A unified approach for parameterizing the boundary layer and moist convection

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OUTLINE

- Why unified models?
- ADHOC
- Lateral mixing and sub-plume fluxes
- Model versatility
- ADHOC2/Momentum fluxes
- Parting wisdom

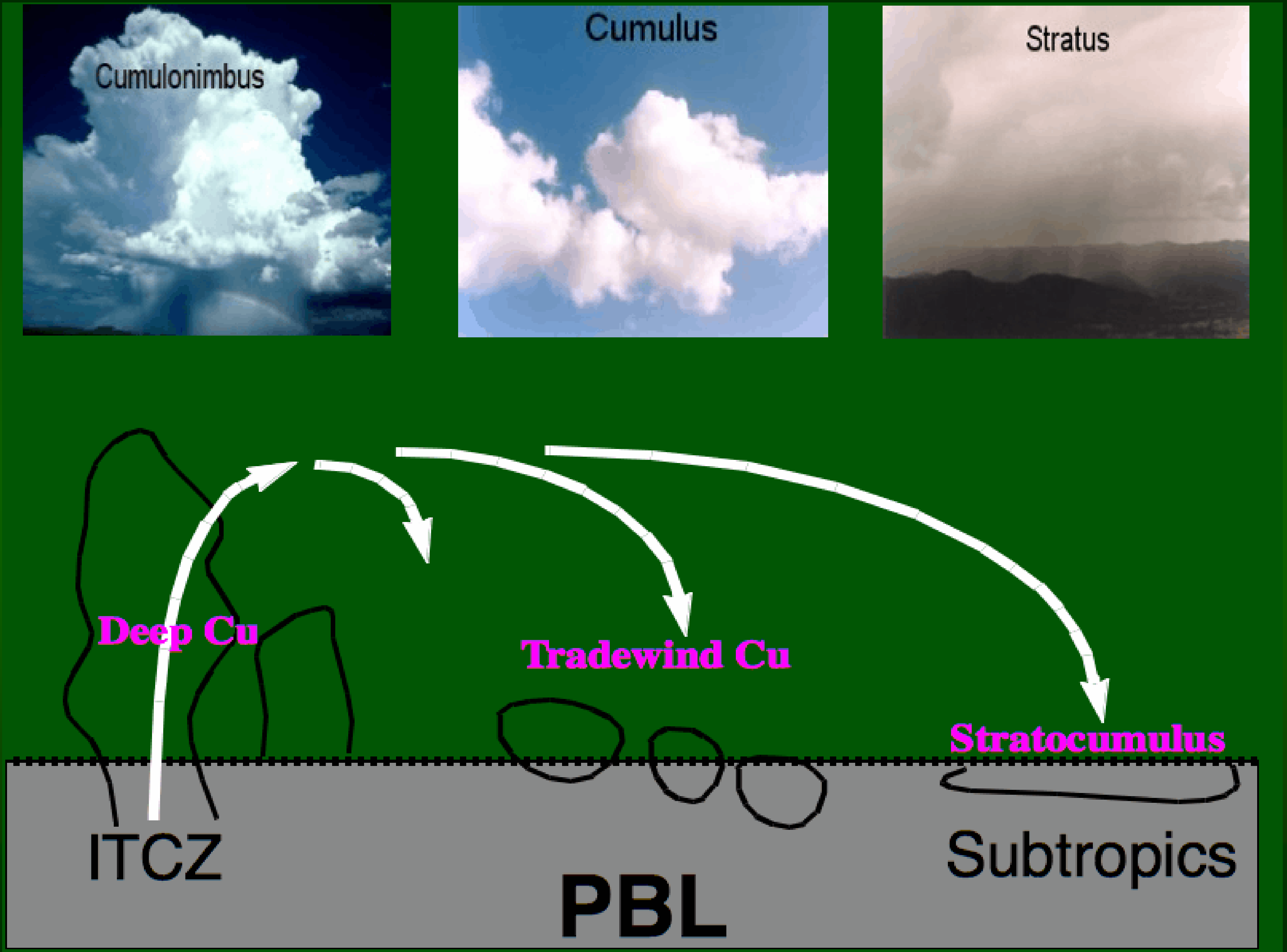
Little boxes....

Traditional AGCM structure

Dynamics

Radiation | Stratiform Clouds | Boundary Layer | Cumulus Convection

Why are there so many little boxes?


Cumulonimbus
Cumulus
Stratus
Deep Cu
Tradewind Cu
Stratocumulus
ITCZ
Subtropics
PBL

Its all really just fluid flow… isnt it?

QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

*Movies courtesy of Marat Khairoutinov's RICO simulations

Little boxes....

A more logical AGCM structure

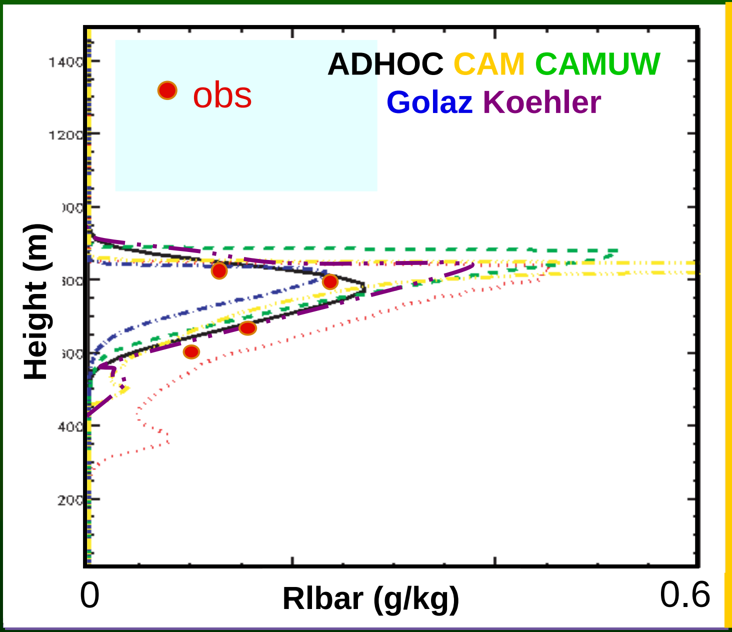
Dynamics

Radiation | **Stratiform Clouds** | **Boundary Layer and Cumulus Convection**

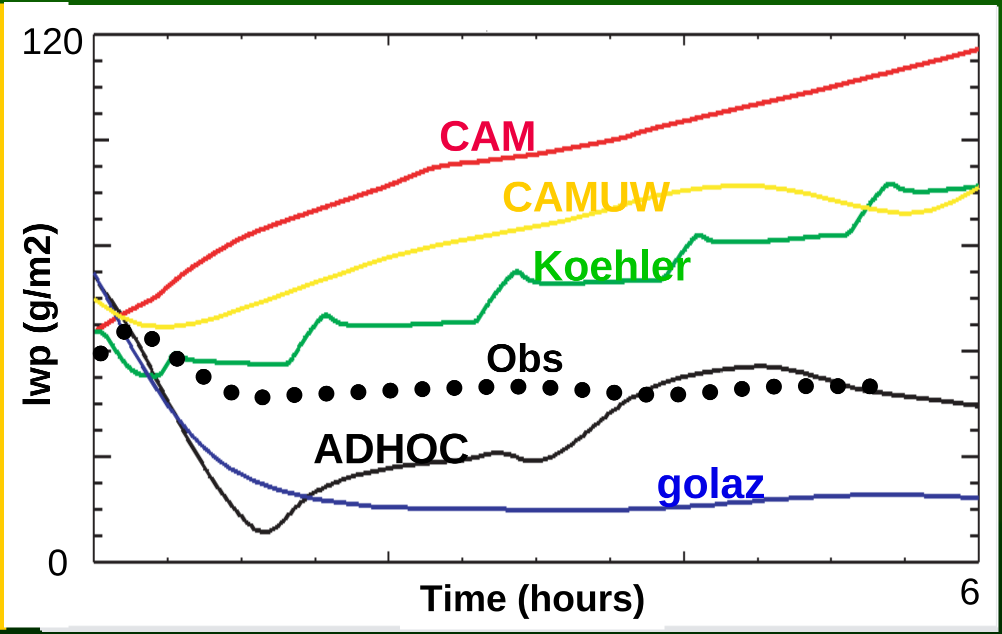
This is more natural because the equations governing these processes are the same!

Different levels of unification

CAM	Siebesma (Koehler-ECMWF)	ADHOC2	Golaz
No unification	Unified in *1st order closure*	Unified in *higher-order moments with tophat pdf*	Unified in *higher-order moments with dbl Gauss pdf*



DYCOMS RF01

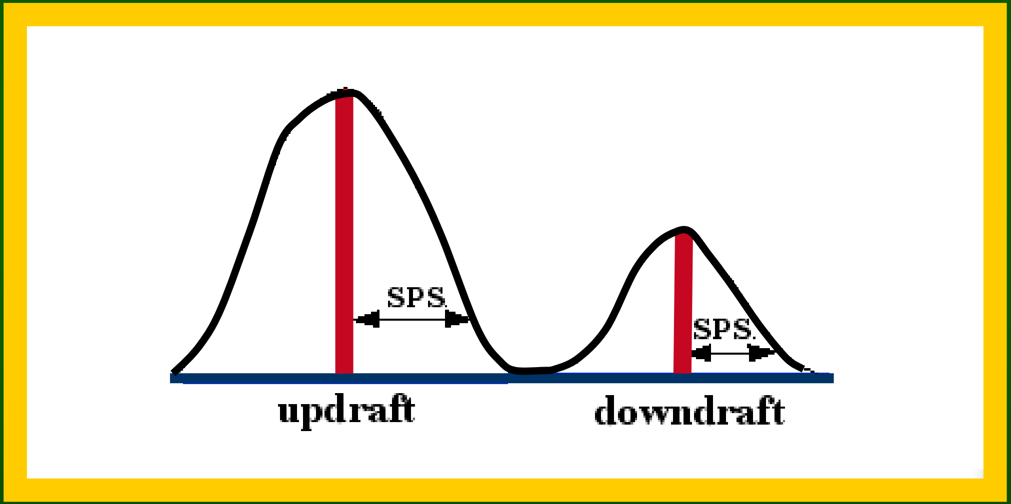


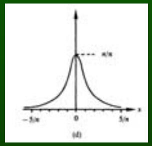
ADHOC

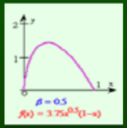
Amateurs Doing Higher Order Closure

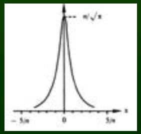
ADHOC

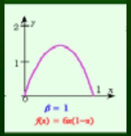
Assumed Distribution Higher Order Closure

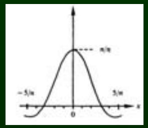


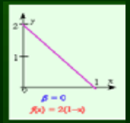






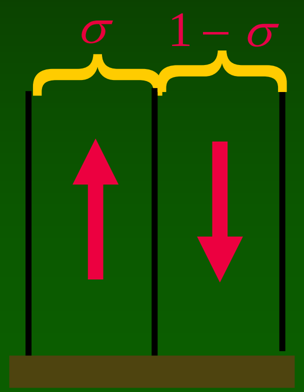






Randall et al. (1992)

