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WRFLES - A system for high-resolution limited area numerical simulations

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Abstract An open source software system, called WRFLES, has been developed that greatly simplifies running the WRF atmospheric model in Large Eddy Simulation (LES) mode. The work was funded by the Bergen Center for Computational Science, Uni Research AS, in Norway, and carried out by the Institute for Meteorological Research in Iceland. Here, the system is tested in three different situations. Firstly it is found that modifying the land-use data, so as it becomes coherent with the high resolution topography data, is of importance for both simulated surface winds and temperature. This is especially true for coastal regions. Secondly, it is found that for a weather event of weak synoptic forcing the LES simulations overestimate the surface wind speed and underestimate the surface temperature, compared to observations and simulations done with the Mellor-Yamada-Janjic planetary boundary layer (MYJ PBL) scheme. This behavior is largely independent of the number of vertical sigma levels chosen, ranging from 55 to 139. Thirdly, when used to simulate a strongly synoptically forced weather event the over-prediction of surface winds of the WRF model in LES mode is still present. The under-prediction of surface temperature is however not present. This may be connected to how the LES model interacts with the surface model. In particular, the energy transport between surface and the atmosphere may have to be refined with the LES model.

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1 Introduction

A novel, open source, software system has been developed that greatly simplifies running the WRF atmospheric model (Skamarock et al, 2008) in Large Eddy Simulation (LES) mode. The system is named WRFLES, and was funded by the Bergen Center for Computational Science, Uni Research AS, in Norway, and carried out by the Institute for Meteorological Research in Iceland. Running the WRF model in LES mode can be both time consuming and confusing. Typically, one runs the model with a regular planetary boundary layer (PBL) scheme down to a horizontal resolution of few kilometers using the model's nesting option. Using the output data from the innermost (i.e. highest resolution) PBL domain, one can create initial and boundary data for the WRF model in LES mode. This is done by using a component of the WRF modeling suite called NDOWN (short for Nest DOWN). Once that is done, one can finally run the WRF model in LES mode for the chosen area. Care must be taken when editing the WRF model's control files (called namelist.wps and namelist.input) during this procedure. As the user defines the domain setup "top down", it can be very time consuming getting the exact location of the innermost domain correct. The new software package solves this by allowing the user to define the exact location, and extent, of the innermost domain. Either by defining two corner points, or by setting the domains center latitude and longitude as well as a radius. From these information the system than sets up the necessary control files in such a way that the innermost domain is as the user wishes for. The system further sets up a unique directory structure for each simulation, copies or links relevant input data and creates the necessary runtime scripts that make it straight forward to run the WRF model through all the necessary steps. Additionally, the system includes methods to use the (near global) 1 second ASTER topography data and the high resolution

Corine land-use data, that are available for large parts of Europe. The system has been tested for a number of locations in Norway, Denmark and Iceland. Main usability is foreseen in research of wind energy for regions with relatively complex terrain.

Here we describe how the WRFLES system works and represent results from three types of tests. Firstly the effects of syncing the land-use categories with the high resolution ASTER topography data are investigated. Secondly, the effects of varying the number of vertical levels on surface winds and temperatures is investigated for a weakly synoptically forced event of the coast of W-Norway in June 2008. It is also investigated how the relatively coarse resolution (1350 meters) LES simulations differ from simulations done with the Mellor-Yamada-Janjic (MYJ) PBL scheme (Janjić, 2001), and how the LES simulation respond to increased surface roughness. Model results are further compared to available surface observations. Thirdly, the system is tested on a southwesterly windstorm in W-Iceland in 2011. The windstorm is of the same type as described as a stone-mover in the saga of Egill Skallagrimsson and is influenced by the mountains south of the town of Borgarnes, located in the fjord of Borgarfjörður in W-Iceland.

2 Features of WRFLES and recommended use

The WRFLES software tool includes the following features:

- Setting up a directory hierarchy suitable for executing the steps of a WRF LES simulation.
- Calculating the namelist parameters corresponding to user defined criteria for the simulation region and generating the necessary namelists.
- Generating PBS scripts from templates that take care of the various steps in a WRF run.
- Includes stand alone python scripts to correct the geo_em and met_em files.
- Includes instructions on how to import 1 second ASTER topography data into WRF.
- Can be used with high resolution Corine land-use data.

In the WRFLES system the WRF model is run in LES mode and fully coupled to the surface physics of the Noah Land Use model. Figure 1 shows a typical domain setup resulting from WRFLES. In this case the innermost domain covers the island of Utsira off the west coast of Norway. The only part of WRFLES that is hard-coded to the system is the total number of domains used for the setup, currently the number of domains is six. The two outermost domains are run in PBL mode and are used to create the necessary input data for the remaining four LES domains. The resolution of the domains is defined by the user, the user defines the resolution of the innermost domain directly. The horizontal resolution of the remaining domains is than set by

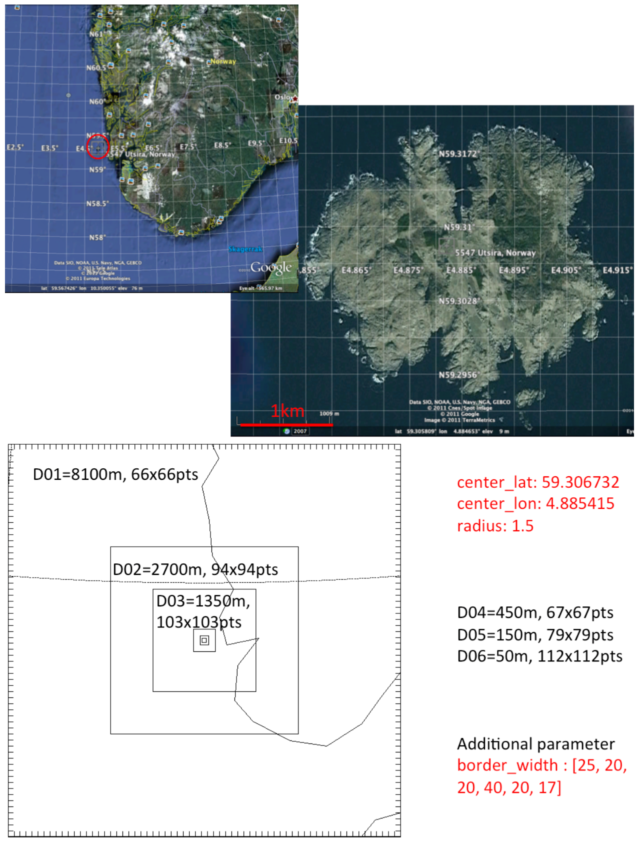

Fig. 1 Example of a six domain setup, using WRFLES. The innermost domain, covering the island of Utsira (top panel), has a 50 meter horizontal resolution, but the outermost domain has 8100 meter resolution.

defining the grid ratios (typically 2 or 3) between the domains. In the example shown in Fig. 1 the ratios are defined as $3(50\times3=150\text{m=D05}), 3(3\times150=450\text{m=D04}), 3(3\times450=1350\text{m=D03}), 2(2\times1350=2700\text{m=D02})$ and $3(3\times2700=8100\text{m=D01})$.

The parameter named `border_width` controls the number of grid points between individual domains. The value of 17, shown in Fig. 1 (lower panel to the right), shows that there are 17 "domain 1 grid points" around domain 2, 20 "domain 2 grid points" around domain 3, 40 "domain 3 grid points" around domain 4, etc. It is important that the outermost domains are sufficiently large in order to capture the synoptic situtaion forcing the atmospheric flow in the innermost LES domains. Consequently, the last three values of the `border_width` variable should not be too small.

By default the number of vertical sigma levels is 55, but as will be shown in sections 4 and 5 this number may be too low for regions where the topography is very steep. Different setups of the sigma levels are found in Appendix B.

A link to a tar bundle containing the WRFLES software suite, and detailed documentation of it and its use, is given in Appendix A. The system includes all necessary static and setup files to run WRF in LES mode for the island of Utsira, and the Havsul-area in Norway, as well as for the Bolund hill in Denmark.

3 Sensitivity to land-use data

To test the sensitivity of the LES model to changes in land-use we choose to simulate an event over the Danish island of Sjælland, with a focus on the hill of Bolund, just north of Roskilde (cf. Fig. 2). The reason for this choice is twofold. Firstly, the topography is relatively smooth and the effects of modified land-use will not be masked by local orography. Secondly, in late 2007 and early 2008 Risø/DTU hosted a field campaign[1] in order to provide a comprehensive dataset for validating models of atmospheric flow in complex terrain. Due to this, the WRFLES system includes a pre-configured

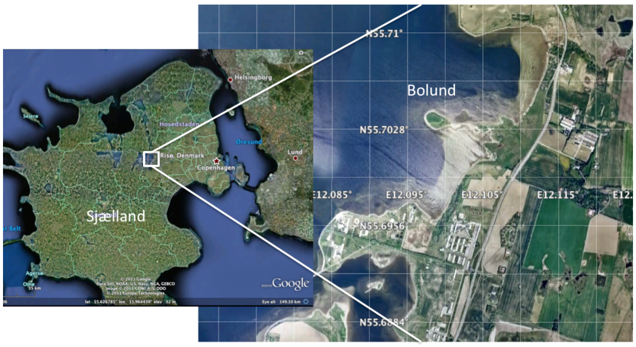

Fig. 2 Overview of Sjællend (left panel), the Bolund hill (right panel) is approximately 200×200 meters a side.

setup for the Bolund area. Figure 3 shows the differences in two meter temperature (top panel) and ten meter winds (middle and bottom panels) between LES simulations using the un-modified Corine land-use data and land-use data that have been synchronized with the high resolution ASTER topography data (modified minus un-modified). Not surprisingly, the main differences are near the coast and close to water bodies, i.e. in locations where grid cells are changed from being a "water point" to "land point" or vice versa. Figure 4 shows a time series of simulated wind speed at the Bolund hill (cf. black dot in Fig. 3) at 1 January, 2008. The resolution of the LES model is 1350 and 50 meters. For this particular location and time there is little difference between the 1350 and 50 meter resolution simulations. The simulated wind speed with the modified land-use is on average about 1 m/s greater than the simulated wind speed with the un-modified Corine land-use data.

Two python programs have been written to correct the geo_em and met_em files, these are called `ModifyGeoem.py` and `ModifyMetem.py`, respectively and are called from within the `preprocessing.sh` PBL script thusly:

```
for i in 3 4 5 6
do python2.6 ../bin/ModifyGeoem.py geo_em.d0$i.nc
done
```

and

```
for i in 3 4 5 6
do
list=`ls met_em.d0$i.*.nc`
for j in $list
do
python2.6 ../bin/ModifyMetem.py $j
done
done
```

One important threshold value can be tuned within the `ModifyGeoem.py` program, called `hgt_m`. This parameter decides whether the `landmask` variable is set to 0 or 1 (i.e. `landmask`=0 if `hgt_m`>`threshold`, else `landmask` is set to 1). Typically, the threshold value ranges between 0.01 and 0.1 meters. The purpose of the `ModifyGeoem.py` program is to ensure that the coastline, as seen by the ASTER data set, is in harmony with the `landmask` variable, derived from the Corine land-use data. The purpose of the `ModifyMetem.py` program is to ensure that the values of the `landsea` variable, derived from the GRIB input field, is identical to the modified `landmask` field. Further, `ModifyMetem.py` ensures that grid cells that have been re-classified as above see level are not defined as be "water bodies", i.e. the 3D variable `landusef` is modified accordingly.

[1] http://www.risoe.dtu.dk/da/research/sustainable_energy/wind_energy/projects/vea_bolund.aspx?sc_lang=en

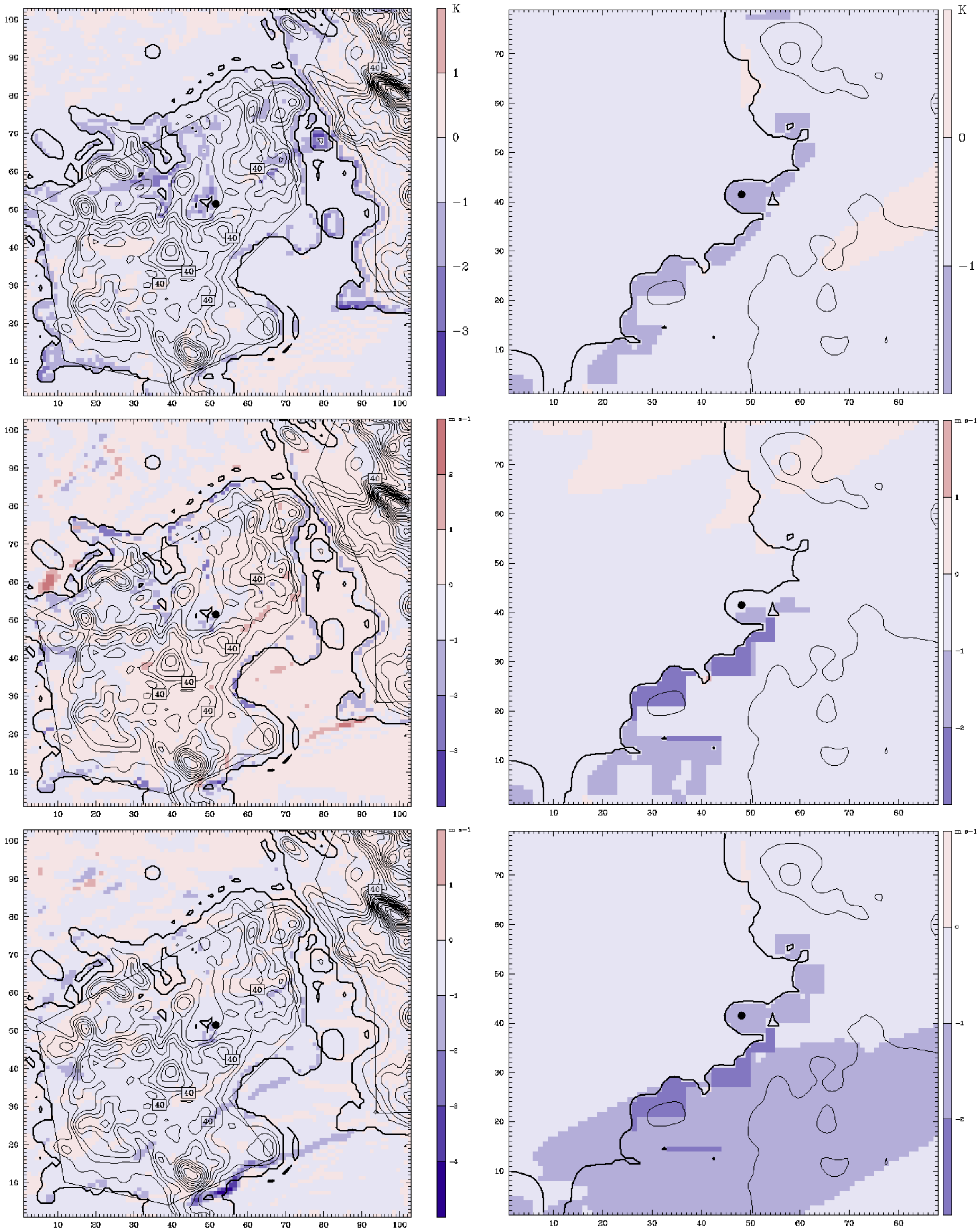

Fig. 3 Differences in surface temperature (top panel) [K] at 1350 (left panel) and 50 meter (right panel) resolution between modified and unmodified land-use. Middle panel shows the difference between east-west wind speed [m/s] at 10 meters above ground and bottom panel shows the difference between north-south wind speed component. The location of the island Bolund is indicated with a black dot. The difference is plotted at 1900 UTC, 1 January 2008.

