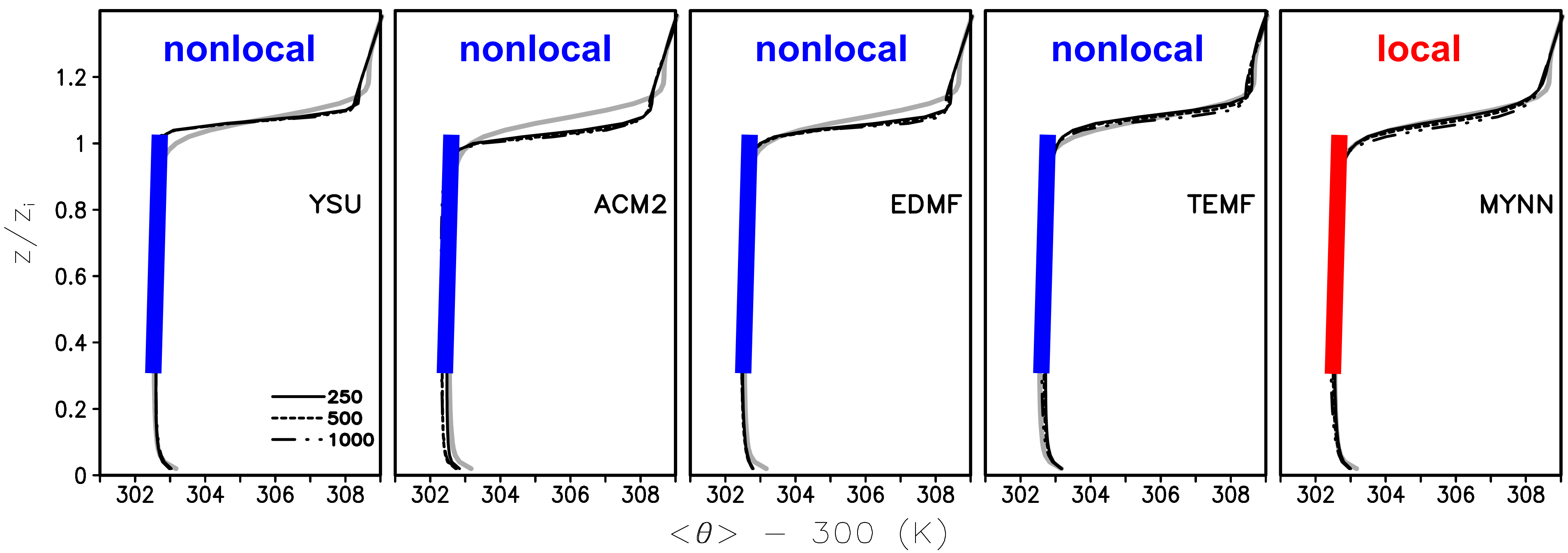
3 km

Local schemes maintain unstable profiles

Nonlocal schemes have stable profiles

(1) Temperature profile

At sub-kilometer and 1-km grid spacing



1. **The local PBL scheme reproduces a weakly stable/neutral profile.**
2. **There is almost no resolution dependency.**

PBL Scheme Scale Sensitivity

- At 3 km and greater local schemes such as most tke-only schemes leave the thermal profile unstable
  - Because they can only transfer heat in the presence of a thermal gradient
  - This is not a problem for schemes that have non-local fluxes that can produce the correct slightly stable thermal profile
- At 1km local schemes can achieve neutral profile
  - Because they produce resolved eddies to do the transport
  - Not clear that these eddies are the right scale but they help the mean profile
- Even at 1 km and less nonlocal schemes can't produce resolved eddies
  - Because nonlocal parameterized fluxes stabilize profile and suppress resolved eddies from forming

Additional and Concluding Remarks

- TKE schemes may need a non-local term to help thermal profile at low resolutions (> 1 km)
- Nonlocal schemes may need to turn off this term for sub-km grids
- Shallow cumulus convection not addressed here
  - Similar questions of what should be resolved versus unresolved eddies and local versus nonlocal sub-grid vertical transport issues exist, and likely also affect shallow to deep transition
- Stratocumulus or fog conditions: radiation-driven top-down mixing not addressed here
  - Wilson and Fovell (UCLA) have added top-down mixing in YSU PBL scheme with an extra nonlocal term
  - Probably different grey-zone transition scale

