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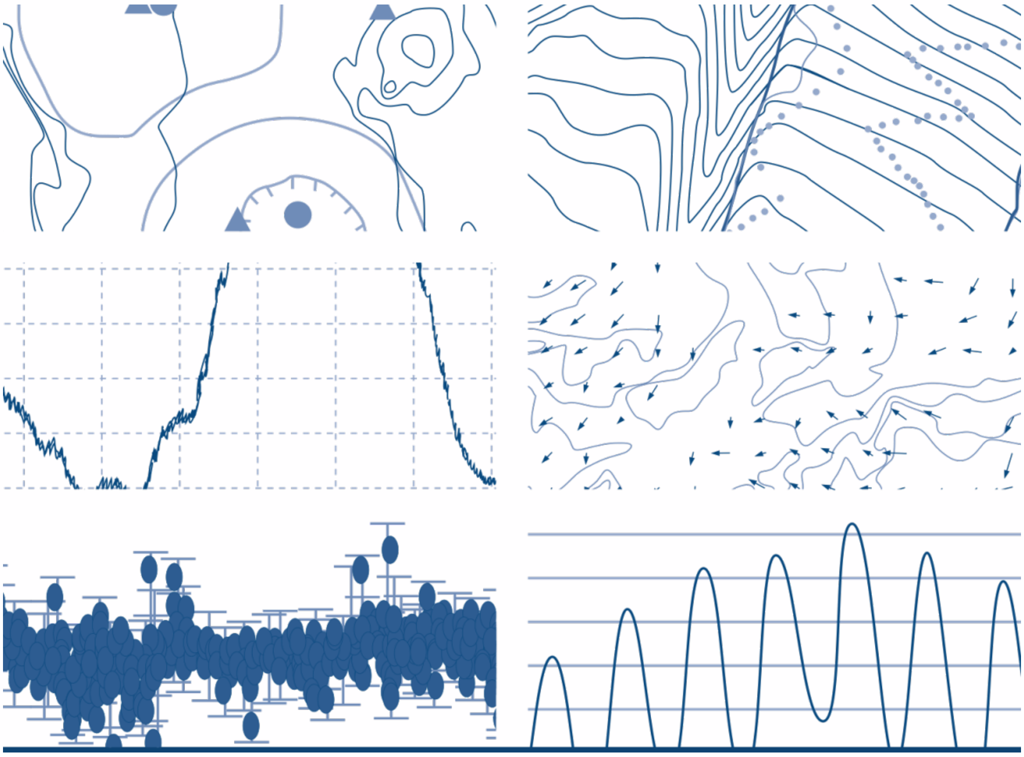

Evaluation of HARMONIE reanalyses of surface air temperature and wind speed over Iceland

Nikolai Nawri

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In this study, reanalyses are being evaluated, which have been produced with the numerical weather prediction model HARMONIE, used operationally by the Icelandic Meteorological Office. Systematic biases in 2-m air temperature and 10-m wind speed were found, especially over the interior of the island. It is shown that the temperature biases are being introduced by the external surface scheme SURFEX, rather than by the core model. Consequently, the accuracy of near-surface air temperature is improved, if temperature is linearly projected downwards from higher model fields. Wind speed biases are the result of excessive surface roughness. Both biases can be statistically corrected, using station measurements.

Keywords:	Managing director's signature:
HARMONIE numerical weather prediction model SURFEX external surface scheme Reanalyses Surface air temperature Surface wind speed Iceland	Jórunn Harðardóttir **Project manager's signature:** Halldór Björnsson **Reviewed by:** Sigurður Þorsteinsson, SG

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1 Introduction

In the spring of 2013, the Icelandic Meteorological Office (IMO) started a reanalysis project, using the HARMONIE numerical weather prediction model. Operationally, this model has been in use at IMO since the autumn of 2011, and has proven to provide overall better results within the Icelandic forecast domain than other mesoscale models. However, based on the standard model setup and parameterisations, there are systematic biases in 2-m air temperature and 10-m wind speed over the land area of Iceland (de Rosnay et al. (2013), Pálmason et al. (2013); see also the various experiments at http://brunnur.vedur.is/pub/bolli/harmonie/verif/).

For wind speed, previous work at IMO has shown that these biases are at least partially due to excessive surface roughness in the default drag parameterisation of the external model surface scheme (Pálmason et al., 2013). It was shown that changing the default parameterisation not only improves 10-m wind speeds but also 2-m temperature and relatively humidity. After a testing phase, the modified parameterisation became operational in September 2013.

However, for the ongoing reanalysis project, particularly for data that has already been archived, it is important to find ways to correct biased surface data. The purpose of this study therefore is to analyse in more detail HARMONIE model errors in 2-m temperature and 10-m wind speed, mainly by separating the results of the surface scheme from the core model, and to test a statistical correction procedure, based on station measurements.

The analysis uses data for the January and July months of the 2010 – 12 period.

2 Model setup and data

The equations and parameterisations, which constitute the core of the HARMONIE model, are described by Brousseau et al. (2011) and Seity et al. (2011).[1] The specific model version used for the IMO reanalysis project is 37h1.2. The simulations were run on the c2a supercomputer at the European Centre for Medium Range Weather Forecasts (ECMWF). The model domain is the same as the one used for the IMO operational forecast runs (DOMAIN=ICELAND)[2], with 300×240 horizontal grid points, and a horizontal grid-point spacing of about 2.5 km in both directions.

HARMONIE uses a terrain-following sigma coordinate system, where model levels are defined as iso-surfaces of pressure, scaled by the pressure at the lower model boundary. For IMO reanalyses, the model is run with the standard 65 vertical levels, and with a non-hydrostatic dynamic core (DYNAMICS="nh"). Radiation, turbulence, convection, and microphysics (clouds and precipitation) are determined by the AROME upper air physics scheme (PHYSICS="arome").

Surface and soil processes are described by version 6 of the external single-layer coupled surface scheme SURFEX (SURFACE="SURFEX"), consisting of special components for four different surface types: continental natural surfaces (including natural vegetation, bare soils, rocks, and permanent snow), town (including buildings, roads, and gardens), inland water (including lakes and rivers), and ocean (including sea ice) (Le Moigne, 2009). SURFEX uses input from the

[1] Further information can be found online at http://hirlam.org/index.php/documentation/harmonie.

[2] In this section, expressions in parentheses refer to parameter values and settings in the config_exp.h model configuration file.

lowest level of the atmospheric model, together with static fields describing the model terrain, to calculate radiative surface properties, as well as surface fluxes of momentum, sensible and latent heat, aerosols, CO_2, and various other chemical species. These properties are then used as lower boundary conditions for the upper air dynamical model and physics scheme, and to calculate fixed-height atmospheric "surface" variables that are not located on model levels, such as 2-m air temperature, and 10-m horizontal wind.

Initial and boundary conditions for the model simulations discussed here are provided by ECMWF operational analyses (BDSTRATEGY=simulate_operational), with a boundary data interval of three hours (BDINT=3), and a horizontal resolution of 0.125 degrees in longitude and latitude (Andersson and Thépaut, 2008; Bechtold et al., 2008). The lateral boundaries of the HARMONIE model have a relaxation zone of 10 grid points, wherein the coarse-resolution outer data from the host model is blended with the high-resolution data within the dependent model domain. At the upper boundary, defined as the 10-hPa isobaric surface, vertical velocity is set to zero.

The model is run in upper-air and surface data assimilation mode. The atmospheric analysis is handled such that initial and boundary conditions, for each forecast run, are combined with the last output from the previous run (ANAATMO=blending). Gridded surface analyses for 2-m air temperature and relative humidity, sea surface temperature, and snow water equivalent are prepared by the spatial interpolation tool CANARI (ANASURF=CANARI_OI_MAIN).

The model is run uninterrupted for an entire hydrological year which, in Iceland, is defined to begin on 1 September. Each one-year simulation is set up with a cold-start forecast ({BUILD-yes}) on 31 August at 18 UTC, with a lead time of 6 hours ({LL-06}),

The initial conditions provided by ECMWF operational analyses introduce an unrealistically high late-summer snow cover into the HARMONIE simulations. To avoid this, as well as associated effects, such as too low 2-m air temperatures, variable snow cover is completely removed from the entire model domain after completion of the first cold-start forecast.[3] Based on the corrected initial data, the 6-hour cold-start forecast run is repeated, without building the model domain again ({BUILD-no}). Beginning with the end of the "no-snow cold-start" on 1 September at 0 UTC, the model is run in surface data assimilation mode with successive 6-hour forecast runs until 1 September the following year. Since the variable snow amount over the glaciers at the end of summer is overestimated by the model, the simulation of the next hydrological cycle is begun again with a "no-snow cold-start".

Model results are evaluated in comparison with quality controlled hourly measurements of wind speed and direction, as well as air temperature, from the IMO operational surface station network. Most anemometers are installed at 10 m above ground level (mAGL). However, at some stations, surface winds are measured at different heights, *h*, varying between 4.0 and 18.3 m.

[3]This is done using a GRIB-API command on Parameter 141 (snow depth) in the earliest boundary data file: `grib_set -f -d 0.0 -w indicatorOfParameter=141 <earliest boundary data filename> <modified filename>`. Glaciers are defined as permanent snow and ice in the model, and are described by static fields in the surface scheme.

These differences are taken into account following WMO guidelines (WMO, 2008), whereby wind speeds are projected to 10 mAGL by

$$S(10\text{m}) = S(h)\,\frac{\ln(10/z_0)}{\ln(h/z_0)}\ . \tag{1}$$

For Iceland the surface roughness length z_0 over land is set to 3 cm (Troen and Petersen, 1989). Surface air temperature is measured at 2 mAGL. As described in Nawri et al. (2012b), for any given variable, only those locations are considered, for which station records have at least 75% valid data within any specific period under consideration. The names, ID numbers, and coordinates of all stations from which data was used are given in Nawri et al. (2012b) (see the appendix there).

To evaluate the representativeness of the model terrain in different parts of Iceland, a digital elevation model (DEM) with a 100×100 m resolution is used. This DEM was produced in 2004 by IMO, the National Land Survey of Iceland (Landmælingar Íslands, LMI), the Science Institute of the University of Iceland (Raunvísindastofnun Háskólans), and the National Energy Authority (Orkustofnun).

3 Model terrain and surface type

The HARMONIE model dominant surface type and terrain elevation are shown in Figures 1 and 2, respectively. Surface type is specified in SURFEX by the global land surface database ECOCLIMAP-I (Champeaux et al., 2005). Within each grid box, ground coverage is represented by fractions of one for each category of surface type. In the figure, only values above 0.5 are shown. In those situations, grid boxes are covered primarily by one particular surface type.

The model terrain type can be compared with a detailed land cover classification for Iceland, prepared in 2008 for the Coordination of Information on the Environment (CORINE) programme, organised by the European Environment Agency (EEA). In 2009, these results were incorporated into the CORINE Land Cover 2006 (CLC2006) inventory (Árnason and Matthíasson, 2009).

In the model, the total land area (95,570 km^2) is broken down into the following surface types (percentages of terrain type coverage refer to the total *model* land area):

- Sparse tundra: 39,421 km^2 (41.3%)
- Tundra: 23,688 km^2 (24.8%)
- Subpolar pastures: 11,364 km^2 (11.9%)
- Permanent snow: 10,046 km^2 (10.5%)
- Subpolar wetlands: 7,208 km^2 (7.5%)
- Subpolar crops: 2,380 km^2 (2.5%)
- Inland water[4]: 1,463 km^2 (1.5%)

[4]Including also the coastal lagoon Hópið, and the estuary at Höfn.

