Stable and transitional (and cloudy) boundary layers in WRF

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WRF PBL and Land Surface options

- Too many options!
- PBL here:
  - MYJ (traditional, local, TKE)
  - TEMF (EDMF, total turbulent energy)
- Land surface:
  - Slab (5-layer thermal diffusion, no vegetation)
  - NOAH (Everything)

Total Energy Mass Flux (TEMF)

- EDMF-type scheme
- Targeted toward stable boundary layers and shallow / fair-weather cumulus cases
- Moist conserved variables
- Released in WRF v3.3

TEMF: The stable side (Mauritsen et al. 2007 JAS)

- Use of total turbulent energy in stable stratification (potential + kinetic energy)
  - therefore no implicit critical Ri
- Use of local gradient Ri stability functions
- Length scale incorporates z, f and N
- Avoids self-correlation in selection of empirical coefficients
- Tested in almost 100 LES cases

Stability functions

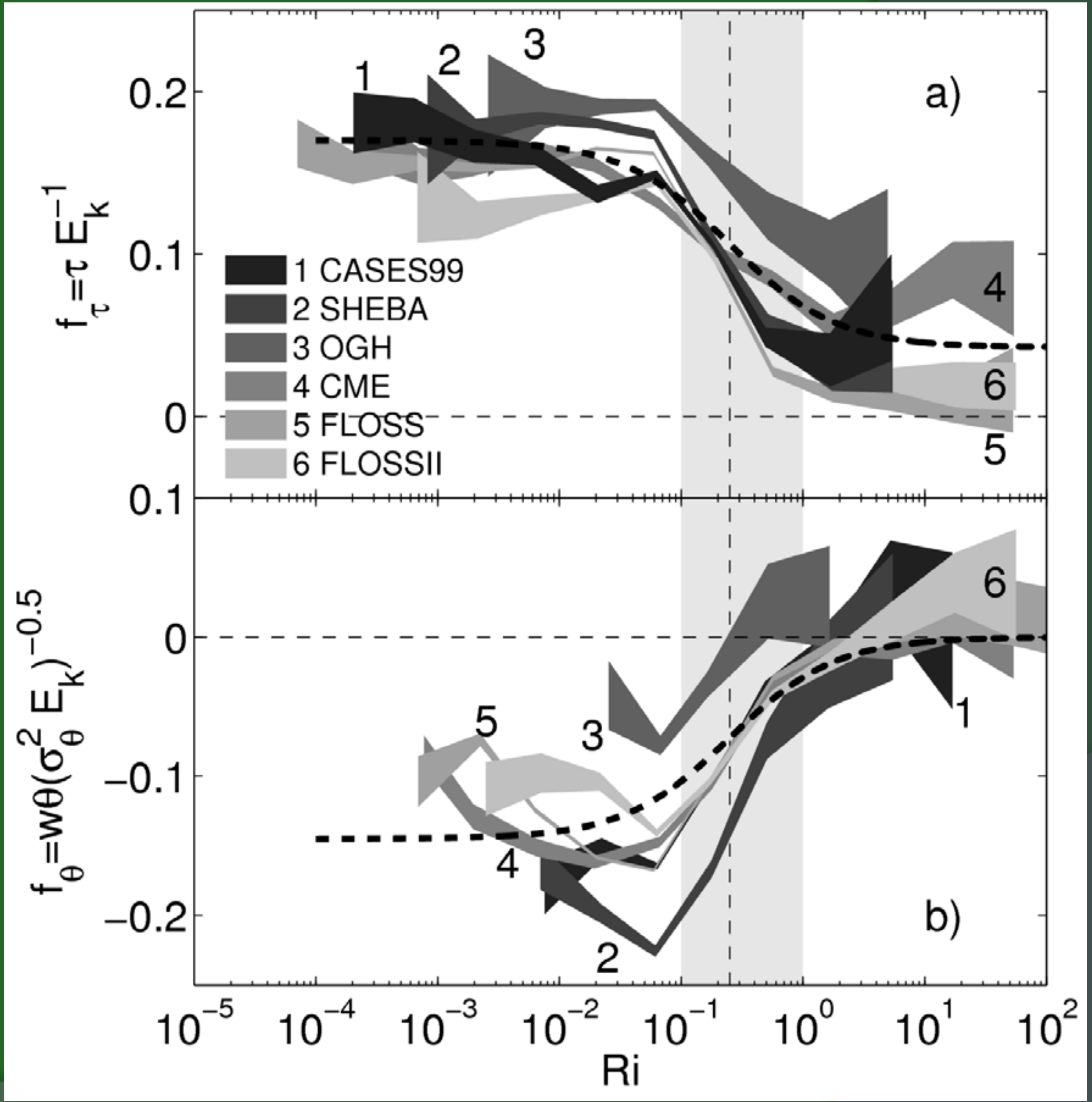
Dashed lines show empirical fits used in the scheme

(Normalized) momentum transport continues at high Ri

(Moderately) sharp tails

Momentum

Heat



The convective side (Angevine 2004 JAM)

- Eddy diffusion – Mass flux (EDMF) scheme
- Patterned after work by Siebesma, Teixeira, and others
- Diffusion coeffs. based on total energy (TE)
- Mass flux transports all quantities, including TE, U, V
- Length scale based on distance from surface and inversion

Differences between TEMF and other EDMF-type schemes

- Entrainment & detrainment rates
- TE rather than TKE or profile as basis for diffusion coefficients
- Length scale (minor differences?)
- Cloud base mass flux is continuous and proportional to w*
- Mass flux and updraft velocity are prognostic, area fraction not (directly) specified
- Updraft properties initialized at z_0, no excess
- No explicit top entrainment
- Surface layer uses same stability functions as BL, not M-O

Total Energy vs. TKE

GOMACCS 11 Sept.

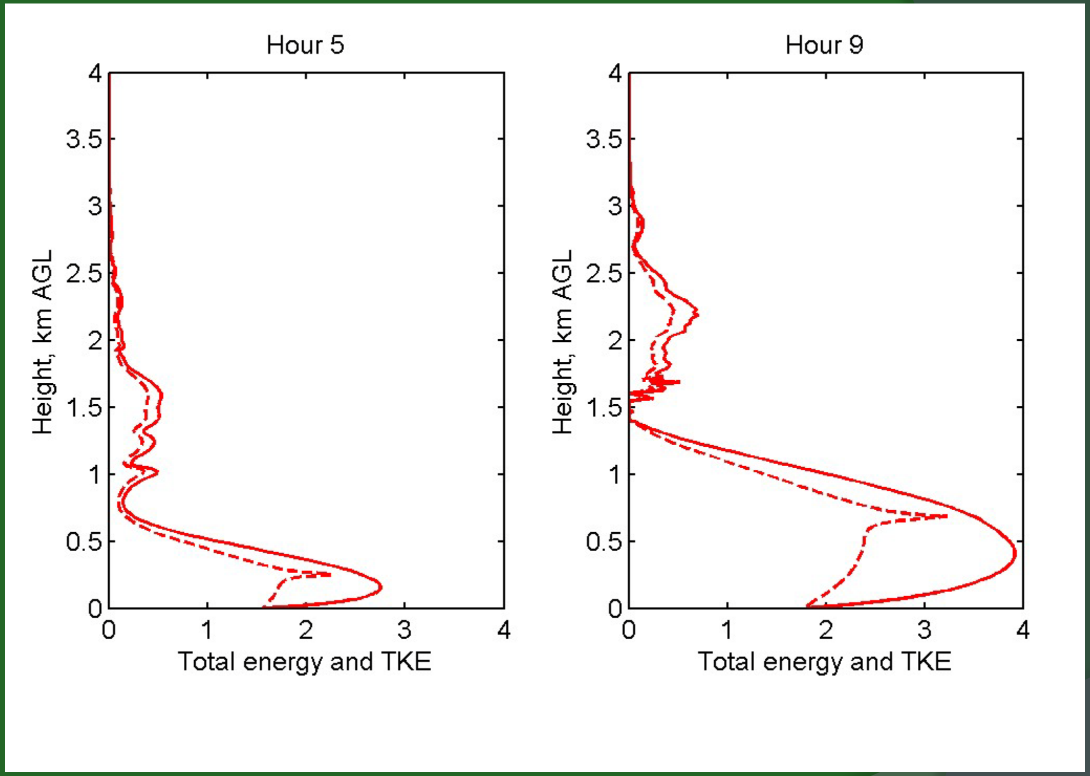
Solid = TE, dashed = TKE

TKE is slightly smaller throughout

Most significant in upper subcloud layer

Lack of TKE near cloud base can cause problems for TKE-based EDMF schemes. TEMF addresses this by using TE and by transporting TE with mass flux.

