Presentations from “The Bolund Experiment: Workshop” 3-4th December 2009

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Presentations from “The Bolund Experiment: Workshop” 3-4th December 2009

Edited by Andreas Bechmann
Risø-R-1745(EN)
August 2010
This report contains copies of the presentations given at “The Bolund Experiment: Workshop” held on the 3-4th December 2009 at Risø DTU. The agenda of the two days and a participant list is given before the presentations.

The workshop was held as part of the EFP project “Metoder til kortlægning af vindforholdene i komplekst terræn”.
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1 Introduction

The wind industry is increasingly relying on a large number of different micro-scale models for resource assessment of sites in complex terrain. There is, however, no consensus from the wind energy community on a standardized methodology for resource assessment modeling. The difficulties in providing guidelines are twofold: The experimental data available for validating the flow models is very limited and no systematic comparison of different flow models exist. With the Bolund Experiment both of these difficulties are approached.

The Bolund experiment is a measuring campaign from a complex terrain performed in 2007 and 2008 where high frequency data from 35 anemometers provides a unique database designed to validate micro-scale flow models [1]. Since no systematic comparison of micro-scale models existed it was decided to challenge micro-scale modelers to simulate the wind over Bolund and compare the results systematically. Since the Bolund measurements had not been published the comparison could be made blindly, i.e. the participants would not have prior knowledge of the measurement results. To broaden the types of models participating, modelers were invited worldwide from research institutes, universities and industry. More than 40 groups participated in the blind comparison with well over 50 model predictions and the blind comparison therefore gives an overview of the accuracy of micro-scale models anno 2010.

On the 3-4 December 2009, 80 specialists in modeling of wind over complex terrain meet at a Risø DTU workshop where the model predictions and the Bolund measurements were revealed. During the workshop, interesting presentations were given about different flow modeling approaches. This report contains copies of the presentations given at the workshop.

1.1 Agenda

Below the agenda for the two day workshop is given. The topics of the first day were related to the Bolund experiment and blind comparison while the second day was about different micro-scale modelling approaches.

**Program**

<table>
<thead>
<tr>
<th>Thursday December 3</th>
<th>Friday December 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>9:00 Registration / Coffee</td>
<td>9:00 Resume / Coffee</td>
</tr>
<tr>
<td>9:30 Welcome</td>
<td>9:15 LES Simulation of Terrain</td>
</tr>
<tr>
<td></td>
<td>Vijayant Kumar, Macquarie Cpttal</td>
</tr>
<tr>
<td></td>
<td>Marc Parlange &amp; Chad Higgins, EPFL</td>
</tr>
<tr>
<td>9:45 The Askervein Experiment</td>
<td>10:00 Coffee</td>
</tr>
<tr>
<td>Peter A. Taylor, York University</td>
<td>10:10 Wind Tunnel Modeling of Bolund</td>
</tr>
<tr>
<td></td>
<td>Brad C. Cochran, CPP Wind</td>
</tr>
<tr>
<td>10:30 Coffee</td>
<td>10:50 RANS Simulation of Bolund</td>
</tr>
<tr>
<td></td>
<td>Niels Sorensen, Risø DTU</td>
</tr>
<tr>
<td>10:40 The Bolund Experiment</td>
<td>11:30 Poster Introduction</td>
</tr>
<tr>
<td>J. Berg, J. Mann &amp; H.E. Jørgensen, Risø DTU</td>
<td>12:00 Lunch + Poster / Coffee</td>
</tr>
<tr>
<td>12:10 Group Photo</td>
<td>14:00 Panel Discussion: Flow modeling</td>
</tr>
<tr>
<td>12:30 Lunch</td>
<td>Peter Taylor, Brad Cochran, Vijayant Kumar</td>
</tr>
<tr>
<td></td>
<td>Niels Sorensen, Jakob Mann</td>
</tr>
<tr>
<td>13:30 Blind Comparison Results</td>
<td>15:45 Close</td>
</tr>
<tr>
<td>Andreas Bechmann, Risø DTU</td>
<td></td>
</tr>
<tr>
<td>14:45 Coffee</td>
<td></td>
</tr>
<tr>
<td>16:00 Questions to Bolund Team</td>
<td></td>
</tr>
<tr>
<td>17:00 Bus to Scandic Hotel &amp; Dinner</td>
<td></td>
</tr>
<tr>
<td>19:00 Conference Dinner</td>
<td></td>
</tr>
<tr>
<td><em>Sponsored by Vestas Technology R&amp;D</em></td>
<td></td>
</tr>
</tbody>
</table>
1.2 Participants

About 80 participants joined the workshop to discuss the results of the blind comparison. We want to thank you all for your positive and constructive attitudes and for making it a memorable event. Below, the workshop participants are listed. Many of the workshop participants also participated in the blind comparison but it has been chosen to keep the participants of the comparison anonymous. We would like to give special thanks for some very interesting presentation to the three invited speakers:

Peter A. Taylor (York University, Zephyr North Canada)
Vijayant Kumar (Macquarie Holdings)
Brad C. Cochran (CPP, inc.)

Participant list:

- Christiane Montavon
- Steve Evans
- Dennis Nagy
- Bibiana Garcia
- Javier Sanz Rodrigo
- John Prospathopoulos
- Brad Cochran
- Rémi Gando
- Jonathon Sumner
- Per Nielsen
- Morten Lybeck Thagesen
- Hanne Thomassen
- Mano Benso
- Carlos Hernández Medina
- Moreira Raquel
- Anja Geiger
- Paolo Muscioni
- Pascale Podstransky
- Jose Laginha Palma
- Thomas Hahn
- Steffen Wussow
- Sharad Tripathi
- Lars Landberg
- Joel Manning
- Richard Whiting
- Per Osterdahl
- Sven Perzon
- Michael Schatzmann
- Espen Akervik
- Ove Undheim
- Vijayant Kumar
- Roshan Oberoi
- Céline Bazault
- Stephane Popinet
- Ferran Palau
- Keld Olsen
- Gerd Habenicht
- Andreas Bechmann
- Jacob Berg
- Jesper Grønnegaard Pedersen
- Per Hansen
- Poul Hummelshøj
- Niels Otto Jensen
- Hans E. Jørgensen

Christiane Montavon
Steve Evans
Dennis Nagy
Bibiana Garcia
Javier Sanz Rodrigo
John Prospathopoulos
Brad Cochran
Rémi Gando
Jonathon Sumner
Per Nielsen
Morten Lybeck Thagesen
Hanne Thomassen
Mano Benso
Carlos Hernández Medina
Moreira Raquel
Anja Geiger
Paolo Muscioni
Pascale Podstransky
Jose Laginha Palma
Thomas Hahn
Steffen Wussow
Sharad Tripathi
Lars Landberg
Joel Manning
Richard Whiting
Per Osterdahl
Sven Perzon
Michael Schatzmann
Espen Akervik
Ove Undheim
Vijayant Kumar
Roshan Oberoi
Céline Bazault
Stephane Popinet
Ferran Palau
Keld Olsen
Gerd Habenicht
Andreas Bechmann
Jacob Berg
Jesper Grønnegaard Pedersen
Per Hansen
Poul Hummelshøj
Niels Otto Jensen
Hans E. Jørgensen

ANSYS UK Ltd
CD-adapco
CD-adapco
CENER
CENER
Centre for Renewable Energy Sources and Saving
CPP
DONG Energy
Ecole de technologie supérieure
EMD International A/S
EMD International A/S
Energifylserne
EREDA
EREDA
EREDA
ETHZ, GWH
ETHZ, GWH
ETHZ, GWH
FEUP, CEsA
Fluid & Energy Engineering GmbH & Co. KG
Fluid & Energy Engineering GmbH & Co. KG
FLUIDYN
Garrad Hassan and Partners Ltd
Garrad Hassan and Partners Ltd
Garrad Hassan and Partners Ltd
Go Virtual Nordic AB
Go Virtual Nordic AB
Hamburg University
Kjeller Vindteknikk AS
Kjeller Vindteknikk AS
MeteoDyn
National Institute of Water and Atmospheric research (NIWA)
Normawind
Råd. Ing. Keld E. Olsen
RES
Risø DTU
Risø DTU
Risø DTU
Risø DTU
Risø DTU
Risø DTU
Risø DTU
Risø DTU

“Welcome” - by Andreas Bechmann

Welcome

Andreas Bechmann, Jacob Berg, Mike Courtney, Hans E. Jørgensen, Jakob Mann, Pierre-Elouan Rethore, Niels N. Sørensen and many others ...

Risø DTU
National Laboratory for Sustainable Energy

This day, two years ago ...
This day, two years ago ...
This day, two years ago ...
This day, two years ago ...
Thank You!

- Energistyrelsen (Danish Energy Agency)
- Vestas Technology R&D
- Thank you modelers!
  Preparation time: 652 hours
  Comp. time: 587 days
Submitted Results

52 model results!

