Lecture for International Summer School on the Atmospheric Boundary Layer,
Les Houches, France, June 18, 2008

Modeling clear atmospheric boundary layers

Some basics, evaluations and applications

Bert Holtslag

Thanks to all particpants in the
GEWEX Atmospheric Boundary Layer Study!

WAGENINGEN UNIVERSITY
METEOROLOGY AND AIR QUALITY

GABLS
GEWEX Atmospheric Boundary Layer Study

Typical boundary layer profiles over land without clouds

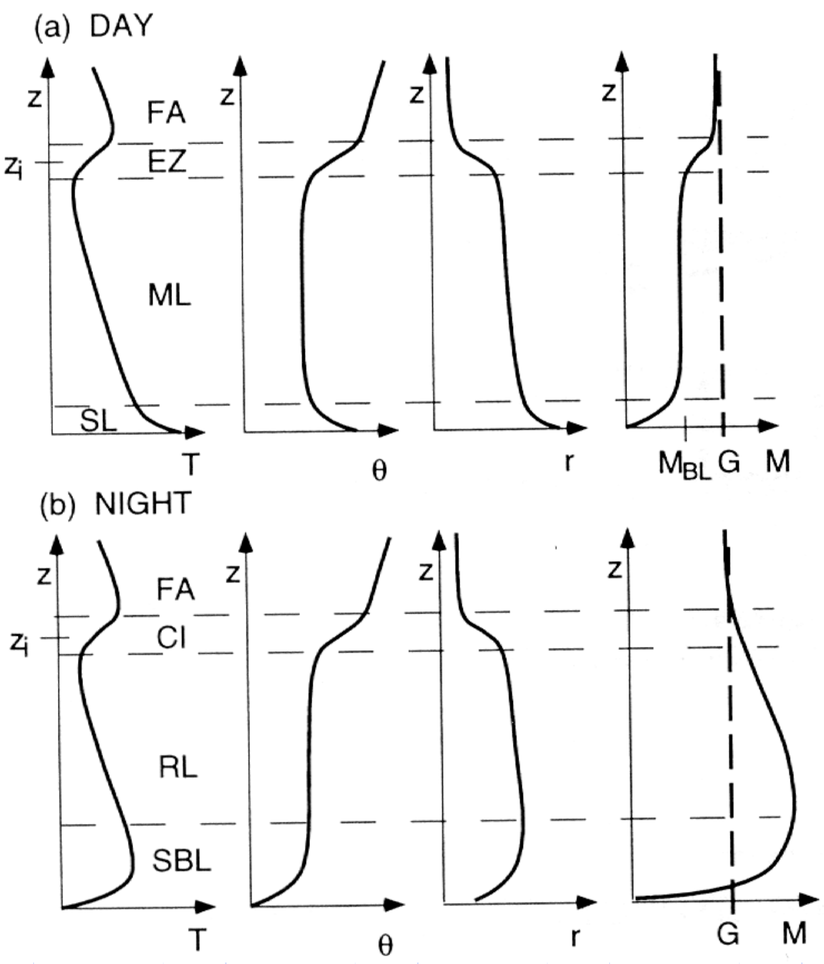


Figure adapted from Stull (1988)

Model is needed to
make forecasts
in response to
atmospheric forcings
and surface conditions

Critical issues:
Diurnal Cycle
Mean Profiles and Fluxes

What is the status?

Basics of a boundary layer model after Reynolds decomposition

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} + V\frac{\partial C}{\partial y} + W\frac{\partial C}{\partial z} = -\frac{\partial \overline{wc}}{\partial z} \ldots$$

$$\overline{wc} = -K\frac{\partial C}{\partial z} + \ldots.$$

Can be solved for given initial and surface conditions, and if the diffusivities are known

Valid for wind and any ‘conserved’ quantity *C* (potential temperature, specific humidity, tracers,…)

How to deal with turbulent mixing and eddy diffusivity?

$$K = f(height, stability, ABL\ depth, \ldots)$$

Strategy

Distinguish between stable and unstable conditions

Use theoretical concepts, observations and numerical simulations (LES and DNS) as a guidance

Compare model results with independent data

Turbulent Kinetic Energy (TKE) closure scheme

(applied in many atmospheric models…)

$$\frac{\partial TKE}{\partial t} = S + B + T + P - \varepsilon$$

$$K = l\sqrt{TKE}$$

TKE represents the major characteristics of turbulence

How to do the length scale?

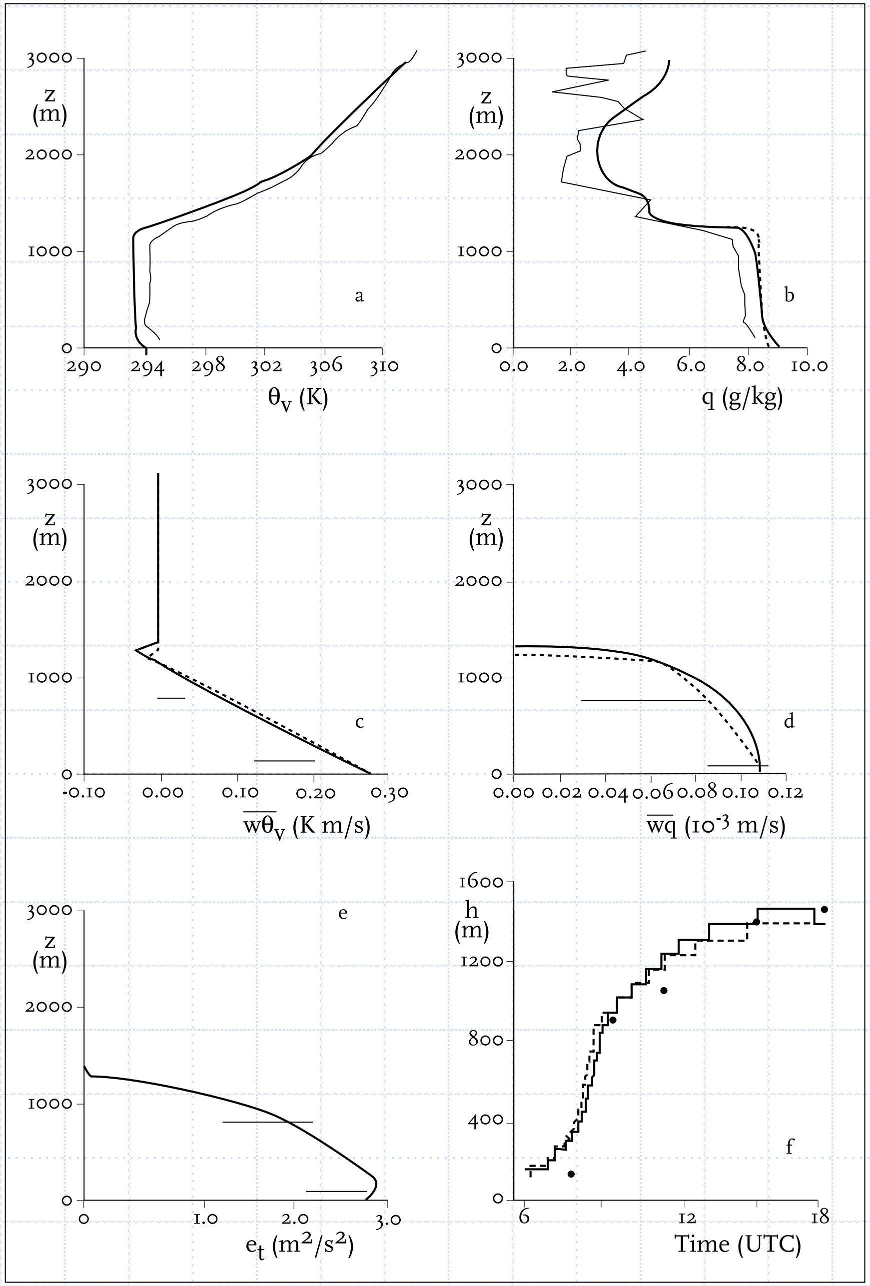
Is local gradient assumption valid?

Many proposals have been made for various boundary layers

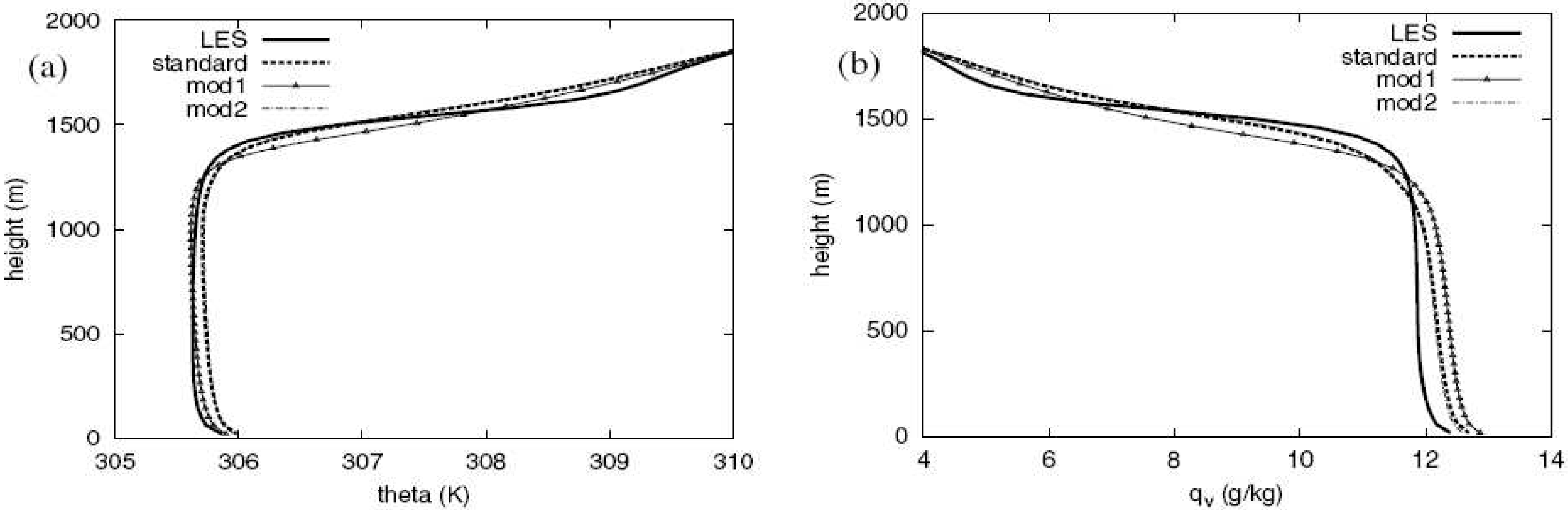
Single column study

Example of ABL model results during daytime in comparion with observations of Hapex-Mobilhy, France, July 8, 1986 (Cuxart et al, 1994)

(using prescribed surface fluxes and advection terms neglected)



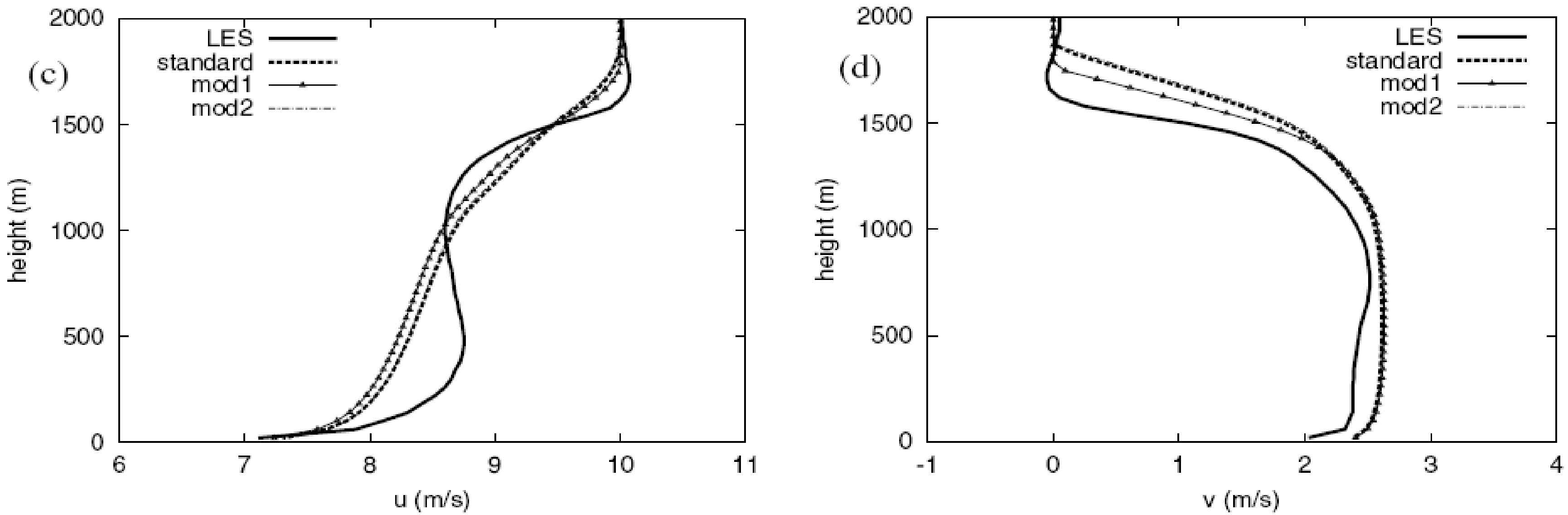
Results with a TKE scheme for a convective boundary layer (using an updated length scale with a parcel method)