Comparison is imperfect because stability functions might need to be different in a TKE-based scheme



CalNex evaluation

- CalNex air quality and climate study
  - May-June 2010
- WRF run for two months in real-time forecast mode
  - Two major retro runs since, another underway
- 16 May case study chosen because aircraft and ship were present and interacting in cloudy area
- P3 provides profiles and tracks in and above cloud
- Atlantis provides continuous cloud base, top, and fraction

Model configurations

WRF REF:
36/12/4 km horizontal grid
ERA-Interim initialization (was GFS for forecast)
60 vertical levels, 18 below 1 km, lowest level ~15 m
Eta microphysics
RRTM-G radiation (LW & SW)
Grell-Devenyi cumulus, outer domain only
MYJ boundary layer & surface layer
Navy GODAE high-resolution SST (6-hourly)

WRF TEMF:
Same as REF except for TEMF boundary layer and surface layer on domains 2 and 3

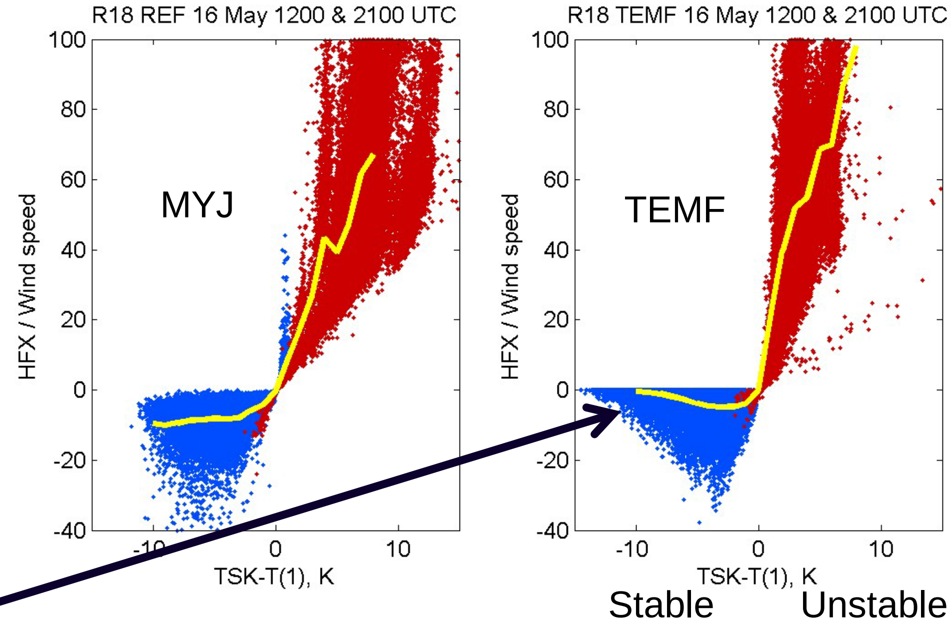
COAMPS:
Navy operational mesoscale model run at Pt. Mugu by Lee Eddington
Cycling mode with assimilation of all available data

Effective bulk transfer coefficient for heat (C_H)

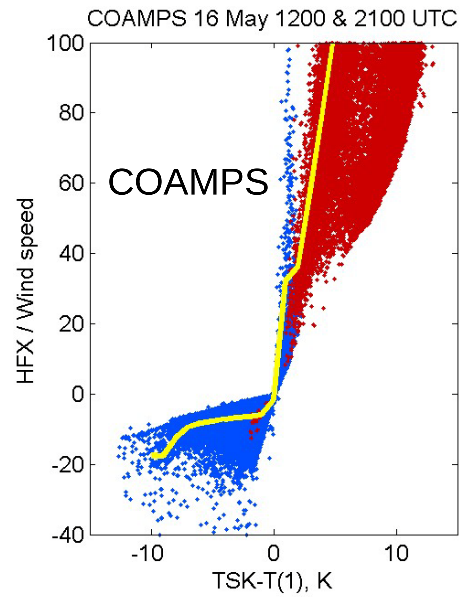
(Normalized) heat transfer decreases at strong stability in TEMF, not in MYJ or COAMPS

