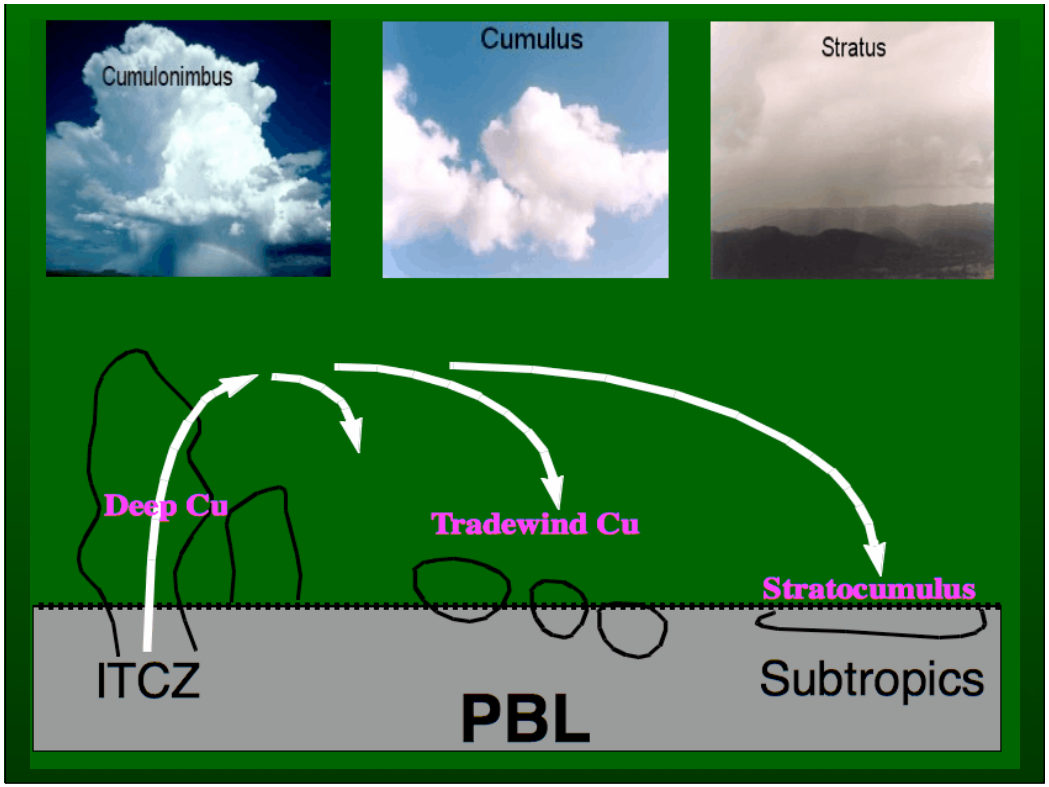
A higher-order closure model with an explicit PBL top

Cara-Lyn Lappen, Dave Randall, Tak Yamaguchi
Colorado State University


Cumulonimbus
Cumulus
Stratus
Deep Cu
Tradewind Cu
Stratocumulus
ITCZ
PBL
Subtropics

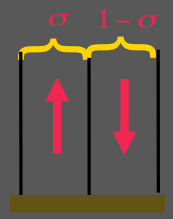
Moments & mass fluxes

$$\overline{w} = \sigma w_{up} + (1-\sigma) w_{dn}$$

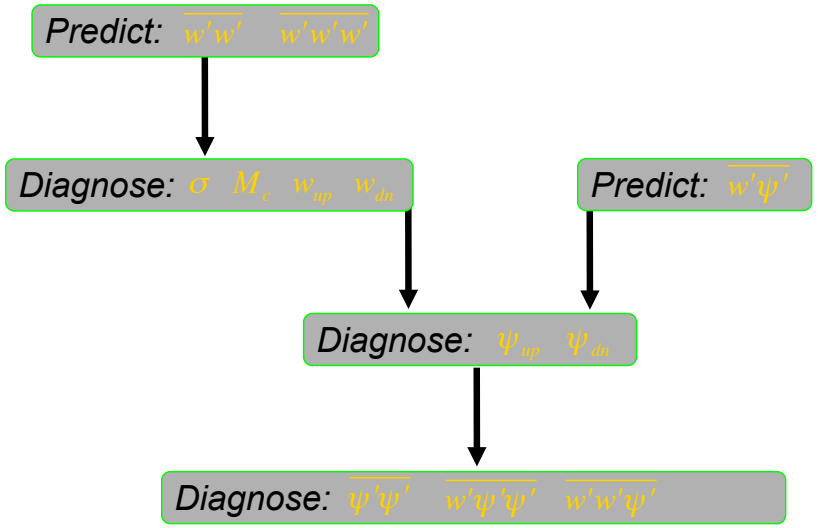
$$\overline{w'w'} = \sigma(1-\sigma)(w_{up} - w_{dn})^2$$

