Analysis of large errors in dynamic downscaling of atmospheric flow over complex terrain

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Abstract

Four years of atmospheric flow over Iceland have been simulated with the WRF model, based on boundary conditions from the ECMWF analysis, and the results are compared with observations from selected weather stations. The greatest errors are singled out and investigated separately. The greatest errors in simulated temperatures appear to be related to incorrect surface fluxes, particularly during the snow melting season local variability in surface characteristics (islands) or to radiative cooling being wrong due to wrong cloud cover. The greatest errors in wind speed are related to orographic effects on the flow but not to non-resolved orography. None of the large errors can clearly be traced to the atmospheric boundary conditions provided by the ECMWF.

1 Introduction

Iceland is an island of about 100.000 km^2, located at the juncture of the North Atlantic and Arctic Oceans, at 65°N and 20°W. The island is mountainous, with large mountain plateaus and only about a quarter of the land surface below 200 m.a.s.l. Because of the high latitude, the total radiation balance is in deficit, and there is a net transfer of heat by the oceanic and atmospheric circulations. The weather in Iceland is characterized by frequent extratropical cyclones, strong winds and frequent precipitations, mild winters and cool summers. Because of the mountainous topography, the weather in Iceland is subject to a large spatial variability (Björnsson et al.(2007); Einarsson (1984); Ólafsson et al. (2007)).

The economy of Iceland is heavily dependent on both the weather and the climate and it is of substantial importance to accurately describe both in time an space. It is furthermore of interest to assess the capability of a state-of-the-art numerical modelling system to simulate the atmosphere over Iceland and to acquire an insight into the physics related to the simulation errors.

In this study, we will evaluate the 2-m temperatures and 10-m winds by comparing in situ surface observations with the WRF model. In order to assess and classify the physics associated with the largest errors, various kinds of data from both the simulations and observations are used, depending on the nature of the case.

The article is organised as follow, The observations and the simulations are in Section 2. Section 3 presents the methodology of the analysis of the errors of simulated temperatures and wind speeds and the classification of the largest errors. The results are presented in Section 4 and discussed in Section 5. Conclusions are presented in Section 6.

2 Data

2.1 The atmospheric simulations

The simulations presented here are carried out within the research project "Reikningar á veðri" (RÁV)(Rögnvaldsson et al.(2007, 2011a)). The flow over Iceland is simulated with the Weather, Research and Forecasting model (WRF), version 3.1.1. (see Skamarock et al. (2008) for details). The microphysics are based on the Thomphson scheme (Thompson et al. (2008)), the Betts-Miller-Janjic scheme (Janjic, 1994) is employed for cumulus, the Bao two-equation scheme is employed for the atmospheric boundary layer (???), the RRTM scheme (Mlawer et al. (1997)) for longwave radiation, the Dudhia scheme (Dudhia, 1989) for shortwave radiation and the surface is according to NOAH Land Surface Model (Tewari et al. (2004)).

Simulations were performed in three nested domains centered around Iceland (Figure 2) : an outer domain with 43 x 42 points and a spatial resolution of 27 km, an intermediate domain with 95 x 90 grid points and a spatial resolution at 9 km and an inner domain with 196 x 148 grid points spaced at 3 km. Except for the outer domain, where the northwest corner covers part of the southeast coast of Greenland, Iceland is the only land mass included in the model.

Initial and boundary conditions were provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), valid at 00, 06, 12 and 18 UTC. Once initialized, these data are only applied at the boundaries.

In this study, only data from the inner domain are used. Values every 3 hours during the period 1 November 2005 to 31 October 2009 are used for comparison with observations.

2.2 Observations

As of 2014, Iceland counts more than 250 stations covering the entire country and some of the surrounding islands. However, a large majority of these stations are located either in surroundings where there is substantial non-resolved topography at a horizontal resolution of 3 km or in regions of large horizontal gradients in certain weather conditions (mainly coastal stations). In this study, we have chosen to use nine weather stations where the above characteristics can be expected to be relatively small. The 9 chosen stations reflect the geography of Iceland to some extent (Figure 1). They can be separated in three categories : **Highlands** (Hveravellir, Sandbúðir, Upptyppingar), **Lowlands** (Kálfhóll, Ásbyrgi, Egilsstaðaflugvöllur) and **Islands** (Grímsey, Vestmannaeyjabær, Stykkishólmur). Stykkishólmur is strictly speaking not an island, but being located at the tip of a narrow peninsula, which extends into the sea from another peninsula, it is reasonable to classify it as an island in this context.

Some details of the climatology of the stations are given in Table 1. Mean temperatures in the Highlands are the lowest because of high altitude and they have the largest standard deviations, reflecting larger differences between summer and winter. In the selected islands, the mean temperatures are higher than in the other categories, reflecting the heating by the surrounding ocean.

Mean wind speeds are quite strong in all our stations, especially in the Highlands with strong gusts recorded in Sandbúðir and Hveravellir (respectively 41.4 and 34.4 $m.s^{-1}$).

In individual cases, satellite images and radiosoundings from Keflavík airport are compared with the relevant fields from the simulations, but the statistical evaluation and the investigation of the greatest errors are based on 2-m temperature and 10-m wind speed.

3 Classification of errors

In order to analyse the physics of the largest errors, we define the following groups for temperatures :

- Group A : mild temperatures, $T_{sim} > T_{obs}$
- Group B : mild temperatures, $T_{obs} > T_{sim}$
- Group C : cold temperatures, $T_{obs} > T_{sim}$
- Group D : cold temperatures, $T_{sim} > T_{obs}$

while for the wind speed, we select only two groups :

- Group E : $U_{sim} > U_{obs}$
- Group F : $U_{obs} > U_{sim}$

In this study, we focus mainly on the largest errors. A temperature difference between simulation and observation of 5_1 °C qualifies as large. Several large errors the same day only count as one. Some categories do not have any large errors : in the islands, the model never gives a large underestimation of temperature when the observations are below zero and it never gives a large overestimation when the temperature is above 5_°C. A large wind speed error in the context of this study is set to 10 m.s^{-1}. The total number of large temperature errors turns out to be 80 and the total number of wind speed errors is 54. All these cases have been studied individually with all available data and this has led to the following classification.