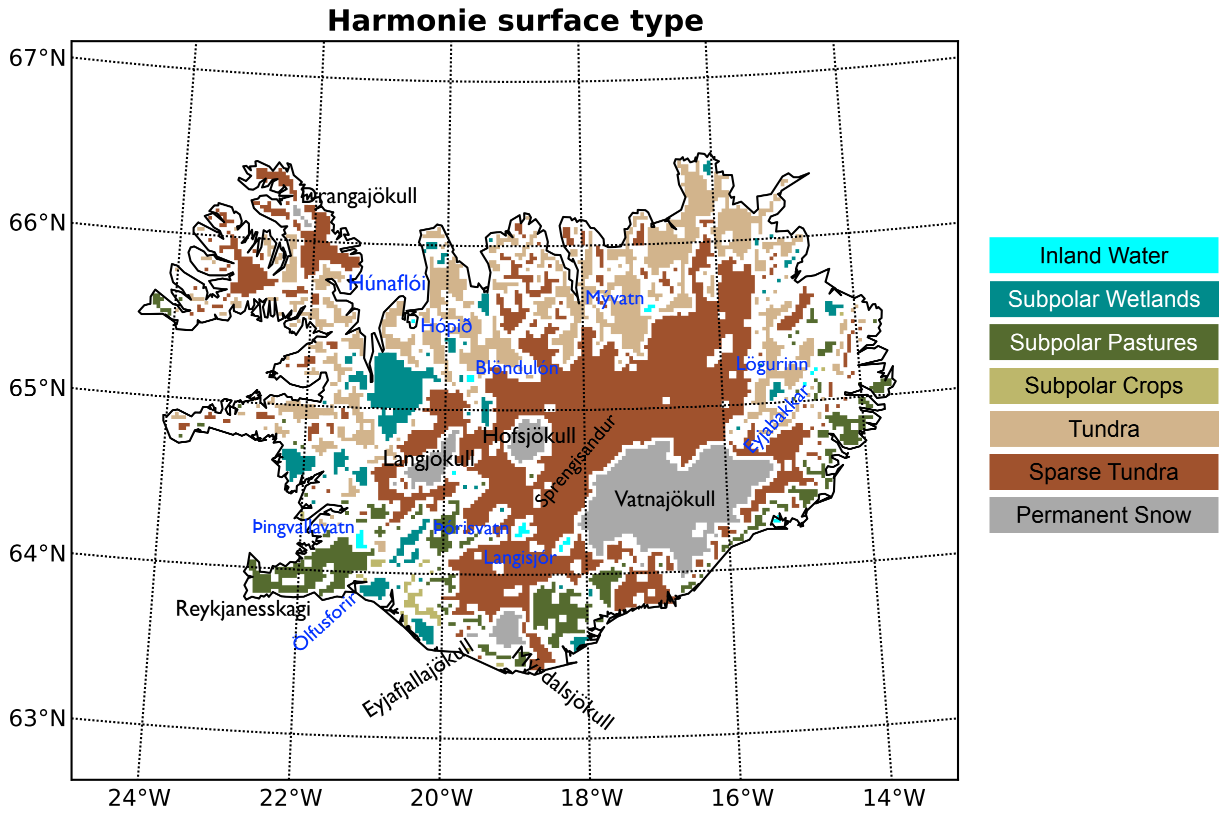

Figure 1. HARMONIE model dominant surface type.

The location and size of areas covered by permanent snow are well represented in the model. According to CLC2006, glaciers and permanent snow (class 335) cover 10,971 km^2, or 10.6% of the *actual* land area (103,440 km^2).

Generally, the distribution of wetlands also agrees well with the CLC2006 map of Iceland. However, the total model area covered by wetlands is somewhat overestimated (Árnason and Matthíasson, 2009). The main reason for this is that, in reality, the largest regions containing wetlands are interspersed with other surface types, primarily moors and heathland (class 322). According to CLC2006, the total area of peatbogs[5] (class 412) is 6,200 km^2 (6.0%), while inland marshes (class 411) cover 367 km^2 (0.4%). Despite the overall overestimation of wetland areas, some significant wetlands are not recognised or underrepresented in the model, most notably the Mývatn – Laxá region, Þjórsárver south of Hofsjökull, Eyjabakkar northeast of Vatnajökull, and the area around Höfn, east of Vatnajökull (see Figure 1 for place names).

The largest lakes are recognised by the model, such as Þórisvatn, Þingvallavatn, Blöndulón (a dammed lake), Lögurinn, Mývatn, Hvítárvatn (east of Langjökull), and Langisjór. According to CLC2006, inland water bodies (class 512) cover 1,220 km^2 (1.2%), coastal lagoons (class 521) cover 268 km^2 (0.3%), and estuaries (class 522) cover 71 km^2 (0.1%), for a total of 1,559 km^2 (1.5%), which agrees well with the total area of inland water as represented in the model. However, some significant lakes are absent. These are primarily Hálslón (a dammed lake northeast of

[5]In CLC2006, areas identified as peatbogs in Iceland are primarily slope mires, that do not always have a thick peaty ground (Árnason and Matthíasson, 2009). They may also be pastures, where ditches have little draining effect.

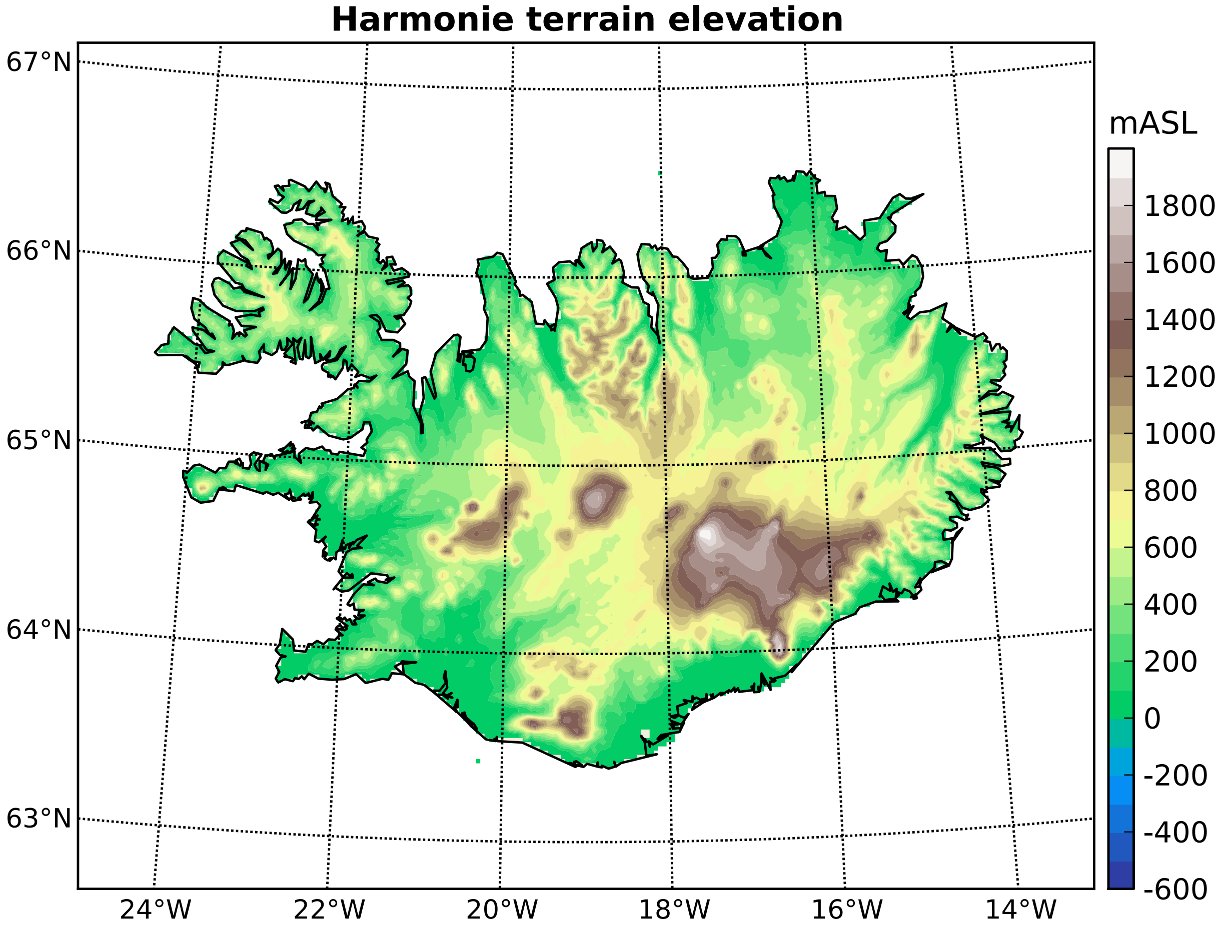

Figure 2. HARMONIE model terrain elevation.

Vatnajökull), as well as Hágöngulón and a group of lakes around Kvíslavatn in the Sprengisandur region between Vatnajökull and Hofsjökull. Also missing in the model are some main water courses (class 511; 789 km^2, 0.8%), most notably the wide southern outflow from Vatnajökull.

The main problem with the model characterisation of surface type is the overestimation of vegetated areas. According to LMI (http://www.lmi.is/island-i-tolum/), the total vegetated area is 23,805 km^2 (23.0%), whereas 64,538 km^2 (62.4%) are unglaciated barren land (e.g., lava, ash, gravel, sand, scree and rock outcrops). In the model, densely vegetated regions such as subpolar pastures, wetlands, and crops alone cover 21.9% of the model land area. According to CLC2006, much of the area covered in the model with sparse tundra is in fact bare rock (class 332; 23,761 km^2, 23.0%) or sand plains (class 331; 3,200 km^2, 3.1%). Most of the remaining part of the region is however classified as sparsely vegetated areas (class 333; 13,505 km^2, 13.1%) in CLC2006. Areas defined in the model as tundra, primarily overlap with CLC2006 moors and heathland (class 322; 36,144 km^2, 34.9%). According to CLC2006, regions of dense grass, such as pastures (class 231; 2,482 km^2, 2.4%) and natural grassland (class 321; 2,896 km^2, 2.8%) cover a smaller relative area than in the model. These inaccuracies in the identification of surface type may affect climatological properties, such as evaporation (water balance), albedo (radiation balance), and surface roughness (momentum balance).

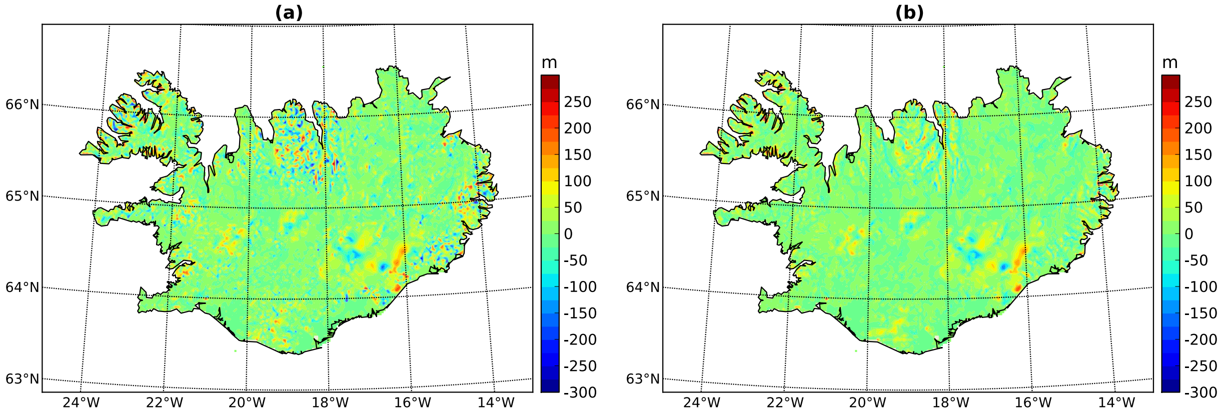

Figure 3. Differences in terrain elevation between HARMONIE model and 100-m-resolution DEM (model minus DEM): (a) original DEM interpolated onto the HARMONIE model grid, and (b) DEM horizontally averaged around each model grid point, using an exponential shape function with a half-width of 1 km.

In addition to surface type, boundary-layer atmospheric properties are strongly influenced by the height and shape of the underlying terrain. There is the possibility that model simulations are accurate with respect to the model terrain, but still compare poorly to surface measurements, due to subgrid-scale variability of terrain elevation. Therefore, to be able to identify as much as possible model errors that are not related to a limited description of orography, the influence of local terrain effects on measurements has to be minimised, before making comparisons between model results and station data.

The HARMONIE model terrain elevation, in comparison with the 100-m-resolution Icelandic DEM, is shown in Figure 3 (a). Interpolated values of the DEM at each HARMONIE model grid point are given by inverse distance weighted averages from the four surrounding DEM grid-points. Overall, differences between model terrain and DEM are essentially unbiased, with an average of 2.0 m, and a mean absolute difference of 10.0 m. The largest deviations, with magnitudes of up to 300 m, are found in regions with the highest variability in actual terrain elevations, most notably in the central northern part of the island, as well as along the eastern and southeastern coast, and in the outlying parts of the Westfjords. Assuming a standard vertical temperature lapse rate of 6.5 $\mathrm{K\,km^{-1}}$, these differences in terrain elevation alone may be responsible for absolute differences of up to 2 K between longterm averages of simulated and measured surface air temperatures, possibly with opposite signs at nearby locations.

As shown in Figure 3 (b), differences in terrain elevation are reduced if the model terrain is compared with a smoothed version of the DEM. This smoothing is done by horizontal averaging with an exponential shape function, $\exp(-a\,r)$, where r is the distance from a given model grid point, and $a = \log(2)/r_h$, with half-width r_h. The smallest mean absolute difference of 6.3 m between model terrain elevation and smoothed DEM is obtained for an exponential half-width of 1 km. This is accomplished primarily by reducing small-scale fluctuations of DEM elevations. Larger-scale deviations between model terrain and DEM, such as on and around Vatnajökull, remain.

