Blind Comparison Simulation Cases

Bechmann, Andreas; Berg, Jacob; Courtney, Michael; Ejsing Jørgensen, Hans; Mann, Jakob; Sørensen, Niels N.

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Presentations from “The Bolund Experiment: Workshop” 3-4\textsuperscript{th} 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”.

Abstract (max. 2000 char.):
Contents

1 Introduction 4
   1.1 Agenda 5
   1.2 Participants 6

2 Presentations 8
   2.1 “Welcome” - by Andreas Bechmann 8
   2.2 “The Askervein Experiment” - by Peter A. Taylor 15
   2.3 “The Bolund Experiment” - by J. Berg, J. Mann and H.E. Jørgensen 33
   2.4 “Blind Comparison Results” - by Andreas Bechmann 72
   2.5 “LES of turbulent wind flows in the ABL.” - by Vijayant Kumar 102
   2.6 “Physical Modeling of Bolund” - by Brad C. Cochran 120
   2.7 “RANS simulations of flow around Bolund” - by Niels Sørensen 137

3 Blind Comparison Simulation Cases 153
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>9:45 The Askervein Experiment</td>
<td>Vijayant Kumar, Macquarie Capital</td>
</tr>
<tr>
<td>Peter A. Taylor, York University</td>
<td>Marc Parlange &amp; Chad Higgins, EPFL</td>
</tr>
<tr>
<td>10:30 Coffee</td>
<td>10:00 Coffee</td>
</tr>
<tr>
<td>10:40 The Bolund Experiment</td>
<td>10:10 Wind Tunnel Modeling of Bolund</td>
</tr>
<tr>
<td>J. Berg, J. Mann &amp; H.E. Jørgensen, Riso DTU</td>
<td>Brad C. Cochran, CPP Wind</td>
</tr>
<tr>
<td>12:10 Group Photo</td>
<td>10:50 RANS Simulation of Bolund</td>
</tr>
<tr>
<td>12:30 Lunch</td>
<td>Niels Sorensen, Riso DTU</td>
</tr>
<tr>
<td>13:30 Blind Comparison Results</td>
<td>11:30 Poster Introduction</td>
</tr>
<tr>
<td>Andreas Bechmann, Riso DTU</td>
<td>12:00 Lunch + Poster / Coffee</td>
</tr>
<tr>
<td>14:45 Coffee</td>
<td>14:00 Panel Discussion: Flow modeling</td>
</tr>
<tr>
<td>16:00 Questions to Bolund Team</td>
<td>Peter Taylor, Brad Cochran, Vijayant Kumar</td>
</tr>
<tr>
<td>17:00 Bus to Scandic Hotel &amp; Dinner</td>
<td>Niels Sorensen, Jakob Mann</td>
</tr>
<tr>
<td>19:00 Conference Dinner</td>
<td>15:45 Close</td>
</tr>
</tbody>
</table>

