A Wind Atlas of Iceland

Tasks 2.1 and 2.2 of Work Package 2 of IceWind

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Introduction

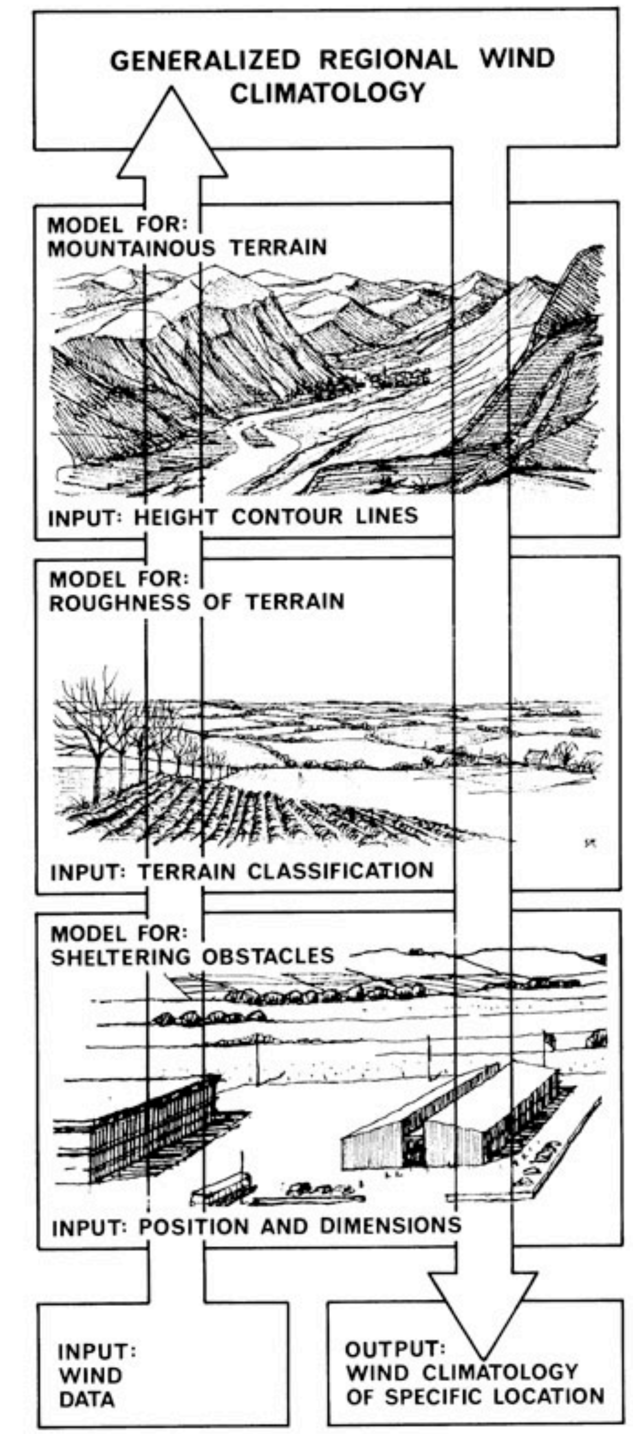
- Goal of Work Package 2: Determination of wind energy potential of Iceland
  - Task 2.1 – Icelandic Wind Atlas: Assessment of wind energy potential for the entire island, based on WRF mesoscale model simulations with 3 km grid-point spacing
  - Task 2.2 – Priority Test Sites: Based on assessment for entire island, identification of 14 smaller regions (~ 20 km x 20 km) for more detailed analyses of wind energy potential; WAsP resource grids with 100 m grid-point spacing
- Results of large-scale assessment made available through online wind atlas
- Results for priority test sites published in open access journal article:
  - Nawri et al., 2014: The wind energy potential of Iceland, *Renewable Energy*, **69**, 290-299

Data Reliability

- Neither station data nor WRF model data are absolutely reliable
- Weather stations: anemometers at 7.2 - 11.6 mAGL; heavily influenced by local terrain features and obstacles; uncertainties about projecting to higher altitudes
- WRF model: limited spatial resolution, poor representation of orography; problems with terrain type, surface roughness; approximations through turbulence parameterisations near the ground

RNL/DTU Wind Atlas Method

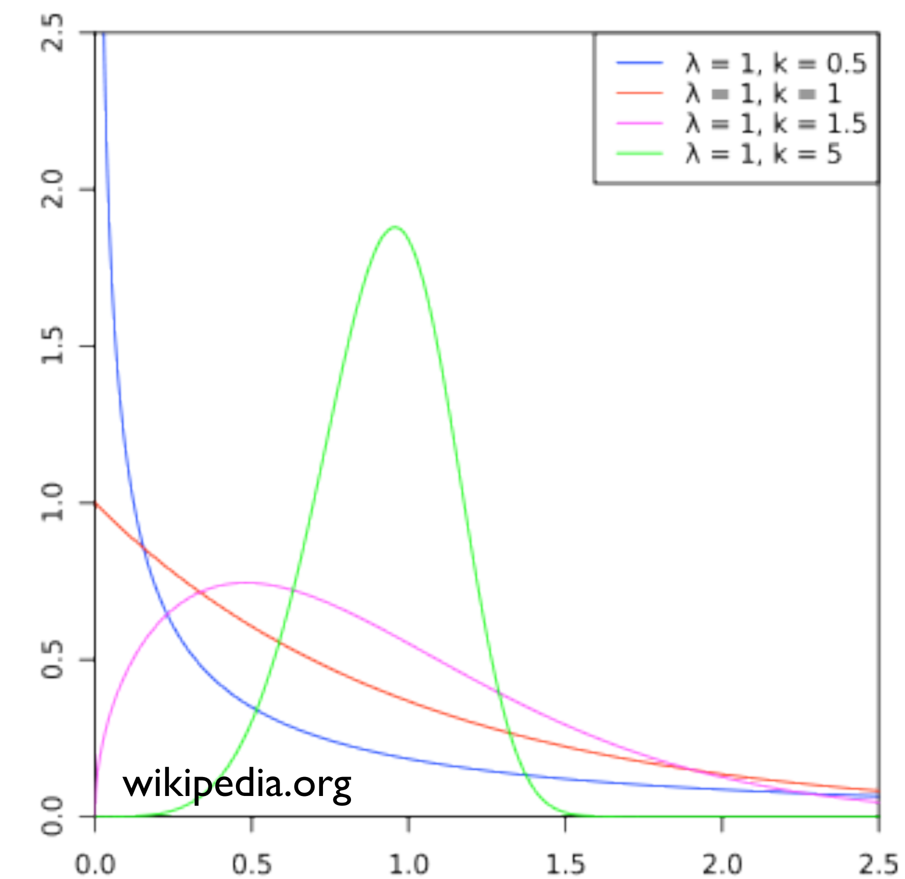
- Designed to remove effects of local terrain features and obstacles from measured wind data, or model orography and surface type from simulated winds; reverse (or "upward") modelling
- Direct (or "downward") modelling to either standard surface roughness classes and height levels above ground (wind atlas files), or to specific conditions at other locations within the same domain (resource grids)
- Parameterisation of boundary-layer wind conditions:
  - Logarithmic vertical wind shear, with small heat flux modification
  - Geostrophic drag law: pressure gradients vs. frictional forces
  - Response to surface roughness changes
  - Sheltering for objects with sizes comparable to sensor height, and distances comparable to object size
  - Orographic effects, assuming potential flow, with viscous modification in shallow surface layer



