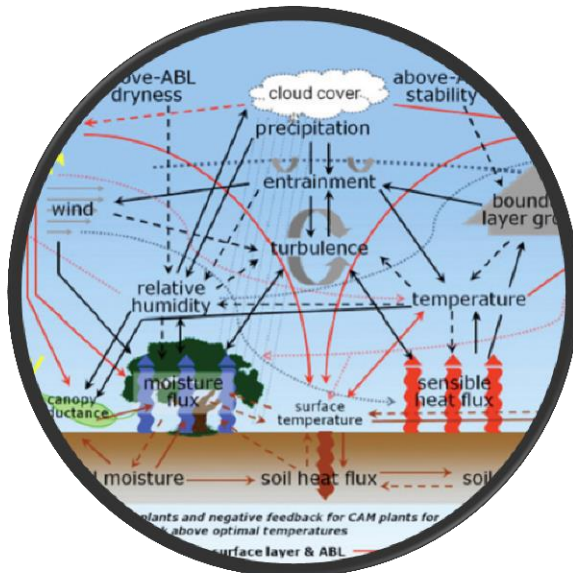


# Stable Atmospheric Boundary Layers and Diurnal Cycles

## Challenges for Weather and Climate Models

Bert Holtslag

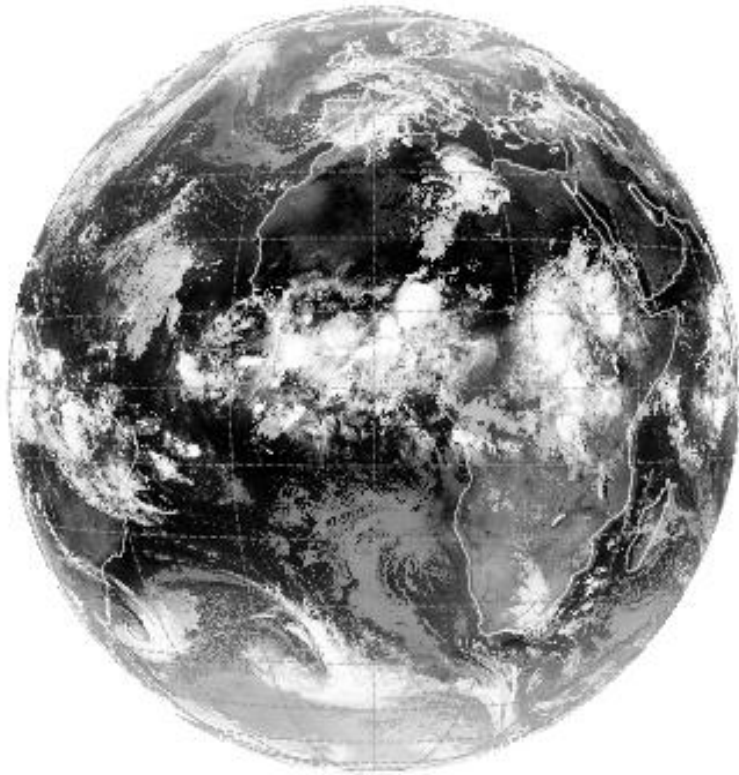
EMC Seminar, NCEP, Washington DC, December 2, 2013



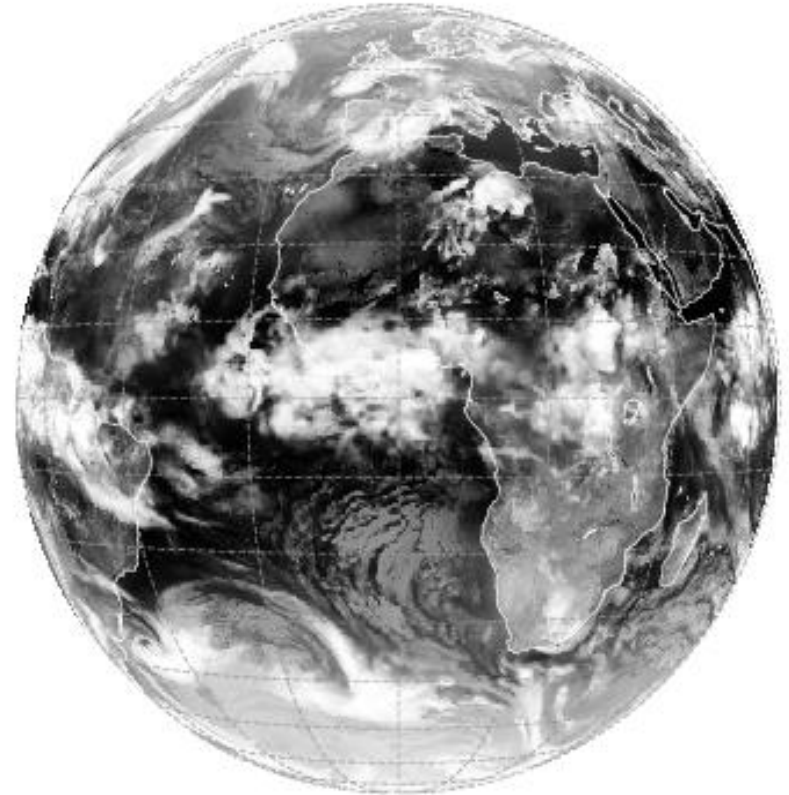
# Progress in the Atmospheric Sciences: Connecting scales

Meteosat observations versus ECMWF predictions (T1279 ~ 15 km)  
(Courtesy MeteoSat and ECMWF)

**Meteosat 9 IR10.8 20080525 0 UTC**



**ECMWF Fc 20080525 00 UTC+0h:**



# Atmospheric Budget Equations

$$\frac{du}{dt} = -\frac{1}{\rho a \cos \phi} \frac{\partial p}{\partial \lambda} + fv + uv \frac{\tan \phi}{a} + F_\lambda$$

$$\frac{dv}{dt} = \frac{1}{\rho a \sin \phi} \frac{\partial p}{\partial \phi} - fu - u^2 \frac{\tan \phi}{a} + F_\phi$$

$$\frac{\partial p}{\partial z} = -\rho g$$

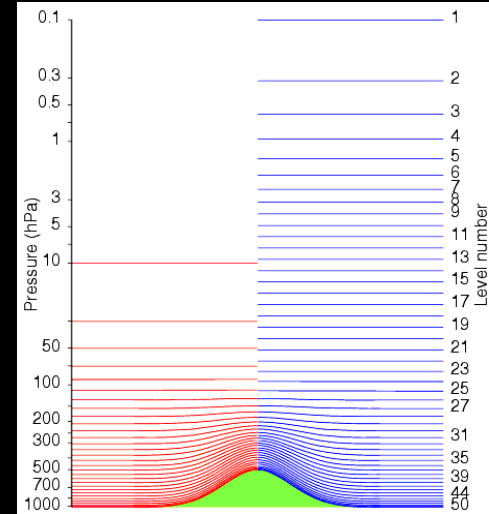
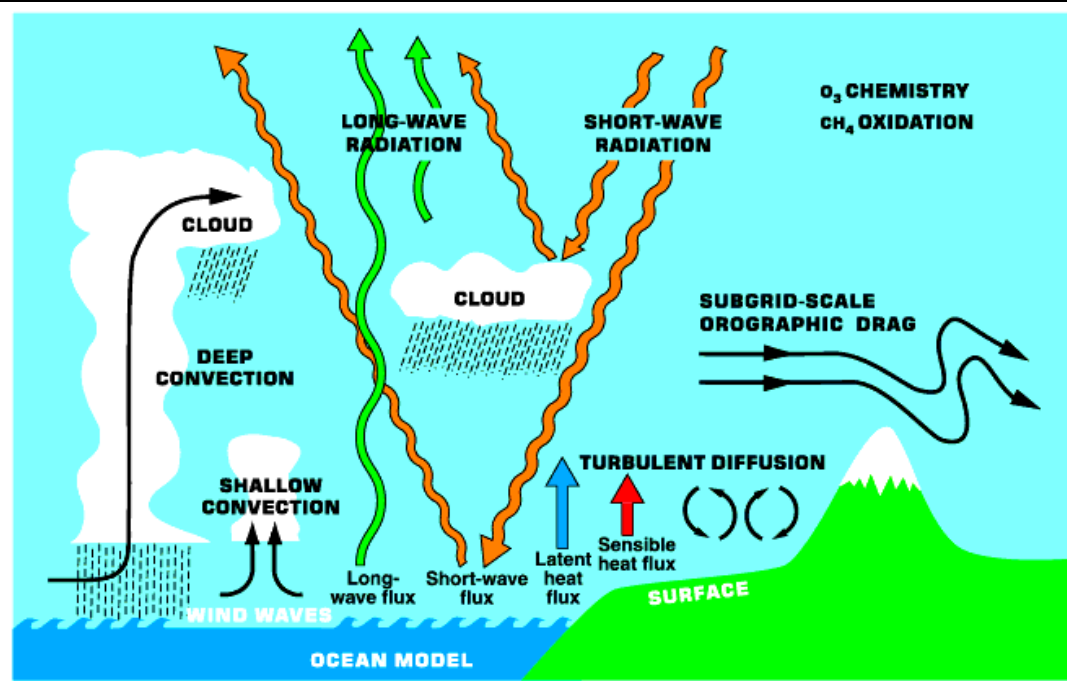
$$\frac{\partial \rho}{\partial t} = -\nabla \cdot \rho \mathbf{V}$$

$$p = R \rho T$$

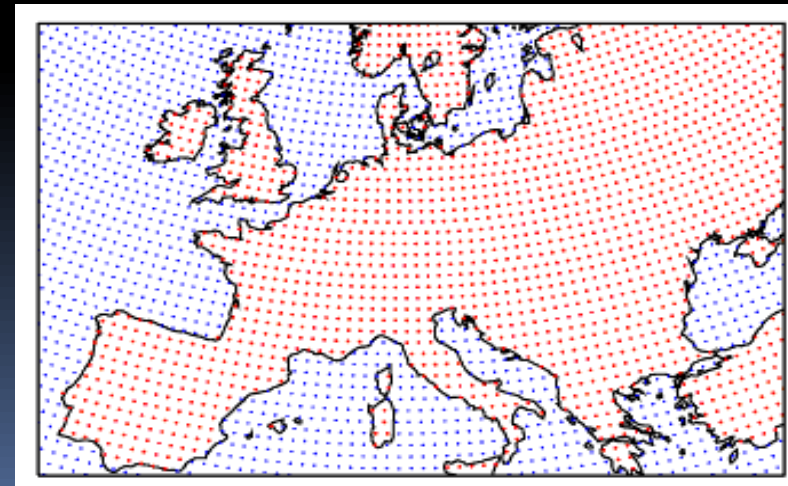
$$C_p \frac{d\Theta}{dt} = \frac{\Theta}{T} Q$$