Results by Lenderink and Holtslag (QJRMS, 2004)

Momentum mixing

(these results by Lenderink and Holtslag, 2004)

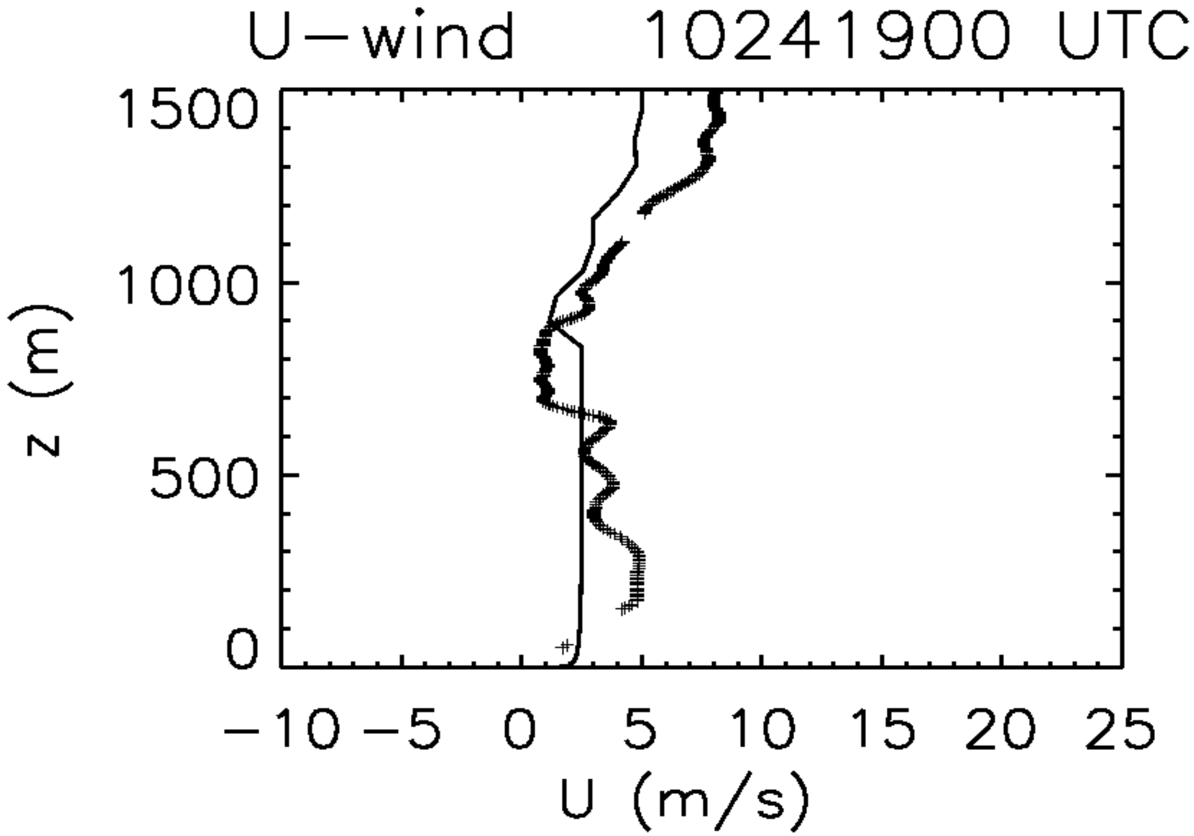


Nonlocal mixing for momentum is also needed, but often ignored

Proposals are available in literature (e.g Frech and Mahrt, 1995; Brown and Grant, 1997, …)

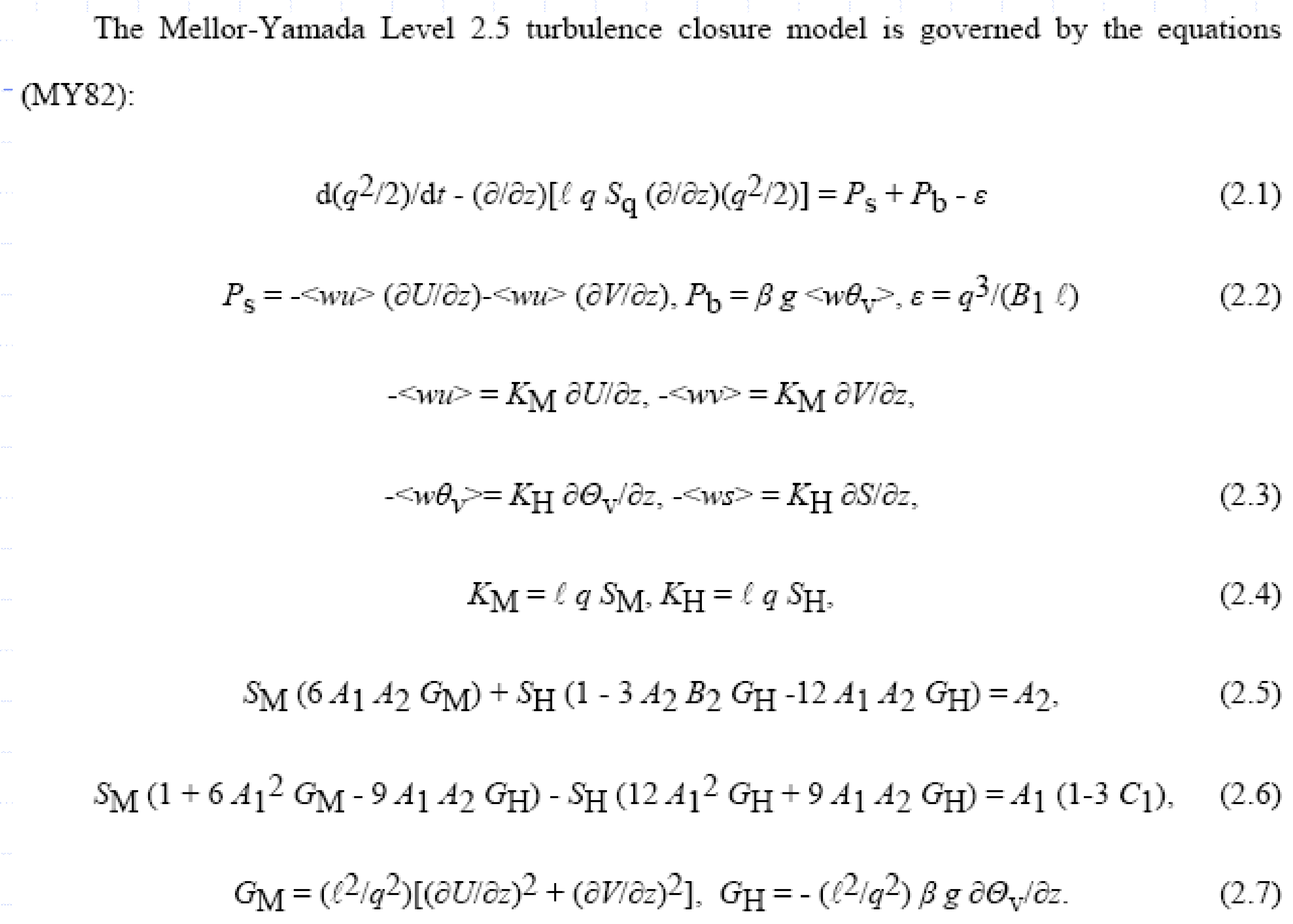
Wind in CBL may also be influenced by inertial oscillation (e.g, Schröter et al, 18th BLT, Stockholm)

Wind profiles in reality are not that easy…



Example of CASES99 by Steeneveld et al, 2006

Does more complexity help?



The Mellor-Yamada Level 2.5 turbulence closure model is governed by the equations (MY82):

$$d(q^2/2)/dt - (\partial/\partial z)[\ell\ q\ S_q\ (\partial/\partial z)(q^2/2)] = P_s + P_b - \varepsilon \qquad (2.1)$$

$$P_s = -\langle wu\rangle\ (\partial U/\partial z) - \langle wu\rangle\ (\partial V/\partial z),\ P_b = \beta\ g\ \langle w\theta_v\rangle,\ \varepsilon = q^3/(B_1\ \ell) \qquad (2.2)$$

$$-\langle wu\rangle = K_M\ \partial U/\partial z,\ -\langle wv\rangle = K_M\ \partial V/\partial z,$$

$$-\langle w\theta_v\rangle = K_H\ \partial\Theta_v/\partial z,\ -\langle ws\rangle = K_H\ \partial S/\partial z, \qquad (2.3)$$

$$K_M = \ell\ q\ S_M,\ K_H = \ell\ q\ S_H, \qquad (2.4)$$

$$S_M\ (6\ A_1\ A_2\ G_M) + S_H\ (1 - 3\ A_2\ B_2\ G_H - 12\ A_1\ A_2\ G_H) = A_2, \qquad (2.5)$$

$$S_M\ (1 + 6\ A_1^2\ G_M - 9\ A_1\ A_2\ G_H) - S_H\ (12\ A_1^2\ G_H + 9\ A_1\ A_2\ G_H) = A_1\ (1\text{-}3\ C_1), \qquad (2.6)$$

$$G_M = (\ell^2/q^2)[(\partial U/\partial z)^2 + (\partial V/\partial z)^2],\ \ G_H = -\ (\ell^2/q^2)\ \beta\ g\ \partial\Theta_v/\partial z. \qquad (2.7)$$

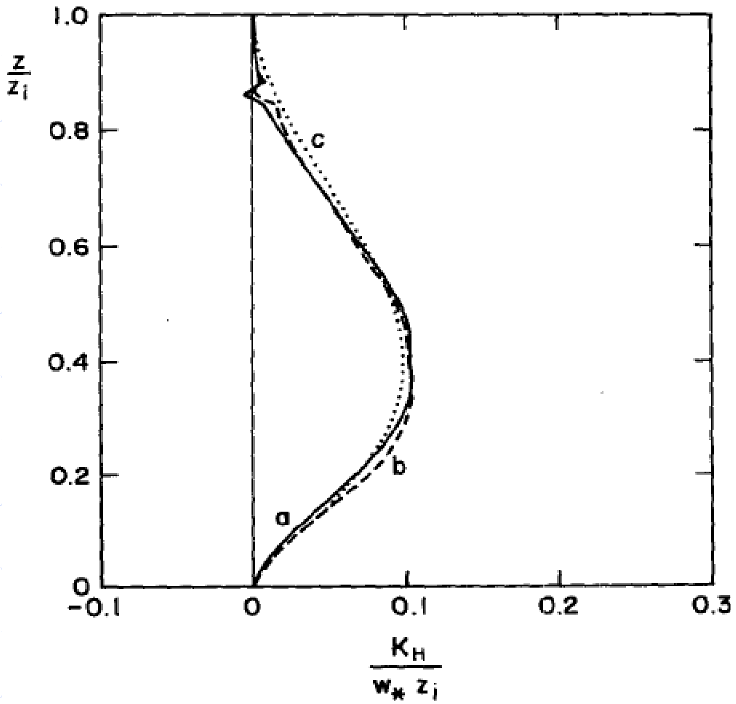
Or even more complexity?

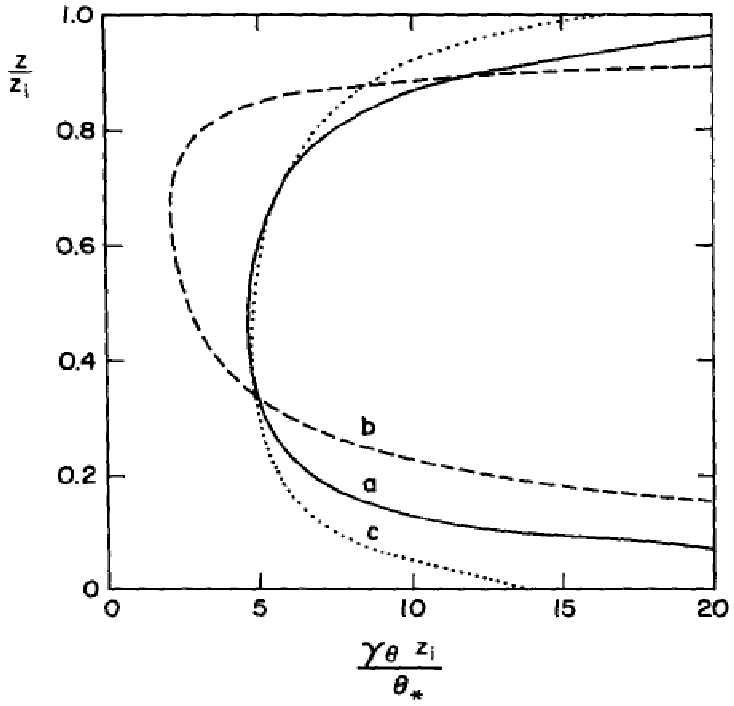
$$\frac{D\overline{w'\psi'}}{Dt} = -\overline{w'^2}\frac{\partial\Psi}{\partial z} + \frac{g}{\Theta_{v0}}\overline{\theta'_v\psi'} - \frac{1}{\rho_0}\overline{\psi'\frac{\partial p'}{\partial z}} - \frac{\partial\overline{w'^2\psi'}}{\partial z} + S_i$$

Attractive to simplify this,
for instance by using LES results for flux budgets
in convective boundary layer

(Deardorff, 1966, 1972; Holtslag and Moeng, 1991;
Cuijpers and Holtslag, 1998 among others)