Troen and Petersen (1989): European Wind Atlas, Risø National Laboratory

Wind Speed Distribution

- Occurrence of wind speeds, s, is typically approximated well by a Weibull distribution, characterised by two parameters:
  - Scale parameter: A (> 0, units of speed); ~ measure of wind intensity
  - Shape parameter: k (> 1, nondim.); ~ measure of wind speed variance
- For each standard surface roughness class, height level, and wind direction sector, parameters are derived by requiring average power density and the probability of above average wind speeds to be equal to the values derived from the measured or modelled wind speed distribution



Weibull Probability Distribution Function

$$f(s; A, k) = \frac{k}{A}\left(\frac{s}{A}\right)^{k-1} \exp\left[-\left(\frac{s}{A}\right)^{k}\right]$$

Average Wind Speed

$$\mu_w = A\,\Gamma\left(1 + 1/k\right)$$

Average Power Density

$$E_w = \frac{1}{2}\rho_0\, A^3\, \Gamma\left(1 + 3/k\right)$$

Wind Atlas Files (.lib files)

```
RAV 3km 2005110100-2009103121    1    3     0 0.0001 -23.75346   63.12115
  5   5 12
 0.000 0.030 0.100 0.400 1.500
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 2.319 2.273 2.225 2.053 2.241 2.157 2.055 2.188 2.256 2.303 2.028 2.170
  9.33 10.43 10.16 10.95 12.52 11.18 10.81 10.91 11.61 10.76  9.26  9.39
 2.305 2.255 2.214 2.033 2.262 2.154 2.039 2.170 2.255 2.300 2.027 2.142
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 2.288 2.254 2.191 2.014 2.278 2.154 2.034 2.151 2.277 2.309 2.018 2.109
 10.35 11.69 11.20 12.19 14.19 12.65 12.08 12.06 12.78 11.95 10.05 10.41
 2.238 2.311 2.187 1.942 2.336 2.181 2.003 2.149 2.280 2.394 2.027 2.096
 10.71 12.23 11.82 12.77 15.19 13.73 13.28 13.12 13.41 12.58 10.64 10.78
 2.090 2.250 2.211 1.822 2.238 2.153 1.993 2.113 2.232 2.314 2.046 2.031
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  8.59  9.87  9.84  9.97 12.07 11.05 10.45 10.28 10.81 10.46  9.15  8.71
 2.253 2.300 2.364 1.977 2.272 2.321 2.116 2.070 2.340 2.424 2.195 2.088
  9.19 10.80 10.60 10.62 13.35 12.39 11.83 11.63 11.88 11.31  9.90  9.35