Curve rises more steeply on unstable side than MYJ, but less than COAMPS

TEMF does not allow large instabilities



Thanks to
Michael Tjernström
for the idea

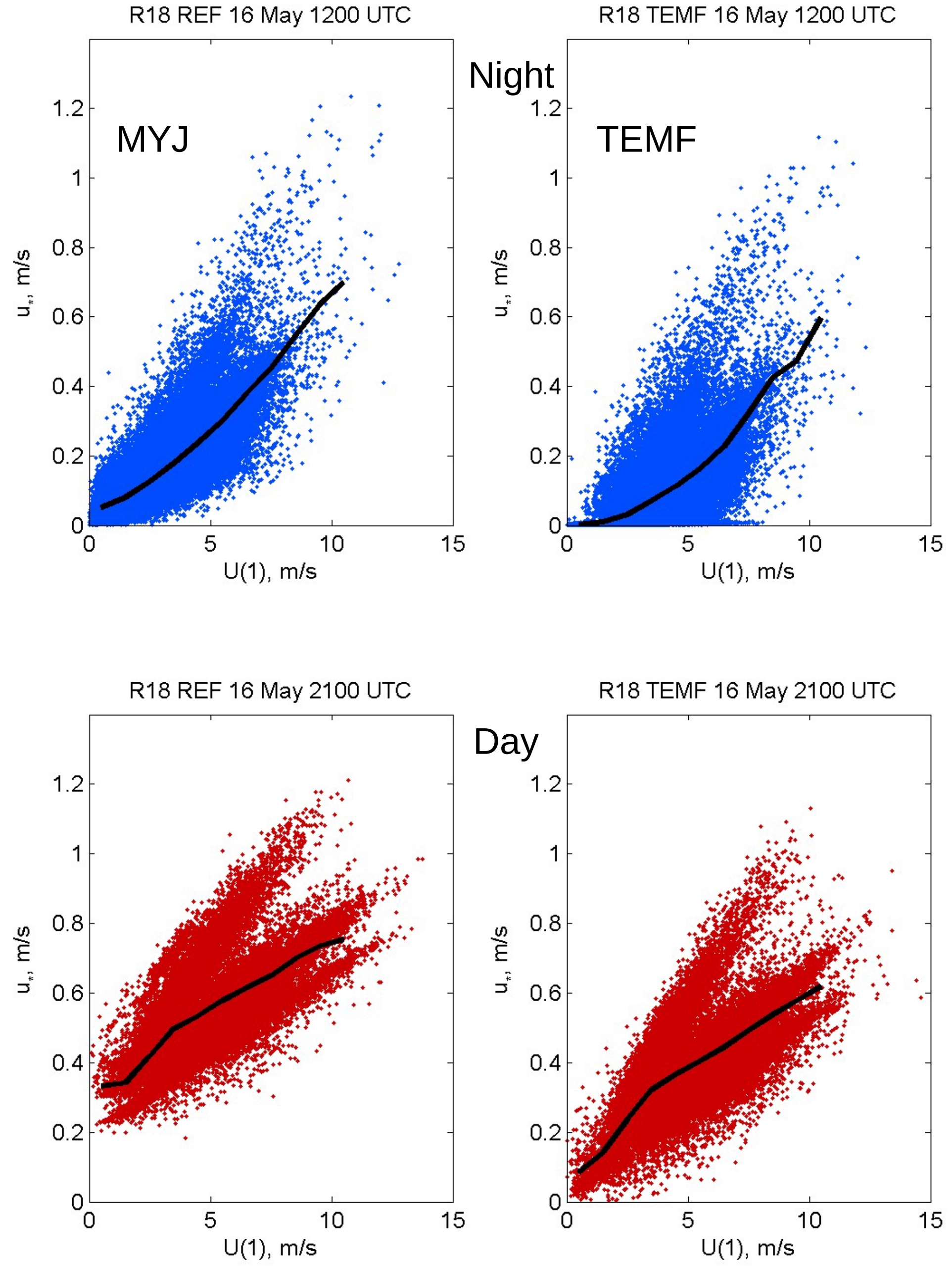


Drag relationship

TEMF has less stress at small speed

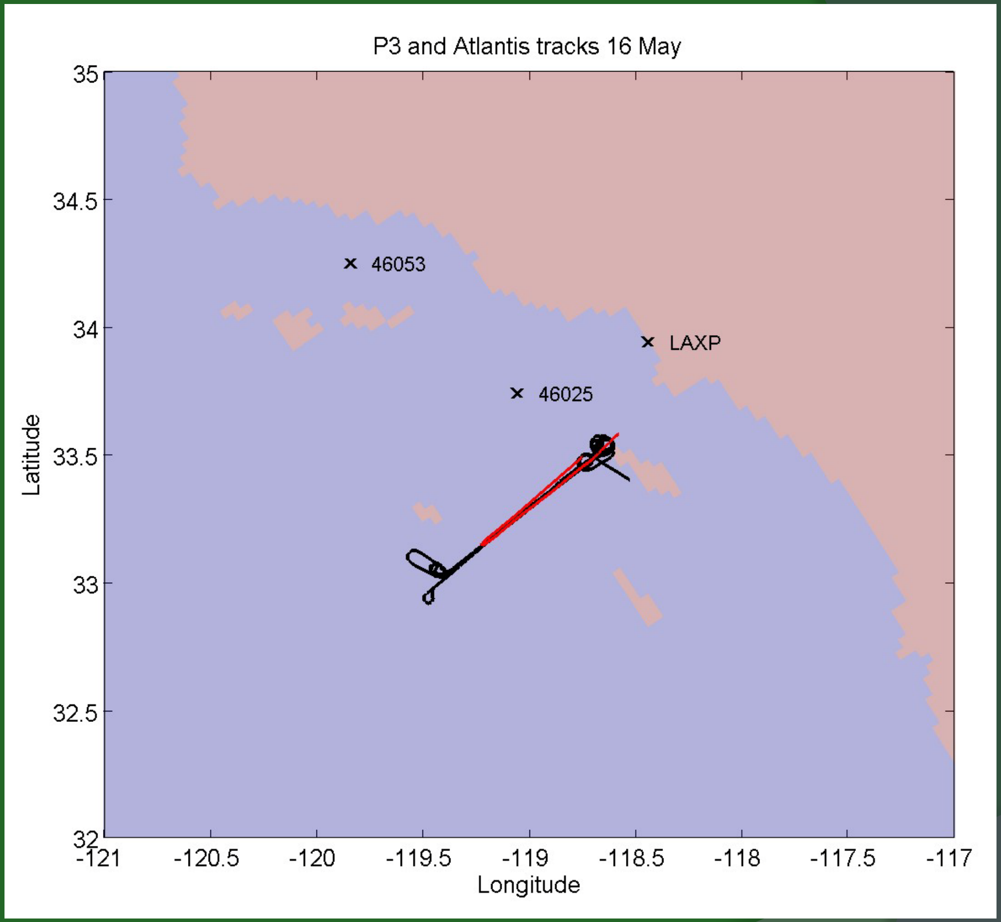
TEMF has fewer very small speeds at night

Overall surface wind speed distribution is similar



P3 and Atlantis cloud study track

P3: 1818 – 2124 UTC
Atlantis: 1800 – 0000 UTC



Profiles on P3 track

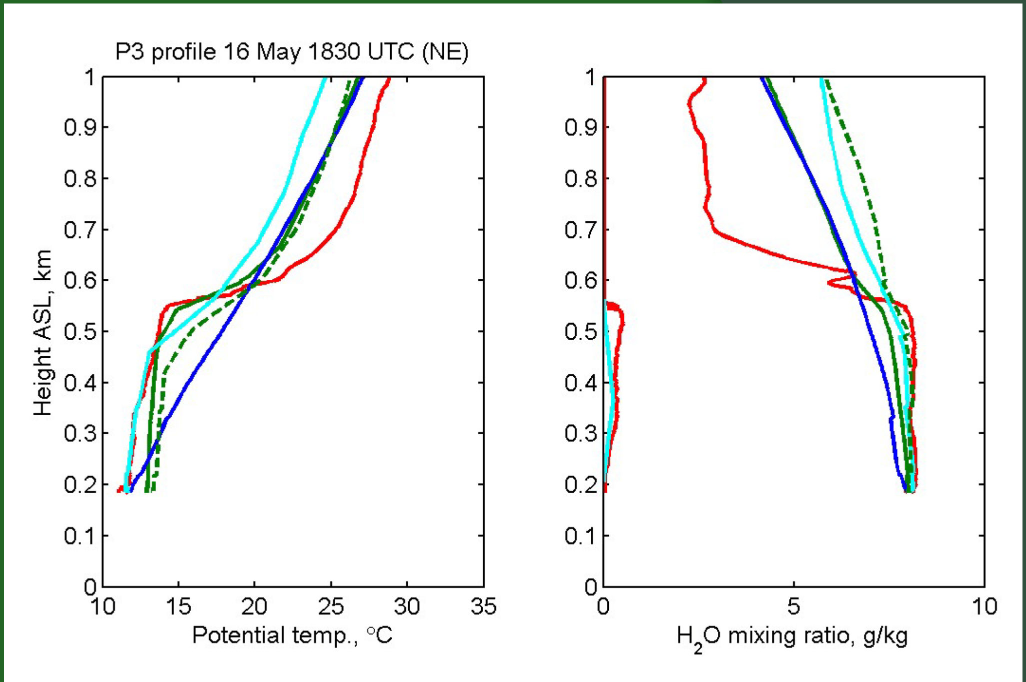
Obs have ~550 m roughly well-mixed cloudy BL with strong, sharp inversion and dry layer above

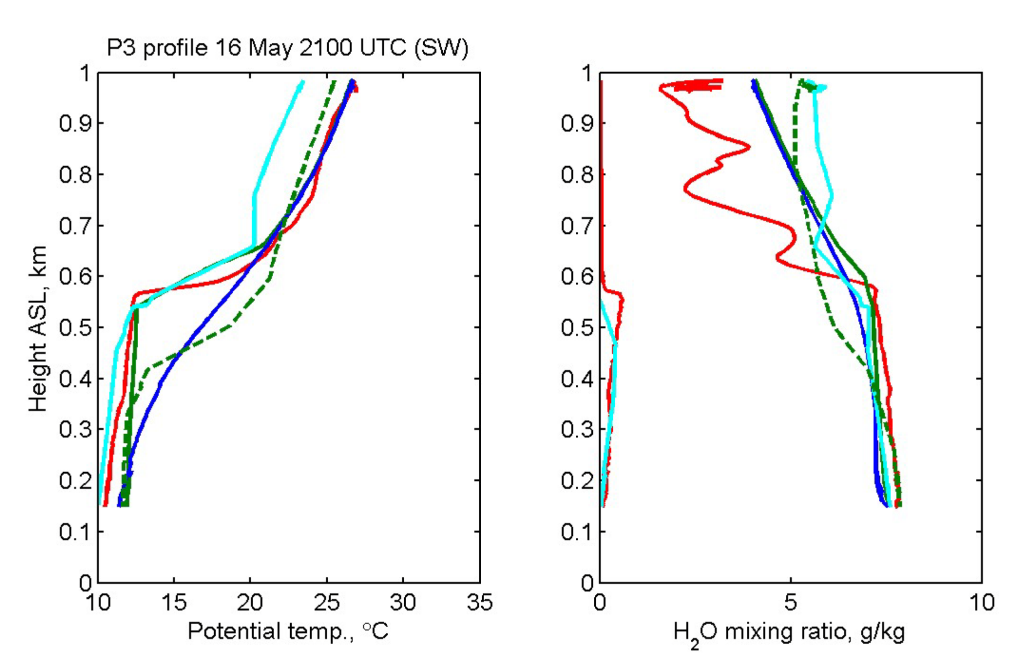
REF has shallow, stable BL
No cloud water because profile is unsaturated