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



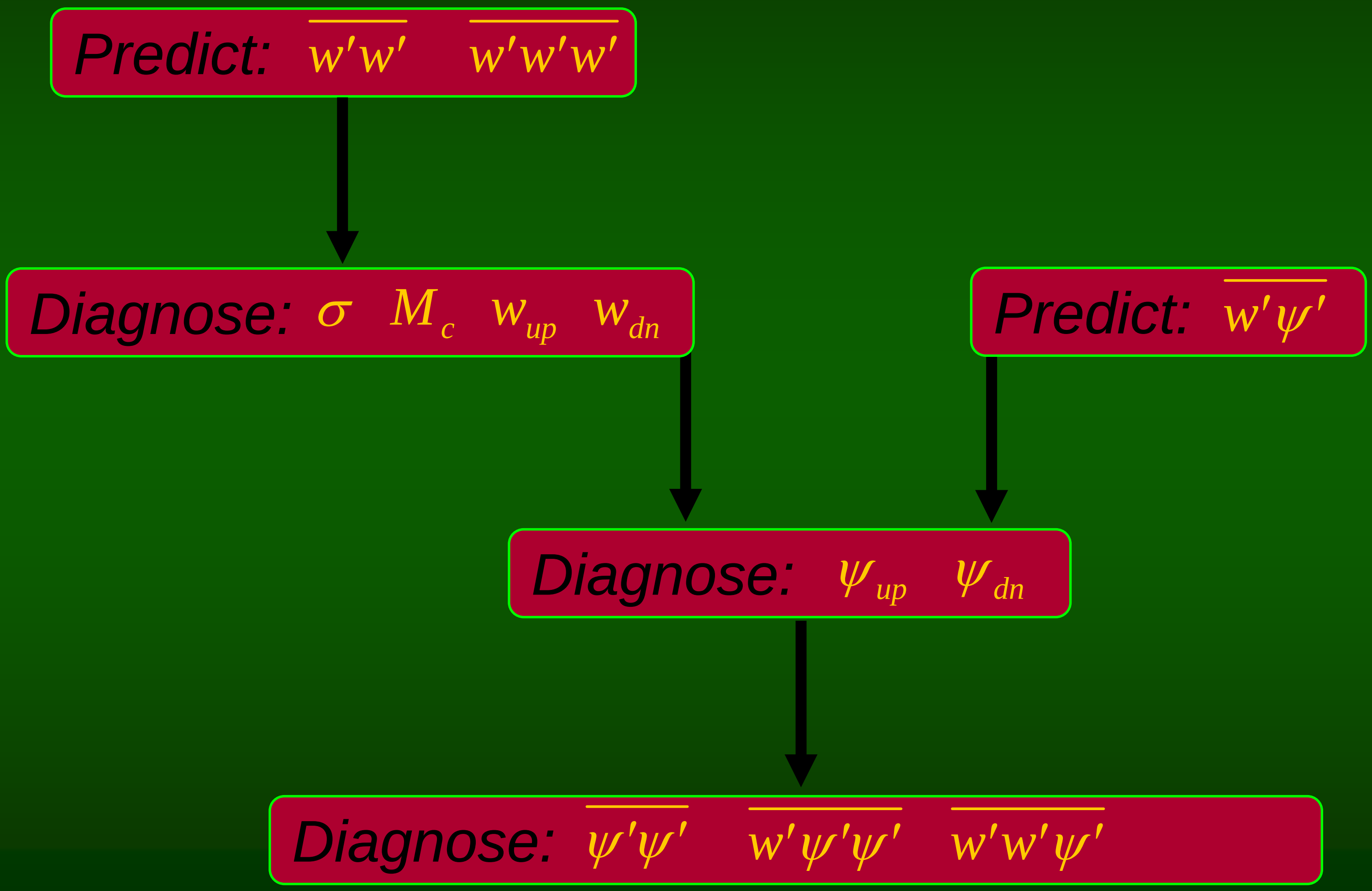
$$\overline{w'w'} = \sigma(1-\sigma)(w_{up} - w_{dn})^2$$

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

Solving, we can diagnose the mass flux:

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

ADHOC: Basic Idea



Forcing realizability

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

updraft

$$\frac{\partial \psi_{up}}{\partial t} = E\psi_{dn} - D\psi_{up} - \frac{\partial (w_{up}\psi_{up})}{\partial z} + (S_{\psi})_{up}$$

downdraft

$$\frac{\partial \psi_{dn}}{\partial t} = E\psi_{up} - D\psi_{dn} - \frac{\partial (w_{dn}\psi_{dn})}{\partial z} + (S_{\psi})_{dn}$$

continuity

$$\frac{\partial \sigma}{\partial t} = E - D - \frac{\partial M_{c}}{\partial z}$$

HOC	ADHOC
$\frac{\partial \overline{w'\psi'}}{\partial t} =$	$\frac{\partial}{\partial t}\sigma(1-\sigma)(w_{up}-w_{dn})(\psi_{up}-\psi_{dn}) =$
$-\overline{w'w'}\frac{\partial \overline{\Psi}}{\partial z}$	$-M_c(w_{up}-w_{dn})\frac{\partial \overline{\Psi}}{\partial z}$
$-\frac{\partial \overline{w'w'\psi'}}{\partial z}$	$-\frac{\partial}{\partial z}M_c(1-2\sigma)(w_{up}-w_{dn})(\psi_{up}-\psi_{dn})$
$\frac{g}{\theta_0}\overline{w'\theta'_v}$	$M_c[(S_\psi)_{up}-(S_\psi)_{dn}]$
$-C\frac{\overline{w'\psi'}}{\tau}$	$-(E+D)(w_{up}-w_{dn})(\psi_{up}-\psi_{dn})$
$-\frac{1}{\rho}\overline{(\psi'\frac{\partial p'}{\partial z})}$	$\sigma(1-\sigma)(\psi_{up}-\psi_{dn})[(S_w)_{up}-(S_w)_{dn}]$

E and D

$$\frac{\partial \overline{w'w'}}{\partial t} : -C\frac{\overline{w'w'}}{\tau} = -C\frac{\sigma(1-\sigma)(w_{up}-w_{dn})^2\sqrt{VelocityScale}}{L}$$

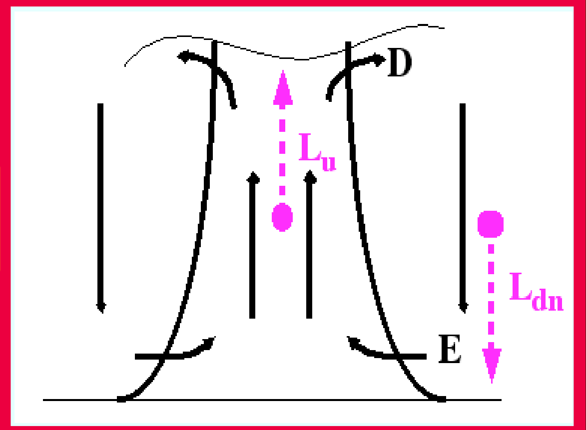
HOC

$$\frac{\partial \overline{w'w'}}{\partial t} : -(E+D)(w_{up}-w_{dn})^2$$

ADHOC

parameterization

$$E = C\frac{\sigma(1-\sigma)(M_c/\rho)}{L_{dn}} \quad ; \quad D = C\frac{\sigma(1-\sigma)(M_c/\rho)}{L_{up}}$$



ADHOC: Basic Idea

Predict: $\overline{w'w'}$ $\overline{w'w'w'}$

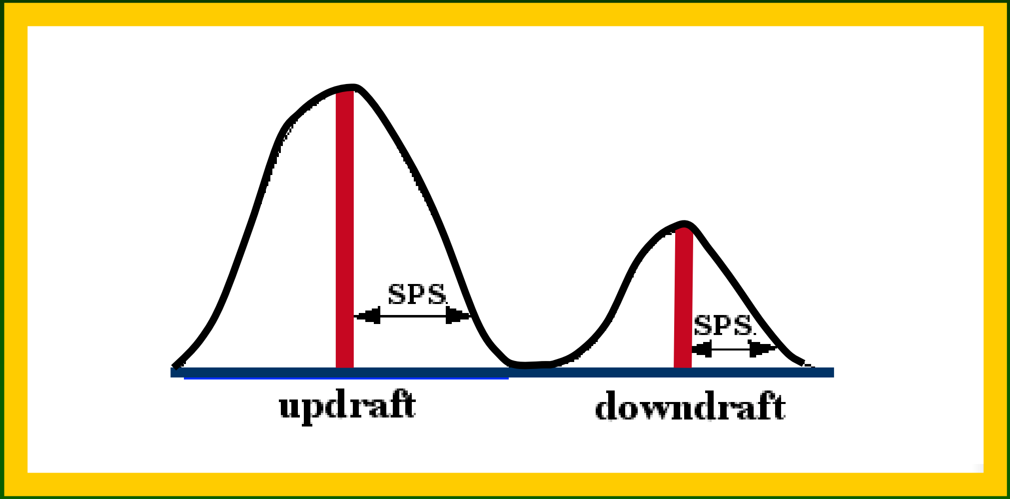
Diagnose: σ M_c w_{up} w_{dn}

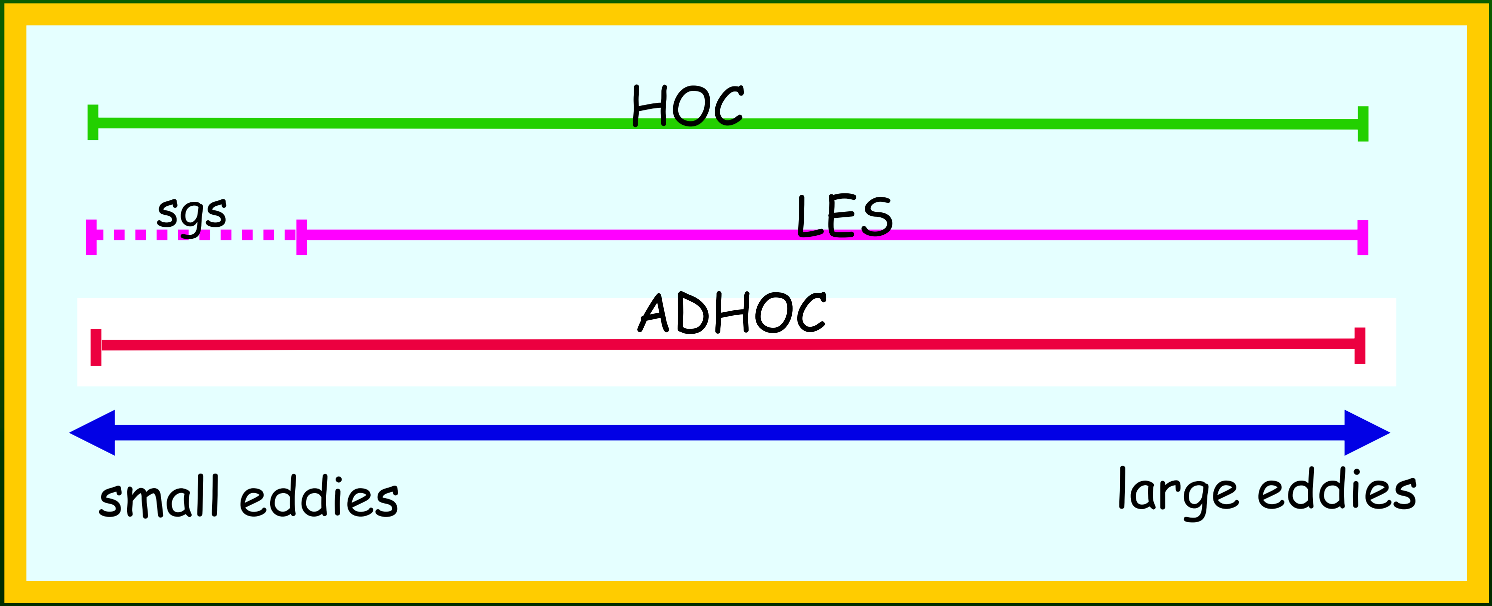
Predict: $\overline{w'\psi'}$

Diagnose: ψ_{up} ψ_{dn}

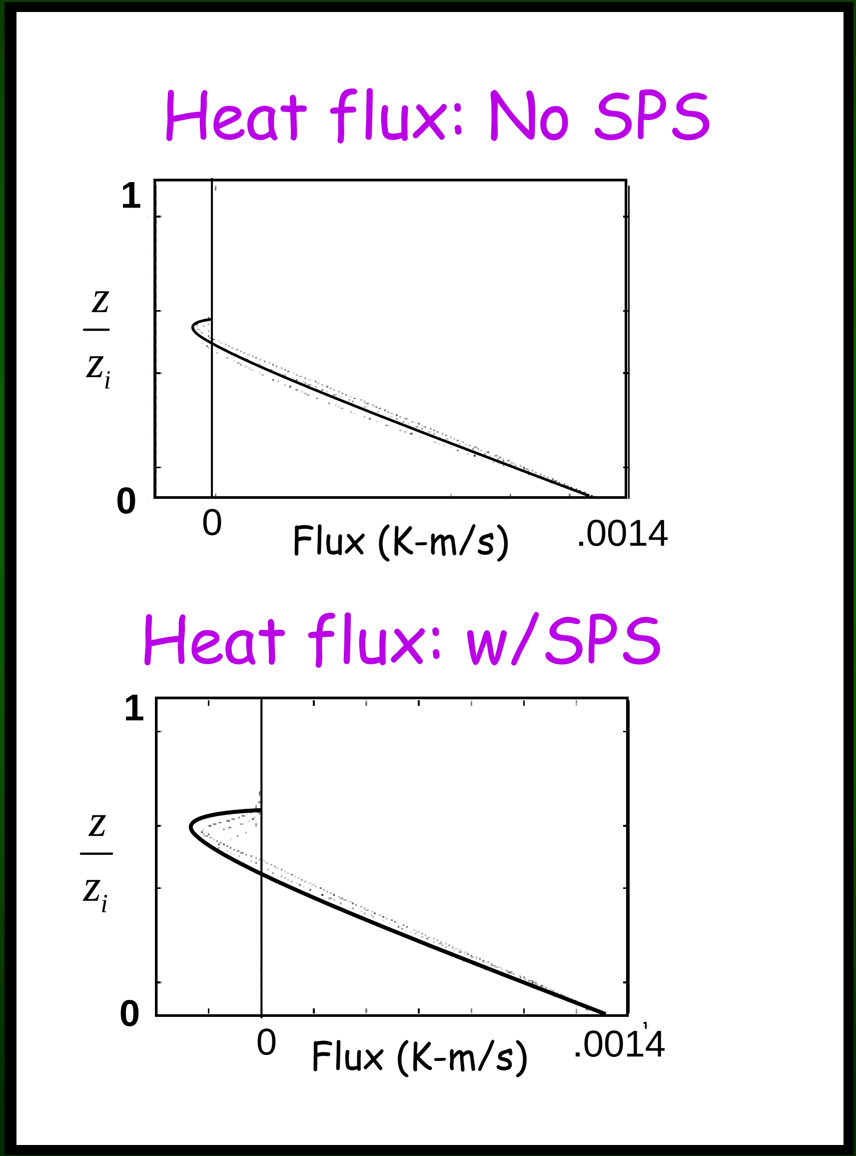
Diagnose: $\overline{\psi'\psi'}$ $\overline{w'\psi'\psi'}$ $\overline{w'w'\psi'}$ •••••