$$\overline{w'w'w'} = \sigma(1-\sigma)(1-2\sigma)(w_{up} - w_{dn})^3$$

$$M_c = \rho\sigma(1-\sigma)(w_{up} - w_{dn})$$



ADHOC: Basic Idea

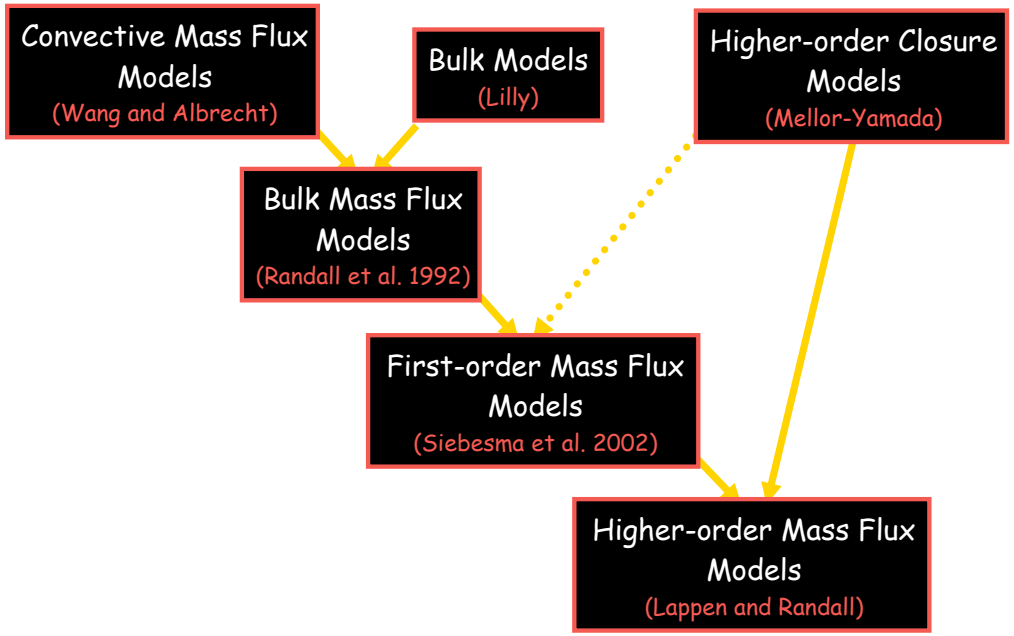


The problems along the way

- Momentum fluxes
  (Lappen and Randall, 2005)
- Pressure terms
  (Lappen and Randall, 2006)
- Microphysics
  (modified Khairoutdinov and Randall, 2003)
- Timestep and grid spacing
  (conversion to σ coordinate model)

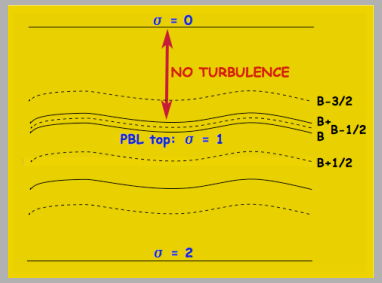
  ↳ Sub-problem --> entrainment
  (Lappen, Randall, and Yamaguchi 2009)

Hierarchy of PBL Models



Entrainment

$$\int_{Z_B}^{Z_{B^+}} \left[\rho \left(\frac{\partial A}{\partial t} + v \cdot \nabla A + w \frac{\partial A}{\partial z} \right) = - \frac{\partial F_A}{\partial z} + S_A \right] dz$$



Set $A = \overline{w'w'}$ and $A = \overline{w'w'w'}$

$$\overline{w'w'w'_B} = \left(\overline{w'w'_B} + B\right) E - \frac{2g\delta z}{C_p T_0} C_R \Delta R$$

$$\overline{w'w'w'_B} = \frac{3\left(\overline{w'w'_B}\right)^3}{\left(\overline{w'w'_B} + B\right) E - \frac{2g\delta z}{C_p T_0} C_R \Delta R}$$

Entrainment rate

$$E = \frac{\pm 3\left(\overline{w'w'}_B\right)^{\frac{3}{2}} + \frac{2g\delta z}{C_p T_0} C_R \Delta R}{\overline{w'w'_B} + B}$$

where $B \equiv \frac{2g\delta z}{C_p T} \Delta\tau$

For clear convection : $\Delta\tau = \Delta s_v$ and $C_R = 0$

For smoke cloud : $\Delta\tau = \Delta s_v$ and $C_R = 1$

For Sc cloud : $\Delta\tau = \Delta s_v - \left(\Delta s_v\right)_{crit}$ and $C_R = 1$

For clear convection.....