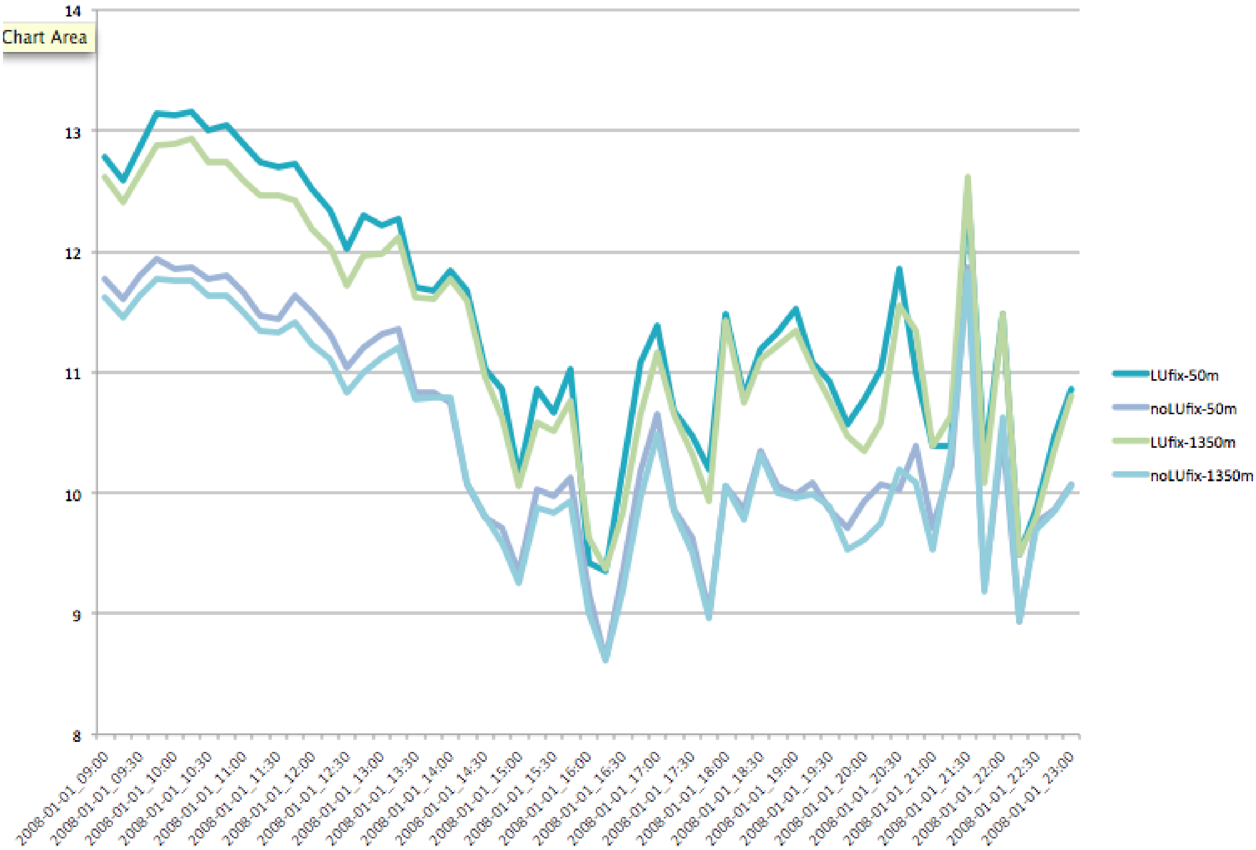

Fig. 4 Simulated surface wind speeds at Bolund, Denmark, at 50 and 1350 meter horizontal resolution with WRF in LES mode. The simulated wind speed is on average 0.5 to 1 m/s greater (top two lines labeled LUfix-50m and LUfix-1350m) when the Corine land-use data has been synchronized with the 1 second ASTER topography data. The simulations are valid for 1 January, 2008.

4 Sensitivity to vertical resolution and surface roughness

Figure 5 shows the domain setup of the 1350 meter resolution simulations for the island of Utsira. The domain is the same as the one marked as "D03" in Fig. 1 (bottom panel). All simulations were initialized with operational analysis from the ECMWF and are valid for 1 June, 2008. Number of full σ-levels range from 55 to 139 (55, 90, 91, and 139). In addition to different total number of sigma levels, the number of levels in the lowest 2000 meters differ between the setups. At 55 sigma levels there are approximately 30 levels in the lowest 2000 meters, about 15 for the 90 sigma level setup, 45 for the 91 sigma level setup and approximately 60 for the 139 sigma level setup.

Upper air observations for this day (00, 12, 24UTC) from Stavanger airport, located approximately 60 km southeast of the island of Utsira, show calm winds at the surface with southerly flow aloft. Surface observations reveal weak northerly flow during the night, veering to the south in the early morning and back north in a clockwise direction between 10 and 11 UTC.

Figure 6 shows the simulated surface wind speed at 1350 meter horizontal resolution using the MYJ PBL scheme (left panels) and the LES method (right panels) with various number of vertical levels. All simulations are valid at 18UTC, 1 June, 2008. The initial and boundary conditions are created using the NDOWN method, based on simulations using the MYJ PBL scheme. Hence, the behavior observed at the boundaries is a result of different numerics and parameterizations applied in the boundary layer. Initially (04UTC) the simulated surface flow is from the south, compared to observed flow from the north and northeast in the late night/early morning. The observed veering from southerly to northerly flow is delayed by 2–3 hours in all simulations compared to surface observations. This can presumably be linked to too short spin up time in the simulation used to force the 1350 meter grid. For the purposes of this study this is of little importance, but may play an important role in operational forecasts in situations where there is weak synoptical forcing. In all cases the wind speed is greater when simulated with the LES method compared to the MYJ PBL scheme. The total number of vertical sigma levels does not seem to be a decisive factor for surface wind speed in the LES simulations. Rather, the number of levels in the lowest 2000 meters is of greater importance. Coarser resolution, i.e. the 90 sigma level simulation, leads to weaker surface winds, compared to the other three setups (cf. Fig. 7). Figure 8 shows the difference in simulated surface winds and two meter temperature using the MYJ PBL scheme and the LES method (LES minus PBL). In all cases the LES simulations have greater wind speed, especially over land. The least difference in wind speed is when simulated with 90 sigma levels.

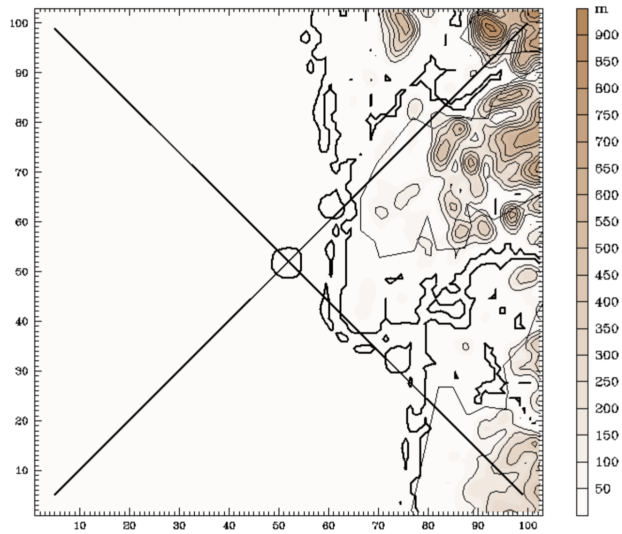

Fig. 5 Terrain height above sea level [m] of the 1350 meter resolution domain, the island Utsira is located in the center of the domain. Locations of cross-sections are indicated with the two straight lines.

The LES simulations are also in general slightly colder than the PBL simulations. The abnormal temperature difference seen in the top right panel of Fig. 8 (i.e. the difference between LES and MYJ PBL at 55 sigma levels) is an artifact of the NDOWN procedure and will be discussed in greater detail in subsection 4.1. This can also be seen in the time series for the two meter temperature at the Haugesund airport (cf. Fig. 7, green solid line, bottom panel). Figure 9 shows the differences between the LES and MYJ PBL simulations along the SW-NE cross-section shown in Fig. 5. All simulations are done at 1350 meter resolution and for various number of sigma levels (55, 90, 91, and 139). It is seen that the differences between the LES and PBL simulations at the surface are a shallow feature and are not found aloft. The differences between simulated flow in the lowest 200 hPa is linked to differences in vertical resolution rather than to different methods used to simulate the flow (LES vs. PBL). The low level wind shear is also similar in all simulations, regardless of which method is used to parameterize vertical transport of momentum. This indicates that the vertical mixing within the two methods are similar away from the surface. Energy transport between surface and the atmosphere is however different and needs to be refined with the LES model. This task is however beyond the scope of the current study.

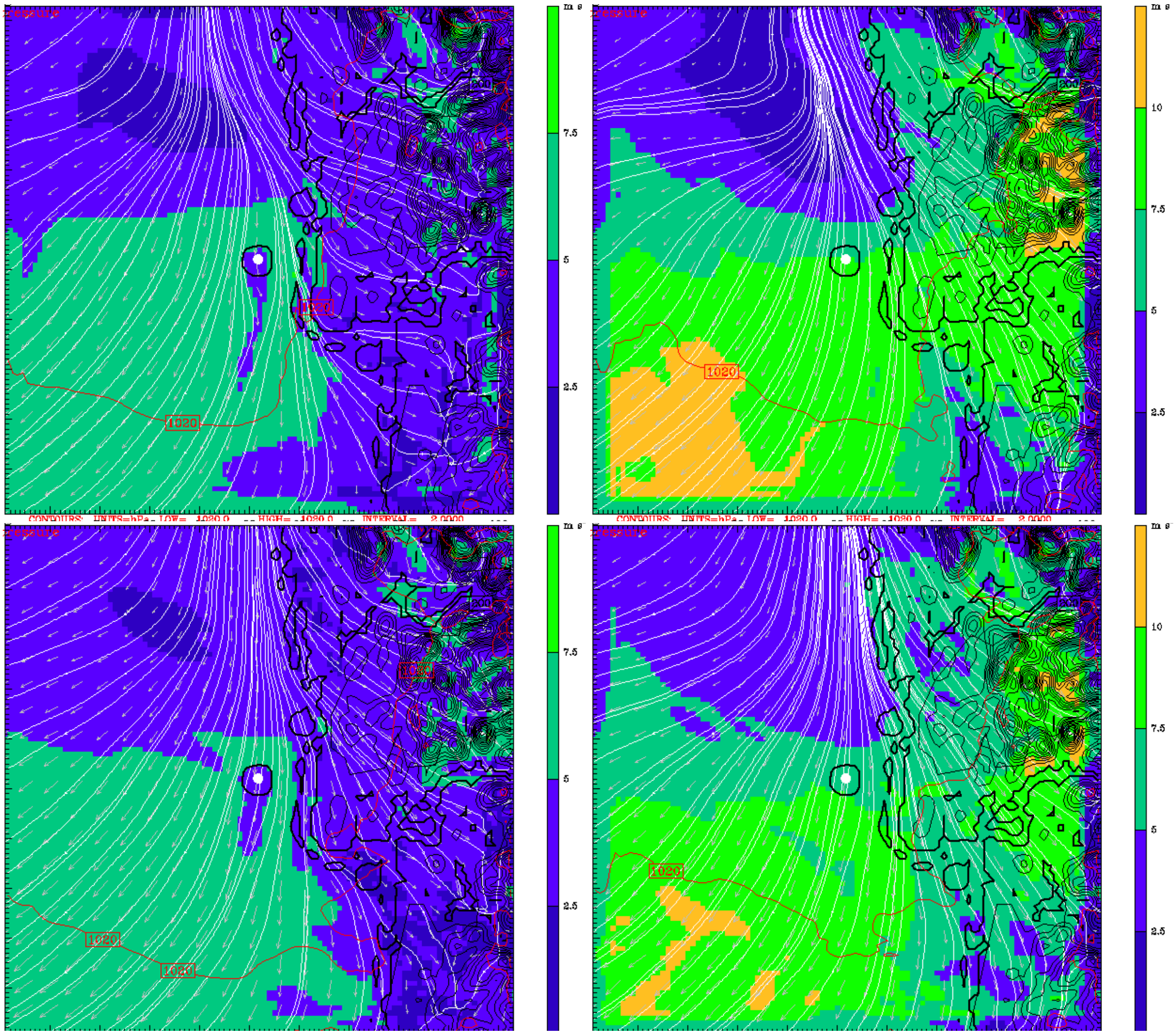

Fig. 6 Simulated surface winds [m/s], and streamlines, at 1350 meter horizontal resolution using the MYJ PBL scheme (left panels) and the LES (right panels) for various number of vertical sigma levels: 55 levels (top), 90 levels (bottom). Simulations are valid at 18UTC, 1 June 2008.

