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The Bolund Experiment: A Validation Dataset

1 Introduction

The Bolund experiment was a field campaign that provides validation data for models that resolve the flow on scales relevant for wind turbine siting, and was the basis for a blind comparison of flow models. This document contains instructions that enable modelers to simulate the four test cases used in a recent blind comparison. Files relevant to this document:

`Ris-R-1658.pdf` (Report about the experiment)
`Bolund_Orography.zip` (The Bolund topography)
`Bolund_Measurements.zip` (The blind comparison dataset and present document)
`Bolund_Questionnaire.zip` (Blind comparison questionnaire and extraction points)

You are free to use the data in the four files but please remember to cite Bechmann et al. [2], Berg et al. [3]. Also, if you need access to the full measurement database please contact A. Bechmann.

2 The Experiment

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 Risø DTU. Figure 1 gives an

overview of the Bolund orography and the positions of the ten masts that supported the instrumentation. For a detailed description of the Bolund experiment please see [1] (`Ris-R-1658.pdf`). A short description of the experiment is found below. This description was made in connection with a recently held blind comparison and contains the suggested simulation parameters for the blind comparison participants. The suggested parameters are a good starting point when performing simulations.

2.1 Topography Description

The topography information (`Bolund_Orography.zip`) 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` and `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 will change with wind speed and direction (fetch length) but a mean value of 0.0003m is recommended (see Figure 2).

On Figure 1 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 given below have, among other parameters,

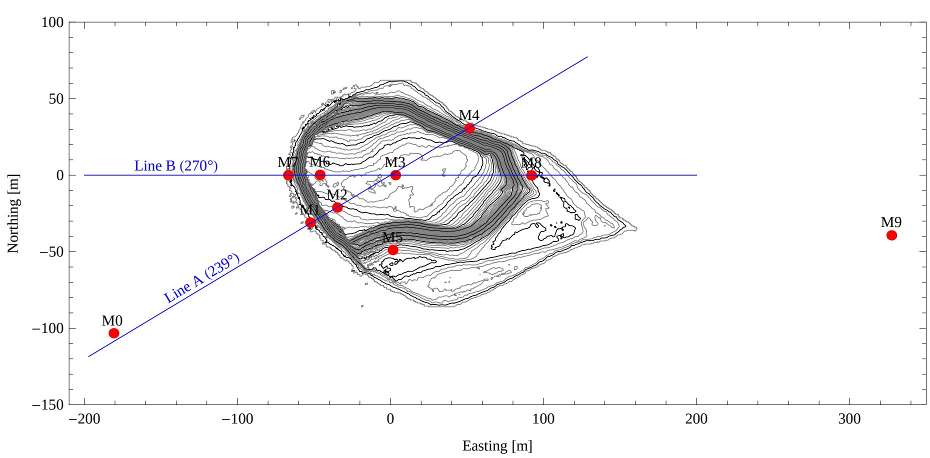

Figure 1: The Bolund orography and the positions of the ten masts

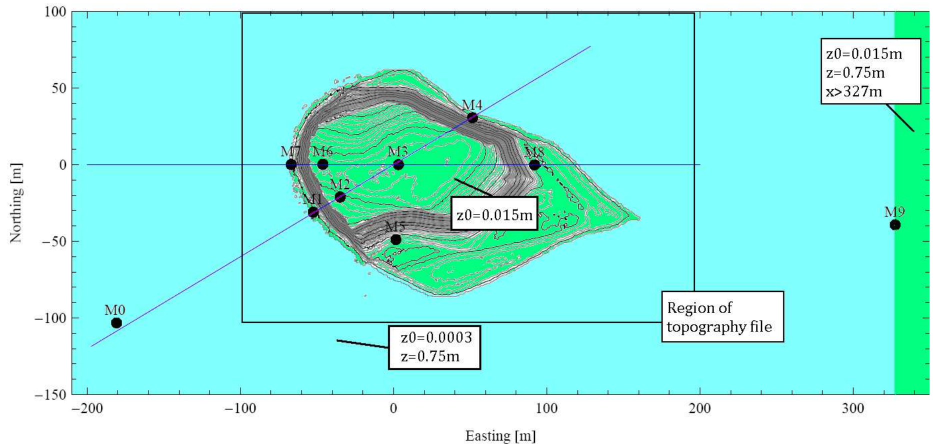

Figure 2: Definition of surface roughness and terrain height used for the the blind comparison.

been sorted based on water level (0.75m $\pm$ 0.40m).