SubPlume-Scale Contributions

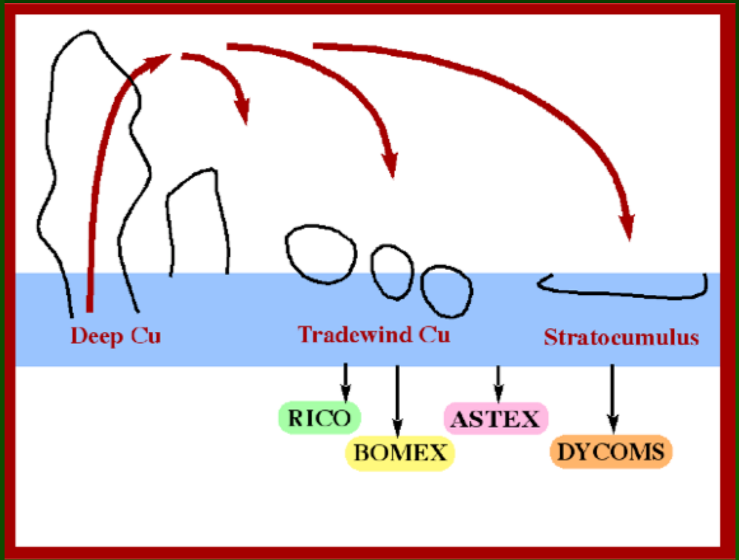


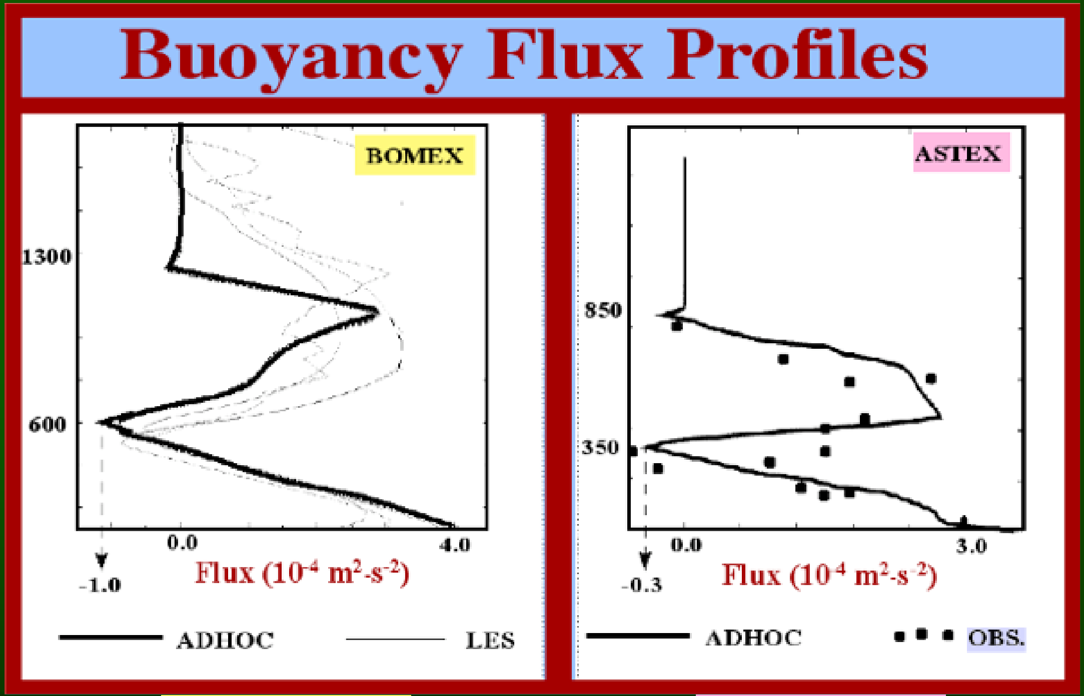


Clear convection: sps vs no sps



Versatility of ADHOC

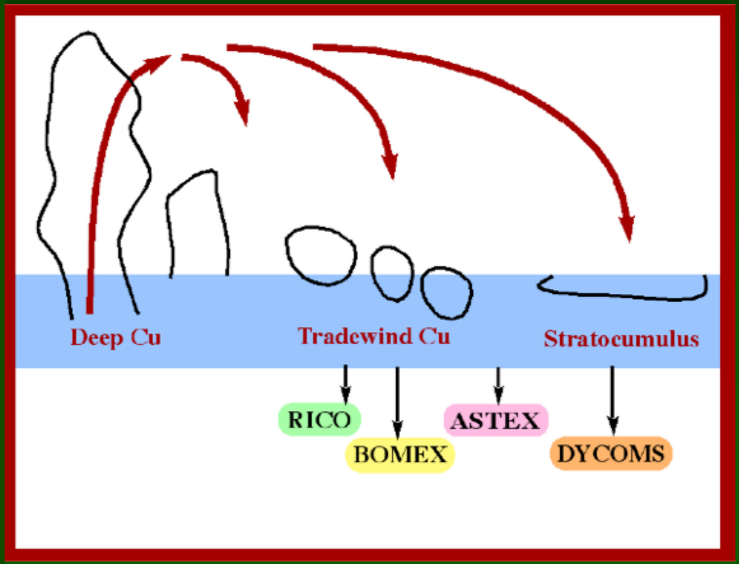


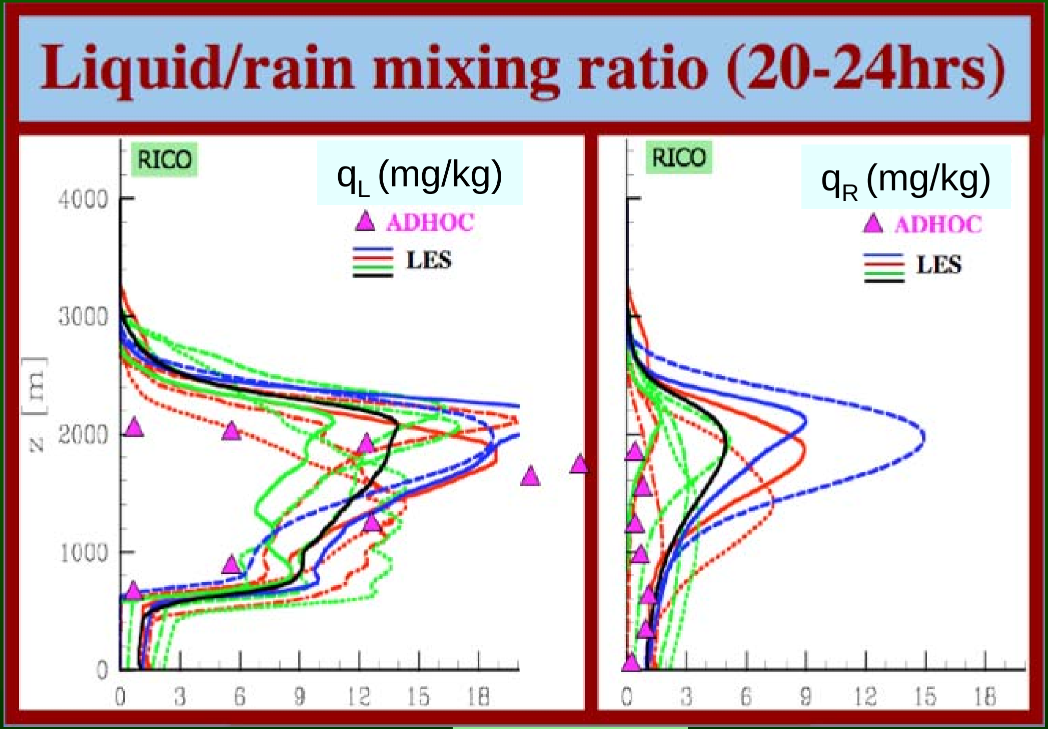


BOMEX

ASTEX

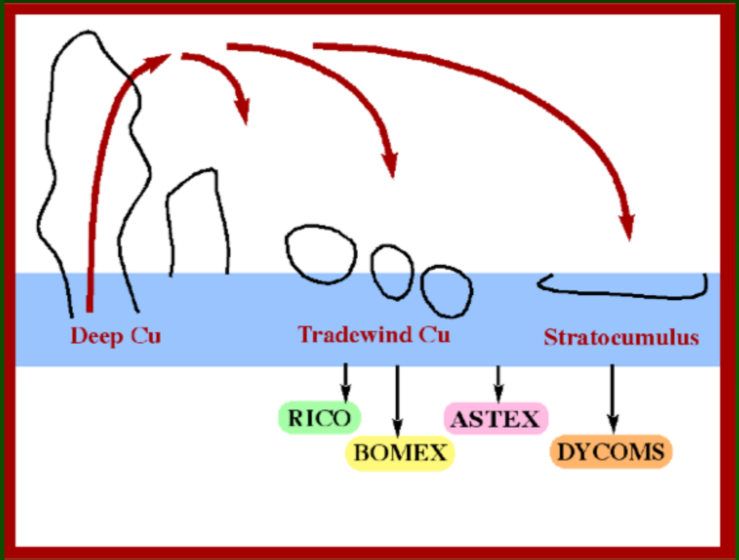
Versatility of ADHOC



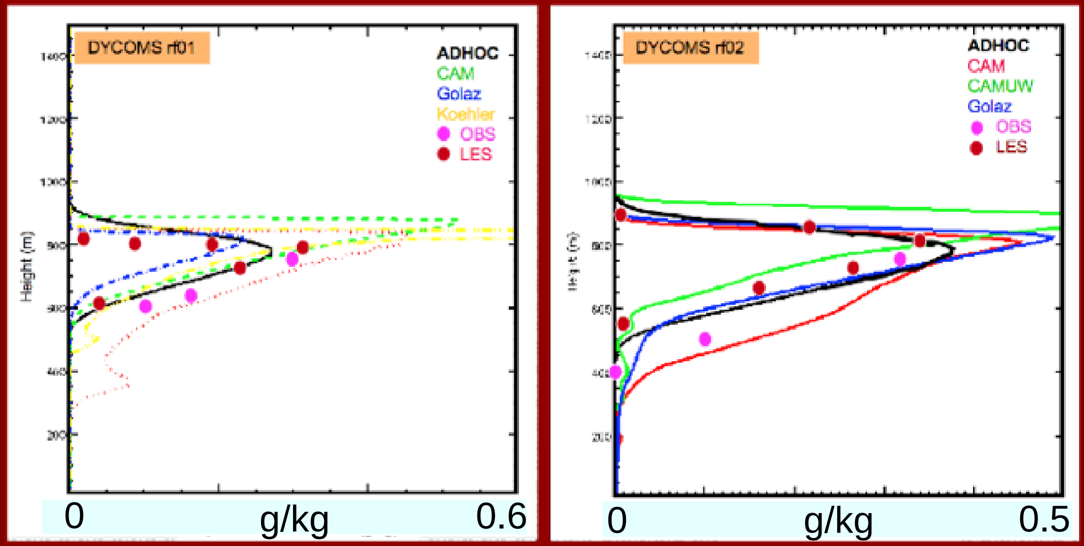


RICO

Versatility of ADHOC



Liquid water mixing ratios



DYCOMS

ADHOC2

ADHOC: Basic Idea

Predict: $\overline{w'w'}$ $\overline{w'w'w'}$

Diagnose: σ M_c w_{up} w_{dn}

Predict: $\overline{w'\psi'}$

Diagnose: ψ_{up} ψ_{dn}

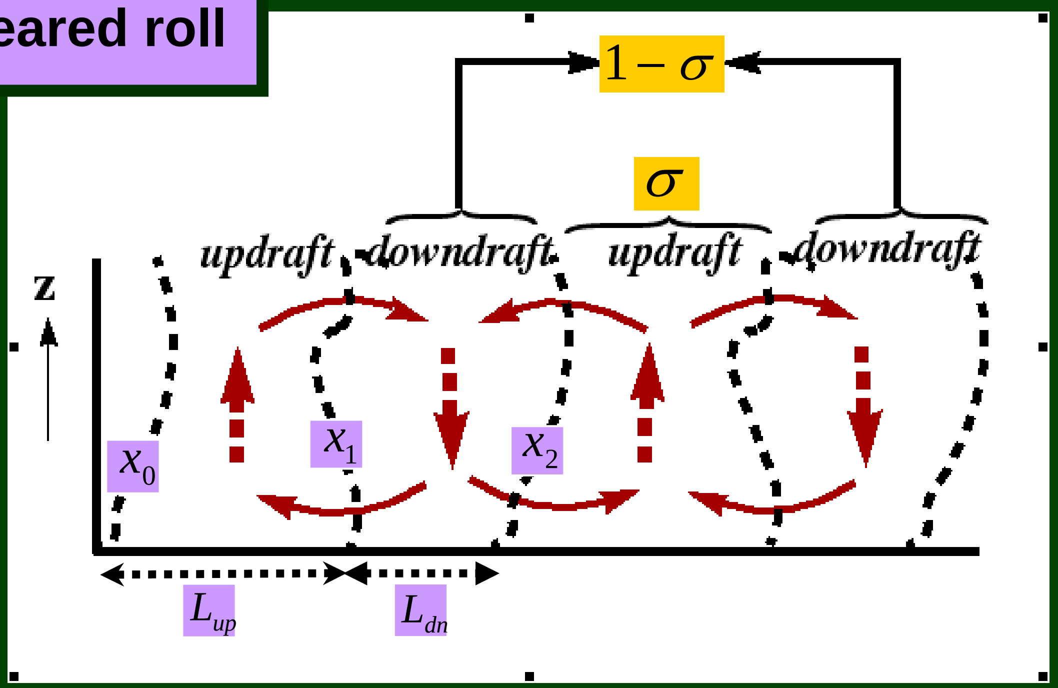
Diagnose: $\overline{\psi'\psi'}$ $\overline{w'\psi'\psi'}$ $\overline{w'w'\psi'}$ •••••

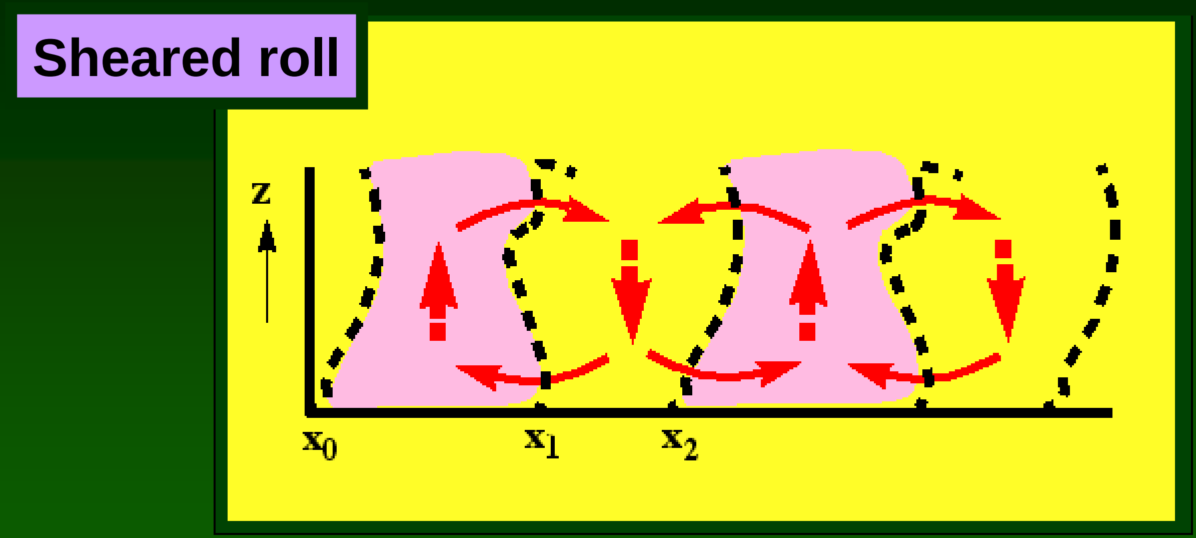
Momentum fluxes

(Lappen and Randall, 2005)

Assumed probability distribution (PDF) → **Assumed spatial distribution (SDF)**

Sheared roll





At each height, integrate the continuity equation over the roll. In the updraft, this will be:

$$\int_{x_0+\varepsilon}^{x_1-\varepsilon}\left[\frac{\partial u}{\partial x}+\frac{\partial w_{up}}{\partial z}\right]dx=0$$

This will give us u(x) in the updraft

We now have expressions for $u_{up}(x)$ and $u_{dn}(x)$

We now find the average of $\overline{u}\,(x)$ using:

$$\overline{u}(x) = \frac{1}{L}\int_{x_0}^{x_0+L} u\,dx = \frac{1}{L}\left(\int_{x_0}^{x_0+L_u} u_{up}(x)\,dx + \int_{x_1}^{x_1+L_d} u_{dn}(x)\,dx\right)$$

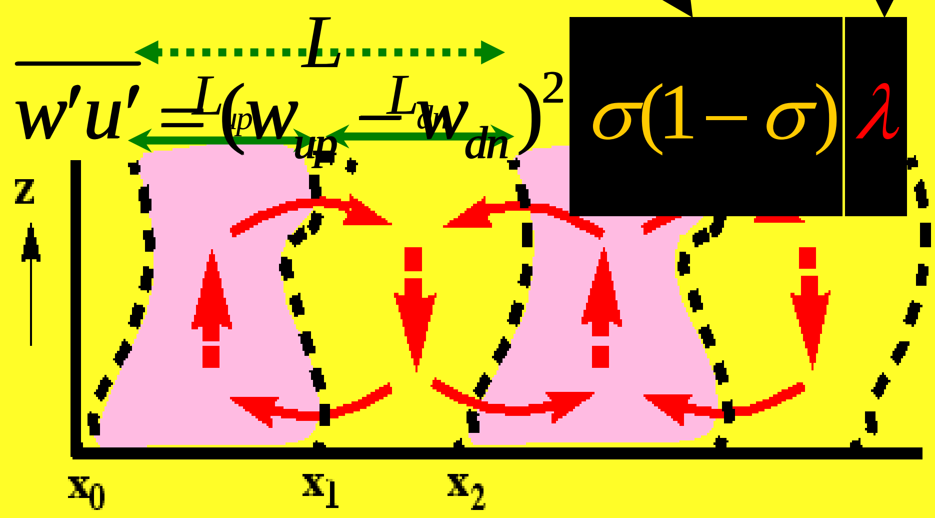
We now find the departure of u from its average: $u'(x) = u - \overline{u}$

We can then construct momentum fluxes directly using:

$$\overline{w'u'} = \frac{1}{L}\left(\int_{x_0}^{x_0+L_u} w_{up}u'_{up}(x)\,dx + \int_{x_1}^{x_1+L_d} w_{dn}u'_{dn}(x)\,dx\right)$$

$$\overline{w'u'} = (w_{up} - w_{dn})^2 \left(\frac{L_{up}L_{dn}}{L^2}\right)\left[\frac{1}{2}\left(\frac{\partial x_0}{\partial z} + \frac{\partial x_1}{\partial z}\right)\right]$$

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



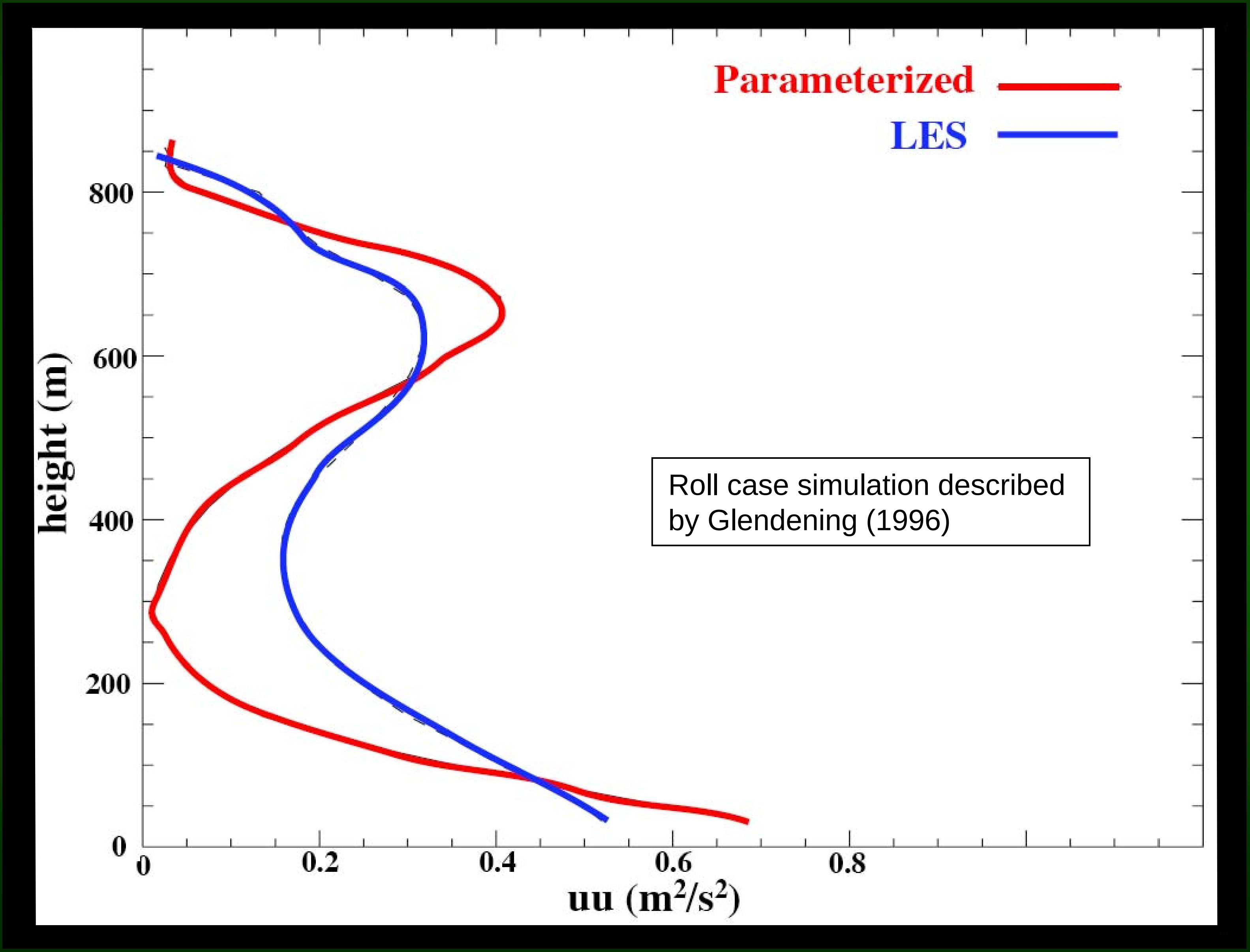
Slightly more complicated, we have….