 2.147 2.276 2.348 1.831 2.220 2.264 2.061 2.060 2.335 2.327 2.176 2.015
  6.57  7.91  7.23  5.29  9.39 10.87  9.60 10.60 10.96  8.67  6.31  6.62
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  4.34  4.92  5.04  4.98  6.00  5.66  5.24  5.23  5.57  5.47  4.88  4.54
 2.328 2.374 2.317 2.228 2.252 2.318 2.204 2.061 2.404 2.397 2.201 2.161
  5.37  6.11  6.23  6.17  7.47  7.04  6.50  6.47  6.86  6.77  6.00  5.60
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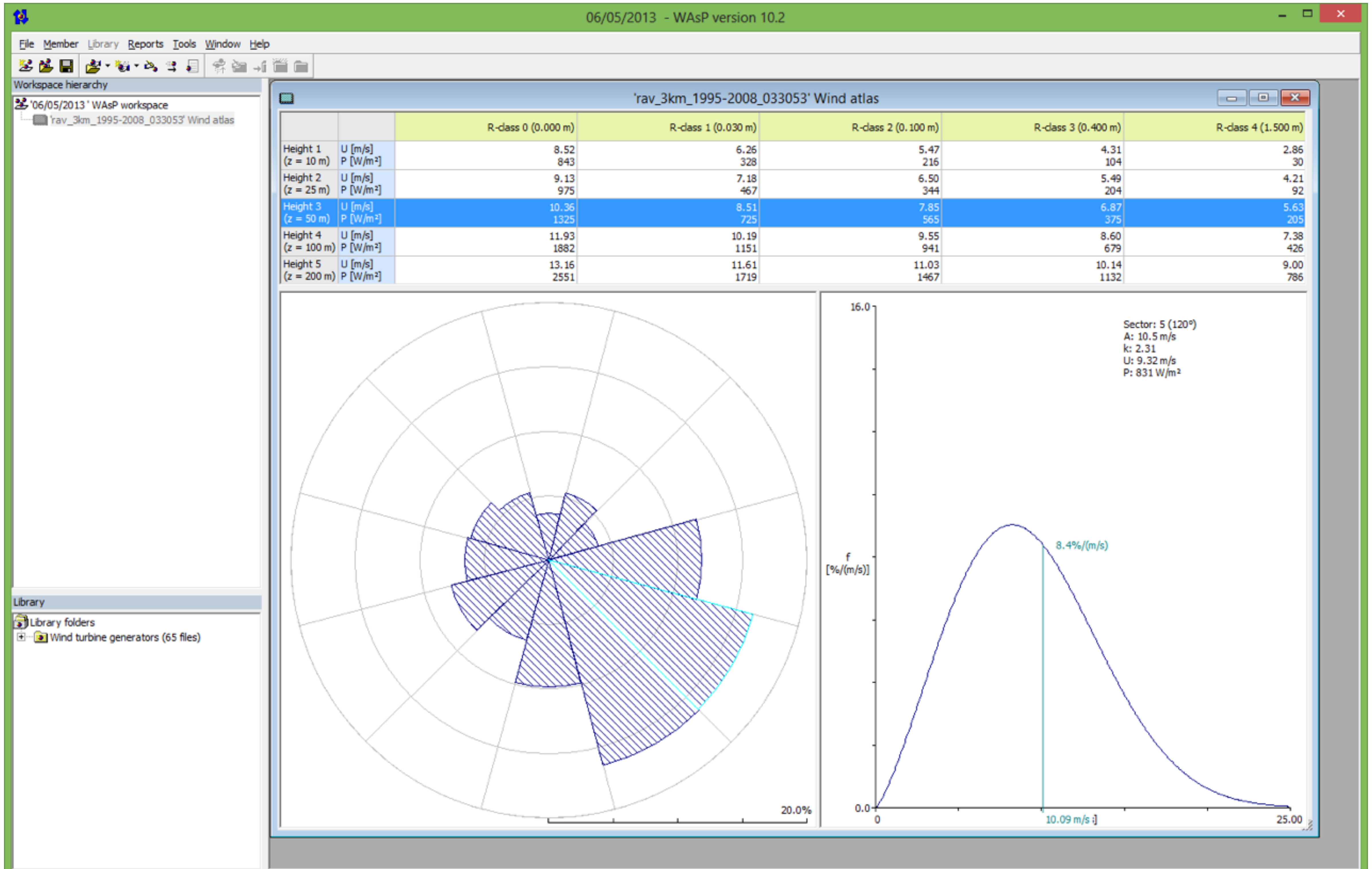
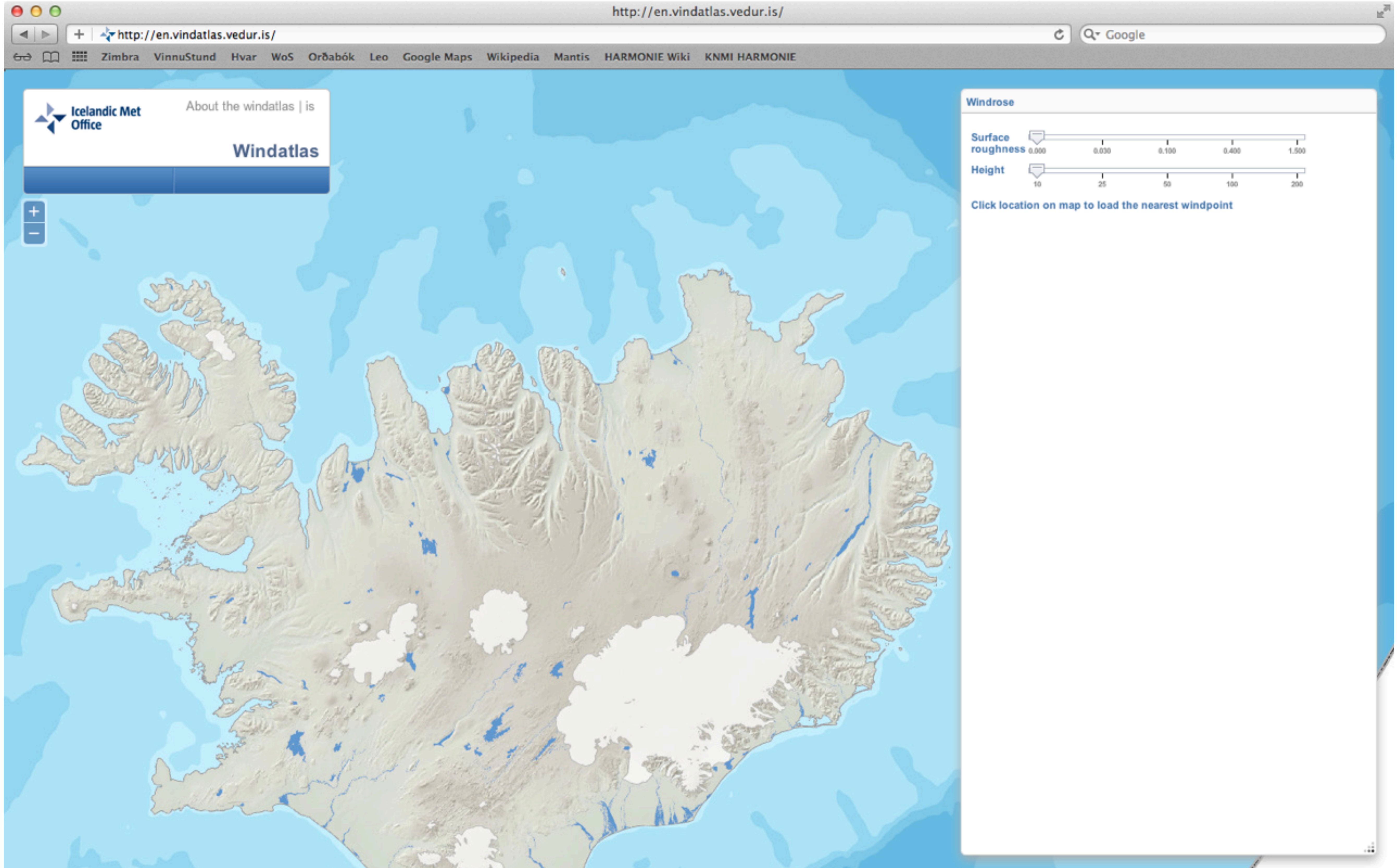
Wind Atlas Analysis and Application Program (WAsP)

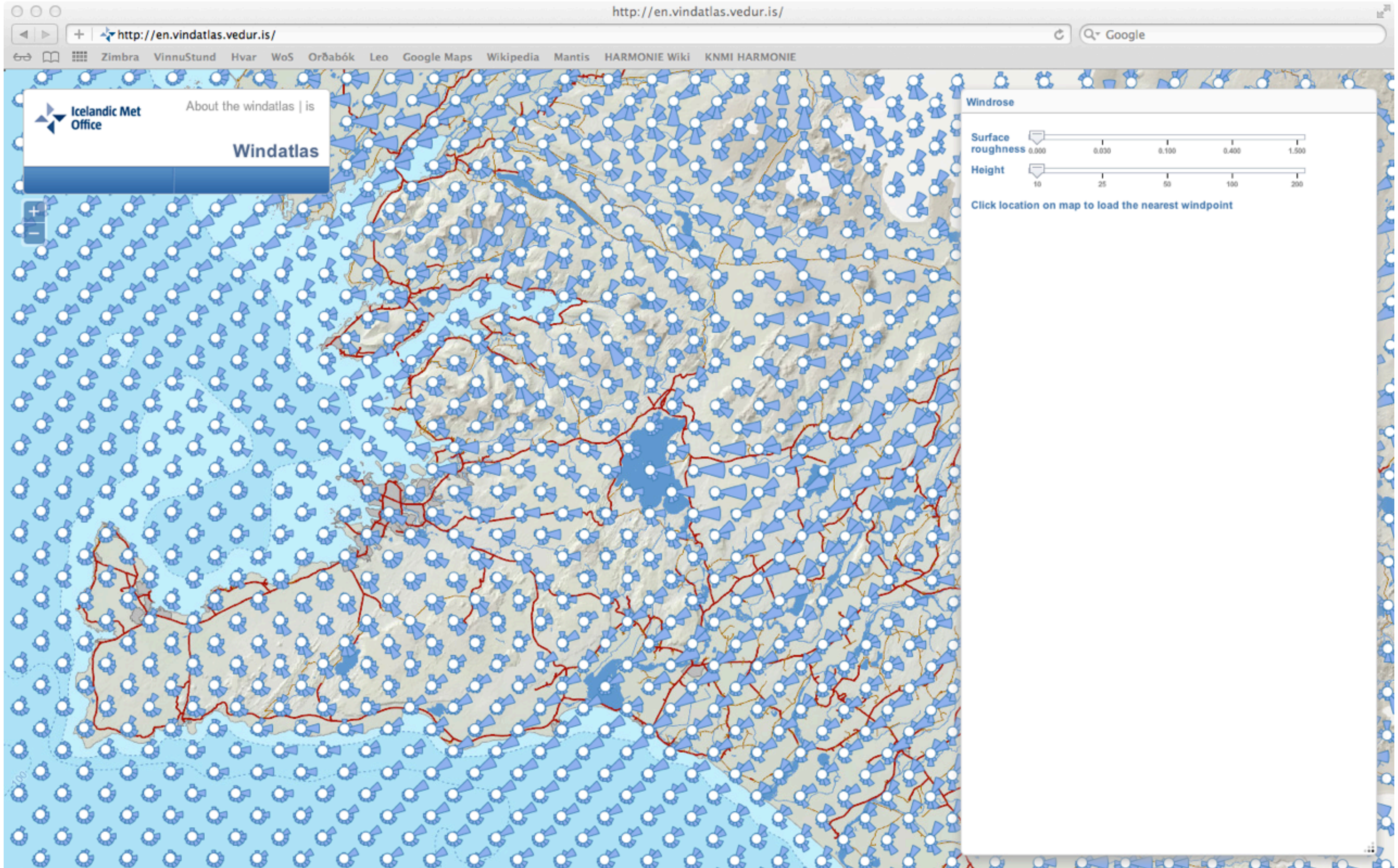
WAsP (for PCs only)
can be obtained from
http://wasp.dk
No license required for
analysing wind atlas files



Online Wind Atlas - en.vindatlas.vedur.is



Online Wind Atlas



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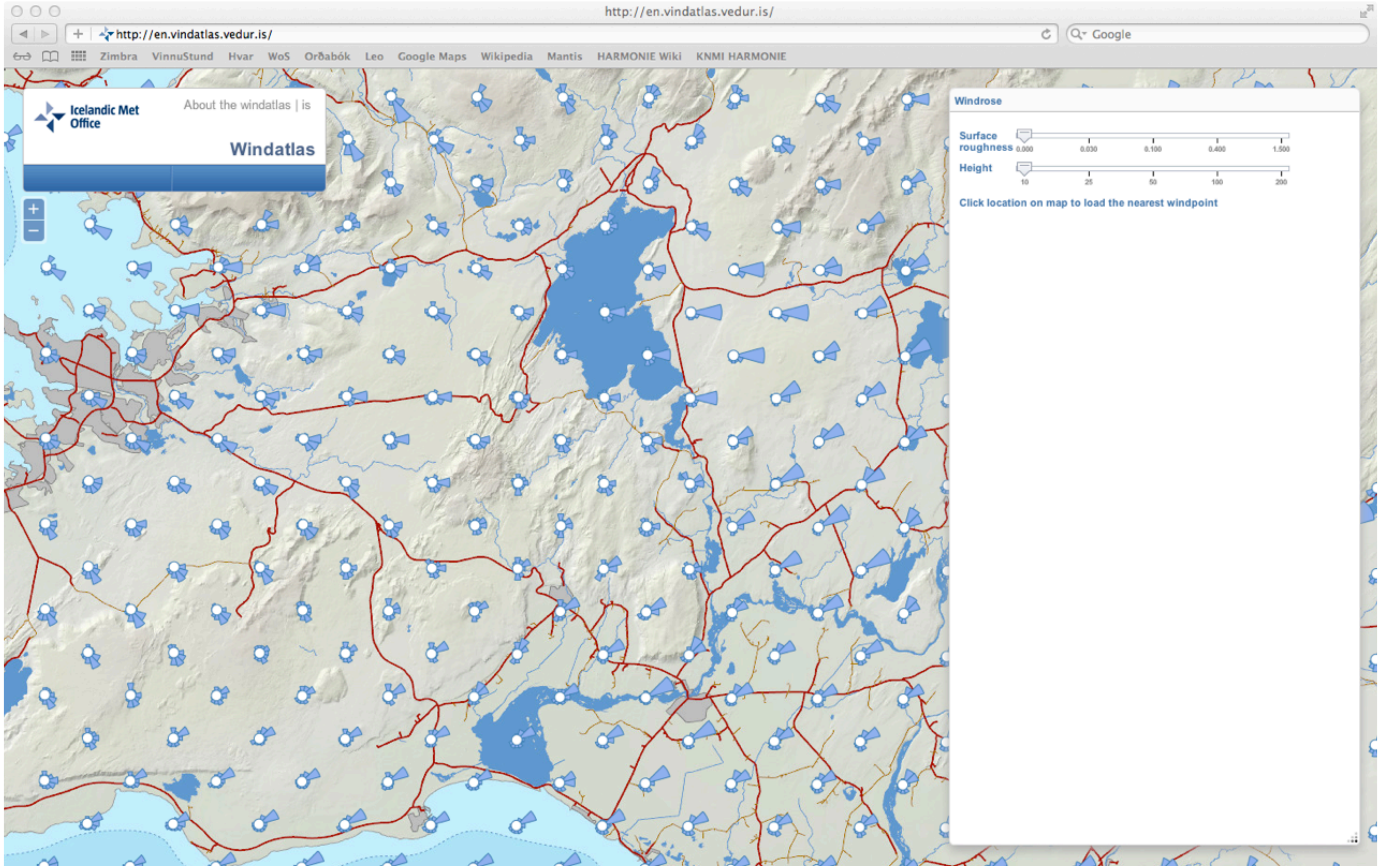

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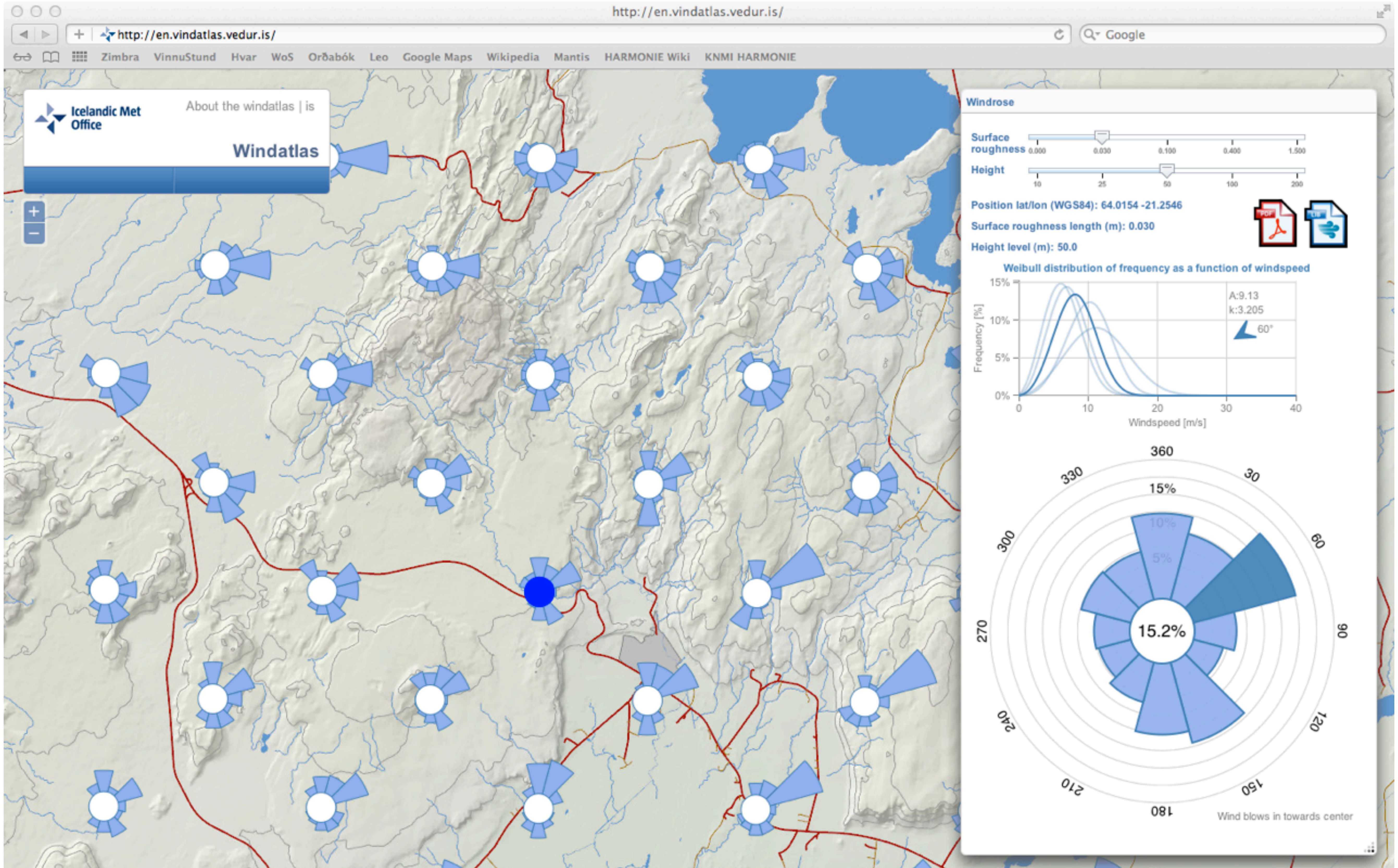