The topography files only cover the region very close to Bolund (see Figure 2). Modelers must expand the map as far as they feel appropriate for their particular model, however, for the blind comparison $x = \pm 400$m was the minimum. When expanding the map the terrain/water height of 0.75m is recommended and a roughness length corresponding to water (z0=0.0003m) should be kept around Bolund. The only exception is for the eastern region ($x > 327$m) (see Figure 2) where the coast starts and the value of land roughness (z0=0.015m) should be used.

The participants of the blind comparison were asked to simulate four cases (see description below). Each of the cases were characterized by the velocity and turbulent kinetic energy at an upstream location (reference location) where the wind was considered undisturbed by Bolund. For the experiment this location is mast M0 for westerly winds and M9 for easterly winds. To ease the work, we recommended modelers to apply the reference measurements at the inlet boundary of their modeling space even though this location did not coincide with the reference location. Modelers were not encouraged to optimize their inlet boundary condition in order to achieve the measured velocity profiles at M0 and M9.

2.2 Instrumentation description

During the campaign, velocity and turbulence were collected simultaneously from 35 anemometers (23 sonics and 12 cups) on ten masts (see Figure 1). 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 and going through the coordinate center. 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.

Table 1: The positions of the masts. The real ground level for M9 is 1.39m, however, since no topography file exist for this region and in order to simplify simulations this height has been changed to 0.75m

Mast ID.	x (E) [m]	y (N) [m]	gl [m]
M0	-180.8	-103.3	0.75
M1	-52.4	-31.0	0.80
M2	-34.9	-21.1	10.80
M3	3.2	0.0	11.70
M4	51.5	30.6	1.40
M5	1.5	-48.9	2.60
M6	-46.1	0.2	11.50
M7	-66.9	0.0	0.80
M8	92.0	-0.1	2.00
M9	327.3	-39.3	0.75

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

Mast. ID	2m	5m	9m	15m	Lidar
M0	C	C,S	C	C	-
M1	S	S	S	-	-
M2	S	S	C,S	-	L
M3	S	S	C,S	-	-
M4	S	S	S	-	-
M5	S	S	-	-	-
M6	S	S	C	-	-
M7	S	S	-	-	-
M8	S	S	C	-	-
M9	C	C,S	C	C	L

This is due to actual changes in the water level during the experiment. However, we recommend not to change the topography files and to use the official water level of 0.75m. The actual positions of the instruments (positioned on booms on the masts) are given below.

The masts were instrumented with a combination of sonic (S) and cup (C) anemometers. Table 2 gives an overview of the instrumentation while the precise locations of cups and sonics can be found in the file `Bolund_Measurements.zip`, where the instrumentation ID is defined by *mastnumber_approx height_intrsument type*, eg. *M0Z05S* is the sonic placed at M0 at approximately 5m height.

Mast M0 and M9 were instrumented with 4 cups in approximately 2m, 5m, 9m and 15m height in order to measure the mean velocity profile and sonics were placed in 5m height on both masts to measure turbulence. The friction velocity measured by these sonics, *M0Z05S* and *M9Z05S*, are used as reference for westerly and easterly wind respectively. Generally, the measurements at M0 and M9 should provide the boundary conditions for simulations. Temperature measurements were performed at M0 and M9, which in addition to the heat fluxes measured by the sonics enable the data to be sorted based on temperature stratification (only neutral data has been selected below). The eight other masts were mostly instrumented with sonics and had as a minimum sonics in 2m and 5m height. During the experiment some of the sonics were moved to new locations. These instruments can be identified by having a lower number of 10min timeseries included in the statistics (`Bolund_Measurements.zip`)

3 The Validation Case

This section describes the four cases (wind directions) that modelers simulated for the Bolund blind comparison. Three of the cases are for westerly wind directions and the final case is for wind from the east. Below, a description of how the simulations were defined is found. The aim of the blind comparison was to compare flow models. It was designed to minimize user errors and unify the input used, therefore it was important that modelers strived to use the same boundary conditions. The boundary conditions specified for the blind comparison are given below.