The greatest temperature errors can be attributed to :

- **Wrong boundary conditions** : the temperature of the airmass over Iceland provided by the ECMWF is too cold or too warm.
- **Wrong surface conditions (surface fluxes)** : local snow cover, water surfaces or surface humidity are badly estimated.
- **Wrong vertical mixing** : the process is over- or underestimated in the boundary layer leading to an erroneous estimation of the temperature.
- **Wrong radiation conditions** : over- or underestimation of the cloud cover.
- **Wrong orographic impact** : bad simulation of lee-side flows (wrong Foehn or wake flow).
- **Wrong thermal breeze** : the presence or the spatial extent of the breeze is not correctly estimated.

The greatest wind speed errors can been attributed to :

- **Wrong boundary conditions** : the mean sea level pressure gradient and the wind speed at the boundaries of the domain provided by the ECMWF, are either too weak or too strong.
- **Shift in the time of occurrence** of a sudden change in the weather (e.g. a front).
- **Wrong orographic impact** : the impacts of the mountain on the mean flow are badly simulated.
- **Wrong vertical mixing** : mixing is over- or underestimated in the boundary layer leading to an erroneous estimation of the wind speed.

4 Results

4.1 Comparison between observations and simulations

Tables 3 and 4 show the bias, mean absolute error (MAE) and the root mean square error (RMSE) of the entire dataset for all the stations. Correcting for the bias gives „corrected“ MAE and RMSE. The model overestimates both winds and temperatures at the islands, but underestimates the winds in the highlands. In the temperature, the bias-corrected MAE is typically between 1 and 2 °C and there are not clear differences between categories of stations.

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4.2 Greatest temperature errors

For the Highlands category, almost all of the errors in warm weather (Group B) are the consequence of a surface flux problem (8 cases out of 9). Those erroneous simulations occur between late April and early June which corresponds to the snow melting season.

For colder temperatures (Groups C and D), a lot of the errors are the consequence of incorrect radiation as the model fails to reproduce clouds (7 out of 7 cases for Group C, 6 cases out of 9 for Group D).

In Group A, the causes of the errors are more various. The presence of an obstacle close to the instruments may have had lead to the observations not being representative for a large area : those errors have been listed under "Other".

At the Lowlands stations, surface flux errors are also frequent and cases of wrong vertical mixing have been observed in all the groups. As for the Highlands, incorrect radiation generates a lot of errors in the Group C (4 out of 6 cases).

At the selected Islands, the errors for both Groups B and D are all related to wrong surface fluxes as the model does not detect the presence of the islands. The simulated temperatures are systematically higher than the observed ones in winter and lower during summer as the ocean's temperature does not fluctuate as much as the temperature on the land.

No error has been attached to wrong boundary conditions.

4.3 Greatest wind speed errors

In the Highlands and the Lowlands, we found clear indications that wrongly simulated orographic effects are the main cause of the wind speed errors (8 cases out of 9 for Groups E and F both in the Highlands and the Lowlands). The model simulates the events but fails to extend the orographically generated patterns correctly.

In the Islands category, a lot of errors are related to small shifts in time (6 out of 9 cases in Group E, 2 out of 9 cases in Group F). This can be related to the fact that a sudden wind change due to a passing front is typically more pronounced over the ocean, than over land. Some orographic effects have also been shown to be the cause of strong errors (3 cases out of 9 in Group E, 2 out of 9 in Group F), especially in Stykkishólmur as the station is closer to the mountains. In Vestmannaeyjabær, it appears that the station does not observe strong winds. This is presumably related to the immediate surroundings of the station. We listed those errors as "Others". [RESTE À CONSIDÉRER].

5 Focus on Wind speed errors

[A COMPLÉTER : UTILISER L'EXEMPLE DE SANDBÚÐIR ? CF: FIGURES 7 et 8]

6 Discussion

We presented in Section 3.1 mean statistics for the selected stations. The MAE and RMSE calculated are in agreement with the study of Crochet (2004) who calculated MAE and RMSE for a large number of stations in Iceland, including Hveravellir and Vestmannaeyjabær. However, the MAE for the wind speed are much larger in our study than in e.g. Žagar et al.(2006) or Sweeney et al.(2011) because of the complex orography of Iceland and the fine resolution of our simulations.

Regarding the wind, the MAE and RMSE in our study are stronger than in Horvath et al.(2012), emphasizing the effect of mountain interactions in the generation of stronger gusts. In the Highlands and the Lowlands, the model overestimates the frequency of the weak winds ($f < 6$ m.s^{-1}) while it underestimates the frequency of the stronger winds. The opposite phenomena can be observed at the Islands stations.

Concerning the temperature, the results of our study showed that the largest underestimations of the temperature inland during warm days can be attributed to surface fluxes. Those errors occur late spring, during the snow melting season.

On cold days, the main contribution to the model giving far too low temperatures is incorrect radiation. The model does not see the clouds that prevent heat loss at the surface.

Both the temperature and wetness of the soil as well as the cloudiness may be difficult to simulate correctly. They can however be observed and assimilation of such observations to improve the simulations may be a way to go.

Surface fluxes are the main cause of errors at the Islands. This is presumably due to their presence not being resolved by the model : instead of a land surface, the model sees only water. Consequently, those errors are found both in warm and cold weathers.

In the wind fields, the main source of large errors is orography. This is of particular interest because none of the stations (except perhaps Vestmannaeyjabær) in the study are in the vicinity of significant non-resolved topography. Therefore those errors are the result of the model reproducing disturbances from resolved mountains incorrectly : the model is able to simulate quite accurately the orographic effect but fails to extend it properly. This may be related to the non-stationary nature of the downslope/wake flows but other sources such as strong sensitivity of the orographic response to details in the incoming flow may play a role too.

Large errors of the wind speed simulation at the Islands are due to mesoscale weather systems (such as fronts) arriving a little earlier or later in the model. These errors are confined to the Islands, mainly because the orographic response is dominating over land and the frontal wind contrasts are more diffuse over land than over the sea.

The boundary conditions are only responsible of a small portion of the greatest errors in the wind speed simulations. This confirms the quality of the boundary data from the ECMWF and underlines that there are indeed unresolved tasks in improving the tool we use for the dynamical downscaling.

7 Summary

The aim of our study was to determinate which processes generate largest errors in the simulation of the 2-meters temperature and the 10-meters wind speed. We focused on three groups of three stations in order to represent the complexity of the Icelandic geography.

Regarding the temperature errors, wrong surface fluxes proved to be the cause of large errors at the stations inland (overestimation of the snow cover in the model) as well as at the islands (water surface instead of land surface). In cold weather, incorrect estimation of the cloud cover in the model appears to generate larger errors in the simulation of the temperature.