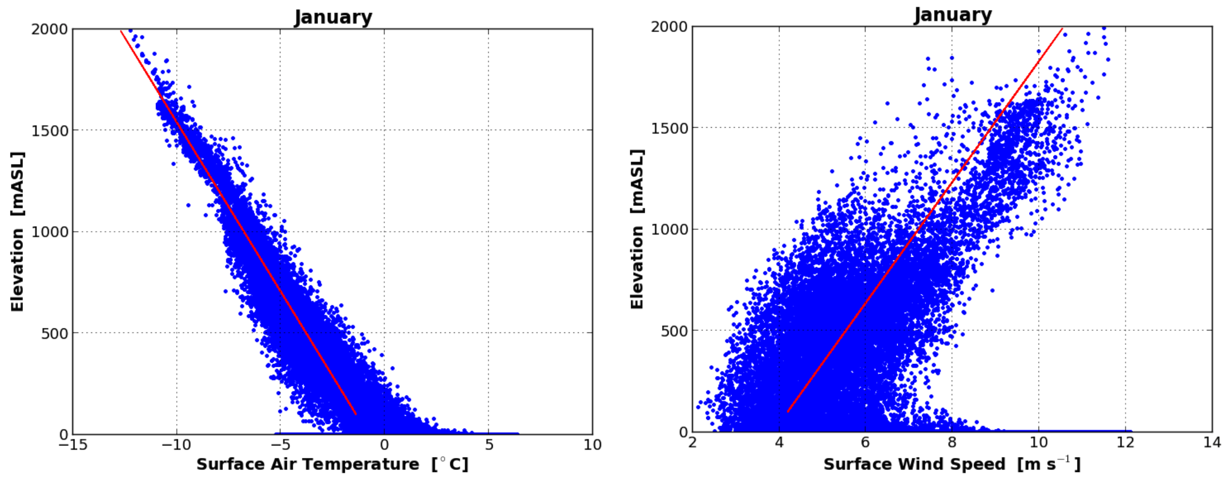

Figure 4. Dependence of HARMONIE 2-m air temperature and 10-m wind speed on model terrain elevation in January.

Observational time-series are made more representative of the spatial scales resolved by the model through horizontal averaging, using the same distance weighting as for the smoothing of the DEM. Prior to averaging, measured temperature and wind speed are projected from the station elevation to mean sea level using the linear terrain-following vertical gradients described in Nawri et al. (2012a). Values projected to mean sea level are then horizontally averaged around each station location, using an exponential shape function with the same half-width of 1 km, that minimises the mean absolute difference between model terrain elevation and smoothed DEM. Horizontally averaged values at mean sea level are then linearly projected upwards again to the local height of the smoothed DEM. Due to the narrow half-width, this horizontal averaging primarily has an effect in regions with a high density of stations.

Similarly, for the interpolation of model data to station locations, differences between model and actual terrain need to be taken into account. Therefore, prior to horizontal interpolation, model data is vertically projected down to mean sea level, using model-specific linear terrain-following vertical gradients, calculated separately for each month. Due to a large spread of near-surface air temperature and wind speed over terrain below 100 m above mean sea level (mASL) (see Figure 4), model grid-points below that level are ignored for the calculation of best linear fits of vertical profiles. Terrain-following gradients obtained for 2-m air temperature are -6.0 $\mathrm{K\,km^{-1}}$ in January, and -7.2 $\mathrm{K\,km^{-1}}$ July. For 10-m wind speed, the terrain-following gradients are 3.4 $\mathrm{m\,s^{-1}\,km^{-1}}$ in January, and 1.0 $\mathrm{m\,s^{-1}\,km^{-1}}$ in July.

Interpolated values at station locations are given by inverse distance weighted averages from the four surrounding grid-points, if these grid-points are all over land, according to the model land-sea mask. Along the coast, if any of the surrounding grid-points are over the ocean, the nearest land grid-point value is used at the station location. Interpolated values at mean sea level are then linearly projected up to the local height of the smoothed DEM.

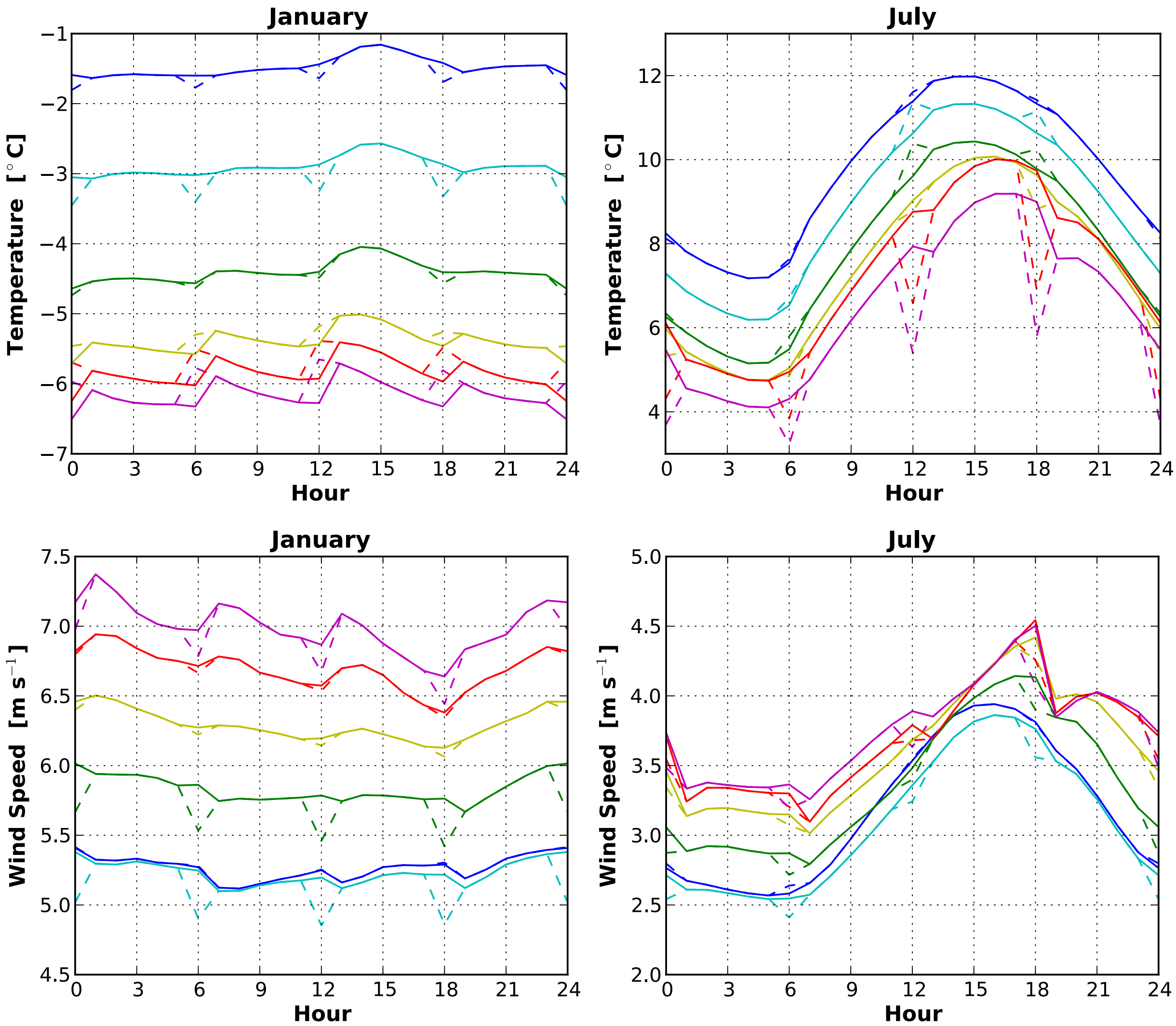

Figure 5. Average diurnal cycles of 2-m temperature and 10-m wind speed based on HARMONIE model simulations for grid points within bands of different onshore distances to the coast (DTC), with $0 < \mathrm{DTC} \leq 10$ km *(blue lines),* $10 < \mathrm{DTC} \leq 30$ km *(cyan lines),* $30 < \mathrm{DTC} \leq 50$ km *(dark green lines),* $50 < \mathrm{DTC} \leq 75$ km *(light green lines),* $75 < \mathrm{DTC} \leq 100$ km *(red lines),* $\mathrm{DTC} > 100$ km *(magenta lines). Individual grid-point time-series were compiled either from forecast hours 1 – 6 (solid lines), or from the initial field of each run and forecast hours 1 – 5 (dashed lines).*

4 Impact of initial conditions in blending mode

As mentioned in Section 2, the initial fields for each 6-hourly model run in surface data assimilation (blending) mode are a combination of ECMWF operational analyses, station measurements of 2-m temperature, and the last forecast field from the previous model run. Due to discrepancies between the temporal evolution of model forecasts on the one hand, and of operational analyses and measured temperatures on the other, there are some discontinuities between the sixth forecast hour of each model run, and the blended initial field for the subsequent run. During the first forecast hour, model simulations tend towards the values at the end of the previous run, but especially in the interior of the island, some significant differences remain.

For 2-m air temperature and 10-m wind speed, this is illustrated in Figure 5, based on average diurnal cycles, calculated separately for grid points within bands of different onshore distances to the coast (DTC). Onshore DTC is defined here as the horizontal distance of each land grid point to the nearest ocean grid point.

For temperature, in the coastal region up to 50 km inland, the seasonal cycle based on model forecasts is weaker than based on the initial values of each forecast run, with warmer winter and colder summer temperatures. In the interior, the seasonal cycle based on model forecasts is more intense. Starting from the initial conditions of each individual 6-hour forecast run, the model tends towards colder temperatures in winter, whereas in summer, forecast temperatures are warmer than the initial conditions.

For wind speed, in winter and summer, average initial values across the island are consistently lower than the average model forecasts. As seen below, in comparison with station measurements, the average forecast wind speeds, while still being too weak, are more accurate than the initial fields.

To minimise discontinuities in model time-series compiled from individual forecast runs, the initial field is dropped. Time-series longer than the individual 6-hour runs are constructed using the first to sixth forecast hours.

5 Errors associated with SURFEX

As shown in Figure 6, there are some significant biases in simulated 2-m air temperature and 10-m wind speed compared with horizontally averaged station data. For temperature in January, small positive biases are found near the south coast and over the southwest interior of Iceland. Primarily, however, there are large negative biases in the northeast interior, with smaller negative biases throughout most of the island. In July, with the exception of a few outliers[6], model errors are smaller, with the main negative biases located along the north coast, particularly in the northwest. For wind speed, with a few exceptions, biases are negative throughout the year.

The question then arises, whether these biases are due to the initial and boundary conditions, the HARMONIE model core, or the external surface scheme (SURFEX). As discussed in the previous section, due to too weak 10-m winds in ECMWF operational analyses, average wind speeds in the “blended” initial conditions of each 6-hour forecast run are lower than the forecast wind speeds. This, in combination with excessive surface roughness in SURFEX (see the introduction), might explain the negative wind speed biases. However, for 2-m temperature in winter, the initial conditions over the interior of the island are warmer than the actual model forecasts. ECMWF operational analyses can therefore not be the cause of the large negative temperature biases.

The impact of the surface scheme can be determined by analysing 2-m temperature and 10-m wind speed from SURFEX in connection with vertical boundary-layer profiles calculated directly from HARMONIE model levels. Due to the temporal and spatial variability of model level heights, for the calculation of average vertical profiles, individual model profiles above

[6]The large positive bias northeast of Vatnajökull is due to the unusually cold summertime temperatures measured at Station 5932, situated near the edge of Brúarjökull at 866 mASL.