TEMF BL matches obs well
Not saturated at grid scale

COAMPS also does well but slightly shallow NE

Red = P3 obs
Blue = WRF REF
Green = TEMF
Cyan = COAMPS
(R18/new CM)



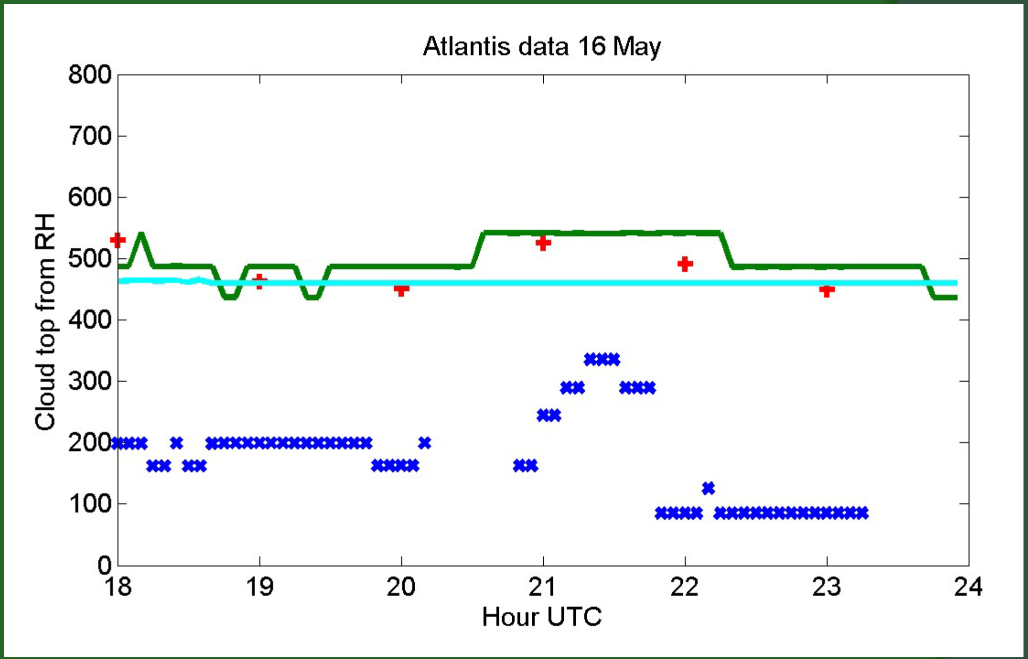


Cloud top along ship track

TEMF & COAMPS tops good

REF too low

Red = measured
Green = TEMF
Blue = REF
Cyan = COAMPS
(R18/new CM)



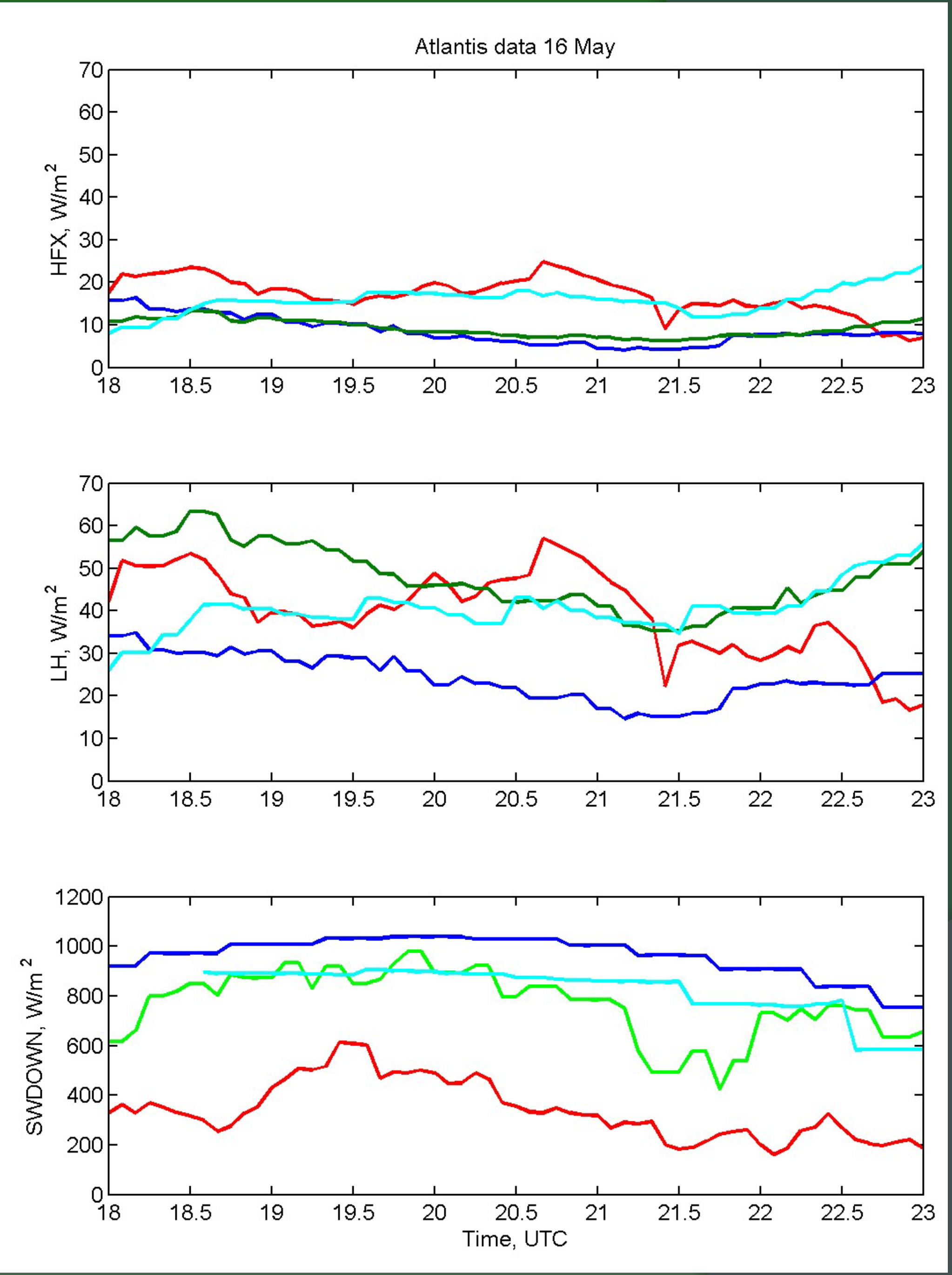
Flux data along ship track

Latent heat flux too low in REF

COAMPS best sensible heat flux

REF has little cloud influence on radiation, TEMF and COAMPS some but not enough

Red = measured
Green = TEMF
Blue = REF
Cyan = COAMPS
(R18/new CM)