$$\overline{u'u'} = \frac{1}{3}\left[L\sigma(1-\sigma)\frac{\partial(w_{up}-w_{dn})}{\partial z}\right]^2 +$$

$$\frac{1}{3}L\sigma(1-\sigma)\frac{\partial(w_{up}-w_{dn})^2}{\partial z}\left[(1-2\sigma)L\frac{\partial\sigma}{\partial z}+4\sigma(1-\sigma)\lambda\right]+$$

$$\overline{w'u'}\left[\lambda+\frac{(1-2\sigma)}{2}L\frac{\partial\sigma}{\partial z}\right]+\left[(w_{up}-w_{dn})L\frac{\partial\sigma}{\partial z}\right]^2\left(\frac{1-3\sigma+3\sigma^2}{2}\right)$$

$\overline{u'u'}$ comparison



Pressure terms

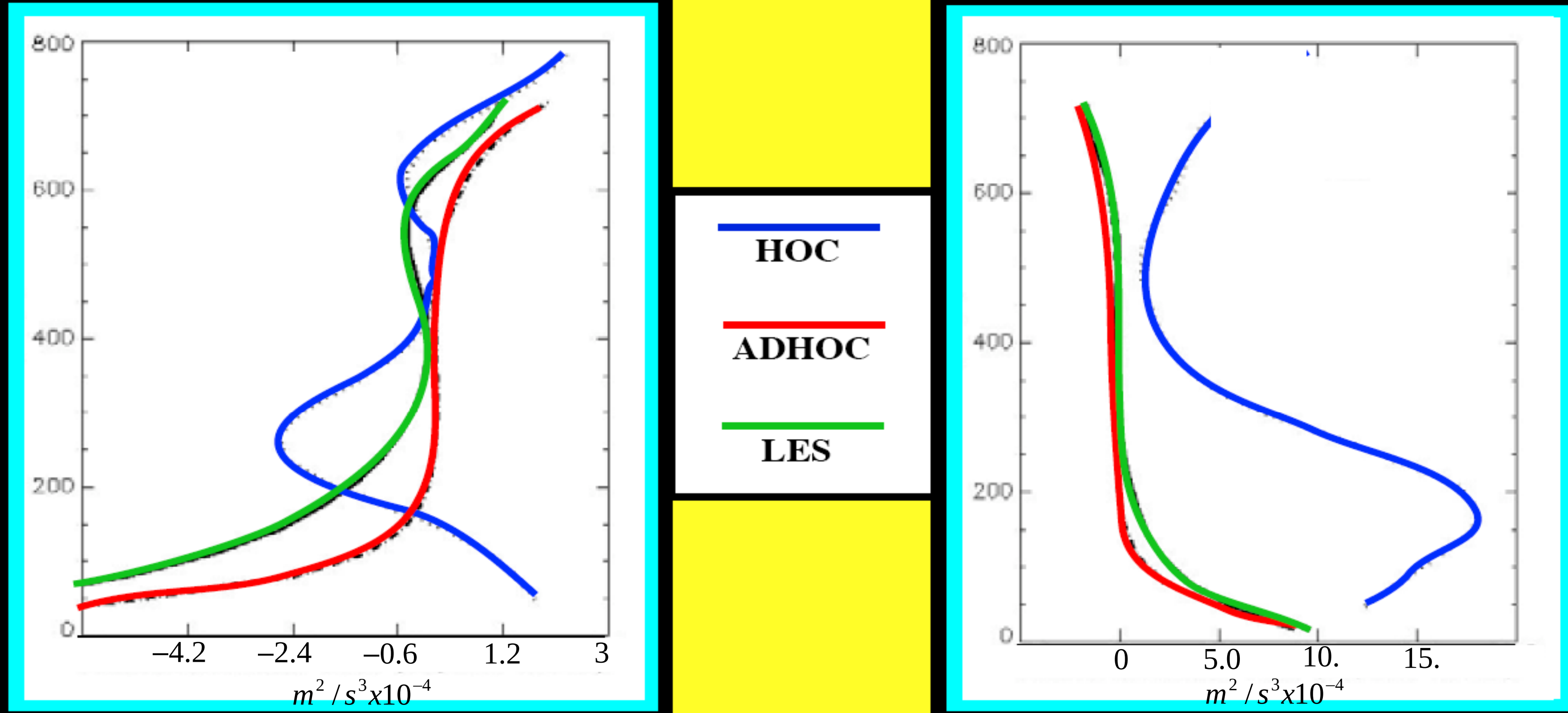
(Lappen and Randall, 2006)

$$\nabla^2\left(\frac{p}{\rho}\right) = f(u, v, w, B)$$

Using the ADHOC model, we know all of the terms on the RHS of the Poisson equation. We can integrate twice to determine the pressure, p.

We can then form the pressure terms that appear in the higher moment equations by direct integration.

Roll convection (Glendening, 1996)



$$\frac{\partial}{\partial t}\overline{u'u'} \sim 2\left[\overline{p'\frac{\partial u'}{\partial x}}\right]$$

$$\frac{\partial}{\partial t}\overline{w'w'} \sim 2\left[\overline{p'\frac{\partial w'}{\partial z}}\right]$$

We can do more than rolls…

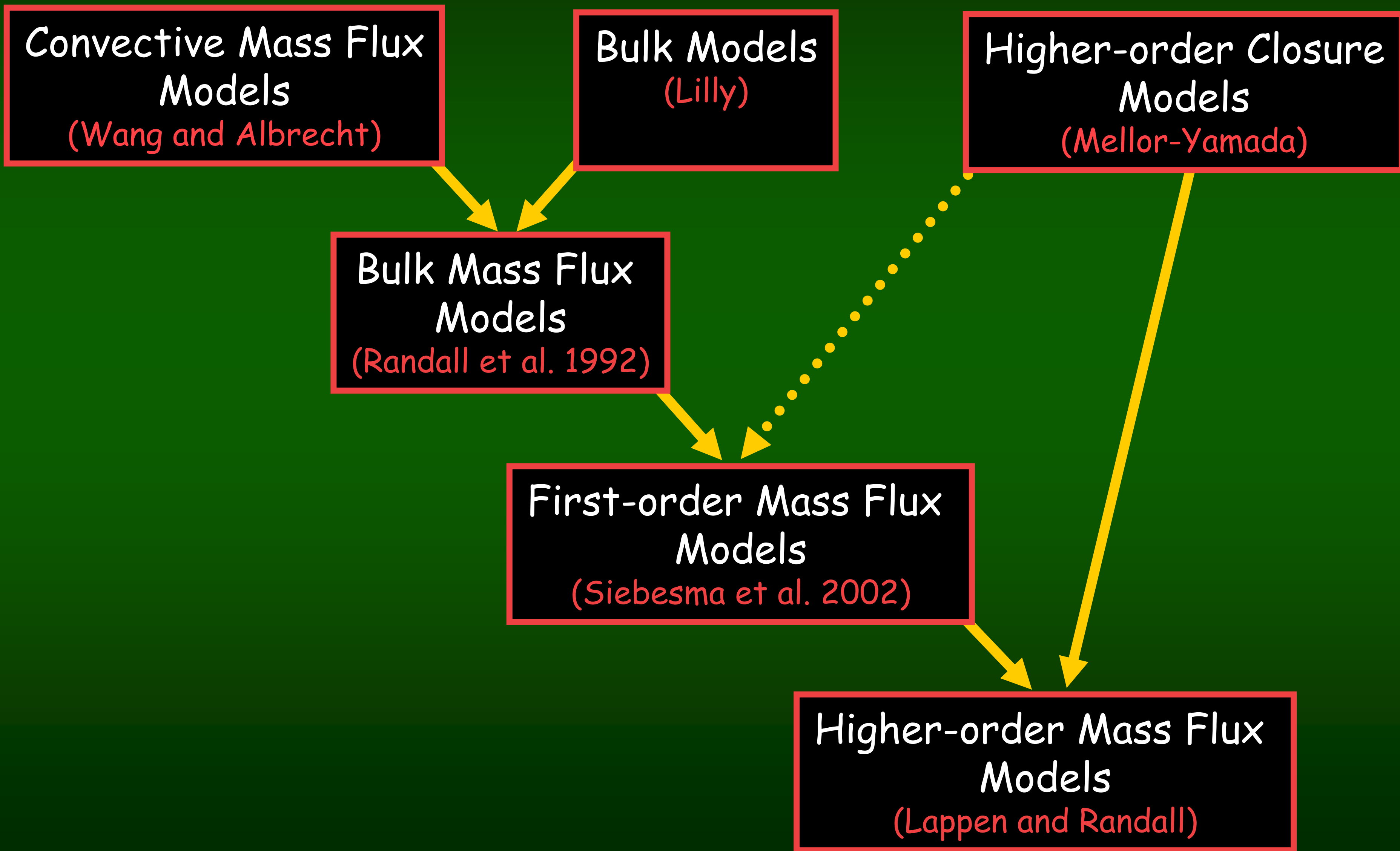
I
b
is in between these two cases.

- I have also successfully developed this technique for an axisymmetric convective plume.

Summary

- Transitional regimes are more naturally represented.
- σ and M_c are determined from the physics of the flow.
- There are no realizability issues with higher moments.
- A natural method to represent lateral mixing emerges.
- Criterion used to define updrafts not important because we have an SPS model.
- Momentum fluxes can be determined within the same framework by combining the mass-flux PDF with an SDF.
- The pressure field and the pressure terms in the 2nd moment equations can be calculated directly.
- ADHOC has successfully simulated a range of PBLs from the tropics through the subtropics

Hierarchy of PBL Models

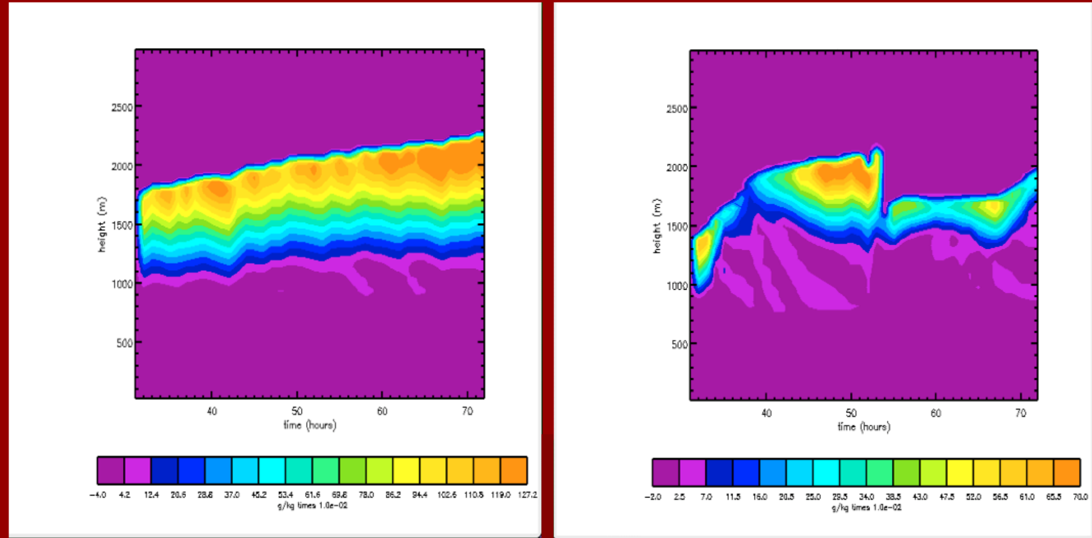



After all,
its all just fluid flow,
.....isnt it?

Precipitation scheme for ADHOC

I have implemented a modified version of Khairoutdinov and Randall (2003). We prognose precip species separately for the updraft and downdraft and then mass-flux weight them.