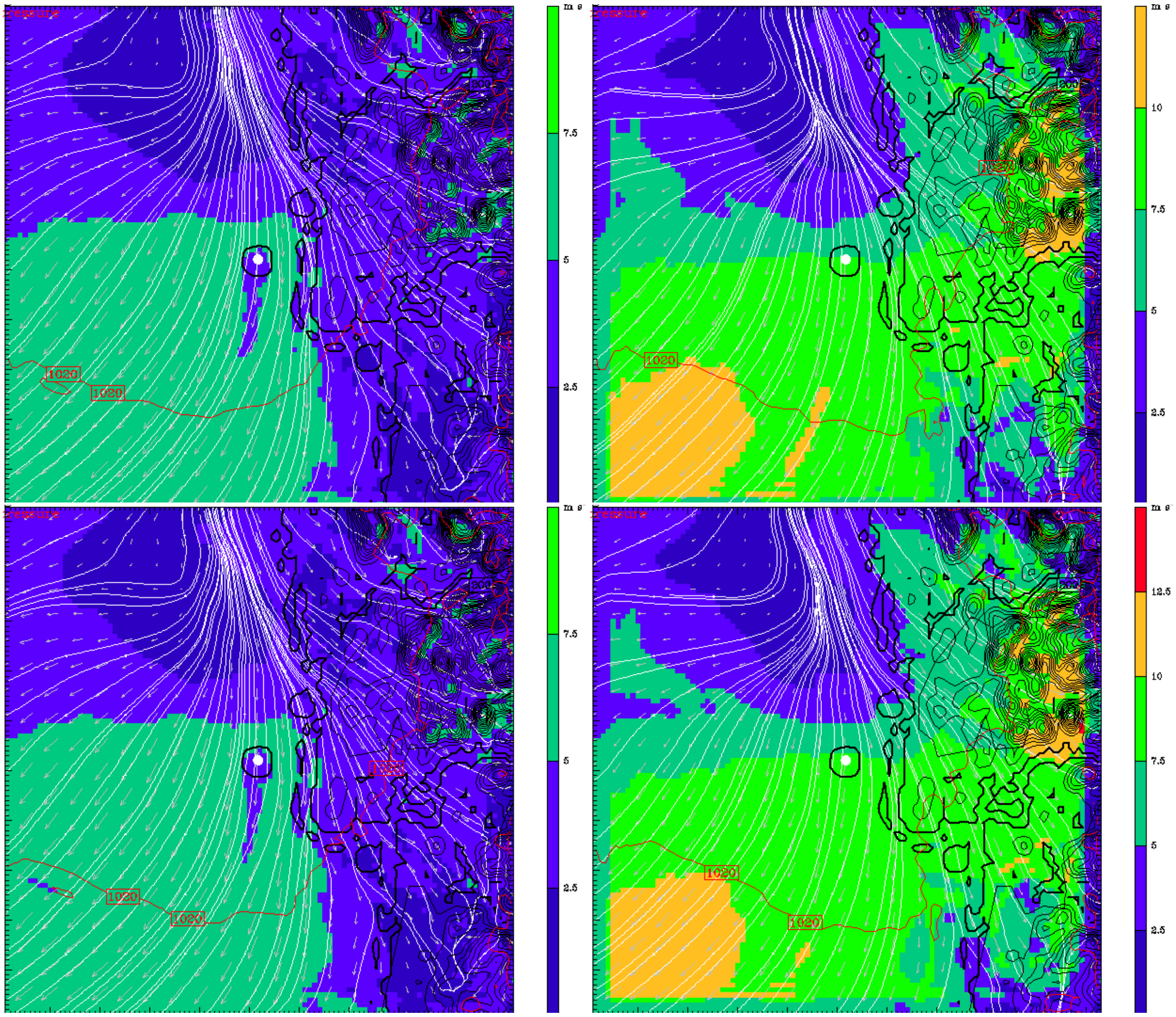

Fig. 6 continued. Simulated surface winds [m/s], and streamlines, at 1350 meter horizontal resolution using the MYJ PBL scheme (left panels) and the LES (right panels) for various number of vertical sigma levels: 91 level (top), and 139 levels (bottom). Simulations are valid at 18UTC, 1 June 2008.

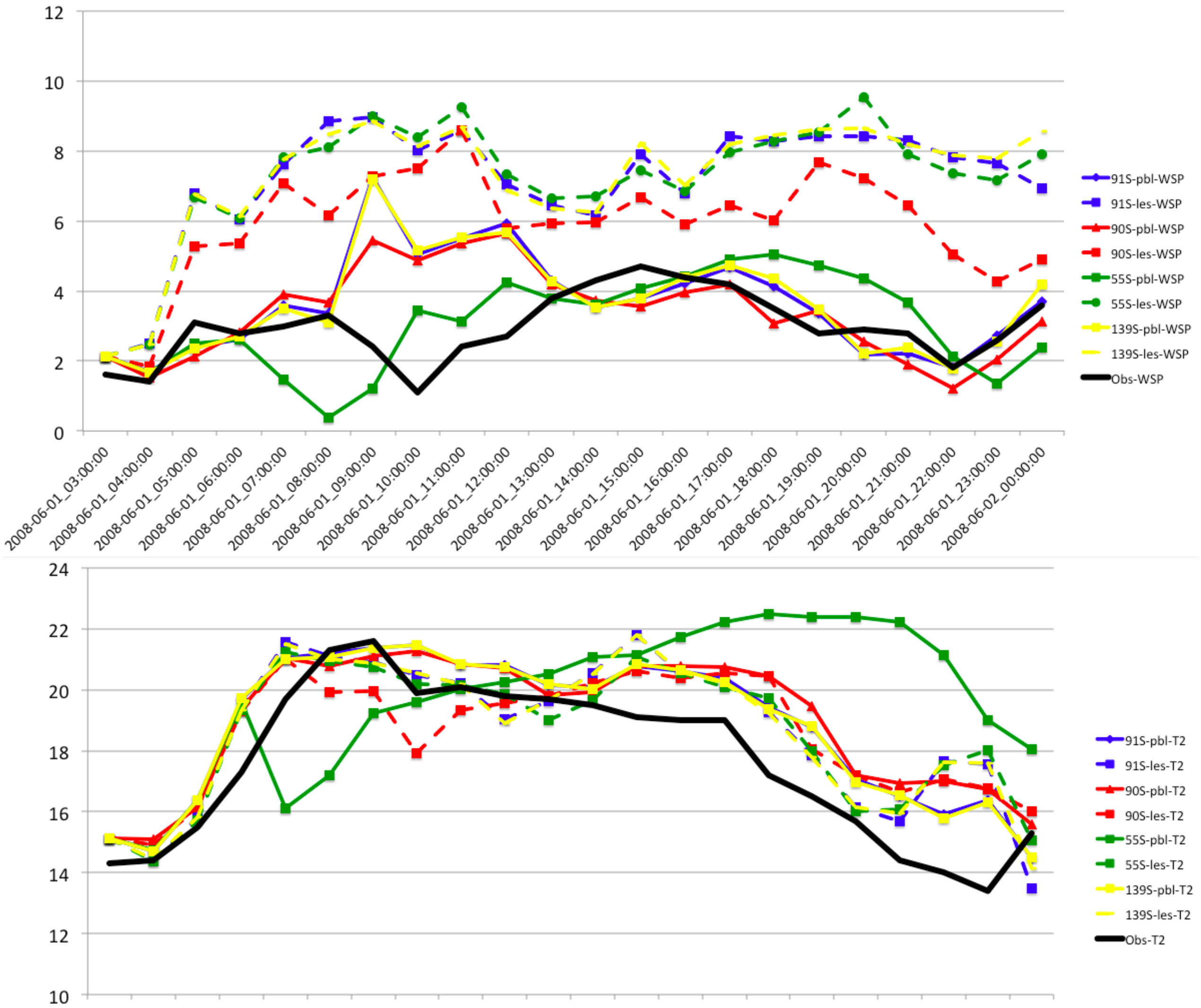

Fig. 7 Observed (black lines) and simulated surface wind speeds [m/s] (top panel) and two meter temperatures [°C] (bottom panel) for the Haugesund airport (approximately 25 km ENE of Utsira). Simulations are made with LES (dashed lines) and the MYJ PBL scheme (solid lines) for various number of vertical sigma levels (55 - green, 90 - red, 91 - blue, and 139 - yellow). Horizontal resolution is the same for all simulations, 1350 meters. Simulations and observations are valid at 1 June, 2008.

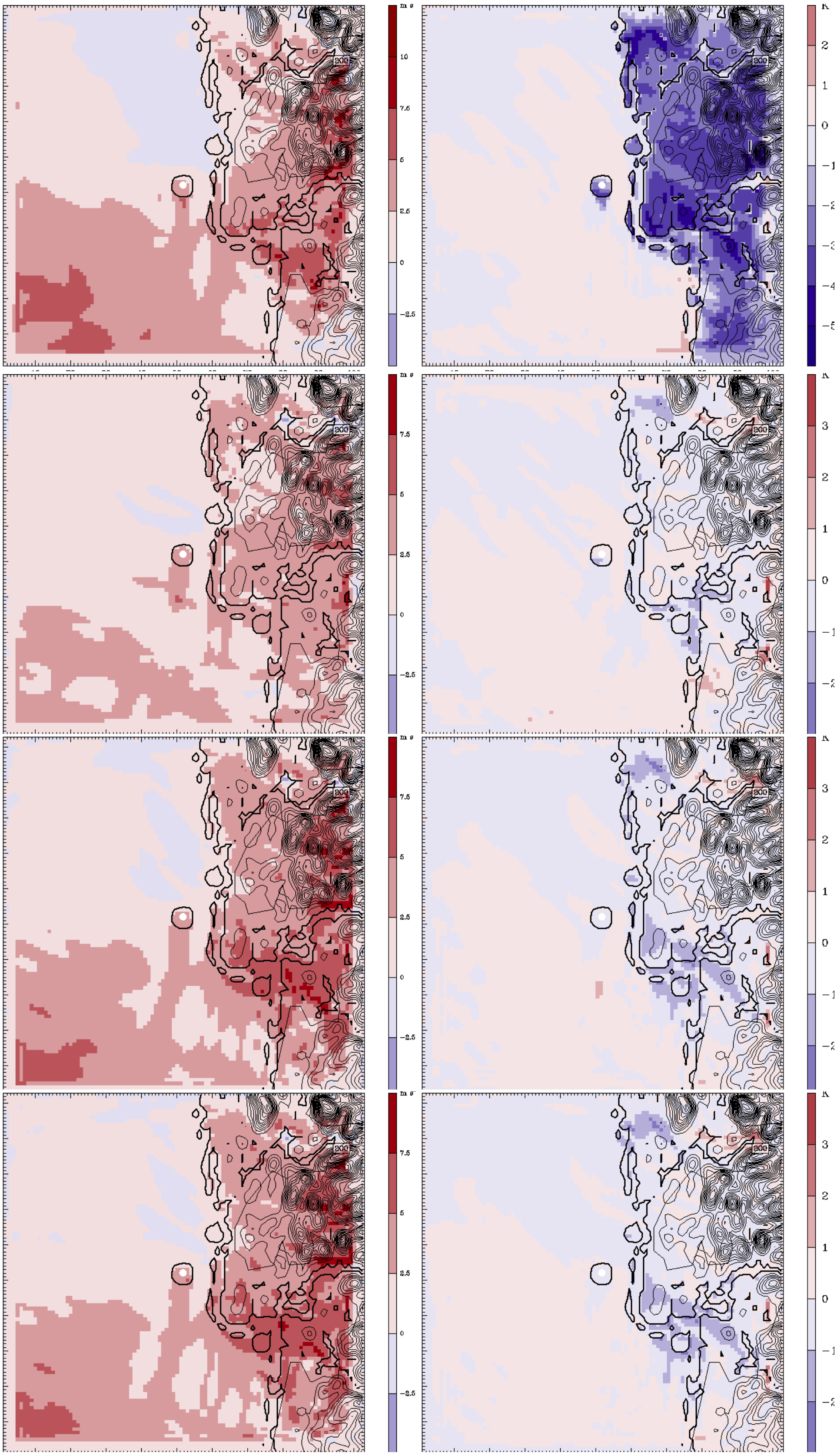

Fig. 8 Difference in surface wind speed [m/s] (left panel) and two meter temperature [K] (right panel) between simulations using the LES and MYJ PBL scheme (LES minus MYJ-PBL) for various number of vertical sigma levels: 55 levels (top), 90 levels (second from top), 91 level (second from bottom), and 139 levels (bottom). Simulations are valid at 18UTC, 1 June, 2008.