* Sponsored by Vestas Technology R&D
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                      ANSYS UK Ltd
Steve Evans                             CD-adapco
Dennis Nagy                             CD-adapco
Bibiana Garcia                          CENER
Javier Sanz Rodrigo                     CENER
John Prosapopoulos                      Centre for Renewable Energy Sources and Saving
Brad Cochran                            CPP
Rémi Gandoin                            DONG Energy
Jonathon Sumner                         Ecole de technologie superieure
Per Nielsen                             EMD International AS
Morten Lybech Thøgersen                 EMD International AS
Hanne Thomassen                         Energiyløsen
Mano Benso                              EREDA
Carlos Hernandez Medina                  EREDA
Moreira Raquel                          EREDA
Anja Geiger                             ETHZ, GWH
Paolo Muscioniaco                       ETHZ, GWH
Pascal Podstransky                      ETHZ, GWH
Jose Lagonha Palma                      FEUP/CEsA
Thomas Hahn                             Fluid & Energy Engineering GmbH & Co. KG
Steffen Wussow                          Fluid & Energy Engineering GmbH & Co. KG
Sharad Tripathi                         FLUIDYN
Lars Landberg                           Garrad Hassan and Partners Ltd
Joel Manning                            Garrad Hassan and Partners Ltd
Richard Whiting                         Garrad Hassan and Partners Ltd
Per Østergaard                          Go Virtual Nordic AB
Sven Perzon                            Go Virtual Nordic AB
Michael Schatzmann                      Hamburg University
Espen Akervik                           Kjeller Vindteknikk AS
Ove Undheim                            Kjeller Vindteknikk AS
Vijayant Kumar                          Macquarie Capital
Roshan Oberoi                           Metacomp Technologies, Inc.
Céline Bazault                          MeteoDyn
Stephane Popinet                        National Institute of Water and Atmospheric research (NIWA)
Ferran Palau                            Normawind
Keld Olsen                              Råd. Ing. Keld E. Olsen
Gerd Habenicht                          RES
Andreas Bechmann                        Risø DTU
Jacob Berg                              Risø DTU
Jesper Grønnegaard Pedersen             Risø DTU
Per Hansen                              Risø DTU
Poul Hummelsjøh                         Risø DTU
Niels Otto Jensen                       Risø DTU
Hans E. Jørgensen                       Risø DTU
<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Georgios Mandrekas</td>
<td>Rise DTU</td>
</tr>
<tr>
<td>Jakob Mann</td>
<td>Rise DTU</td>
</tr>
<tr>
<td>Pierre-Elouan Mikael Rethore</td>
<td>Rise DTU</td>
</tr>
<tr>
<td>Morten Nielsen</td>
<td>Rise DTU</td>
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<td>Niels Nørmark Sørensen</td>
<td>Rise DTU</td>
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<td>Andrey Sogachev</td>
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<td>Frederik Zahle</td>
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<td>Flemming Rasmussen</td>
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<td>Ib Troen</td>
<td>Rise DTU</td>
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<tr>
<td>Corinne Weaver</td>
<td>RWE npower Renewables Ltd</td>
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<tr>
<td>Jeppe Johansen</td>
<td>Siemens Wind Power</td>
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<td>Jesper Laursen</td>
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<td>Kasper Mortensen</td>
<td>Siemens Wind Power</td>
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<td>Morten Rams Quistgaard</td>
<td>Siemens Wind Power</td>
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<tr>
<td>Brian Broe</td>
<td>Suzlon Wind Energy A/S</td>
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<tr>
<td>Jørgen Højstrup</td>
<td>Suzlon Wind Energy A/S</td>
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<tr>
<td>Monika Polster</td>
<td>TÜV NORD Systec GmbH &amp; Co. KG</td>
</tr>
<tr>
<td>Mathias Gehl</td>
<td>Vattenfall Research &amp; Development AB</td>
</tr>
<tr>
<td>Jens Madsen</td>
<td>Vattenfall Research &amp; Development AB</td>
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<td>Ylva Odemark</td>
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<td>Javier Püvi</td>
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<td>Mark Zagar</td>
<td>Vestas Wind &amp; Site Competence Centre</td>
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<tr>
<td>Søren Holm Mogensen</td>
<td>Vestas Wind Systems A/S</td>
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<td>Tavor Hristov</td>
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<tr>
<td>Cheng-Hu Hu</td>
<td>Vestas Wind Systems A/S</td>
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<tr>
<td>Gregory Oxley</td>
<td>Vestas Wind Systems A/S</td>
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<tr>
<td>Arne Gravdahl</td>
<td>WindSim AS</td>
</tr>
<tr>
<td>David Weir</td>
<td>WindSim AS</td>
</tr>
<tr>
<td>Xiao Yu</td>
<td>York University</td>
</tr>
<tr>
<td>Peter Taylor</td>
<td>York University</td>
</tr>
<tr>
<td>Wengsong Weng</td>
<td>York University</td>
</tr>
</tbody>
</table>
“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 ...
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-l, 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
2 Zephyr North Canada, Burlington, Ontario

Originated from IEA meetings about 1980
Discussions with Unsal Hassan (then with CERL),
Paul Mason (UKMO) and others.
BASIC 1982, 1983 reports at:
http://www.yorku.ca/pat/research/Askervein/index.html

Report: MSRB-83-3

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
Askervein Map B Master Grid

Figure 2: Same as Figure 1 except the area covered is referred to in the text as Map B and the original contour map was specially prepared for the Askerven study at a scale of 1:5,000, see text for further details. Heights are in metres above sea level and the contour interval is 10 m. Topographic features to the north and east of Askerven have been blanked out as they were incomplete on the original map.
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 FLOW OVER TOPOGRAPHY: IMPACTS OF THE ASKERVEIN 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 Askervein 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 Askervein 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 Askervein are outlined. Problems associated with model simulations are noted and model results are compared with the field measurements.