Grey-Zone Shallow Convection

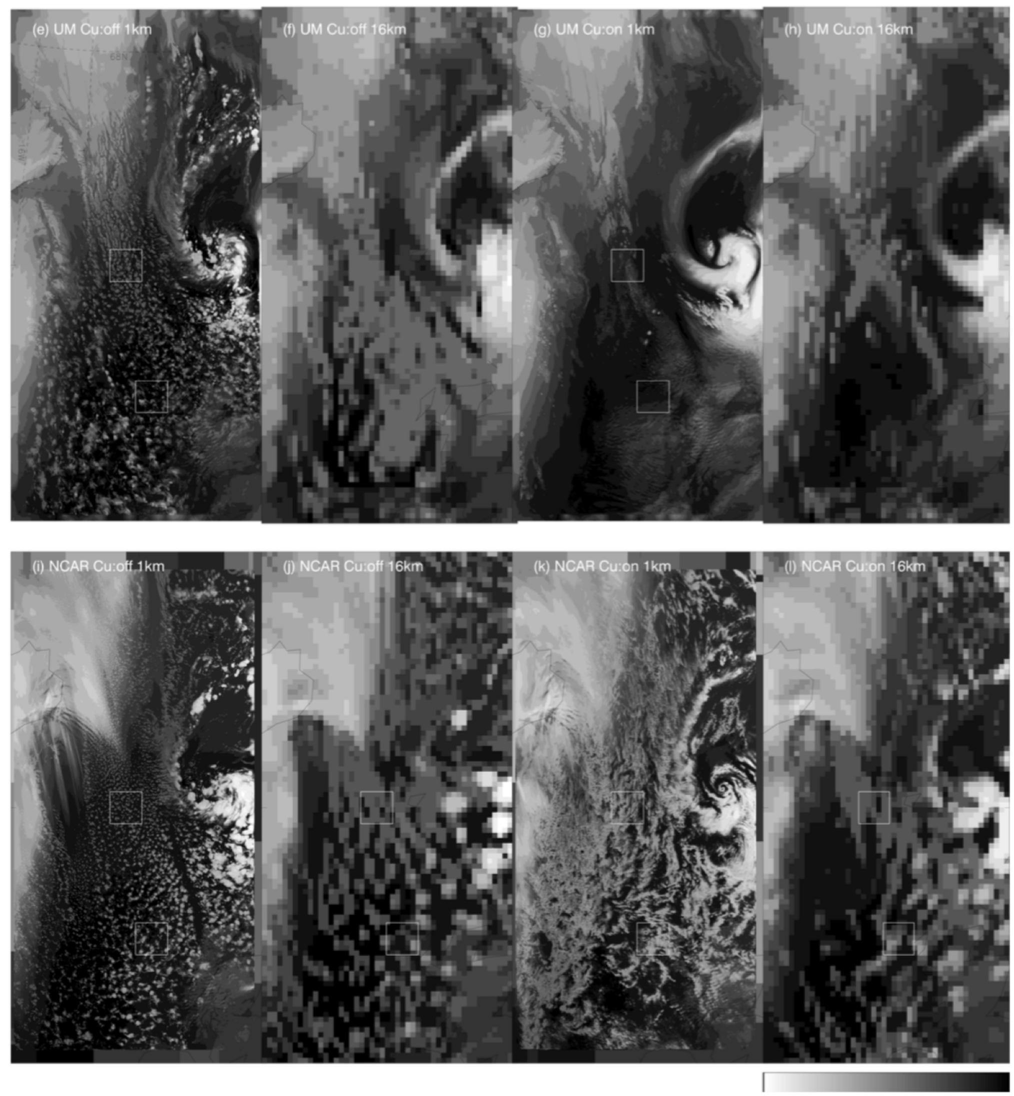
Field et al. (2017, QJRMS) CONSTRAIN cold-air outbreak

- 1 – 16 km grids
- Cu on/off
- 8 models

Showed various degrees of resolution sensitivity among models and parameterizations of convection

Simulated TOA OLR UM(upper), NCAR WRF(lower)