3.1 Definitions

The coordinate system used 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. The wind direction (where the wind comes from) is defined with 0° true north and increasing clockwise, i.e. 270° denotes westerlies. In the selected coordinate system, the velocity vector is $\mathbf{u} = (u, v, w)$. If the wind originates from the east (90°), the u-component of the velocity will bear a negative sign.

If u_i^n denotes the n^{th} sample of the velocity vector u_i ($i = 1, 2 \,\text{and}\, 3$) recorded by a sonic (sampling rate is 20 Hz) and N is the number of samples within a 10 min time series, then the 10 min mean, $\overline{u}_i$, is given by

$$\overline{u}_i = (\overline{u}, \overline{v}, \overline{w}) = \frac{1}{N} \sum_{n=1}^{N} u_i^n \, . \tag{1}$$

Similarly, the mean variances and covariances can be calculated by

$$\overline{u_i' u_j'} = \frac{1}{N} \sum_{n=1}^{N} [u_i^n - \overline{u}_i] \left[u_j^n - \overline{u}_j\right] \tag{2}$$

from which the friction velocity, $u_\star = \left[|\overline{u'w'}| + |\overline{v'w'}|\right]^{1/2}$ and the turbulent kinetic energy, $\overline{k} = \left[|\overline{u'u'}| + |\overline{v'v'}| + |\overline{w'w'}|\right]^{1/2}/2$, can be calculated. The wind speed, $\overline{s}$, can be

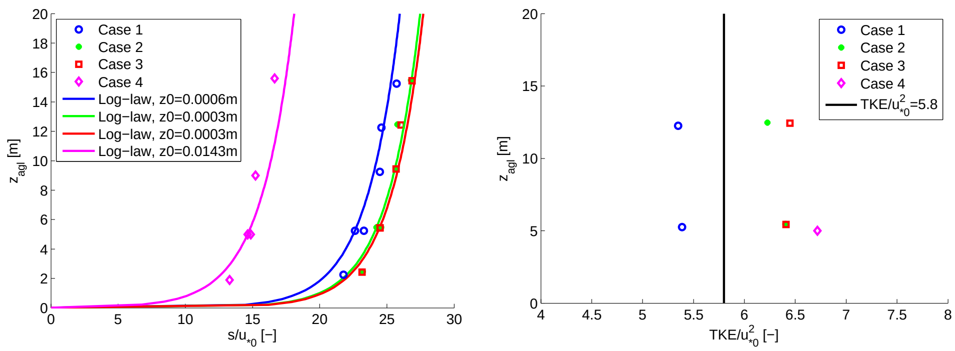

Figure 3: The freestream profiles of velocity and TKE. Symbols are measurements and full lines empirical functions.

found by vector or scalar averaging. Because vector scaling is comparable to most numerical methods, this following approach is used:

$$\bar{s} = \left[\overline{u}^2 + \overline{v}^2 + \overline{w}^2\right]^{1/2} . \tag{3}$$

Each of the 10-min averaged velocity vectors are made non-dimensional with the reference friction velocity, $u_{\star 0}$, of the particular time series, and the ensemble average of several 10 min means is determined. The lowercase 0 denotes the reference friction velocity evaluated at the upstream mast M0 or M9 for western and eastern winds, respectively, measured by sonic *M0Z05S* or *M9Z05S*. Measurements from cup anemometers are also made non-dimensional with the friction velocity measured by the two reference sonics.

3.2 Measurements

The three first cases used in the blind comparison were for easterly wind (270°, 255°, 239°)where the wind is coming from the sea and the fourth case was with the wind from the east (90°) where the upstream terrain has a somewhat larger roughness.

All the measurements made during the measuring period were corrected, aligned to the chosen coordinate system and stored in a MySQL database [1] (`Ris-R-1658.pdf`). When retrieving data from the database for the four cases only neutral conditions are considered and therefore only data with 10min averaged wind speeds exceeding $5ms^{-1}$ and $|1/L| < 0.004m^{-1}$ has been chosen, where L is Obukhov length.