$u, v, w, p, \rho, T$

## Sub-grid processes



## Discretization



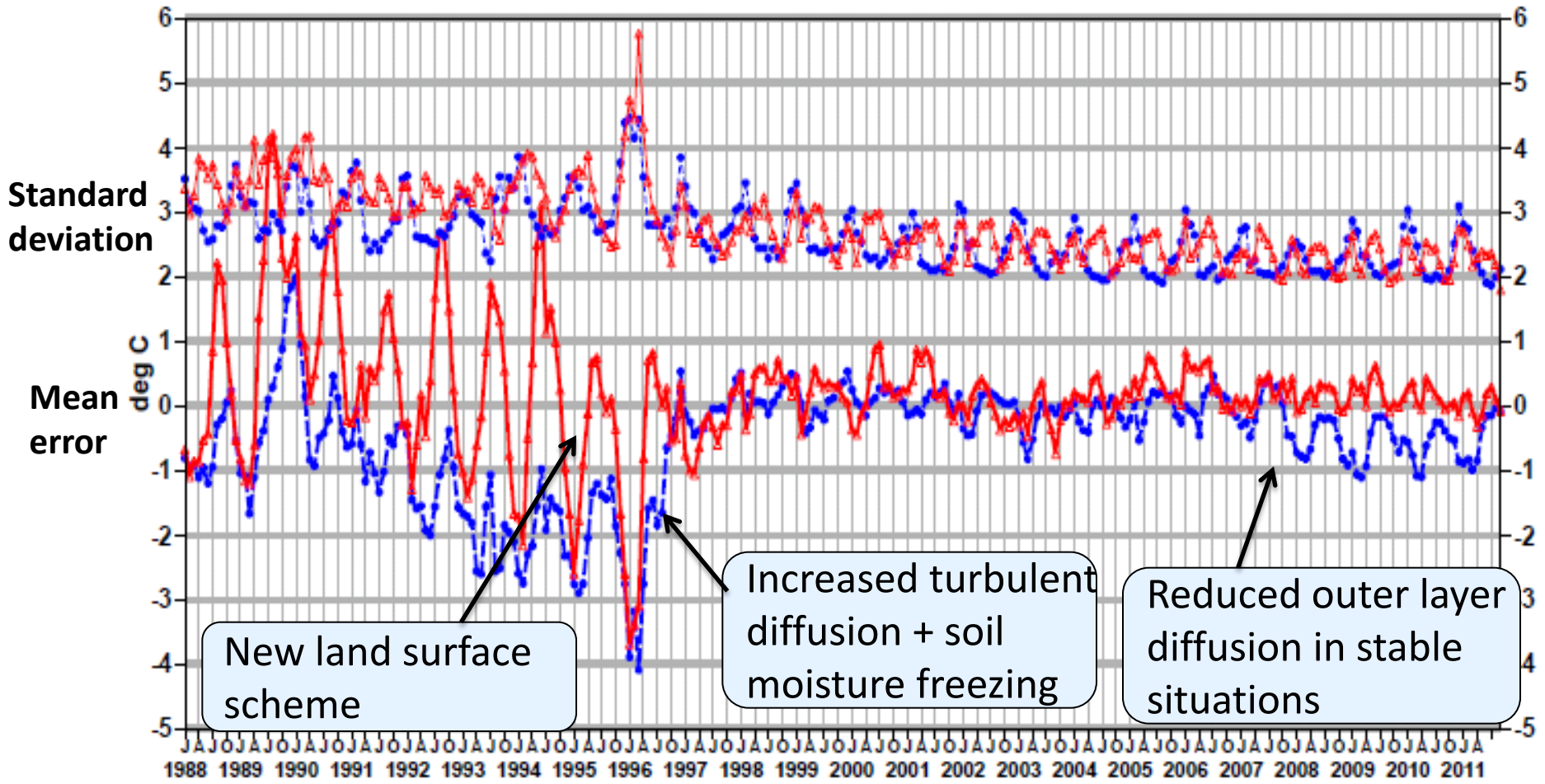


# History of **day** and **night** time temperature errors

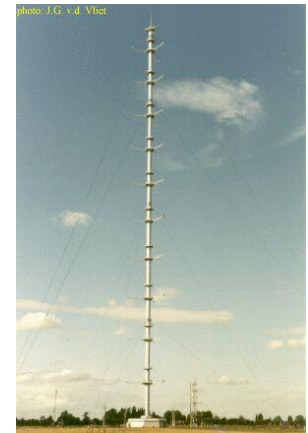
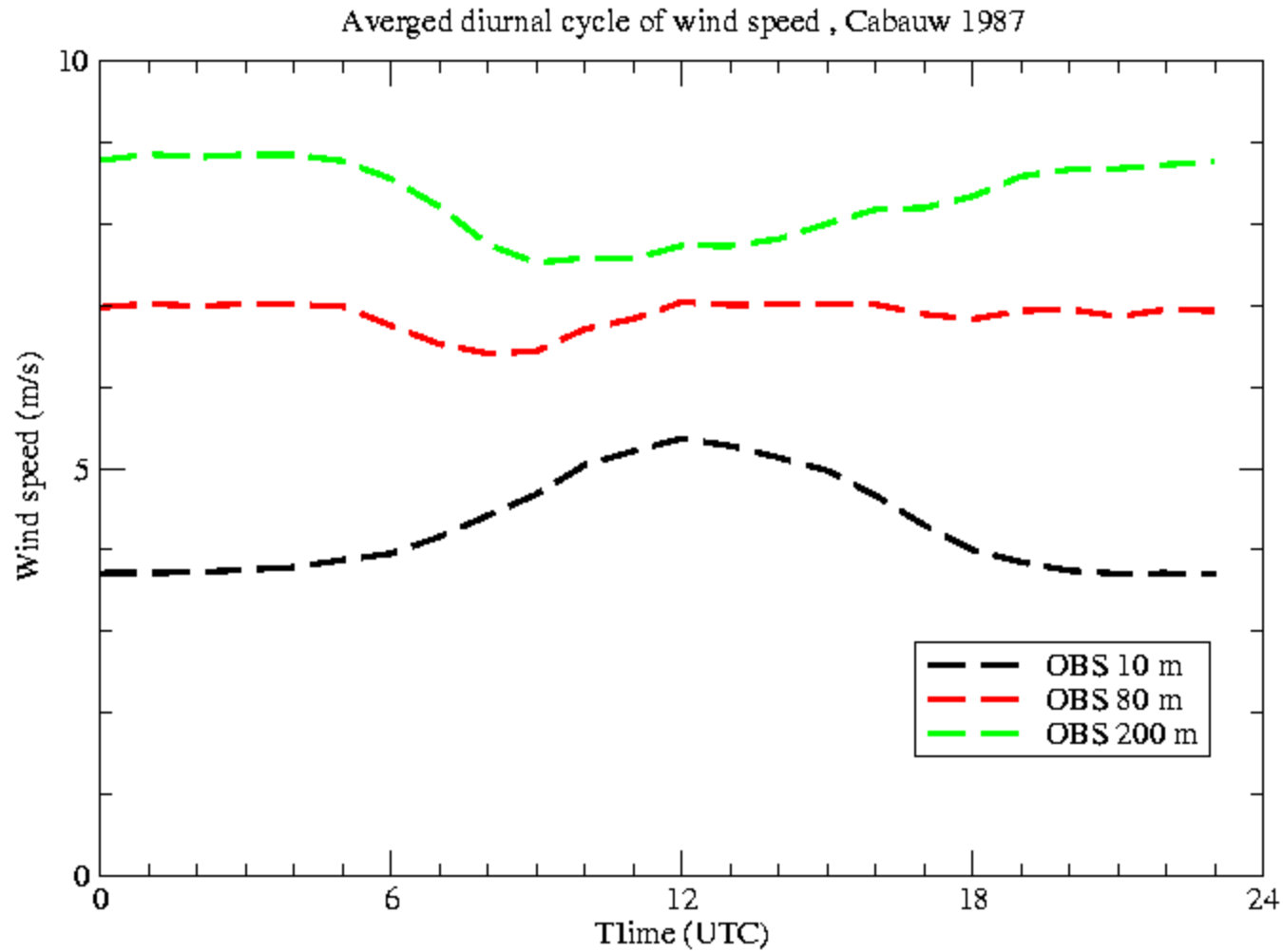
## Monthly averages over Europe

Forecast error of 2 m Temperature [ deg C] Europe 30.0 -22.0 72.0 42.0

—●— bias 60h —▲— bias 72h —●— stdv 60h —▲— stdv 72h



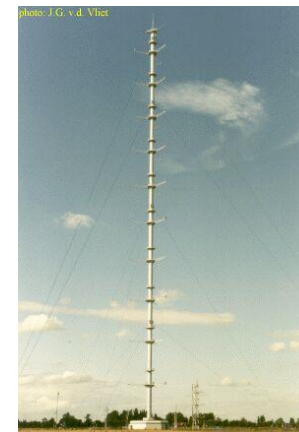
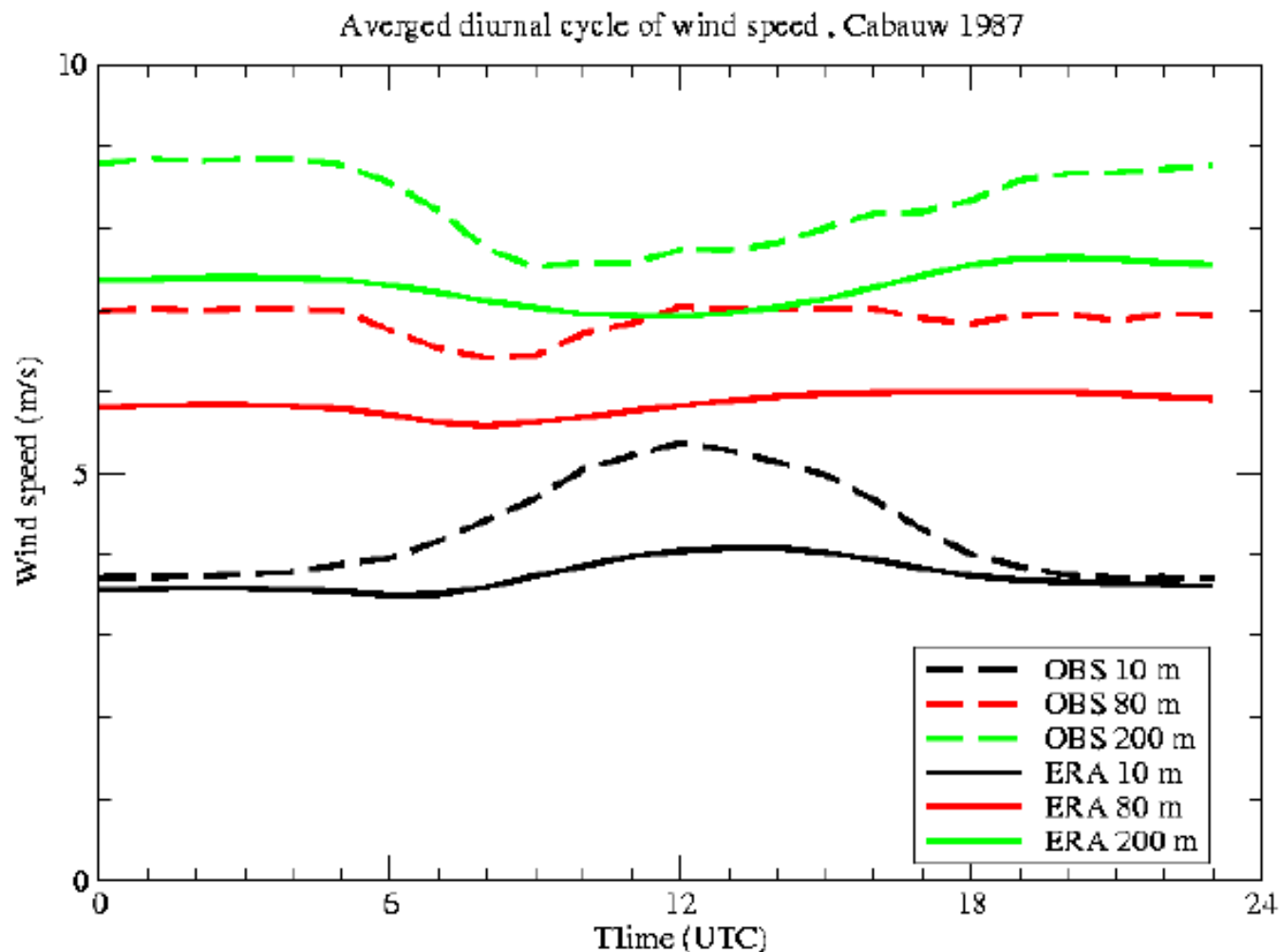
# Diurnal cycle over land: Cabauw 1987 annual average