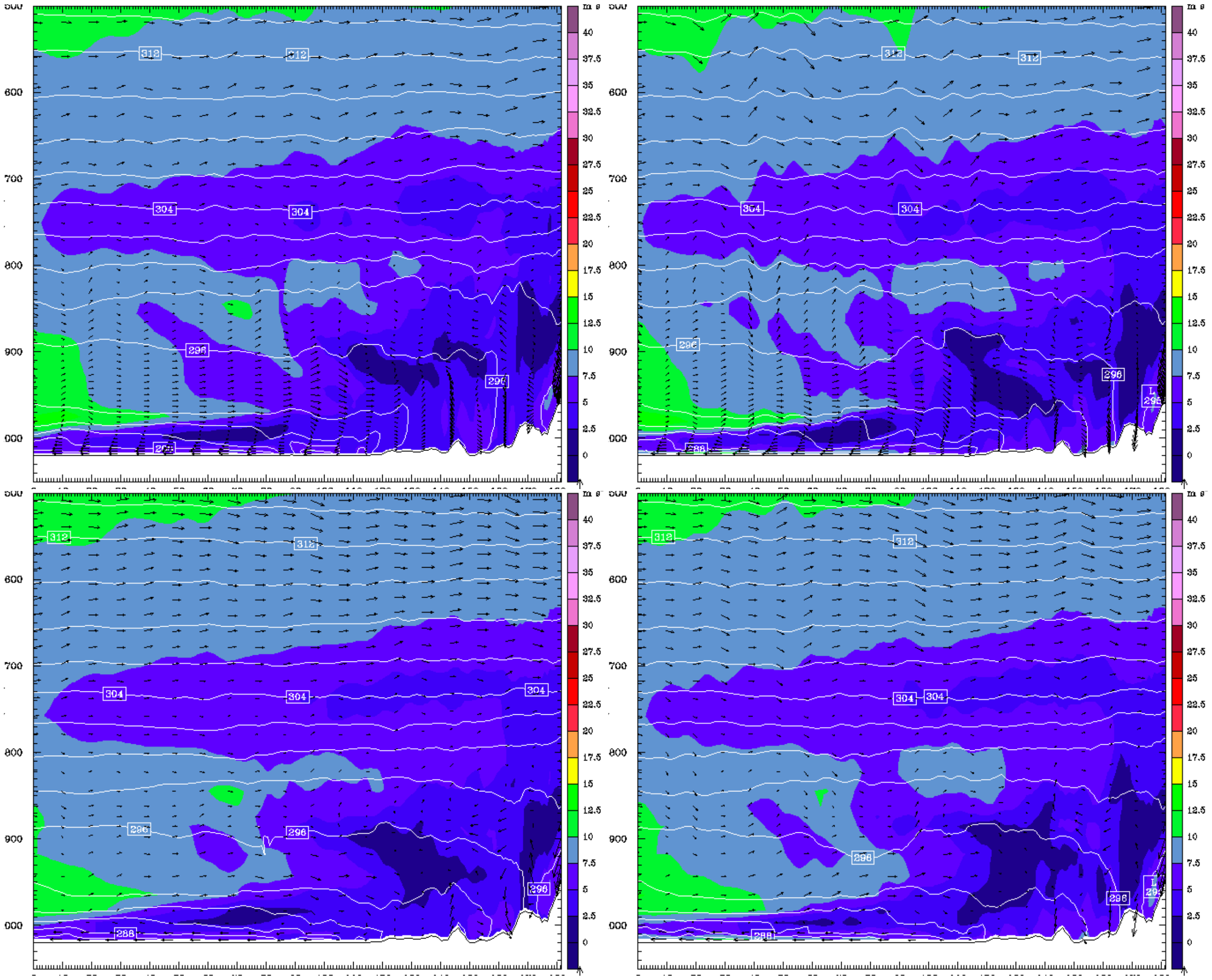

Fig. 9 Cross-sections along the SW-NE line (cf. Fig. 5) showing horizontal wind speed [m/s] (color scale to the right), circulation vectors, and isolines of potential temperature. Simulations are done at 1350 meter horizontal resolution using the MYJ PBL scheme (left panels) and the LES (right panels) for various number of vertical sigma levels: 55 levels (top), and 90 levels (bottom). Vertical coordinates are pressure based [hPa]. Simulations are valid at 18UTC, 1 June, 2008.

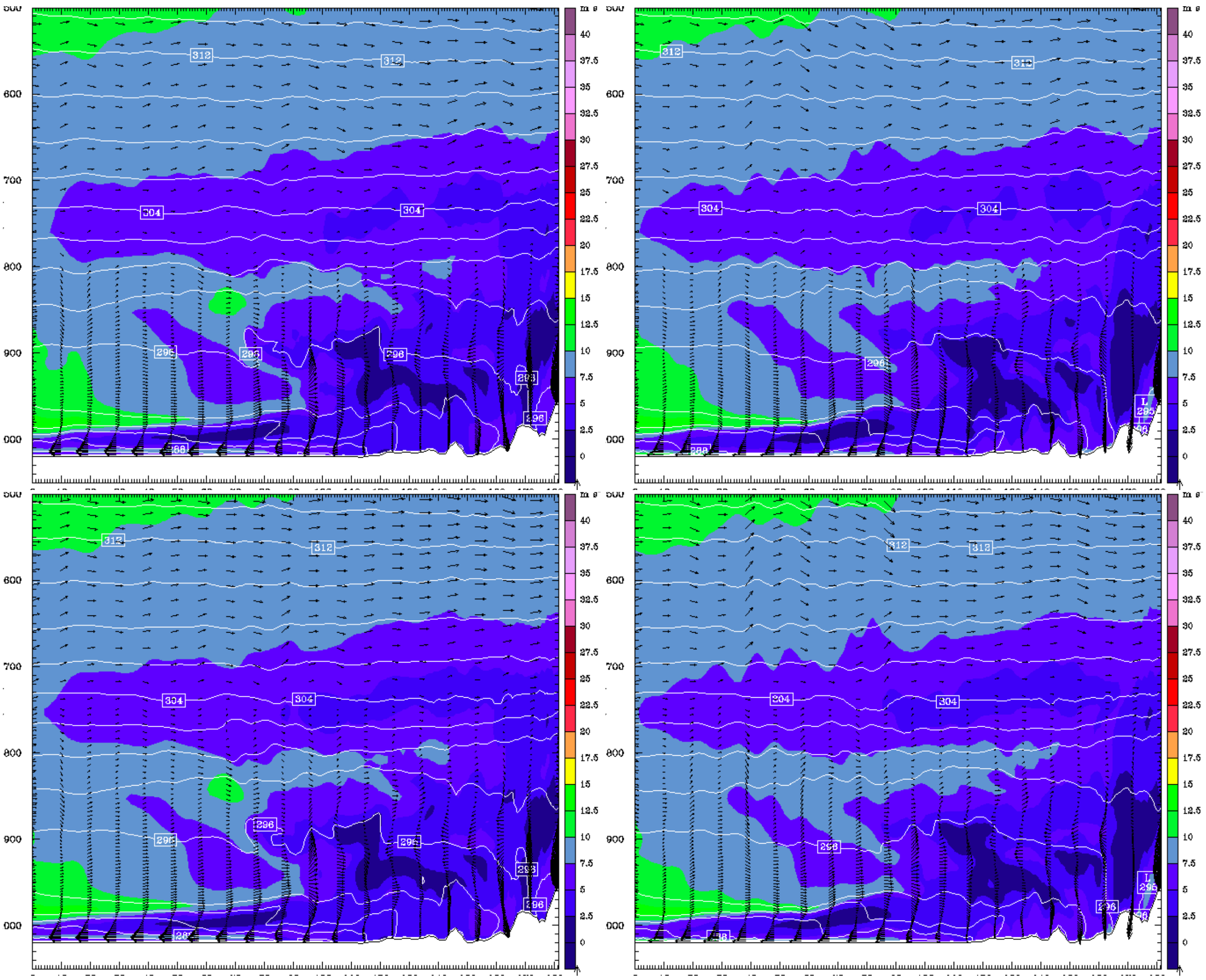

Fig. 9 continued. Cross-sections along the SW-NE line (cf. Fig. 5) showing horizontal wind speed [m/s] (color scale to the right), circulation vectors, and isolines of potential temperature. Simulations are done at 1350 meter horizontal resolution using the MYJ PBL scheme (left panels) and the LES (right panels) for various number of vertical sigma levels: 91 level (top), and 139 levels (bottom). Vertical coordinates are pressure based [hPa]. Simulations are valid at 18UTC, 1 June, 2008.

4.1 Impacts of using NDOWN

The abnormal simulated temperatures seen in the simulation using 55 sigma levels (cf. Fig. 7, green solid line, bottom panel and Fig. 8, top right panel) was traced back to the NDOWN method when running a simulation with in-line nesting using multiple domains. In this case 1350 m resolution (shown) and 450 m resolution (not shown). The second domain was initiated three hours into the Domain-01 simulation, at 06UTC. At that time, the short wave forcing for Domain-01 was reset to what it was at the start of the simulation (in this case, 03UTC). This then led to a sharp drop in surface temperature. Later in the day, when the short wave forcing became unrealistically strong due to the three hour shift in time, the situation is reversed. Figure 10 shows the difference between the 55 sigma NDOWN simulation (which included a second nested 450 m domain) and one using a regular three domain, in-line nesting (8100-2700-1350 m resolution). During the morning (cf. Fig. 10, top) the NDOWN simulation is considerably colder over land (right panel) near the surface and simulated wind speed is greater for most of the domain (left panel). At 18UTC (cf. Fig. 10, bottom) the situation has changed, the NDOWN simulation now being warmer over land than the simulation using regular nesting. Differences in wind speed are less distinct. Figure 11 shows this behavior for the island of Utsira.

Using the MYJ (and also the MYNN (Nakanishi and Niino, 2006)) PBL schemes, using the same initial and boundary data as when running the MYJ PBL scheme with the additional in-line nesting, gives results very similar to that of the 90, 91, and 139 sigma MYJ PBL simulations (not shown) and that of using regular, three domain in-line, nesting. This irregularity was later traced to a faulty default value in the `namelist.input` file. To be specific, the value of `reset_simulation_start` needs to be set as `.true.`. The exact cause of this behaviour is as yet unknwown, but lead developers of the WRF model have been notified.

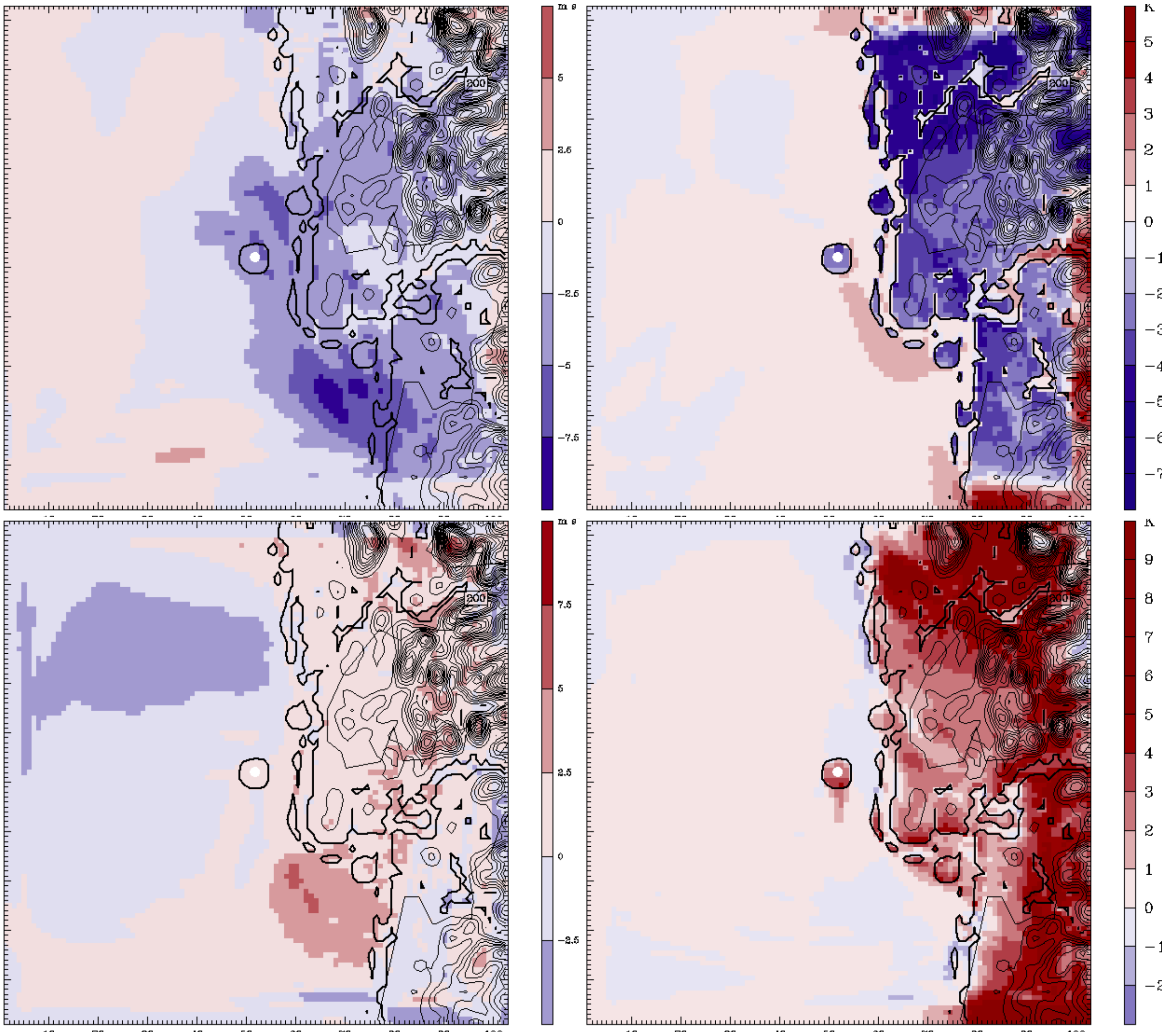

Fig. 10 Difference in surface wind speed [m/s] (left panel) and two meter temperature [K] (right panel) between simulations using the MYJ PBL scheme with the NDOWN method and direct nesting (NDOWN minus no-NDOWN) at 55 sigma levels. Simulations are valid at 07UTC (top), and 18UTC (bottom), 1 June, 2008.

