Stable Atmospheric Boundary Layers and Diurnal Cycles
Challenges for Weather and Climate Models

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

Meteorology and Air Quality Department
Progress in the Atmospheric Sciences: Connecting scales

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

\[
\frac{du}{dt} = -\frac{1}{\rho a \cos \phi} \frac{\partial p}{\partial \lambda} + f v + uv \frac{\tan \phi}{a} + F_x
\]

\[
\frac{dv}{dt} = -\frac{1}{\rho a \partial \phi} - fu - u^2 \frac{\tan \phi}{a} + F_y
\]

\[
\frac{dp}{dz} = -\rho g
\]

\[
\frac{\partial p}{\partial t} = -\nabla \cdot \rho \mathbf{v}
\]

\[
p = R \rho T
\]

\[
C_p \frac{d\Theta}{dt} = \frac{\Theta}{T} Q
\]

\(u, v, w, p, \rho, T\)

Sub-grid processes

Discretization
History of **day** and **night** time temperature errors
Monthly averages over Europe

- **Increased turbulent diffusion + soil moisture freezing**
- **New land surface scheme**
- **Reduced outer layer diffusion in stable situations**

**Forecast error of 2 m Temperature [deg C] for Europe**

**Standard deviation**

**Mean error**

---

ECMWF/GABLS workshop 7-10 November 2011 (4)
Diurnal cycle over land: Cabauw 1987 annual average

Averaged diurnal cycle of wind speed, Cabauw 1987

Wind speed (m/s)

T ime (UTC)

OBS 10 m
OBS 80 m
OBS 200 m

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)

From long “relaxation” integrations starting 1 Oct 1995
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
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

**GHCN and Average GCM Trend Differences (TMAX - TMIN)**
for Global Land Surface Temperatures

- GHCN Adjusted
- Average GCM

**Trend Difference (deg C per decade)**

- **1900-1978**
  - GHCN Adjusted: 0.04
  - Average GCM: 0.01

- **1900-1999**
  - GHCN Adjusted: 0.06
  - Average GCM: 0.02


- NCAR CCSM3.0
- GISS AOM
- NCAR PCM1
- CSIRO Mark 3.0
- INM-CM3.0
- MIROC3.2
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

<table>
<thead>
<tr>
<th>GABLS1</th>
<th>GABLS2</th>
<th>GABLS3</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td><strong>LES</strong> as reference</td>
<td>Data (CASES99)</td>
<td>Data (CABAUW)</td>
</tr>
<tr>
<td>Academic set up</td>
<td>Idealized forcings</td>
<td>Realistic forcings</td>
</tr>
</tbody>
</table>
| Prescribed $T_s$ | Prescribed $T_s$ | Full coupling (SCM)  
Prescribed $T_s$ (LES) |
| No Radiation | No Radiation | Radiation included |
| Turbulent mixing | Diurnal cycle | Low levet jet + transitions |

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

Cabauw tower (KNMI, NL)
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 (W/m²)

Momentum flux (N/m²)

Flux profiles 03-04 UTC

(Red dots: Cabauw Tower observations)

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

![Graph a) showing temporal evolution of Θ_40 (K) vs. Time (UTC).]

![Graph b) showing temporal evolution of U_40 (m s⁻¹) vs. Time (UTC).]
**GABLES3**

**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)

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

Hours Since 2006070112

noon  midnight  noon
Surface fluxes

Long wave downward radiation at surface

Hours Since 2006070112

noon  midnight  noon
Air temperature at 2 m

Hours Since 2006070112

noon midnight noon
Air temperature at 2 m

Hours Since 2006070112

noon midnight noon
Low level jet
Wind speed at 200m

noon          midnight          noon
Profile at midnight

wind speed 20060702 0
Dominant processes in stable boundary layer over land

- Mixing
- Coupling
- Radiation

Bl height

Vegetation

Soil
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

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
7th International Scientific Conference on the Global Energy and Water Cycle

World Forum
The Hague, The Netherlands
14-17 July 2014
7th 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

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