Courtesy  
Anton Beljaars



# Diurnal cycle: Cabauw 1987 vs. ERA-40 12-36 hour daily forecasts



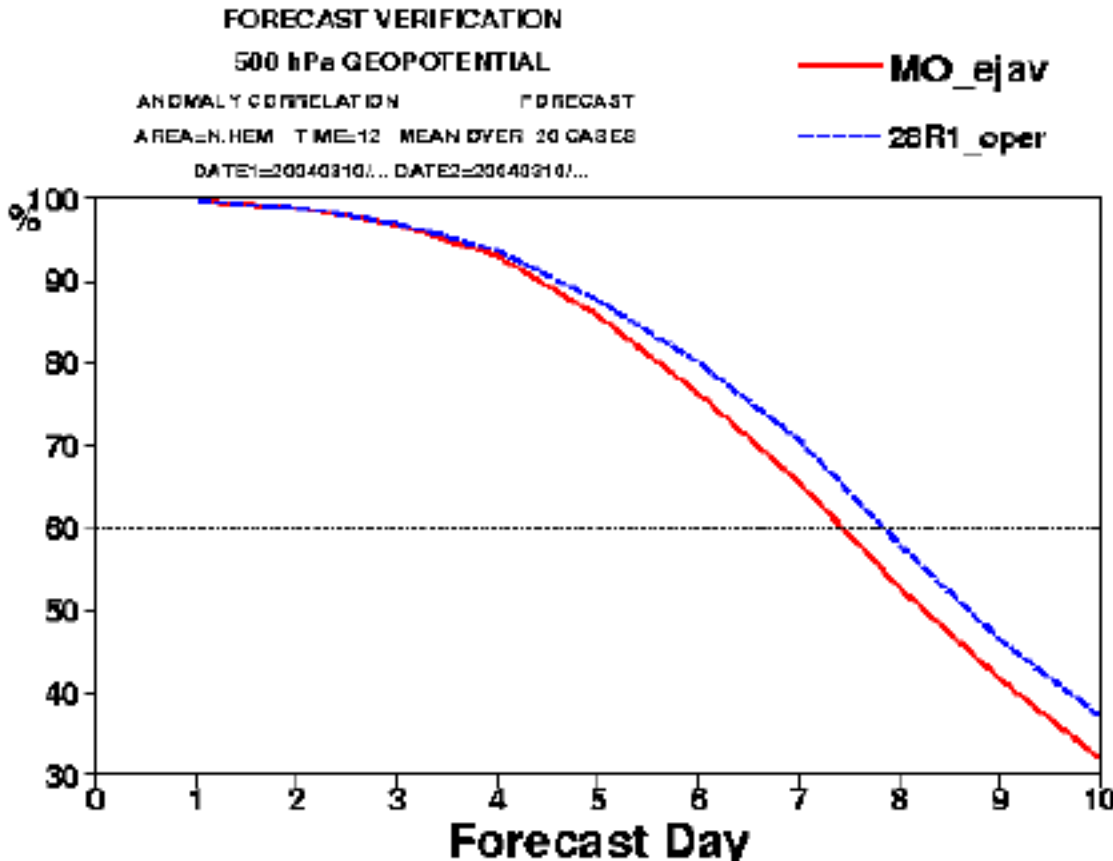
Model underestimates diurnal cycle at 10 m and at 200 m

# Stable boundary layer diffusion affects large scale scores

Effect of **MO-stability functions** (reduced diffusion) instead of **operational formulation**, on 500hPa NH height scores

Model somehow needs larger drag over land than can be obtained from schemes that produce reasonable stable boundary layer structure.

Ground truth for drag over land does not exist.



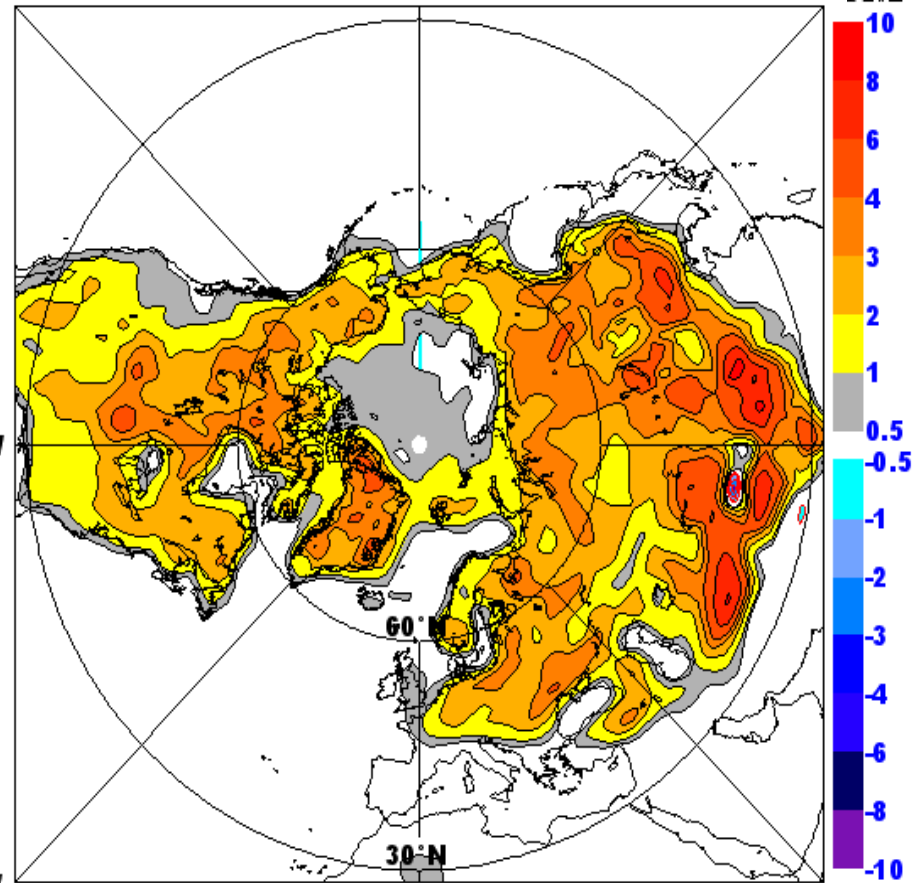
Courtesy

Anton Beljaars

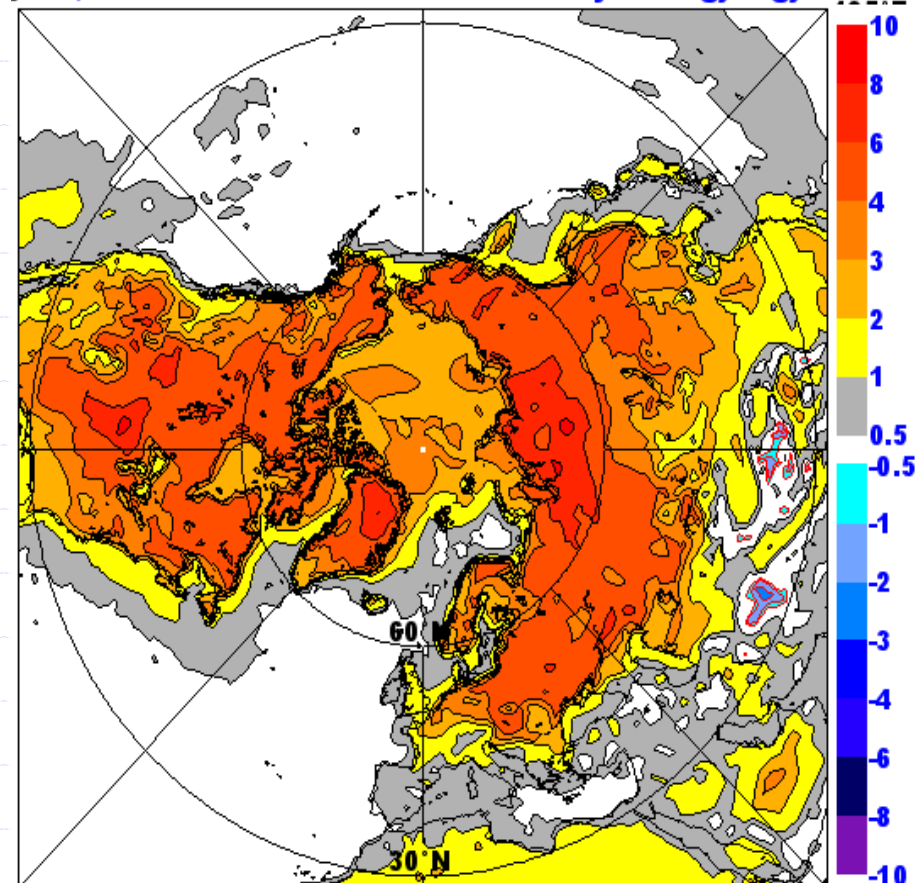


# Mean model difference in 2 meter temperature for January 1996 using two different stability functions in ECMWF model (Courtesy A. Beljaars)

Effect of revised LTG in 1994 model version



Effect of revised LTG in 2011 model version



From long "relaxation" integrations starting 1 Oct 1995



DJF

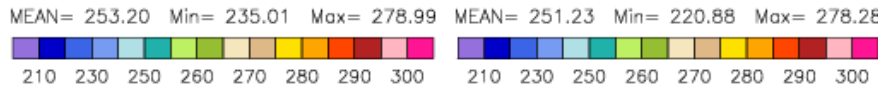
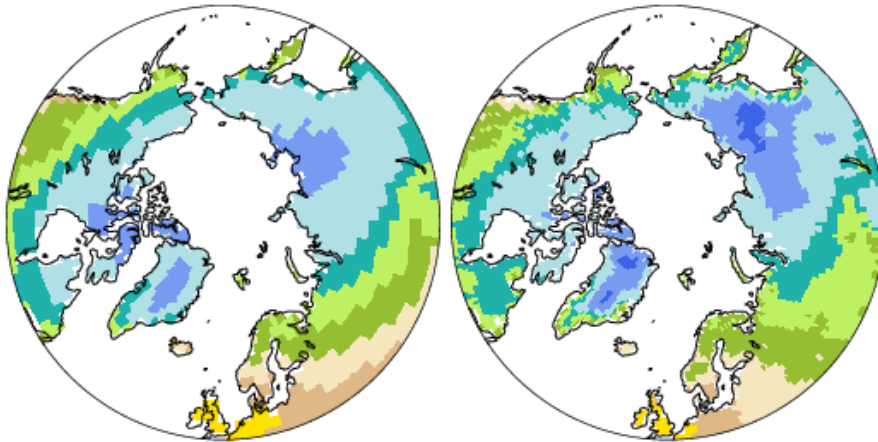
cam3\_5\_04 (yrs 1-10)

WILLMOTT

2-meter Temp (land)

K 2-meter Temp (land)

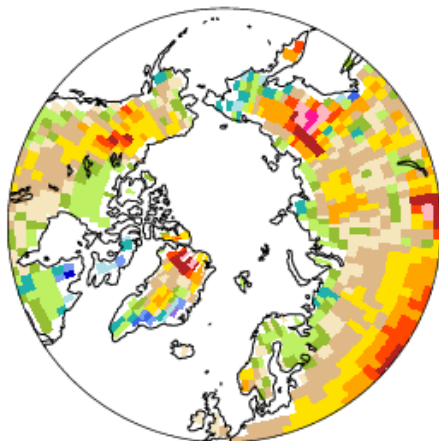
K



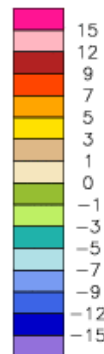
cam3\_5\_04 - WILLMOTT

2-meter Temp (land)

K



MIN = -15.90 MAX = 20.40



Comparison of climate models (such as NCAR-CAM4) 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

DJF

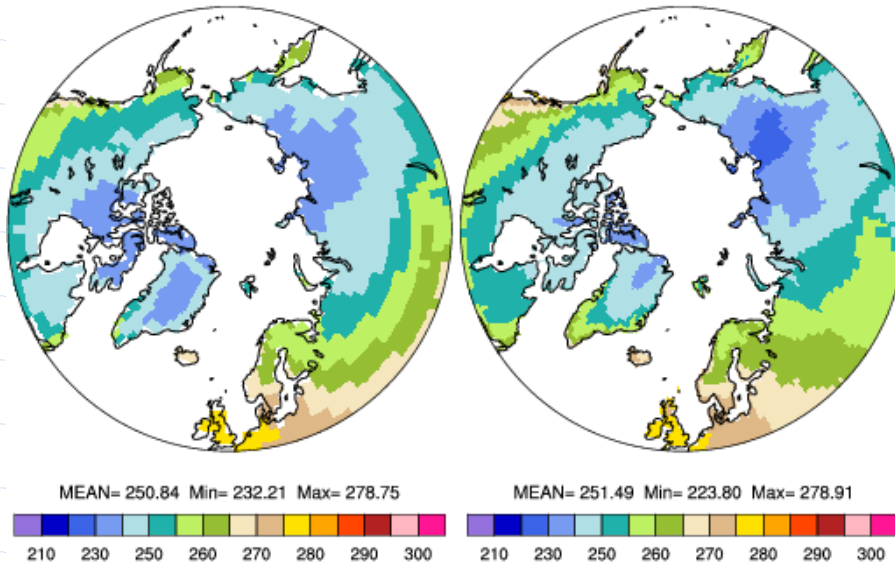
cam3\_5\_04\_uw00\_bi (yrs 1-10)