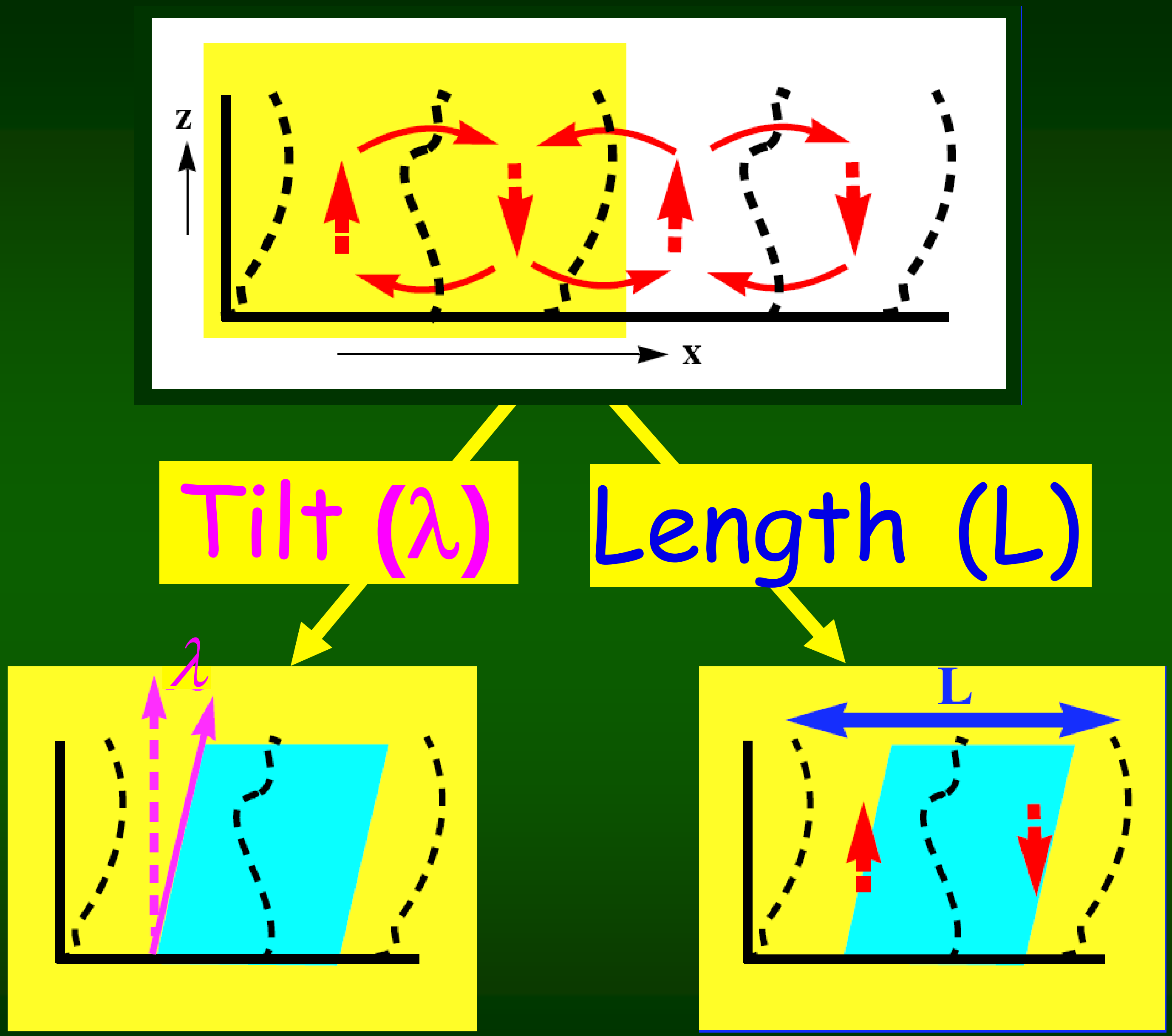
Non-precip mixing ratio w/ and w/o precipitation scheme



RICO

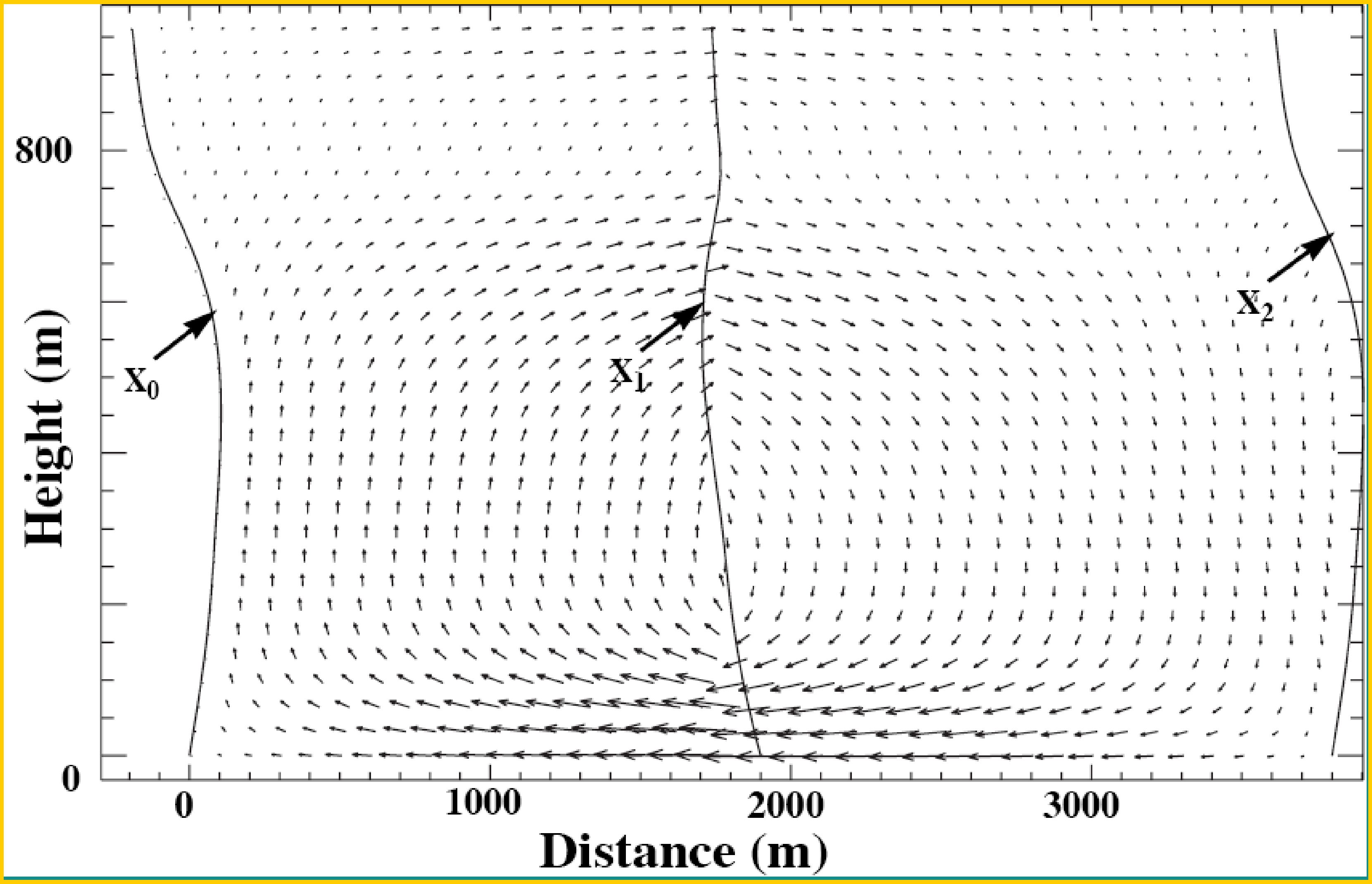
Whats new in ADHOC2?

- New ADHOC-consistent momentum flux parameterization (Lappen and Randall, 2005)
- New ADHOC-consistent pressure term parameterization (Lappen and Randall, 2006)
- A few new prognostic equations
- New ADHOC-consistent microphysics



z
x
Tilt (λ)
Length (L)
λ
L

Parameterized roll



Summary of new research

Using parameters of the spatial distribution of the flow (SDF), momentum fluxes can be incorporated into a mass-flux model in a manner consistent with the thermodynamic fluxes

From the predicted values of ADHOC2, we can determine:

- The 3-D roll circulation
- The tilt
- The wavelength
- The orientation angle
- The pressure field and the pressure terms in the 2nd moment equations

Slightly more complicated, we have….

$$\overline{u'u'} = \frac{1}{3}\left[L\sigma(1-\sigma)\frac{\partial(w_{up}-w_{dn})}{\partial z}\right]^2 +$$

$$\frac{1}{3}L\sigma(1-\sigma)\frac{\partial(w_{up}-w_{dn})^2}{\partial z}\left[(1-2\sigma)L\frac{\partial\sigma}{\partial z}+4\sigma(1-\sigma)\lambda\right]+$$

$$\overline{w'u'}\left[\lambda+\frac{(1-2\sigma)}{2}L\frac{\partial\sigma}{\partial z}\right]+\left[(w_{up}-w_{dn})L\frac{\partial\sigma}{\partial z}\right]^2\left(\frac{1-3\sigma+3\sigma^2}{2}\right)$$

ADHOC2 predicts $(\overline{u'u'})_M = \dfrac{1}{\delta z_{pbl}}\int_{PBL}(\overline{u'u'})dz$

Thus, we can determine L.

ADHOC2: Basic idea

Diagnose: $\overline{u'u'}$ $\overline{u'v'}$ $\overline{v'v'}$

Predict: $(\overline{u'u'})_M$ $(\overline{u'v'})_M$ $(\overline{v'v'})_M$

$$(\overline{u'u'})_M = \int_{PBL} \overline{u'u'}\,dz$$

Diagnose: L

Diagnose: $\overline{w'w'u'}$ $\overline{w'w'v'}$ •••••

Predict: $\overline{w'u'}$ $\overline{w'v'}$

Diagnose: λ η

ADHOC2: Basic idea

Diagnose: $\overline{u'u'}$ $\overline{u'v'}$ $\overline{v'v'}$

Predict: $(\overline{u'u'})_M$ $(\overline{u'v'})_M$ $(\overline{v'v'})_M$

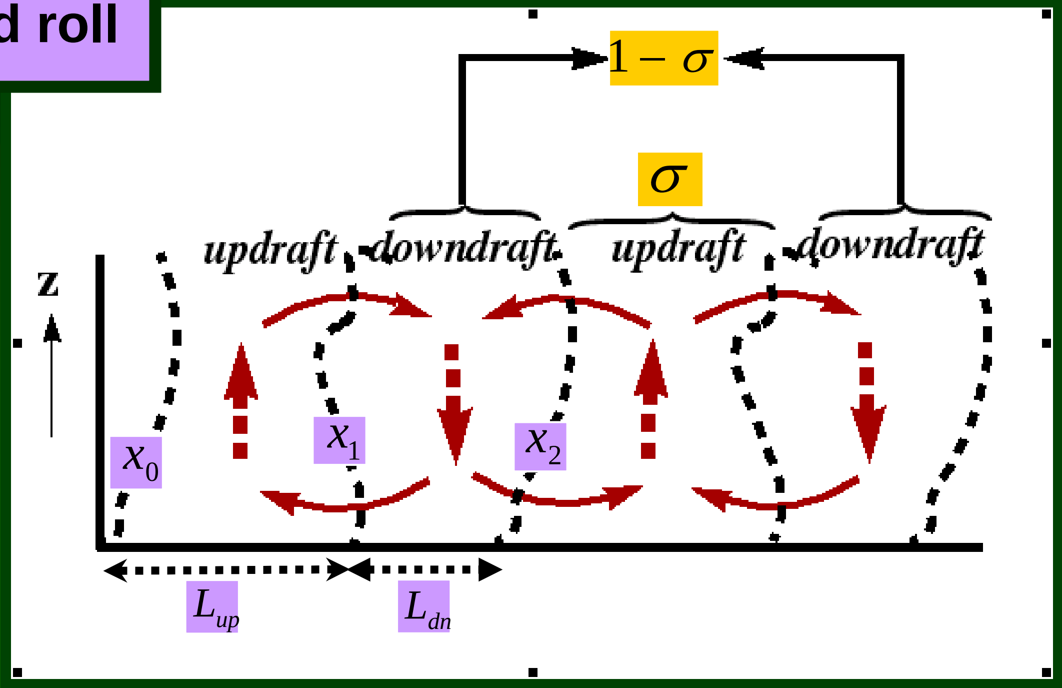
$$(\overline{u'u'})_M = \int_{PBL} \overline{u'u'}dz$$