The file `Bolund_Measurements.zip` can be downloaded from the Bolund web page (`http://bolund.risoe.dk`) and contains eight files (`Dir_case.dat`) with tabulated mean values and standard deviations for all cases used in the blind comparison. Table 3 and Figure 3 give the total velocity and turbulent kinetic energy at the reference masts. On Figure 3, logarithmic velocity profiles have been fitted to the measurements.

Table 3: 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 the height of the ground (water level) is given. Note that the height above ground level is found by $z_{agl} = z - gl$
.

Inst. type	x $[m]$	y $[m]$	z $[m]$	gl $[m]$	s/u_{*0} $[-]$	TKE/u_{*0}^2 $[-]$
			CASE 1			
Cup	-183.5	-102.7	3.1	0.8	21.77 (1.65)	-
Cup	-180.8	-103.3	6.1	0.8	23.29 (1.68)	-
Cup	-180.8	-103.3	10.1	0.8	24.48 (1.68)	-
Cup	-181.7	-101.7	16.1	0.8	25.72 (1.67)	-
Sonic	-181.3	-102.5	6.1	0.8	22.57 (1.71)	5.39 (0.67)
Sonic	-180.8	-103.3	13.1	0.8	24.53 (1.63)	5.35 (0.80)
			CASE 2			
Cup	-183.5	-102.7	3.1	0.6	23.21 (1.24)	-
Cup	-180.8	-103.3	6.1	0.6	24.57 (1.31)	-
Cup	-180.8	-103.3	10.1	0.6	25.69 (1.35)	-
Cup	-181.7	-101.7	16.1	0.6	26.80 (1.41)	-
Sonic	-181.3	-102.5	6.1	0.6	24.15 (1.26)	6.40 (1.04)
Sonic	-180.8	-103.3	13.1	0.6	25.69 (1.33)	6.23 (1.15)
			CASE 3			
Cup	-183.5	-102.7	3.1	0.6	23.16 (2.80)	-
Cup	-180.8	-103.3	6.1	0.6	24.50 (2.95)	-
Cup	-180.8	-103.3	10.1	0.6	25.68 (2.64)	-
Cup	-181.7	-101.7	16.1	0.6	26.87 (3.13)	-
Sonic	-181.3	-102.5	6.1	0.6	24.39 (2.97)	6.41 (1.14)
Sonic	-180.8	-103.3	13.1	0.6	25.98 (3.18)	6.45 (1.40)
			CASE 4			
Cup	327.3	-39.3	3.3	1.4	13.29 (1.26)	-
Cup	327.3	-39.3	6.4	1.4	14.88 (1.38)	-
Cup	327.3	-39.3	10.4	1.4	15.22 (1.40)	-
Cup	327.3	-39.3	17.0	1.4	16.64 (1.52)	-
Sonic	327.3	-38.4	6.4	1.4	14.62 (1.36)	6.72 (0.93)

3.3 Simulation parameters

Table 4 lists the four simulation cases for the blind comparison including wind direction, suggested roughness length, ground level at reference mast and TKE of the free wind. The roughness in Table 4 is the suggested value for defining the free stream velocity (see below). A friction velocity is also given in Table 4. If modelers needed to specify a specific wind speed / friction velocity in their model then this was the suggested value.

Participants were encouraged to apply the well-known logarithmic velocity profile at their reference location / computational boundary,

$$s = \frac{u_{*0}}{\kappa} \log\left(\frac{z_{agl}}{z_0}\right) \tag{4}$$

where $\kappa = 0.4$ and the surface roughness (z_0) and friction velocity (u_{*0}) is given in Table 4. z_{agl} is the height above ground level i.e. $z_{agl} = z - gl$ ($gl = 0.75$m). Similarly, the turbulent kinetic energy should be prescribed as constant with height with the following value,

$$\frac{TKE}{u_{*0}^2} = 5.8 \tag{5}$$

Profiles of velocity and TKE are shown on Figure 3. The roughness values shown on the figure were found by fitting the logarithmic velocity profile to the velocity measured by the reference sonic (*M0Z05S* or *M9Z05S*). When performing simulations, however, we recommend that modelers use a logarithmic velocity profile with $z_0 = 0.0003m$ for case 1-3 and $z_0 = 0.015m$ for case 4 since these values were used as boundary conditions in the blind comparison.