IPCC/CRU

2-meter Temp (land)

K 2-meter Temp (land)

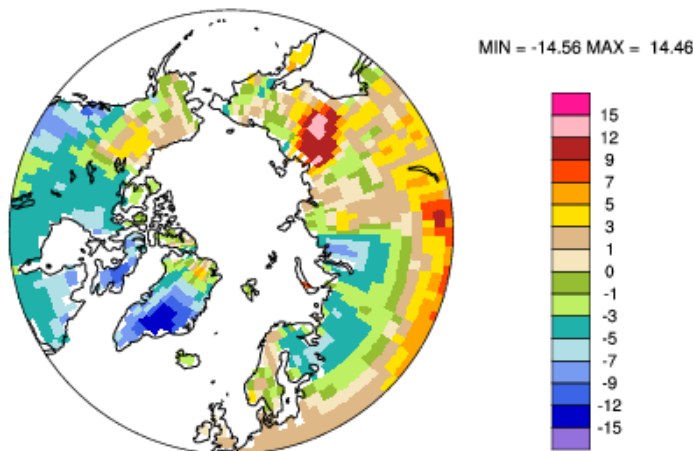
K



cam3\_5\_04\_uw00\_bi - IPCC/CRU

2-meter Temp (land)

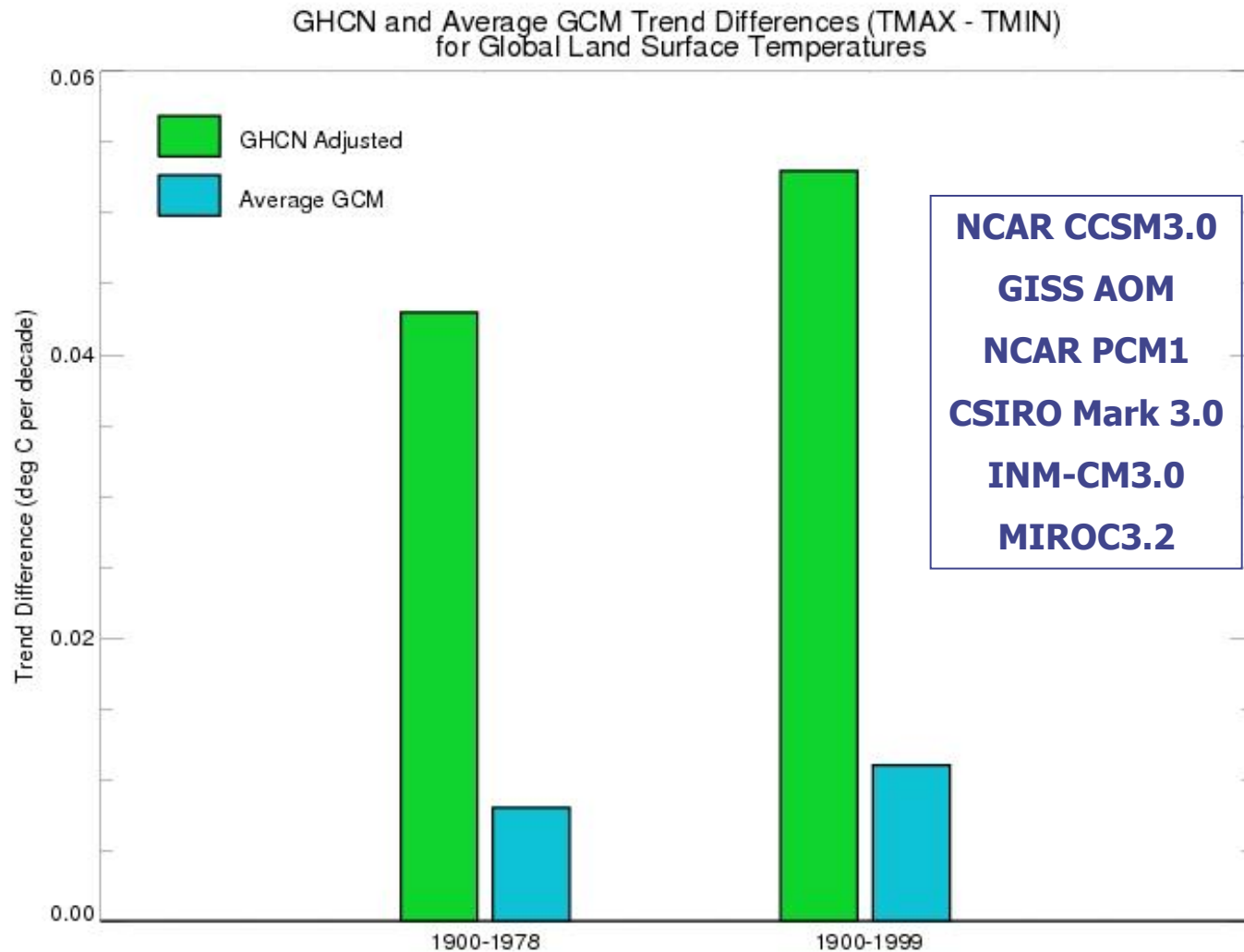
K



Comparison of climate models (such as NCAR-CAM5) 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; Bretherton and Park (2009)

# Climate models only capture small fraction of the change in the diurnal temperature range



McNider et al (2012)

# *Modeling Atmospheric Boundary Layers: It is still a challenge!*

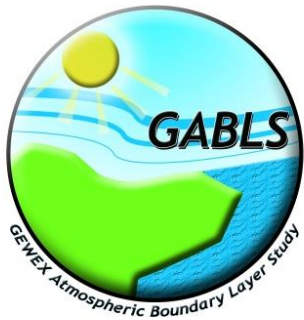
Atmospheric models do have problems in representing the stable boundary layer and the diurnal cycle

Sensitivity to details in mixing formulation




## Strategy

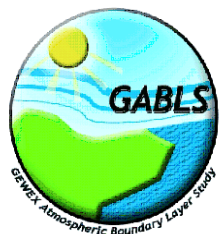
Enhance understanding by benchmark studies over land and ice in comparison with observations and fine scale numerical model results

So far focus on clear skies!



**GEWEX Atmospheric Boundary Layer Studies (GABLS)**  
 provides platform for model intercomparison and development to  
 benefit studies of Climate, Weather, Air Quality and Wind Energy

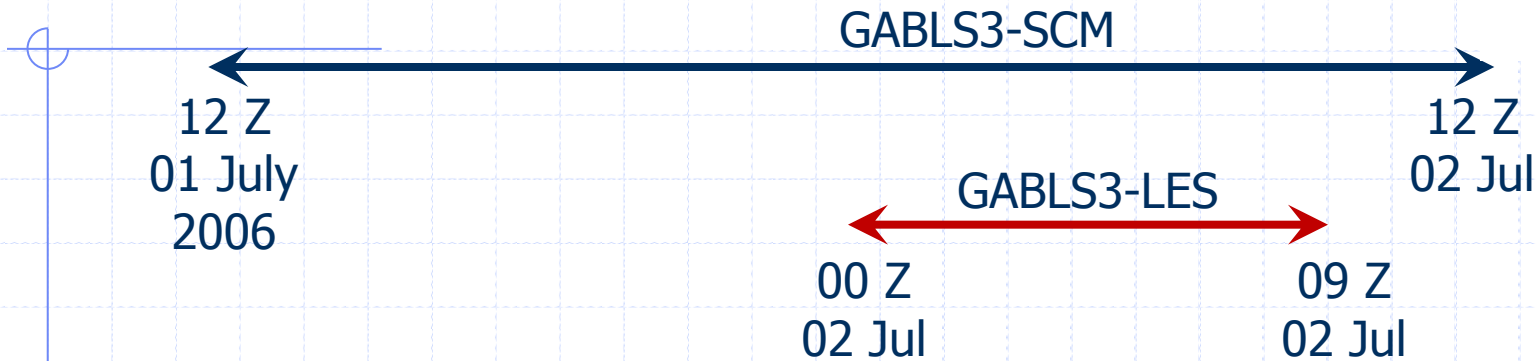
GABLS1	GABLS2	GABLS3
		
<i>LES</i> as reference	Data (CASES99)	Data (CABAUW)
Academic set up	Idealized forcings	Realistic forcings
Prescribed $T_s$	Prescribed $T_s$	Full coupling ( <i>SCM</i> ) Prescribed $T_s$ ( <i>LES</i> )
No Radiation	No Radiation	Radiation included
Turbulent mixing	Diurnal cycle	Low level jet + transitions



*LES*: Large Eddy Simulation; *SCM*: Single Column Model



# GABLS3: SCM and LES model studies



Cabauw tower  
(KNMI, NL)

## Initialization Profiles

Cabauw tower, Profiler, De Bilt Sounding

## Geostrophic Wind (time-height dependent)

Similar for both SCM and LES

## Large-scale Advection (time-height dependent)

Similar for both SCM and LES

## Surface Boundary Conditions

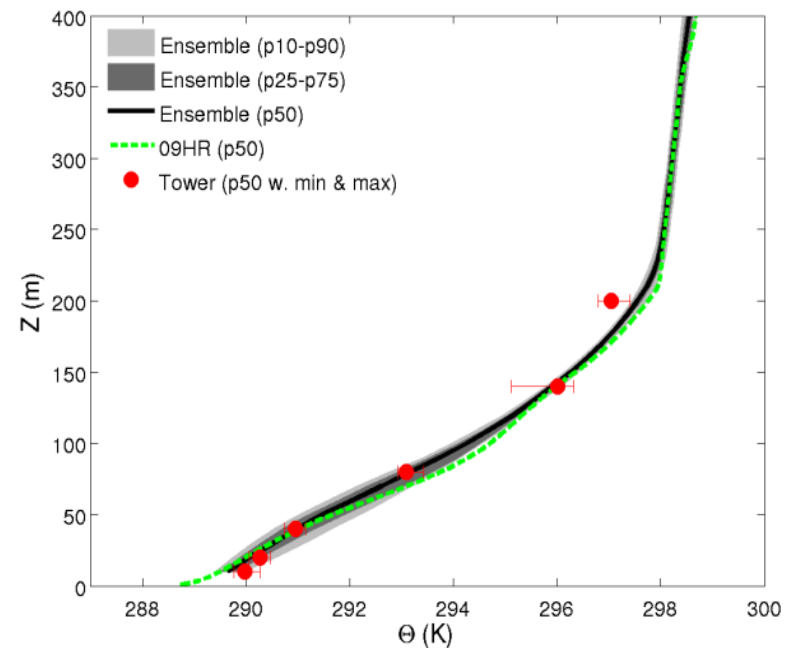
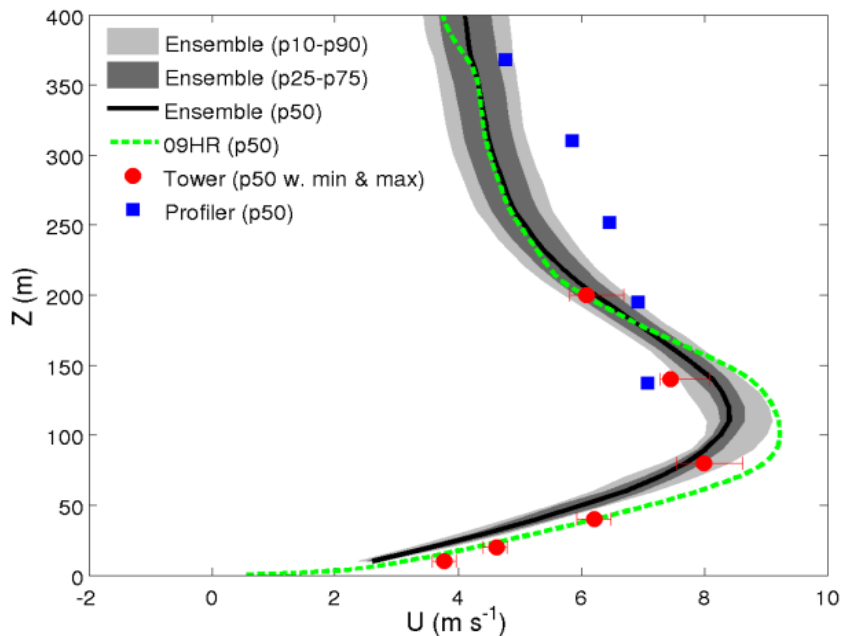
Cabauw tower

# GABLS3 Large Eddy Simulation intercomparison (coordinated by Sukanta Basu, NC State Univ)

Initialized at midnight (02-jul-2006 00:00 UTC) and run for 9 hours (11 LES models)  
Prescribed temperature at lowest model level from observations!