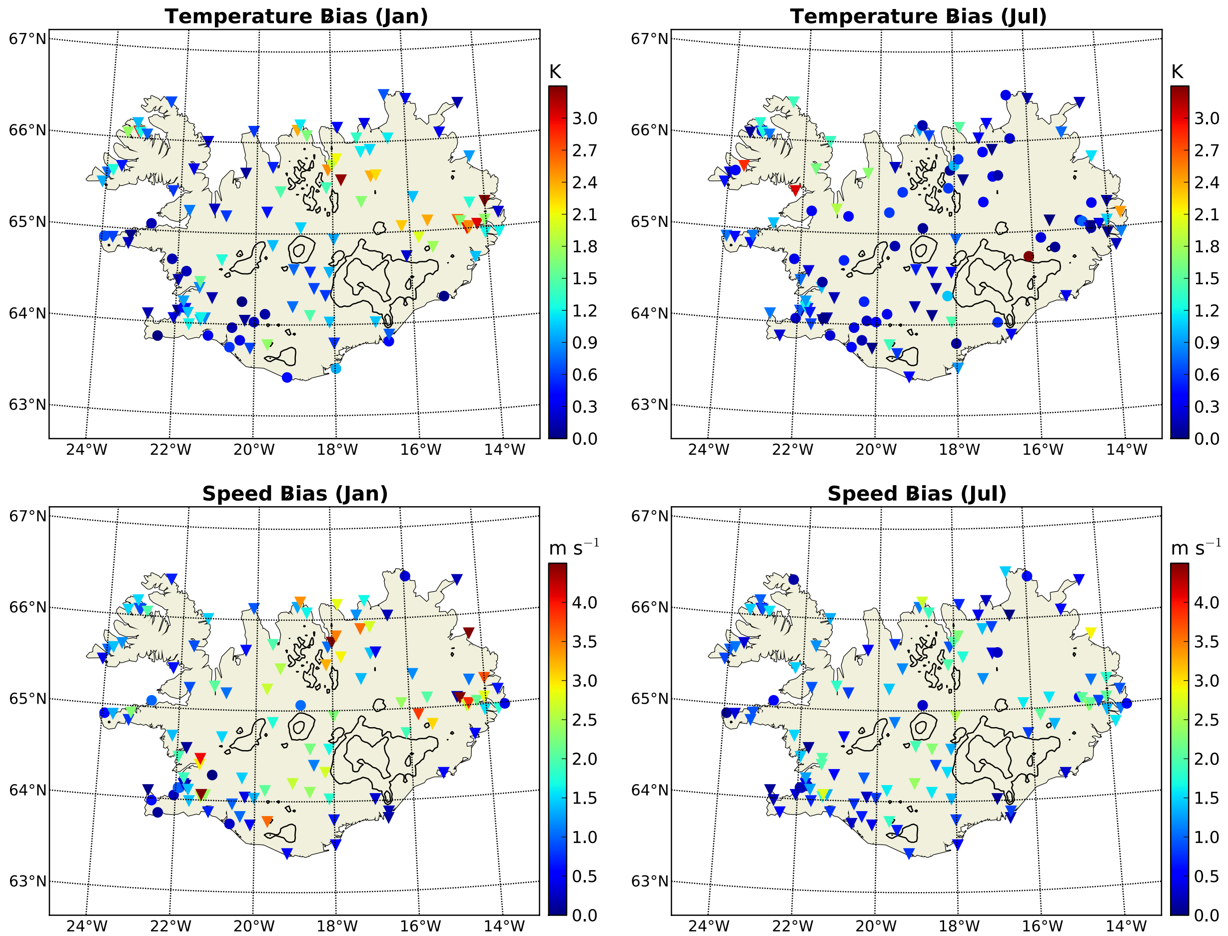

Figure 6. Absolute mean errors of SURFEX 2-m air temperature and 10-m wind speed compared with horizontally averaged station data (model minus measurements). Triangles indicated locations, where mean errors (biases) are negative. Terrain elevation contour lines are drawn at 1000 and 1500 mASL.

each grid point are linearly projected onto the same heights above ground, with the lowest level at 15 m.

The January average profiles for temperature and wind speed, together with the average surface values, are shown in Figure 7. For wind speed, the 10-m averages from SURFEX are relatively smooth continuations of the average model profiles. However, for temperature, the surface scheme introduces shallow inversion layers near the ground, which result in the negative biases in 2-m temperature shown in Figure 6. Temperatures at 2 mAGL, as determined by SURFEX, can be compared with 2-m temperatures determined directly from HARMONIE, by linearly projecting from the lowest two model levels. The lowest model level (L65) has an average height above ground of 11.9 m in January, and 12.2 m in July. The second lowest model level (L64) has an average height of 35.9 m in January, and 36.8 m in July. The model temperature lapse rates between L65 and L64 vary between -3.4 and 21.2 $\mathrm{K\,km^{-1}}$ in January, with an average of 7.8 $\mathrm{K\,km^{-1}}$, and between -8.2 and 13.3 $\mathrm{K\,km^{-1}}$ in July, with an average of 7.3 $\mathrm{K\,km^{-1}}$. As shown in Figure 7, differences between average SURFEX and projected 2-m temperatures are largest in onshore regions near the coast, and smallest in the offshore coastal region.

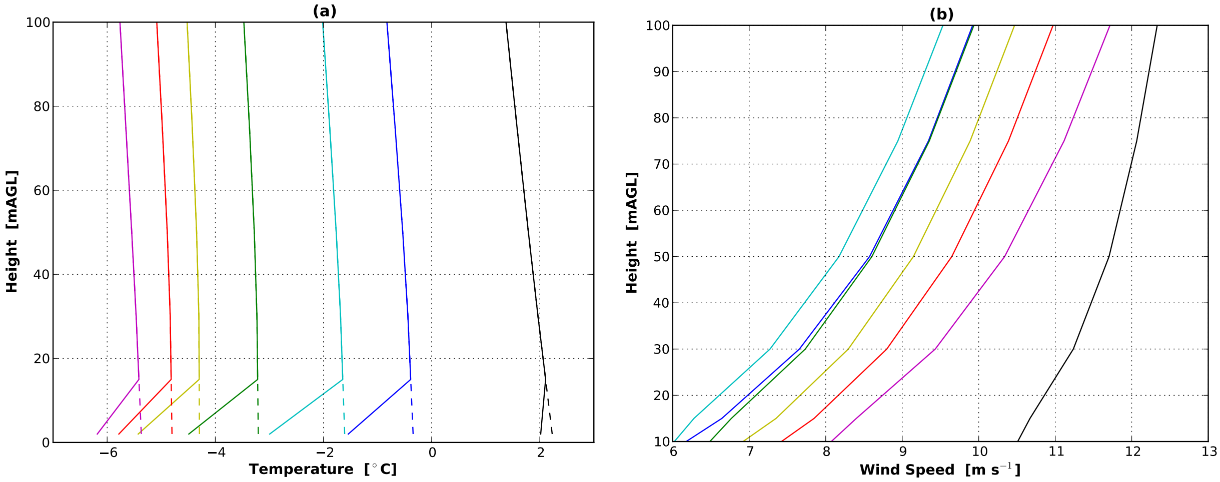

Figure 7. Average profiles of (a) air temperature and (b) wind speed in January within the lowest 100 m above ground, for grid points within bands of different onshore distances to the coast (DTC), with $0 < \mathrm{DTC} \leq 10$ km *(blue lines),* $10 < \mathrm{DTC} \leq 30$ km *(cyan lines),* $30 < \mathrm{DTC} \leq 50$ km *(dark green lines),* $50 < \mathrm{DTC} \leq 75$ km *(light green lines),* $75 < \mathrm{DTC} \leq 100$ km *(red lines),* $\mathrm{DTC} > 100$ km *(magenta lines). Additionally, the average profiles for offshore distances to the coast of up to 30 km are shown by the black lines. For temperature, the dashed lines indicate linear projection from the two lowest model levels to 2 m above ground.*

A comparison of monthly averages of simulated 2-m temperature with station measurements, both for SURFEX and projected values, is shown in Figure 8. On average, taking into account all stations and all hourly values, the absolute biases of projected model temperatures are smaller than for SURFEX temperatures, especially in January. However, there are also systematic errors in the projected temperatures, essentially underestimating the seasonal cycle, with too warm January temperatures, and too cold July temperatures. A similar problem exists for the diurnal cycle in July. For SURFEX temperatures, day- and night-time biases are similar. However, for projected temperatures, the summertime diurnal cycle is too weak, with a positive bias at night, and a negative bias during the day. In January, the diurnal temperature cycle is weak, and differences in simulated day- and night-time temperatures are small. Overall, while the absolute mean error in 2-m temperature is increased by the external surface scheme, the magnitude of temporal variability, related to changes in the near-surface radiation balance, is improved.

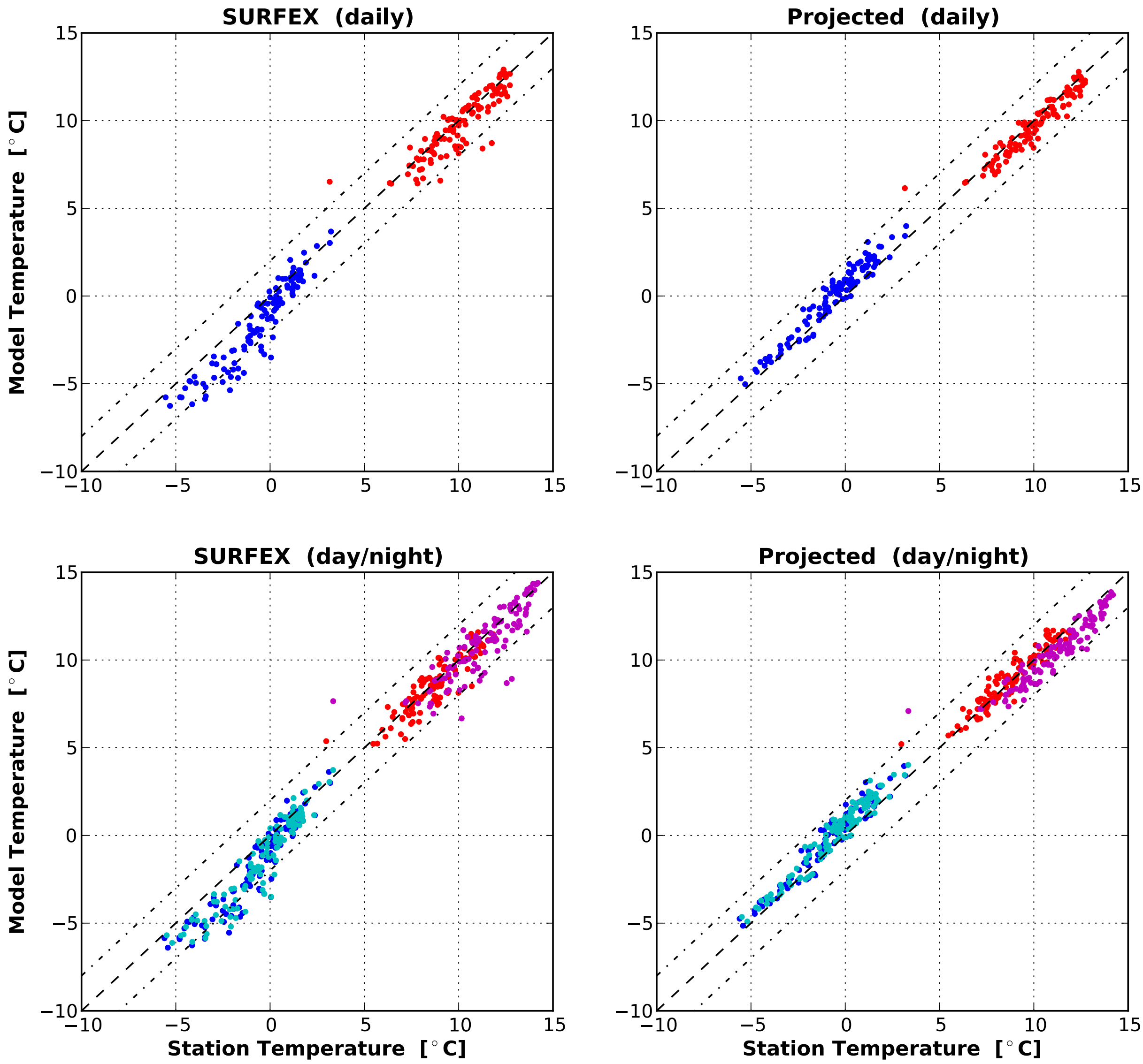

Figure 8. Monthly averages of simulated 2-m air temperature from either SURFEX or projected from the two lowest HARMONIE model levels, in comparison with station measurements. In the top panels, all hourly values are used to calculate January (blue) and July (red) averages. In the bottom panels, hourly values are separated into day (hours 7 to 18) and night (hours 19 to 6), with day/night averages indicated by cyan/blue dots in January, and magenta/red dots in July.

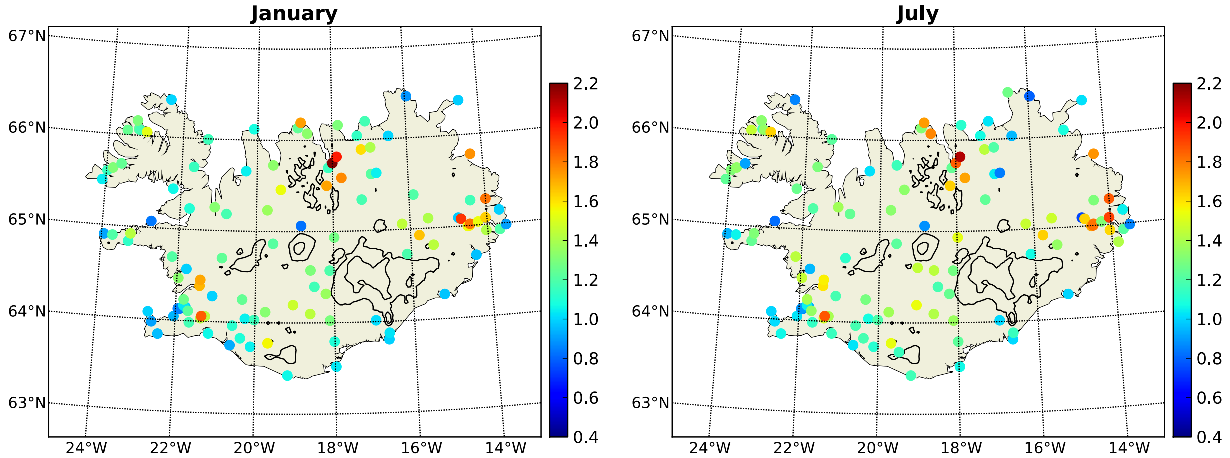

Figure 9. Correction factors for 10-m wind speed, determined at station locations.