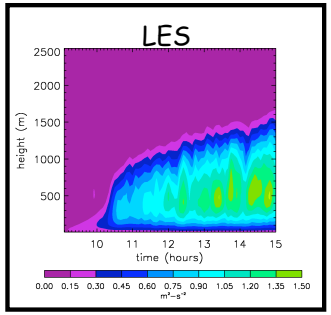
ADHOC's new entrainment formula:

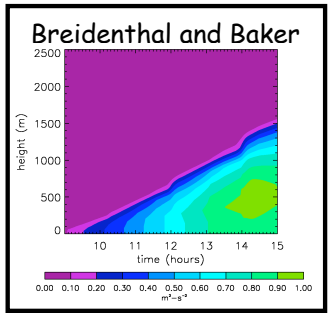
$$E = \frac{3\sqrt{\overline{w'w'}_B}}{1 + \dfrac{B}{\overline{w'w'}_B}} = \frac{3\sqrt{\overline{w'w'}_B}}{1 + \left(\dfrac{g}{c_p T_0}\right)\dfrac{\delta z_B \Delta s_v}{\overline{w'w'}_B}}$$

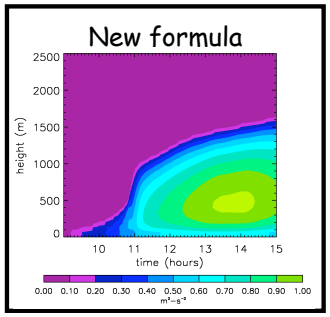
Breidenthal and Baker formula:

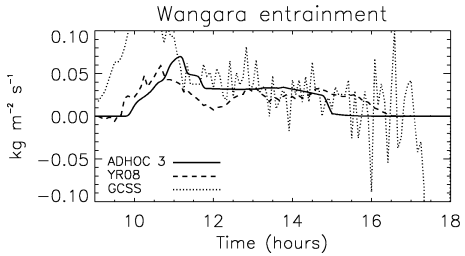
$$E = \frac{b_1\sqrt{e_M}}{1 + b_2 R_{i\Delta}} = \frac{b_1\sqrt{e_M}}{1 + b_2\left(\dfrac{g}{c_P T_B}\right)\dfrac{\delta z_M \Delta s_v}{e_M}}$$

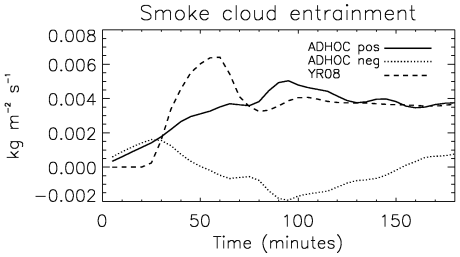
Wangara w'w'

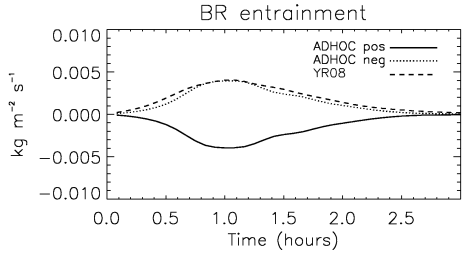

LES
height (m)
2500
2000
1500
1000
500
10 11 12 13 14 15
time (hours)
0.00 0.15 0.30 0.45 0.60 0.75 0.90 1.05 1.20 1.35 1.50
m²-s⁻²

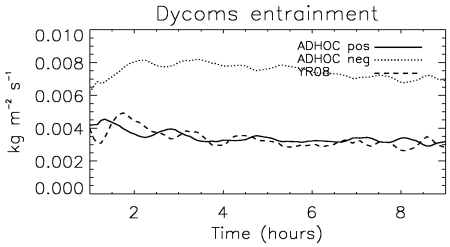

Breidenthal and Baker
height (m)
2500
2000
1500
1000
500
0
10 11 12 13 14 15
time (hours)
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00
m²-s⁻²