Wind speed magnitude

Potential Temperature



Mean profiles 03-04 UTC

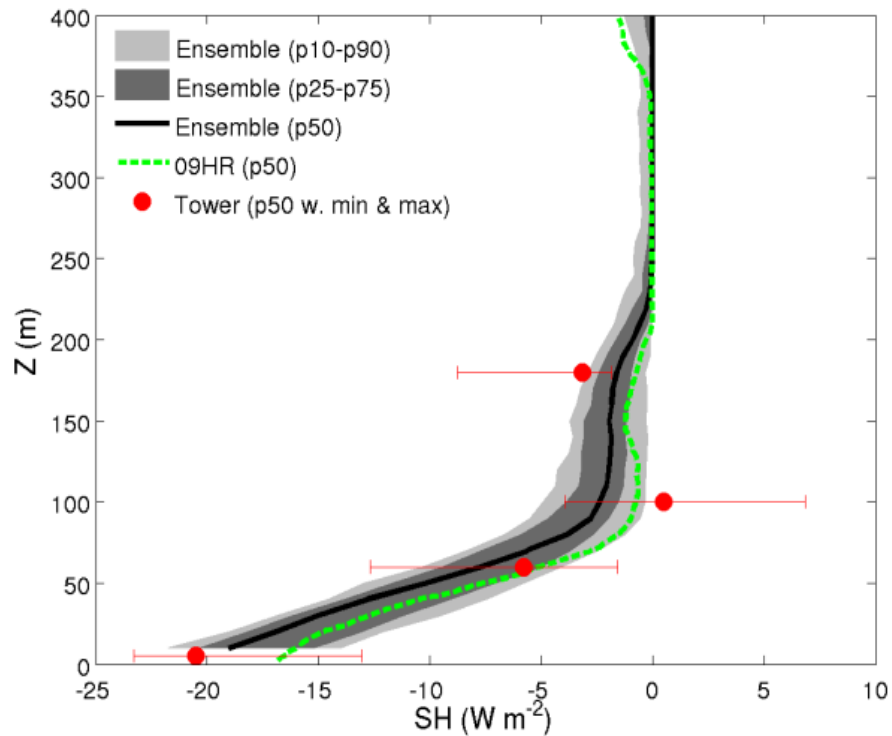
(Red dots: Tower; Blue squares: Wind Profiler)

Green dashed line: 1m LES run (Courtesy Siegfried Raasch)

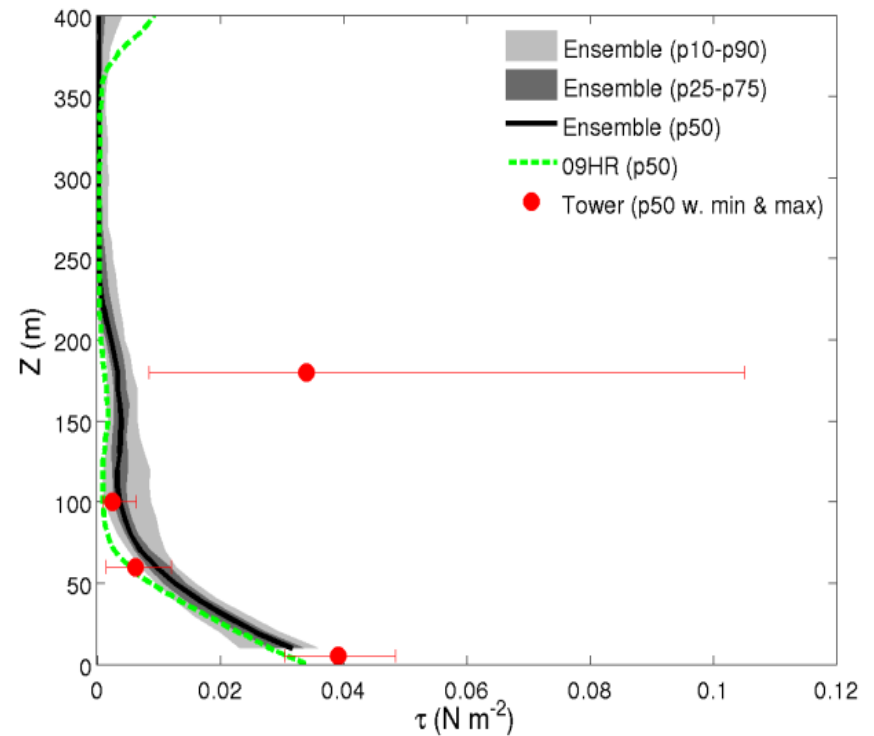


# GABLS3 Large Eddy Simulation intercomparison (coordinated by Sukanta Basu, NC State Univ)

## Sensible Heat flux ( $\text{W}/\text{m}^2$ )



## Momentum flux ( $\text{N}/\text{m}^2$ )



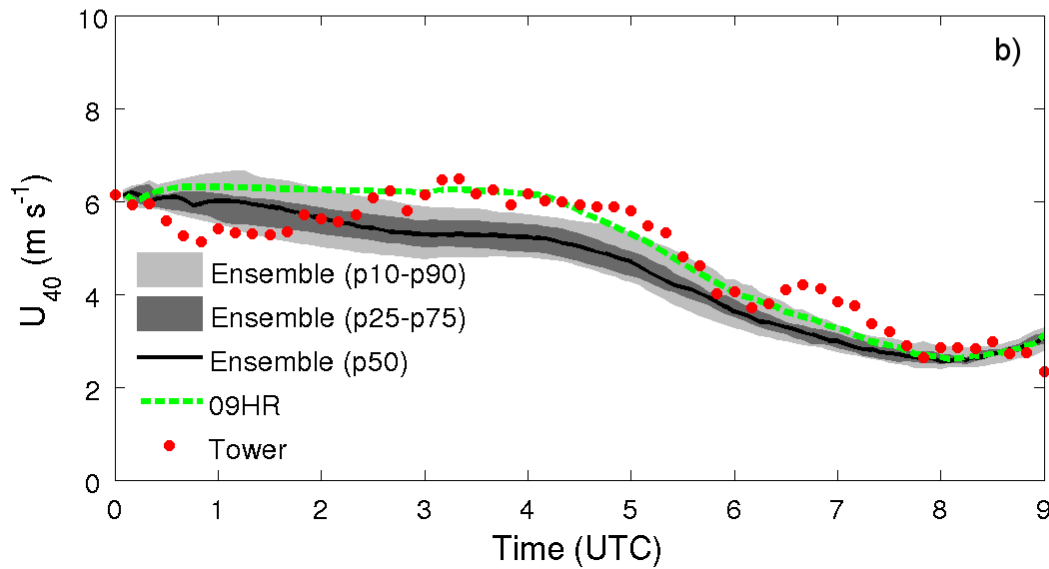
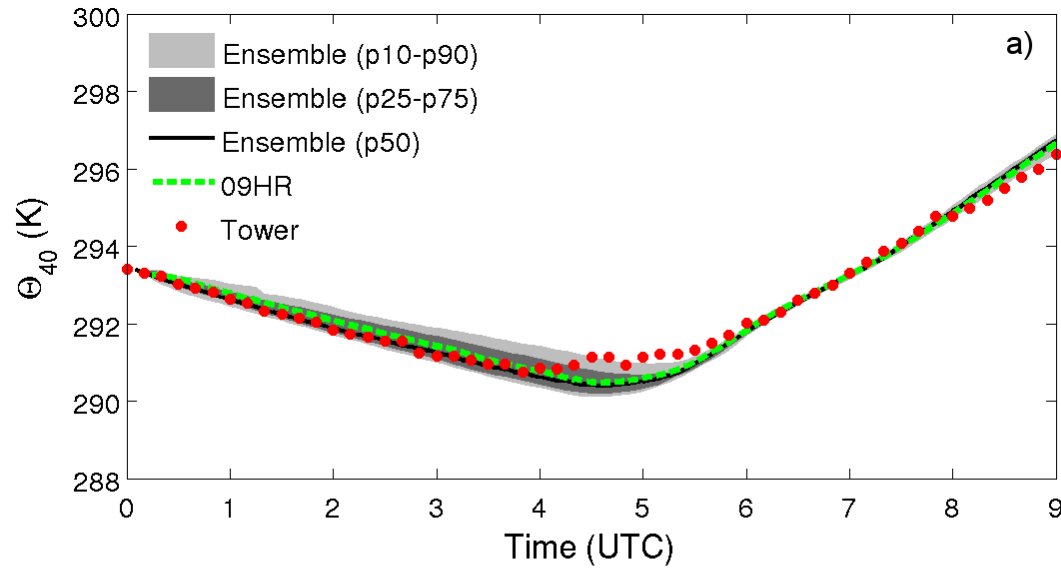
Flux profiles 03-04 UTC

(Red dots: Cabauw Tower observations)

Green dashed line: 1m LES run (Courtesy Siegfried Raasch)



# Temporal evolution



## GABLS3

intercomparison of  
Single Column versions  
(SCM) of operational  
and research models  
(Coordinated by  
**Fred Bosveld, KNMI**)

Note:

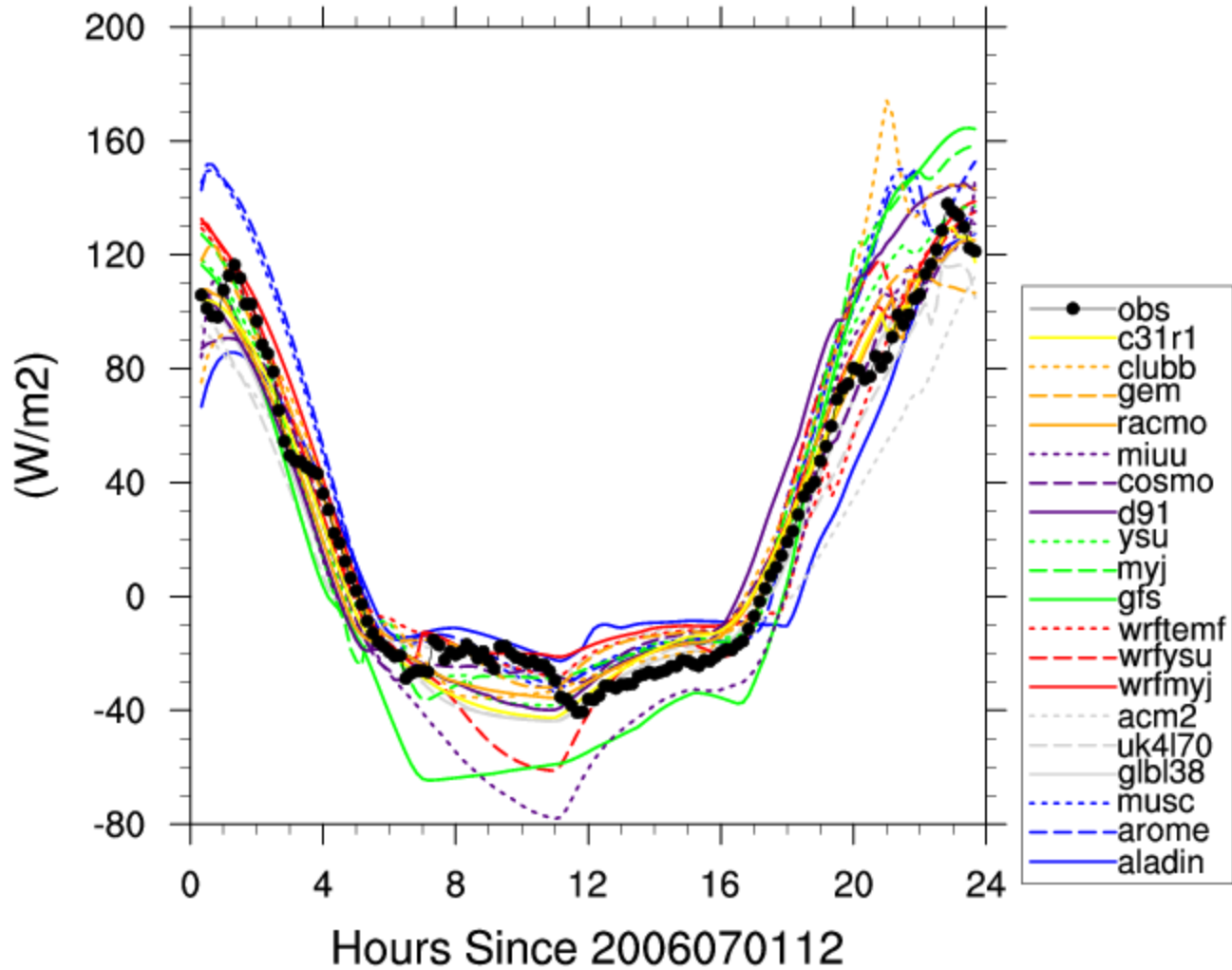
Each SCM uses its  
own radiation and land  
surface scheme  
interacting with the  
boundary layer scheme  
on usual resolution!  
(Nlev is number of  
vertical levels in whole  
atmosphere)