6 Statistical correction of model results

To reduce the systematic model errors discussed in the previous section, a model time-series of 2-m temperature or 10-m wind speed, $M_i(t)$, interpolated to the i-th station location, can be linearly transformed such that the mean square error compared with the local station time-series is minimised. Generally, the corrected time-series is then given by

$$\tilde{M}_i(t) = a_i M_i(t) + b_i \ , \qquad (2)$$

where at each station location, the correction coefficients a_i and b_i are determined by least-squares fit with the local station data. However, for wind speed, to avoid negative values and to preserve the percentage of calms, the offset b_i is set identically zero. Model wind speeds are then adjusted through rescaling only.

For wind speed, the local correction factors are shown in Figure 9. In those areas with a high density of surface stations, it becomes apparent that there may be large differences in correction factors within a few kilometres, even for the spatially smoothed station data, as described in Section 3. Similarly, for temperature, there are some significant horizontal differences, especially between local offsets in summer (not shown).

Using local extreme values of correction coefficients for the adjustment of model fields would result in reduced accuracy at nearby locations. Therefore, those stations are excluded from the statistical correction, for which correction coefficients are outliers. For temperature, all stations are excluded, for which the absolute deviation from the overall mean value in July of either the correction factor or the offset is within the highest 10th percentile. For wind speed, all stations are excluded, for which the absolute deviation of the correction factor in either January or July is within the highest 10th percentile.

The statistical correction is applied to model fields by horizontally interpolating the local correction coefficients onto the model grid, using linear radial basis functions. Since only onshore station data is used, at 10 km or more offshore, correction factors for temperature and wind speed are set to 1 prior to horizontal interpolation. For temperature, the offset at those distances from the coast is set to 0.

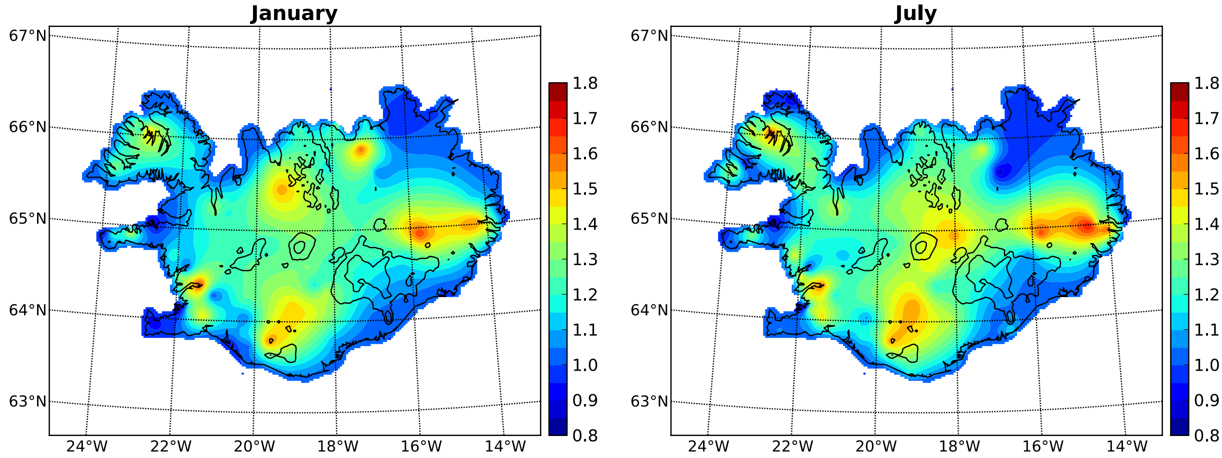

Figure 10. Correction factors for 10-m wind speed, linearly interpolated between station locations.

For wind speed, the interpolated fields of correction factors in January and July are shown in Figure 10. For the most part, the correction factors are greater than 1. The few locations near the coast, where correction factors are below 1, coincide with positive biases of model wind speed, as shown in Figure 6.

To test the effects of the correction procedure away from sites at which measurements are available, for each station location, corrected model time-series are calculated without the use of local station data, by interpolating correction coefficients from nearby station locations. These corrected time-series are then compared with the excluded station data. A comparison of monthly averages of either original or corrected SURFEX 2-m air temperature and 10-m wind speed with station measurements is shown in Figure 11. Averages of the individual values at all station locations of mean errors (biases) and mean absolute errors (MAEs) are listed in Table 1. For temperature, the overall bias in January is reduced by 86%, with a reduction in overall MAE of 17%. For wind speed, the overall January bias is reduced by 74%, with a reduction in overall MAE of 9%. Both, for temperature and wind speed, the main benefit of the correction procedure is a reduction of differences between monthly mean values. Mean absolute differences between individual values are reduced to a lesser extent, and correlations are completely unaffected by any linear transformation.

Table 1. Averages of the individual values at all station locations of mean errors (biases) and mean absolute errors (MAEs) of 2-m air temperature and 10-m wind speed for original and corrected SURFEX data.

	Temperature				Wind Speed			
	Bias [K]		MAE [K]		Bias [m s^{-1}]		MAE [m s^{-1}]	
	Orig.	Corr.	Orig.	Corr.	Orig.	Corr.	Orig.	Corr.
January	-1.03	-0.14	1.71	1.42	-1.23	-0.32	2.37	2.16
July	-0.14	-0.10	1.16	1.16	-0.89	-0.30	1.62	1.50

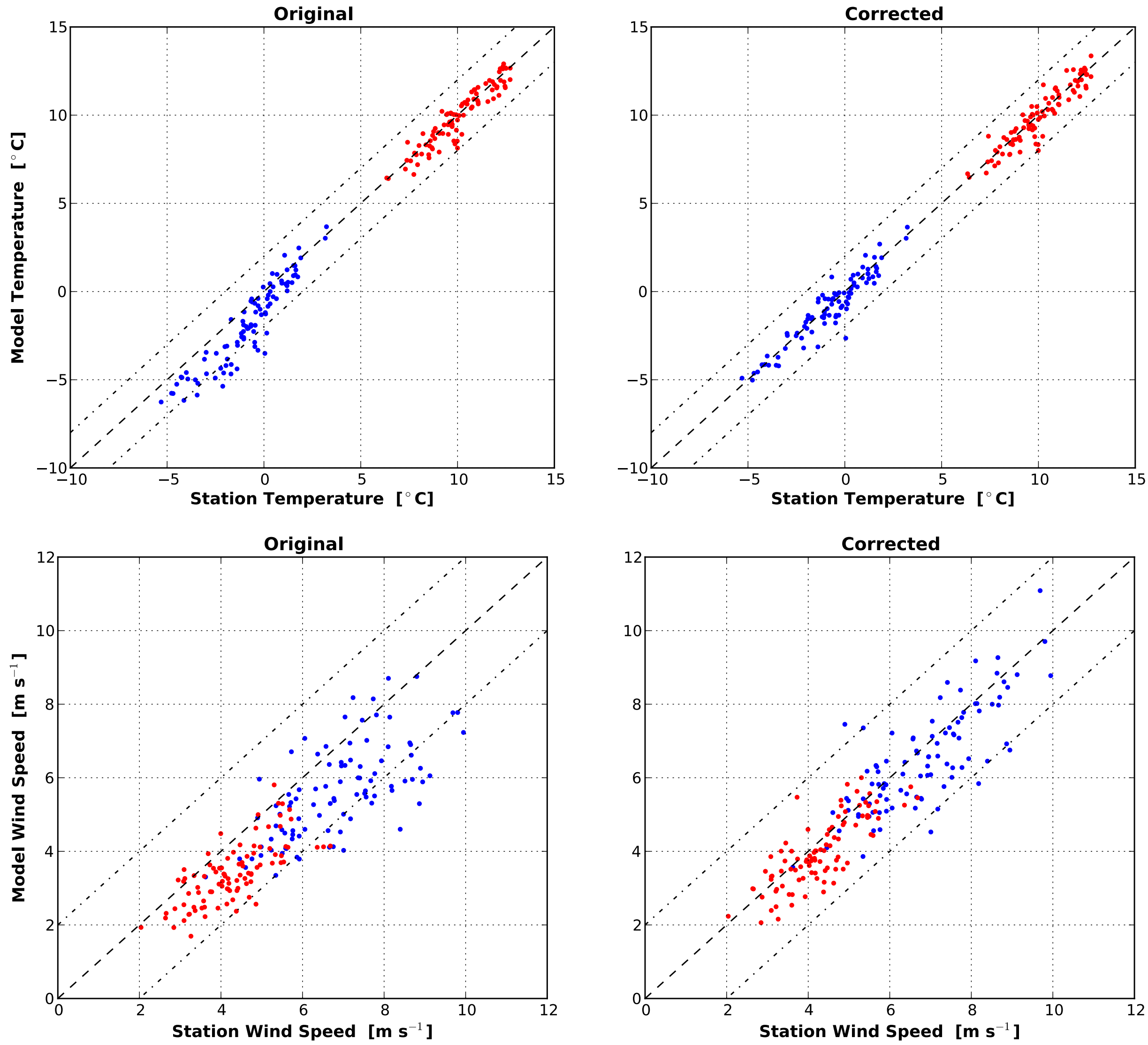

Figure 11. Monthly averages (January blue; July red) of original or corrected SURFEX 2-m air temperature (top row) and 10-m wind speed (bottom row), in comparison with station measurements.

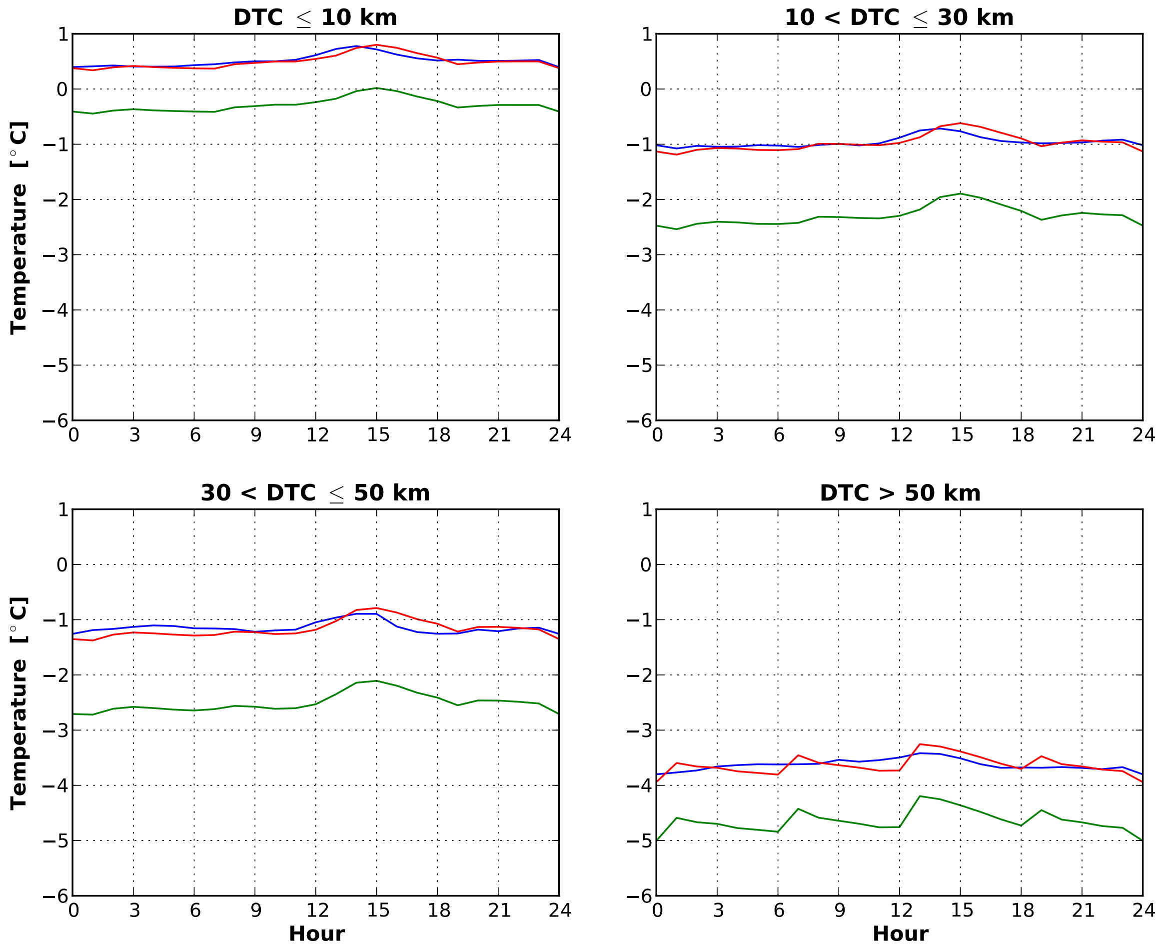

Figure 12. Average diurnal cycles of 2-m temperature in January, for different bands of onshore distances to the coast (DTC), based on station measurements (blue lines), original SURFEX data (green lines), and corrected SURFEX data (red lines).