1 km cu off 16 km cu off 1 km cu on 16 km cu on



Deep Convection Parameterization

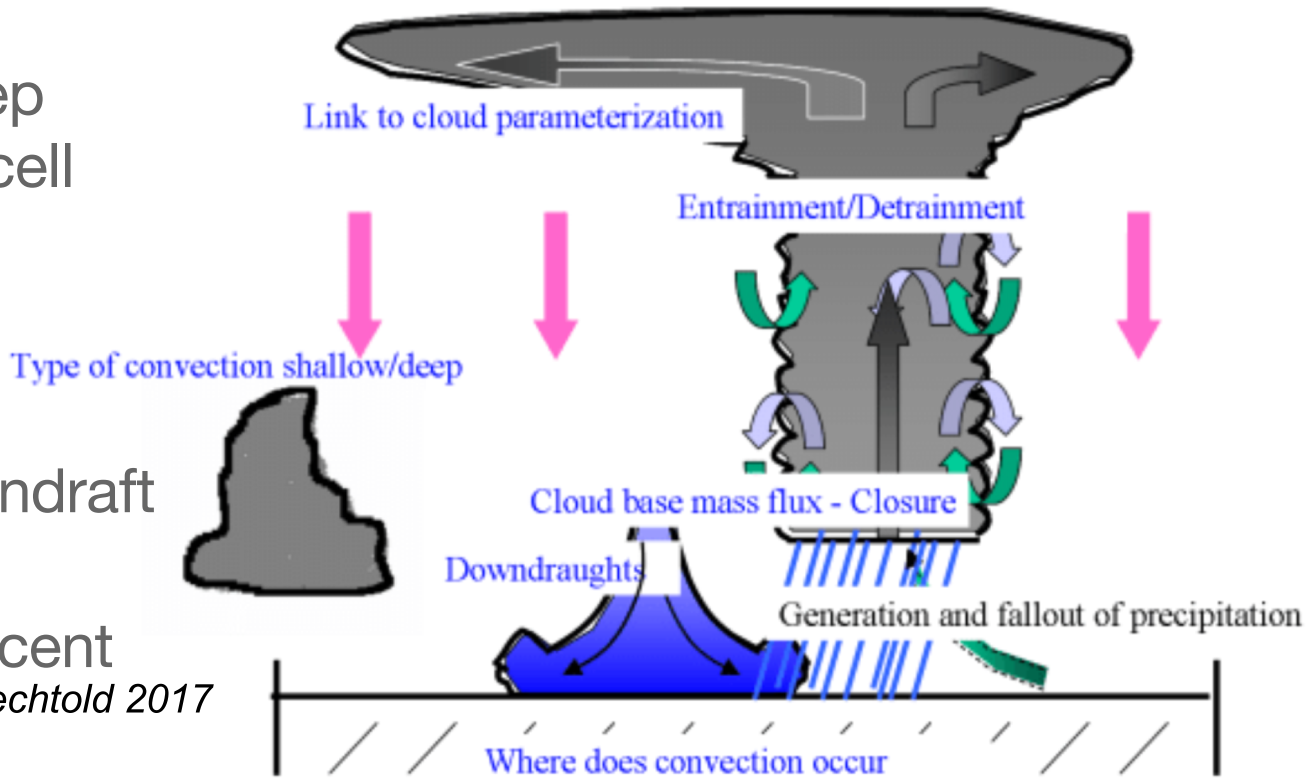
For dx > 10 km

One or more deep clouds in a grid cell

Mass fluxes for updraft and downdraft

Subsidence compensates ascent

Bechtold 2017



Schematic of a bulk convection scheme with a shallow and deep entraining/detraining cloudy ascending plume, and downdraught region. Further represented features are trigger of convection, environmental subsidence, microphysics and precipitation, and detrainment of cloud mass in anvils (Bechtold, 2017).

Deep Convection Parameterization

Scale Awareness Issues

- All subsidence is assumed to be in same grid column
  - However for dx = 5-10 km, it may not be and methods include
  - Grell 3d cumulus that can spread subsidence to neighboring cells
  - Reducing deep convective mass flux in grey zone
- Convective Adjustment Time Scale
  - Too fast scheme suppresses resolved scale dynamics and microphysics from developing convection
  - Can be made dx-dependent to allow resolved scale to act instead at high enough resolution