27. Article The Askervein Hill project: Overview and background data P. A. Taylor and H. W. Teunissen
The Askervein 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 Askervein 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 Askervein Hill Project. It presents results from the Askervein 1982 and 1983 experiments... Volume 43, Numbers 1-2 / April, 1988 PDF (1.6 MB)
Bolund, $L/z_0 = 0.73 - 3.7 \times 10^3$; $h/L = 1.0 - 0.2$; $h = 10.9$ 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 $z_0 = h/2$.

Run TU-03B, $\Phi = 210^\circ$, 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 ($z_0$)</th>
<th>$Ri^*$</th>
<th>$z_0/\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mont03</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>-0.0038</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

Askervein '83, Raw Data – Tala Kites and Turbulence Runs
Fig. 6a. Sample plots of normalized wind speed at Δr = 10 m along A and B lines, Askervein '82. (a) A line; (b) B line. Each mean of 30 min values, error bars denote one standard deviation; ( ) questionable data; —— MS3DH/3 model results.

Fig. 10. Normalized wind speed at Δr = 10 m along AA line for selected wind directions and comparisons with MS3DH/3 model results. Data are based on averages for the direction groups listed in TT87, Table 7b excluding runs with |RE| > 0.015. Upstream wind directions: (a) 135°; (b) 180°; (c) 210°; (d) 265°. Each mean of 10 min values, error bars denote one standard deviation; —— MS3DH/3 model results.

MS3DH does well on upstream side of the hill but not in lee of the hill when intermittent separation occurs.
Simple Guidelines estimates, GLW: $A = 3.5 - 4$, $B = 1.8 - 1.6$

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; + Askervie '82 runs, $\Delta z = 10$ m; x Askervie '83 runs, $\Delta z = 10$ m; O Askervie '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

$\varphi = 165^\circ$

$\varphi = 180$

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, $\varphi$. 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. Run 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

![Diagram of turbulence statistics](image)

Fig. 4a. Profiles of wind speed and integral turbulence statistics at RS and ASW60. (a) Run TU01-B, \( \varphi = 180^\circ \). (b) Run TU03 B, \( \varphi = 210^\circ \).

- RS data: ◊ Cup anemometers; + Sonic anemometers; × Tilted Gill UVW anemometers; □ Vertical Gill UVW (10 m).
- ASW60 data: ■ Vertical Gill UVW.

\( \varphi = 210^\circ \), note blocking at ASW 60

![Diagram showing turbulence statistics](image)

= 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 formulas to be considered (JH, JEN and CL, respectively) are:

1. \( (L/L) w(L/L) = 2\nu^2 \)
2. \( (L/L) w^2(L/L) = 2\nu^2 \)
3. \( (L/L) w(L/L) = \text{constant} \)

![Graph showing inner layer depths as a function of wind direction.

The roughness length anomaly

Table 3.7: Profile-derived \( z_0 \) and \( u_* \) values at CP and BSE10 during selected NF runs, Oct. 7-10, 1993.

<table>
<thead>
<tr>
<th>Run</th>
<th>( z_0 ) (m)</th>
<th>( u_* ) (m/s)</th>
<th>( \zeta_0 ) (m)</th>
<th>( u_0 ) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MF01-A</td>
<td>0.0003</td>
<td>0.63</td>
<td>0.0013</td>
<td>0.55</td>
</tr>
<tr>
<td>MF01-B</td>
<td>-</td>
<td>-</td>
<td>0.0010</td>
<td>0.68</td>
</tr>
<tr>
<td>MF02</td>
<td>-</td>
<td>-</td>
<td>0.0000</td>
<td>0.63</td>
</tr>
<tr>
<td>MF03</td>
<td>0.0012</td>
<td>0.64</td>
<td>0.0006</td>
<td>0.58</td>
</tr>
<tr>
<td>MF04</td>
<td>0.0011</td>
<td>0.65</td>
<td>0.0013</td>
<td>0.60</td>
</tr>
<tr>
<td>MF06</td>
<td>0.0007</td>
<td>0.58</td>
<td>0.0009</td>
<td>0.59</td>
</tr>
<tr>
<td>MF06-C</td>
<td>-</td>
<td>-</td>
<td>0.0011</td>
<td>0.62</td>
</tr>
<tr>
<td>MF10-A</td>
<td>-</td>
<td>-</td>
<td>0.0008</td>
<td>0.56</td>
</tr>
<tr>
<td>MF10-B</td>
<td>-</td>
<td>-</td>
<td>0.0007</td>
<td>0.53</td>
</tr>
</tbody>
</table>

Based on winds measured at 0.5m and 3m levels.