Model types:
- 3: Experimental method
- 3: No answer
- 9: Linearized flow model
- 0: Mesoscale model
- 37: Non-linear CFD model

\{ 
- 1: Wind tunnel
- 1: Flow channel
- 5: LES / hybrid RANS-LES
- 7: RANS 1 eqn. (k-I, Spalart-Allmaras)
- 25: RANS 2 eqn. (k-epsilon, k-omega) 
\}
The Askervein Experiment (1982, 1983)

Peter A. Taylor
Centre for Research in Earth and Space Science, York University, Toronto and
2Zephyr North Canada, Burlington, Ontario

Originated from IEA meetings about 1980
Discussions with Unsal Hassan (then with CERL),
Paul Mason (UKMO) and others.
BASIC 1982, 19083 reports at:
http://www.yorku.ca/pat/research/Askervein/index.html

Report: MSRB-83-8
ASKERVEIN '82: Report on the September/October 1982 Experiment to Study Boundary-Layer Flow over Askervein, South Ulst
by P.A. Taylor and H.W. Teunissen

Research Report: MSRB-84-6
by P.A. Taylor and H.W. Teunissen

Ordance Survey Map that we had in 1962

Google Earth 2009. HT
57°11'16.63"N, 7°22'45.07"W
I should have a better copy somewhere!!!
Instrumentation

- Lots of cup anemometers, mostly on about fifty 10-m posts – Gill, Casella, Vector, Friedrichs
- Gill UVW propeller anemometers – signal conditioning problems. RM Young windmonitor
- TALA kites, single (Peter Taylor et al) and multiple (Nick Cook)
- Sonics (Risø + AES, Hans Teunissen) Radiosondes
- 50-m towers at HT and RS, 30-m tower near upwind base of hill.

- Data acquisition! Computers and lots of magnetic tape in hilltop caravan and Reference station shed. Sea Data tape loggers. Pulse counters, electronic and mechanical (Casella anemometers)
Boundary-Layer Meteorology: Search, Askerven – 31 papers

BOUNDARY-LAYER FLOW OVER TOPOGRAPHY: IMPACTS OF THE ASKERVEN STUDY

JOHN L. WALMSLEY
Atmospheric Environment Service, Downsview, Ontario M3H 5T4 Canada
and
PETER A. TAYLOR
Department of Earth and Atmospheric Science, York University, North York, Ontario M3J IP3
Canada
(Received in final form 20 October, 1995)

Abstract. One of the objectives of the Askerven Hill Project was to obtain a comprehensive and accurate dataset for verification of models of flow and turbulence over low hills. In the present paper, a retrospective of the 1982 and 1983 Askerven experiments is presented. The field study is described in brief and is related to similar studies conducted in the early 1980s. Data limitations are discussed and applications of numerical and wind-tunnel models to Askerven are outlined. Problems associated with model simulations are noted and model results are compared with the field measurements.

27. Article The Askerven Hill project: Overview and background data P. A. Taylor and H. W. Teunissen
The Askerven Hill project was a collaborative study of boundary-layer flow over low... Volume 39, Numbers 1-2 / April, 1987 PDF (4.8 KB)

This is one of a series of papers on the Askerven Hill Project. It presents results on the variations in mean wind speed... Volume 43, Number 3 / May, 1988 PDF (1.9 MB)

This is one of a series of papers on the Askerven Hill Project. It presents results from the Askerven 1982 and 1983 experiments... Volume 43, Numbers 1-2 / April, 1988 PDF (1.6 MB)
Bolund, \( \frac{L}{z_0} = 0.73 - 3.7 \times 10^{-2} \), \( h/L = 1.0 - 0.2 \); \( h = 10.9 \) m. \( L \) was not well defined – not the simple hill we had looked for in 1980s. Note that \( L \) is upward distance to point where \( z_* = h/2 \).

Run TU-03B, \( \Phi = 210 \), October 1983

<table>
<thead>
<tr>
<th>Date</th>
<th>Run number</th>
<th>Time (BST)</th>
<th>Duration (hr)</th>
<th>Mean wind at RS (m/s)</th>
<th>RS profile data</th>
<th>Ri*</th>
<th>( \Delta z )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mon03</td>
<td>TU03-A</td>
<td>1200–1300</td>
<td>1.0</td>
<td>210/9.8</td>
<td>0.63</td>
<td>0.022</td>
<td>-0.0008</td>
</tr>
<tr>
<td></td>
<td>-B</td>
<td>1400–1700</td>
<td>3.0</td>
<td>210/8.9</td>
<td>0.57</td>
<td>0.020</td>
<td>-0.0074</td>
</tr>
</tbody>
</table>
Raw Data – Mean Flow

| Table 3.1 | Integrated Mean Flow (m³/s) from Surface Data – and Structural
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wind No.</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
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<tr>
<td></td>
<td>11</td>
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<tr>
<td></td>
<td>12</td>
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</tbody>
</table>

Askervein '83, Raw Data – Taia Kites and Turbulence Runs

<table>
<thead>
<tr>
<th>Table 3.2</th>
<th>Taia Kite No.</th>
<th>Time (h)</th>
<th>Mean Flow (m³/s)</th>
<th>Std. Dev. (m³/s)</th>
<th>Mean Flow (m³/s)</th>
<th>Std. Dev. (m³/s)</th>
</tr>
</thead>
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<tr>
<td></td>
<td>1</td>
<td>1.1</td>
<td>200</td>
<td>3.0</td>
<td>0.200</td>
<td>0.300</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.2</td>
<td>150</td>
<td>2.0</td>
<td>0.250</td>
<td>0.250</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.3</td>
<td>200</td>
<td>2.0</td>
<td>0.270</td>
<td>0.270</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.4</td>
<td>150</td>
<td>1.0</td>
<td>0.300</td>
<td>0.300</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1.5</td>
<td>200</td>
<td>1.0</td>
<td>0.300</td>
<td>0.300</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1.6</td>
<td>150</td>
<td>1.0</td>
<td>0.300</td>
<td>0.300</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>1.7</td>
<td>200</td>
<td>1.0</td>
<td>0.300</td>
<td>0.300</td>
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<td></td>
<td>8</td>
<td>1.8</td>
<td>150</td>
<td>1.0</td>
<td>0.300</td>
<td>0.300</td>
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<tr>
<td></td>
<td>9</td>
<td>1.9</td>
<td>200</td>
<td>1.0</td>
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<td></td>
<td>10</td>
<td>2.0</td>
<td>150</td>
<td>1.0</td>
<td>0.300</td>
<td>0.300</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>2.1</td>
<td>200</td>
<td>1.0</td>
<td>0.300</td>
<td>0.300</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>2.2</td>
<td>150</td>
<td>1.0</td>
<td>0.300</td>
<td>0.300</td>
</tr>
</tbody>
</table>
Fig. 6a. Sample plots of normalized wind speed at $\Delta z = 10$ m along A and B lines, Arrested Hill (a) A line; (b) B line. X mean of 30 min values, error bars denote one standard deviation; ( ) questionable data; --- MS3DHJ /3 model results.

Fig. 10. Normalized wind speed at $\Delta z = 10$ m along AA line for selected wind directions and comparisons with MS3DHJ /3 model results. Data are based on averages for the direction groups listed in Table 7b excluding runs with $|U| > 0.915$. Upstream wind directions: (a) 135°; (b) 180°; (c) 210°; (d) 265°. X mean of 10 min values, error bars denote one standard deviation; --- MS3DHJ /3 model results.

MS3DHJ does well on upstream side of the hill but not in lee of the hill when intermittent separation occurs.
Fig. 2. Normalized wind speeds at HT as a function of $\phi$, the wind direction at RS: —— guidelines estimate, $\Delta z = 10\ m$; —— guidelines estimate, $\Delta z = 3\ m$; + Askervin '82 runs, $\Delta z = 10\ m$; x Askervin '83 runs, $\Delta z = 10\ m$; O Askervin '83 runs, $\Delta z = 3\ m$.

Fig. 4. L, A, and B as functions of direction: —— HT; —— CP.
Sample hilltop profiles, with kite and tower data

\[ \phi = 165^\circ \]

\[ \phi = 180 \]

HT Profile contours

Fig. 7. Contour plot of fractional speed-up ratio, \( \Delta S \), at HT as a function of height, \( \Delta z \), and RS wind direction, \( \phi \). Based on data from 1982 and 1983 experiments. The dashed portion of the 0.2 contour indicates an area with limited data. The 1.3 contour is dashed to indicate a different contour interval.
Fig. 7. Contour plot of normalized wind speed at $\Delta z = 10$ m along A line for different wind directions, Askervein '82. Topographic cross-section also shown. Runs 1.22a (low wind speed) and 2.29a (direction change during the run) have been excluded.

Fig. 12. Contour plots of normalized wind speed data at $\Delta z = 10$ m along AA line for different wind directions, Askervein '83. Data based on averages for the directional groups.
Sample turbulence statistics, RS + upwind hill foot

Fig 4a.

Fig 4. Profiles of wind speed and integral turbulence statistics at RS and ASW60. (a) Run TU01-B, $\phi = 180^\circ$. (b) Run TU03 B, $\phi = 210^\circ$. RS data: O Cup anemometers; + Sonic anemometers; x Tilted Gill UVW anemometers; □ Vertical Gill UVW (10 m). ASW60 data: ■ Vertical Gill UVW.

$\phi = 210^\circ$, note blocking at ASW 60

= ASW 60
Hilltop (HT) turbulence

Flow from 210 degrees, normal to ridge. $\sigma$ is based on cup anemometer variance and 3-opt Gill at 10m.

The main limitation of the Askervein dataset at the time of writing is the lack of more extensive published turbulence data for hilltop locations. Work is presently in hand at Risø to rectify this limitation. It would be interesting to run a third experiment at the site to obtain additional turbulence data, and perhaps to add surface pressure measurements.