Mixing in Convective boundary layers using results of simplified heat flux budget equation (a: LES; b: Deardorff, 1972; c: Holtslag and Moeng, 1991)





$$\theta_* \equiv \frac{\overline{w\theta_0}}{w_*}$$

$$\frac{K_H}{w_* z_i} = \left(\frac{z}{z_i}\right)^{4/3}\left(1 - \frac{z}{z_i}\right)^2$$

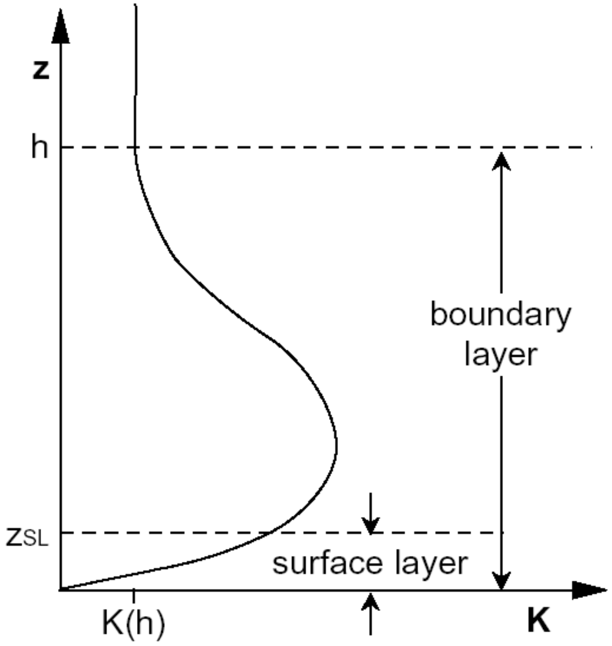
$$\gamma_\theta = c_4 \frac{\overline{w\theta_0}}{w_* z_i}$$

$$w_* \equiv (\beta g \overline{w\theta_0} z_i)^{1/3}$$

Non-local mixing in convective boundary layers

Use profile function for eddy-diffusivity and non-local ('counter-gradient') corrections

$$\overline{w\theta} = -K\left(\frac{\partial\theta}{\partial z} - \gamma\right)$$

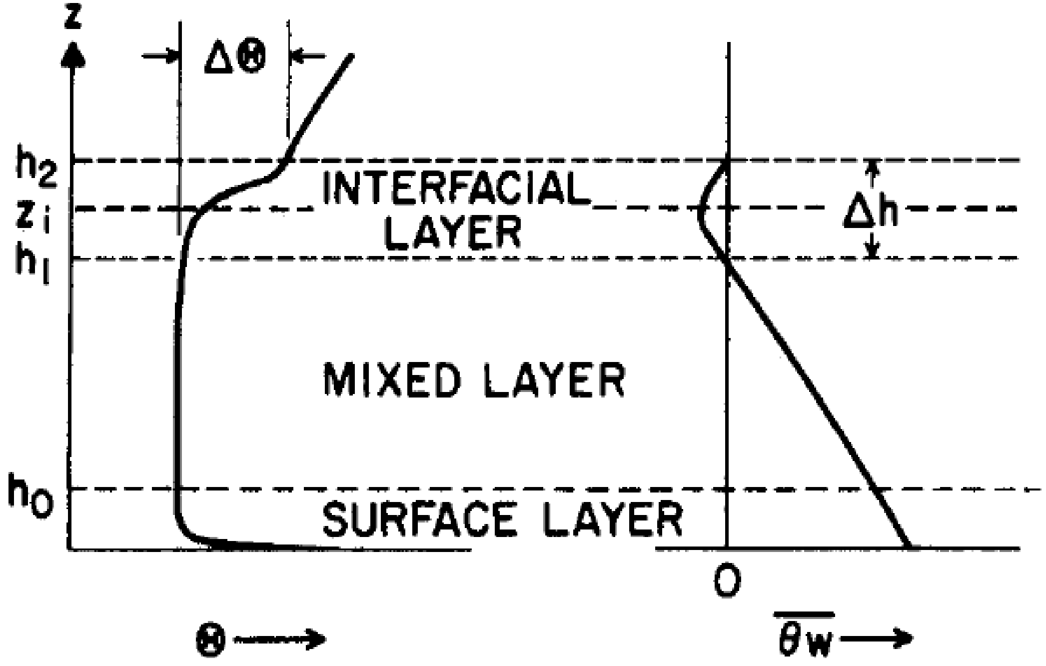


Deardorff (1966, 1972)
Troen and Mahrt (1986)
Holtslag and Boville (1993)
Large et al (1994)
Hong and Pan (1996)
Beljaars and Viterbo (1998)
Lock et al (2000)
et cetera

This approach is now widely adopted (e.g., NCAR, NCEP, UKMO, ECMWF,...), but details differ...

Entrainment

$$-\frac{g}{\theta_v}\left(\overline{w\theta_v}\right)_h = 0.2\frac{g}{\theta_v}\left(\overline{w\theta_v}\right)_o + \frac{u_*^3}{h}$$



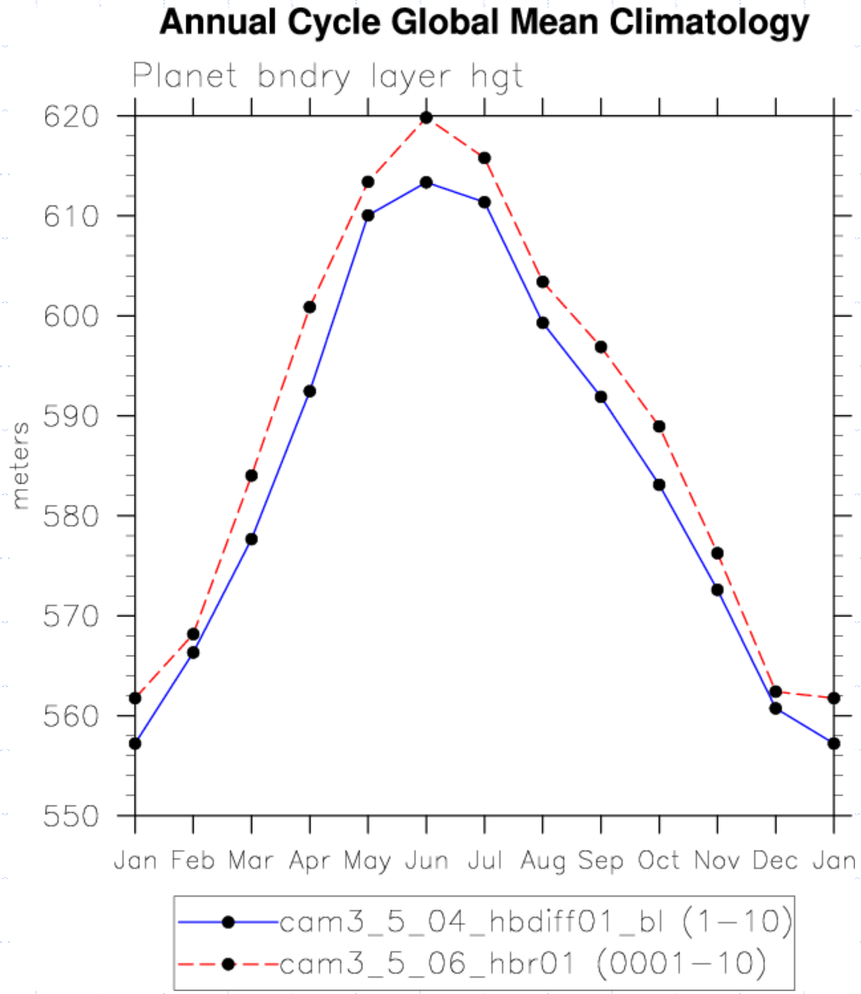
Potential Temperature Profile

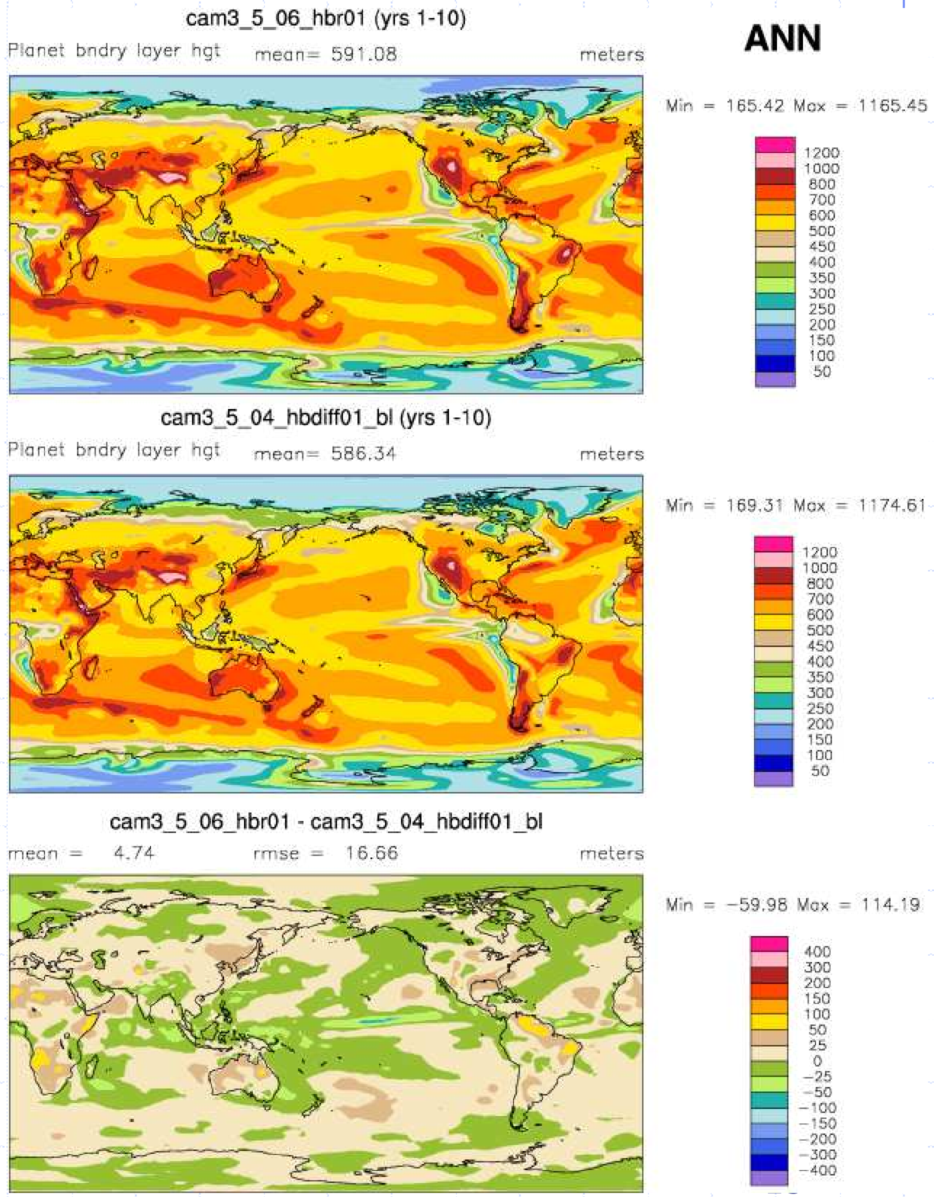
Heat Flux

To avoid sensitivity for numerical details, prescribe entrainment **explicitly** using surface buoyancy flux and friction velocity (Moeng and Sullivan, 1994 among others)

Some impact of entrainment on pbl height in NCAR Climate model

(Holtslag, Svensson, Rasch and Large, 18th BLT





CAM 3.5 - 26 levels

A simple mixing scheme:
Flux-Gradient Theory or First Order Closure

$$\overline{w'c'} = -K \frac{\partial C}{\partial z}$$

Turbulent Flux

$$K = \left| \frac{\partial U}{\partial z} \right| l^2 F_{m,h}(Ri)$$

Diffusivity K depends on characteristics of turbulent flow

$$l : length\ scale$$

$$Ri = \frac{g}{\theta} \frac{\partial \theta}{\partial z} \Bigg/ \left| \frac{\partial U}{\partial z} \right|^2$$