Note: Hilltop area appears rougher than \( z_0 \), \( u_* \) 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 Lochbuisdale Hotel. Back row left to right: Elizabeth Moughton (ERA), Peter Taylor (AES), David Hudson (BRE), Tony Bewen (U. of Canterbury), Nick Cook (BRE), Bob Johnson (ERA), Jim Arnold (AES), Finn Hansen (Riso), Mogens Nielsen (Riso), Bob Wickle (AES), Thomas Kurer (U. of Hanover). Seated: Karl Yanek (AES), Hans Teunissen (AES), Kurt Engel (U. of Hanover), Jim Salmon (CAM), Rasool Nourshargh (ERA), Niels Otto Jensen (Riso). Seated on floor: Wes Roberts (AES), Gunnar Rispeard (Riso), John Deary (AES). Not in photo: Bob Belton (ERA), Doug Wurte (ERA), Martin Shaw (BRE).
**The Bolund Experiment**

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:
- $h = 12 \text{ m}$
- $L = 86 \text{ m}$
- $z_0 = 2 \text{ cm}$
- $I = 1.9 \text{ m (m', NDJ)}$

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”. 

Beddows et al. The Bolund Experiment
The Bolund peninsula
Map width: 50 km

The Bolund peninsula
Map width: 7 km
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

![Laser scan image]

### Masts

![Diagram of masts]

---

Bechmann et al. | The Solund Experiment
### Erection of masts

![Images of masts being erected](images)

Buchmann et al., The Bolund Experiment

### Instrumentation

- 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

![Images of various instruments](images)

Buchmann et al., The Bolund Experiment
### Sonic Configuration

<table>
<thead>
<tr>
<th>Mast. ID</th>
<th>2m</th>
<th>5m</th>
<th>9m</th>
<th>15m</th>
<th>Lidar</th>
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<tbody>
<tr>
<td>M0</td>
<td>C</td>
<td>C,S</td>
<td>C</td>
<td>C</td>
<td>-</td>
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<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>
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</tr>
<tr>
<td>M5</td>
<td>S</td>
<td>S</td>
<td>-</td>
<td>-</td>
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<tr>
<td>M6</td>
<td>S</td>
<td>S</td>
<td>C</td>
<td>-</td>
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<td>M7</td>
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<td>-</td>
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<td>M8</td>
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<td>C</td>
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<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

[Image of technical diagram]
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
The upstream mast M0: Atmospheric stability

\[ Ri = \frac{g \Delta \Theta_v}{\Theta_v \Delta U^2} \]

\[ L = \frac{u^2 \Theta_v}{\kappa \bar{g} \bar{w} \Theta_v} \]

Bochmann et al.  The Bolund Experiment

Fetch

\[ \approx 7 \text{ km} \]

\[ \approx 4 \text{ km} \]

\[ = 0 \text{ km} \]
Atmospheric stability: $z/L$ versus $Ri$

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

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

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

$180^\circ < \theta < 360^\circ$ and $U_0 > 8$ m/s

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

$180^\circ < \theta < 360^\circ$ and $U_0 > 12$ m/s
Neutral upwind profile

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

Log-profile with

$\kappa = 0.46$

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

Upstream turbulence
$U_v < U < 10 \text{ m/s}$

Bechmann et al.  The Bolund Experiment
Upstream covariances

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

Upstream spectra

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

Bechmann et al. | The Baland Experiment

The experiment | The upstream conditions | Flow around the hill | Main2 | Downstream | Conclusions

---

[Graph showing wind direction and tilts at different distances]

---

[Graph showing wind direction and tilts at different distances]

---

[Graph showing wind direction and tilts at different distances]
Deflection at line A (5 m above terrain)

Bechmann et al.

The Boland Experiment
Turbulence spectra at line A (5 m above terrain)

Speed at M2

Bechmann et al.  The Bolund Experiment
Turbulence intensity at M2

Bechmann et al., The Bølund Experiment

Turbulence spectra at Mast 2 (239 degrees)

Bechmann et al., The Bølund Experiment
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)

¹European 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
  - 5: LES / hybrid RANS-LES
- 37: Non-linear CFD model
  - 7: RANS 1 eqn. (k-ε, Spalart-Allmaras)
  - 25: RANS 2 eqn. (k-epsilon, k-omega)
Content
1. Introduction
2. Measurements & Simulations
3. Results
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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: ± 80°
2. Monin-Obukhov length: |1/L| < 0.004 m\(^{-1}\) (L > 250 m)
3. Water level: ± 0.4 m
4. Wind speed 5 m agl: 5 ms\(^{-1}\) < \(\nu\) < 12 ms\(^{-1}\) (\(z_0\approx 1.5\times10^{-4}\) m, Charnock)
5. 10 min time series