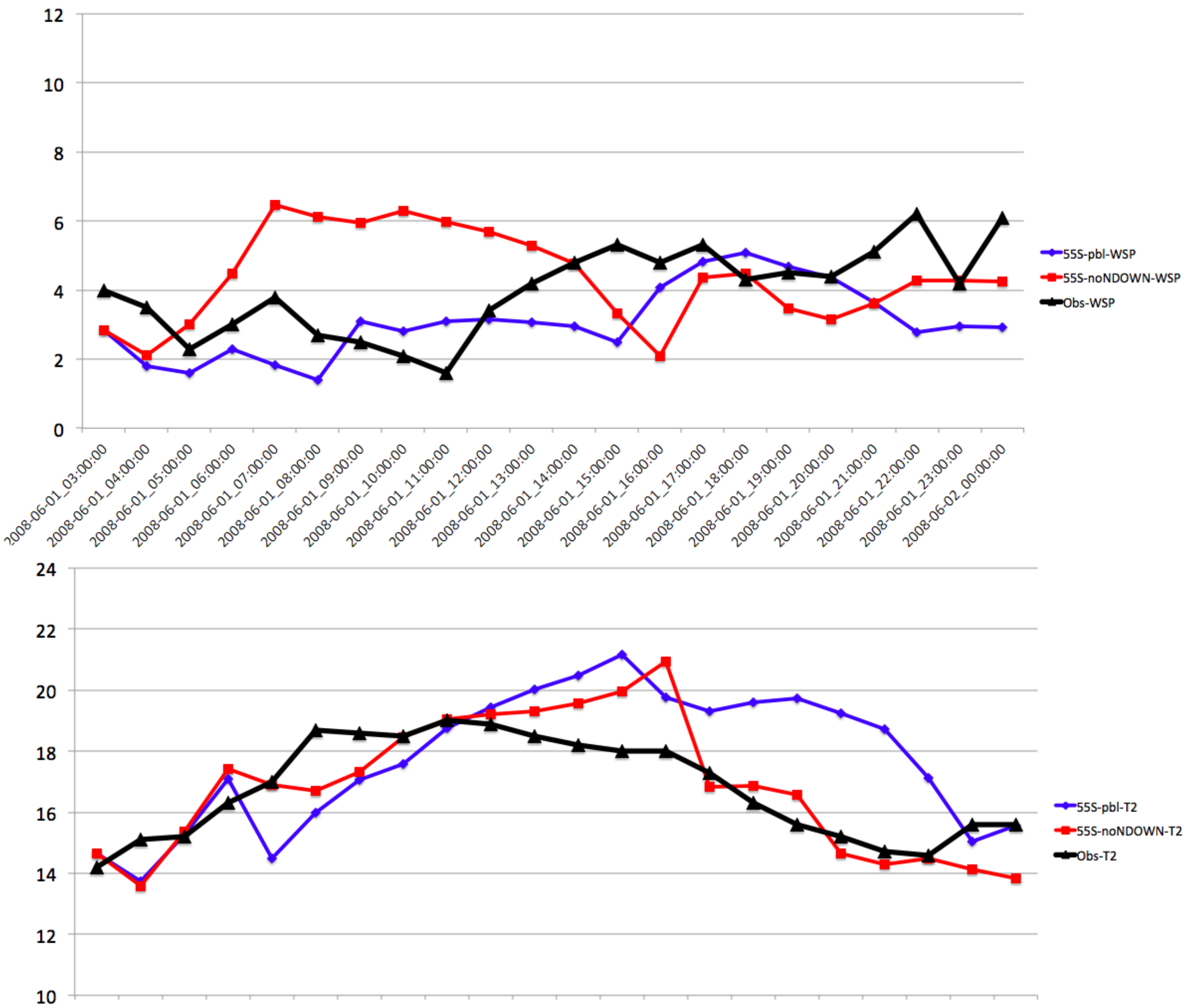

Fig. 11 Oberved (black lines) and simulated surface wind speeds [m/s] (top panel) and two meter temperatures [°C] (bottom panel) for the island of Utsira comparing two different methods of nesting. Red solid lines shows the results for the simulation using regular nesting and the blue solid lines for the simulation using the NDOWN method. Simulations and observations are valid at 1 June, 2008.

4.2 Effects of surface roughness and comparison with observations

To investigate the effects of friction on the LES simulations we increased the surface roughness by a factor of ten. When this is done the simulated winds become weaker and simulated two meter temperature increases (cf. Fig. 12). Notably, the surface winds and temperature for the 1350 meter resolution LES simulation (cf. Fig. 12, blue dashed line) are reminiscent of the MYJ PBL simulation using the same NDOWN procedure (cf. Fig. 11, blue solid line). This indicates possible problems with the NDOWN procedure, and as such was not investigated further in this report. Figure 13 shows the simulated wind speed (left panels) and two meter temperature (right panel) at 50 meter horizontal resolution for the island of Utsira at 15UTC, 1 June, 2008. The simulations run at a 50 meter resolution reveal considerable spatial and temporal variability. At this resolution, the 90 sigma simulation shows more disturbances at the domain lateral boundaries, indicating that the relatively coarse resolution in the lowest 2000 meters may be insufficient.

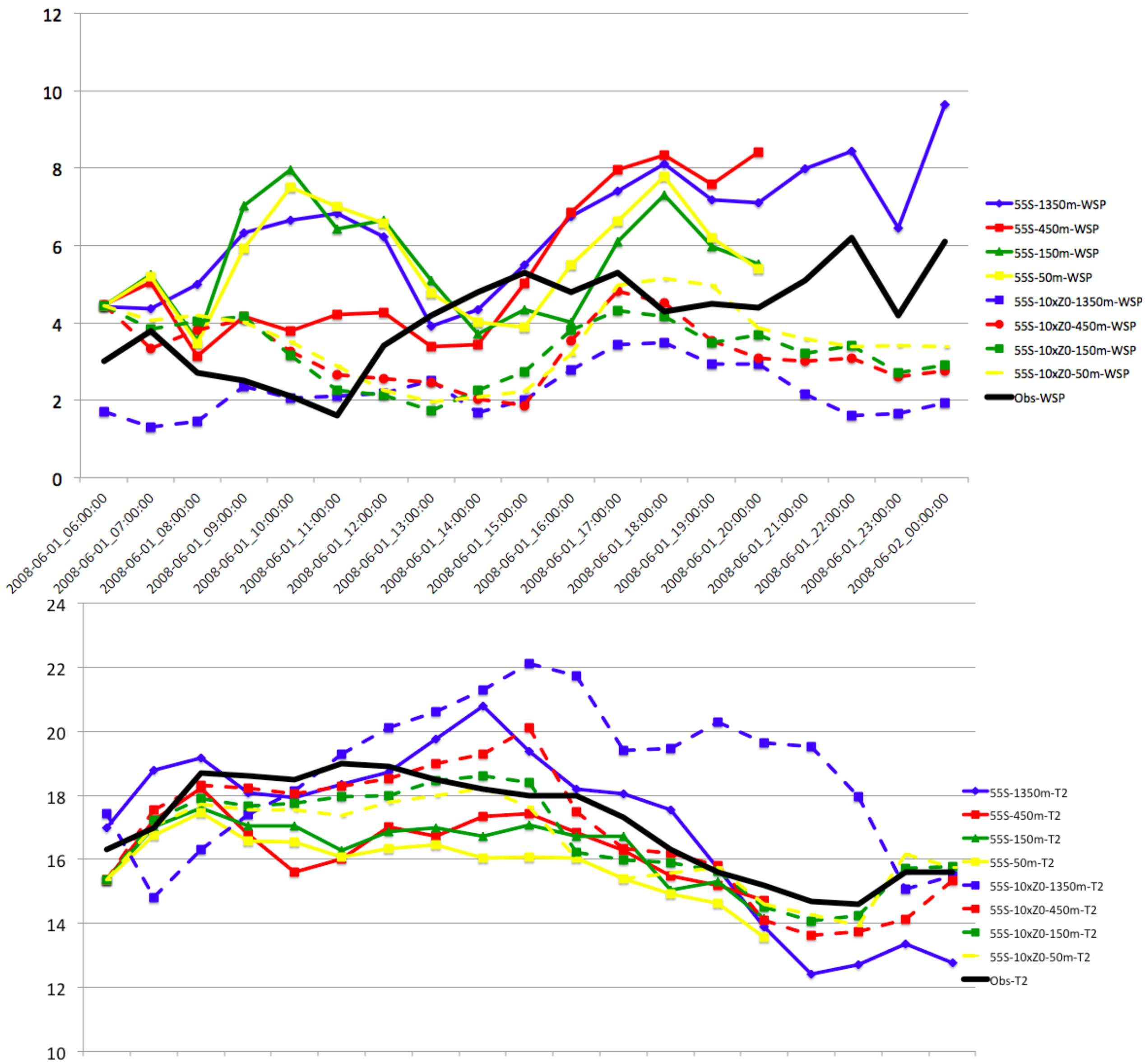

Fig. 12 Simulated and observed (black line) surface wind speeds [m/s] (top panel) and two meter temperatures [°C] (bottom panel) at the island of Utsira. Horizontal resolution is 1350m (blue lines), 450m (red lines), 150m (green lines), and 50m (yellow lines) and the simulations are done with unmodified (solid lines) and increased (dashed lines) surface roughness. Number of vertical levels are 55. Simulations and observations are valid at 1 June, 2008.

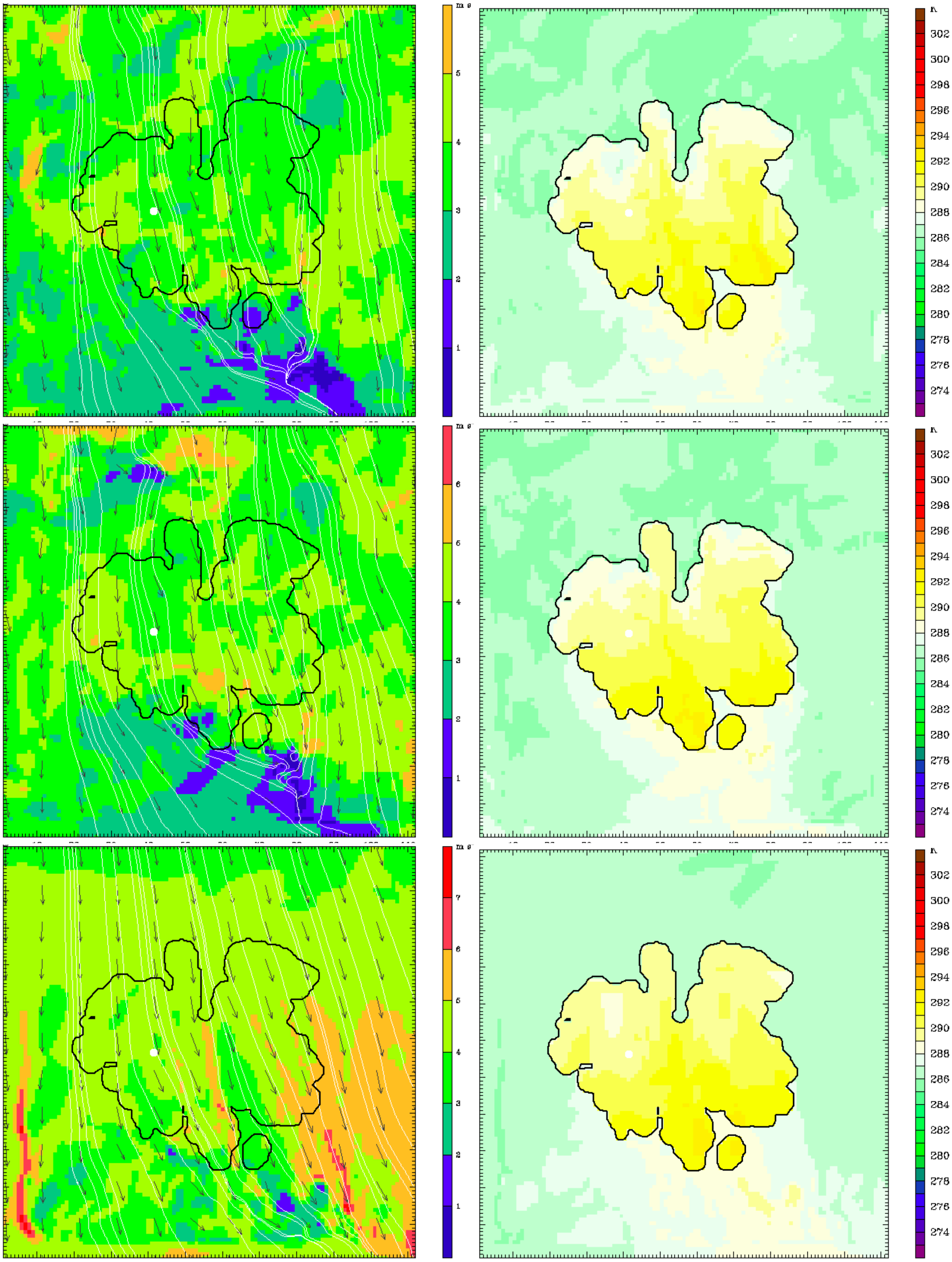

Fig. 13 Simulated surface winds [m/s] (left panels), and two meter temperature [K] (right panels), at 50 meter horizontal resolution for the island of Utsira using the LES model. Number of vertical levels are 55 (top two panels) and 90 (bottom panel). Results from the simulation using increased surface roughness (by a factor of ten) is shown in the middle panel. Simulations are valid at 15UTC, 1 June, 2008.

5 Stone moving winds

A severe wind storm hit SW-Iceland in the afternoon of 10 April, 2011. During this storm 10 minute average wind speed exceeded 24 m/s at Keflavík international airport with maximum gusts exceeding 42 m/s. Due to this, the airport was closed for all traffic for more than five hours in the afternoon (cf. Fig. 14). The winds were also very strong in the fjord of Borgarfjörður, W-Iceland, where cars were damaged by moving stones when crossing a bridge over the fjord (cf. Fig. 15). This event has been simulated using the MYJ PBL scheme and the LES model down to a horizontal resolution of 450 meters. In this case, initial and boundary data are from NOAAs GFS forecasting system. Figure 16 shows the simulated surface wind speed and direction using the MYJ PBL scheme and the LES method at 18UTC. Both simulations show strong wind speed with the LES simulation creating even stronger winds than the MYJ PBL run. The two meter temperature field, shown in Fig. 17, is however quite similar in the two simulations. Observed and simulated wind speed and temperature at locations Hafnarmelar (west of mountain) and Hvanneyri (north of mountain, cf. Fig. 15) is shown in Figures 18 and 19. The figures show that the MYJ PBL simulation does not capture the full strength of the wind storm but the LES model is over-predicting the average winds by a factor 1.5 (Hafnarmelar) to 2 (Hvanneyri). In fact, the simulated wind speed from the LES model is closer to the observed maximum gusts for the two locations. This raises the question whether the simulated winds from the LES model should perhaps be compared to 1 minute averaged observed winds rather than 10 minute averages. There is little difference between the two models in simulated two meter temperature. Both simulations underestimate the temperature west of the mountain and tend to over-predict the temperature north of the mountain. Figures 20 and 21 show cross sections along lines S–N and SW–NE (cf. Fig. 15) at 18UTC. The cross sections reveal that the MYJ PBL simulation creates a substantially greater deceleration than the LES simulation immediately upstream and downstream of the 1000 meter high mountain in a non-blocked flow. The flow along the fjord (i.e. along line SW–NE, cf. Fig. 21) in the LES simulation shows hardly any deceleration at the surface at all. This again emphasizes the need to refine the energy transport between surface and the atmosphere in the LES model. The LES simulations of the 1 June case for Utsira proofed to be quite numerically robust and showed limited sensitive to vertical resolu-

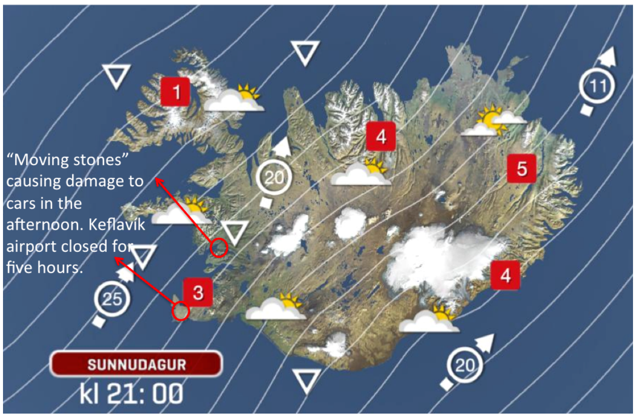

Fig. 14 A sever wind storm hit SW-Iceland in the afternoon of 10 April, 2011.