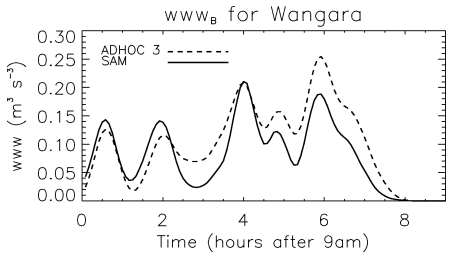

New formula
height (m)
2500
2000
1500
1000
500
0
10 11 12 13 14 15
time (hours)
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00
m²-s⁻²

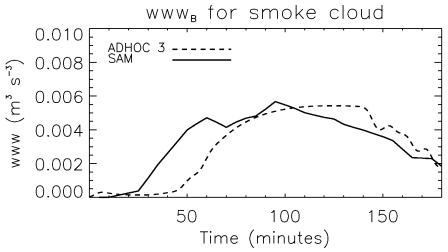

Wangara entrainment
0.10
0.05
0.00
−0.05
−0.10
kg m^{-2} s^{-1}
ADHOC 3
YR08
GCSS
10
12
14
16
18
Time (hours)

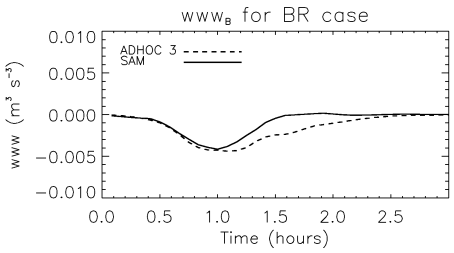

Smoke cloud entrainment
0.008
0.006
0.004
0.002
0.000
−0.002
kg m^{-2} s^{-1}
ADHOC pos
ADHOC neg
YR08
0
50
100
150
Time (minutes)

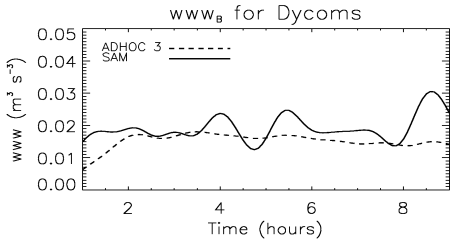

BR entrainment
0.010
0.005
0.000
−0.005
−0.010
kg m^{-2} s^{-1}
ADHOC pos
ADHOC neg
YR08
0.0
0.5
1.0
1.5
2.0
2.5
Time (hours)


Dycoms entrainment
0.010
0.008
0.006
0.004
0.002
0.000
kg m^{-2} s^{-1}
ADHOC pos
ADHOC neg
YR08
2
4
6
8
Time (hours)


www$_B$ for Wangara
ADHOC 3
SAM
www (m^3 s^{-3})
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
2
4
6
8
Time (hours after 9am)


www$_B$ for smoke cloud
ADHOC 3
SAM
www (m^3 s^{-3})
0.010
0.008
0.006
0.004
0.002
0.000
50
100
150
Time (minutes)


www$_B$ for BR case
ADHOC 3
SAM
www (m^3 s^{-3})
0.010
0.005
0.000
−0.005
−0.010
0.0
0.5
1.0
1.5
2.0
2.5
Time (hours)


www$_B$ for Dycoms
ADHOC 3
SAM
www (m^3 s^{-3})
0.05
0.04
0.03
0.02
0.01
0.00
2
4
6
8
Time (hours)

Summary of ADHOC 3

- ADHOC is a unified higher-order closure/mass-flux model. The new version, ADHOC 3, uses an explicit PBL top and diagnoses the entrainment rate using the predicted higher-order moments. This allows for a longer time step and greater grid spacing making it more suitable for use in a large-scale model.

- ADHOC has successfully simulated a range of PBLs from clear convection to stratocumulus at with significantly larger vertical grid spacing.

The problem is that it required too small of a timestep and too high vertical resolution to be used in a large scale model.

Summary

We have converted ADHOC to σ coordinates. This reduces the number of PBL layers required and makes it possible to increase the time step. However, entrainment is now an explicit quantity that must be parameterized.

We have derived an entrainment parameterization by integrating the ww and www equations across the jump at the PBL top and using the ADHOC mass-flux relationships.

Most previous approaches use integrated TKE in their entrainment parameterization. These models don't have knowledge of the internal turbulent structure of the PBL. Since ADHOC knows this structure, we developed an entrainment parameterization that depends on the turbulent moments at the PBL top, where the entrainment is occurring. This has been successful at simulating clear convective, smoke cloud, and Sc-topped PBLs.