Measurements: Comparing with Simulation

1. \(u^*\): 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, Mast M0, Dir 270°

Wind speed-up, Mast M7, Dir 270°

Riso DTU, Technical University of Denmark
Results of the Inravel Wind Comparisons 03 dec 2009
Simulation: Normalizing

Content
1. Introduction
2. Measurements & Simulations
3. Results
4. Analysis
5. Conclusions
Results: Speed-up

Wind speed-up, Line B, Dir 270°

Z=5m

Z=2m

Relative position along line B [m]

Results: Speed-up

Wind speed-up, Mast M7, Dir 270°

Wind speed-up, Mast M8, Dir 270°

Height [m]

s/s_{ref} [-]
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
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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5. Conclusions
Analysis

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

RANS 1 eq. models
RANS 2 eq. models

Wind speed-up, Line A, Dir. 239°

Z = 5m

\[
\text{LES} \quad \text{RANS 1 eqn.} \quad \text{RANS 2 eqn.}
\]

20/25 models

Z = 2m

RANS 2 eqn.: 18%

RANS 2 eq. models

Wind speed-up, Line A, Dir. 239°

Z = 5m

\[
\text{Linearized} \quad \text{LES} \quad \text{RANS 1 eqn.} \quad \text{RANS 2 eqn.}
\]

19/25 models

Z = 2m

RANS 2 eqn.: 17%
### Top 10 List

<table>
<thead>
<tr>
<th>ID</th>
<th>Turb. model</th>
<th>Error [%]</th>
<th>Error 5m [%]</th>
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<td>6</td>
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<td>5</td>
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<td>5</td>
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<td>RANS k-epspilon</td>
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<td>7</td>
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<td>5</td>
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<td>ID0034</td>
<td>RANS 1 eqn.</td>
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<td>7</td>
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<td>10</td>
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<tr>
<td>ID0006</td>
<td>RANS k-epspilon</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 Kumar
Chad Higgins
Marc Parlange
Charles Meneveau

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

Bolund Workshop: Dec 4, 2009
Understanding the ABL: Methods

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

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

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

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

- Direct Numerical Simulation (DNS)
- Resolve all scales
- Computationally impossible for realistic ABL flows

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

DNS: Direct Numerical Simulation
LES: Large Eddy Simulation
RANS: Reynolds Averaged Navier-Stokes Model
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(uncr) => GIGO (-)

Incompressible Navier-Stokes, Re \sim 10^8

\[ \frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial (\tilde{u}_i \tilde{u}_j)}{\partial x_j} = 0 \]

\[ \frac{\partial \tilde{u}_i}{\partial t} + \frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \frac{\partial \theta}{\partial x_j} \right) \delta_{ij} - \frac{\partial \tau_{ij}}{\partial x_j} + f(\tilde{u}_2 - \bar{V}_2) \delta_{i1} - f(\tilde{u}_1 - \bar{V}_1) \delta_{i2} \]

Subgrid scale modeling

\[ \tau_{ij} = \tilde{u}_i \tilde{u}_j - \bar{u}_i \bar{u}_j \quad \pi_{ij} = \bar{u}_i \theta - \bar{u}_i \bar{\theta} \]
**LES: SGS Modeling**

\[
\tau_{ij} = -2\nu_c \delta_{ij}; \quad \pi_j = -\frac{\nu_c}{P_{\text{SGS}}} \frac{\partial \theta}{\partial x_j}; \quad \nu_t = (C_{S_\delta} \Delta)^2 |S_{ij}|; \quad S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)
\]

Eddy Viscosity ($\nu_t$) type models:

<table>
<thead>
<tr>
<th>Static Smagorinsky</th>
<th>Dynamic Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant value $C_{S_\delta, \lambda}$ imposed everywhere</td>
<td>$C_{S_\delta, \lambda}$ determined dynamically from the resolved scales</td>
</tr>
<tr>
<td></td>
<td>$C_{S_\delta, \lambda}$ 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**

- **DNS**: Direct Numerical Simulation
- **LES**: Large Eddy Simulation
- **RANS**: Reynolds Averaged Navier-Stokes Model
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 = fit user => GIGO (-)