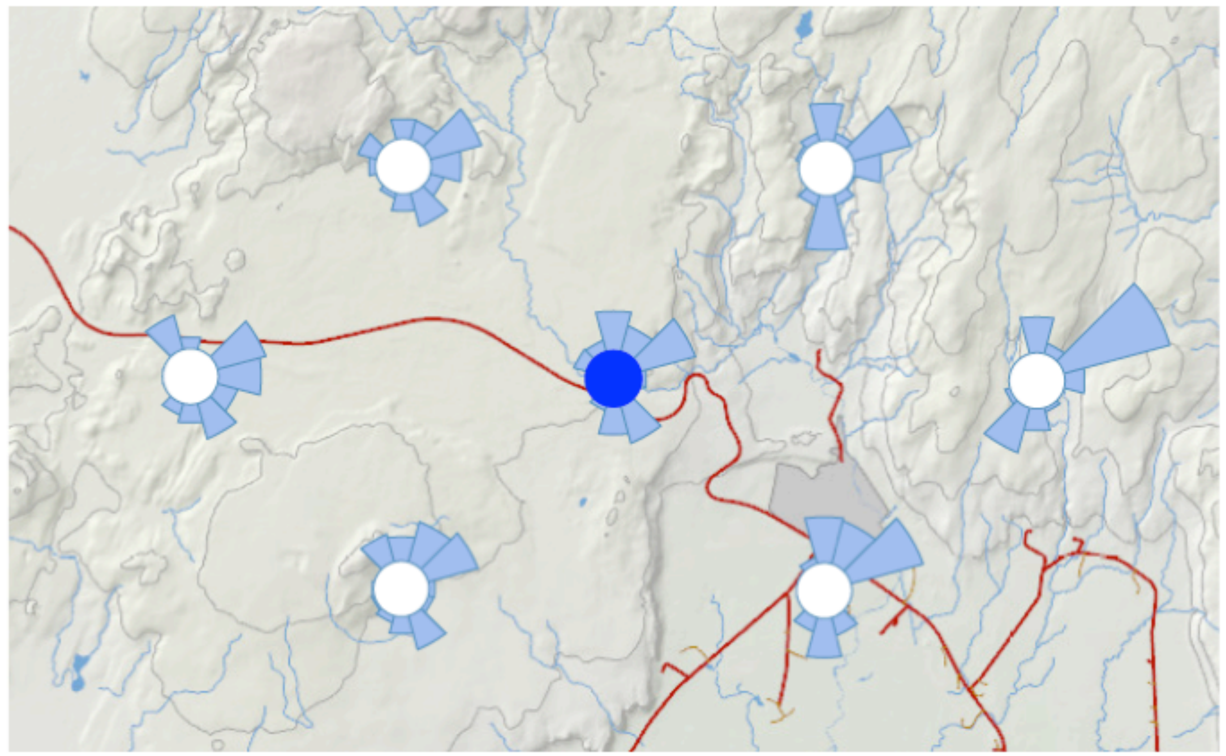
Wind Atlas Report

Icelandic Met Office

Windatlas

2014-11-28 10:45
(year-mon-date hrs:min)

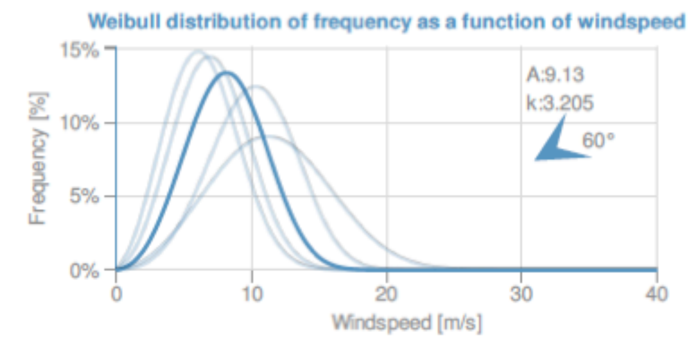
64.015N 21.255W
(decimal degrees WGS84)

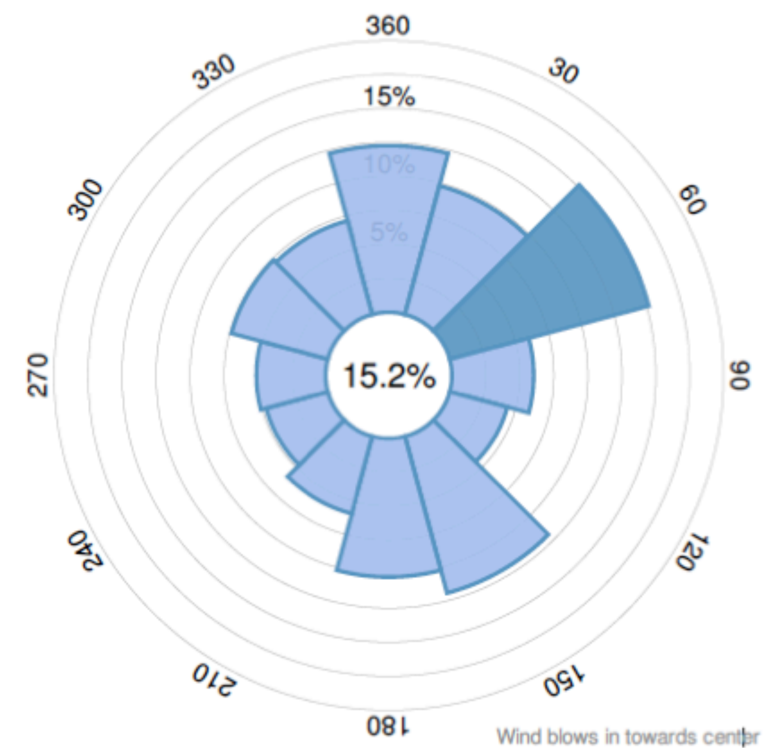


Position lat/lon (WGS84): 64.0154 -21.2546

Surface roughness length (m): 0.030

Height level (m): 50.0





Summary of mean windspeed and power density

Height [m]	Parameter	0.000 m	0.030 m	0.100 m	0.400 m	1.500 m
10	Mean windspeed [m/s]	8.3	6.1	5.4	4.2	2.8
10	Power density [W/m^2]	704	275	182	88	26
25	Mean windspeed [m/s]	8.8	7.0	6.3	5.3	4.1
25	Power density [W/m^2]	778	376	276	165	74
50	Mean windspeed [m/s]	9.9	8.1	7.5	6.6	5.4
50	Power density [W/m^2]	1 013	555	433	290	160
100	Mean windspeed [m/s]	11.2	9.5	8.9	8.0	6.9
100	Power density [W/m^2]	1 422	859	703	509	322
200	Mean windspeed [m/s]	12.0	10.6	10.0	9.2	8.1
200	Power density [W/m^2]	1 853	1 249	1 055	812	564

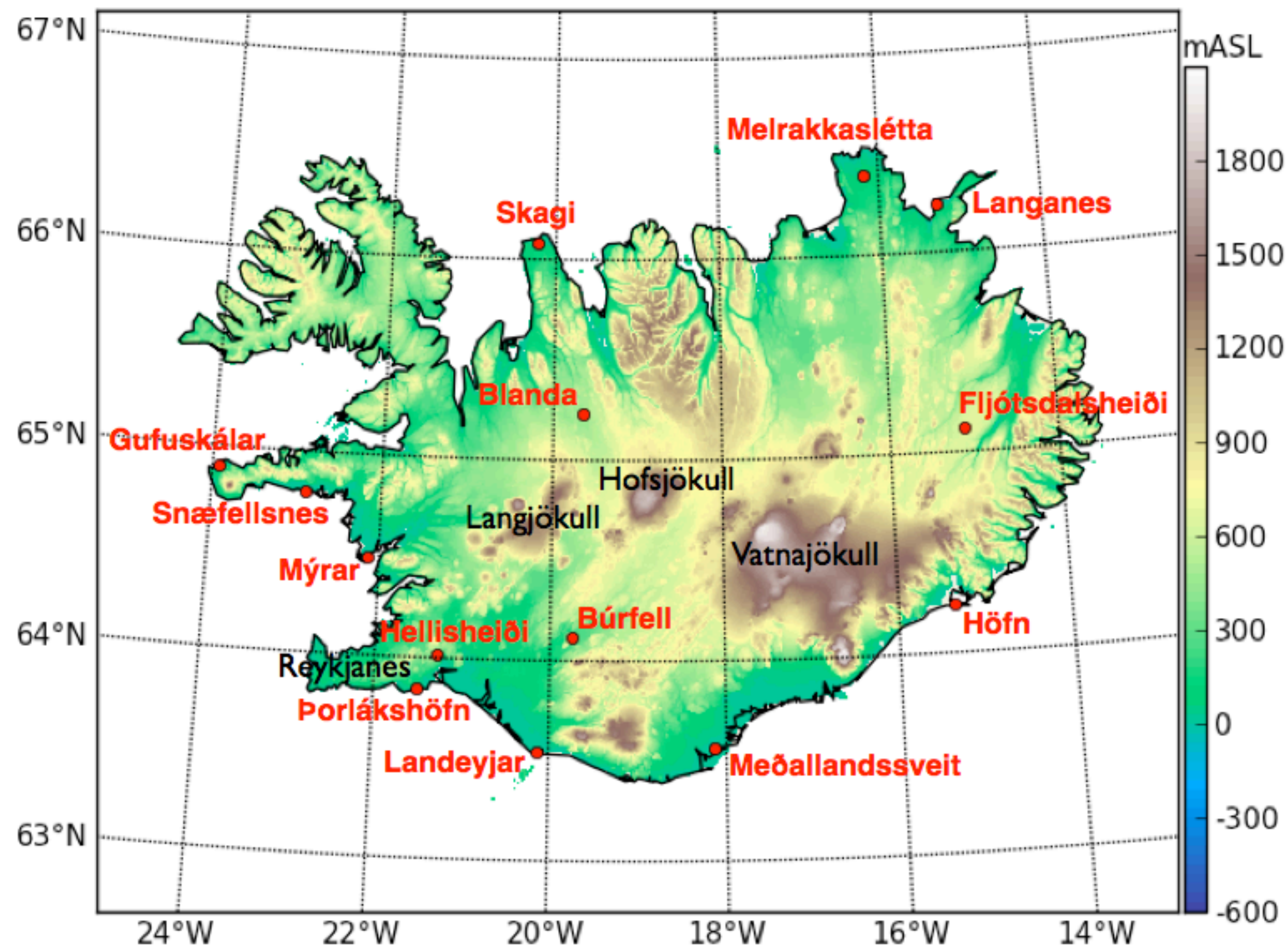
Wind Atlas Report

