Land Surface Climate and the role of the Stable Boundary Layer

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Towards a better representation of the Atmospheric Boundary Layer in Weather and Climate models
Climate: Many factors

Changes in the Atmosphere: Composition, Circulation

Changes in the Hydrological Cycle

Volcanic Activity

Atmosphere

N₂, O₂, Ar,
H₂O, CO₂, CH₄, N₂O, O₃, etc.
Aerosols

Atmosphere-Biosphere Interaction

Soil-Biosphere Interaction

Land-Atmosphere Interaction

Precipitation Evaporation

Heat Exchange

Wind Stress

Atmosphere-Ice Interaction

Human Influences

Hydrosphere: Ocean

Cryosphere:
Sea Ice, Ice Sheets, Glaciers

Changes in the Ocean:
Circulation, Sea Level, Biogeochemistry

Changes in/on the Land Surface:
Orography, Land Use, Vegetation, Ecosystems

Ice-Ocean Coupling

Sea Ice

Terrestrial Radiation

Land Surface

Clouds
Why is the stable boundary layer (SBL) important?

- Surface temperature forecasting at night
- Fog forecasting
- Polar climate
- Land Climate (night and in winter)
- Dispersion studies
- Built up of high CO2 concentrations at night...
Mean model bias for the 2 meter temperature in present winter climate (30 years)

Courtesy, Geert Lenderink, KNMI

Also impact on diurnal cycle
Comparing ERA40 and Cabauw mean values over lowest 200 m clear nights, 1-6 May 1990 (Courtesy F. Bosveld, KNMI)

Wind components relative to 200 m wind vector

\[
\begin{align*}
\langle U \rangle & \text{ Forward wind component (m/s)} \\
\langle V \rangle & \text{ Cross wind component (m/s)} \\
\langle \theta \rangle - \theta(200 \text{ m}) & \text{ Potential Temperature (K)} \\
\langle q \rangle - q(200 \text{ m}) & \text{ Specific Humidity (g/kg)}
\end{align*}
\]
Sensitivity to SBL parameterization in Hadley Centre Climate Model, over Antarctic

Difference between new (2nd order closure) and current scheme (1st order closure) for 1.5m Temperature (K), JJA season, 5 year mean (King et al. 2001, QJRMS)
Mean model difference in 2 meter temperature for January 1996 using two different stability functions in ECMWF model (Courtesy A. Beljaars)
Stable boundary layer mixing

\[
\frac{\partial \phi}{\partial z} = -K \frac{\partial \phi}{\partial z}
\]

Flux-gradient Relationship

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

Richardson number

\[
Ri = \frac{g}{\theta} \frac{\partial \theta}{\partial z} \left| \frac{\partial U}{\partial z} \right|^{-2}
\]

Specification needed for length scale \( l \) and \( F(Ri) \)
Stable boundary layer mixing

Diffusion coefficients by updated ‘Monin-Obukhov (MO)’ versus alternatives (LTG)

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

MO based on Cabauw data (Beljaars and Holtslag, 1991)

LTG ‘s used in ECMWF model (Louis et al; Beljaars et al)
State of the Art

Great Sensitivity to Stable ABL formulation!

Operational models typically like enhanced mixing in stable cases

What can we learn from fine-scale modeling (LES) and observations?

How do models compare?

How important is vertical resolution?
Strong recommendation of participants at GABLS meeting in Wageningen (about 80 attendees):

Start with simple CASE for Stable Boundary Layer!
**GABLS first inter comparison case**
Simple shear driven case *(after Kosovic and Curry, 2000)*

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

Geostrophic wind 8 m/s, latitude 73N
An intercomparison of large-eddy simulations of the stable boundary layer

Coordinated by
Bob Beare, Malcolm MacVean, Anne McCabe
Met Office, UK

- Domain 400m x 400m x 400m
- Resolutions: 12.5m, 6.25m, 3.125m, 2m, 1m

10 results sets, 17 investigators

See: http://www.gabls.org
Large Eddy Simulation (LES) of stable boundary layers

Use very high resolution to solve the turbulent flow on numerical grid

Image of the 0.2 m/s vertical velocity iso-surface
LES Participants

• Met Office, UK (Beare, MacVean, McCabe)
• CSU, USA (Khairoutdinov)
• IMUK, Germany (Raasch and Noh)
• LLNL, USA (Lundquist and Kosovic)*
• NERSC, Norway (Esau)
• WVU, USA (Lewellen)
• NCAR, USA (Sullivan)
• UIB, Spain (Cortes and Cuxart)
• CORA, USA (Lund and Paulos)
• Wageningen University, NL (Moene and Holtslag)