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

\[
\begin{align*}
\frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial (\tilde{u}_i \tilde{u}_j)}{\partial x_j} &= 0 \\
\frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial (\tilde{u}_i \tilde{u}_j)}{\partial x_j} &= \frac{1}{\rho} \frac{\partial \tilde{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \frac{\rho}{\partial x_j} - f(\tilde{u}_2 - \tilde{u}_1) \right) \frac{\partial \tilde{u}_j}{\partial x_j} \\
\frac{\partial \tilde{\theta}}{\partial t} + \tilde{u}_j \frac{\partial \tilde{\theta}}{\partial x_j} &= \frac{\partial}{\partial x_j} \delta_{ij} - \omega_{ij} \delta_{ij} + f(\tilde{u}_2 - \tilde{u}_1) \delta_{ij} - f(\tilde{u}_1 - \tilde{u}_2) \delta_{ij}
\end{align*}
\]

\( \tau_{ij} = \tilde{u}_i \tilde{u}_j - \tilde{u}_i \tilde{u}_j \)

\( \pi_{ij} = \tilde{u}_i \tilde{\theta} - \tilde{u}_i \tilde{\theta} \)
LES: SGS Modeling

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

Eddy Viscosity (v_t) type models:

<table>
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</tr>
</thead>
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<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>

Dynamic SGS model formulation

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

\[ L_{ij}^m = T_{ij}^m - \tau_{ij}^m \]
Assume scale invariance \(\rightarrow C_{s,2\Delta} = C_{s,\Delta} \)

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

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

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**
  \[ \overline{C_{n,n}} \]

- **Spatial averaging**

- **New averaging method**

- **Averaging over fluid pathlines**

- **Lagrangian Dynamic Model (LASI)**

- **Scale-dependence**

- **Lagrangian Dynamic scale-dependent SGS model (LASD)**

- **Properties**
  - Physically motivated averaging
  - Ideal for complex topography
  - Point-wise unique
  - 3D local variability preserved
  - Can handle unsteady flows
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 $\Rightarrow$ 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, 1988
**LES of Nocturnal Stable ABL**

---

SGS models become important

---

**LES of Quasi-steady ABLs: A review**

**Unstable ABL** (Schmidt & Schumann, 1999; 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
SGS model performance: Energy spectra

Unstable (0.2 Km/s) and Stable (-0.02 Km/s) simulations:
Lagrangian Dynamic Scale-invariant and Scale-dependent models

LES of Diurnal ABL

FREE TROPOSPHERE

Entrainment

CONVECTIVE (UNSTABLE) LAYER

Eddies/Plumes

RESIDUAL LAYER

STABLE LAYER

RESIDUAL LAYER

STABLE LAYER
Results: Diurnal ABL characteristics

Evolution of the stable and unstable ABL

Evolution of the nocturnal low-level jet

Results: Diurnal ABL characteristics

Sensible Heat Flux (resolved+SGS): $\overline{w'\theta'} + \overline{\pi_3}$

Smagorinsky coefficient, $C_s$
**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**

- **Precursor run:** LES over flat terrain
  
  $t = t + 1$

- **Inflow fields for LES**
- **LES over topographic features**
- **Buffer region at the end of domain:** Buffers outflow to inflow field for next time step

**LES Results**
**LES study: Flow over a Gaussian Hill**

Data from Iwamura et al. 1981

**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

Balund Workshop: Dec 4, 2009
LES study: Flow over a steep Alpine Hill

Cross ridge flow

- 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. (2009), CURMS'
LES study: Flow over a steep real-world Hill
“Physical Modeling of Bolund” - by Brad C. Cochran

Physical Modeling of Bolund in an Atmospheric Boundary Layer Wind Tunnel

Brad C. Cochran
Sr. Associate
CPP, Inc.
1415 Blue Spruce Drive
Fort Collins, CO
www.cppwind.com

Atmospheric Boundary Layer Wind Tunnel Schematic

Low Velocity Region w/ Turning Vanes
4 – 12 kW Fans
Blockage Resistant Roof
Converging Nozzle
Flow Straighteners
Boundary Layer Development Section
Test Section
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
Physical Modeling

Theory

Navier-Stokes Equations

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

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

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

Physical Modeling

Scaling Parameters

- Undistorted scaling geometry
- Equal dimensionless boundary and approach flow conditions
- Equal Rossby number – \( \frac{UL}{\Omega} \)
- Equal gross Richardson number – \( \frac{\Delta T/T}{UL^2} \)
- Equal Reynolds number – \( \frac{UL}{\nu} \)
- Equal Prandtl number – \( \frac{\nu}{k/\rho C_p} \)
- Equal Eckert number – \( \frac{U^2}{\rho C_p(\Delta T)} \)
Physical Modeling
Scaling Parameters