<i>Name</i>	<i>Institute</i>	<i>Nlev</i>	<i>BL.Scheme</i>	<i>Skin</i>
ALADIN	Meteo France	41	TKE	No
AROME	Meteo France	41	TKE	No
GLBL38	Met Office	38	K (long tail)	Yes
UK4L70	Met Office	70	K (short tail)	Yes
D91	WUR	91	K	Yes
GEM	Env. Canada	89	TKE-I	No
ACM2	NOAA	155	K+non-local	No
WRF YSU	NOAA	61	K	No
WRF MYJ	NOAA	61	TKE-I	No
WRFTEMF	NOAA	61	Total E	No
COSMO	DWD	41		
GFS	NCEP	57	K	Yes
WRF MYJ	NCEP	57	TKE-I	Yes
WRF YSU	NCEP	57	K	Yes
MIUU	MISU	65	2nd order	
MUSC	KNMI	41	TKE-I	No
RACMO	KNMI	80	TKE	Yes
C31R1	ECMWF	80	K	Yes
CLUBB	UWM	250	Higher order	No



# Surface fluxes

Surface sensible heat flux



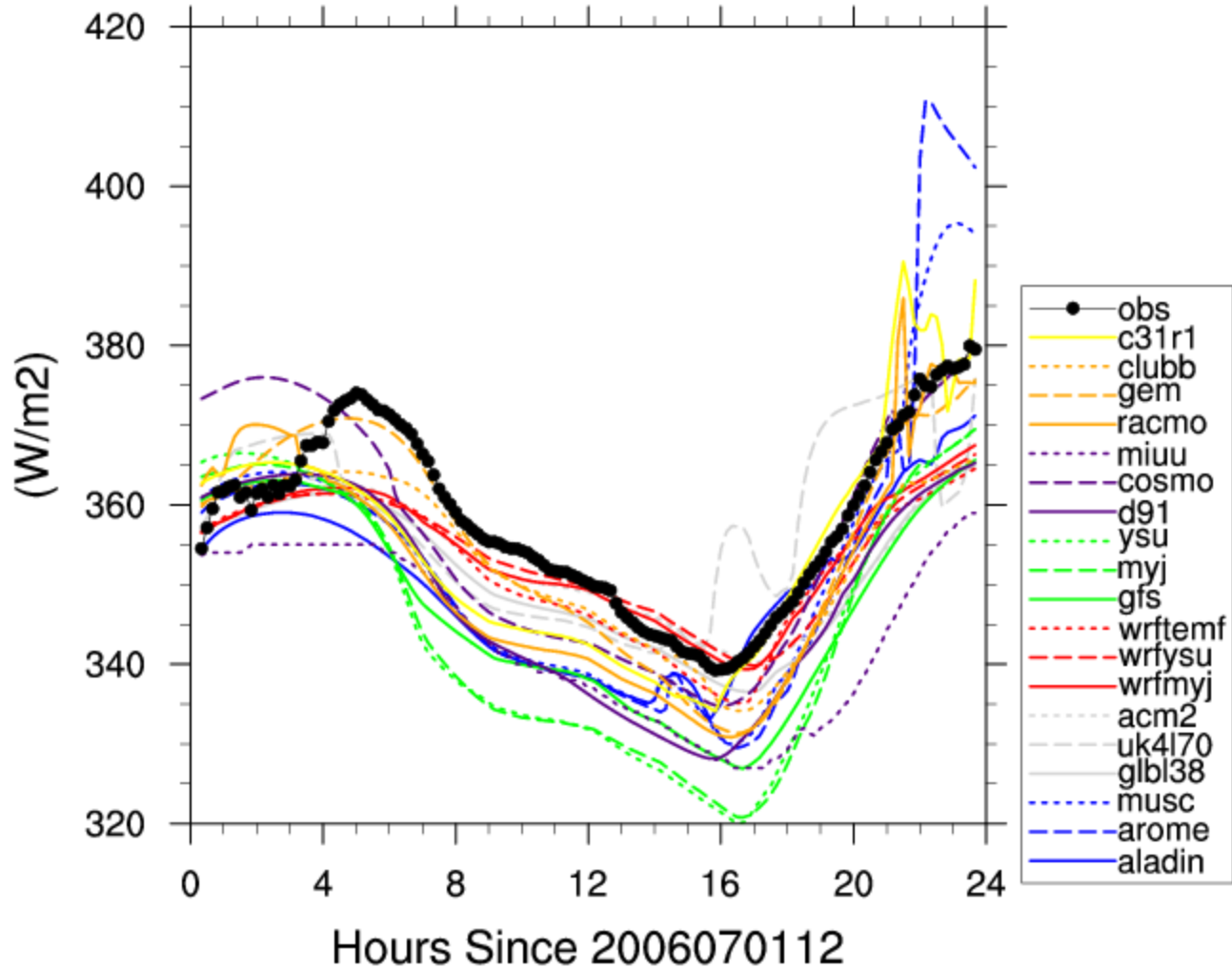
noon

midnight

noon

# Surface fluxes

Long wave downward radiation at surface

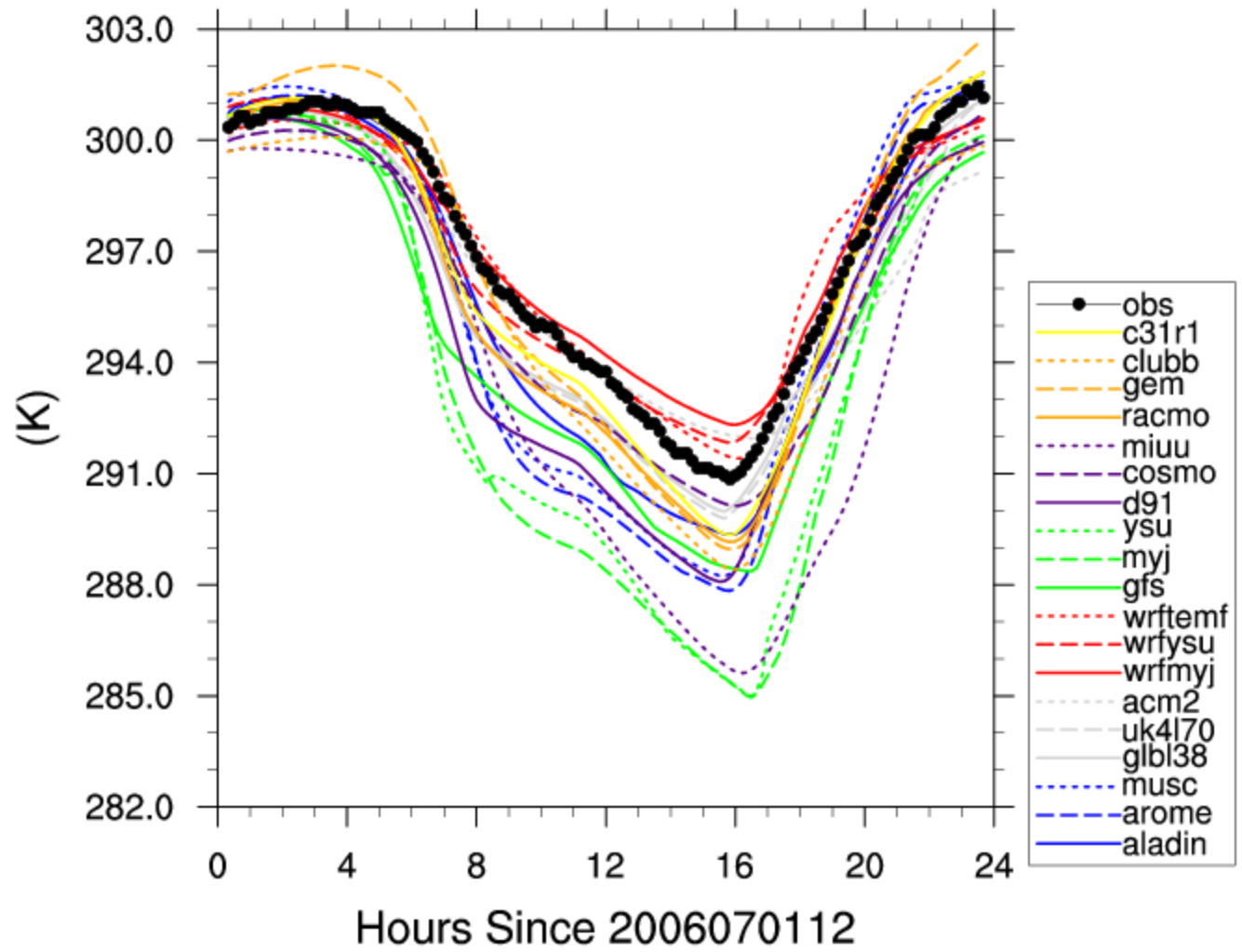


noon

midnight