Even though none of the selected stations is in the vicinity of a major non-resolved topography, orographic effects remain the main cause of erroneous wind speed simulations as the model fails to reproduce the spatial extension of local windstorms accurately.

The boundary conditions provided by the ECMWF used in the simulations appear to be very good : except for small shifts in the time of occurrence of fronts, almost none of our selected errors was the consequence of erroneous boundary conditions.

The results indicate that increasing the horizontal resolution of the model beyond 3 kilometres will probably lead to improvements in dynamic downscaling of winds over Iceland. Observations of the state of the soil are needed and large errors in the temperature may be prevented by assimilating them as well as the cloudiness.

Those corrections would then not only contribute to improvements in dynamical downscaling of climate simulations, but also to weather forecasting to the extent that same or similar tools are used for both tasks.

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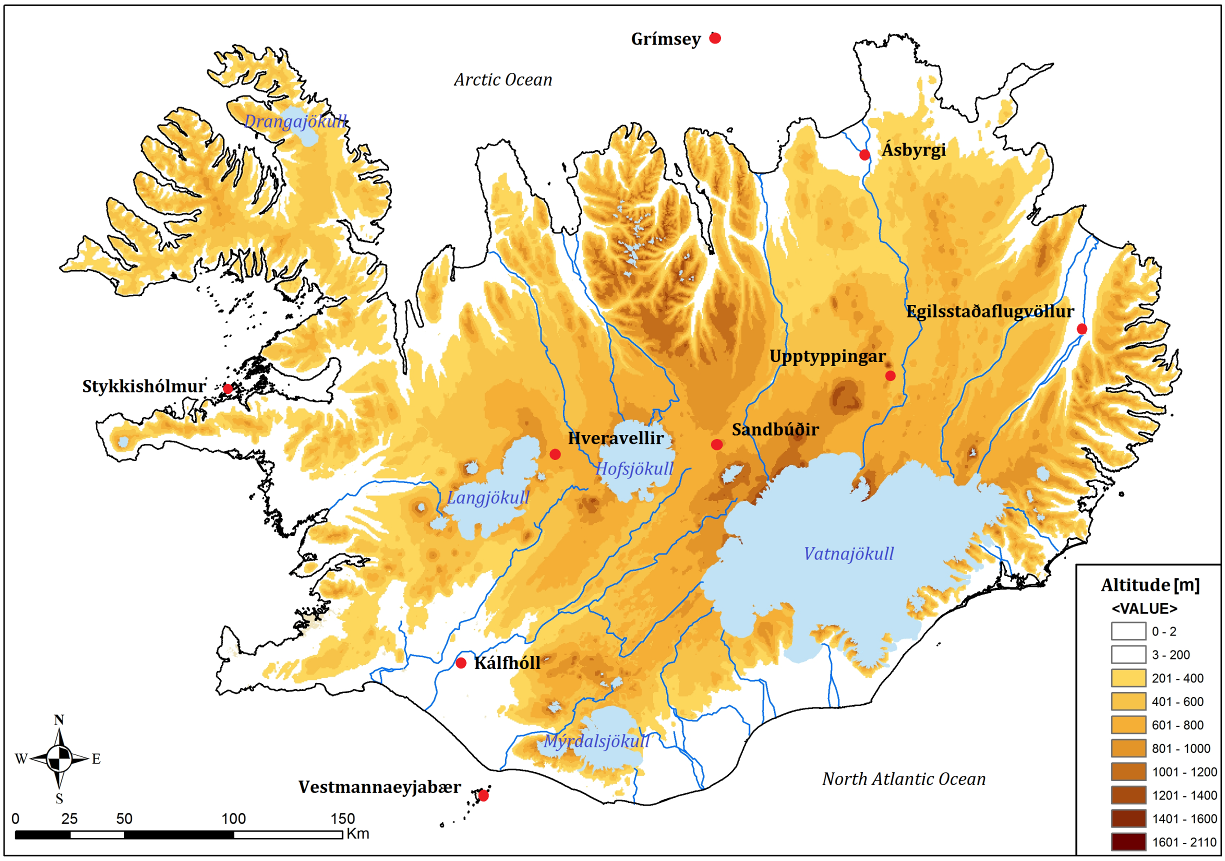

Figure 1: Topographic map of Iceland with the location of the stations selected for our study.

Table 1: Parametrization scheme used for dynamical downscaling using version 3.1.1 of the WRF model

Microphysics	Thompson Scheme
Cumulus	Betts-Miller-Janjic
Planetary Boundary Layer	Bao Two Equations (??)
LW Radiation	RRTM
SW Radiation	Dudhia
Land Surface	NOAH LSM
Surface Layer Physics	Monin-Obukhov (??)

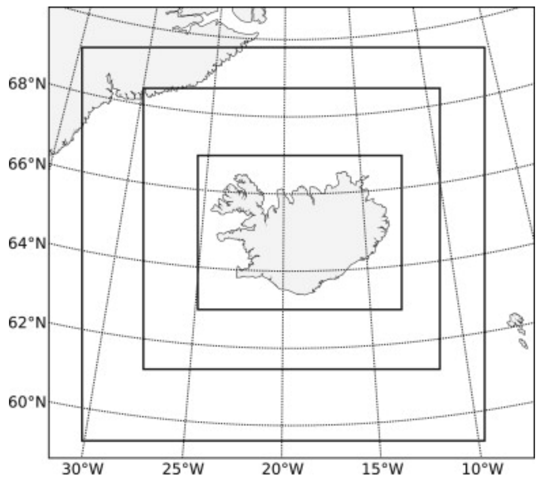

Figure 2: Boundaries of the three nested WRF model domains (Nawri et al.(2014)).

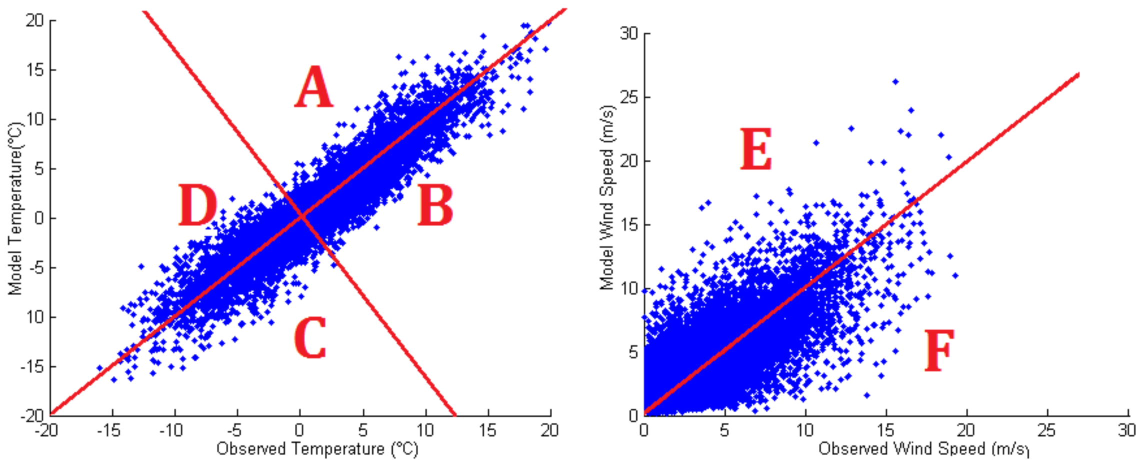

Figure 3: Idealized scatterplots for temperature (left) and wind speed (right) introducing the different groups considered for our study.