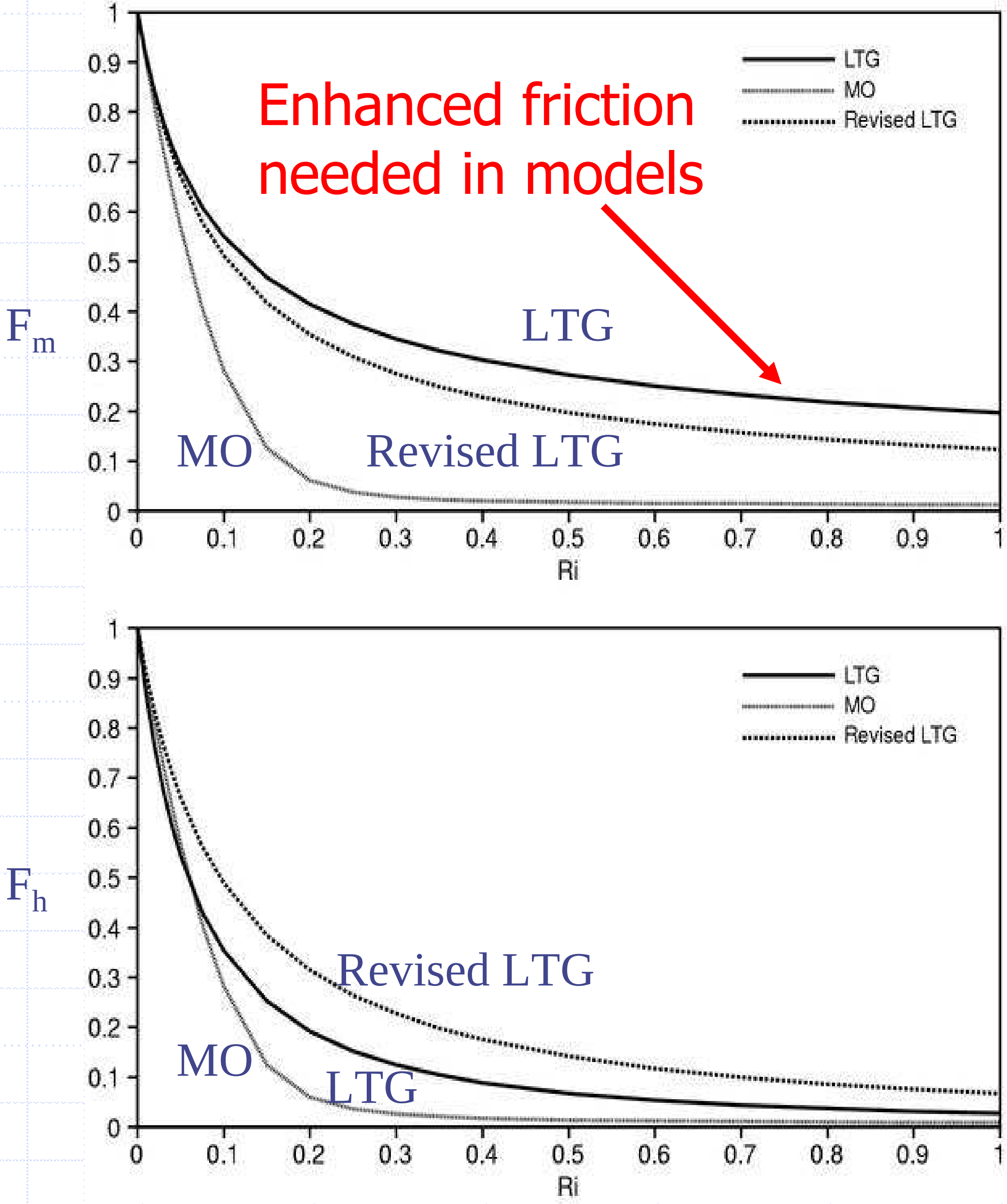
Richardson number
(measure for local stability)

Stable boundary layer mixing

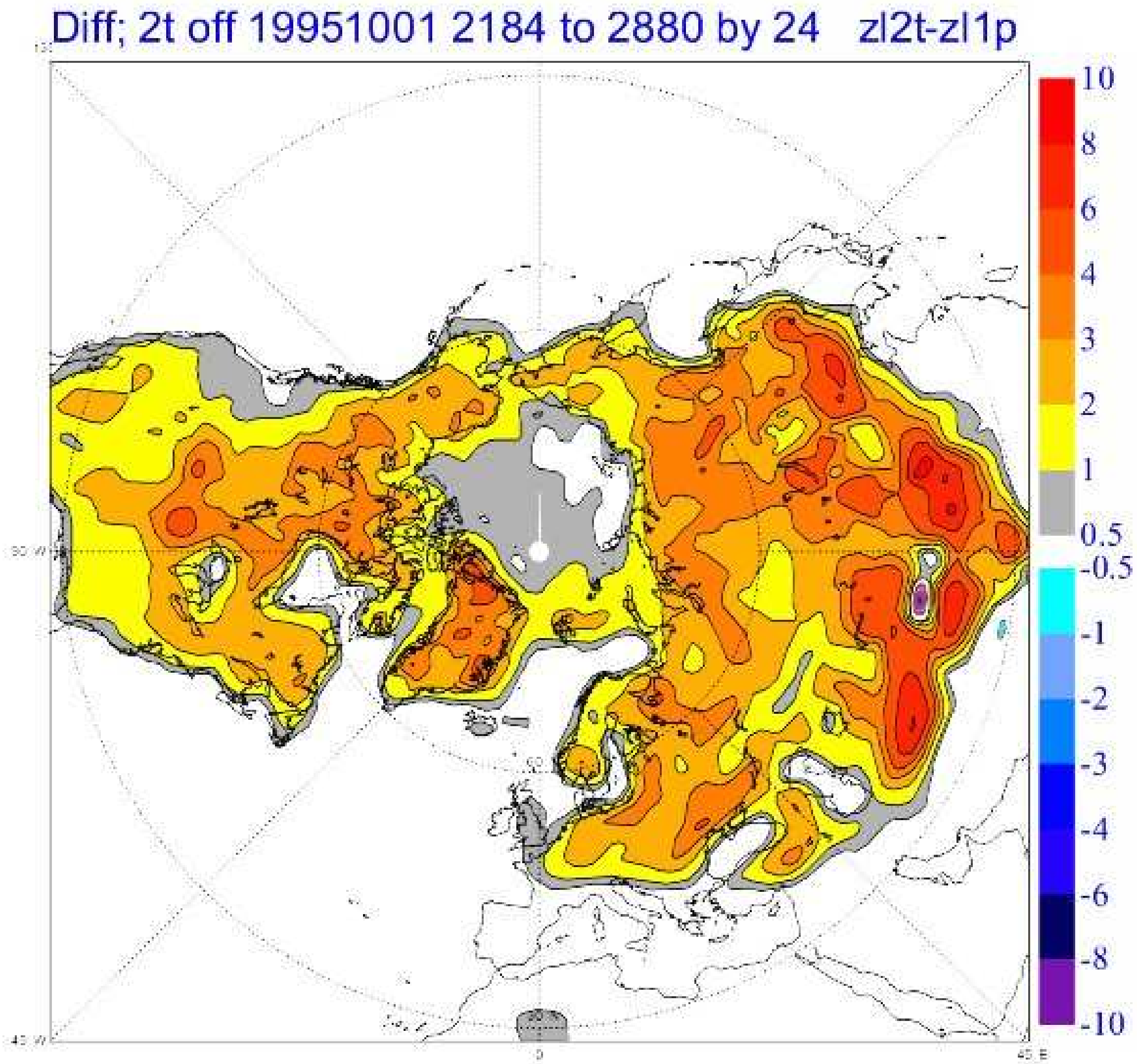
Three alternatives for stability functions of heat and momentum

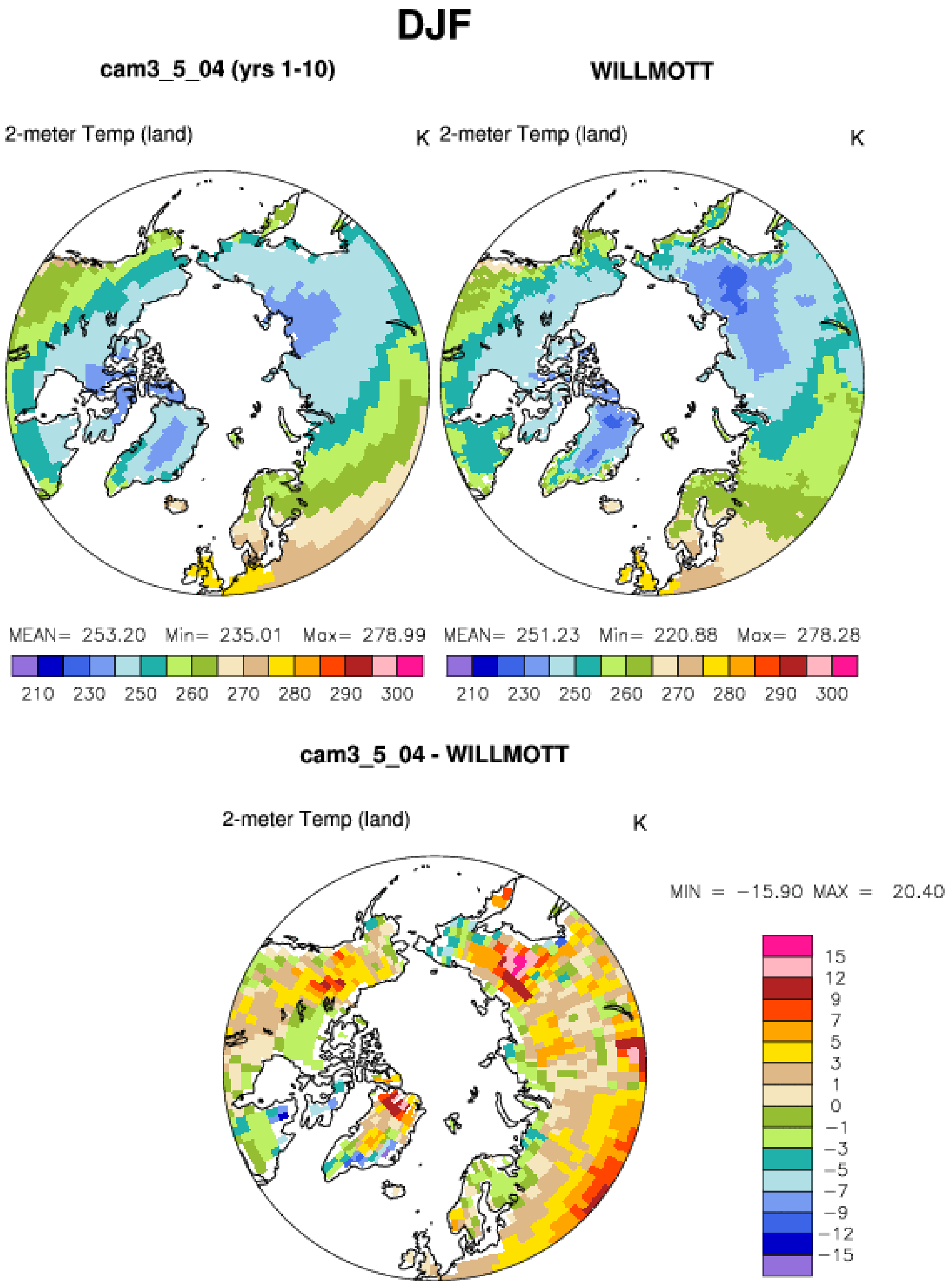
LTG: Louis et al (1982)

MO: Extended Monin-Obukhov type, in agreement with Cabauw tower observations (Beljaars and Holtslag, 1991)


Enhanced friction needed in models

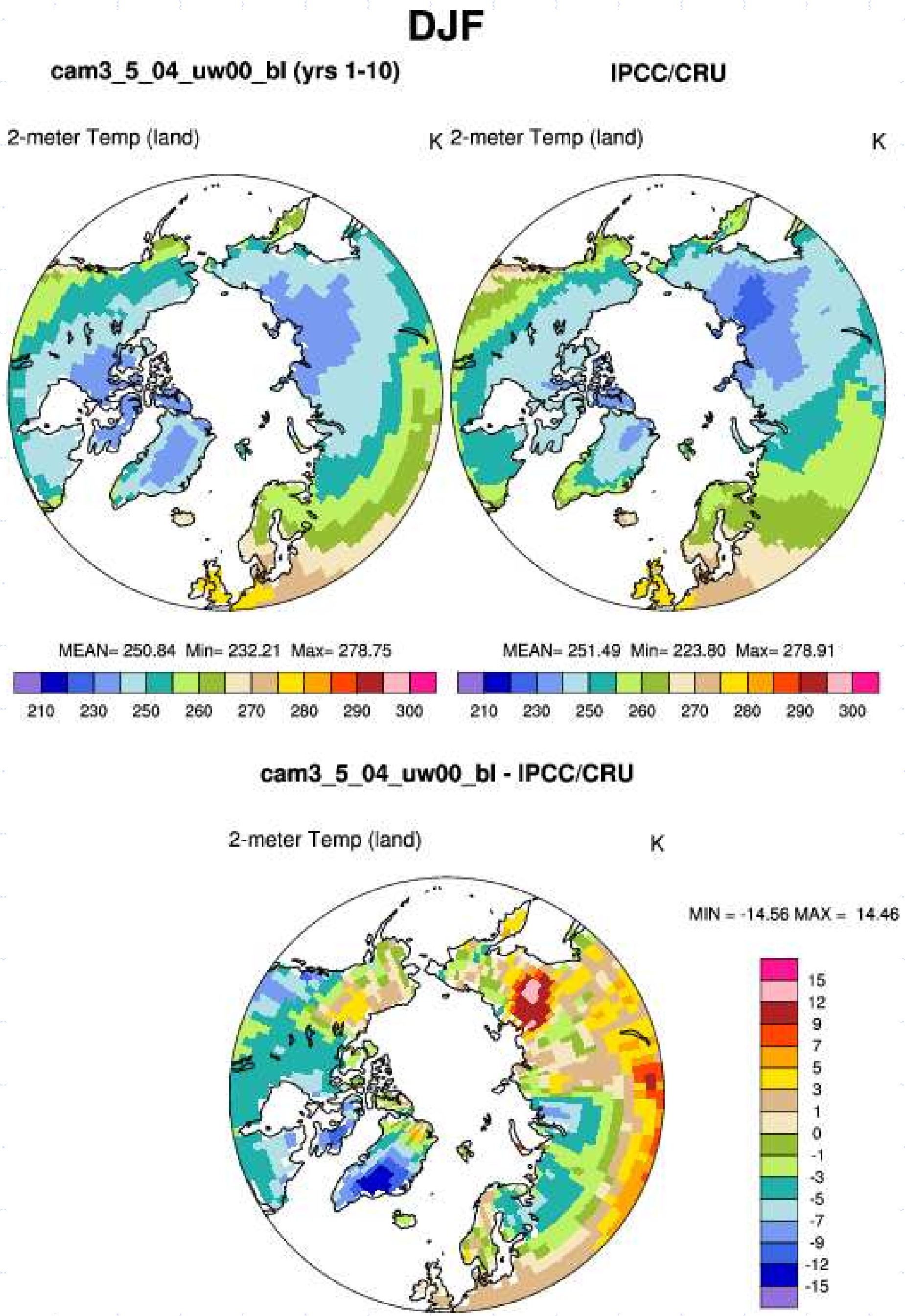
Mean model difference in 2 meter temperature for January 1996 using two different stability functions in ECMWF model (Courtesy A. Beljaars)