Height [m]	Parameter	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
	Sector-wise Weibull distributions for surface roughness length 0.000 m												
10	Frequency [%]	12.0	9.6	14.7	8.3	4.0	9.8	12.4	6.2	4.8	4.9	5.7	7.7
10	Weibull A	9.620	7.640	9.510	8.990	9.050	11.480	10.360	9.800	9.930	8.170	8.020	8.420
10	Weibull k	1.822	1.973	2.708	1.902	2.004	2.278	1.890	1.843	1.819	1.728	1.678	1.991
10	Mean windspeed [m/s]	8.6	6.8	8.5	8.0	8.0	10.2	9.2	8.7	8.8	7.3	7.2	7.5
10	Power density [W/m^2]	808	368	553	626	602	1 092	964	842	890	531	524	488
25	Weibull A	10.950	8.120	9.900	9.120	9.150	11.840	10.800	10.150	9.850	8.800	8.900	9.450
25	Weibull k	2.175	2.125	2.930	2.037	2.054	2.361	1.935	1.898	1.759	1.853	1.865	2.269
25	Mean windspeed [m/s]	9.7	7.2	8.8	8.1	8.1	10.5	9.6	9.0	8.8	7.8	7.9	8.4
25	Power density [W/m^2]	986	410	600	606	607	1 166	1 063	902	908	605	621	611
50	Weibull A	12.830	9.450	11.040	10.060	9.580	12.880	11.830	11.030	10.690	10.310	10.020	10.700
50	Weibull k	2.631	2.491	3.184	2.397	2.038	2.489	1.974	1.928	1.805	2.157	1.907	2.572