Diagnose: λ η L

Diagnose: $\overline{w'w'u'}$ $\overline{w'w'v'}$ •••••

Predict: $\overline{w'u'}$ $\overline{w'v'}$

Sheared roll

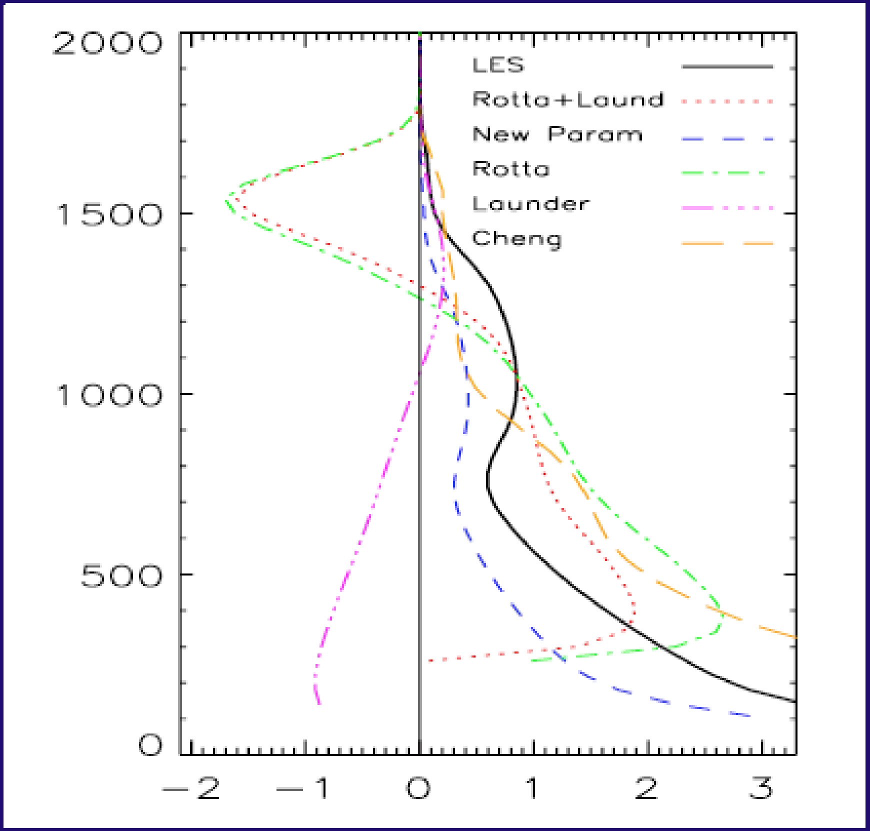


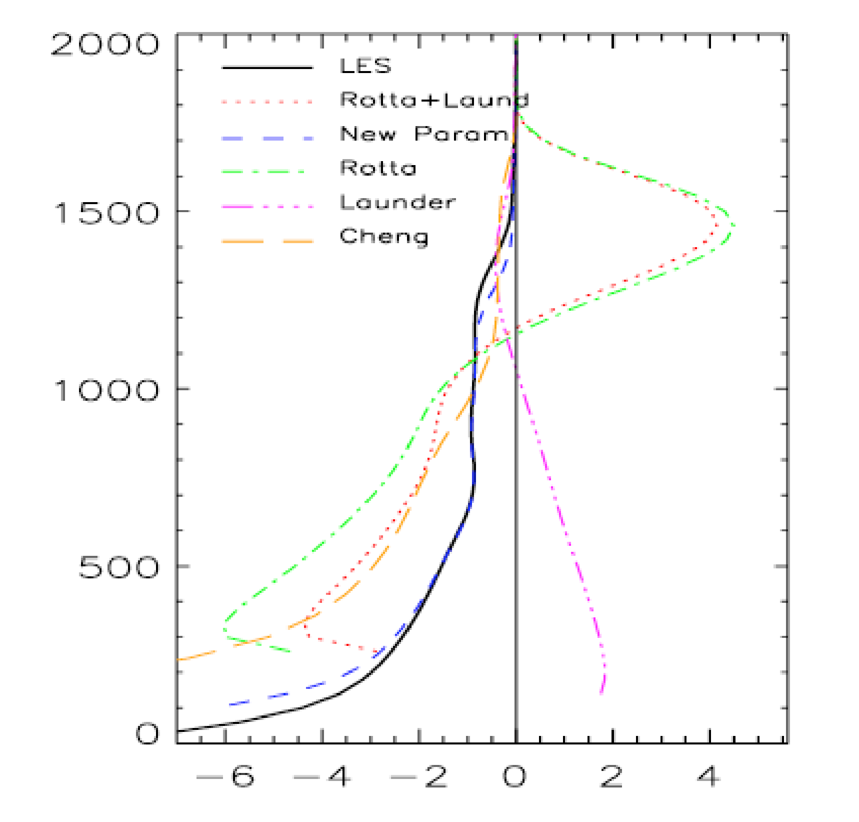
$w = w_{up}(w_{dn})$, $\theta = \theta_{up}(\theta_{dn})$ everywhere in the updraft (downdraft)

$L = L_{up}(z) + L_{dn}(z)$ is **independent** of height

$\sigma = L_{up}(z)/L \quad ; \quad 1-\sigma = L_{dn}(z)/L$

Clear convection (Wangara)





$$\frac{\partial \overline{u'u'}}{\partial t} \sim \overline{p' \frac{\partial u'}{\partial x}}$$

$$\frac{\partial \overline{w'w'}}{\partial t} \sim \overline{p' \frac{\partial w'}{\partial z}}$$

Defining updrafts and downdrafts

(1) Humidity threshold ($q' > q_{crit}$) [CBL: Oceans]

(Lenschow and Stephens, 1980)

(2) $w' > 0$ and $q' > 0$ [Cloud-topped mixed layers]

(Nicholls and Lemone, 1980 ; Penc and Albrecht, 1987)

(3) Vertical velocity threshold ($w' > w_{crit}$) [Oceans]

(Greenhut and Khalsa, 1982 ; 1987)

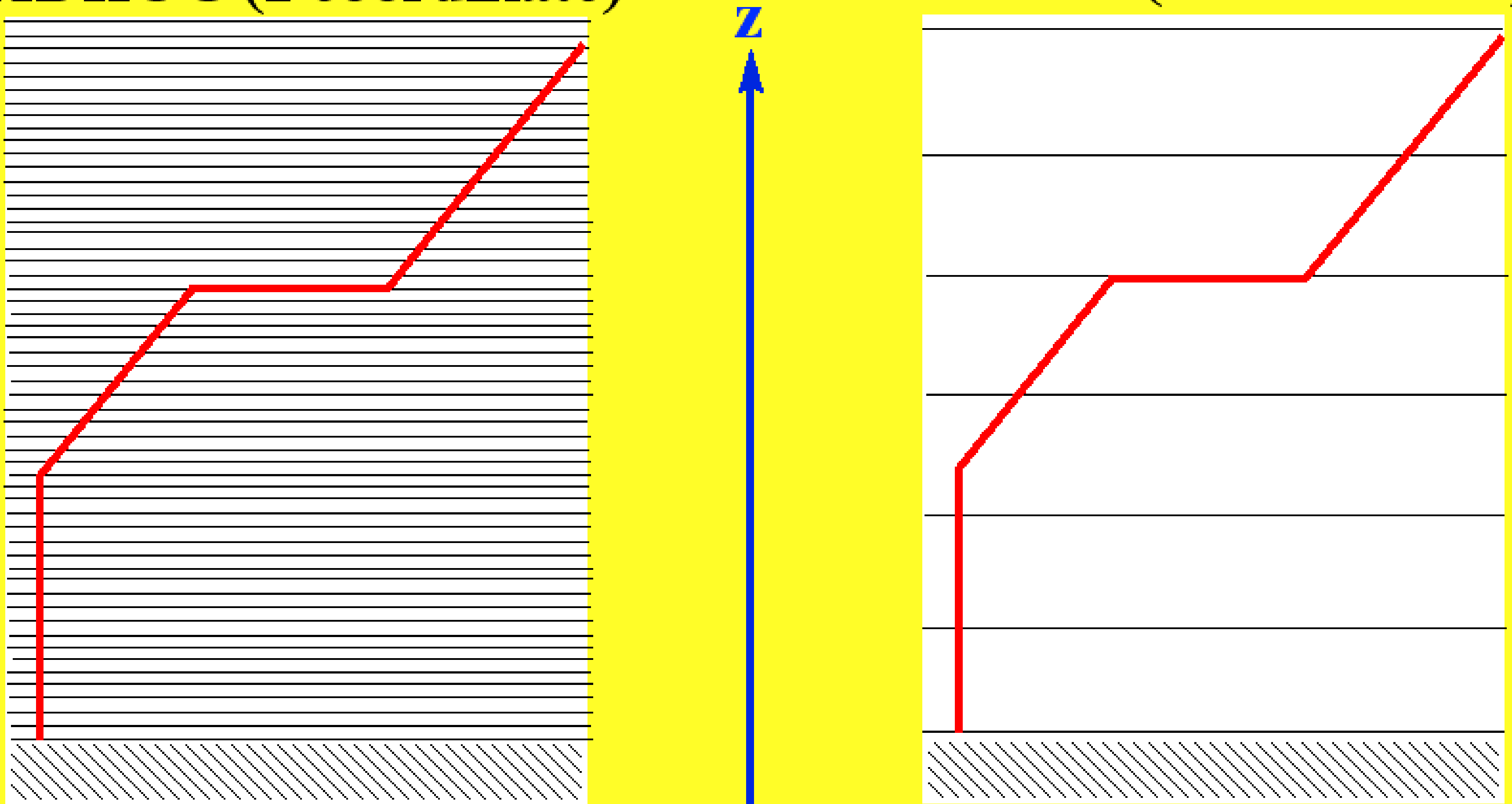
(4) Vertical velocity ($w' > 0$) [CBL: land]

(Young, 1988 a,b)

(5) $w' > 0$, $ql > 0.0$, and positive buoyancy [Tradewind Cu]

(Siebesma and Cuijpers, 1995)

ADHOC (z coordinate) | ADHOC (σ coordinate)



implicit ← PBL top height → explicit

implicit ← Entrainment → explicit

~ 1 second ← Timestep → ~ 5 minutes

~20 m ← dz → ~ 200 m

How wide?

We can derive an expression for

$$\overline{u'u'}$$

We predict

$$[\overline{u'u'}]_M$$

and choose the width of the rolls so that the implied value agrees with the predicted value.

1969 — MF modeling of deep Cu convection
(Arakawa)

Late 60s
Early 70s — HOC and MF- simultaneously developed
(MY, Lumley, Launder, Deardorff- HOC)
(Arakawa and Schubert, Yanai- MFC)

Mid 70s — MF ideas extended to tradewind Cu
(Betts)

Late 70s — MF ideas extended to dry convective subcloud layer (Betts)

Early 80s — Observations- MFC applicability to CBLs
(Lenschow and Stevens, Nicholls and Lemone, Greenhut and Khalsa, Young-1988)

Mid 80s — First mass-flux PBL models
(Penc and Albrecht, Wang and Albrecht- ScTBL)
(Chatfield and Brost (dry CBL)

1990 — Extension of 1980s work
(Wang and Albrecht- extended model to dry CBL)
(Businger and Oncley- convective surface layer)
(Schumann and Moeng- first LES studies)

Early 90s
Mid 90s — LES surge and more observations
(Siebesma and Holtslag/Cuijpers- TWBL)
(de Laat and Duynkerke- ScTBL)

Today — Unified Schemes
(Lappen and Randall, add EUROPEAN GROUPS)

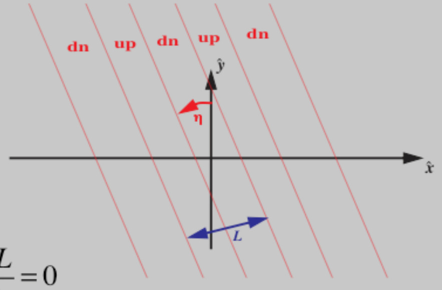
Roll-parallel wind

The roll-parallel wind has a top-hat structure in the cross-roll direction.