From WT 95

---

Hilltop (HT) turbulence

Flow from 130 degrees, approximately parallel to ridge. $\sigma$ is based on cup anemometer variance and 3-opt Gill at 10m.
Inner Layer Depths

The formulae to be considered (JH, JEN and CL, respectively) are:

\[ (\ell / L) \ln (\ell / \alpha) = 2 \alpha, \]
\[ (\ell / L) \ln^2 (\ell / \alpha) = 2 \alpha^2, \]
\[ (\ell / L) \ln (\ell / \alpha) = \text{constant}. \]

Fig. 5. Estimates and observations of inner-layer depth as functions of wind direction. Asterisks signify estimated (EST) and observed heights at 1200 m, *O* observed height at which \( \alpha_{\text{obs}} = 2 \). -- , -- Jackson–Hard estimate (JH, equation (14)); --, --, -- Jennifer estimate (JEN, equation (15)); -- Longshore estimate (CL).}

The roughness length anomaly

Table 3.7: Profile-derived \( z_0 \) and \( u_* \) values as CP and BS10 during selected NF runs, Oct. 7–10, 1992.}

<table>
<thead>
<tr>
<th>Run</th>
<th>( z_0 ) (m)</th>
<th>( u_* ) (m/s)</th>
<th>( z_{CP} ) (m)</th>
<th>( u_{CP} ) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MF01-A</td>
<td>0.0003</td>
<td>0.43</td>
<td>0.0011</td>
<td>0.55</td>
</tr>
<tr>
<td>MF01-B</td>
<td>-</td>
<td>-</td>
<td>0.0013</td>
<td>0.56</td>
</tr>
<tr>
<td>MF02</td>
<td>0.0012</td>
<td>0.64</td>
<td>0.0026</td>
<td>0.58</td>
</tr>
<tr>
<td>MF03</td>
<td>0.0007</td>
<td>0.56</td>
<td>0.0013</td>
<td>0.40</td>
</tr>
<tr>
<td>MF10-A</td>
<td>0.0006</td>
<td>0.56</td>
<td>0.0017</td>
<td>0.42</td>
</tr>
<tr>
<td>MF10-B</td>
<td>0.0007</td>
<td>0.53</td>
<td>0.0013</td>
<td>0.56</td>
</tr>
</tbody>
</table>

Based on winds measured at 6.5 m and 3 m levels.

Note: Hilltop area appears rougher than \( z_0 \) = 1 mm. Should look at other ways to estimate \( z_0 \) and \( u_* \).
Some Conclusions

- Simple, linear models (MS3DJH, MSFD) appear to predict speed-up well on upwind side of the hill, and at hilltop locations.
- Good speed-up near the ground, $\Delta S \approx 1$ but at 100m, $\Delta S \approx 0.1-0.2$. Still an advantage for wind energy.
- Limited success with turbulence measurement, sonics and tilted Gills.
- RDT predictions of turbulence reductions ($\sigma_s$) above the hilltop were validated.
- A good data set for model validations – widely used.

Acknowledgements

- All participants in the experiment (next slide), plus those who have used the data.
- Various funding agencies, then and now, IEA for support of the project.
- Environment Canada (formerly AES)
- Risø National Laboratories (Denmark)
- University of Hannover (Germany)
- ERA Technology Ltd (UK)
- Building Research Establishment (UK)
- University of Canterbury (New Zealand)
Participants in the experiment relaxing at The Loughbourdale Hotel. Back row left to right: Elizabeth Moughton (ERA), Peter Taylor (AES), David Woodforf (BRE), Tony Newmen (U. of Canterbury), Nick Cook (BRE), Bob Johnson (ERA), Jim Arnold (AES), Finn Hansen (Algorithmics), Mogens Nielsen (Algorithmics), Bob Hickle (AES), Thomas Burger (U. of Hanover), Seated: Karl Yonek (AES), Hans Tumitsen (AES), Kurt Engel (U. of Hanover), Jim Salmon (CAN), Rasood Koushargh (ERA), Niels Otto Jensen (Algorithmics). Seated on floor: Wes Robelka (AES), Gunnar Balsgaard (Algorithmics), John Beary (AES). Not in photo: Bob Belton (ERA), Doug Warne (ERA), Martin Shaw (BRE).
“The Bolund Experiment” - by J. Berg, J. Mann and H.E. Jørgensen

Andreas Bechmann, Jacob Berg, Mike Courtney, Hans E. Jørgensen, Jakob Mann, Niels N. Sørensen
in cooperation with Vestas

Risø DTU, Roskilde, Denmark

December 3-4, 2009 – Bolund Workshop, Risø DTU, Denmark

Approvals needed for the Bolund experiment:

- Landowners' approval (Karen, Christian and Benny)
- Fredningsnævnet
- Building approval (Byggesagsgodkendelse, Roskilde Kommune)
- Environmental Center Roskilde
- Neighbor hearing (two complaints filed)
- Meeting with the neighbors (a very peaceful meeting with some understanding)
- Danish Maritime Safety Administration (Farvandsdirektoratet in Thisted)

Normal processing time 1/2 year - Bolund ~ 3 months
Previous experiments

Bolund:
- $h = 12$ m
- $L = 86$ m
- $z_0 = 2$ cm
- $l = 1.9$ m ($\gamma^c$, NDJ)

Bolund vs. Askervein

**Askervein Experiment 1983**
- Well-defined inflow conditions.
- Uniform Roughness.
- Low hill / simple terrain.
- "Linear".

**Bolund Experiment 2008**
- Well-defined inflow conditions.
- Roughness change.
- Steep Escarpment.
- "Complex".
The Bolund peninsula

Map width: 1 km

Height scanning with laser
Optech Airborne Laser Terrain Mapper: ≈ 2 m resolution
Height scanning with laser
Cliff to steep: additional < 0.1 m resolution scanning applied
Height scanning with laser

Cliff to steep: additional < 0.1 m resolution scanning applied

Masts
Erection of masts

- 23 Metek USA-1 Basic sonics – off-line flow correction
- 12 Risø cup anemometers (WindSensor P2546)
- 2 ZephIR lidars + one scanning lidar
- Temperature and temperature difference
- No pressure and no humidity
### Sonic Configuration

<table>
<thead>
<tr>
<th>Mast. ID</th>
<th>2m</th>
<th>5m</th>
<th>9m</th>
<th>15m</th>
<th>Lidar</th>
</tr>
</thead>
<tbody>
<tr>
<td>M0</td>
<td>C</td>
<td>C,S</td>
<td>C</td>
<td>C</td>
<td>-</td>
</tr>
<tr>
<td>M1</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>M2</td>
<td>S</td>
<td>S</td>
<td>C,S</td>
<td>-</td>
<td>L</td>
</tr>
<tr>
<td>M3</td>
<td>S</td>
<td>S</td>
<td>C,S</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>M4</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>M5</td>
<td>S</td>
<td>S</td>
<td>-</td>
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<td>-</td>
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</tr>
<tr>
<td>M7</td>
<td>S</td>
<td>S</td>
<td>-</td>
<td>-</td>
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</tr>
<tr>
<td>M8</td>
<td>S</td>
<td>S</td>
<td>C</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>M9</td>
<td>C</td>
<td>C,S</td>
<td>C</td>
<td>C</td>
<td>L</td>
</tr>
</tbody>
</table>

---

### Technical Diagram

![Technical Diagram](image-url)
Database and Rodeo

- Central Acquisition of all Meteorological Data (20 Hz)
- Direct Data Transfer to Risø via RadioLink
- Database Storage MySQL (20 Hz and 10 min averages)
- Online Data Display

Water level in Roskilde Fjord

[Graphs and images related to water levels and Roskilde Fjord]
The upstream mast M0: Atmospheric stability

\[ Rl = \frac{g \Delta \theta_v}{\theta_v \Delta U^2} \]

\[ L = \frac{u^2 \theta_v}{\kappa g \langle w \theta_v \rangle} \]

Fetch

\( \approx 7 \text{ km} \)

\( \approx 4 \text{ km} \)

\( \approx 0 \text{ km} \)
Measurement period and stability

Stability in terms of the Monin-Obukhov stability parameter $z/L$
Atmospheric stability: $z/L$ versus $Ri$

$180^\circ < \theta < 360^\circ$ and $U_2 > 0 \text{ m/s}$

---

Atmospheric stability: $z/L$ versus $Ri$

$180^\circ < \theta < 360^\circ$ and $U_2 > 4 \text{ m/s}$
Atmospheric stability: $z/L$ versus $Ri$

$180^\circ < \theta < 360^\circ$ and $U_b > 8$ m/s

Atmospheric stability: $z/L$ versus $Ri$

$180^\circ < \theta < 360^\circ$ and $U_b > 12$ m/s
Neutral upwind profile

$-0.02 < z/L < 0.02$ and $260^\circ < \theta < 300^\circ$ (long fetch)

Log-profile with

$\kappa = 0.46$

$z_0 = 1.3 \times 10^{-4} \text{ m}$

The upstream conditions

Is the flow "undisturbed"? ($-0.02 < z/L < 0.02$)
The upstream conditions
Stability changes the wind gradient $\partial U/\partial z$ slightly

Very unstable
Unstable
Neutral
Stable
Very stable

Upstream turbulence
$8 \text{ m/s} < U_z < 10 \text{ m/s}$
Upstream covariances

$8 \text{ m/s} < U_x < 10 \text{ m/s}$

Upstream spectra

Along wind, $u$, transverse $v$, vertical $w$, co-spectrum $uv$
Upstream spectra
Along wind, $u$, transverse $v$, vertical $w$, co-spectrum $uw$
Speed at line A (5 m above terrain)

Tilt at line A (5 m above terrain)
Turbulence spectra at line A (5 m above terrain)
Turbulence spectra at line A (5 m above terrain)

Speed at M2

Bechmann et al. | The Bolund Experiment
Speed at M2

Bechmann et al. The Bolund Experiment
Deflection at M2

Turbulence intensity at M2
Turbulence intensity at M2

Bechmann et al. The Bolund Experiment

Turbulence spectra at Mast 2 (239 degrees)

Bechmann et al. The Bolund Experiment
The downstream direction at Mast 9

Bechmann et al. The Ullend Experiment
The downstream direction at Mast 9

Conclusions

- Instrumentation and data acquisition worked well. Proximity to Risø very convenient.
- We have successfully captured the gross features of flow over a steep hill.
- No significant stability effects
- Very turbulent recirculation zones behind hill and at "leading edge".
- At the downstream mast M9 the flow relaxed to normal.
- Should we do it over again: Only measurements along one line, but more heavily instrumented.
“Blind Comparison Results” - by Andreas Bechmann

Results of the Blind Comparison

Riso DTU: Andreas Bechmann (andh@risoe.dtu.dk), Pierre-Elouan Rethore, Mike Courtney, Hans E. Jørgensen, Jacob Berg, Jakob Mann and Niels N. Sørensen
Vestas Technology R&D: Lars Chr. Christensen and many others ...