noon

# Air temperature at 2 m

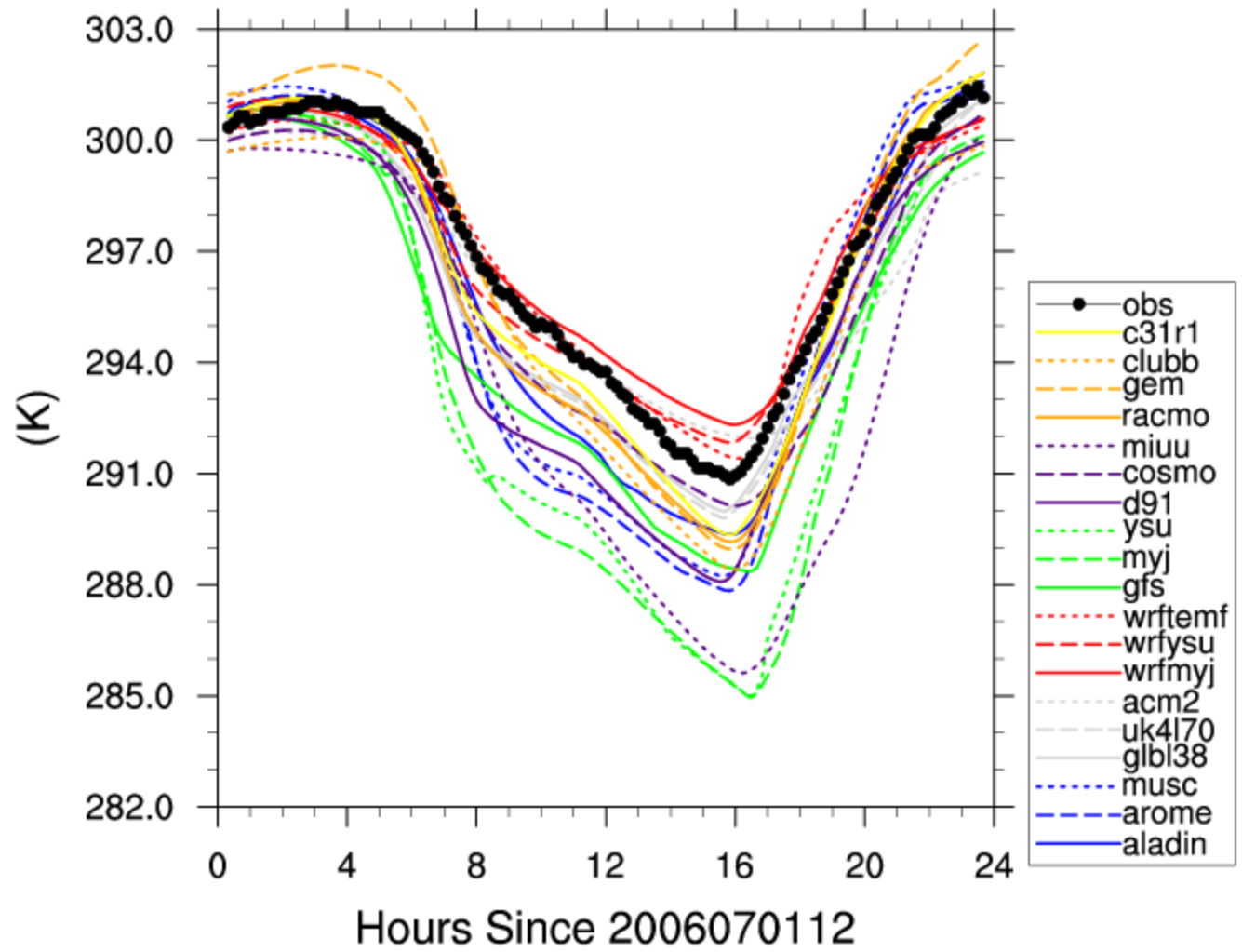


noon

midnight

noon

# Air temperature at 2 m



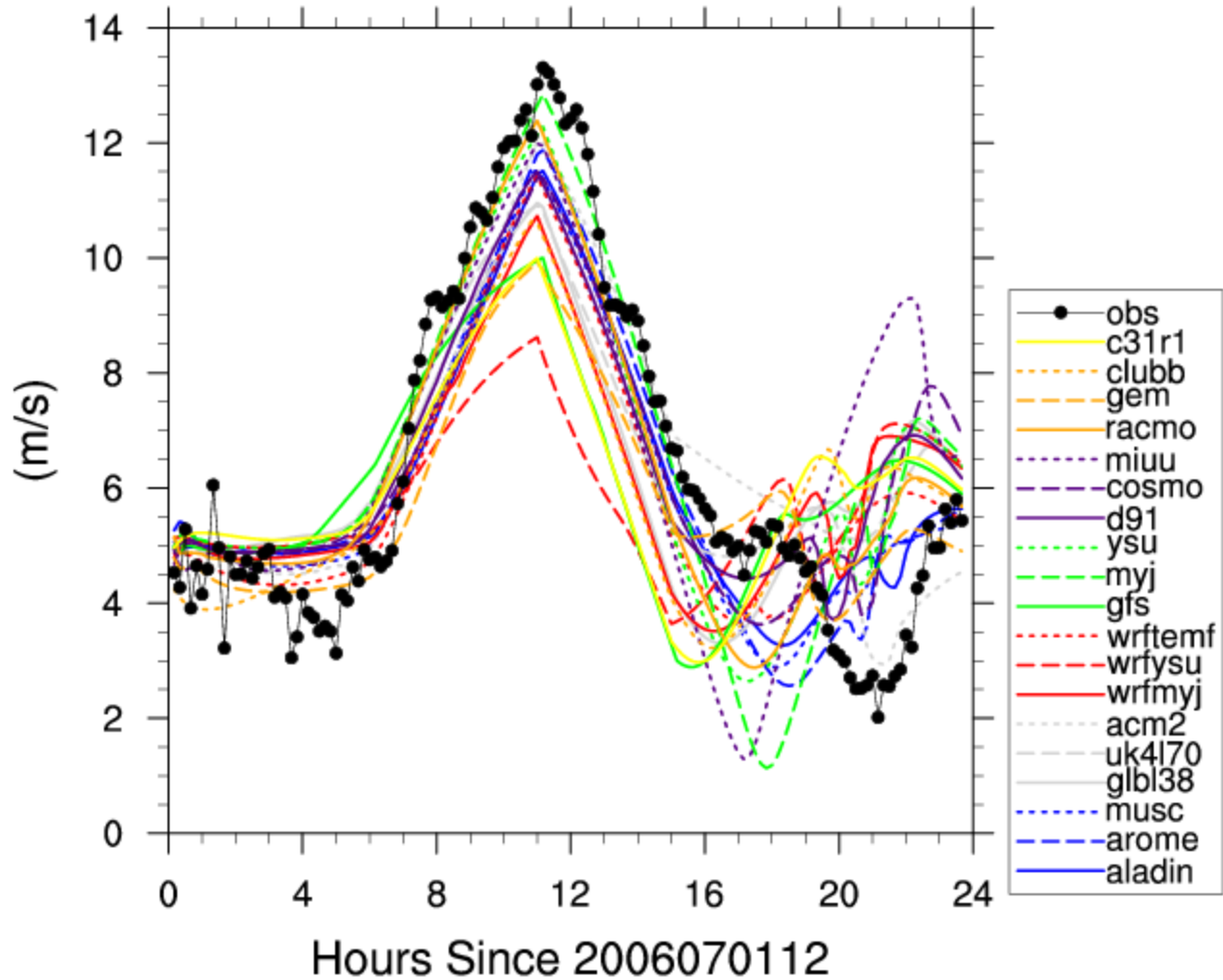
noon

midnight

noon

# Low level jet

Wind speed at 200m



noon

midnight

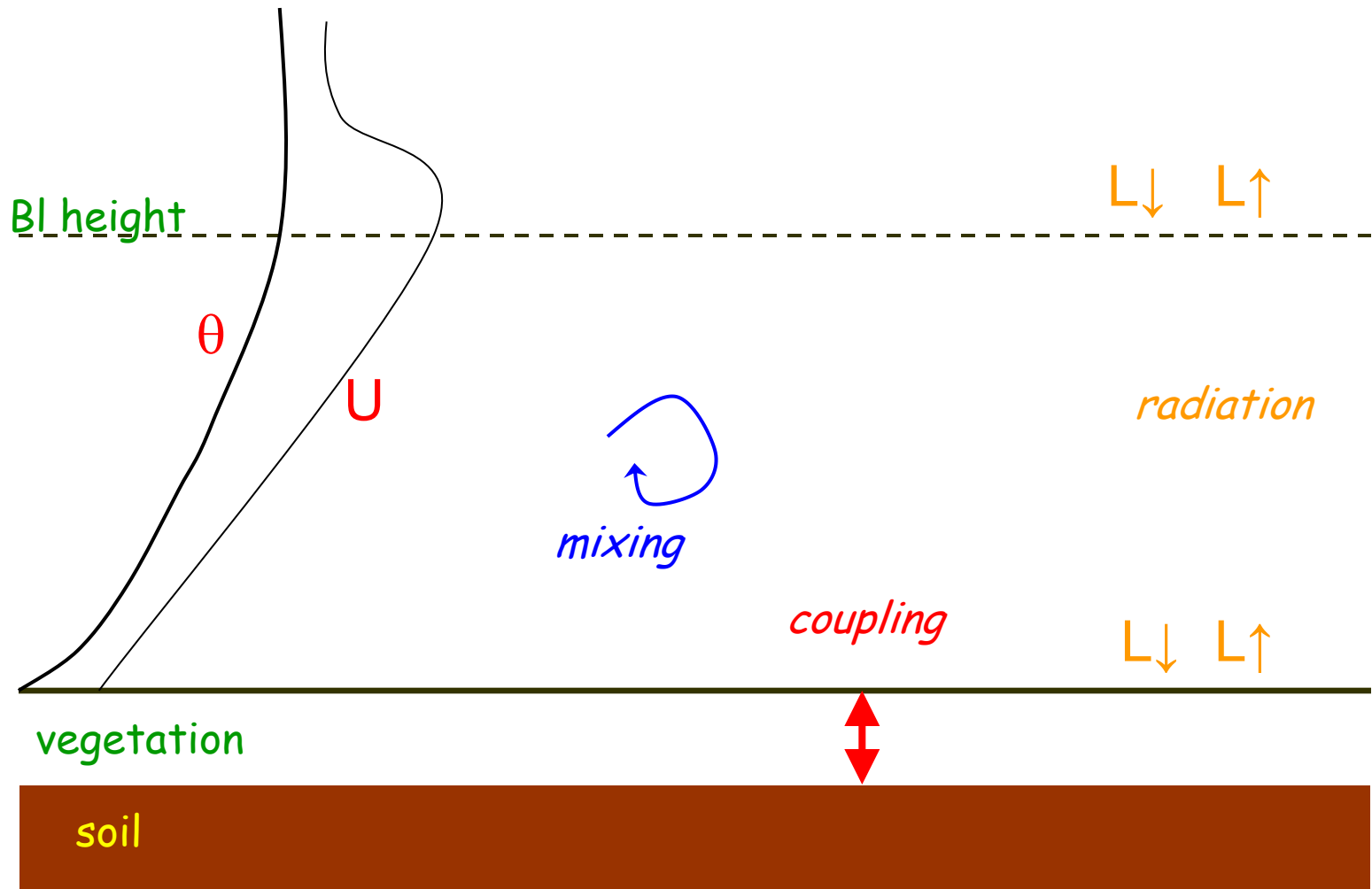
noon







# Dominant processes in stable boundary layer over land



# Sensitivity runs with RACMO-SCM (Bosveld et al, 2011, 2013)

## *mixing*

varying the TKE-I parameters that relates turbulent length scale to the properties of the flow

## *coupling:*

varying the thermal conductance between the skin layer and the soil

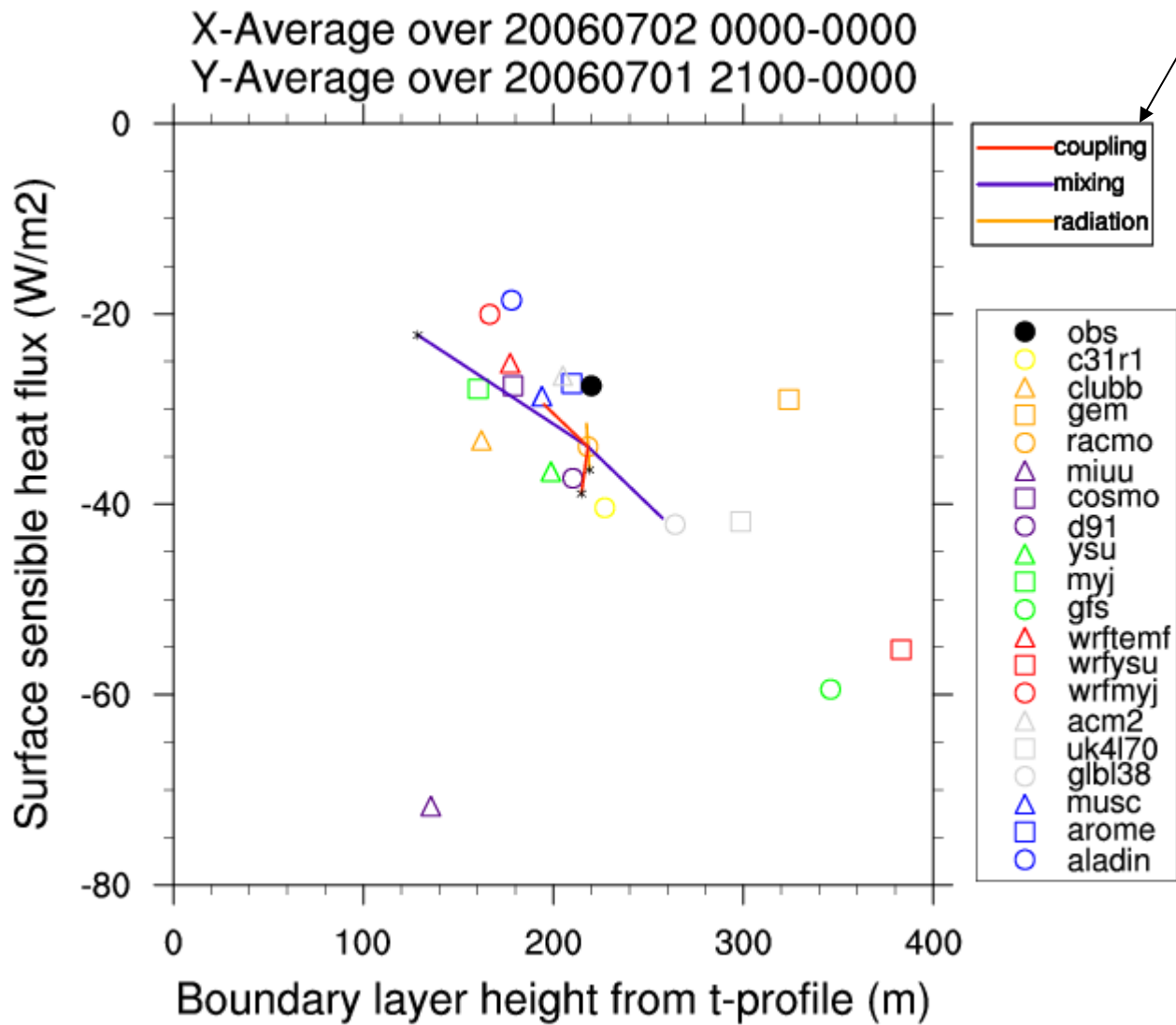
## *radiation*

varying specific humidity to affect long wave incoming radiation

( $L_{\downarrow} \pm 15 \text{ W/m}^2$ )