Comparison of climate models (such as NCAR-CAM) with observations for 2m temperature reveals large differences over land and ice in stratified conditions (here for HB scheme; 10 year winter averages)

Holtslag+Boville, J. Clim., 1993



Comparison of climate models (such as NCAR-CAM) with observations for 2m temperature reveals large differences over land and ice in stratified conditions (here for UW scheme; 10 year winter averages)

University of Washington scheme;
Songsu Park and Chris Bretherton

State of art

Larger scale atmospheric models have problems in representing stable boundary layers and typically allow for more mixing than can be seen in local observations

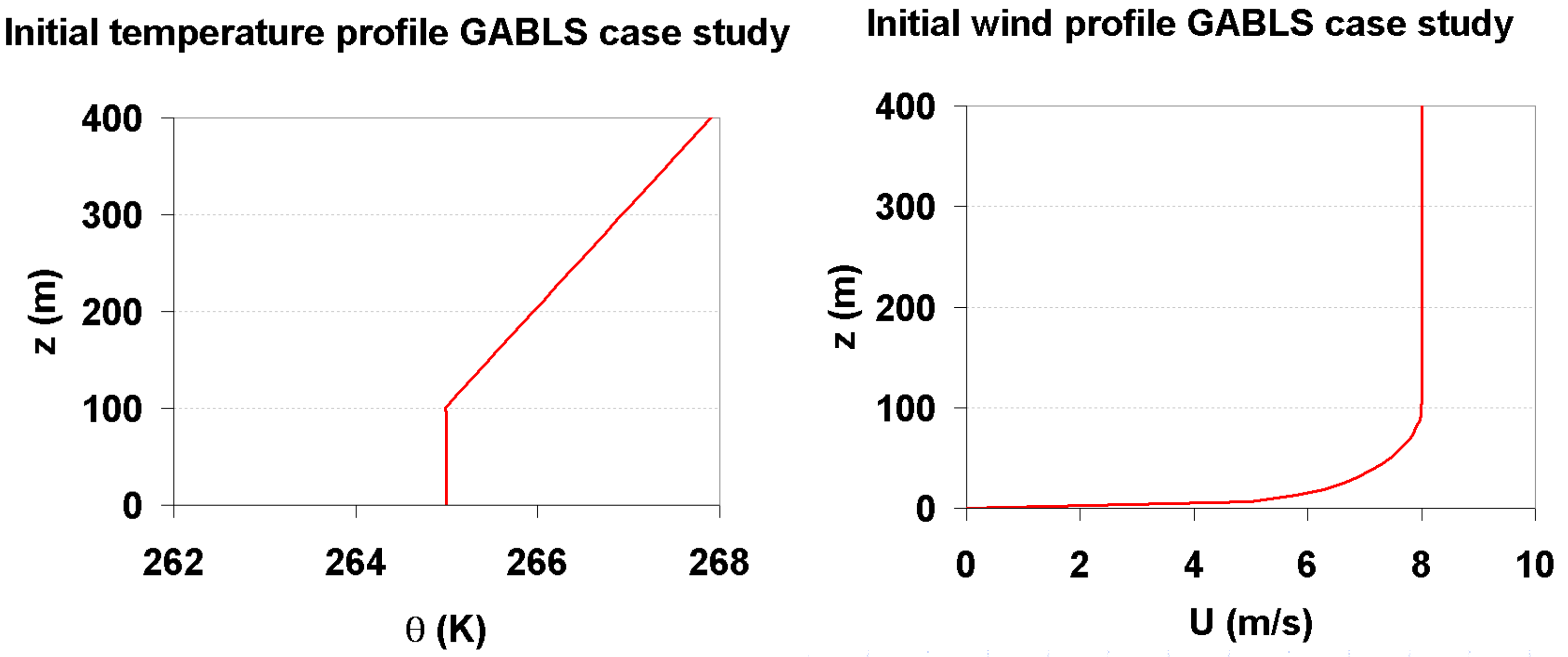
Sensitivity to details in formulation, in particular over land and ice

One of the motivations to organize the GEWEX Atmospheric Boundary Layer Study (see www.gewex.org)

***GABLS** first model inter-comparison case*

Simple shear driven case for a stable boundary layer over ice

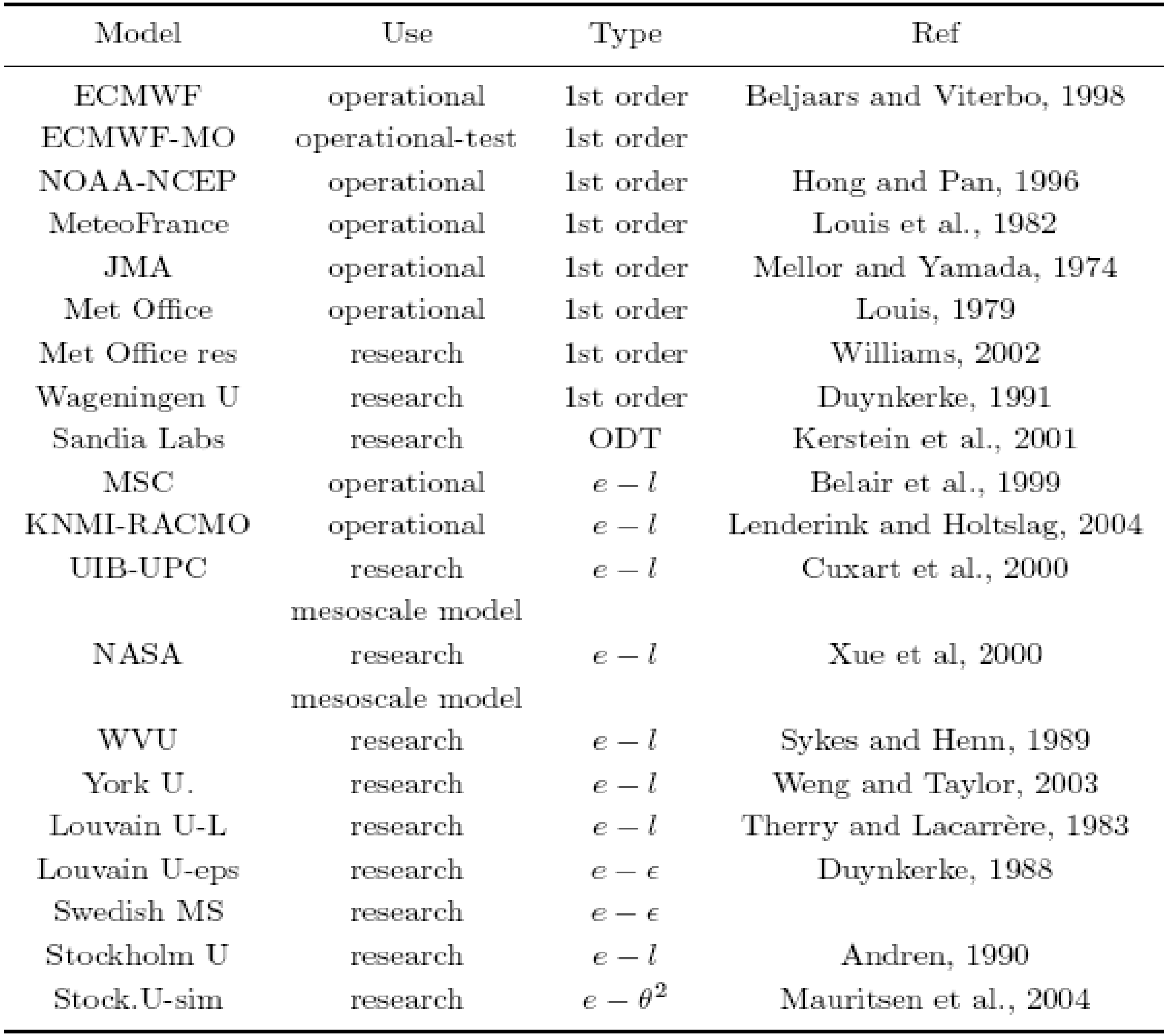
(after Kosovic and Curry, 2000)



Prescribed surface cooling 0.25 K/h for 9 hours to quasi- equilibrium; no surface and radiation scheme

Geostrophic wind 8 m/s, latitude 73N

List of 20 participating 1D models (Cuxart et al, 2006)



Model	Use	Type	Ref
ECMWF	operational	1st order	Beljaars and Viterbo, 1998
ECMWF-MO	operational-test	1st order	
NOAA-NCEP	operational	1st order	Hong and Pan, 1996
MeteoFrance	operational	1st order	Louis et al., 1982
JMA	operational	1st order	Mellor and Yamada, 1974
Met Office	operational	1st order	Louis, 1979
Met Office res	research	1st order	Williams, 2002
Wageningen U	research	1st order	Duynkerke, 1991
Sandia Labs	research	ODT	Kerstein et al., 2001
MSC	operational	$e-l$	Belair et al., 1999
KNMI-RACMO	operational	$e-l$	Lenderink and Holtslag, 2004
UIB-UPC	research mesoscale model	$e-l$	Cuxart et al., 2000
NASA	research mesoscale model	$e-l$	Xue et al, 2000
WVU	research	$e-l$	Sykes and Henn, 1989
York U.	research	$e-l$	Weng and Taylor, 2003
Louvain U-L	research	$e-l$	Therry and Lacarrère, 1983
Louvain U-eps	research	$e-\epsilon$	Duynkerke, 1988
Swedish MS	research	$e-\epsilon$	
Stockholm U	research	$e-l$	Andren, 1990
Stock.U-sim	research	$e-\theta^2$	Mauritsen et al., 2004

List of 11 participating LES models (Beare et al, 2006)