Table 2: Temperature and wind speed observations for the selected stations between 1 November 2005 and 31 October 2009.

		Temperature				**Wind Speed**		
	Alt.	**Mean**	**Std. Dev**	**Min**	**Max**	**Mean**	**Std. Dev.**	**Max**
Hveravellir	641 m	0.3	6.58	-19.4	24.1	7.6	4.70	34.4
Sandbúðir	820 m	-1.2	6.75	-24.4	20	8.8	5.39	41.4
Upptyppingar	563 m	1.0	6.91	-25.1	20.6	5.2	3.76	28.3
Highlands		**0.0**	**6.75**			**7.2**	**4.62**	
Kálfhóll	52 m	4.5	6.29	-21.8	27.8	5.8	3.56	27.6
Ásbyrgi	38 m	3.6	6.91	-16	24.5	4.7	3.08	19.3
Egilsstaðaflugvöllur	23 m	4.0	6.32	-19.2	24.3	4.6	3.06	22.0
Lowlands		**4.0**	**6.51**			**5.0**	**3.23**	
Vestmannaeyjabær	40 m	6.4	4.25	-10.1	22.4	5.1	3.54	25.5
Grímsey	19 m	3.7	4.47	-9.9	17.8	6.5	3.56	24.3
Stykkishólmur	40 m	4.7	5.11	-13.4	18.4	5.5	3.38	23.8
Islands		**4.9**	**4.61**			**5.7**	**3.49**	

Table 3: Mean Error (ME), Mean Absolute Error (MAE) and Root-mean square deviation (RMSE) comparing observations to simulations of the temperature for the selected stations.

	Temperature				
	ME	**MAE**	**corrected MAE**	**RMSE**	**corr RMSE**
Hveravellir	-0.02	1.22	1.23	1.70	1.70
Sandbúðir	0.04	1.44	1.45	2.03	2.03
Upptyppingar	1.17	1.90	1.70	2.62	2.34
Highlands	**0.40**	**1.52**	**1.46**	**2.11**	**2.02**
Kálfhóll	-1.78	2.20	1.73	2.90	2.29
Ásbyrgi	0.50	1.50	1.46	1.98	1.91
Egilsstaðaflugvöllur	1.06	1.90	1.78	2.64	2.41
Lowlands	**-0.08**	**1.90**	**1.65**	**2.51**	**2.20**
Vestmannaeyjabær	-2.00	2.45	1.78	2.98	2.21
Grímsey	-2.56	2.93	1.73	3.38	2.20
Stykkishólmur	-2.55	3.07	2.23	3.71	2.70
Islands	**-2.37**	**2.82**	**1.91**	**3.36**	**2.37**

Table 4: Mean Error (ME), Mean Absolute Error (MAE) and Root-Mean Square Deviation (RMSE) comparing observations to simulations of the wind speed for the selected stations.

	Wind Speed				
	Bias	**MAE**	**corr MAE**	**RMSE**	**corr RMSE**
Hveravellir	1.76	2.47	2.12	3.31	2.81
Sandbúðir	2.73	3.40	2.10	2.79	2.72
Upptyppingar	0.60	2.12	2.46	4.27	3.28
Highlands	**1.70**	**2.66**	**2.23**	**3.45**	**2.94**
Kálfhóll	-0.10	1.69	1.69	2.24	2.24
Ásbyrgi	-0.32	1.73	1.71	2.30	2.28
Egilsstaðaflugvöllur	-0.13	1.84	1.83	2.47	2.47
Lowlands	**-0.19**	**1.76**	**1.75**	**2.34**	**2.33**
Vestmannaeyjabær	-3.8	4.00	2.29	4.80	2.93
Grímsey	-2.13	2.63	1.97	3.33	2.56
Stykkishólmur	-2.14	2.79	2.20	3.55	2.83
Islands	**-2.69**	**3.14**	**2.15**	**3.89**	**2.77**

Table 5: Mean errors of the selected cases for each group and station. The presence of '-' denotes the absence of data.

	Temperature				**Wind Speed**	
	A	**B**	**C**	**D**	**E**	**F**
Hveravellir	7.6	8.4	7.0	8.9	9.3	16.4
Sandbúðir	5.5	12.6	10.4	7.2	11.8	20.9
Upptyppingar	5.8	11.5	10.0	13.4	10.9	14.9
Highlands	**6.3**	**10.8**	**9.1**	**9.8**	**10.7**	**17.4**
Kálfhóll	-	5.7	-	13.7	10.5	13.5
Ásbyrgi	7.3	8.1	7.9	7.3	12.0	11.5
Egilsstaðaflugvöllur	11.9	6.4	-	12.5	15.0	11.6
Lowlands	**9.6**	**6.7**	**-**	**11.1**	**12.5**	**12.2**
Vestmannaeyjabær	-	6.6	-	9.8	16.4	8.4
Grímsey	-	7.3	-	9.4	15.3	9.6
Stykkishólmur	-	6.0	-	12.1	14.6	9.9
Islands	**-**	**6.6**	**-**	**10.4**	**15.4**	**9.3**