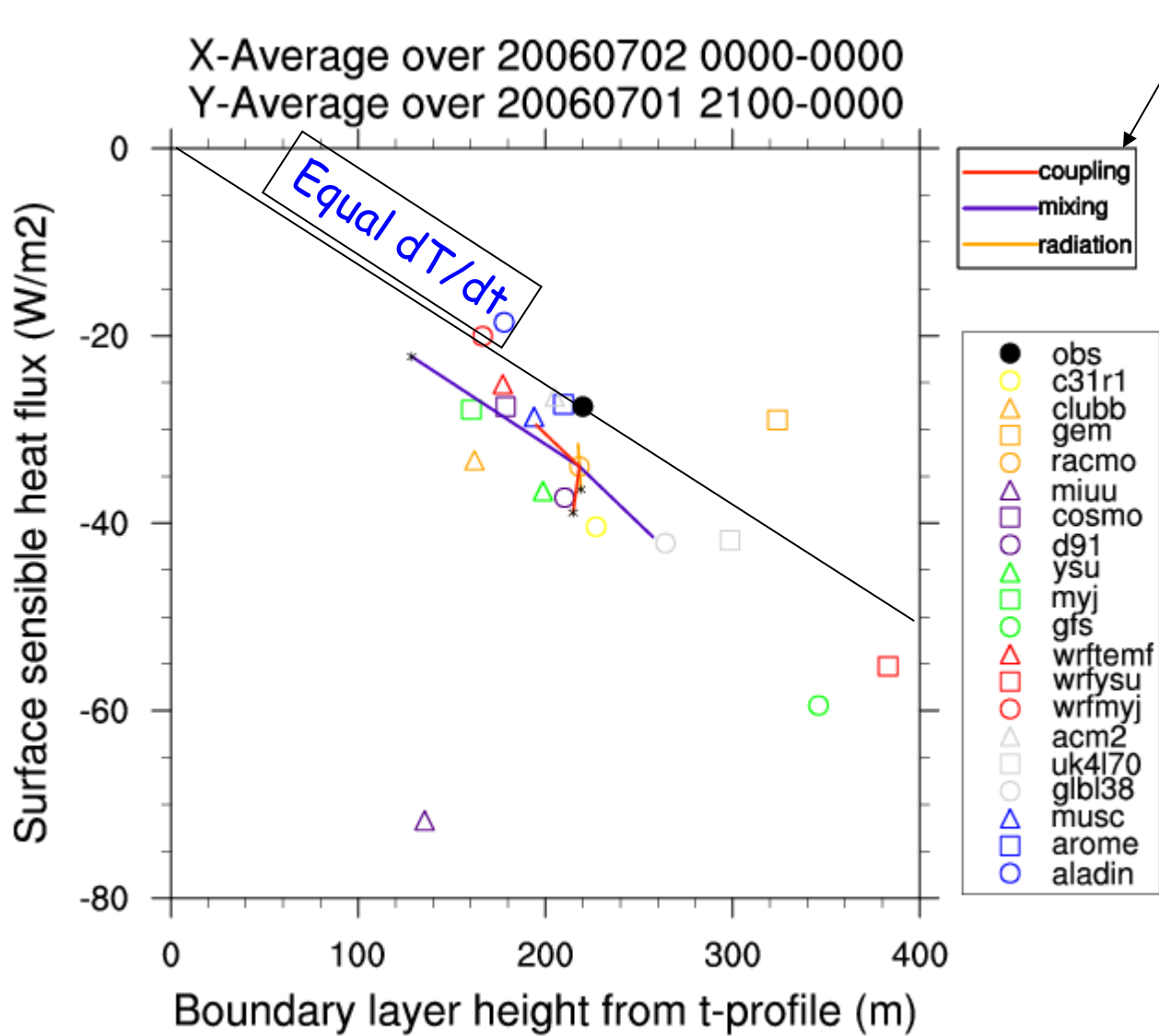
# Influence of mixing



Sensitivity runs with RACMO-SCM using various parameters and forcings



# Influence of mixing



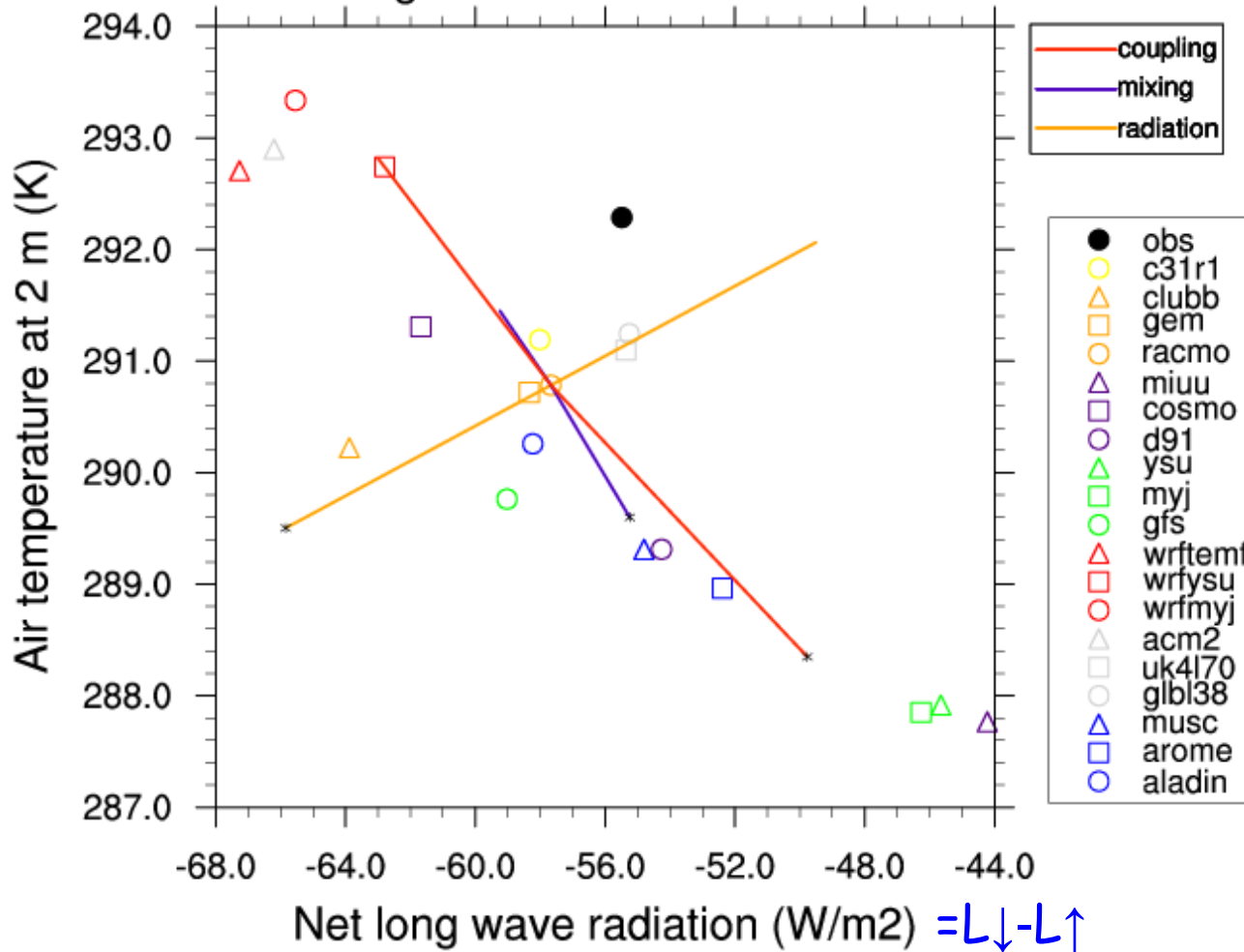
Sensitivity runs with RACMO-SCM using various parameters and forcings





# Influence of surface radiation

X-Average over 20060701 2100-0300  
 Y-Average over 20060702 0000-0300



Note:  
 $L\uparrow$  is strong  
 function of  
 surface  
 temperature

Warmer surface

Colder Surface



# *Diurnal cycles of temperature and wind – A challenge for weather and climate models!*

Significant variation in all aspects of the Stable Boundary layer are seen in models which can be related to relevant atmospheric and land surface processes

Sensitivity to details in mixing formulation,  
interaction with the land surface,  
the representation of radiation (divergence),  
et cetera



Overview of results and citations in  
Holtslag et al, 2013, BAMS (online)

## On going activities

Set up GABLS4 case focussing on Antarctic  
(by Eric Bazille, Timo Vihma and others)

Revisit GABLS2 and couple to land surface using long  
spin up for land surface schemes (DICE)  
(by Martin Best and Adrian Lock)

## GABLS basic publications

(plus many conference and invited presentations)

### GABLS1:

Special issue Feb 2006, Boundary Layer Meteorology (7 papers)  
Svensson and Holtslag, 2009, BLM (wind turning issue)

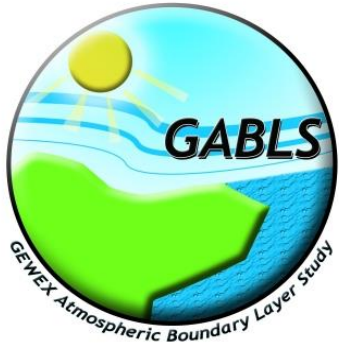
### GABLS2:

Steeneveld et al, 2006, JAS (SCM) and 2008, JAMC (Mesoscale study)  
Holtslag et al, 2007, BLM (Coupling to land surface)  
Kumar et al, 2010, JAMC (LES study)  
Svensson et al, 2011, BLM (SCM intercomparison)

### GABLS3:

Baas et al 2010, QJRMS (set up case and SCM tests)  
New special issue of BLM planned for 2014, including intercomparison papers by Bosveld et al (SCM), Basu et al (LES), Edwards et al (LES + Radiation scheme)....

GABLS overview paper in 2013 (Holtslag et al, BAMS, online)




*Thanks to all the participating scientists  
in GABLS, GLASS-LOCO and many others  
who gave feed back and shared ideas!*



GABLS workshop ECMWF, November 2011



A photograph of the World Forum building in The Hague, The Netherlands, at night. The building is a large, modern structure with a curved facade and many lit windows. The name "world forum" is visible on a sign below the main building. The building is reflected in a body of water in the foreground. A blue diagonal graphic element is overlaid on the left side of the image.

# 7<sup>th</sup> International Scientific Conference on the Global Energy and Water Cycle

World Forum  
The Hague, The Netherlands  
14-17 July 2014



# 7<sup>th</sup> International Scientific Conference on the Global Energy and Water Cycle



Conference format will be similar to the 2011 WCRP

Open Science Conference

- a. Plenary with speakers  
(including Land-Atmosphere Interaction Session)
- b. Poster sessions

Call for papers soon, see [www.gewex.org](http://www.gewex.org)

The Conference will be followed by Pan-GEWEX  
and Pan-CLIVAR Meetings

# Thank you!