7 Original and corrected 2-m air temperature

Average diurnal cycles of 2-m temperature for different bands of onshore distances to the coast (DTC) are shown in Figures 12 and 13, for January and July, respectively. The average decreasing tendency during the first 6 hours of model simulations in January, for DTC greater than 50 km, has already been mentioned in Section 4. This model trend is not removed by the correction procedure. At shorter distances to the coast, in addition to the overall negative bias, there is a 1-hour delay in the timing of the daily maximum temperatures, occurring at 15 UTC in the model. The small amplitude of the wintertime diurnal cycle is generally well reproduced by the model, particularly near the coast. In July, the agreement in amplitude, phase, and offset of simulated and measured diurnal cycles is significantly better than in January. The main difference between original and corrected SURFEX data is a reduction of biases within 10 km of the coast.

Monthly averages of 2-m temperature, as a function of terrain elevation, are shown in Figure 14. The largest biases in excess of 2 K are found at intermediate elevations between 300 – 500 mASL in January. Vertical terrain-following gradients of 2-m temperature, based on monthly averages, are listed in Table 2. As in Section 3, values below 100 mASL were omitted when determining

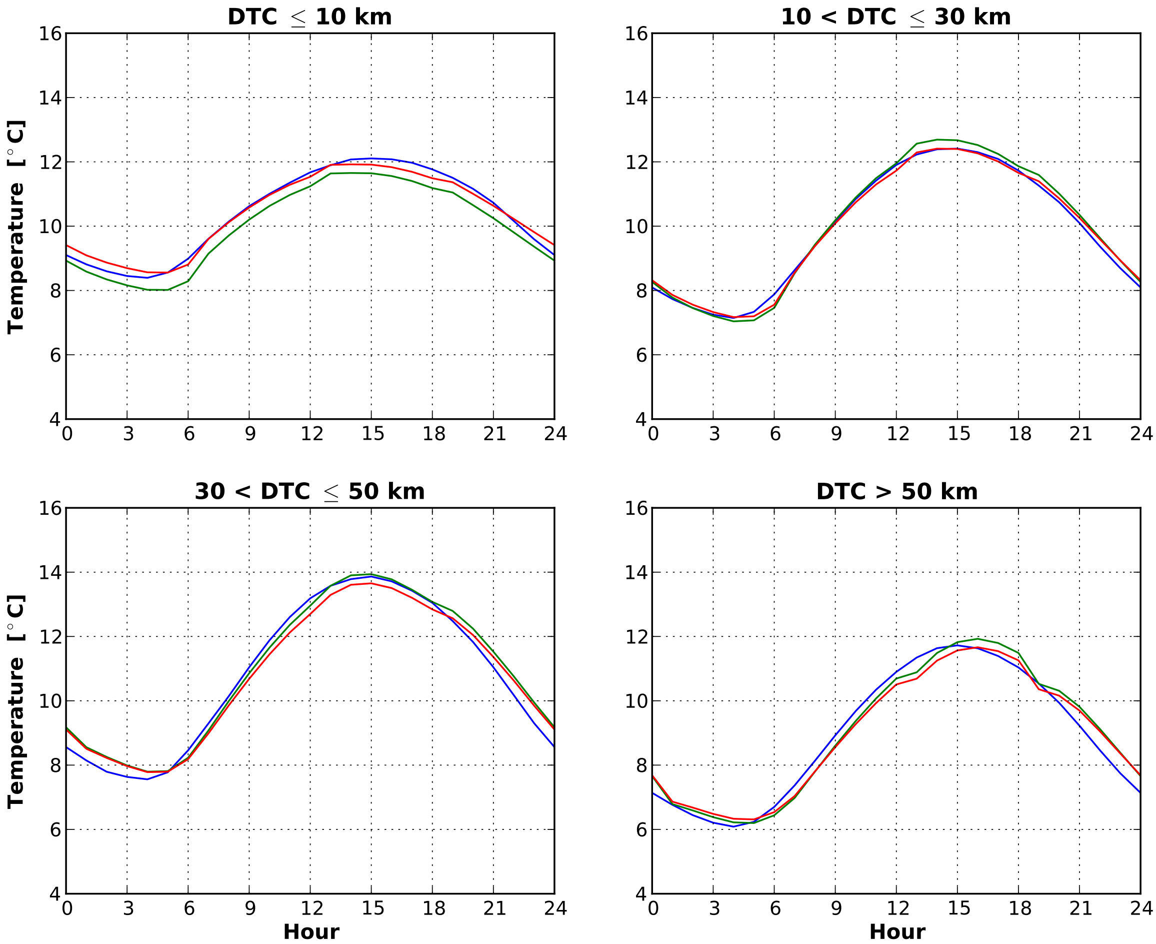

Figure 13. As Figure 12, for July.

the least-squares fits for vertical profiles. The simulated vertical terrain-following gradients are close to the measured values, even based on the original model data.

Monthly mean model fields of 2-m temperature, based on original and corrected SURFEX data, are shown in Figure 15. In January, the main difference due to the correction procedure is a general increase in temperature in the northeast. In July, differences due to the correction procedure are generally small. At terrain elevations below 1000 mASL, the main difference is an increase in temperature in the Sprengisandur region between Vatnajökull and Hofsjökull. There is the possibility, that wintertime cold biases over the glaciers are smaller than at surrounding lower elevations. Therefore, corrected 2-m air temperatures over the glaciers may be too high.

Table 2. Vertical terrain-following gradients of 2-m temperature [K km^{-1}], *based on monthly averages.*

	Measurements	SURFEX (orig.)	SURFEX (corr.)
January	-7.1	-7.7	-7.0
July	-5.4	-5.3	-5.4

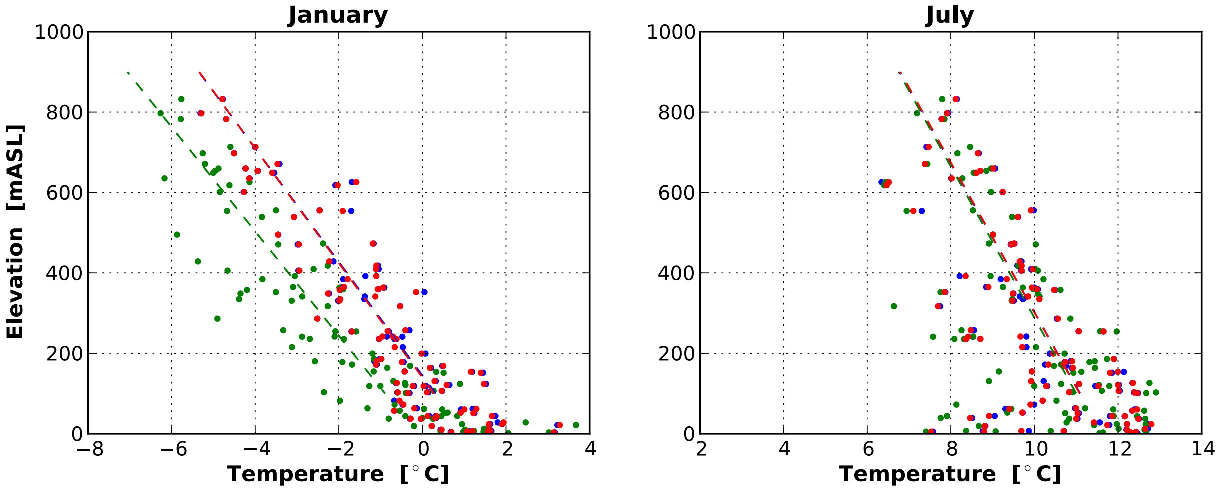

Figure 14. Monthly averages of 2-m temperature, as a function of terrain elevation, based on station measurements (blue dots), original SURFEX data (green dots), and corrected SURFEX data (red dots).

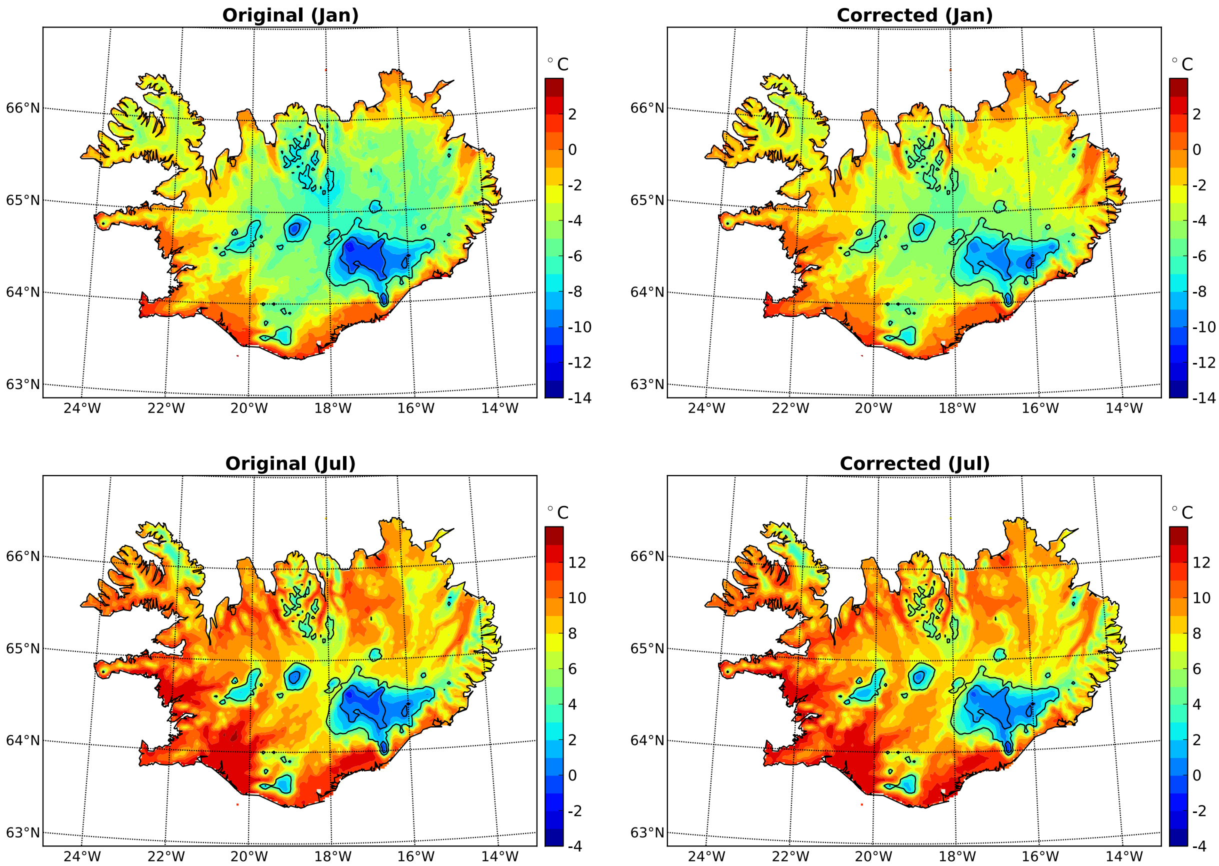

Figure 15. Monthly mean fields of 2-m temperature, based on original and corrected SURFEX data. Terrain elevation contour lines are drawn at 1000 and 1500 mASL.