Content

1. Introduction
2. Measurements & Simulations
3. Results
4. Analysis
5. Conclusions
Introduction: Purpose of Blind Comparison

1. Make The Bolund Data Visible

2. Evaluate Flow Modeling Accuracy
   (TPWind: uncertainty less than 3% \(^1\))

3. Standardize Resource Assessment Modeling?
   (Top Priority of TPWind)

\(^1\)European Wind Energy Technology Platform.
Strategic research agenda, market deployment strategy, from 2008 to 2030

Introduction: 1. The Bolund Data

Askervein Experiment, 83
- Well-defined inflow conditions
- Well-defined and Uniform roughness
- 120m high
- Low hill / "simple" terrain

Bolund Experiment, 08
- Well-defined inflow conditions
- Well-defined roughness change
- 12m high
- Steep escarpment / "complex"
Introduction: 2. Evaluate Model Accuracy

Uncertainties:
- **Modeling** (Turb. model, Discretization, Experience)
- **Boundary Conditions** (Orography, Free wind description etc.)
- **Measurements**

Blind Comparison:
- **Evaluation of Modeling Accuracy** (Measure & BC Errors Minimized)
- **Evaluation of Different Approaches** (WASP, CFD, Wind tunnel etc.)
- **Only constraint: Boundary Conditions** (Evaluation of state-of-the-art)

Introduction: 3. Standardize the Modeling

52 Different Submissions,
52 Different Approaches,
52 Different Results!

**Model types:**
- 3: Experimental method
  - 1: Wind tunnel
  - 1: Flow channel
- 3: No answer
- 9: Linearized flow model
  - 3: WASP like
  - 5: WASP Eng.
- 0: Mesoscale model
- 37: Non-linear CFD model
  - 5: LES / hybrid RANS-LES
  - 7: RANS 1 eqn. (k-l, Spalart-Allmaras)
  - 25: RANS 2 eqn. (k-epsilon, k-omega)
Content

1. Introduction
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Measurements: Selected cases

data for 4 Cases:
1. 270 direction
2. 255 direction
3. 239 direction
4. 90 direction
Measurements: Selecting Data

**Selection Criteria** (evaluated at upstream mast, M0/M9)
1. Wind direction: $\pm 80^\circ$
2. Monin-Obukhov length: $|l/L| < 0.004 \text{ m}^{-1}$ ($L > 250 \text{ m}$)
3. Water level: $\pm 0.4 \text{ m}$
4. Wind speed 5 m agl: $5 \text{ m s}^{-1} < u < 12 \text{ m s}^{-1}$ ($z_0 \approx 1.5 \times 10^{-4} \text{ m}$, Charnock)
5. 10 min time series

Measurements: Comparing with Simulation

1. $u^*/u_0$: 0.4 / 0.469 ms$^{-1}$ (42 time-series)  Direction: 270 / 268.4
2. $u^*$: 0.4 / 0.582 ms$^{-1}$ (25 time-series)  Direction: 255 / 254.3
3. $u^*$: 0.4 / 0.356 ms$^{-1}$ (9 time-series)  Direction: 239 / 241.7
4. $u^*$: 0.5 / 0.509 ms$^{-1}$ (19 time-series)  Direction: 90 / 94.1
Simulation: Normalizing

Wind speed-up, Line: B, Dir: 270°

Relative position along line B [m]

Simulation: Normalizing

Wind speed-up, Line: B, Dir: 270°

Relative position along line B [m]
Simulation: Normalizing

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1. Introduction
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5. Conclusions
Results: Speed-up

Wind speed-up, Line B, Dir 270°

Z=5m

Z=2m

Results: Speed-up

Wind speed-up, Mast M7, Dir 270°

Wind speed-up, Mast M8, Dir 270°
Results

Turning of the wind, Mast M3, Dir 239°

Turning of the wind, Mast M4, Dir 239°

Results

TKE, Line B, Dir 270°

Z=5m

Z=2m

Relative position along line B [m]
ERROR

- The averaged error in velocity for line A and B (TPWind: 3%)

@ 2m above ground = 35%
@ 5m above ground = 17%

Mean Error: 26%

Content
1. Introduction
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3. Results
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Analysis

Model types:
1. Experimental method
2. Linearized flow model
3. LES
4. RANS 1 eq.
5. RANS 2 eq.

All models
LES models

RANS 1 eq. models
RANS 2 eq. models

All models

Mean Error: 26%
Linearized: 35%
LES: 26%
RANS 1 eqn.: 25%
RANS 2 eqn.: 20%
RANS 2 eq. models

Wind speed-up, Line A, Dir. 239°

Z=5m

Z=2m

RANS 2 eqn.: 18%

20/25 models

RANS 2 eqn.: 17%

19/25 models
RANS 2 eq. models

19/25 models
RANS 2 eqn.: 17%

16/25 models
RANS 2 eqn.: 16%
RANS 2 eq. models

Wind speed-up, Mast M3, Dir. 270°

Wind speed-up, Mast M8, Dir. 270°

16/25 models

RANS 2 eqn.: 16%

12/25 models

RANS 2 eqn.: 15%
RANS 2 eq. models

12/25 models

RANS 2 eqn.: 15%
No wake: 11%
Only 5m agl: 6%

Top 10 List

<table>
<thead>
<tr>
<th>ID</th>
<th>Turb. model</th>
<th>Error [%]</th>
<th>Error 5m [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID0053</td>
<td>RANS k-epsilon</td>
<td>13</td>
<td>6</td>
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<tr>
<td>ID0037</td>
<td>RANS k-epsilon</td>
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<td>4</td>
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<tr>
<td>ID0000</td>
<td>RANS k-epsilon</td>
<td>14</td>
<td>5</td>
</tr>
<tr>
<td>ID0036</td>
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<td>5</td>
</tr>
<tr>
<td>ID0016</td>
<td>RANS k-epsilon</td>
<td>14</td>
<td>5</td>
</tr>
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<td>RANS k-epsilon</td>
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<tr>
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<td>7</td>
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<tr>
<td>ID0009</td>
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<td>ID0034</td>
<td>RANS 1 eqn.</td>
<td>17</td>
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<td>ID0068</td>
<td>RANS k-epsilon</td>
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<td>10</td>
</tr>
<tr>
<td>ID0006</td>
<td>RANS k-epsilon</td>
<td>17</td>
<td>6</td>
</tr>
</tbody>
</table>
Content
1. Introduction
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Conclusions
Physical models:
- Mean velocity looks well predicted
- TKE is too low

Lin. Models:
- Gave the largest error – not designed for Bolund (90 dir better)
- The peak in speedup was missing and a some spread in model results

LES:
- Many modelers had problems doing LES of Bolund
- The spread was large (not matured but showed potential)

RANS:
- State-of-the-art!
- Many models showed similar trends
- Some RANS simulations seems to be too "coarse" (two trends)
Conclusions

• TPWind: uncertainty of less than 3% - We have a long way!
• Bolund is an “ideal” case to test flow models. The uncertainty would be larger on “real” WT-sites
• How do you compare measurements and simulations?
• With best practice CFD guides results could probably be improved considerably (eg. Convergence test: results must be grid independent)
• The top 10 list consisted of 7 different CFD solver:
   1. You can get good results with most solvers
   2. The user is more important than the solver
• Recommendation: RANS will be the workhorse for many years to come

• Take a break - look at your results and discuss - make your own conclusions 😊

Thank you
“LES of turbulent wind flows in the Atmospheric Boundary Layer” - by Vijayant Kumar

LES of turbulent wind flows in the Atmospheric Boundary Layer

Vijayant Kumar¹
Chad Higgins²
Marc Parlane²
Charles Meneveau³

¹ Macquarie Holdings, Austin, Texas, USA
² Ecole Polytechnique Federal de Lausanne, Switzerland
³ Johns Hopkins University, Baltimore, USA

Wind Resource Assessment: The Process

- Turbulence
- Vertical structure / Wind shear
- Diurnal variability / Stability
- Spatial variability (heterogeneity)
- Land-atmosphere interactions
- Flow - structure interactions/ Wake

Diagram showing the relationship between Wind Resource Assessment, Atmospheric Boundary Layer, and various factors affecting wind flow.
Atmospheric Boundary Layer: Spatial Complexity

Capping Inversion

Atmospheric Boundary Layer ~ 1 km

Surface Layer ~ 0.1 km

Turbulent Eddies

Buildings, Forest, Terrain

Atmospheric Boundary Layer: Temporal Complexity

FREE TROPOSPHERE

Entrainment

CBL Growth

Convective (Unstable) Layer

Eddies/Plumes

Residual Layer

Stable Layer
Understanding the ABL: Methods

Observational/Experimental
- "Truth"
- Code / model validation
- Height limitations
- Lack of spatial info
- Sensitivities
- Expensive
- Not comprehensive

Theoretical/Analytical
- Physics
- Modeling holism
- Simplified
- Often non-universal

Numerical/Computational
- Complex flows
- Repeatability
- Test models
- Infrastructure
- Accuracy / Validation
- Over-tweaking
- GIGO