In order to unify comparisons participants were asked to use the same air properties if these were needed as input for the models. Simulations should be run with dry air with a density at sealevel of $\rho = 1.229$kg/m^3, dynamic viscosity of $\mu = 1.73 \cdot 10^{-5}$kg/ms and temperature of $T = 15$°C (zero heat flux $\overline{w'\theta'} = 0$). 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: The four simulation cases

Case	Wind direction [°]	Roughness length, z_0 $[m]$	gl $[m]$	TKE_0/u_{*0}^2 $[-]$	u_{*0} $[m/s]$
1	270	0.0003	0.75	5.8	0.4
2	255	0.0003	0.75	5.8	0.4
3	239	0.0003	0.75	5.8	0.4
4	90	0.015	0.75	5.8	0.5

3.4 Simulation Output

For each of the 4 cases specified in Table 4, participants were asked to provide the model results in simple text files (ascii format) with the output as described below. The filename of the 4 files followed the conversion *codenumber_casenumber.dat*. For instance a participant that 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 output that was to be provided in the result files and their units are given in Table 5. Participants were 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 - value. The result files (*codenumber_casenumber.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, $\overline{u'u'}$, $\overline{v'v'}$, $\overline{w'w'}$, u_* (see Table 5). The result files therefore consisted of 600 lines (one for each point) and 12 columns (one for each quantity). Some models were 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 could predict wind speed and TKE but not the variances ($\overline{u'u'}$, $\overline{v'v'}$, $\overline{w'w'}$ and u_*) then column 9-12 should consist of ”nan”. Most models that participated could not predict the variances so most result files consisted 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 was from the east the u-component of the velocity would have a negative sign. Finally, all quantities should be given SI units i.e. meters and seconds. Experimental modelers were only required to simulate case 1 and 3 and had fewer result points.

Table 5: Output quantities and measurement conventions.

Quantity	quantity description	Convention
x	Position in the east/west direction [m]	See definition section
y	Position in the north/south direction [m]	See definition section
z	Vertical position [m]	See definition section
s	The total velocity [m/s]	See Equation 3
u	East/west component of the velocity [m/s]	See definition section
v	North/south component of the velocity [m/s]	See definition section
w	Vertical component of the velocity [m/s]	See definition section
TKE	Turbulent kinetic energy [m^2/s^2]	See definition section
$\overline{u'u'}$	East/west component of TKE [m^2/s^2]	See definition section
$\overline{v'v'}$	North/south component of TKE [m^2/s^2]	See definition section
$\overline{w'w'}$	Vertical component of TKE [m^2/s^2]	See definition section
u_*	Local friction velocity [m/s]	See definition section

3.5 Conclusion

The present document shortly describes the Bolund experiment including the topography and instrumentation. For more details please see [1, 2, 3]. With focus on the blind comparison methodology, the document describes how modelers can perform their own simulations of the Bolund hill. For information about the results of the blind comparison and a recommended method of presenting simulation results please consult Bechmann et al. [2]. We would like to thank all the participants of the Bolund blind comparison for their great effort.

References

[1] Bechmann A, Berg J, Courtney M, Jørgensen H, Mann J, Sørensen N (2009) The Bolund Experiment: overview and background. Risø DTU report Risø-R1658(EN), 50 pp.

[2] Bechmann A, Sørensen, Berg J, Mann J, Réthoré PE (2011) The Bolund Experiment, Part II: Blind Comparison of Micro-Scale Flow Models. DOI:10.1007/s10546-011-9637-x. Boundary-Layer Meteorol -:–

[3] Berg J, Mann J, Bechmann A, Courtney M, Jørgensen H (2011) The Bolund Experiment, Part I: Flow Over a Steep, Three-Dimensional Hill. DOI:10.1007/s10546-011-9636-y. Boundary-Layer Meteorol -:–