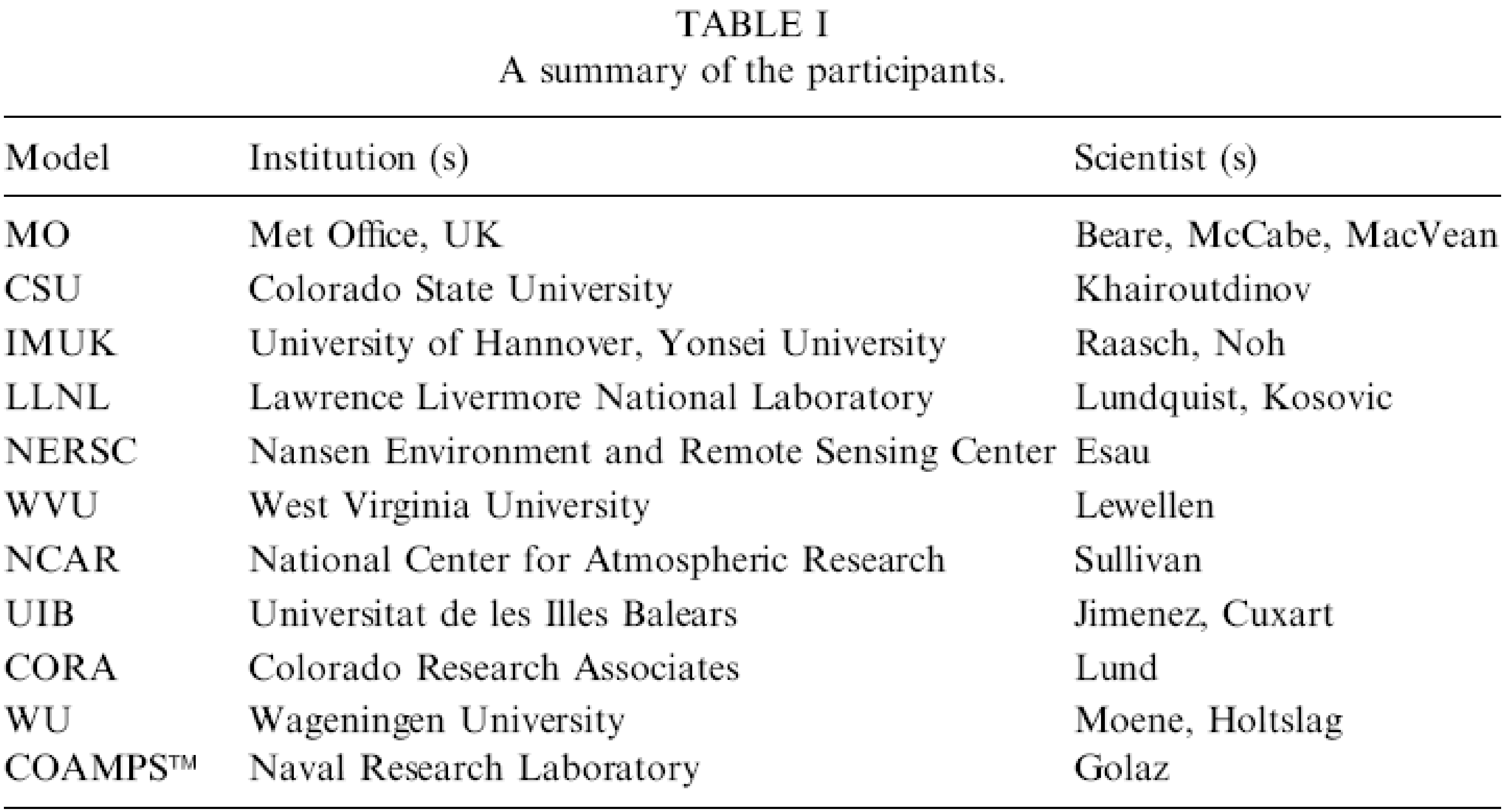
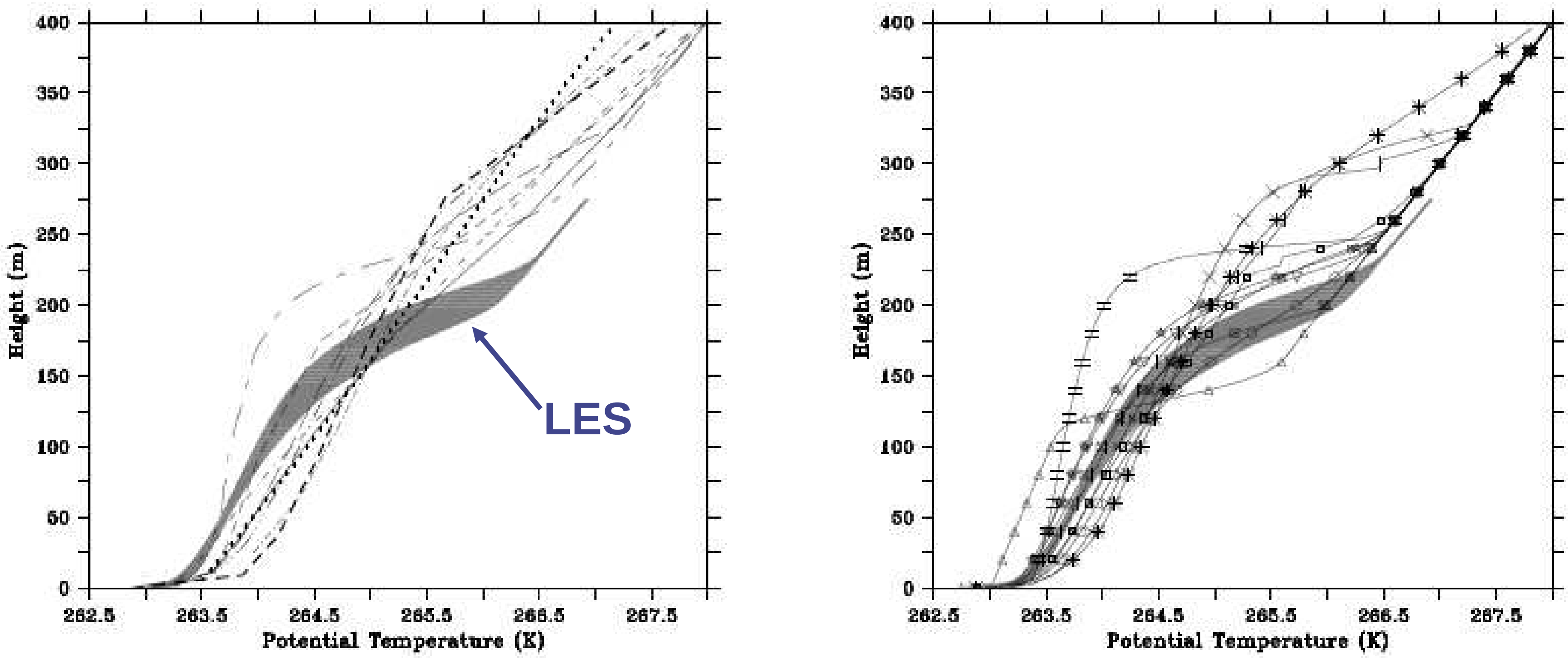


TABLE I
A summary of the participants.

Model	Institution (s)	Scientist (s)
MO	Met Office, UK	Beare, McCabe, MacVean
CSU	Colorado State University	Khairoutdinov
IMUK	University of Hannover, Yonsei University	Raasch, Noh
LLNL	Lawrence Livermore National Laboratory	Lundquist, Kosovic
NERSC	Nansen Environment and Remote Sensing Center	Esau
WVU	West Virginia University	Lewellen
NCAR	National Center for Atmospheric Research	Sullivan
UIB	Universitat de les Illes Balears	Jimenez, Cuxart
CORA	Colorado Research Associates	Lund
WU	Wageningen University	Moene, Holtslag
COAMPS™	Naval Research Laboratory	Golaz

LES: Large-Eddy Simulation model
(e.g. fine-scale model resolving largest turbulent motions)
Ensemble of LES results is taken as reference!

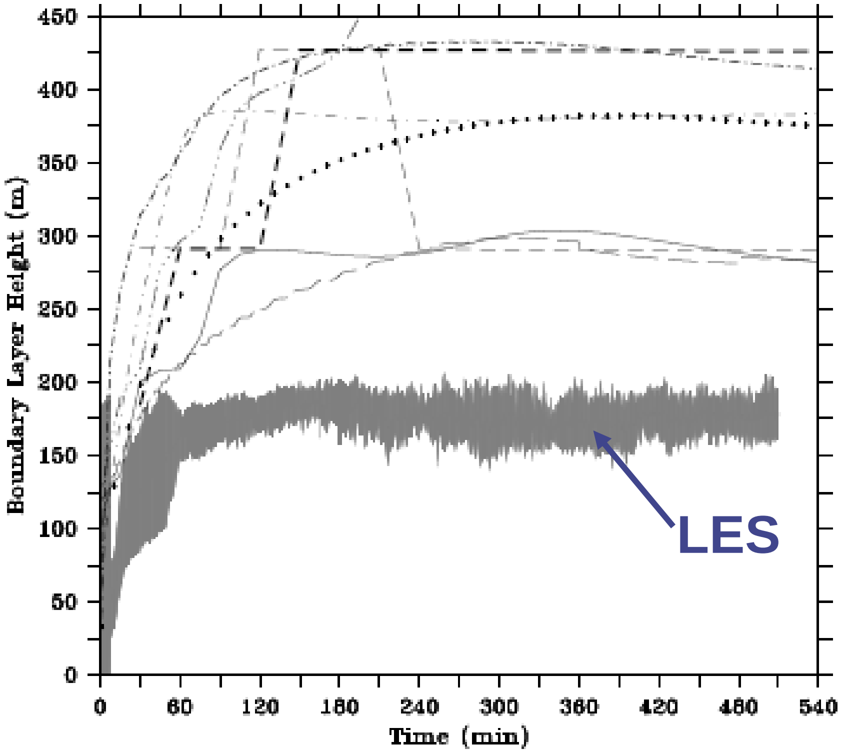
Potential temperature



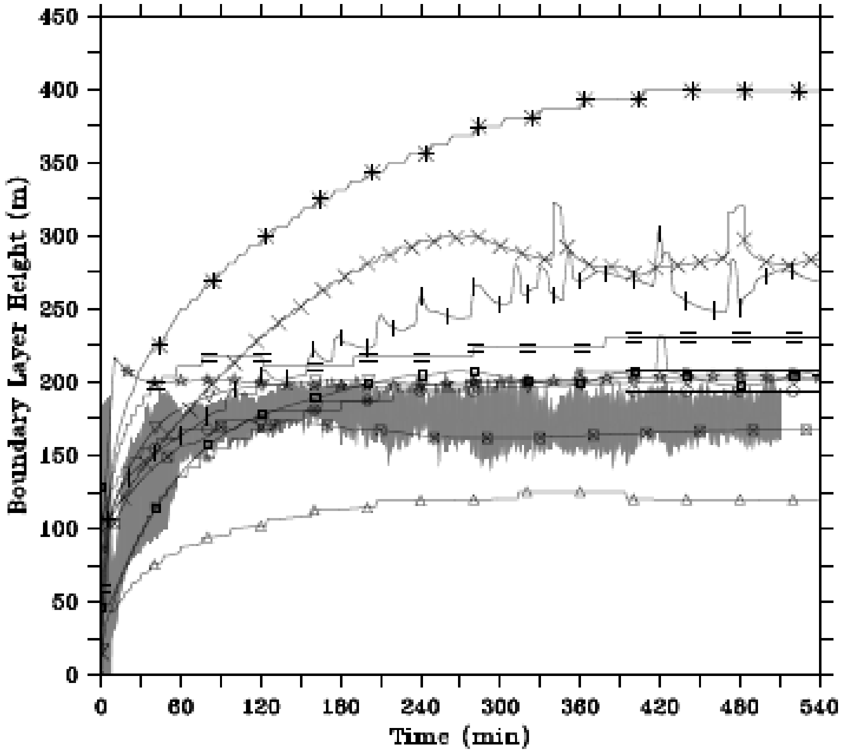
Operational **Research**

Comparison of Single-Column Models with Large Eddy Simulations (LES)
(Beare et al, 2006; Cuxart et al, 2006)

Boundary-Layer Height



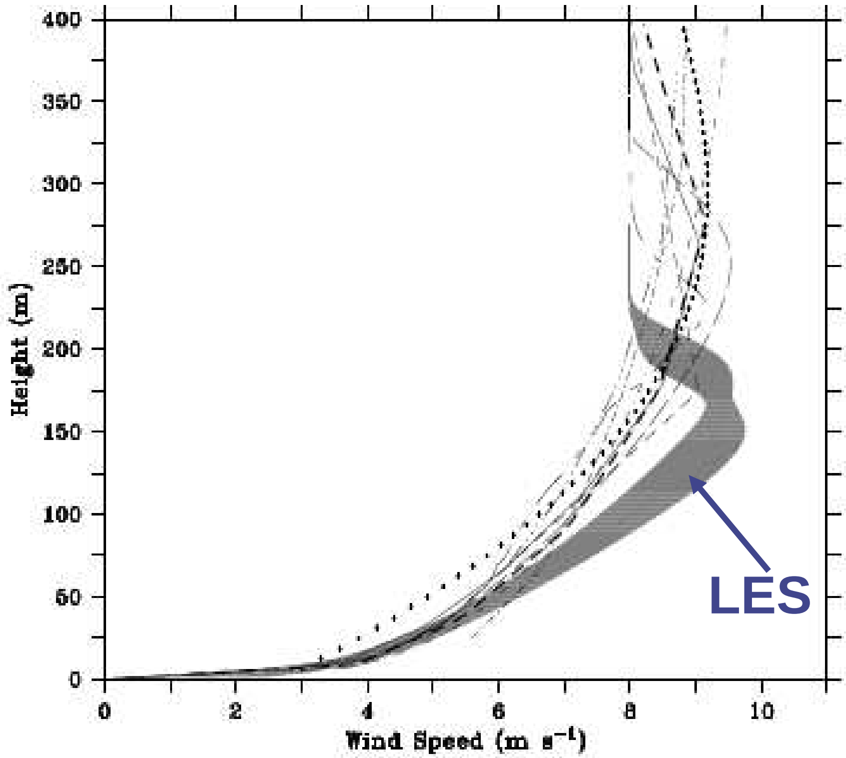
Operational



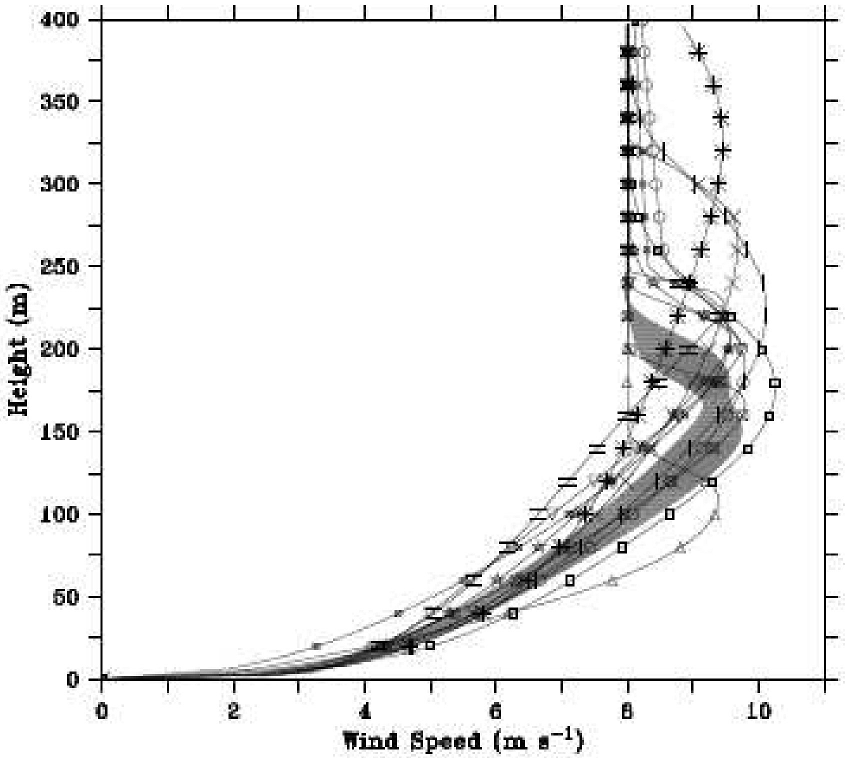
Research

Resolution (most) operational models is set to 6.25 m!