- Undistorted scaling geometry
- Equal dimensionless boundary and approach flow conditions
  - Equal Rossby number: $U/L\Omega$
  - Equal gross Richardson number: $[\Delta T/T](L/U^2)g$
  - Equal Reynolds number: $UL/\nu$
  - Equal Prandtl number: $\nu/(k/\rho C_p)$
  - Equal Eckert number: $U^2/[C_p(\Delta T)]$

*Coriolis effects minimal in the near field

[Neutral Stratification]
Physical Modeling
Scaling Parameters

\[
\left( \frac{UL}{v} \right)_{\text{model}} = \left( \frac{UL}{v} \right)_{\text{fullscale}}
\]

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

\[
(v)_{\text{model}} = (v)_{\text{fullscale}} \quad \text{NOT}
\]

\[
(U)_{\text{model}} = \left( \frac{(U)_{\text{fullscale}}}{100} \right) = 1000 \text{ m/s}
\]

Physical Modeling
Reynolds Number Independence

- Ensure a fully turbulent wake flow

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

- \( U = 10 \text{ m/s} \)
- \( H_T = 0.25 \text{ m} \)
- \( v = 1.15 \times 10^{-5} \text{ m}^2/\text{s} \)
- \( R_{e_T} = 217,391 \)
History Timeline


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

Golden (1961) Defines minimum acceptable Reynolds number to achieve Reynolds number independence
Risø-R-1745(EN)

**History Timeline**

- **Cermak and Davenport (1964)** measured wind loads on a scale model of the World Trade Centers in New York.

**Wind Engineering & Air Quality Consultants**

---

**History Timeline**

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

**Wind Engineering & Air Quality Consultants**
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

WIND ENGINEERING & AIR QUALITY CONSULTANTS
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
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

\[
\begin{align*}
\text{Data Power Law} & : \quad n^* = 0.09 \\
\text{Intercept} & : \quad 0.905
\end{align*}
\]

Data Log Law

\[
\begin{align*}
\text{Data Log Law} & : \quad \beta^* = 0.12 \\
\text{Intercept} & : \quad 0.302 \\
\text{Slope} & : \quad 0.0001
\end{align*}
\]

Target

\[
\begin{align*}
\text{Target} & : \quad n^* = 0.10 \\
\text{Intercept} & : \quad 0.002
\end{align*}
\]

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
Flow Visualization
270 Degree Wind Direction

Results
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

RANS CFD simulations of flow around Bolund

Niels N. Sørensen and Andreas Bechmann

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.

\[
\bar{U}(z) = \frac{u_\tau}{\kappa} \ln \left( \frac{z}{z_0} \right), \quad \mu_\ell = \rho \kappa u_\tau z, \quad \frac{\epsilon(z)}{\kappa z} = C_{\mu}^{\frac{3}{2}} \frac{k(z)}{\kappa z}, \quad k(z) = \frac{u_\tau^2}{\sqrt{C_\mu}}.
\]

\[
C_{\epsilon 1} = C_{\epsilon 2} - \frac{\kappa}{C_\mu^{\frac{3}{2}} \sigma_\epsilon}.
\]

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.

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.
Surface Grid (1)

Surface Grid (2)
Is the digital terrain correct

- And how good is the roughness estimation?
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**

---

Risø DTU, Technical University of Denmark

RANS predictions of Solund 03/12/2009
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)

---

21 Rise DTU, Technical University of Denmark  RANS predictions of Bolund  03/12/2009

---

22 Rise DTU, Technical University of Denmark  RANS predictions of Bolund  03/12/2009
Grid Convergence (3)

Convergence of the equations
**Order of accuracy**

![Graph showing order of accuracy](image)

**Non-linearities due to the terrain and wind direction**

![Graph showing non-linearities](image)

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.rixoe.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 cause 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 are 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,
Figure 3: Definition of surface roughness and terrain height for the the blind comparison.

However, $x = \pm 0.001m$ is the minimum. When expanding the map the terrain height / water height of 75cm should be kept and a roughness length of $z_0=0.0003m$ should be kept around Bolund. The only exception is for the eastern region ($x > 327m$) (see figure 3) where a roughness length of $0.015m$ 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° and 270° 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 0.75m 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 1.39 m, however, in order to simplify the blind comparison this height has been changed to 0.75 m.