Resolved Deep Convection

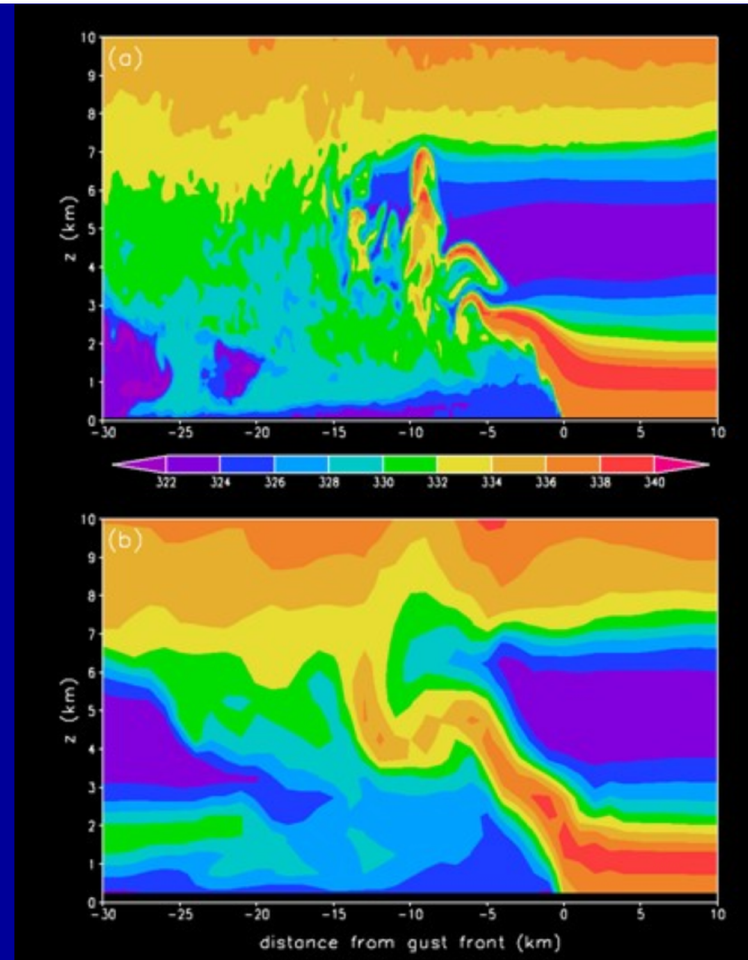
- Many of same issues with updrafts as with thermals
- Updrafts ~1 km
- Resolving them properly requires ~100-250 m
- @ 1 km entrainment is important but likely underestimated
- Consequence is too undilute and deep updrafts

$\Delta x = \Delta z = 125$ m:

θ_e, across-line cross sections with RKW "optimal" shear

$\Delta x = 1000$ m, $\Delta z = 500$ m:

George Bryan



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Common Scale Awareness Themes in Physics

- Parameterization acts too fast and suppresses resolved eddies
  - CP: Too early convection
  - PBL: Lack of small scale PBL eddies that may have been resolvable
- Parameterization not active enough or grid size too coarse leading to unrealistic properties of thermals and updrafts
  - CP+PBL: Too little entrainment, too undilute, too buoyant, too much mass flux
- Scale separation issue when grid size is near thermal or updraft scale
  - CP: Too much subsidence forced in same column
    - Deep convection problem due to its up/down asymmetry (skewness)
  - CP+PBL: Issue of whether sub-grid nonlocal transport is needed or whether dynamics can resolve it well enough

Concluding Remarks 1: Methods of Handling Grey Zone

- Include non-local fluxes if thermals/updrafts are not resolved
- Phase out non-local vertical fluxes as they become resolved
- Increase time scale of parameterization to allow resolved scale to compete or delay its activation (Bechtold)
- Add more “dynamical entrainment” to resolve the too undilute updraft issue (ongoing research topic)
  - This is not just adding diffusion which appears not to help
  - In fact *minimizing* diffusion seems to work better by allowing more resolved scale mixing
  - Methods of adding “non-diffusion” sub-grid terms are being investigated (based on Moeng Giga-LES study for deep convection)

Concluding Remarks 2: General Advisories and Recommendations

- Convection
  - Need a convective scheme for dx > 10 km
  - Only a few schemes are suited to grey zone (dx=3-10 km) and work continues (see talks in this session)
  - Even at 1 km, updrafts are not fully resolved but storm dynamics works well – main issue is that updrafts may not entrain enough
- PBL
  - PBL schemes still work in grey zone (dx =0.3-1 km) – mean profiles are fine but resolved eddies may have too much or too little energy
  - Some schemes are being developed for this range (see talks in this session)
  - LES probably works best at dx < 50 m but still best choice for dx of 50-250 m

end