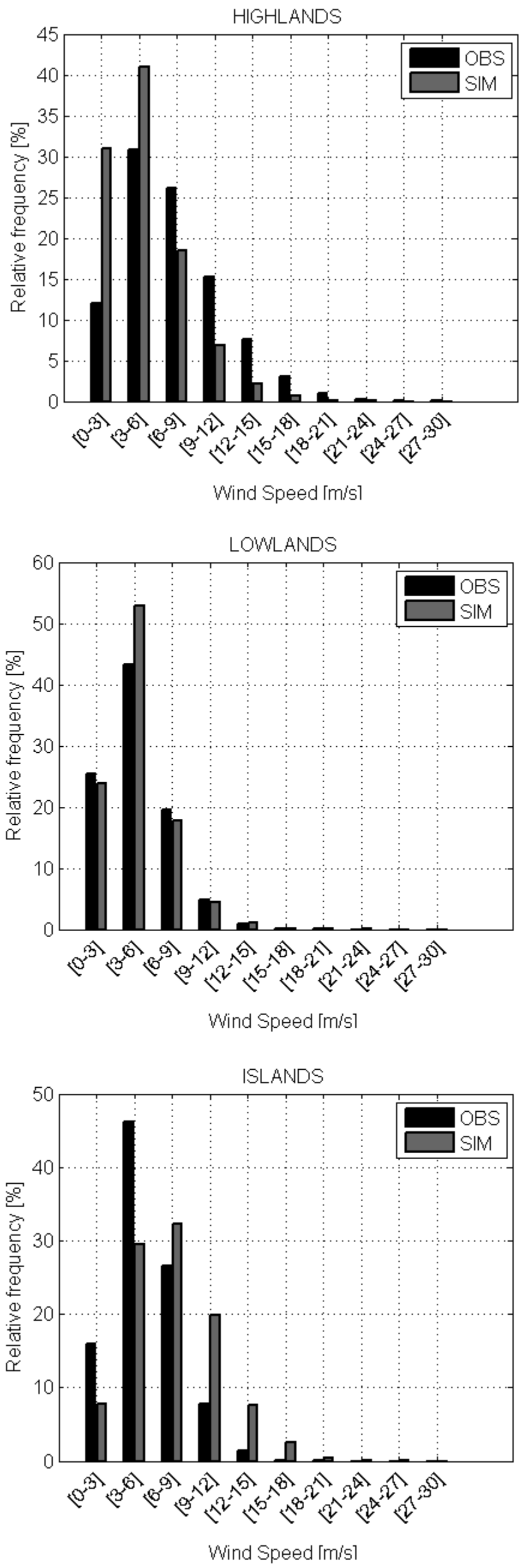

Figure 4: Histograms presenting the relative frequency of wind speed in the Highlands, Lowlands and Islands based on means over three stations in each category.

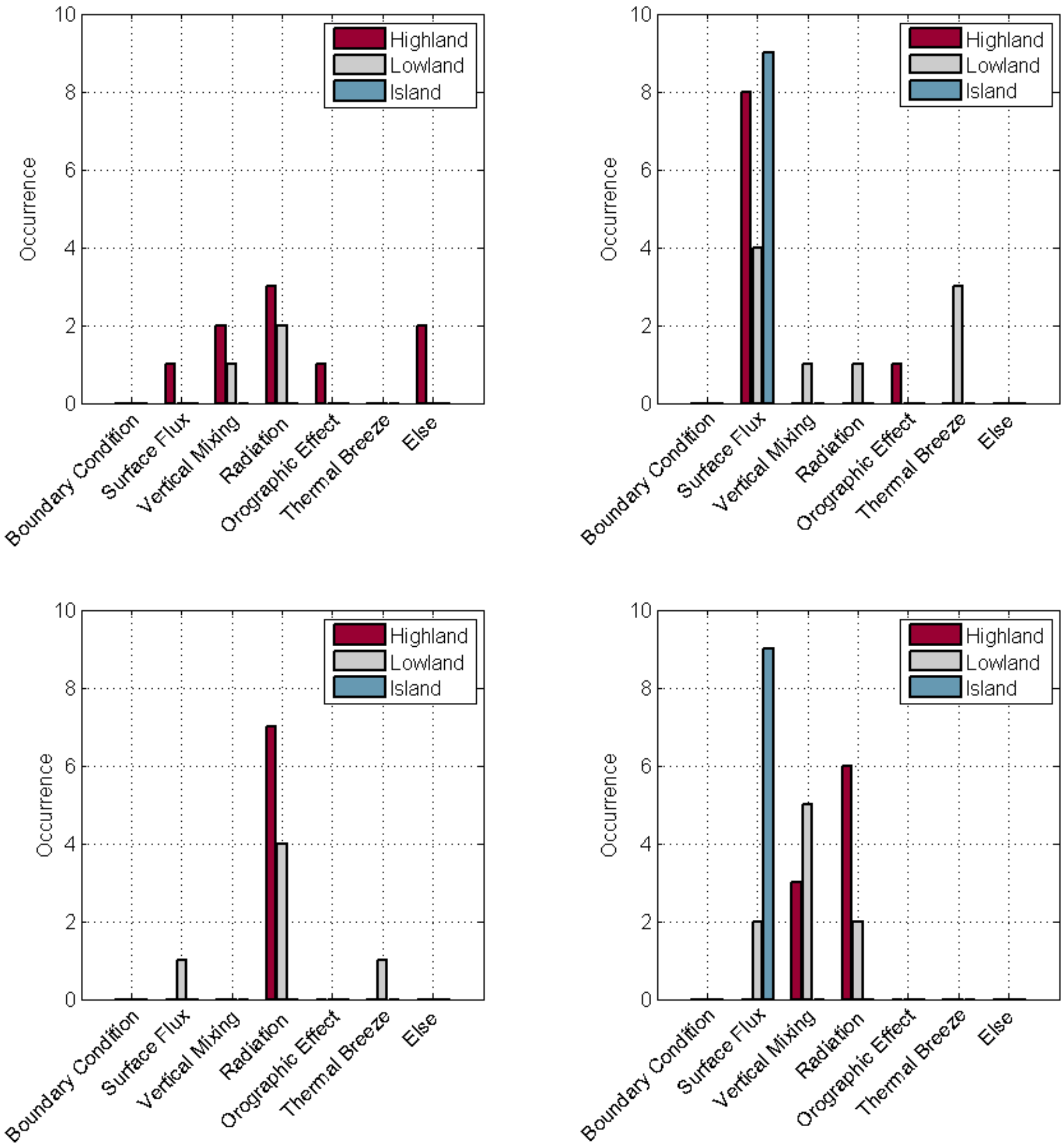

Figure 5: Bar diagrams presenting the number of occurence of each type of error at each station divided into groups for sources of errors.