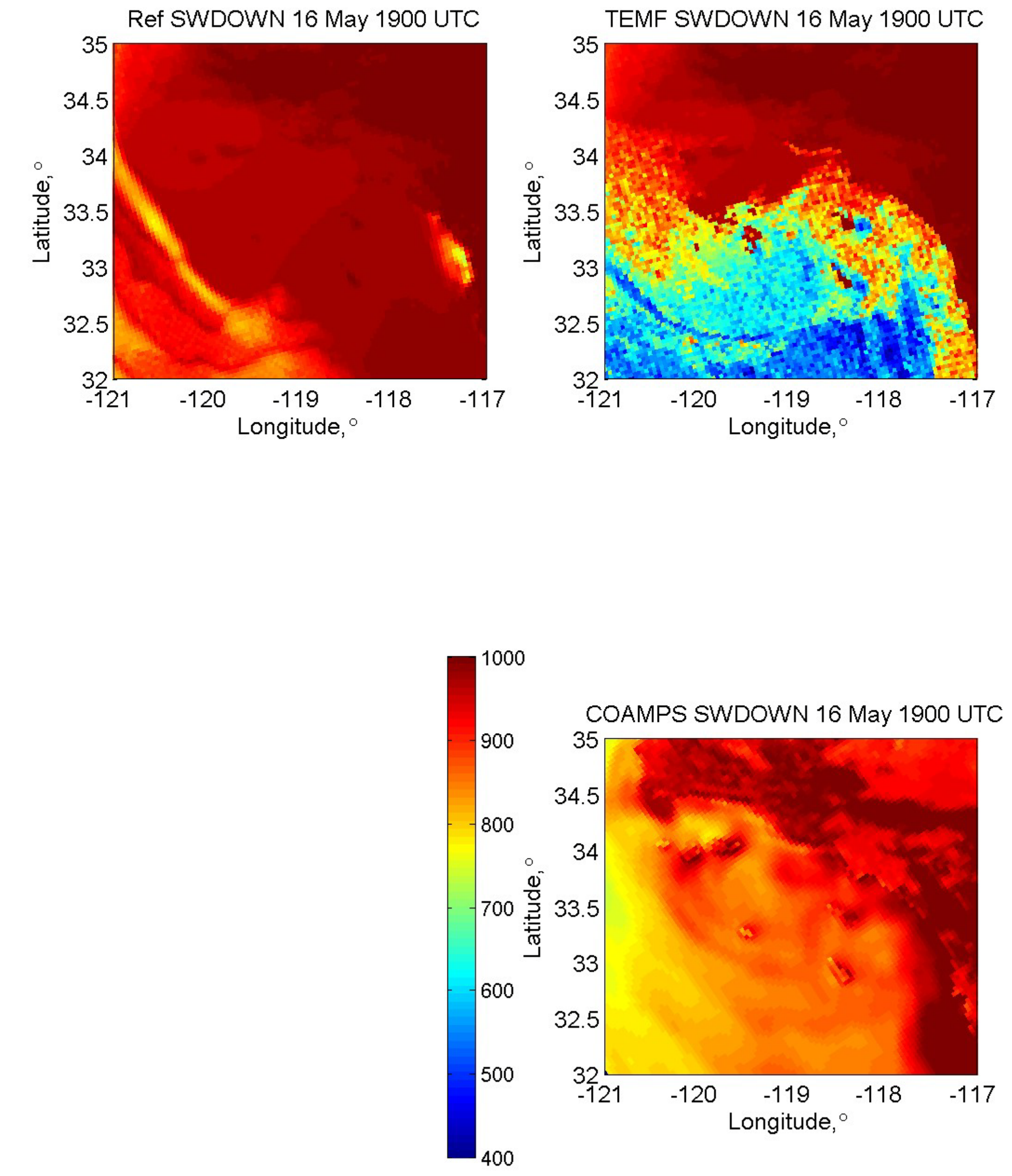
Incoming shortwave radiation

Affected by cloud liquid

TEMF has least SWDOWN but maybe still too much (see ship data)
-- not smooth
-- formulation still experimental

(SWDOWN does not influence SST)

(R18/new CM)



LAX diurnal winds

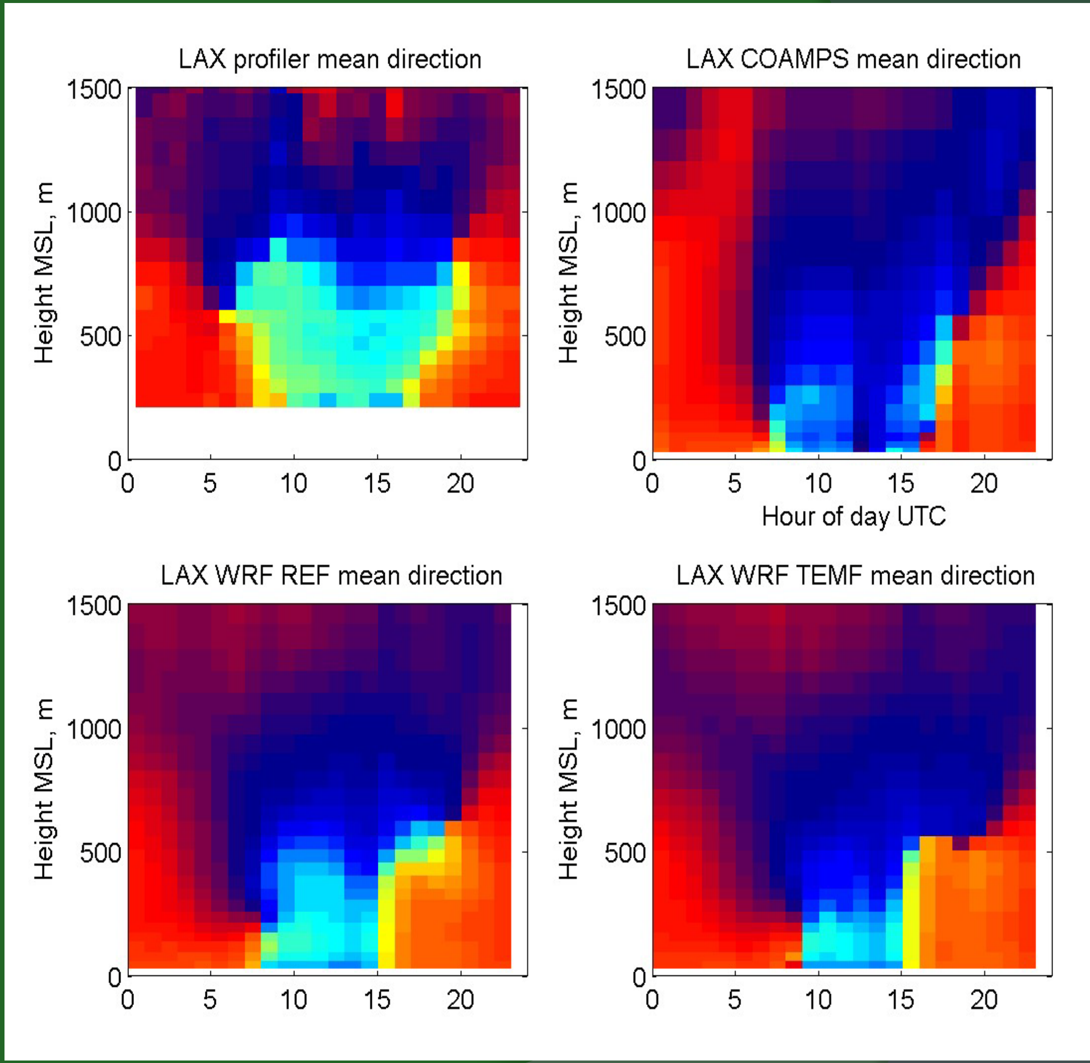
Two-month average

Modeled land breeze shallower, later, and starts near the surface

WRF sea breeze begins earlier and is already deeper by the time the observed sea breeze begins (COAMPS better)

TEMF land breeze even shallower than REF (MYJ)

(R18/new CM)



BLLAST case

Boundary Layer Late Afternoon and Sunset Turbulence study

Lannemezan, France, June-July 2011

Planned mesoscale intercomparison

Presenting preliminary WRF results for 30 June – 1 July

- At primary measurement site
- 4D, including advective effects
- Two PBL schemes (MYJ and TEMF)
- Two land surface models (SLAB and NOAH)