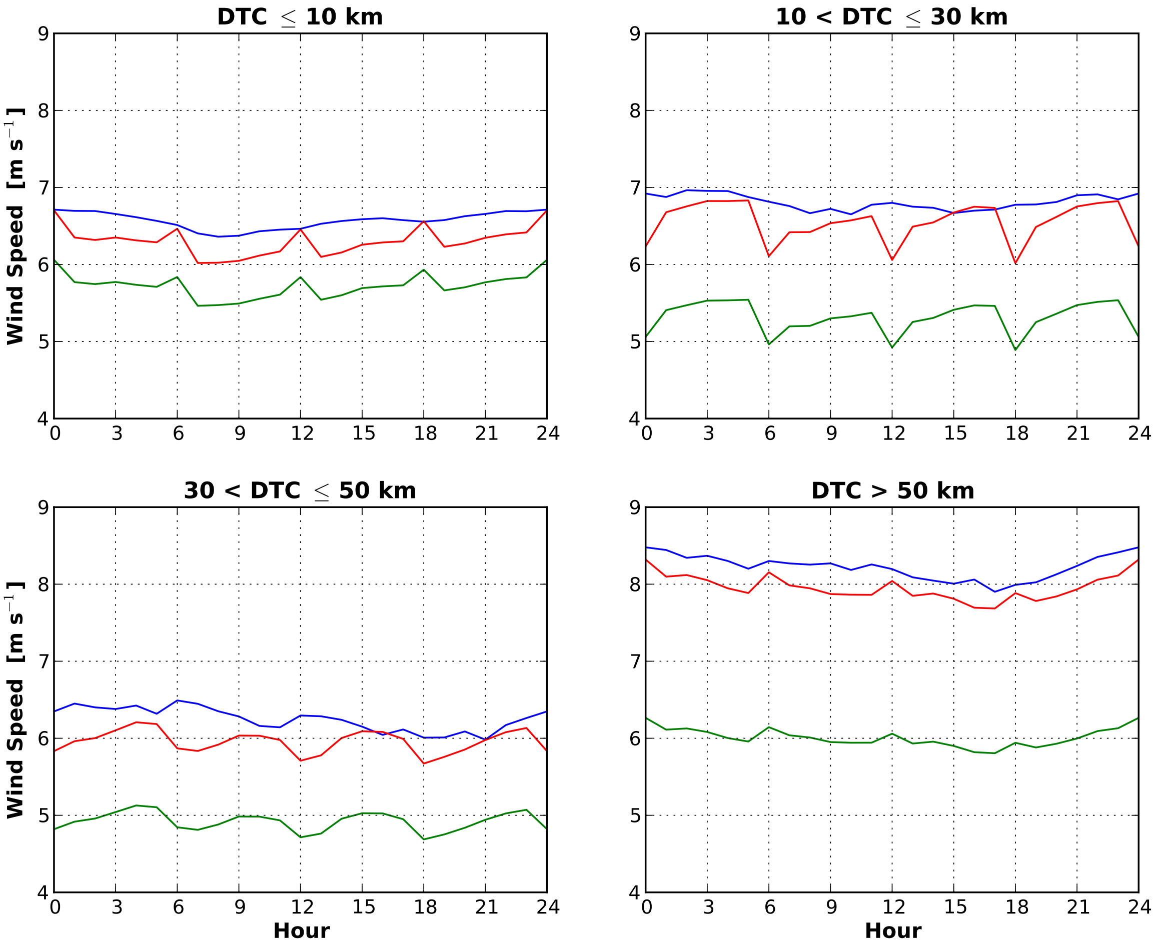

Figure 16. Average diurnal cycles of 10-m wind speed in January, for different bands of onshore distances to the coast (DTC), based on station measurements (blue lines), original SURFEX data (green lines), and corrected SURFEX data (red lines).

8 Original and corrected 10-m wind speed

Average diurnal cycles of 10-m wind speed for different bands of onshore DTC are shown in Figures 16 and 17, for January and July, respectively. The differences compared with the results shown in Figure 5 are due to the limited number of locations taken into account for the comparison with station data. The main problems with the simulated diurnal cycles in wind speed are the overall negative bias, as well as the discontinuities between successive forecast runs. The negative bias is reduced by the correction procedure. However, a small residual bias remains due to the skewed nature of wind speed distributions, with a larger number of below- than above-average values. The criterion for determining correction factors is the minimisation of mean square errors (MSEs), compared with station measurements. An elimination of biases would require a further increase in wind speeds, leading to large positive outliers and an increase in MSEs. Aside from the systematic offset, the amplitudes and phases of the diurnal cycles at different distances from the coast, and in different months, are well reproduced by the model.

Monthly averages of 10-m wind speed, as a function of terrain elevation, are shown in Figure 18. In January and July, the largest biases in excess of 2 m s^{-1} are found at intermediate elevations

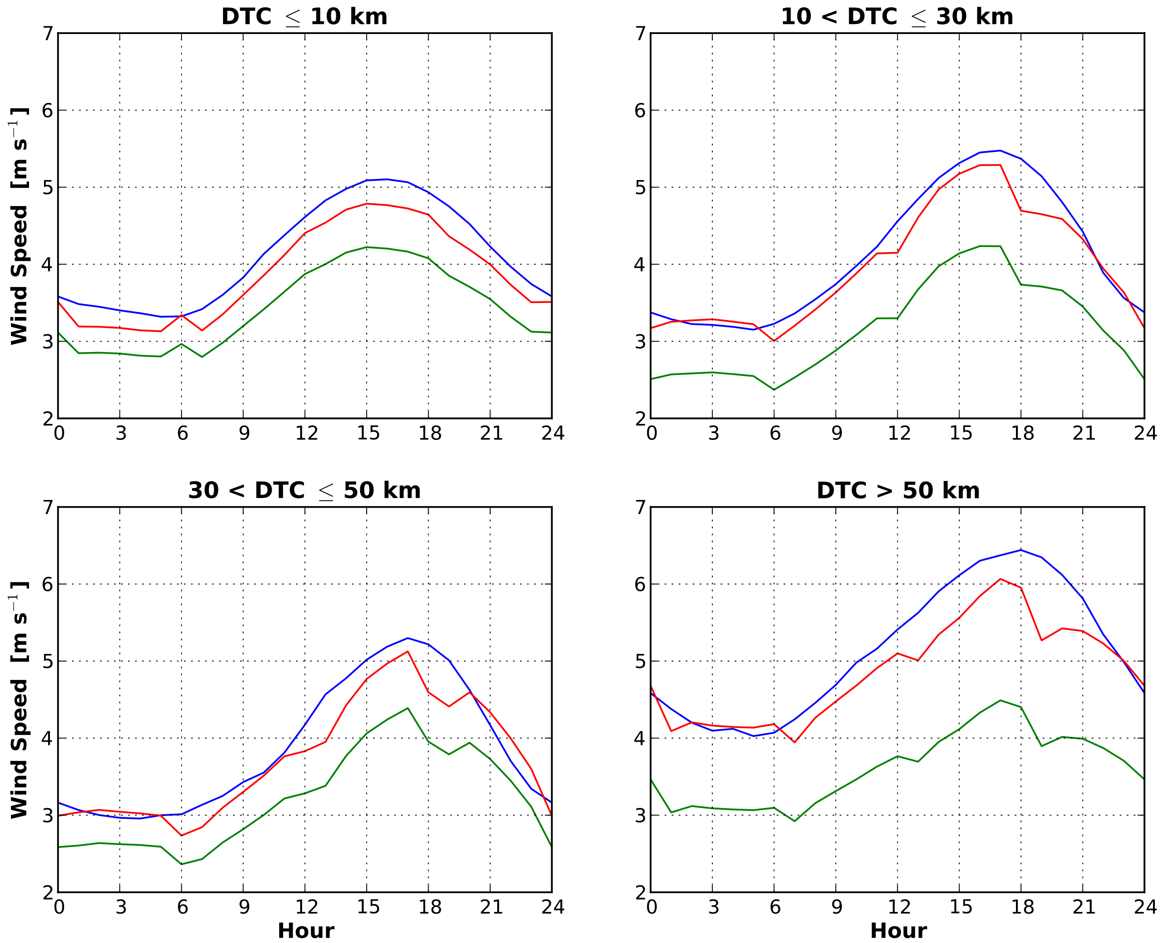

Figure 17. As Figure 16, for July.

between 500 – 700 mASL. Vertical terrain-following gradients of 10-m wind speed, based on monthly averages, are listed in Table 3. As in Section 3, values below 100 mASL were omitted when determining the least-squares fits for vertical profiles. Due to the large negative bias over the interior of the island, the vertical terrain-following gradients based on the original model data are too small compared with the measured values.

Monthly mean model fields of 10-m wind speed, based on original and corrected SURFEX data, are shown in Figure 19. In January and July, wind speeds are increased by the correction procedure throughout most of the island (compare with Figure 10). In July, based on original and corrected SURFEX data, there are high average wind speeds over Þórisvatn (580 mASL), which are stronger than over similarly large lakes, such as Þingvallavatn (100 mASL) or Mý-

Table 3. Vertical terrain-following gradients of 10-m wind speed [m s^{-1} km^{-1}], *based on monthly averages.*

	Measurements	SURFEX (orig.)	SURFEX (corr.)
January	5.1	3.0	5.2
July	3.0	1.7	2.9

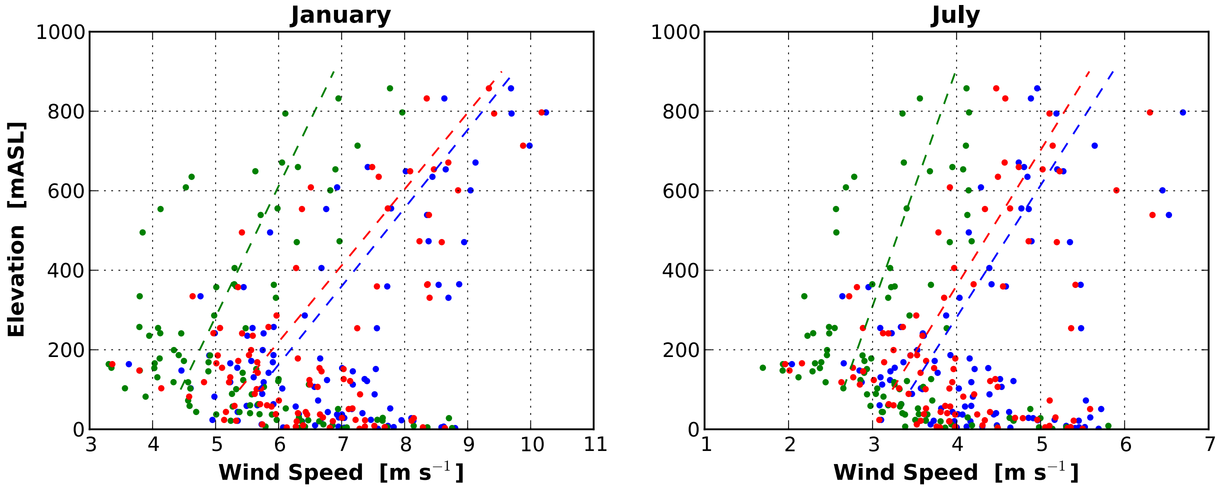

Figure 18. Monthly averages of 10-m wind speed, as a function of terrain elevation, based on station measurements (blue dots), original SURFEX data (green dots), and corrected SURFEX data (red dots).

vatn (280 mASL), and of the same magnitude as the average wind speeds over the surrounding glaciers (for a close-up view see Figure 20). This is primarily related to the particular terrain layout. As shown in Figure 21, if wind conditions are separated into different 45-degree wind direction sectors, average July wind speeds over the lake are weaker than over some parts of the surrounding higher terrain. However, since HARMONIE generates the highest wind speeds on the upper lee-ward slopes of elevated terrain, there is a high variability in wind speed on and around the glaciers, especially in July (see again Figure 20). On the other hand, wind speeds over the lake show relatively low variability, and tend to be high for a wide range of wind directions. For the most part, winds over the lake are either channelled between the glaciers to the north-east, or forced to accelerate over the elevated plateau for winds from the lower coastal regions to the south. The relatively high average wind speeds over Þórisvatn in July, compared with similarly large lakes, are therefore due to the higher terrain elevation and regional orographic forcing effects. Relative to the surrounding higher terrain, average wind speeds over the lake are comparable due to reduced surface friction over the water surface, and a low variability of wind speed for different wind directions.

9 Conclusions

In this report, HARMONIE (Version 37h1.2) model simulations of 2-m air temperature and 10-m wind speed, using version 6 of the external surface scheme SURFEX, were evaluated in comparison with quality controlled hourly surface station measurements over the land area of Iceland. The model was run in surface data assimilation mode with standard settings and parameterisations, using ECMWF operational analyses as initial and boundary conditions.