Wind speed

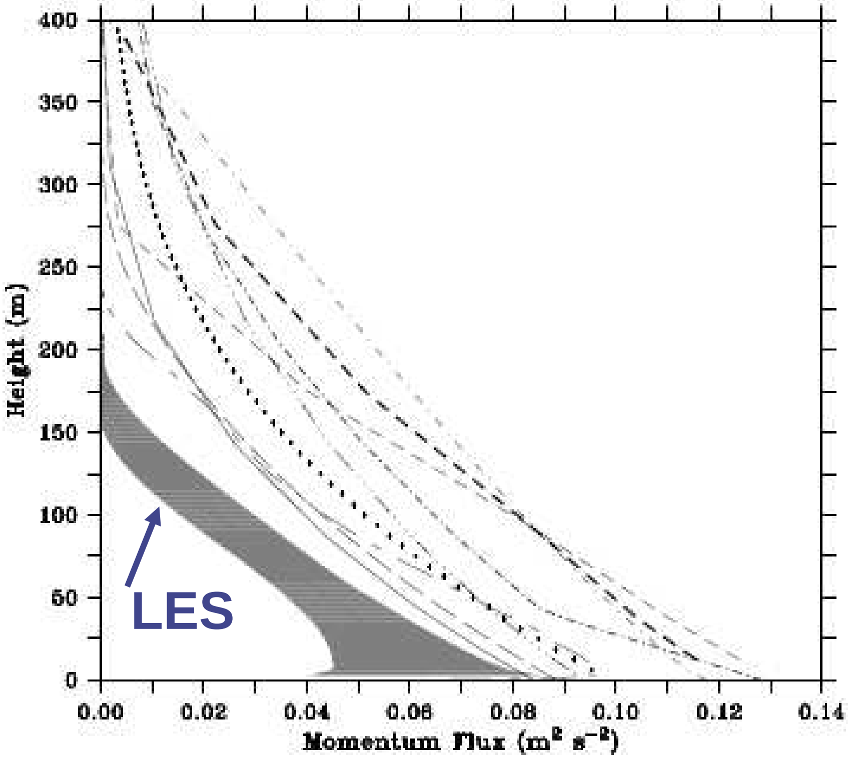


Operational

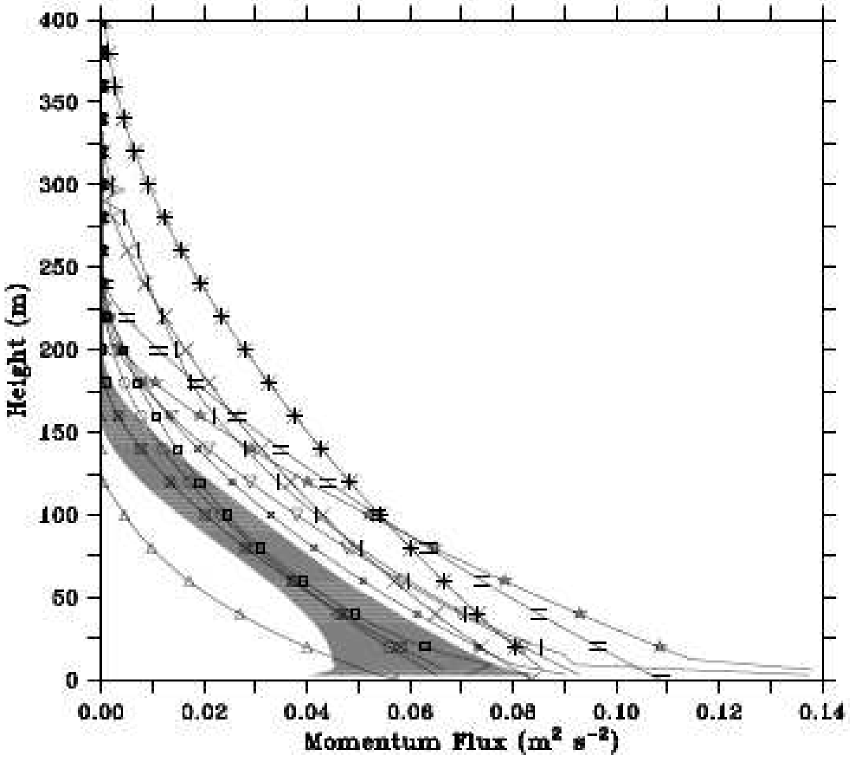


Research

Momentum flux

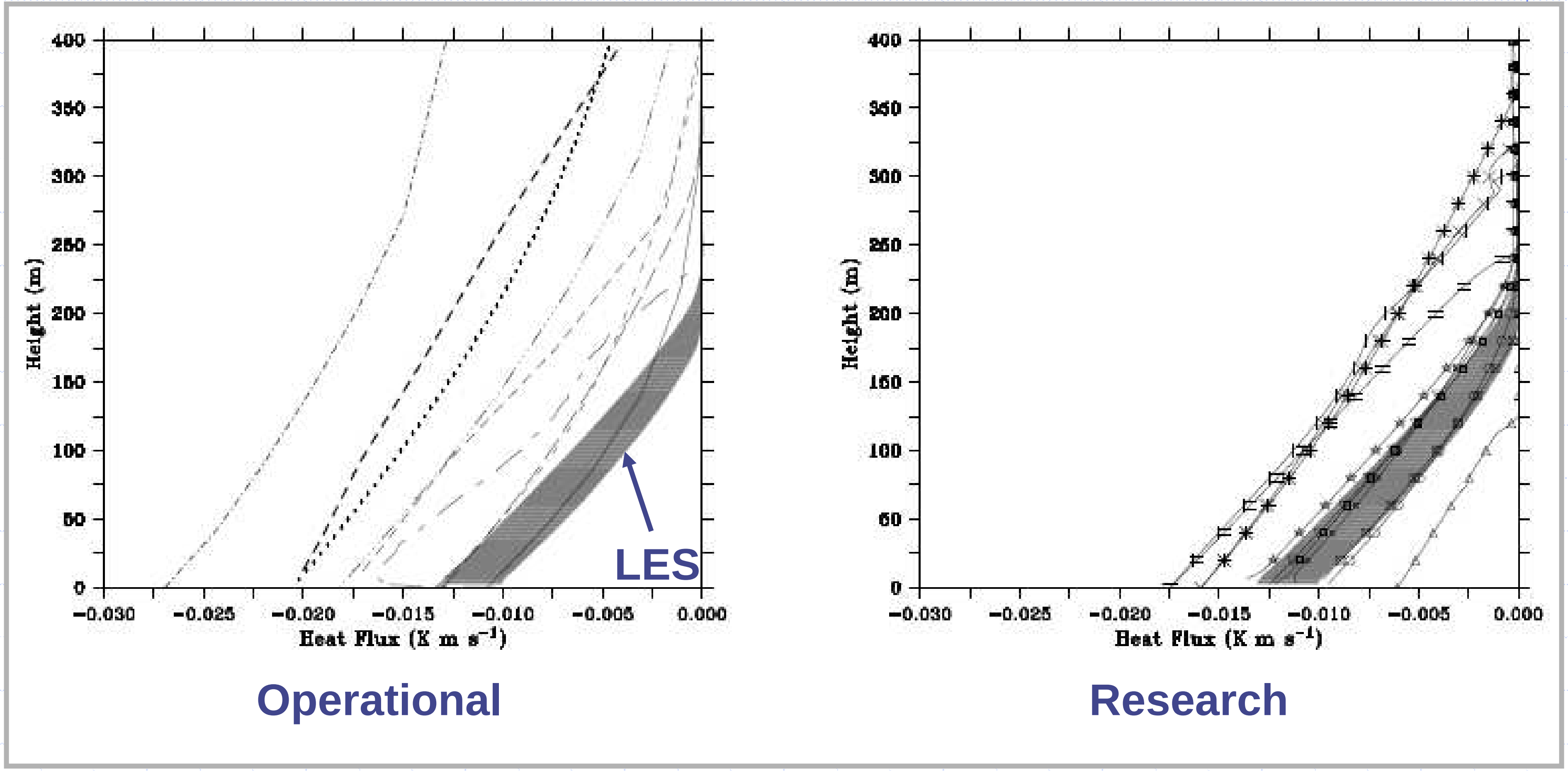


Operational



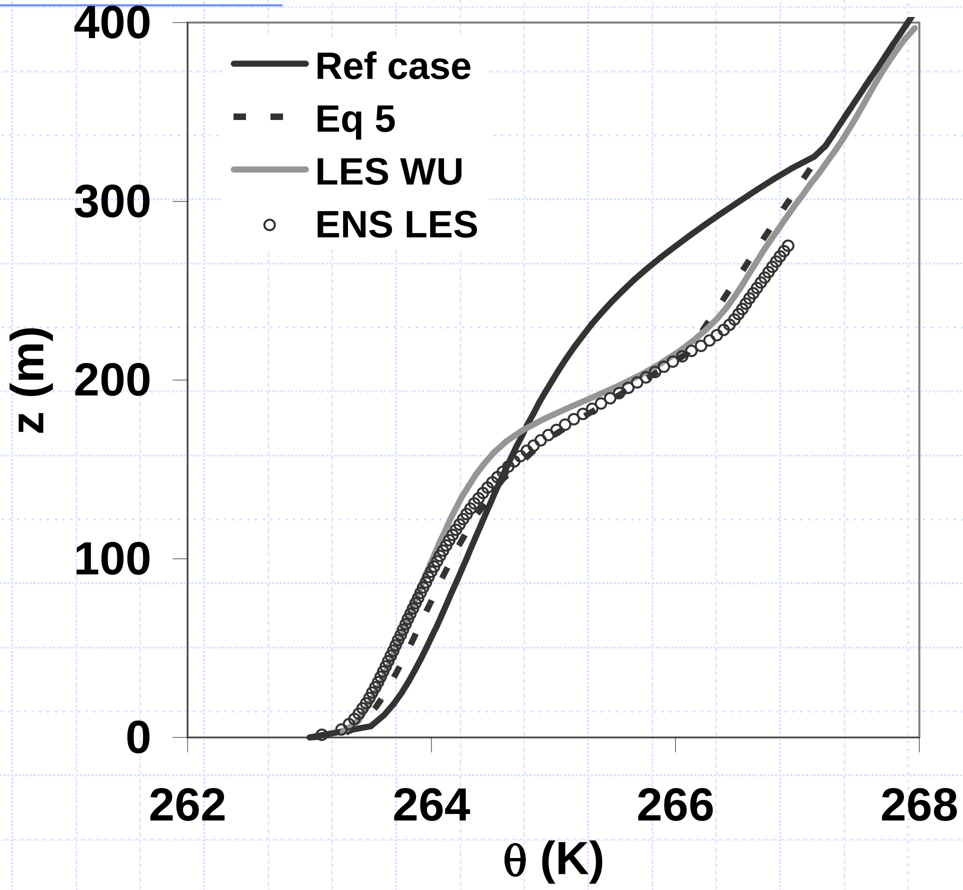
Research

Heat flux



Operational

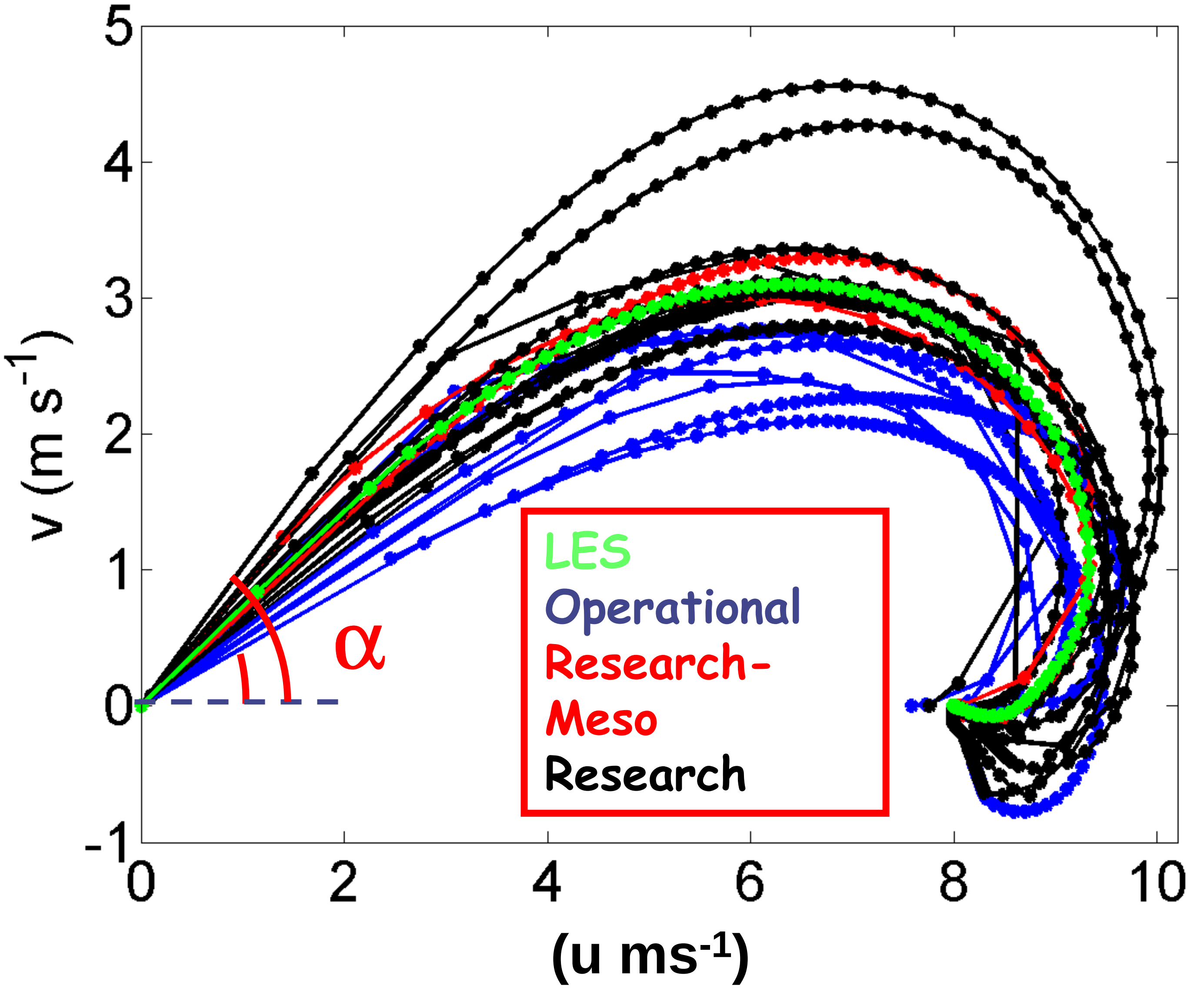
Research



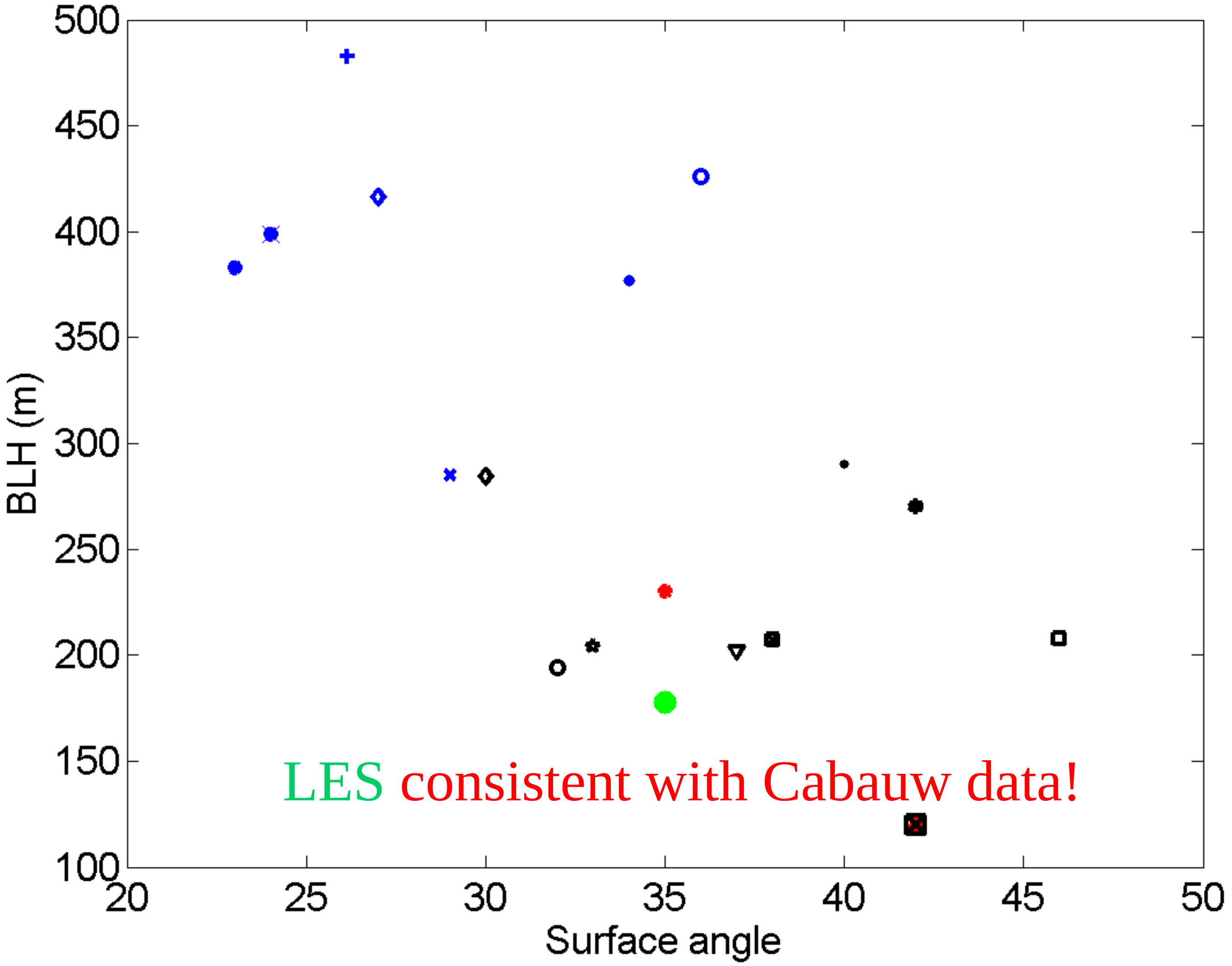
Note:
Models can represent main LES results after adjusting parameters in turbulence scheme

Steeneveld, Van de Wiel, Holtslag, 2006 (BLM)

'Ekman spirals' (Svensson+Holtslag, 2008)

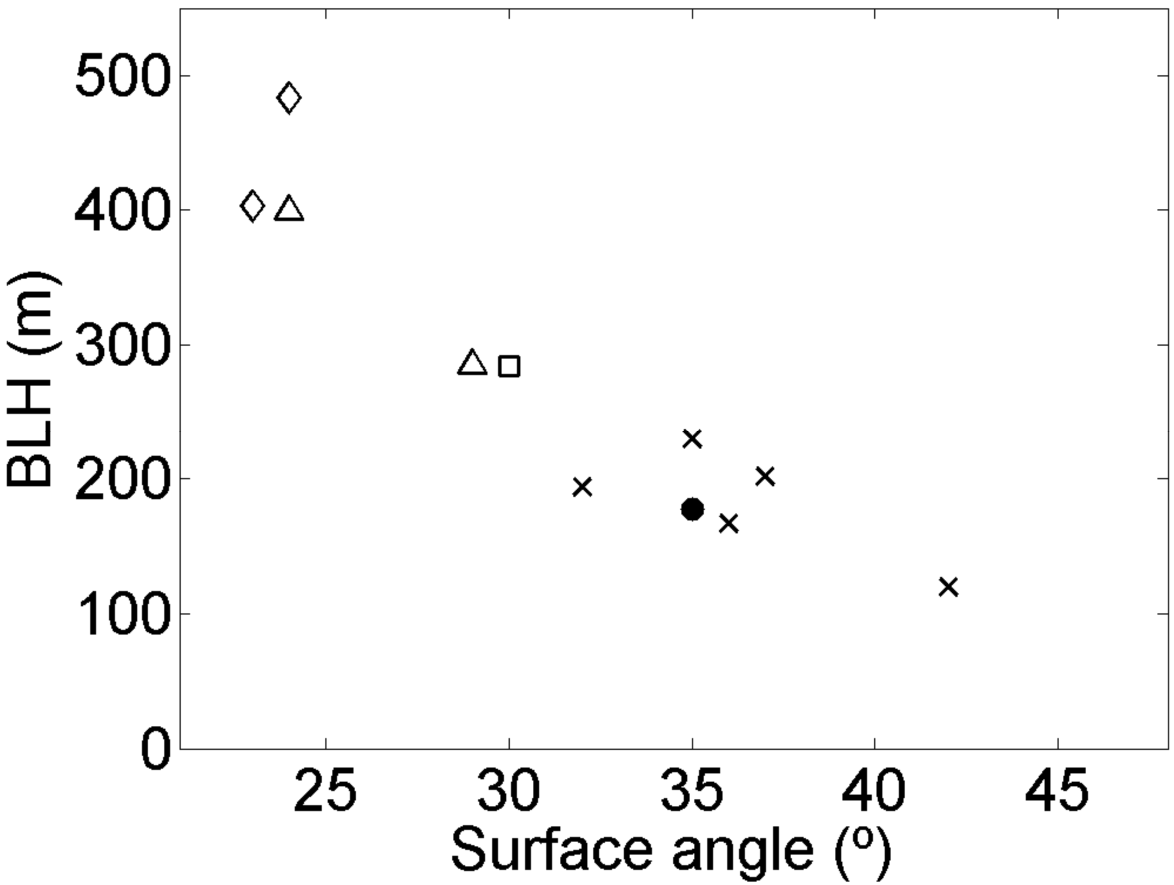


Boundary-layer height and surface angle



LES consistent with Cabauw data!

Models with surface problems removed



Summary

First GABLS model intercomparison on stable boundary layers

Large variation among 1D models, but all operational models show too strong mixing!

Results of LES models in good agreement with observations in relatively homogeneous cases (e.g. Nieuwstadt, 1984)

Eight papers in special GABLS issue of Boundary Layer Meteorology, Feb. 2006

Why do Operational Models need Enhanced Mixing in Stable Cases?

To prevent unrealistic ‘runaway’ surface cooling

To have sufficient ‘Ekman pumping’

To compensate for model errors?

Do we overlook an atmospheric process e.g., gravity waves?

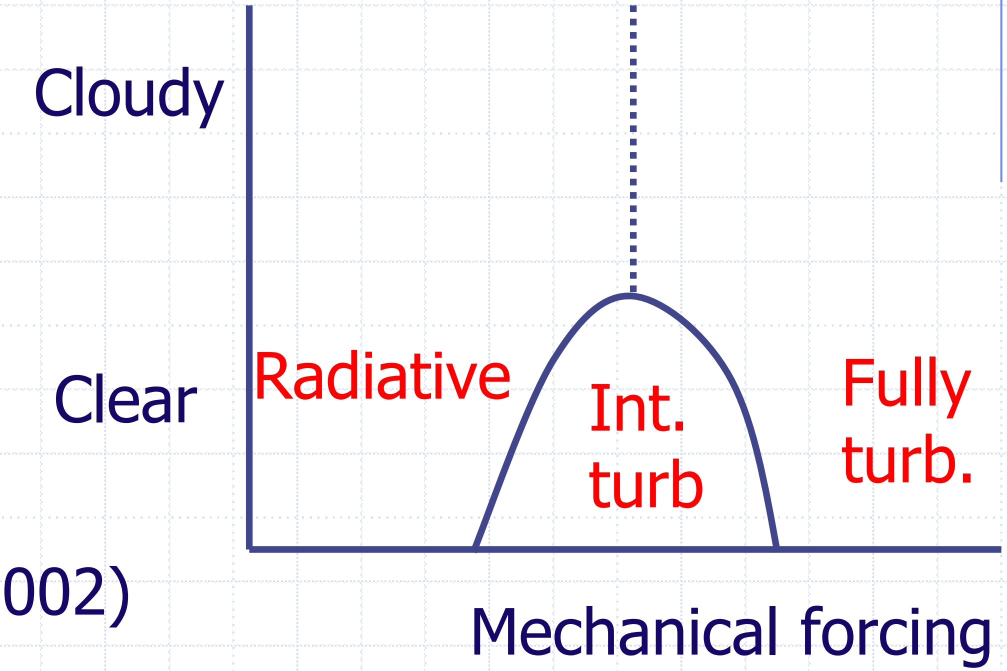
What is impact of surface heterogeneity?

What about more stable cases?

Three different regimes in stable boundary layers over land:

- Fully turbulent (such as in GABLS1)
- Intermittent turbulent
- Radiation dominated

(see Van de Wiel et al, 2002)