CFD: Microscale ABL flow (DNS, LES, RANS)

Level of Detail: DNS>LES>RANS
Computational cost: DNS>>LES>>RANS

Direct Numerical Simulation (DNS) → Resolve all scales → Computationally impossible for realistic ABL flows
CFD: Microscale ABL flow (DNS, LES, RANS)

Level of Detail: DNS >> LES >> RANS
Computational cost: DNS >> LES >> RANS

Large Eddy Simulation (LES)
- Predict instantaneous flow characteristics (+)
- A large portion of the turbulence spectrum is completely resolved (+)
- Represent complex flow regimes such as separation, wakes, stability transitions & stable boundary layers (+)
- Subgrid scale models can be universally applied (+)
- High computational cost: Parallel (-)
- Quality of results = f(user) => GIGO (-)

Large Eddy Simulation (LES)

Incompressible Navier-Stokes, \( Re \sim 10^8 \)

Filtering

\[
\frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial (\tilde{u}_i \tilde{w}_j)}{\partial x_j} = \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \left( \frac{\tilde{\theta}}{\tilde{\theta}_0} \right) \frac{\partial T_{ij}}{\partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} + f(\tilde{u}_2 - \tilde{V}_2) \delta_{ij} - f(\tilde{u}_1 - \tilde{V}_1) \delta_{ij}
\]

\[
\frac{\partial \tilde{\theta}}{\partial t} + \tilde{u}_i \frac{\partial \tilde{\theta}}{\partial x_i} = \frac{\partial \tau_{ij}}{\partial x_j}
\]

Subgrid scale modeling

\[
\tau_{ij} = \tilde{u}_i \tilde{u}_j - \tilde{u}_i \tilde{v}_j
\]

\[
\tau_{ij} = \tilde{u}_i \tilde{\theta} - \tilde{u}_i \tilde{\theta}
\]
### LES: SGS Modeling

\[
\tau_{ij} = -2\nu_s S_{ij}; \quad \pi_j = \frac{\nu_t}{\Pr_{SGS}} \frac{\partial \theta}{\partial x_j} \quad \nu_t = (C_s\Delta^2)^2 |S_{ij}|; \quad S_{ij} = \frac{1}{2} \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right)
\]

Eddy Viscosity (\(\nu_t\)) type models:

<table>
<thead>
<tr>
<th>Static Smagorinsky</th>
<th>Dynamic Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant value (C_{s,\Lambda}) imposed everywhere</td>
<td>• (C_{s,\Lambda}) determined dynamically from the resolved scales</td>
</tr>
<tr>
<td></td>
<td>• (C_{s,\Lambda}) is spatially averaged</td>
</tr>
</tbody>
</table>

### CFD: Microscale ABL flow (DNS, LES, RANS)

**Level of Detail:** DNS>LES>>RANS  
**Computational cost:** DNS>>>LES>>RANS

**Direct Numerical Simulation (DNS)** → **Resolve all scales** → **Computationally impossible for realistic ABL flows**
CFD: Microscale ABL flow (DNS, LES, RANS)

Level of Detail: DNS >> LES >> RANS
Computational cost: DNS >> LES >> RANS

Large Eddy Simulation (LES)
- Predict instantaneous flow characteristics (+)
- A large portion of the turbulence spectrum is completely resolved (+)
- Represent complex flow regimes such as separation, wakes, stability transitions & stable boundary layers (+)
- Subgrid scale models can be universally applied (+)
- High computational cost: Parallel (-)
- Quality of results = f(user) => GIGO (-)

Incompressible Navier-Stokes, Re ≈ 10^8

Filtering

\[
\frac{\partial \bar{u}_i}{\partial x_i} = 0
\]

\[
\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial (\bar{u}_i \bar{u}_j)}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{1}{\rho} \left( \frac{\partial \theta}{\partial x_i} \right) \delta_{ij} - \frac{\partial \tau_{ij}}{\partial x_j} + f(\bar{u}_2 - \bar{v}_2) \delta_{ij} - f(\bar{u}_1 - \bar{v}_1) \delta_{ij}
\]

Subgrid scale modeling

\[
\tau_{ij} = \bar{u}_i \bar{u}_j - \bar{u}_1 \bar{u}_j
\]

\[
\pi_{ij} = \bar{u}_i \bar{\theta} - \bar{u}_i \bar{\theta}
\]
LES: SGS Modeling

\[ \tau_{ij} = -2\nu_T \bar{S}_{ij}; \quad \tau_{ij} = -\frac{\nu_T}{P_{SGS}} \frac{\partial \theta}{\partial x_j}; \quad \nu_T = (C_{s,\Delta} \Delta)^2 |\bar{S}_{ij}|; \quad S_{ij} = \frac{1}{2} \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \]

Eddy Viscosity \( (v_t) \) type models:

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<td></td>
</tr>
</tbody>
</table>

Dynamic SGS model formulation

\[ \tau_{ij}^\Delta = \bar{u}_i \bar{u}_j - \bar{u}_i \bar{u}_j \]
\[ \tau_{ij}^{\Delta, m} = -2(C_{s,\Delta} \Delta)^2 |\bar{S}_{ij}| \bar{S}_{ij} \]
\[ L_{ij} = T_{ij} - \bar{T}_{ij} \]
\[ = \bar{u}_i \bar{u}_j - \bar{u}_i \bar{u}_j - (\bar{u}_i \bar{u}_j - \bar{u}_j \bar{u}_j) \]
\[ = \bar{u}_i \bar{u}_j - \bar{u}_i \bar{u}_j \]

Assume scale invariance \( C_{s,2\Delta} = C_{s,\Delta} \)

\[ L_{ij}^m = C_{s,\Delta}^2 M_{ij}; \quad M_{ij} = 2(\Delta)^2 |\bar{S}| \bar{S}_{ij} - 2(2\Delta)^2 |\bar{S}| \bar{S}_{ij} \]

\[ e_{ij} = L_{ij} - L_{ij}^m = L_{ij} - C_{s,\Delta}^2 M_{ij} \]

Minimize \( e_{ij} \) \( \rightarrow C_{s,\Delta}^2 = \frac{\langle L_{ij}^m M_{ij} \rangle}{\langle M_{ij} M_{ij} \rangle} \)
**SGS modeling: The Dynamic model**

- Scale invariance: $c_s^2 = c_s^2$
- Does not hold in near-surface region
- Results in incorrect energy dissipation
- Scale dependence: $c_s^2 = \beta c_s^2$

**SGS modeling: Lagrangian averaging**

- Averaging of $C_{s,\lambda}$
- Spatial averaging
- Removes spatial/local effects
- New averaging method
- Averaging over fluid pathlines
- Lagrangian Dynamic Model (LASI)
- Scale dependence
- Physically motivated averaging
- Ideal for complex topography
- Pointwise unique
- 3D local variability preserved
- Can handle unsteady flows
- Lagrangian Dynamic scale-dependent SGS model (LASD)
LES code

- Modular Fortran 90/95
- Parallel with FFTW solver
  - Independently verified to be the most efficient parallel code on the NCAR supercomputing clusters
- Lagrangian scale-invariant (LASI) and scale-dependent (LASD) SGS models
- Stability effects => Potential Temperature, Humidity
  - Surface boundary conditions: Flux or Temperature
- Derivatives: Pseudo-spectral (x,y), finite difference (z)
- Pressure forcing: Geostrophic wind (U_g, V_g)
- Terrain: Level set method, Immersed boundary method

LES of Unstable ABL

Good agreement: "Large structures"

Moeng and Sullivan, JAS, 1994
Schmidt and Schumann, JFM, 1989
LES of Nocturnal Stable ABL

SGS models become important

LES of Quasi-steady ABLs: A review

**Unstable ABL** (Schmidt & Schumann, 1989; Nieuwstadt et al., 1991)
- Suited for LES: Large-scale structures e.g. plumes, thermals
- Energy spectra: Over-dissipative SGS models

**Stable ABL** (Kosovic & Curry, 2000; Beare et al., 2006)
- Small-scale structures: Burden on SGS model
- Poor SGS models: Numerical instabilities
- Poor representation of energy spectra
- High resolution required with non-dynamic SGS models
LES: Impact of Pressure forcing/BC

[Graph showing the impact of pressure forcing/BC on various parameters such as friction velocity and time-varying geostrophic wind.

Blinded Workshop, Dec 4, 2009
35 / 40

Blinded Workshop, Dec 4, 2009
35 / 40

Riso-R-1745(EN)
**LES: Representation of structures and topography**

**Methodology:**
1. Describe surface using the level set method & Fluid-structure interaction represented through immersed boundary method.
2. Define a band just outside the surface.
3. Pick a point define the surface normal.
4. Define a tangential velocity and apply a log law to obtain the shear stress.
5. Extrapolate the stress field into the body.
6. Smooth the stress profile inside the body using iterative over-relaxation of the Laplace equation in stress, $\tau$.

---

**LES: Simulation setup for flow over terrain**

1. Precursor run: LES over flat terrain.
2. Inflow fields for LES.
3. LES over topographic features.
4. Buffer region at the end of domain: Buffers outflow to inflow field for next time step.
5. LES Results.
**LES study:** Flow over a Gaussian Hill

Data from Iwamura et al. 1991

---

**LES study:** Flow over a steep real-world Hill

- Gaudergrat ridge, Switzerland
- Dimensions: 1.5kmx1kmx250m
- Slopes of about 45 degrees
- Results to be compared with extensive observations, RANS and mesoscale models
LES study: Flow over a steep Alpine Hill

SIDE VIEW

TOP VIEW

LES study: Flow over a steep Alpine Hill
LES study: Flow over a steep Alpine Hill

Cross ridge flows have been observed even when the mean wind direction is along the ridge.
Also seen in mesoscale simulation of Gaudergradt ridge (Courtesy: Rebecca Mott)
In LES results, we observe cross-ridge flows with ~20% strength of the predominant flow along the ridge.