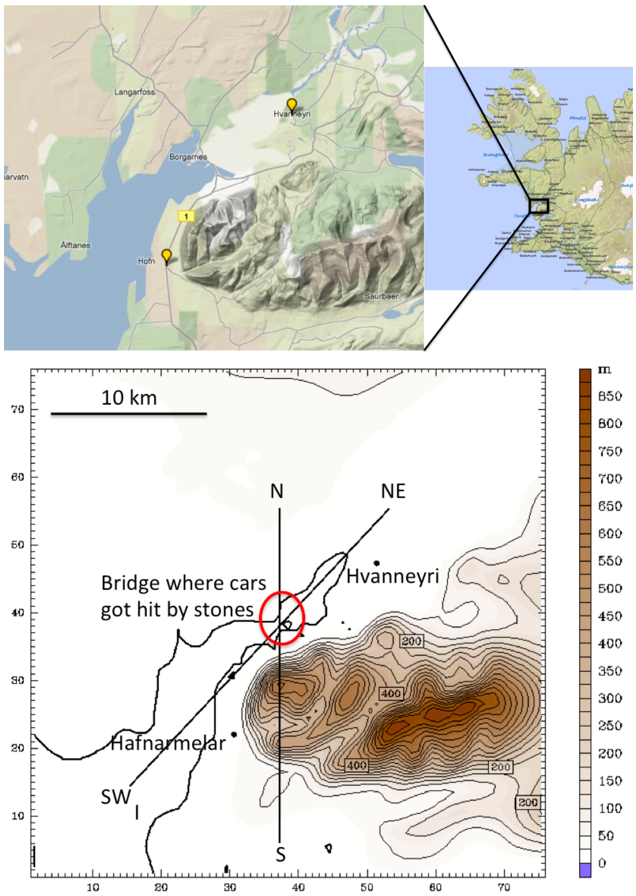

Fig. 15 Region of interest and location of observational sites (top panel). Bottom panel shows the domain setup and terrain height [meters above sea level] of the 450 meter resolution LES and PBL simulations, straight lines show the location of the cross sections.

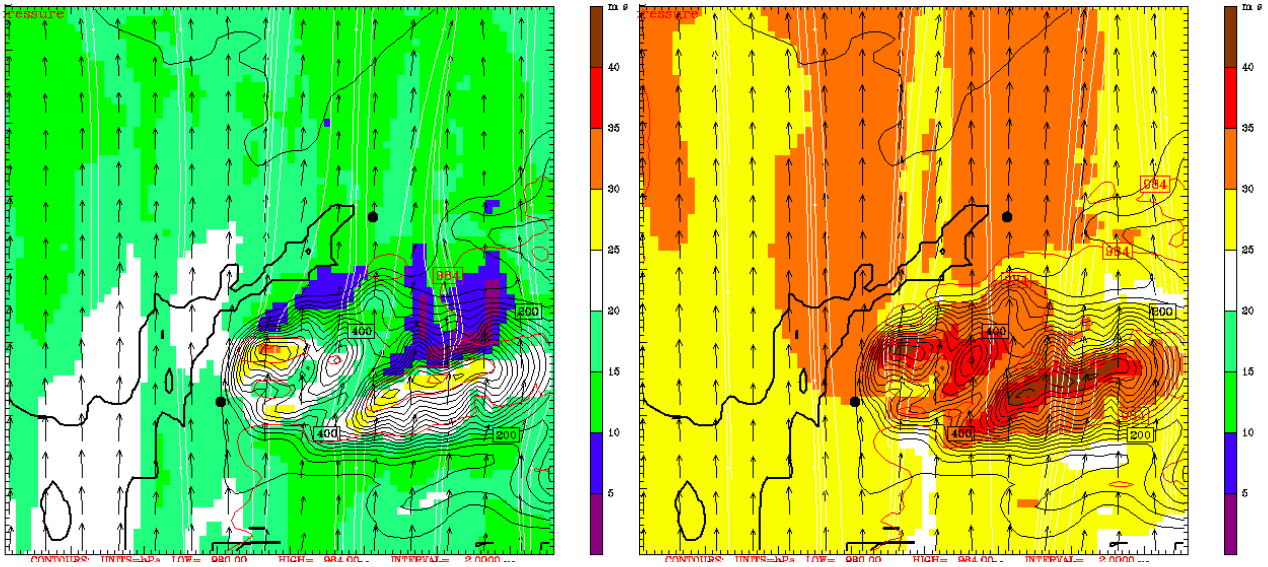

Fig. 16 Simulated surface wind speed [m/s] using the MYJ PBL scheme (left panel) and the LES method (right panel). Both simulations are run at 55 sigma levels. Simulations are valid at 18UTC, 10 April, 2011.

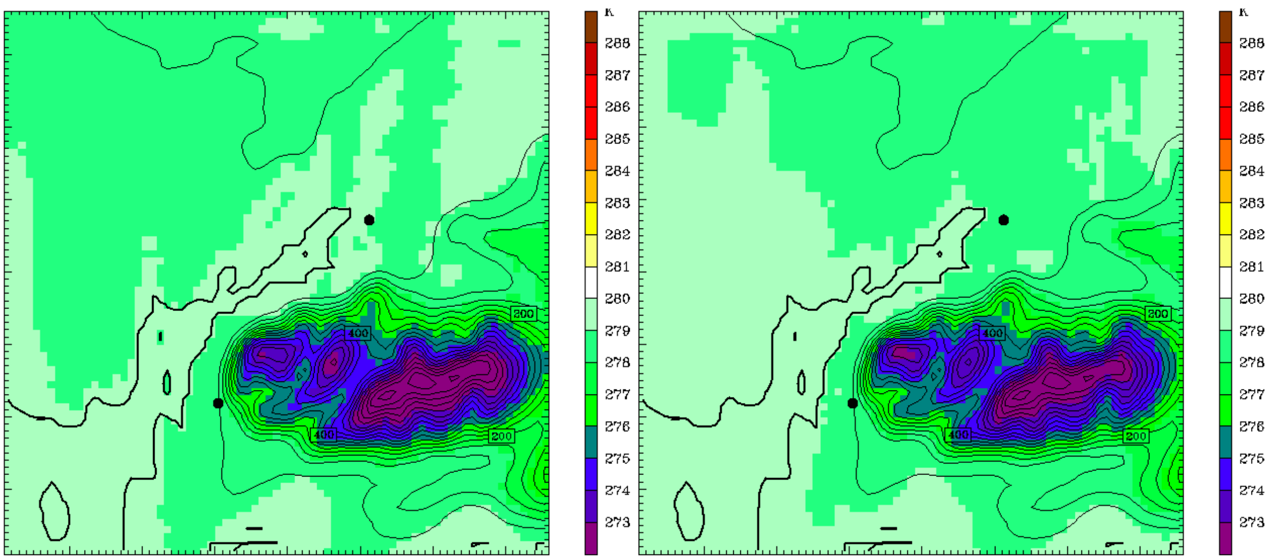

Fig. 17 Simulated two meter temperature [K] using the MYJ PBL scheme (left panel) and the LES method (right panel). Both simulations are run at 55 sigma levels. Simulations are valid at 18UTC, 10 April, 2011.

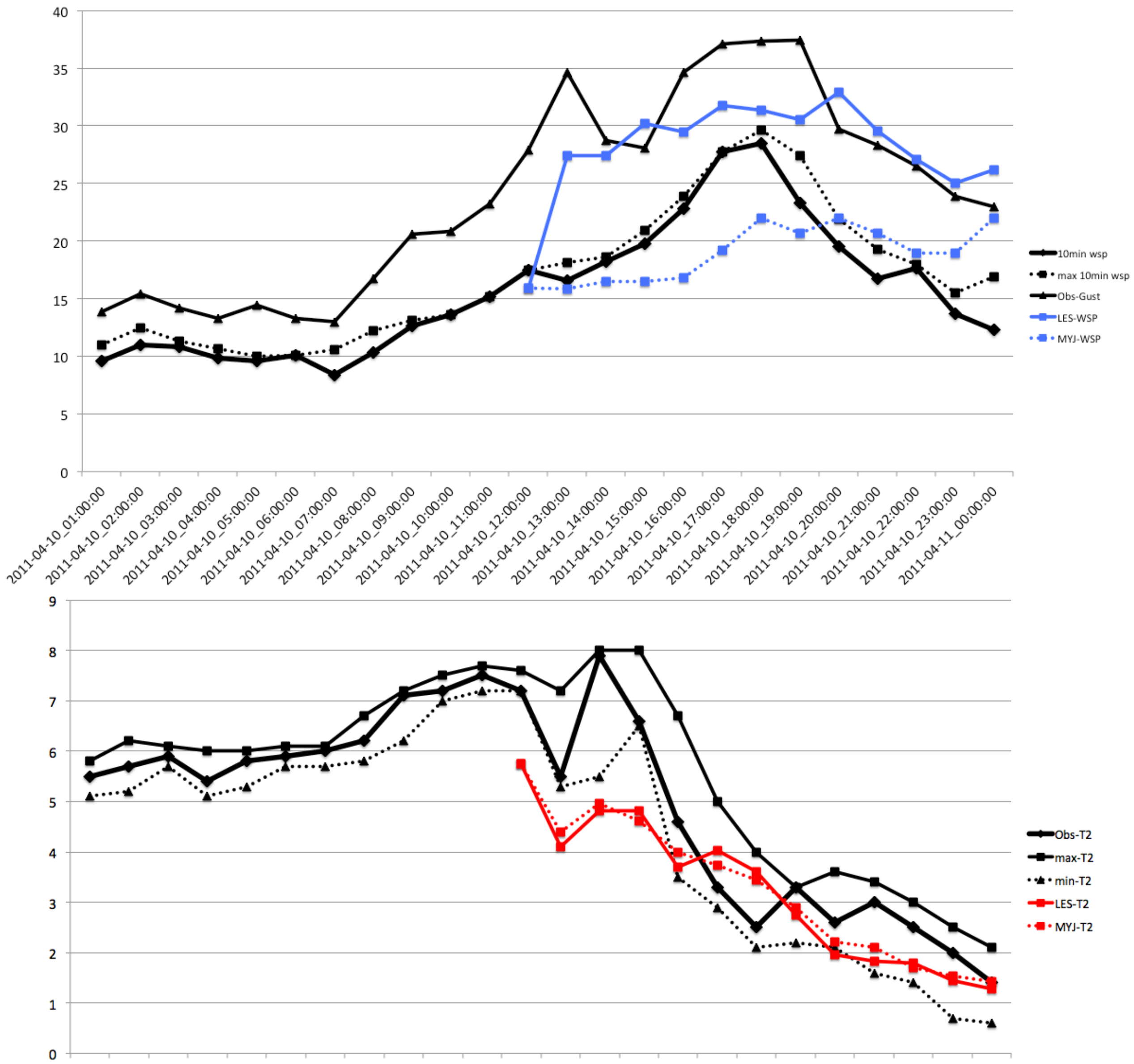

Fig. 18 Oberved (black lines) and simulated surface wind speeds [m/s] (top panel) and two meter temperatures [°C] (bottom panel) for location Hafnarmelar. Simulations and observations are valid at 10 April, 2011.

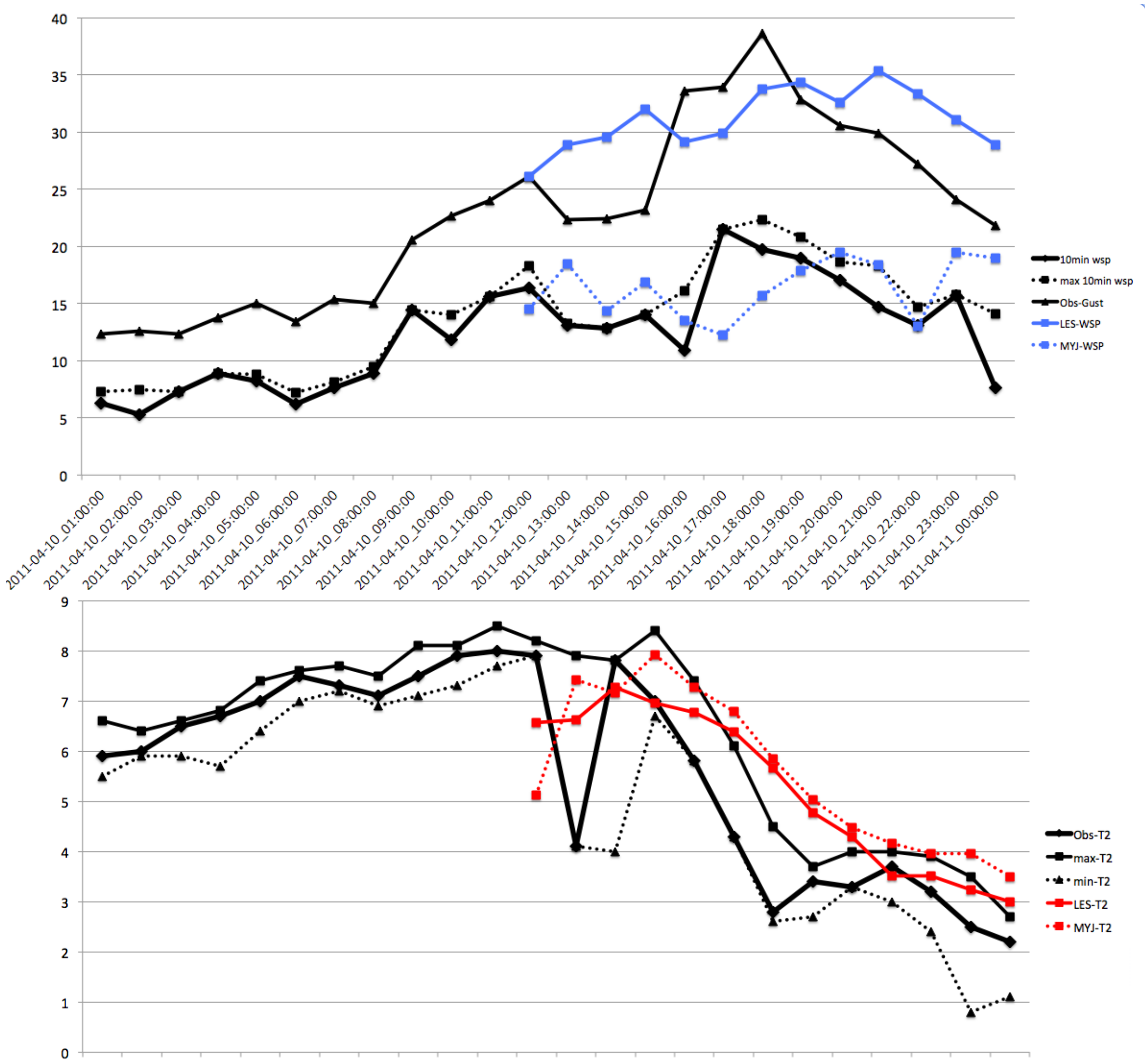

Fig. 19 Observed (black lines) and simulated surface wind speeds [m/s] (top panel) and two meter temperatures [°C] (bottom panel) for location Hvanneyri. Simulations and observations are valid at 10 April, 2011.