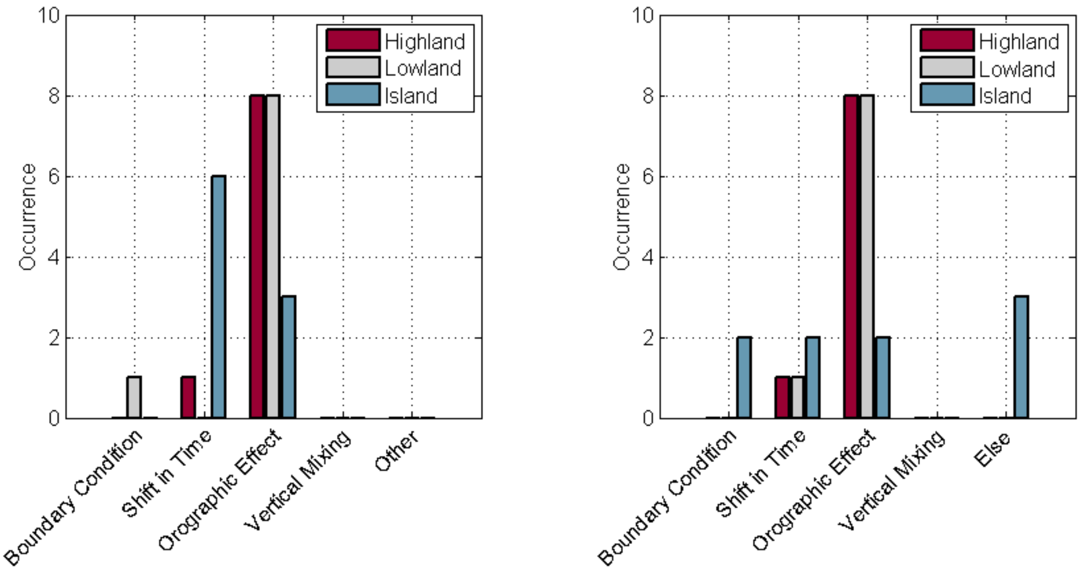

Figure 6: Bar diagrams presenting the number of occurence of each type of error at each station divided into groups for sources of errors

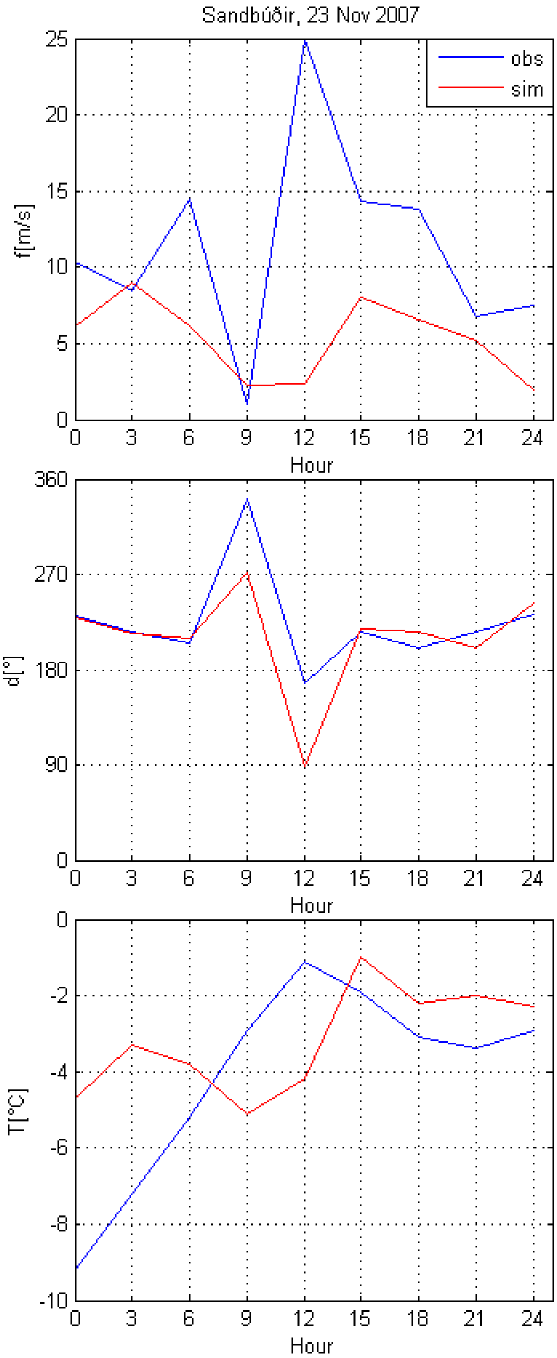

Figure 7: Observed and simulated wind speed [m/s], wind direction [°] and temperature [°C] at Sandbúðir on 23 Nov 2007.

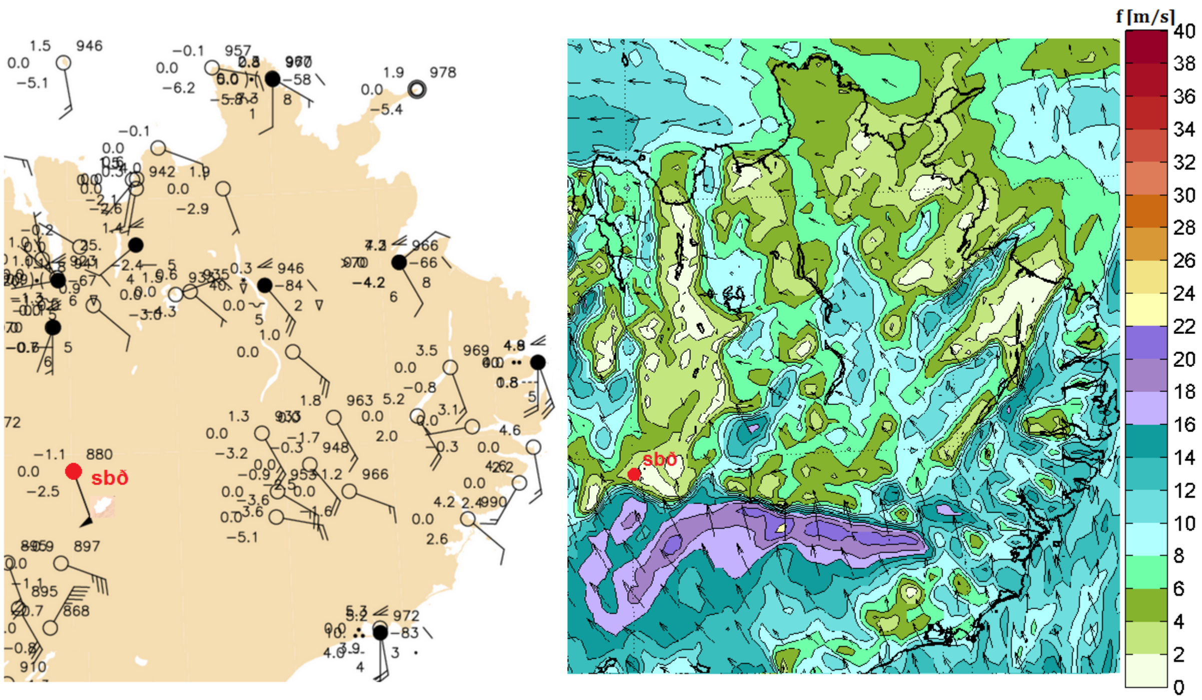

Figure 8: Observed(left) and simulated (right) wind speed and direction at Sandbúðir on 23 Nov 2007.