Can we model these different regimes with a state of the art single column model?

Some recent achievements

SBL modeling benefits from a detailed interaction with vegetation and radiation processes, in particular when local information is used for soil and vegetation parameters and with high resolution in atmosphere and soil near the surface (Steeneveld et al, 2006; 2008).

This also improves the mesoscale model (WRF/MM5)

Surface temperature feedback can compensate for some of the variety introduced by changing model parameters (Holtslag et al, BLM, 2007)

Overview GABLS Studies

- GABLS1
  - Academic set-up
  - LES as reference
  - Special GABLS issue in Boundary Layer Meteorology, Feb. 2006
- GABLS2
  - Based on a dry case (CASES99)
  - Diurnal cycle
  - Notice Prescribed T_s!
  - Manuscripts in preparation!

GABLS3 using a more humid site (Cabauw)

Intercomparison of LES, 1D and possibly regional models with observations

Focus

- SBL, Morning and evening transition
- Land-atmosphere coupling
- Low-level jet

SCM case released, but participation still possible! (contact Fred Bosveld)

LES case released by July 2008 (contact Sukanta Basu)

Take home messages

Many proposals in literature for turbulent mixing regarding diffusivities and length scales

Flux-gradient approach is doing well in stable conditions, with diffusivities on basis of local gradients. However, larger scale models seem to need more drag…

For convective cases, non-local corrections are needed and entrainment needs special attention

Evaluation of approaches is a never ending job (GABLS)!