50	Mean windspeed [m/s]	11.4	8.4	9.9	8.9	8.5	11.4	10.5	9.8	9.5	9.1	8.9	9.5
50	Power density [W/m^2]	1 381	571	805	707	702	1 446	1 367	1 137	1 122	829	863	812
100	Weibull A	14.570	10.950	12.780	12.020	10.400	14.460	13.670	11.740	12.070	12.120	11.210	11.490
100	Weibull k	2.835	2.657	3.352	2.838	2.047	2.670	2.170	1.875	1.879	2.402	1.956	2.372
100	Mean windspeed [m/s]	13.0	9.7	11.5	10.7	9.2	12.9	12.1	10.4	10.7	10.7	9.9	10.2
100	Power density [W/m^2]	1 944	854	1 227	1 091	894	1 961	1 922	1 417	1 536	1 235	1 175	1 062
200	Weibull A	13.930	12.750	13.640	14.150	12.240	15.370	14.570	12.950	13.330	13.360	12.400	11.110
200	Weibull k	1.995	2.611	2.656	2.654	2.459	2.545	2.139	1.932	1.994	2.197	1.860	1.847
200	Mean windspeed [m/s]	12.3	11.3	12.1	12.6	10.9	13.6	12.9	11.5	11.8	11.8	11.0	9.9
200	Power density [W/m^2]	2 207	1 361	1 651	1 843	1 251	2 423	2 357	1 836	1 935	1 774	1 686	1 223

Height [m]	Parameter	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
	Sector-wise Weibull distributions for surface roughness length 0.030 m												