"Lewis et al. (2008), GURMS"
LES study: Flow over a steep real-world Hill
“Physical Modeling of Bolund” - by Brad C. Cochran
Typical Applications
Wind Induced Building Loads

Superdome and New Orleans Arena
John Hancock Building - Boston

Typical Applications
Pedestrian Level Wind Environment

WIND ENGINEERING & AIR QUALITY CONSULTANTS
Typical Applications
Plume Dispersion

Typical Applications
Airflow in Complex Terrain Environments
Physical Modeling

Theory

**Navier-Stokes Equations**

**Continuity**
\[ \frac{\partial}{\partial t} (\rho \mathbf{v}) + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla p + \nabla \cdot \mathbf{\tau} + \rho \mathbf{F} \]

**Momentum**
\[ \frac{\partial}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \]

**Energy**
\[ \frac{\partial}{\partial t} (\rho e) + \nabla \cdot (\rho e \mathbf{v}) = -p \nabla \cdot \mathbf{v} + \mathbf{\tau} : \nabla \mathbf{v} - \nabla \cdot \mathbf{q} \]

---

Physical Modeling

Scaling Parameters

- Undistorted scaling geometry
- Equal dimensionless boundary and approach flow conditions
- Equal Rossby number – \( UI/L\Omega \)
- Equal gross Richardson number – \([\Delta T/T](L/U^2)g \)
- Equal Reynolds number – \( UL/U^2 \)
- Equal Prandtl number \(- n/(k/\tau C_p)\)
- Equal Eckert number – \( U^2/[C_p(\Delta T)] \)
Physical Modeling
Scaling Parameters

- Undistorted scaling geometry
- Equal dimensionless boundary and approach flow conditions
  - Equal Rossby number $- \frac{U}{L \Omega}$
  - Equal gross Richardson number $- \frac{\Delta T}{T} \left( \frac{L}{U^2} \right) g$
  - Equal Reynolds number $- \frac{UL}{U}$
  - Equal Prandtl number $- \frac{v}{(k/r \rho C_p)}$
  - Equal Eckert number $- \frac{U^2}{C_p (\Delta T)}$

Wind Engineering & Air Quality Consultants
Physical Modeling
Scaling Parameters

\[
\left( \frac{U L}{V} \right)_{\text{model}} = \left( \frac{U L}{V} \right)_{\text{full scale}}
\]

\[
(L)_{\text{model}} = (L)_{\text{full scale}} / 100
\]

\[
(V)_{\text{model}} = (V)_{\text{full scale}}
\]

\[
(U)_{\text{model}} = (U)_{\text{full scale}} \times 100 = 1000 \text{ m/s}
\]

Physical Modeling
Reynolds Number Independence

- Ensure a fully turbulent wake flow

Terrain or Building Reynolds Number greater than 11,000 \( (R_{e_T} = UH_T / V) \)

\[
\begin{align*}
U & = 10 \text{ m/s} \\
H_T & = 0.25 \text{ m} \\
V & = 1.15 \times 10^{-5} \text{ m}^2/\text{s} \\
R_{e_T} & = 217,391
\end{align*}
\]
History Timeline

Abe (1929) studies air flow over a scale model of Mt. Fuji

History Timeline

Golden (1961) Defines minimum acceptable Reynolds number to achieve Reynolds number independence
Cermak and Davenport (1964) measured wind loads on a scale model of the World Trade Centers in New York.

Cermak (1975) Publishes Freeman Scholar Lecture on wind tunnel simulation methods (Resulting in wind tunnel modeling being accepted by most building codes)
History
Timeline

A properly executed wind tunnel study is, in effect, equivalent to an analog computer with near infinitesimal resolution and near infinite memory.

The basic equations are solved by simulating the flow at a reduced scale, then measuring the desired quantity

- U.S. EPA Fluid Modeling Guideline
By 2009 over 5000 building have been testing in an atmospheric boundary layer wind tunnel, including the worlds tallest Burj Dubai.
History
Validation in Wind Energy Applications

![Image of wind energy application](image-url)
Conducting a Wind Tunnel Study
Create 3-D representation in CAD

Conducting a Wind Tunnel Study
Create Physical Model using a 3-D Mill
Conducting a Wind Tunnel Study
Establish an Atmospheric Boundary Layer

Data Power Law

$ \beta^* = 0.09 \\
\text{Intercept} = 0.905$

Data Log Law

$ \beta^* = 0.12 \\
\text{Intercept} = 0.900$

Target

$ \beta^* = 0.10 \\
\text{Intercept} = 0.900$

Note: Velocity Profiles and Turbulence Intensity Profiles.

Conducting a Wind Tunnel Study
Install Model in the Wind Tunnel
Conducting a Wind Tunnel Study
Measure wind speeds using a 5-holed probe mounted on a 3-D traverse

5-Holed Probe Used to Measure the Local Wind Vector and Turbulence Intensity

Definition of flow angles: x axis defines the approach wind direction

Conducting a Wind Tunnel Study
Measure wind speeds using a 5-holed probe mounted on a 3-D traverse

WIND ENGINEERING & AIR QUALITY CONSULTANTS
Flow Visualization
270 Degree Wind Direction

Results
239 Degree Wind Direction
Flow Visualization
270 Degree Wind Direction

Flow Visualization
239 Degree Wind Direction
Physical Modeling of Bolund
in an
Atmospheric Boundary Layer Wind Tunnel

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“RANS CFD simulations of flow around Bolund”
- by Niels Sørensen

Outline
- CFD solver for terrain flow
  - Turbulence modeling
  - Boundary conditions
  - Roughness
- Computational domain and surface discretization
- Brief overview of present simulations, number of points and computing time
- Verification of the simulations, Convergence and Grid Convergence.
- Problems when comparing with measurements.
- Terrain resolution.
- A few examples of the results
- Conclusion
Components of a CFD methodology

- Preprocessor
  - Geometry processor (CAD)
  - Grid Generation
  - Specification of Boundary Conditions
  - Roughness treatment
- CFD solver
  - Accurate
  - Efficient solver
  - Versatile
- Postprocessor
  - 3D graphics
  - Extraction of velocities, turbulence etc in predefined points.

Components of a CFD solver

The basic idea is to take the partial differential equations describing the fluid flow, transform them into a set of algebraic equations, and solve these using a numerical method on a computer.

Typical components of a CFD code are listed below:

- Mathematical Model
  - Turbulence Modeling
- Coordinate and basis vector systems
- Discretization Method, space and time
- Solution Method
- Computational Grid
Turbulence Modeling

- Direct Numerical Simulation (DNS)
- Filtered Equations
  - Large Eddy Simulation (LES)
- Time Averaged Equations, Reynolds Averaged Navier-Stokes (RANS)
  - Algebraic Models (e.g. Baldwin-Lomax)
  - One Equations Models (e.g. Spalart-Allmaras, Baldwin-Barth)
  - Two Equation Models (e.g. k-ω, k-ε)
  - Reynolds Stress Models
- Hybrid Models
  - Detached Eddy Models

Boundary conditions (Inlet and outlet conditions)

Inflow boundary conditions for Atmospheric flows:
Log-law profiles for the velocities and turbulent quantities.

\[
\bar{U}(z) = \frac{u_r}{\kappa} \ln \left( \frac{z}{z_0} \right), \quad \mu_1 = \rho \kappa u_r z, \\
\epsilon(z) = \frac{C_{\mu}^{\frac{3}{2}} k_{\mu}^{\frac{1}{2}}}{\kappa z}, \quad k(z) = \frac{u_r^2}{\sqrt{C_{\mu}}}, \\
C_{\epsilon 1} = C_{\epsilon 2} - \frac{\kappa}{C_{\mu}^{\frac{3}{2}} \sigma_{\epsilon}}.
\]

Outflow boundary conditions:
Fully developed flow is assumed in the mesh direction normal to the outlet.


**Boundary conditions (Wall)**

Wall boundary conditions are given by the log-law

- The velocity boundary conditions are implemented through the friction at the wall.
- The implementation assures that flow separation can be handled by evaluating the friction velocity from the turbulent kinetic energy.
- The computational grid is placed on top of the roughness elements, and the actual roughness heights are ignored in connection with the grid generation.
- The TKE boundary condition is an equilibrium between production and dissipation, implemented through a von Neumann condition and specifying the production term from the equilibrium between production and dissipation.
- The epsilon equation is abandoned at the wall, and instead the value of the dissipation is specified according to the equilibrium between production and dissipation.

---

**Roughness Maps**

- In our case, and maybe in most cases the local roughness is determined based on the \((x,y)\) coordinates. This may be a problem for roughness shifts along vertical slopes.
Computational Domain (1)

One domain for all comp. A dedicated mesh for each direction

Computational Domain (2)

- Typically we have a problem of where to specify boundary conditions, especially inflow.
  - For Bolund this is not an issue
- Solutions?
  - Make a very large domain specify simple conditions at inlet
    Expensive or requires a zooming grid
  - Obtain the inflow conditions from external means
    • Measured values
    • Nested computations
    • Mesoscale model
    Often the measurements or computations will not have sufficient resolution.
- For domains dedicated to specific flow directions symmetry conditions are often used at the side ‘walls’. This may make them useless for studies with slightly different flow direction.
Surface Resolution (1)

• Using a true surface grid generation on the terrain surface, will allow
good resolution of steep gradients. As seen below this allows good
resolution even on level 2 and 3 grids.

![Graph showing surface resolution (1)]

Surface resolution (2)
The problem of projected grids

Using just simple projection of a 2D
surface grid onto the terrain, will
naturally lead to coarse cells at steep
slopes in the terrain.