The data used for this analysis, covering the years 2010 – 12, was compiled from successive 6-hour forecast runs. Despite the use of the blending method for the atmospheric analyses of each forecast run, there are significant discontinuities between the sixth forecast hour of each model run, and the initial field of the subsequent run. During the first forecast hour, model simulations tend towards the values at the end of the previous run, but especially in the interior of the island,

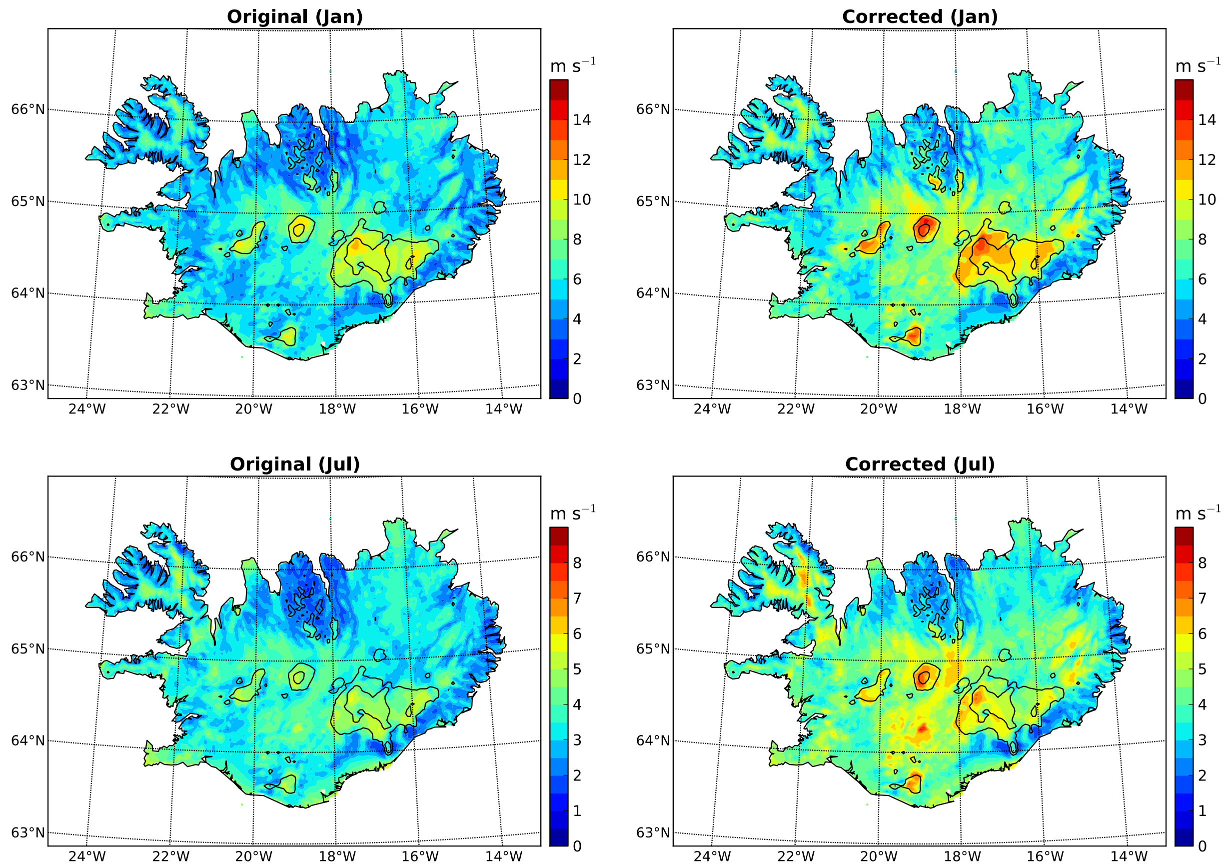

Figure 19. Monthly mean fields of 10-m wind speed, based on original and corrected SURFEX data. Terrain elevation contour lines are drawn at 1000 and 1500 mASL.

some differences remain. This suggests that the last forecast fields are given little weight in the initialisation of the subsequent run, either as a general rule in data assimilation mode, or due to the large deviations between HARMONIE model forecasts and ECMWF operational analyses.

With a few exceptions near the coast, 10-m wind speed is consistently too weak throughout the year. Based on previous work and the results presented here, this appears to be due to weak winds in the initial conditions, as well as excessive surface roughness in the default drag parameterisation of SURFEX.

For 2-m temperature over the interior of Iceland, the main problem with model simulations is the decreasing tendency during the first few forecast hours in winter. This results in an overall cold bias, compared with station measurements. To test, whether this is due to the HARMONIE model core or the external surface scheme, biases of 2-m temperature from SURFEX are compared with biases of temperature projected from the lowest two model levels to 2 mAGL. It is found that the negative temperature biases are due to shallow inversion layers near the ground, which are introduced exclusively by the surface scheme. On average, taking into account all stations and all hourly values, the absolute biases of projected model temperatures are smaller than for SURFEX temperatures, especially in January. However, there are also systematic errors in the projected temperatures, essentially underestimating the seasonal cycle, with too warm January temperatures, and too cold July temperatures. A similar problem exists for the diurnal

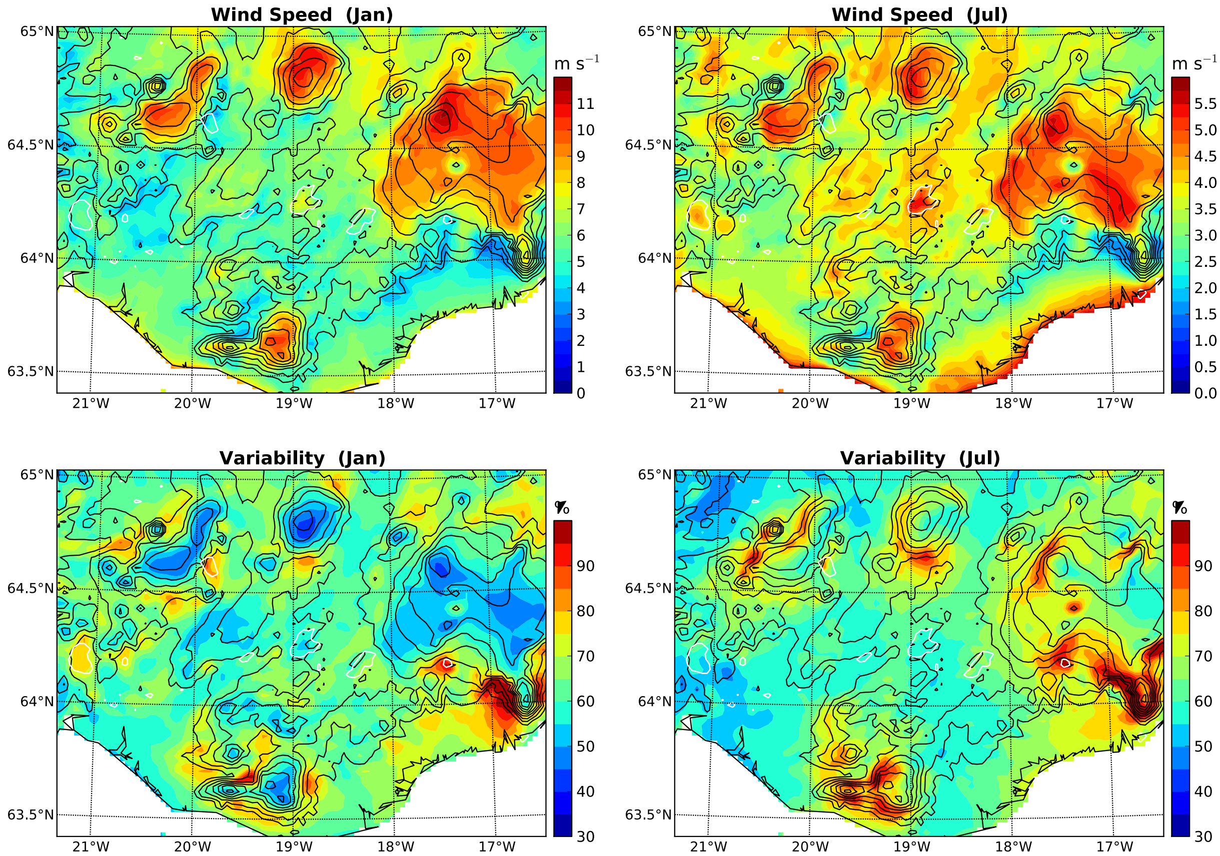

Figure 20. Monthly variability of 10-m wind speed, defined as standard deviation divided by the mean, based on original SURFEX data. The black terrain elevation contour lines are spaced at 200 m. The 0.5 contour lines of inland water surface type are shown in white. Þórisvatn is located in the centre of the domain. Þingvallavatn is near the western edge.

cycle in July. For SURFEX temperatures, day- and night-time biases are similar. However, for projected temperatures, the summertime diurnal cycle is too weak, with a positive bias at night, and a negative bias during the day. In January, the diurnal temperature cycle is weak, and differences in simulated day- and night-time temperatures are small. Overall, while the absolute mean error in 2-m temperature is increased by SURFEX, the magnitude of temporal variability, related to changes in the near-surface radiation balance, is improved.

The weak seasonal temperature cycle in the HARMONIE core model may be related to the initial and boundary conditions. Nawri et al. (2012b) showed, that the amplitude of the seasonal cycle of 2-m temperature over the interior of Iceland is underestimated by ECMWF operational analyses, with a warm bias in winter, and a cold bias in summer.

However, the question remains about the causes for the wintertime negative temperature biases introduced by SURFEX. With a warm bias in the HARMONIE core model, the cooling of the near-surface atmosphere must be related to the description of boundary-layer processes. In comparison with a detailed land cover classification prepared for the Coordination of Information on the Environment (CORINE) programme, the main problem with the model characterisation of surface type is the overestimation of vegetated areas. According to CORINE, much of the

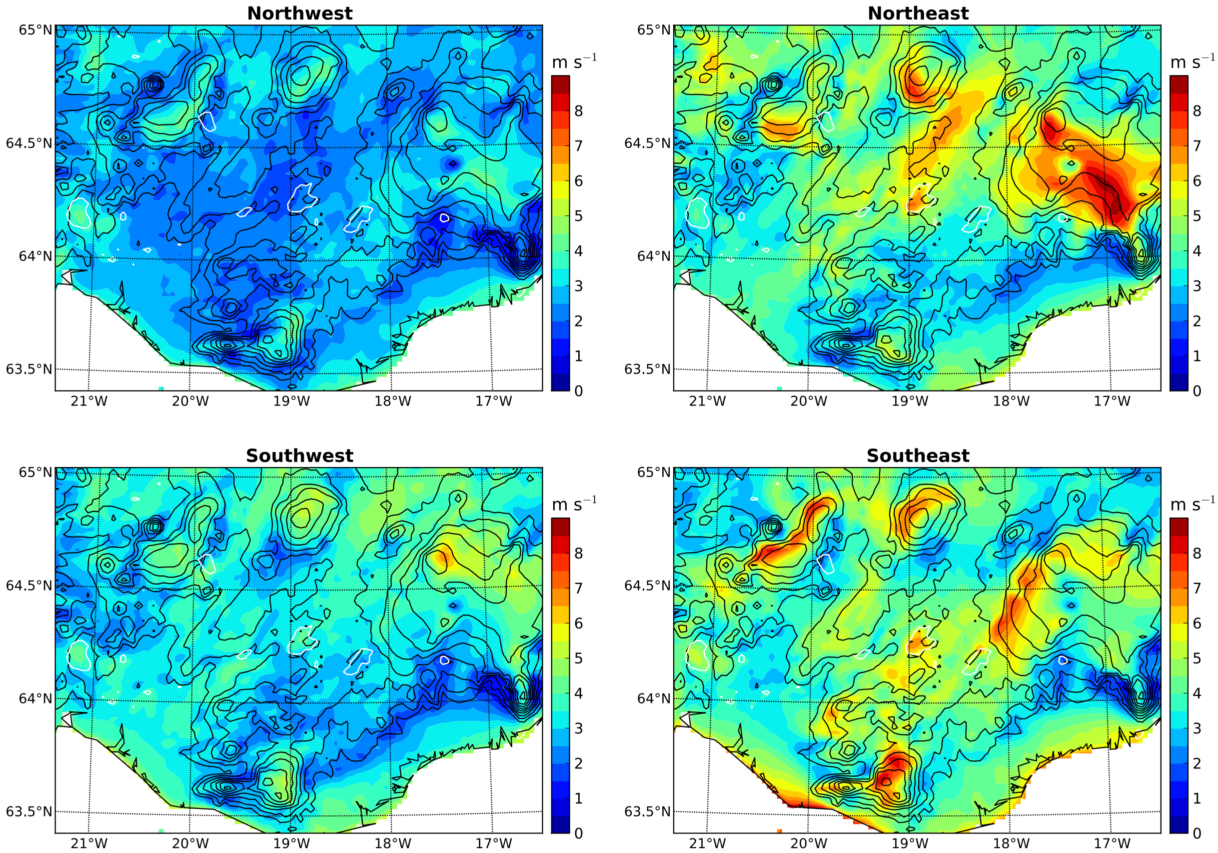

Figure 21. Monthly mean 10-m wind speed for different wind directions over Þórisvatn (18.8963°W, 64.2280°N), based on original SURFEX data. For the classification of wind conditions, wind direction over the lake is rounded to the nearest 45 degrees.

area covered in the model with sparse tundra (41.3% of the model land area) is in fact bare rock or sand plains. The model description of surface type is therefore not a likely cause for the strong wintertime cooling, since replacing at least sparsely vegetated areas in the interior of the island with barren ground would likely increase the negative radiation balance in winter. In summer, excessive variable snow cover might be responsible for significant cold biases. However, in winter, this possibility does not apply, since for much of the year, the interior highlands are genuinely snow covered.

Model biases in 2-m temperature and 10-m wind speed can be significantly reduced by a simple statistical correction procedure, whereby model time-series at each grid point are linearly transposed such that mean square errors against measurements are minimised, where station data is available. Nonetheless, this can only be a temporary measure, to improve model data which has already been archived. In the future, an important step would be to understand and limit the wintertime heat loss in the HARMONIE model, and the tendency towards colder near-surface temperatures during the first few forecast hours.

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