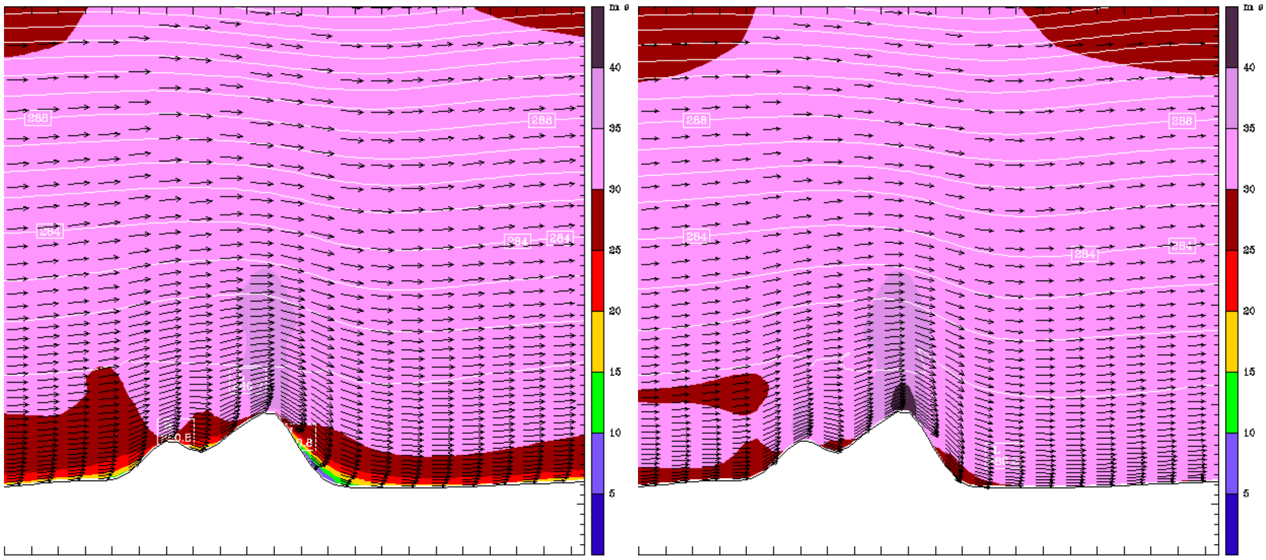

Fig. 20 Cross-sections along the S-N line (cf. Fig. 15) showing horizontal wind speed [m/s] (color scale to the right), circulation vectors, and isolines of potential temperature. Simulations are done at 450 meter horizontal resolution using the MYJ PBL scheme (left panels) and the LES (right panels). Vertical coordinates are pressure based [hPa]. Simulations are valid at 18UTC, 10 April, 2011.

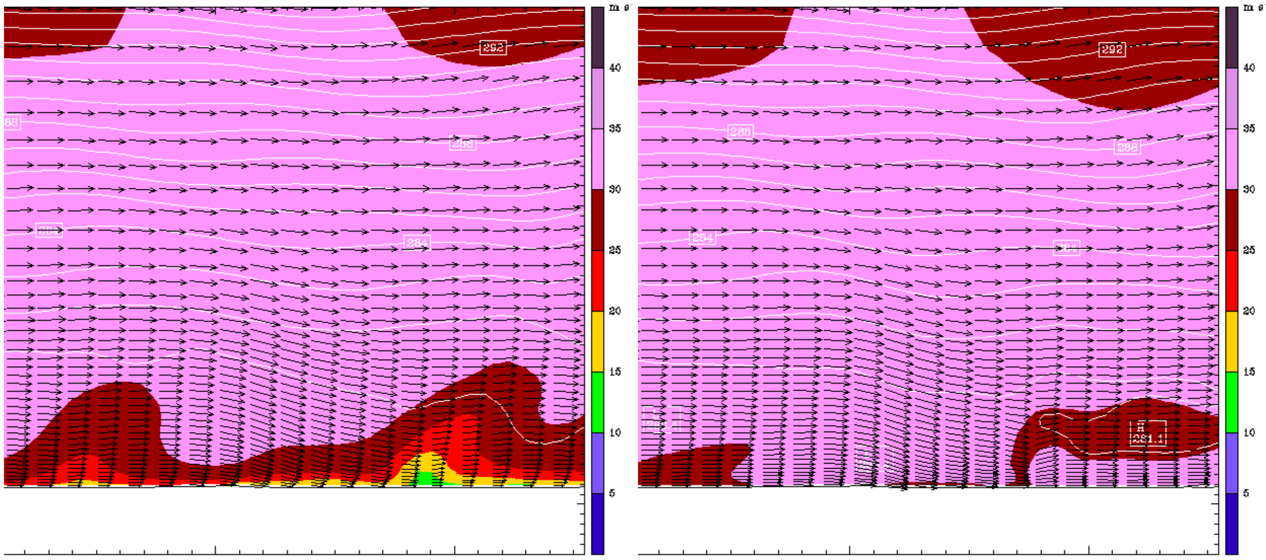

Fig. 21 Cross-sections along the SW-NE line (cf. Fig. 15) showing horizontal wind speed [m/s] (color scale to the right), circulation vectors, and isolines of potential temperature. Simulations are done at 450 meter horizontal resolution using the MYJ PBL scheme (left panels) and the LES (right panels). Vertical coordinates are pressure based [hPa]. Simulations are valid at 18UTC, 10 April, 2011.

tion. The 1 April case for W-Iceland was however different. Using 55 sigma levels resulted in the LES model becoming numerically unstable when run at a 150 meter horizontal resolution, showing that vertical resolution plays a more critcal role in steep terrain and under strong synoptic forcing. Indeed, Doyle et al (2009) used 110 vertical levels to simulate the formation of lee side rotors in the steep terrain of the Sierra Nevadas during the T–REX experiment. Of these 110 vertical levels, 50 were in the lowest 2500 meters, compared to approximately 30 in the lowest 2000 meters in the 55 sigma level setup. On the other hand, Liu et al (2011) used WRF with 37 vertical levels (of which 12 where in the lowest 1000 meters above ground level) to simulate a weather event from November 14 to 16 at the northeastern Colorado wind farm. During this period observed winds at hub height varied between 2 and 15 m/s. The wind farm, aprroximately 10×15 km on side, is located on a local plateau that is 100 to 250 meters higher than the surrounding topography. The modeling approach of Liu et al (2011) differs from the one used in the WRFLES system. A six simultaneous nested domain setup is used, the four outermost domains are used with the MYJ PBL scheme with horizontal resolution being 30, 10, 3.3 and 1.1 km, respectively. For the two innermost domains the WRF model is run in LES mode at a horizontal resolution of 0.37 and 0.123 km. NCAR's Real-Time Four-Dimensional Data Assimilation (RTFDDA) system[2] is used to assimilate the input data for the four outer PBL scheme domains. The authors find that many of the simulated intra-farm wind features verify reasonably well against the turbine-hub-height wind speed observations. Comparisons of simulated and observed winds close to the surface are however not presented in the paper.

One clear difference between the island of Utsira and the Borgarfjordur area in W-Iceland is that the terrain in Iceland is much steeper with mountains reaching 1000 meter altitude compared to 50 meters in Utsira. This should be kept in mind when choosing vertical configuration of the LES model.

6 Summary and conclusions

Synchronizing the land-use categories with terrain height has effects on simulated surface temperatures and winds, both at 1350 and 50 m resolution. This effect is most pronounced for coastal regions and in areas close to water bodies.

The LES simulations give significant stronger wind speed than the MYJ PBL simulations. In both the Utsira and the Iceland windstorm case, the LES simulations give far too strong surface winds.

[2] http://www.rap.ucar.edu/technology/model/rtfdda.php

The total number of sigma levels (55, 90, 91, and 139) does not seem to be a decisive factor when it comes to simulated wind speed in the LES model when there is a weak synoptic forcing and the terrain is relatively smooth. Rather, the number of sigma levels in the lowest 2000 meters is more important. The simulation with 90 sigma levels, but with the least number of sigma levels (15 levels) in the lowest 2000 meters gives in general lower wind speeds than the other three simulations conducted at 1350 m resolution. The differences in surface temperature are less distinctive. However, when used to simulate a strongly synoptically forced event in steep terrain, the LES model became unstable at 150 meter horizontal resolution when using 55 sigma levels.

In the Iceland windstorm, the MYJ PBL scheme gives a substantially greater deceleration than the LES simulation immediately upstream and downstream of a 1000 m high mountain in non-blocked flow.

The LES and MYJ PBL simulations give similar 2 m temperatures in both the Utsira and Iceland cases. However, the ground surface temperatures are lower in the LES simulations and dependent upon time of day.

The MYJ PBL simulation with 55 vertical levels, simulated with NDOWN gives unrealistic 2 m temperatures in the Utsira case. This irregularity was traced to a faulty default value in the `namelist.input` file. To be specific, the value of `reset_simulation_start` needs to be set as `.true.`. The exact cause of this behaviour is as yet unknwown.

When run with increased surface roughness the LES simulated winds become weaker and the simulated two meter temperature increases. The results described here emphasize the need for a more dense mesonet of observations with high temporal resolution, and preferably high-resolution 4-dimensional observations of winds and temperature of the boundary layer, in order to properly validate this kind of simulations. Such observations are also necessary in order to re-calibrate the roughness lengths in the surface flux calculations for LES applications when the land surface model (in this case Noah LSM) is used to provide the lower boundary conditions required by the LES method.

Acknowledgements Observational data are from the Norwegian Meteorological Office (www.eklima.no) and the Icelandic Meteorological Office (www.vedur.is). Computational resources were made available by the University of Bergen.

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A Available data and software

A number of WRF output files have been made available on an open ftp server, as well as data that has been post-processed with RIP. The links are:

– `ftp://betravedur.is/pub/wrf/icam2011/wrfoutput/`
– `ftp://betravedur.is/pub/wrf/icam2011/RIP/`

The WRFLES software suite is further available for downloading on the same ftp server:

– `ftp://betravedur.is/pub/wrf/icam2011/WRFLES.tgz`

The tar bundle includes a technical report describing the system, and its use, in detail.

B List of sigma levels

Four different setups of the vertical sigma levels have been tested, 55, 90, 91, and 139 levels. These are, respectively:

– 1.0000, 0.9960, 0.9935, 0.9899, 0.9861, 0.9821, 0.9777, 0.9731, 0.9682, 0.9629, 0.9573, 0.9513, 0.9450, 0.9382, 0.9312, 0.9240, 0.9165, 0.9088, 0.9008, 0.8925, 0.8840, 0.8752, 0.8661, 0.8567, 0.8471, 0.8371, 0.8261, 0.8141, 0.8008, 0.7863, 0.7704, 0.7531, 0.7341, 0.7135, 0.6911, 0.6668, 0.6406, 0.6123, 0.5806, 0.5452, 0.5060, 0.4630, 0.4260, 0.3890, 0.3480, 0.3020, 0.2420, 0.2120, 0.1820, 0.1520, 0.1210, 0.0910, 0.0610, 0.0300, 0.000

– 1.0000, 0.993, 0.983, 0.97, 0.954, 0.934, 0.909, 0.88, 0.8679349, 0.8558698, 0.8438047, 0.8317396, 0.808384, 0.7855326, 0.7631764, 0.7413065, 0.7199143, 0.6989911, 0.6785285, 0.6585181, 0.6389517, 0.6198213, 0.6011188, 0.5828364, 0.5649666, 0.5475014, 0.5304337, 0.5137559, 0.4974607, 0.4815412, 0.4659901, 0.4508006, 0.4359659, 0.4214793, 0.4073341, 0.3935239, 0.3800422, 0.3668828, 0.3540394, 0.341506, 0.3292765, 0.317345, 0.3057058, 0.294353, 0.2832811, 0.2724845, 0.2619577, 0.2516954, 0.2416923, 0.2319433, 0.2224432, 0.2131869, 0.2041696, 0.1953864, 0.1868325, 0.1785032, 0.1703939, 0.1624999, 0.1548169, 0.1473405, 0.1400662, 0.13299, 0.1261075, 0.1194146, 0.1129074, 0.1065818, 0.1004339, 0.09445987, 0.08865596, 0.08301842, 0.07754362, 0.07222794, 0.06706786, 0.06205991, 0.05720066, 0.05248676, 0.04791492, 0.04348188, 0.03918445, 0.03501949, 0.03098392, 0.0270747, 0.02328882, 0.01962336, 0.01607542, 0.01264213, 0.009320687, 0.006108319, 0.003002291, 0.0000