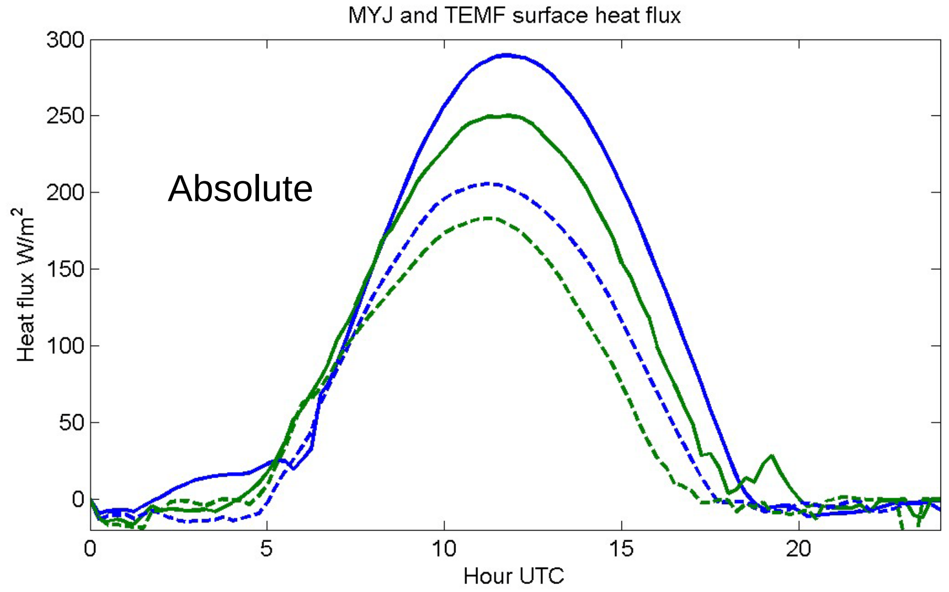
BLLAST sensible heat flux

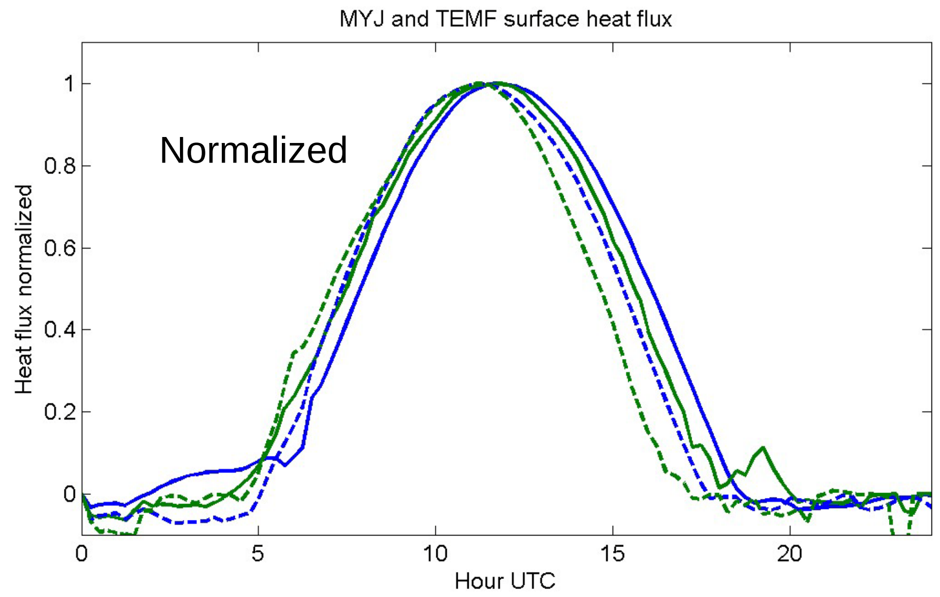
Afternoon timing related to maximum magnitude (larger peak happens later)

NOAH LSM declines sooner (less ground heat storage or greater resistance)

TEMF makes less heat flux than MYJ (contrary to expectations, due to 3D effects?)

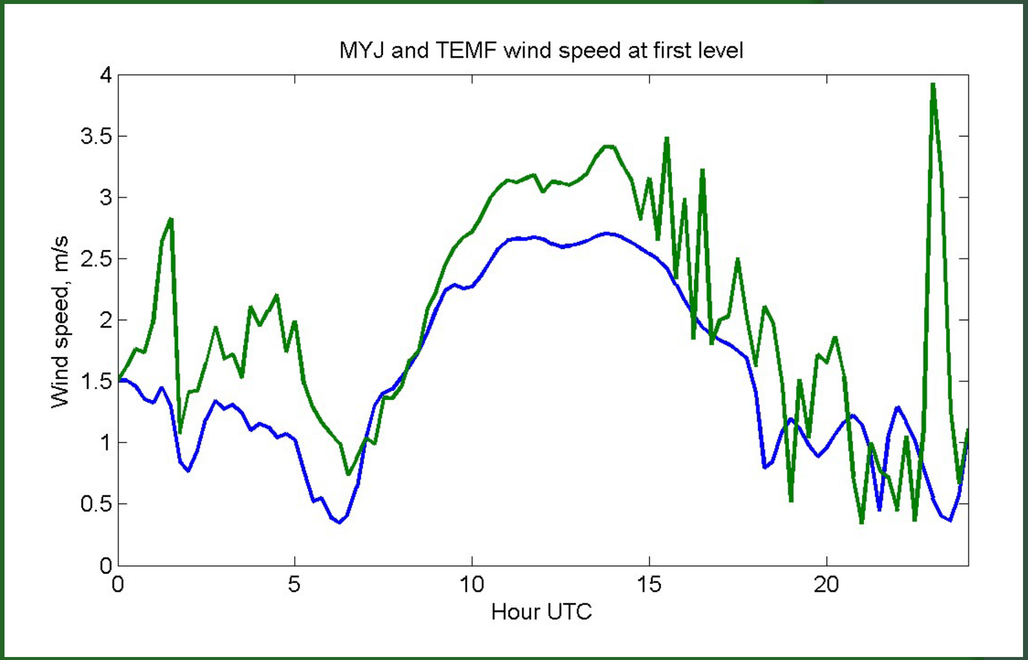
Blue = MYJ
Green = TEMF
Solid = SLAB
Dashed = NOAH





BLLAST surface wind speed

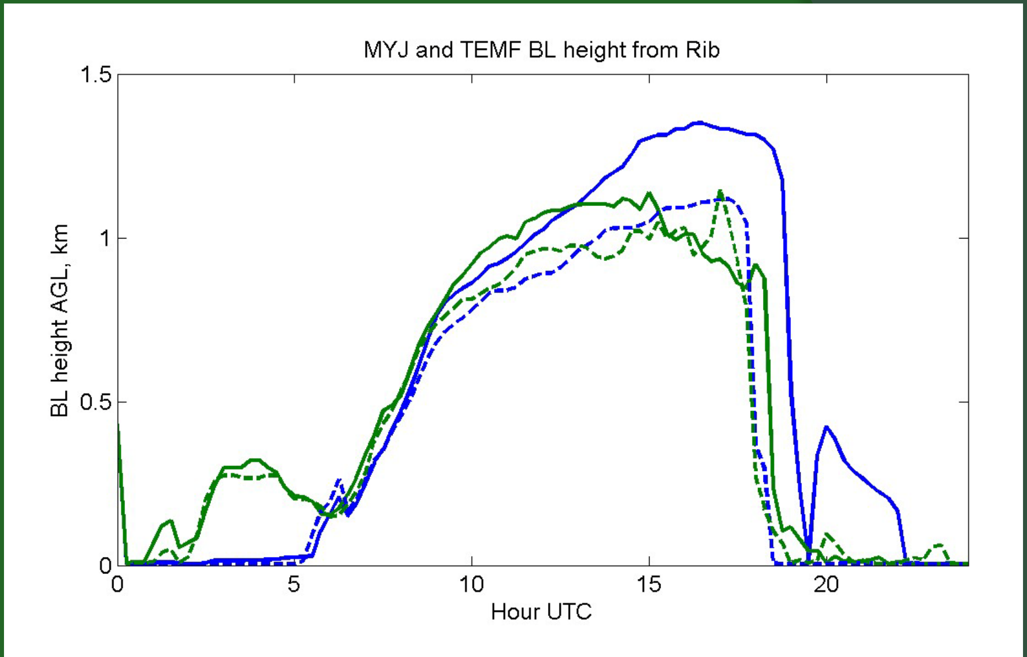
TEMF speeds generally larger than MYJ, somewhat erratic / intermittent