$$\overline{w'v'} = \sigma(1-\sigma)(w_u - w_d)(v_u - v_d)$$

$$\overline{v'v'} = \frac{(\overline{w'v'})^2}{\overline{w'w'}}$$

Orientation angle



$$\frac{\partial L}{dz} = 0$$

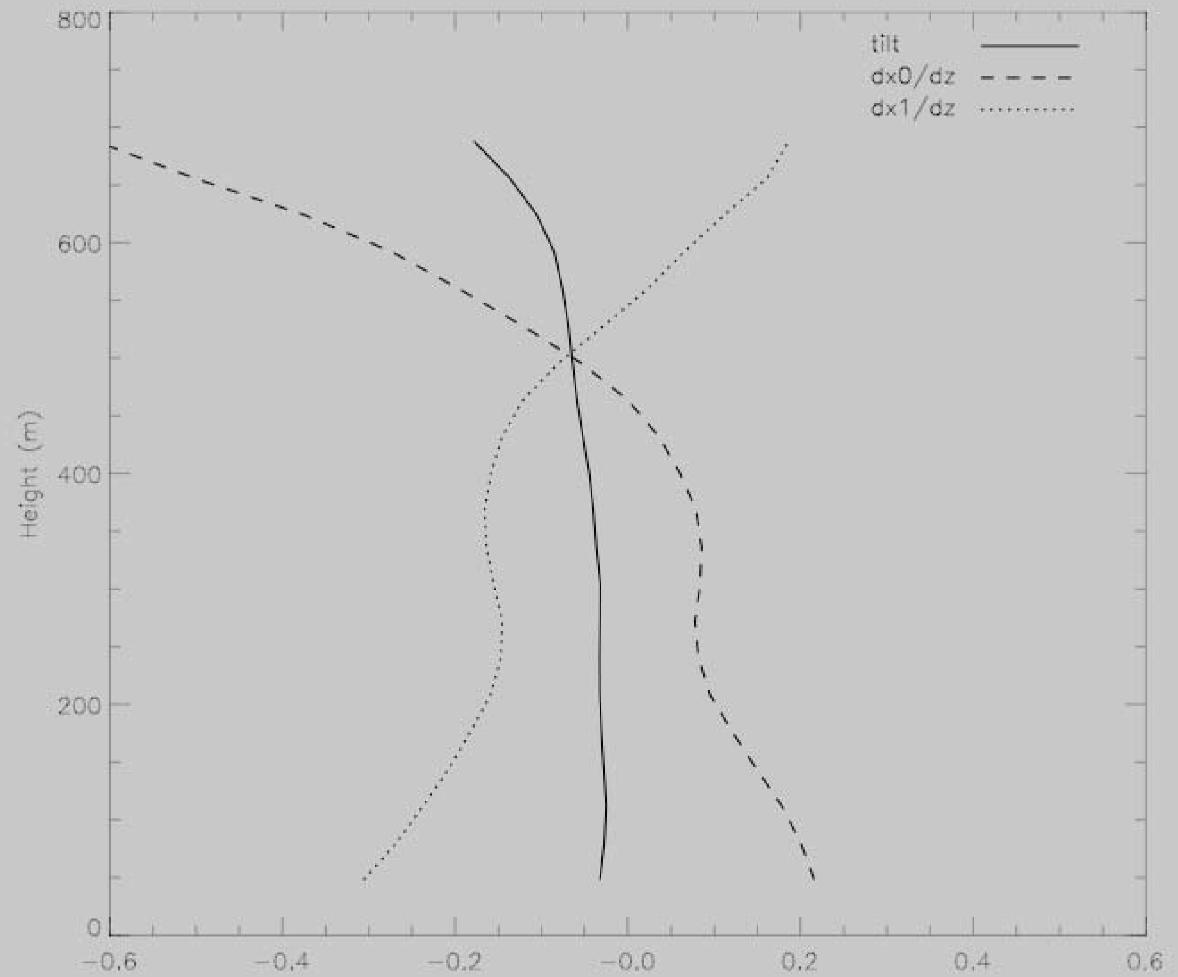
Predict

$$\overline{w'\hat{u}'}(z) \quad \overline{w'\hat{v}'}(z) \quad [\overline{(\hat{u}')^2}]_M \quad [\overline{(\hat{v}')^2}]_M \quad [\overline{\hat{u}'\hat{v}'}]_M$$

Choose the orientation angle so that, in the vertical mean,

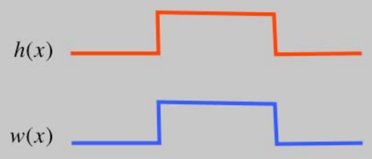
$$\overline{v'v'} = \frac{(\overline{w'v'})^2}{\overline{w'w'}}$$

Tilt from LES



Mass-flux model: Scalar fluxes

$$\overline{w'w'} = \sigma(1-\sigma)(w_u - w_d)^2$$
$$\overline{w'h'} = \sigma(1-\sigma)(w_u - w_d)(h_u - h_d)$$



Vertical fluxes of horizontal momentum

$$\frac{\partial u}{dx} + \frac{\partial w}{dz} = 0$$
$$\frac{\partial w}{dx} = 0$$
$$\frac{\partial^2 u}{\partial x^2} = 0$$

Parameterizing σ and Mc

$$M_c = a\sigma w^*$$

Wang and Albrecht (1986; Sc) $a\sigma = 0.5$

Wang and Albrecht (1990; dry CBL) $a\sigma = 0.04 - 0.9$

Betts (1976; tradewind Cu) $a\sigma = 0.43$

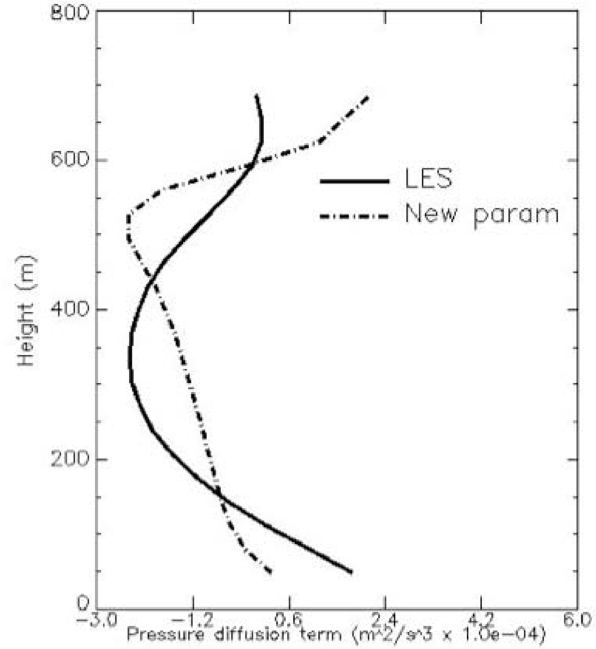
Penc and Albrecht (1986; Sc) $a\sigma = 0.15$

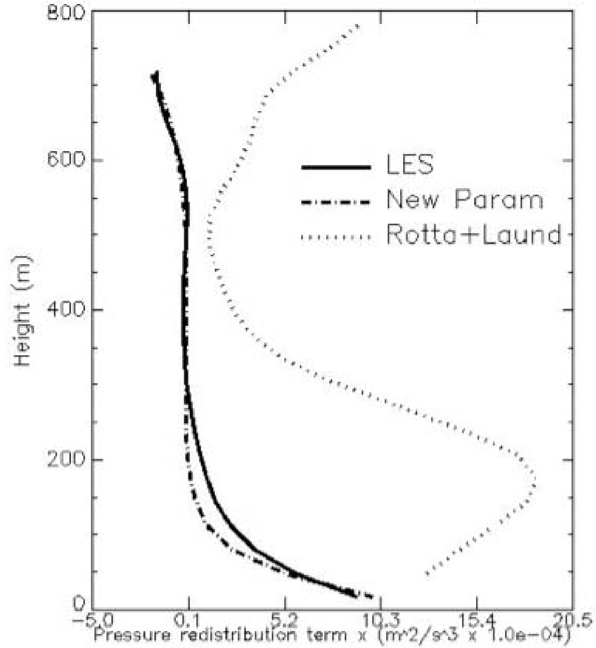
Businger and Oncley (1990; sfc layer) $a\sigma = 0.6$

Pressure terms

Finally, we can solve for the pressure field, and then construct the second moments involving pressure.

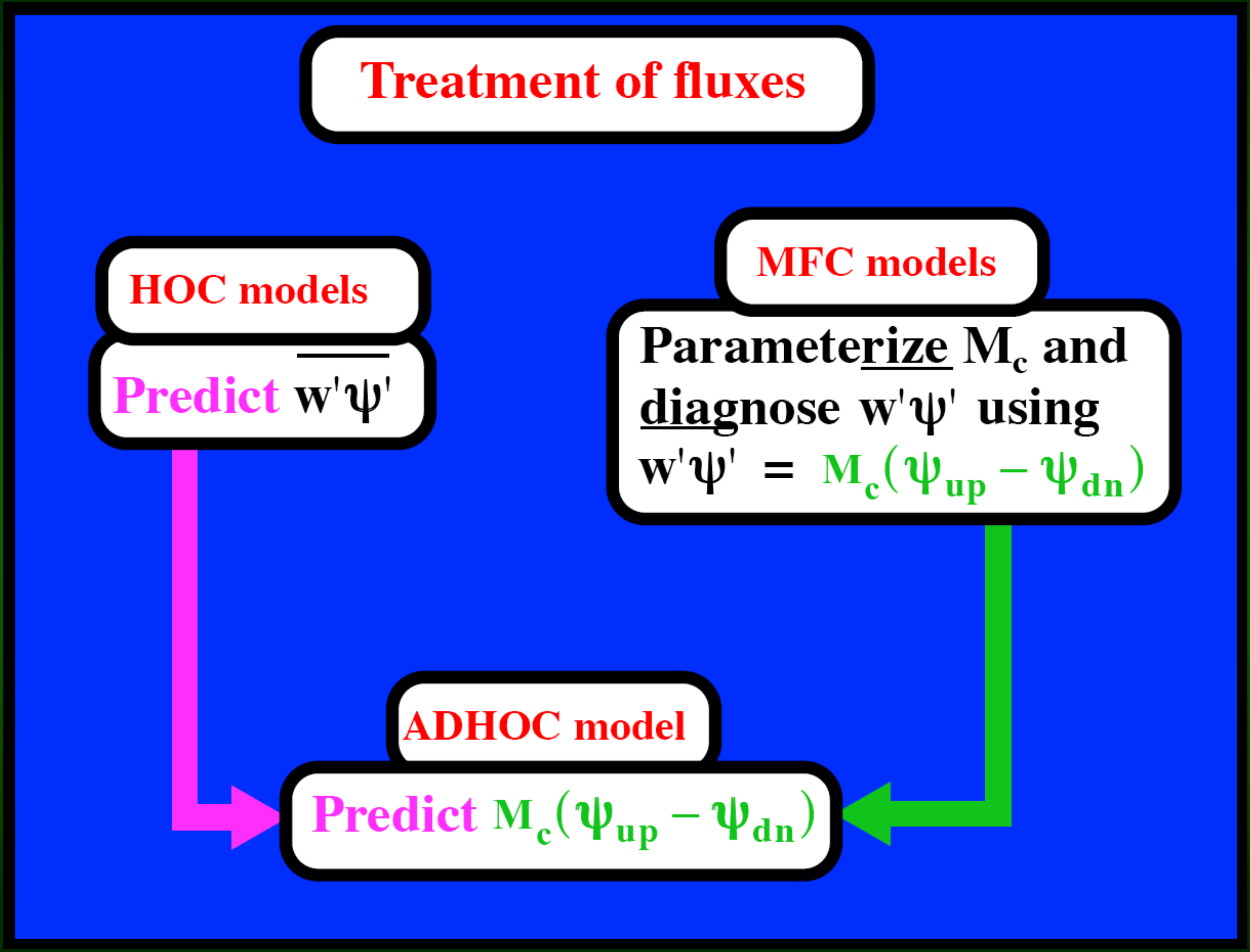
$$\nabla^2\left(\frac{p}{\rho}\right) = f(u,v,w,B)$$





Advantages of ADHOC

- Transitional regimes are more naturally represented
- σ and M_c are determined from the physics of the flow.
- There are no realizability issues with higher moments.
- A natural method to represent lateral mixing emerges.
- Criterion used to define updrafts not important because we have an SPS model
- Momentum fluxes can be determined within the same framework.


Treatment of fluxes
HOC models
Predict $\overline{w'\psi'}$
MFC models
Parameterize M_c and diagnose $w'\psi'$ using
$w'\psi' = M_c(\psi_{up} - \psi_{dn})$
ADHOC model
Predict $M_c(\psi_{up} - \psi_{dn})$

DYCOMS II

nocturnal marine Sc

RF01	RF02
very dry inversion	moister inversion
Warmer and drier than RF02	Cooler and moister than RF01
Winds weaker than RF02	Winds stronger than in RF01
150cm^{-3} droplet concentrations	65cm^{-3} droplet concentrations
No drizzle	Drizzle
surface shf / lhf ~ 15/115	surface shf / lhf ~ 16/93
unstable w.r.t. R-D CTEI criterion but cloud thickened	Cloud and subcloud didn't decouple w/ drizzle- stayed well mixed