– 1.000, 0.9960, 0.99475, 0.9935, 0.9917, 0.9899, 0.9880, 0.9861, 0.9841, 0.9821, 0.9799, 0.9777, 0.9754, 0.9731, 0.97065, 0.9682, 0.96555, 0.9629, 0.9601, 0.9573, 0.9543, 0.9513, 0.94815, 0.9450, 0.9416, 0.9382, 0.9347, 0.9312, 0.9276, 0.9240, 0.92025, 0.9165, 0.91265, 0.9088, 0.9048, 0.9008, 0.89665, 0.8925, 0.88825, 0.8840, 0.8796, 0.8752, 0.87065, 0.8661, 0.8614, 0.8567, 0.8519, 0.8471, 0.8421, 0.8371, 0.8316, 0.8261, 0.8201, 0.8141, 0.80745, 0.8008, 0.79355, 0.7863, 0.77835, 0.7704, 0.7454, 0.7204, 0.6954, 0.6704, 0.6454, 0.6204, 0.5954, 0.5704, 0.5454, 0.5204, 0.4954, 0.4704, 0.4454, 0.4204, 0.3954, 0.3704, 0.3454, 0.3204, 0.2954, 0.2704, 0.2454, 0.2204, 0.1954, 0.1704, 0.1454, 0.1204, 0.0954, 0.0704, 0.0454, 0.0204, 0.0000

– 1.000, 0.996, 0.9948, 0.9935, 0.9917, 0.9899, 0.988, 0.9861, 0.9841, 0.9821, 0.9799, 0.9777, 0.9754, 0.9731, 0.9707, 0.9682, 0.9656, 0.9629, 0.9601, 0.9573, 0.9543, 0.9513, 0.9482, 0.945, 0.9416, 0.9382, 0.9347, 0.9312, 0.9276, 0.924, 0.9203, 0.9165, 0.9127, 0.9088, 0.9048, 0.9008, 0.8967, 0.8925, 0.8883, 0.884, 0.8796, 0.8752, 0.8707, 0.8661, 0.8614, 0.8567, 0.8519, 0.8471, 0.8421, 0.8371, 0.8316, 0.8261, 0.8201, 0.8141, 0.8075, 0.8008, 0.7936, 0.7863, 0.7784, 0.7704, 0.7618, 0.7531, 0.7436, 0.7341, 0.7238, 0.7199143, 0.6989911, 0.6785285, 0.6585181, 0.6389517, 0.6198213, 0.6011188, 0.5828364, 0.5649666, 0.5475014, 0.5304337, 0.5137559, 0.4974607, 0.4815412, 0.4659901, 0.4508006, 0.4359659, 0.4214793, 0.4073341, 0.3935239, 0.3800422, 0.3668828, 0.3540394, 0.341506, 0.3292765, 0.317345, 0.3057058, 0.294353, 0.2832811, 0.2724845, 0.2619577, 0.2516954, 0.2416923, 0.2319433, 0.2224432, 0.2131869, 0.2041696, 0.1953864, 0.1868325, 0.1785032, 0.1703939, 0.1624999, 0.1548169, 0.1473405, 0.1400662, 0.13299, 0.1261075, 0.1194146, 0.1129074, 0.1065818, 0.1004339, 0.09445987, 0.08865596, 0.08301842, 0.07754362, 0.07222794, 0.06706786, 0.06205991, 0.05720066, 0.05248676, 0.04791492, 0.04348188, 0.03918445, 0.03501949, 0.03098392, 0.0270747, 0.02328882, 0.01962336, 0.01607542, 0.01264213, 0.009320687, 0.006108319, 0.003002291, 0.0000

C Default namelist options

Default namelist options are written in YaML format. Most of the options are inheritated between varius steps within the WRFLES system, but some options are modified, e.g. when running the WRF model in LES mode vs. in PBL mode. The files are named

- `namelist_data.wps.yml`
- `namelist_data.input.real.yml`
- `namelist_data.input.wrfpbl.yml`
- `namelist_data.input.ndown.yml`
- `namelist_data.input.wrfles.yml`

and are as follows:

- The WPS namelist

```
# WPS namelist file in YaML format, intended for
# processing by the WRFLES system.
#
'&share':
wrf_core : "'ARW'"
max_dom : NumberOfDomains
start_date : StartDate
end_date : EndDate
interval_seconds: IntervalSeconds
io_form_geogrid : 2
opt_output_from_geogrid_path: "'./'"

'&geogrid':
# It is mandatory to set the following null
# parameters for each system
e_we : null
e_sn : null
dx : null
dy : null
ref_lat : null
ref_lon : null
truelat1 : null
truelat2 : null
stand_lon : null
#
parent_id : 1
parent_grid_ratio : 1
i_parent_start : 1
j_parent_start : 1
# For WRFLES we fix the geog_data_res index for
# all 6 domains here
geog_data_res : "'corine_NORWAY+30s',
'corine_NORWAY+30s','corine_NORWAY+30s',
'corine_NORWAY+1scustom','corine_NORWAY+1scustom',
'corine_NORWAY+1scustom'"
map_proj : "'lambert'"
geog_data_path : "'./geog'"
opt_geogrid_tbl_path: "'./'"

'&ungrib':
out_format: "'WPS'"
prefix : "'./FILE'"

'&metgrid':
fg_name : "'FILE'"
io_form_metgrid : 2
opt_metgrid_tbl_path : "'./'"
```

- The WRF namelist file for the "real" part. Values for bold-faced parameters are inherited from the WPS step and are calculated within the WRFLES system.

```
# WRF namelist file in YaML format, intended
# for processing by the WRFLES system.
#
'&time_control':
run_days : 0
run_hours : 0
run_minutes : 0
run_seconds : 0
start_year : StartYear
start_month : StartMonth
start_day : StartDay
start_hour : StartHour
start_minute : StartMinute
start_second : StartSecond
end_year : EndYear
end_month : EndMonth
end_day : EndDay
end_hour : EndHour
end_minute : EndMinute
end_second : EndSecond
interval_seconds : IntervalSeconds
input_from_file : ".true., .true., .true., .true., .true.,
.true."
history_interval : [ 05, 05, 05, 10, 10, 10 ]
frames_per_outfile : [ 10000, 10000, 10000, 10000, 10000,
10000]
restart : ".false."
restart_interval : 10080
io_form_history : 2
io_form_restart : 2
io_form_input : 2
io_form_boundary : 2
debug_level : 0
io_form_auxinput2 : 2
auxinput4_inname : "'wrflowinp_d<domain>'"
auxinput4_interval : AuxInput4Interval
io_form_auxinput4 : 2


'&domains':
use_adaptive_time_step : ".false."
time_step : 30
time_step_fract_num : 0
time_step_fract_den : 1
step_to_output_time : ".true."
# The following section is only applicable for
# adaptive timesteps
target_cfl : [1.2, 1.2, 1.2, 1.2, 1.2, 1.2]
max_step_increase_pct : [5, 51, 51, 51, 51, 51, 51, 51]
starting_time_step : -1
max_time_step : -1
min_time_step : -1
adaptation_domain : 1
# FIXME: We will need to change the next
# parameter for WRF-PBL step
max_dom : 6
# FIXME: We can use the programmatic setting via
# max_dom : NumberOfDomains
s_we : StartIndices
s_sn : StartIndices
e_we : EndWEFromWPS
e_sn : EndSNFromWPS
dx : DxFromWPS
dy : DyFromWPS
grid_id : GridId
parent_id : ParentIdFromWPS
i_parent_start : IParentStartFromWPS
j_parent_start : JParentStartFromWPS
```

```
parent_grid_ratio : ParentGridRatioFromWPS
parent_time_step_ratio : ParentGridRatioFromWPS
s_vert : [ 1, 1, 1, 1, 1, 1 ]
e_vert : [55, 55, 55, 55, 55, 55]
num_metgrid_levels : 33
num_metgrid_soil_levels : 4
eta_levels : [
1.0000, 0.9960, 0.9935, 0.9899, 0.9861, 0.9821,
0.9777, 0.9731, 0.9682, 0.9629, 0.9573, 0.9513,
0.9450, 0.9382, 0.9312, 0.9240, 0.9165, 0.9088,
0.9008, 0.8925, 0.8840, 0.8752, 0.8661, 0.8567,
0.8471, 0.8371, 0.8261, 0.8141, 0.8008, 0.7863,
0.7704, 0.7531, 0.7341, 0.7135, 0.6911, 0.6668,
0.6406, 0.6123, 0.5806, 0.5452, 0.5060, 0.4630,
0.4260, 0.3890, 0.3480, 0.3020, 0.2420, 0.2120,
0.1820, 0.1520, 0.1210, 0.0910, 0.0610, 0.0300,
0.000
]
p_top_requested : 5000
feedback : 0
smooth_option : 0

'&physics':
mp_physics : [ 8, 8, 8, 8, 8, 8 ]
ra_lw_physics : [ 1, 1, 1, 1, 1, 1 ]
ra_sw_physics : [ 1, 1, 1, 1, 1, 1 ]
radt : [ 8, 8, 8, 8, 8, 8 ]
sf_sfclay_physics : [ 2, 2, 2, 2, 2, 2 ]
sf_surface_physics : [ 2, 2, 2, 2, 2, 2 ]
bl_pbl_physics : [ 2, 2, 2, 2, 2, 2 ]
cu_physics : [ 0, 0, 0, 0, 0, 0 ]
bldt : [ 0, 0, 0, 0, 0, 0 ]
cudt : [ 0, 0, 0, 0, 0, 0 ]
num_land_cat : 25
ensdim : 144
icloud : 1
ifsnow : 0
isfflx : 1
maxens : 3
maxens2 : 3
maxens3 : 16
maxiens : 1
num_soil_layers : 4
sf_urban_physics : [ 0, 0, 0, 0, 0, 0 ]
sst_update : 1
surface_input_source : 1

'&fdda': {}

'&dynamics':
rk_ord : 3
w_damping : 1
diff_opt : 1
km_opt : 4
diff_6th_opt : 0
diff_6th_factor : 0.12
base_temp : 278.
base_lapse : 50.
damp_opt : 3
zdamp : [ 5000., 5000., 5000., 5000., 5000., 5000. ]
dampcoef : [ 0.2, 0.2, 0.2, 0.2, 0.2, 0.2 ]
khdif : [ 0, 0, 0, 0, 0, 0 ]
kvdif : [ 0, 0, 0, 0, 0, 0 ]
non_hydrostatic : ".true., .true., .true., .true., .true.,
.true."
h_mom_adv_order : 5
v_mom_adv_order : 3
h_sca_adv_order : 5
v_sca_adv_order : 3
moist_adv_opt : 1
scalar_adv_opt : 1
use_baseparam_fr_nml : ".true."

'&bdy_control':
spec_bdy_width : 5
spec_zone : 1
relax_zone : 4
specified : ".true., .false., .false., .false., .false.,
.false."
nested : ".false., .true., .true., .true., .true., .true."

'&grib2': {}

'&namelist_quilt':
nio_tasks_per_group : 0
nio_groups : 1,
```

– The WRF namelist file for the "PBL" part

```
# WRF namelist file in YaML format,
# intended for processing by the WRFLES
# system.
#
# This file contains parameters that
# bring us from the basic configuration
# to the configuration suitable for WRF-PBL step.
#
'&domains':
max_dom : 2
```

– The WRF namelist for the "NDOWN" part

```
# WRF namelist file in YaML format, intended
# for processing by the WRFLES system.
#
# This file contains parameters that bring
# us from the basic configuration to the
# configuration suitable for Ndown (nestdown) step.
#
'&time_control':
start_year : StartYearShifted1
start_month : StartMonthShifted1
start_day : StartDayShifted1
start_hour : StartHourShifted1
start_minute : StartMinuteShifted1
start_second : StartSecondShifted1
end_year : EndYearShifted1
end_month : EndMonthShifted1
end_day : EndDayShifted1
end_hour : EndHourShifted1
end_minute : EndMinuteShifted1
end_second : EndSecondShifted1
# The interval_seconds should actually be calculated
# as 60*history_interval in the namelist.input.wrfpbl.yml
# file (or possibly the template for that,
# i.e. namelist_data.input.wrfpbl.yml)
# Note, however, that interval_seconds is a scalar,
# so not possible to let it vary accross domains
interval_seconds : 300

'&domains':
max_dom : 2
time_step : 30
```

```
s_we : StartIndicesShifted1
s_sn : StartIndicesShifted1
e_we : EndWEFromWPSShifted1
e_sn : EndSNFromWPSShifted1
dx : DxFromWPSShifted1
dy : DyFromWPSShifted1
grid_id : GridIdShifted1
parent_id : ParentIdFromWPSShifted1
i_parent_start : IParentStartFromWPSShifted1
j_parent_start : JParentStartFromWPSShifted1
parent_grid_ratio : ParentGridRatioFromWPSShifted1
parent_time_step_ratio : ParentGridRatioFromWPSShifted1
```

– The WRF namelist for the "LES" part

```
# WRF namelist file in YaML format, intended
# for processing by the WRFLES system.
#
# This file contains parameters that bring
# us from the basic configuration
# to the configuration suitable for WRFLES step.
#
'&time_control':
start_year : StartYearShifted2
start_month : StartMonthShifted2
start_day : StartDayShifted2
start_hour : StartHourShifted2
start_minute : StartMinuteShifted2
start_second : StartSecondShifted2
end_year : EndYearShifted2
end_month : EndMonthShifted2
end_day : EndDayShifted2
end_hour : EndHourShifted2
end_minute : EndMinuteShifted2
end_second : EndSecondShifted2
# The interval_seconds should actually be calculated
# as 60*history_interval
# in the namelist.input.wrfpbl.yml file (or possibly
# the template for that,
# i.e. namelist_data.input.wrfpbl.yml)
interval_seconds : 300
# User should be reminded of changing history_interval
history_interval : [ 15, 15, 15, 15 ]

'&domains':
max_dom : 4
time_step : 5
s_we : StartIndicesShifted2
s_sn : StartIndicesShifted2
e_we : EndWEFromWPSShifted2
e_sn : EndSNFromWPSShifted2
dx : DxFromWPSShifted2
dy : DyFromWPSShifted2
grid_id : GridIdShifted2
parent_id : ParentIdFromWPSShifted2
i_parent_start : IParentStartFromWPSShifted2
j_parent_start : JParentStartFromWPSShifted2
parent_grid_ratio : ParentGridRatioFromWPSShifted2
parent_time_step_ratio : ParentGridRatioFromWPSShifted2

'&physics':
bl_pbl_physics : [ 0, 0, 0, 0 ]

'&dynamics':
km_opt : 2
diff_opt : 2
sfs_opt : [ 0, 0, 2, 2 ]
```