<table>
<thead>
<tr>
<th>Mast ID</th>
<th>x (E) [m]</th>
<th>y (N) [m]</th>
<th>zL [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 15 m height in order to measure the mean velocity profile. Additionally, sonics were placed in 5 m height on both masts to measure turbulence. An additional sonic was placed in 12 m 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 2 m and 5 m height. Table 2 gives an overview of the instrumentation. During the experiment some masts were instrumented with additional sonics, e.g. at M2 in 1 m and 3 m 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,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>
<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,S</td>
<td>C</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,

\[
    s = (u^2 + v^2 + w^2)^{0.5}
\]  

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,

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

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

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

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

\[
    L = -\frac{u_\tau^3 \theta}{g \kappa \theta'}
\]

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>$TKE_0/\bar{u}_0^2$</th>
<th>$\bar{u}_0$ [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,

$$s = \frac{u_0}{\kappa} \log \left( \frac{z_{ref}}{z_0} \right)$$  

(5)

where $\kappa = 0.4$ and the surface roughness ($z_0$) and friction velocity ($u_0$) is given in Table 3. $z_{ref}$ is the height above ground level i.e. $z_{ref} = z - 0.75m$. Similarly, the turbulent kinetic energy (if available in the model) should be prescribed as constant with height with the following value,

$$\frac{TKE}{\bar{u}_0^2} = 5.8$$  

(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 ($|\Pi/L| < 0.004$).

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 seal level of $\rho = 1.229 kg/m^3$, dynamic viscosity of $\mu = 1.73 \cdot 10^{-5} kg/ms$ and temperature of $T = 15^\circ C$ (zero heat flux $w'\theta' = 0$). Furthermore the gravitational acceleration is $g = 9.81 m/s^2$ and a coriolis parameter of $f = 1 \cdot 10^{-4} s^{-1}$ 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>( u/u_0 ) [-]</th>
<th>( TKE/u_{so}^2 ) [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CASE 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cup</td>
<td>-180.83</td>
<td>-103.27</td>
<td>3.1</td>
<td>2.3</td>
<td>21.88 (1.68)</td>
<td>-</td>
</tr>
<tr>
<td>Cup</td>
<td>-180.83</td>
<td>-103.27</td>
<td>6.1</td>
<td>5.3</td>
<td>23.39 (1.70)</td>
<td>-</td>
</tr>
<tr>
<td>Cup</td>
<td>-180.83</td>
<td>-103.27</td>
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<td>12.3</td>
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<td>3.1</td>
<td>2.4</td>
<td>23.05 (2.35)</td>
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<td>-103.27</td>
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<td>15.4</td>
<td>26.67 (2.76)</td>
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<td>-103.27</td>
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<td>5.4</td>
<td>24.31 (2.49)</td>
<td>6.55 (1.10)</td>
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<tr>
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<td>-103.27</td>
<td>13.1</td>
<td>12.4</td>
<td>25.85 (2.67)</td>
<td>6.56 (1.31)</td>
</tr>
<tr>
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<td>13.31</td>
<td>13.31 (1.28)</td>
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<td>15.30 (1.41)</td>
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<td>14.66 (1.37)</td>
<td>6.74 (0.87)</td>
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</tbody>
</table>
Figure 4: Inlet profiles of velocity and TKE. Symbols are measurements and full lines are the input that should be used by participants. The blue color are for cases 1-3 while red is for case 4.

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 convention `codenumber.casenameumber.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 sandh@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 a x, y and z - values. The result files (`codenumber.casenameumber.dat`) should also consist of 600 lines in a similar format but each line should consist of the quantities in the following order: x, y, z, s, u, v, w, TKE, u'u', 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 (u'u', v'v', w'w') 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>
</tr>
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<tbody>
<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 [m²/s²]</td>
<td>See Equation 2</td>
</tr>
<tr>
<td>$u'u'$</td>
<td>East/west component of TKE [m²/s²]</td>
<td>See definition section</td>
</tr>
<tr>
<td>$v'v'$</td>
<td>North/south component of TKE [m²/s²]</td>
<td>See definition section</td>
</tr>
<tr>
<td>$w'w'$</td>
<td>Vertical component of TKE [m²/s²]</td>
<td>See definition section</td>
</tr>
<tr>
<td>$u_c$</td>
<td>Local friction velocity [m²/s²]</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.