The grids are not well suited for grid
convergence studies.

![Graph showing surface resolution (2)]
Surface Grid (1)

Surface Grid (2)
Is the digital terrain correct

- And how good is the roughness estimation?

Number of points used for the simulation
Turnaround time

Computing time may be an issue compared to linear models

Computing time on a single Cpu
Computing Time

There is a speed difference of around 50-500 between the fastest and slowest.

Including the parallel runs the difference is more than 5000

Setup of the masts

Line B

Line A

Region of sonography slice

\( z = 0.75 \) m

\( z = -0.915 \) m

\( z = 0.093 \) m

\( z = 0.915 \) m
Grid Convergence (1)

- Flow direction 270 degrees, computations along line B.

\[ Z_{ACL} = 2 \text{ [m]} \]

Level-3 = 0.21 Mill
Level-2 = 1.7 Mill
Level-1 = 13.6 Mill

Grid Convergence (2)
Grid Convergence (3)

Convergence of the equations
Order of accuracy

Non-linearities due to the terrain and wind direction

Computing a single flow direction using CFD we need to consider:
- Non-linear directional effects
- The frequency of the different directions

In the present location and for an inflow variation of +/- 13 degrees the variation is up to ~18%.

In other places the variation can be even larger.
Variation of the velocity with flow angle

- Dir = 270 [deg], Height AGL = 2 [m]

Variation of turbulence with flow angle

- Dir = 270 [deg], Height AGL = 2 [m]
Comparison with measurements

More detailed measurements would be interesting
Conclusion

- The Bolund Blind Comparison shows that good agreement between the majority of involved RANS type models.
- Yesterday we saw that they were also able to predict the measurements with $\sim 15\%$ error.
- The typical number of points ranges from 0.5 to 4 million.
- Typical compute times between 0.01 to 0.1 sec/point.
- Grid refinement studies indicates that already with 0.21 million points a good solution can be obtained (compute time $\sim 10$ min on one CPU)
- With these low computing times the full wind rose with 5 to 10 degrees resolution can easily be computed.

Bolund may not be typical for the majority of sites, due to the well defined inflow boundary conditions. The lack of well defined inflow BC's may severely change the conclusion of good agreement.

Hopefully further large scale experiments aimed directly at code validation will take place in the future.
Blind Comparison Simulation Cases

The description of the simulation cases for the blind comparison is found below.

The Bolund Experiment: Blind Comparison of Flow Models

1 Introduction

The Bolund experiment is a field campaign that provides a new dataset for validating models of flow in complex terrain and is the basis for a blind comparison of flow models. This document contains instructions that enable modelers to participate in the blind comparison. The deadline for returning simulation results is 31/10/09. Good luck!

2 The Experiment - Quick Overview

The Bolund experiment was performed during a three month period in 2007 and 2008. Bolund is a 12m high coastal hill located just north of Riso DTU (see Figure 1). Figure 2 gives an overview of the Bolund orography and the positions of the ten masts that supported the instrumentation. A short description of the experiment is found below. For a detailed description of the Bolund experiment please see [1].

Figure 1: Picture of Bolund taken from a 125m high measuring mast at Riso DTU.
2.1 Topography Description

The topography information can be downloaded from the Bolund web page (http://bolund.risoe.dk) and contains four files: gridded files of the Bolund orography and roughness with 25cm resolution (Bolund grd, Bolund roughness grd), a map file containing the height contours and the roughness of Bolund (Bolund map) and a text file with a description of the file formats. The geometrical shape of the hill consists of a vertical escarpment that makes the Bolund hill a challenging test case for most flow solvers but the sharp change in surface roughness also adds to the complexity. The surface roughness of Bolund is described very simply in the topography files: Bolund is covered by grass with an estimated roughness length of 0.015m and for the surrounding water a roughness length of 0.0003m has been selected. The water roughness changes with wind speed, however, in order to unify the blind comparison a value of 0.0003m must be used (see Figure 3). The roughness in the topography files was updated on 01/06/09 to the values described in this document. Please ensure that you are using the correct roughness.

On figure 2 the 10 masts are numbered from 0-9. At mast M0 and mast M9 the "undisturbed" wind conditions were measured for westerly and easterly winds respectively. The free wind conditions given below were measured at these masts. Mast M0 was placed in the sea on a platform firmly positioned on the sea bed. During the experiment the water level changed, consequently changing the measurement height on M0. This of course complicates things somewhat. In the topography files the water level has been set to z=0.75m. The measurements used in the blind comparison cases have, among other parameters, been sorted based on water level (75cm ± 40cm) and even though the mean water level for some of the cases is slightly different than 75cm all simulations must be performed with a water level of 75cm.

The topography files only cover the region very close to Bolund (see Figure 3). Modelers must expand the map as far as they feel appropriate for their particular model,
however, $x = \pm 400\text{m}$ is the minimum. When expanding the map the terrain height / water height of 75 cm should be kept and a roughness length of $z_0=0.0003\text{m}$ should be kept around Bolund. The only exception is for the eastern region ($x > 327\text{m}$) (see figure 3) where the roughness length of $0.015\text{m}$ should be used. The participants of the blind comparison will be asked to simulate four cases (see description below). Each of the cases will be characterized by the velocity and turbulent kinetic energy at an upstream location (reference location) where the wind is considered undisturbed by Bolund. For the experiment this location is mast M0 for westerly winds and M9 for easterly winds. For participants, the reference measurements should be applied at the inlet boundary of their modeling space even though this location does not coincide with the reference location. Participants are encouraged not to optimize their inlet boundary condition in order to achieve the measured velocity profiles at M0 and M9. The effect of this will be minimal on the final non-dimensional results.

### 2.2 Instrumentation description

During the campaign, velocity and turbulence were collected simultaneously from 35 anemometers (23 sonic and 12 cups) on ten masts (see figure 2). As already described, the “undisturbed” wind was measured at mast M0 and M9. The remaining masts were located along two lines (line A and B) with a $239^\circ$ and $270^\circ$ direction respectively. The positions of the masts are given in Table 1. The ground levels (gl) in Table 1 (water level for mast M0) are the same as in the topography files. In the following, slightly different terrain heights may appear. This is due to changes in the water level during the experiment. However, for all blind comparison simulations the official water level of $0.75\text{m}$ must be used.

The masts were instrumented with a combination of sonic (S) and cup (C) anemometers. Mast M0 and M9 were instrumented with 4 cups in approximately 2m, 5m, 9m
Table 1: The positions of the masts. The real ground level for M9 is 1.39m, however, in order to simplify the blind comparison this height has been changed to 0.75m

<table>
<thead>
<tr>
<th>Mast ID</th>
<th>x (E) [m]</th>
<th>y (N) [m]</th>
<th>g1 [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>M0</td>
<td>-180.832</td>
<td>-103.267</td>
<td>0.75</td>
</tr>
<tr>
<td>M1</td>
<td>-52.426</td>
<td>-30.987</td>
<td>0.78</td>
</tr>
<tr>
<td>M2</td>
<td>-34.840</td>
<td>-21.110</td>
<td>10.80</td>
</tr>
<tr>
<td>M3</td>
<td>3.220</td>
<td>0.000</td>
<td>11.66</td>
</tr>
<tr>
<td>M4</td>
<td>51.458</td>
<td>30.612</td>
<td>1.37</td>
</tr>
<tr>
<td>M5</td>
<td>1.502</td>
<td>-48.926</td>
<td>2.59</td>
</tr>
<tr>
<td>M6</td>
<td>-46.121</td>
<td>0.242</td>
<td>11.47</td>
</tr>
<tr>
<td>M7</td>
<td>-66.887</td>
<td>0.016</td>
<td>0.81</td>
</tr>
<tr>
<td>M8</td>
<td>92.009</td>
<td>-0.136</td>
<td>2.00</td>
</tr>
<tr>
<td>M9</td>
<td>327.326</td>
<td>-39.296</td>
<td>0.75</td>
</tr>
</tbody>
</table>

an 15m height in order to measure the mean velocity profile. Additionally, sonics were placed in 5m height on both masts to measure turbulence. An additional sonic was placed in 12m height at M0 during the experiment. The measurements at these masts will provide the wind input for the blind comparison. Temperature measurements were performed at M0 and M9. In addition to the heat fluxes measured by the sonics these measurements enabled the data to be sorted based on temperature stratification (only neutral conditions are used in the blind comparison). The other masts were mostly instrumented with sonics and all masts had sonics in 2m and 5m height. Table 2 gives an overview of the instrumentation. During the experiment some masts were instrumented with additional sonics, e.g. at M2 in 1m and 3m height.

Table 2: An overview of the instrumentation during the experiment. The heights are only approximate. C - Cup anemometer, S - Sonic anemometer, L - Lidar.

<table>
<thead>
<tr>
<th>Mast ID</th>
<th>2m</th>
<th>5m</th>
<th>9m</th>
<th>15m</th>
<th>Lidar</th>
</tr>
</thead>
<tbody>
<tr>
<td>M0</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>-</td>
</tr>
<tr>
<td>M1</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>M2</td>
<td>S</td>
<td>S</td>
<td>C</td>
<td>S</td>
<td>L</td>
</tr>
<tr>
<td>M3</td>
<td>S</td>
<td>S</td>
<td>C</td>
<td>S</td>
<td>-</td>
</tr>
<tr>
<td>M4</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>M5</td>
<td>S</td>
<td>S</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>M6</td>
<td>S</td>
<td>S</td>
<td>C</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>M7</td>
<td>S</td>
<td>S</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>M8</td>
<td>S</td>
<td>S</td>
<td>C</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>M9</td>
<td>C</td>
<td>C</td>
<td>S</td>
<td>C</td>
<td>L</td>
</tr>
</tbody>
</table>
3 The Blind Comparison

This section describes the four cases (wind directions) that modelers must simulate in the Bolund blind comparison. Three of the cases are for westerly wind directions and the final case is for wind from the east. The description below defines how the simulations should be conducted and must be read carefully. In order to get an accurate picture of how the different flow models behave all modelers should use the same boundary conditions. This is necessary in order to minimize user errors and unify the comparison. Surely, boundary conditions cannot be controlled freely for all the flow models that participate in the comparison, however, each modeler must strive to use the specified input as closely as possible.