Blue = MYJ
Green = TEMF

BLLAST PBL height

MYJ/SLAB is the outlier



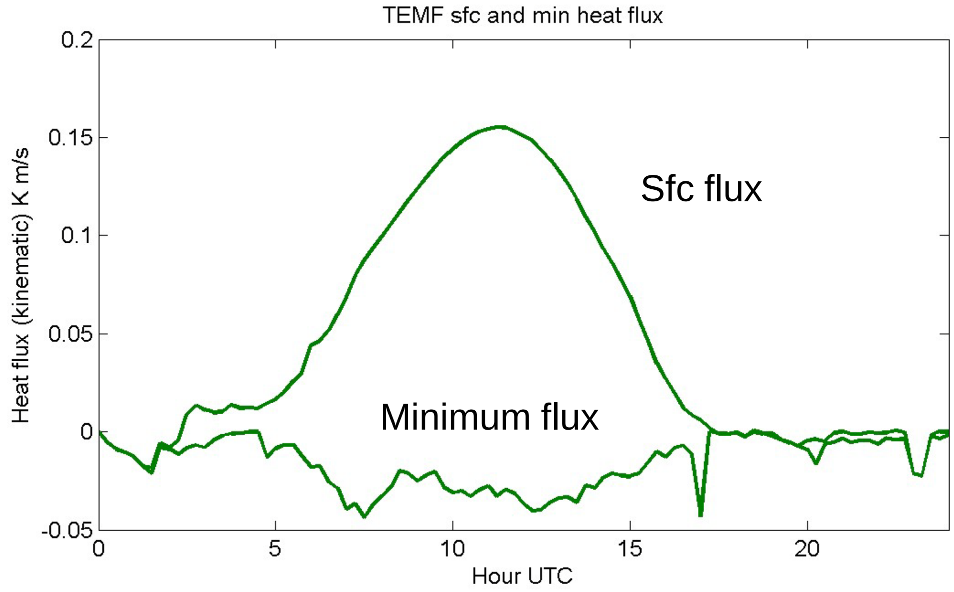
Blue = MYJ
Green = TEMF
Solid = SLAB
Dashed = NOAH

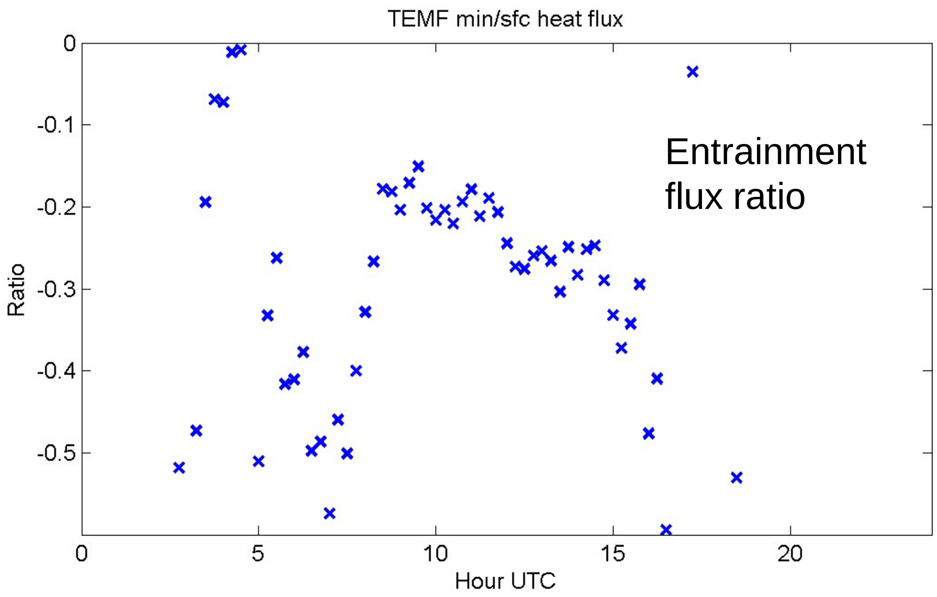
BLLAST Entrainment

Entrainment flux ratio is about 0.2 midday but larger early and late

Reinforces hypothesis that entrainment depends on various processes, which are more important when surface flux is less

Only TEMF shown





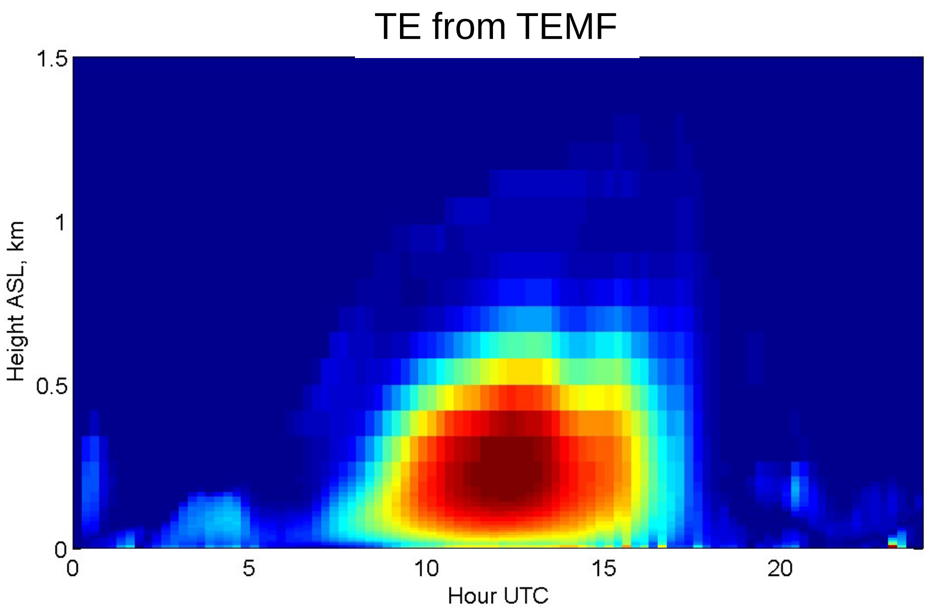
BLLAST Energy variables

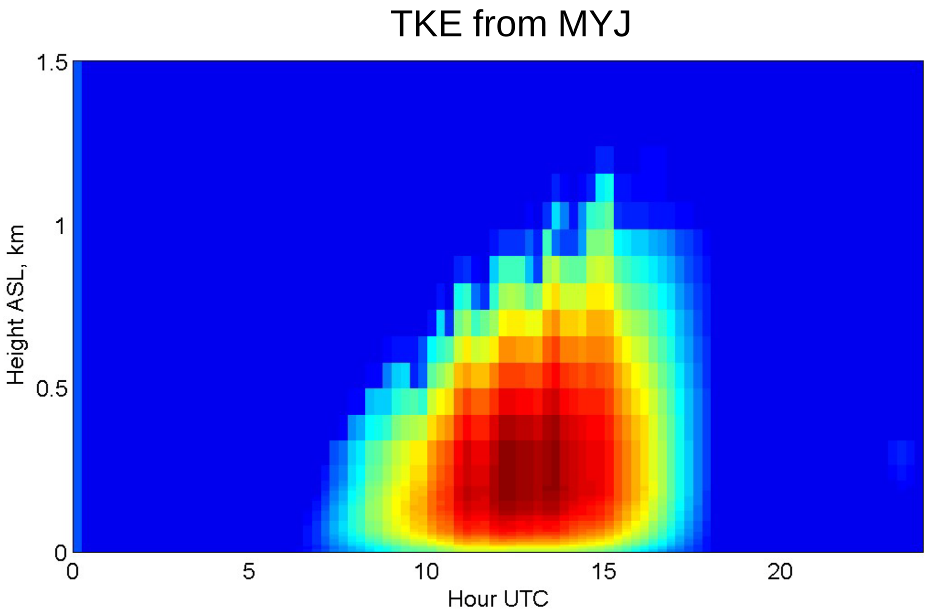
Diurnal cycle on 30 June

Scaled to maximum in each plot, same zero

Min. TKE in MYJ is 0.1

TEMF TE shows some response to intermittent nocturnal events (some support in data)





Conclusions(?) and prospects

- TEMF shows more “ideal” behavior in heat transfer and drag relationships
  - More “sensitive”, fewer empirical limits – good or bad?
- TEMF performs better for stratocumulus off California
- Improvement(?) for stable BLs needs to be documented in well-chosen cases
- Further evaluation, comparison, and development needed
- Issue: Is it appropriate to use the same stability functions for surface-based and elevated layers?