Appendix

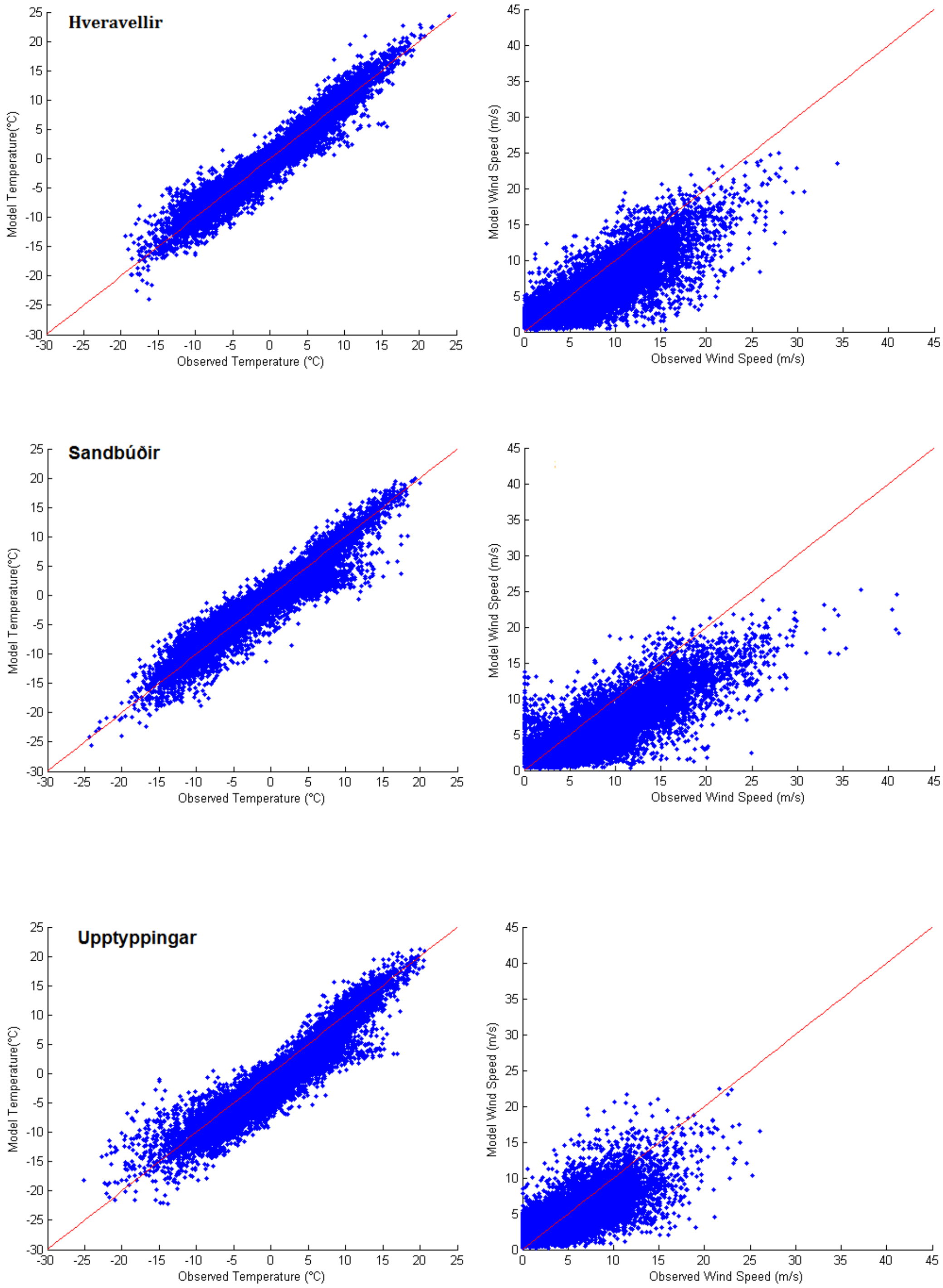

Figure 9: Scatterplots presenting the simulated vs observed temperature (left) and wind speed (right) for the Highlands stations : Hveravellir, Sandbúðir and Upptyppingar.