3.1 definitions

The coordinate system is a right handed regular East (u in the x-direction)- North (v in the y-direction) coordinate system. The vertical axis is pointing upwards for positive values. The coordinate center has been placed at (694682.098; 6177441.825) (UTM WGS84 zone 32) and z=0 is 0.75m below the local water level. The coordinate center has been changed in order to avoid round off errors and must be kept. The wind direction (where the wind comes from) is defined with 0° true north and increasing clockwise, i.e. 270° denotes westerlies. The 10min averaged velocity vector is \( \mathbf{u} = (u, v, w) \) and the total velocity (wind speed), \( s \), is defined by,

\[
s = (u^2 + v^2 + w^2)^{1/2}
\]  

(1)

The r.m.s (root mean square) or standard deviation of \( u \) is denoted by \( u' \) and is also found from 10min averages. It is important to stress that all statistics used in the blind comparison are based on 10 minutes averages. The turbulent kinetic energy, TKE, is defined to be half the sum of mean-square fluctuations,

\[
TKE = 0.5 (u'^2 + v'^2 + w'^2)
\]  

(2)

The shear stress, \( \tau \), is an important scaling parameter and from this the friction velocity, \( u_\tau \), is defined

\[
u_\tau^2 = \tau/\rho = \left( \overline{u'w'^2} + \overline{v'w'^2} \right)^{1/2},
\]  

(3)

where \( \rho \) is the air density. Finally, we define the Monin-Obukhov length,

\[
L = -\frac{u_\tau^2 \theta}{g \kappa \psi}
\]  

(4)

where \( \kappa \) is the von Karman constant, \( g \) is the acceleration of gravity and \( \theta \) is the potential temperature. A lowercase \( \theta \), e.g. \( u_{\theta_{0}} \), denotes that the specific value is evaluated at an upstream reference location (for the experiment at mast M0 or M9 depending on wind direction).
### 3.2 Simulation cases

Participants are asked to provide results for four simulation cases. The three first cases are three easterly wind directions (270°, 255°, 239°), otherwise with the same free wind conditions (the wind is coming from the sea). The fourth case is with the wind from the east (90°) where the upstream terrain has a somewhat larger roughness. The four cases are listed in Table 3 where the wind direction, roughness length and TKE of the free wind are listed. The roughness in Table 3 is used when defining the free stream velocity (see below), the roughness defined in the topography files (and figure 3) should be kept. A friction velocity is also given in Table 3. If participants need to specify a specific wind speed / friction velocity in their model then this is the value that should be used.

<table>
<thead>
<tr>
<th>Case</th>
<th>Wind direction (°)</th>
<th>Roughness length, $z_0$ [m]</th>
<th>$\frac{TKE_{0}}{u_{e0}^2}$</th>
<th>$u_{e0}$ [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>270</td>
<td>0.0003</td>
<td>5.8</td>
<td>0.4</td>
</tr>
<tr>
<td>2</td>
<td>255</td>
<td>0.0003</td>
<td>5.8</td>
<td>0.4</td>
</tr>
<tr>
<td>3</td>
<td>239</td>
<td>0.0003</td>
<td>5.8</td>
<td>0.4</td>
</tr>
<tr>
<td>4</td>
<td>90</td>
<td>0.015</td>
<td>5.8</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Participants should if possible apply the well-known logarithmic velocity profile at their reference location / computational boundary,

$$s = \frac{u_{e0}}{\kappa} \log \left( \frac{z_{egl}}{z_0} \right)$$

(5)

where $\kappa = 0.4$ and the surface roughness ($z_0$) and friction velocity ($u_{e0}$) is given in Table 3. $z_{egl}$ is the height above ground level i.e. $z_{egl} = z - 0.75m$. Similarly, the turbulent kinetic energy (if available in the model) should be prescribed as constant with height with the following value,

$$\frac{TKE}{u_{e0}^2} = 5.8$$

(6)

The profiles of velocity and TKE that should be used in the blind comparison are shown on Figure 4. The actual measured values are also shown on Figure 4 and are also given in Table 4. These measurements and all other measurements used in the blind comparison are for neutrally stratified conditions ($|L/L| < 0.004$).

In order to unify comparisons participants should use the same air properties if these are needed as input for the models. Simulations should be run with dry air with a density at sealevel of $\rho = 1.229\text{kg/m}^3$, dynamic viscosity of $\mu = 1.73 \cdot 10^{-5}\text{kg/m/s}$ and temperature of $T = 15^\circ\text{C}$ (zero heat flux $w^0 = 0$). Furthermore the gravitational acceleration is $g = 9.81\text{m/s}^2$ and a coriolis parameter of $f = 1 \cdot 10^{-4}\text{s}^{-1}$ should be used if needed.
Table 4: Free wind conditions at M0 for case 1-3 (wind direction is 270°, 255°, 239°) and free wind conditions at M9 for case 4 (wind direction is 90°). The table gives the mean velocity from cups and sonics and the turbulent kinetic energy from sonics. The numbers in the brackets are the standard deviations. The heights of the instruments are given in the global coordinate system and as the height above water level.

<table>
<thead>
<tr>
<th>Inst. type</th>
<th>x [m]</th>
<th>y [m]</th>
<th>z [m]</th>
<th>z_{agl} [m]</th>
<th>s/u_{0} [-]</th>
<th>TKE/u_{0}^{2} [-]</th>
</tr>
</thead>
<tbody>
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</tbody>
</table>
3.3 Simulation Output

For each of the 4 cases specified in Table 3, participants are asked to provide the model results in simple text files (ascii format) with the output as described below. The filename of the 4 files must follow the conversion codenumber_casenumber.dat. For instance a participant that has received the "code number” of ID0001 should provide 4 files named ID0001_1.dat, ID0001_2.dat, ID0001_3.dat and ID0001_4.dat. The files should be submitted to Risø DTU before November 1, 2009 by email to andh@risoe.dtu.dk. Please attach the 4 result files to the email and write the model number in the subject line.

The output that should be provided in the result files and their units are given in Table 5. Participants are asked to extract their model results in 600 points given in the file output_points.dat. Each of the 600 lines in output_points.dat consists of x, y, z, s, u, v, w, TKE, w'w', v'v', w'w', u, (see Table 5). The result files therefore consist of 600 lines (one for each point) and 12 columns (one for each quantity). Some models are only capable of predicting the wind speed, for such models the result files should still have 12 columns but column 8-12 should consist of the letters “nan”. Similarly, if a model can predict wind speed and TKE but not the variances (w'w', v'v', w'w' and u,) then column 9-12 should consist of “nan”. Most models that participate cannot predict the variances so most result files will consist of 7 or 8 columns with numbers and 4 or 5 columns with the letters “nan”. The files should not contain a text header. For all four cases (the four wind directions) the results should be given in the already defined coordinate system. For case 4 where the wind is from the east the u-component of the velocity will have a negative sign. Finally, all quantities should be given SI units i.e. meters and seconds.
Experimental modelers are only required to simulate case 1 and 3 and have fewer result points. If you need to be registered as an experimental modeler then please write an email to andh@risoe.dtu.dk.

Table 5: Output quantities and measurement conventions.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Quantity description</th>
<th>Convention</th>
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<tr>
<td>x</td>
<td>Position in the east/west direction [m]</td>
<td>See definition section</td>
</tr>
<tr>
<td>y</td>
<td>Position in the north/south direction [m]</td>
<td>See definition section</td>
</tr>
<tr>
<td>z</td>
<td>Vertical position [m]</td>
<td>See definition section</td>
</tr>
<tr>
<td>s</td>
<td>The total velocity [m/s]</td>
<td>See Equation 1</td>
</tr>
<tr>
<td>u</td>
<td>East/west component of the velocity [m/s]</td>
<td>See definition section</td>
</tr>
<tr>
<td>v</td>
<td>North/south component of the velocity [m/s]</td>
<td>See definition section</td>
</tr>
<tr>
<td>w</td>
<td>Vertical component of the velocity [m/s]</td>
<td>See definition section</td>
</tr>
<tr>
<td>TKE</td>
<td>Turbulent kinetic energy [m$^2$/s$^2$]</td>
<td>See Equation 2</td>
</tr>
<tr>
<td>$w'w'$</td>
<td>East/west component of TKE [m$^2$/s$^2$]</td>
<td>See definition section</td>
</tr>
<tr>
<td>$v'v'$</td>
<td>North/south component of TKE [m$^2$/s$^2$]</td>
<td>See definition section</td>
</tr>
<tr>
<td>$w'w'$</td>
<td>Vertical component of TKE [m$^2$/s$^2$]</td>
<td>See definition section</td>
</tr>
<tr>
<td>$u_c$</td>
<td>Local friction velocity [m$^2$/s$^2$]</td>
<td>See Equation 3</td>
</tr>
</tbody>
</table>

References

Risø DTU is the National Laboratory for Sustainable Energy. Our research focuses on
development of energy technologies and systems with minimal effect on climate, and
contributes to innovation, education and policy. Risø has large experimental facilities
and interdisciplinary research environments, and includes the national centre for nuclear
technologies.