The whole system matters:

- Initialization, land surface, etc.
- PBL scheme is constrained above, below, and on all sides
- Differences are not bigger because (numerical) stability and other constraints don’t allow it

Thanks to:

Thorsten Mauritsen (TEMF development)

Hongli Jiang (GOMACCS cases)

Lee Eddington (COAMPS)

Kevin Durkee, SCAQMD (LA area profiler data)

Chris Fairall, Dan Wolfe, and Dave Welsh, NOAA ESRL (Atlantis flux and sonde data)

Owen Cooper, NOAA ESRL (satellite pics and surface obs)

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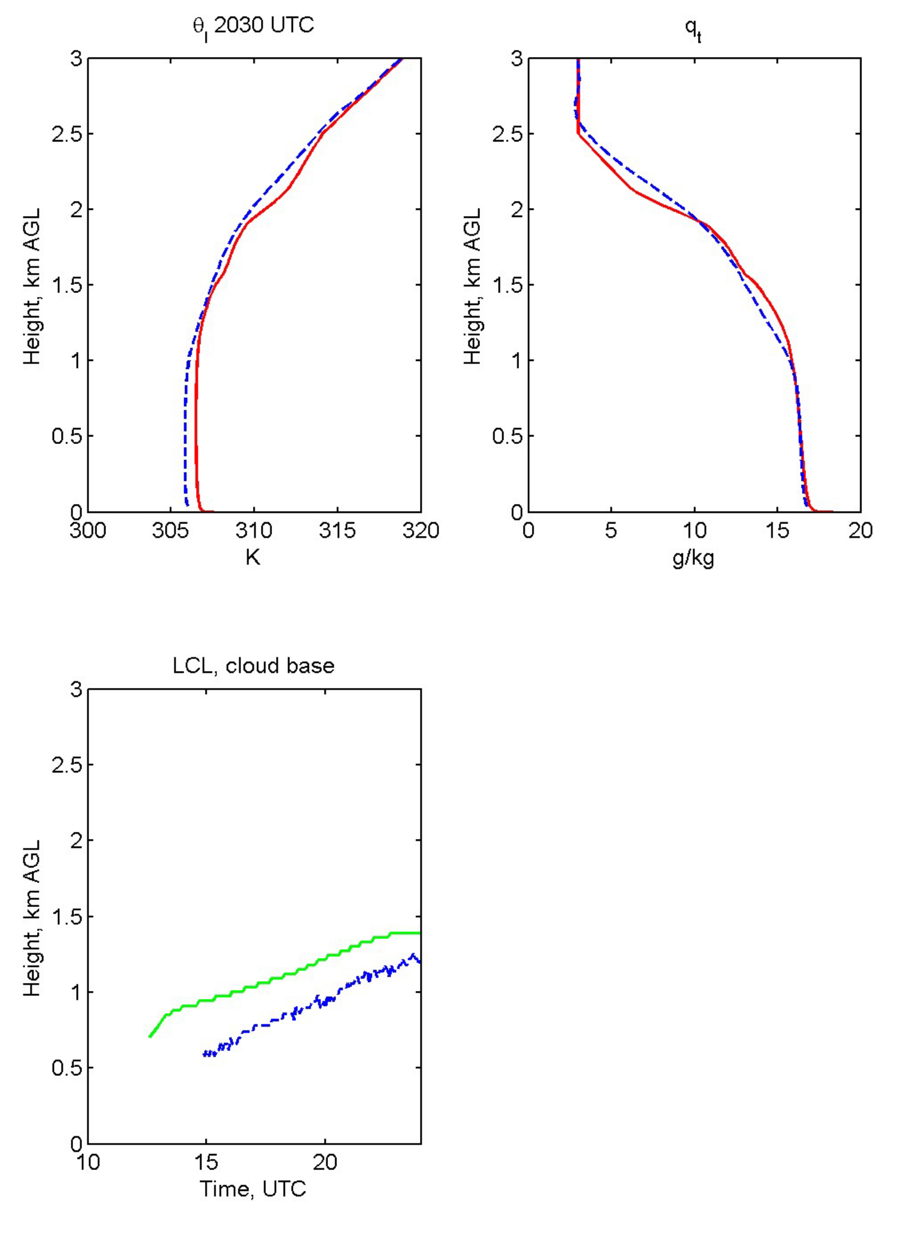
Marie Lothon, Fabienne Louhou, David Pino, Fleur Couvreux (BLLAST experiment and intercomparison setup)

Extra slides

ARM case

Red, solid = TEMF,

Blue, dashed = KNMI LES (thanks to Geert Lenderink)



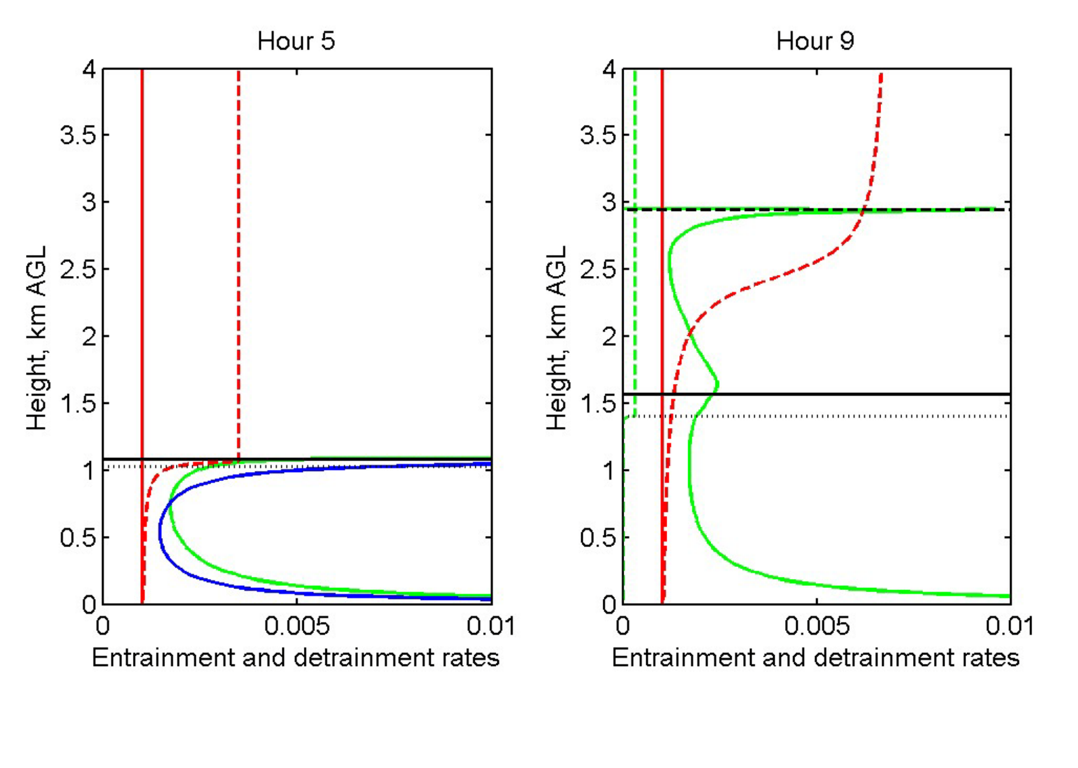
Entrainment and detrainment rates

The only sensitive part of the scheme

Current version uses epsilon ~1/z_i

Example:

GOMACCS 11 Sept.



Red = TEMF

Green = ECMWF

Blue = Siebesma et al. (2007)

Solid = epsilon (lateral entrainment), dashed = delta (detrainment)

Length scale

$$\frac{1}{l} = \frac{1}{kz} + \frac{f}{C_f \sqrt{\tau}} + \frac{N}{C_N \sqrt{\tau}}$$

Main branch treats unstable flow as neutral

Convective branch gives more mixing in upper part of convective BL (necessary?)

$$\frac{1}{l_{conv}} = \frac{1}{kz} + \frac{3}{k\left(h_d - z\right)}$$

Cloud base closure

Mass flux is continuous at cloud base

Updraft properties are modified by entrainment during ascent through subcloud layer

Velocity and therefore area fraction change during ascent

- typical values at cloud base 4-6%

Updraft initialization

$M(z_0) = 0.03\ w_*$

$w_{upd} = 0.5\ w_*$

So updraft area fraction = 6% at z_0

- epsilon = delta until near top, so area fraction stays roughly constant

All other properties take the environment values at z_0

- difference between surface and bulk values is proportional to surface flux