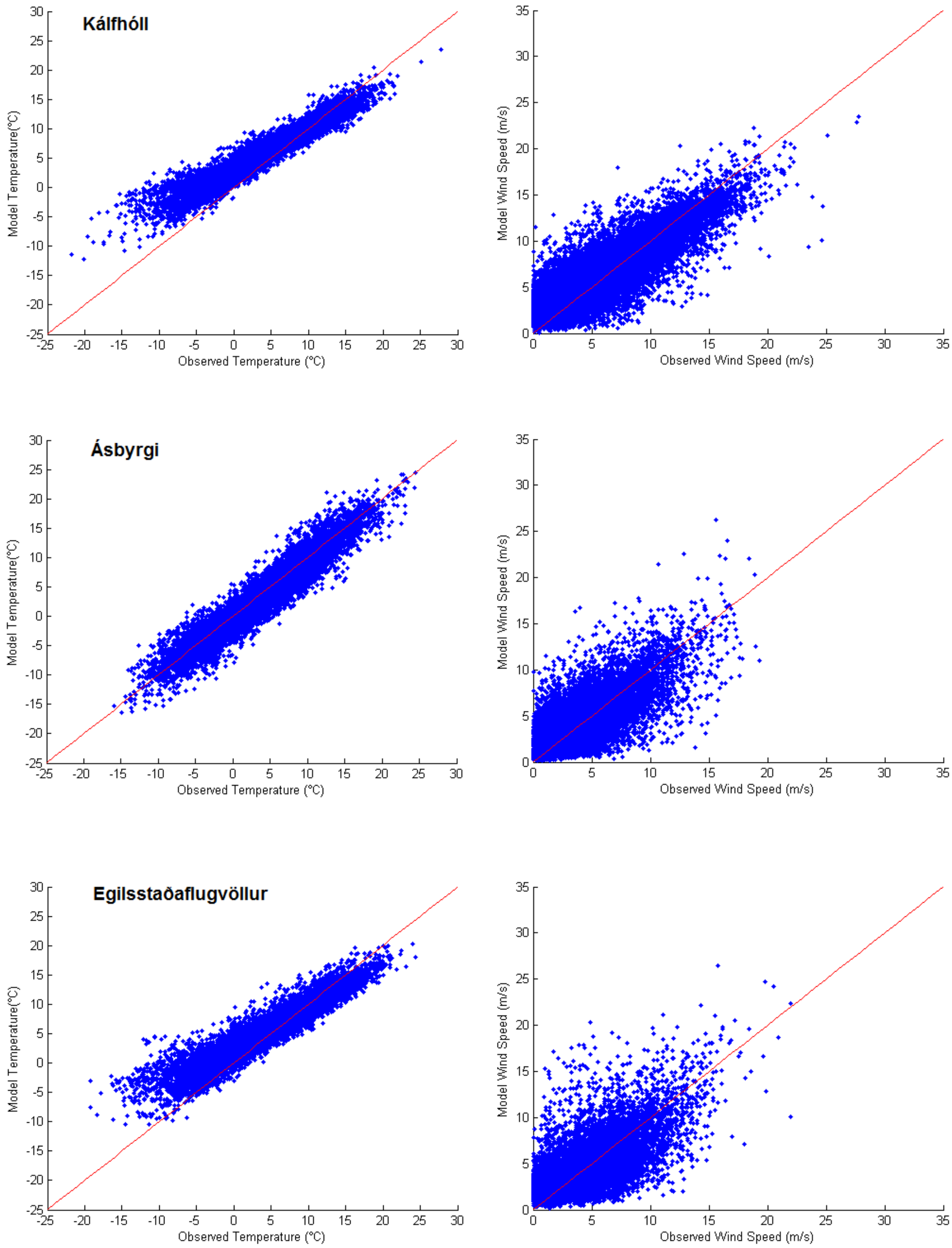

Figure 10: Scatterplots presenting the simulated vs observed temperature (left) and wind speed (right) for the Lowlands stations : Kálfhóll, Ásbyrgi and Egilsstaðaflugvöllur.

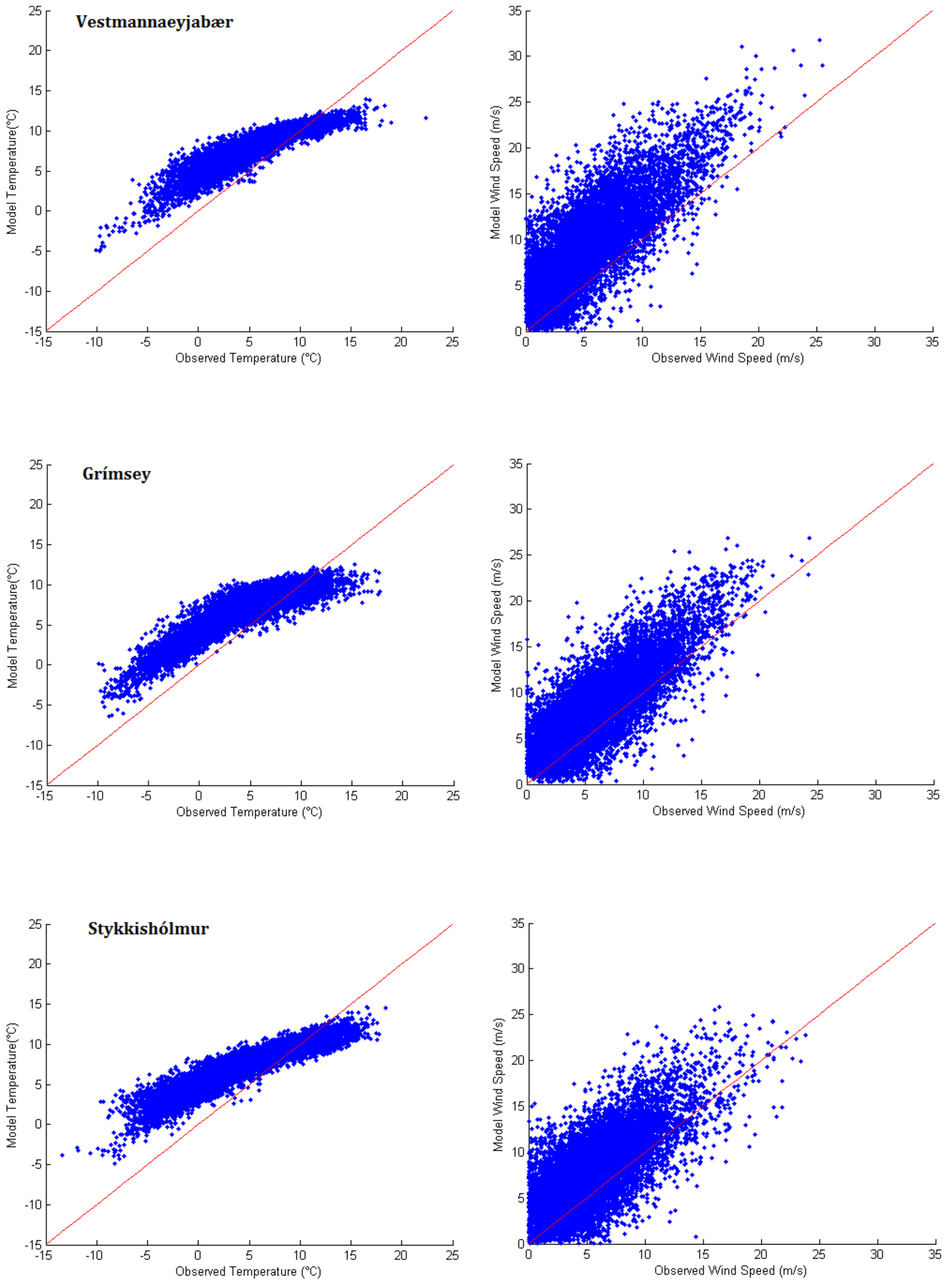

Figure 11: Scatterplots presenting the simulated vs observed temperature (left) and wind speed (right) for the Islands statiosn : Vestmannaeyjabær, Grímsey, Stykkishólmur.