*Work performed under auspices of US Dept of Energy by Univ. of California, Lawrence Livermore National lab., Contract W-7405-Eng-48
Mean potential temperature

Resolution 2 m; Time 9 hours

Resolution 6.25 m; Time 9 hours
Mean heat fluxes

Mean wind

Resolution 2 m; Time 9 hours

Resolution 6.25 m; Time 9 hours
Mean stress
Crosses are based on Cabauw observations (Nieuwstadt 1984), with the standard deviation of the means shown by the shaded regions.
Momentum stability functions

LES is in equilibrium, flat terrain, ‘Sharp tail’ corresponds to observations!
Summary LES results

- Significant spread in results, but convergence at high resolution
- Sensitivity to sub-grid model
- Overall agreement with observations is fair!

*Effective stability functions in agreement with observations and sharper than those typically used in Operational Models!*
Intercomparison of Single-Column Models

Coordinated by
Joan Cuxart i Rodamilans, Maria Jiménez, Laura Conangla
Universitat de les Illes Balears (Mallorca, SP)
http://turbulencia.uib.es/gabls/

At present, results of 25 models
(many of them with sensitivity tests)
8 Operational, 17 Research models (including
10 with ‘higher order’ turbulence)

Various SBL parameterizations and resolutions:
Focus on operational models
The participants with operational models

- ECMWF: (OP, 1st)
  - Anton Beljaars
- NCEP: (OP, 1st)
  - Frank Freedman
* Canadian MS: Environment Canada (OP, 1.5)
  - Jocelyn Mailhot
- KNMI-RACMO: Regional Atmospheric Climate model (OP, 1.5)
  - Geert Lenderink
* French Meso-NH and the Spanish HIRLAM (OP, 1.5),
  - Laura Conangla and Joan Cuxart
The participants with research models

*GSPZ: Group Galperin, Sukoriansky, Perov and Zilitinkevich (R, 1-5 k-e)

*WUR: Wageningen Univ. using Duynkerke's (1991) model (R, 1st)
   Gert-Jan Steeneveld and Bert Holtslag

*WVU: West Virginia Univ (R, 1.5); David Lewellen

*York Univ, Canada: (R, 1.5); Wensong Weng

*University of Stockholm-Group 1 (R, 1.5) Gunilla Svensson

*University of Stockholm-Group 2 (R, 1.5 +EST)
   Thorsten Mauritsen, S. Zilitinkevich, L.Enger, B. Grisogono, G. Svensson

*Univ. Cat. Louvain, Belgium (R, 1.5) Guy Schayes

*Sandia Laboratories, California (R, ODT) Scott Wunsch, Alan Kerstein
*NASA (R, 1.5) Kuan-Man Xu, Anning Cheng
Resolution (most) operational models is set to 6.25 m!
Test with one model (UIB-UPC) changing the mixing length
Summary 1D models

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

Length scale and stability function matter, atmospheric resolution not so much!

Comparison with observations and with scaling results needed

Coupling to surface energy budget will be further explored (Steeneveld, Holtslag)
Open questions

How do models compare with the observations in more complex situations?

Which role for Atmosphere - Land Surface coupling, heterogeneity aspects?

How to classify the available data?

Do we overlook an atmospheric process?
Future work

New *simple* cases for LES and 1D models

Further exploration of data!

More studies with 1D and Mesoscale models inspired by observations, e.g. select cases for CASES-99, Cabauw, Lindenberg (coupling to land), Halley (Antarctica), Sweden (strong inversions), SABLES98 (elevated turbulence), et cetera

Inclusion of full diurnal cycle
Activities 2004

GABLS session at AMS/BLT16,
Portland, Maine, August 2004

Special GABLS issue in
Boundary-Layer Meteorology