10	Frequency [%]	12.3	9.8	15.2	6.0	4.4	12.0	10.2	5.9	4.7	5.1	7.4	7.1
10	Weibull A	6.920	5.780	7.140	6.470	7.220	8.350	7.480	7.000	6.830	6.120	6.360	6.000
10	Weibull k	1.854	2.217	2.722	1.904	2.022	2.300	1.859	1.818	1.742	1.787	2.034	1.699
10	Mean windspeed [m/s]	6.1	5.1	6.4	5.7	6.4	7.4	6.6	6.2	6.1	5.4	5.6	5.4
10	Power density [W/m^2]	294	143	234	233	303	417	370	312	307	213	206	216
25	Weibull A	8.390	6.490	7.920	7.010	8.020	9.290	8.330	7.740	7.560	7.050	7.410	7.480
25	Weibull k	2.257	2.386	2.966	2.038	2.163	2.358	1.890	1.879	1.776	1.934	2.135	1.960
25	Mean windspeed [m/s]	7.4	5.8	7.1	6.2	7.1	8.2	7.4	6.9	6.7	6.3	6.6	6.6

Priority Test Sites for Wind Farms

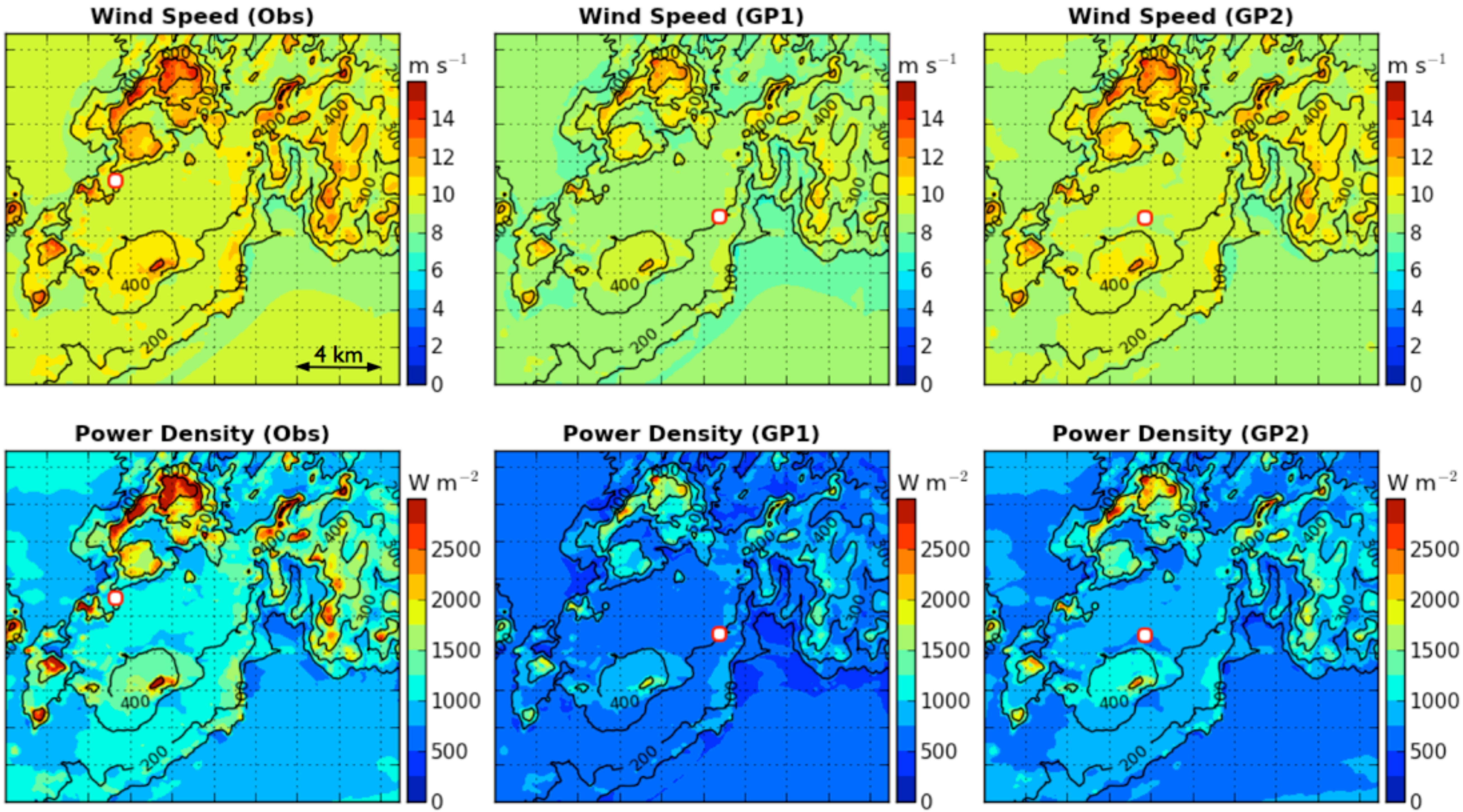
- Criteria:
  - Annual wind power density
  - Locally flat and solid terrain
  - Outside residential areas
  - Limited tall vegetation
  - Away from avalanche paths
  - Year-round road access
  - Grid access, power lines
  - Aviation
  - Nature conservation
  - Tourism



Hellisheiði

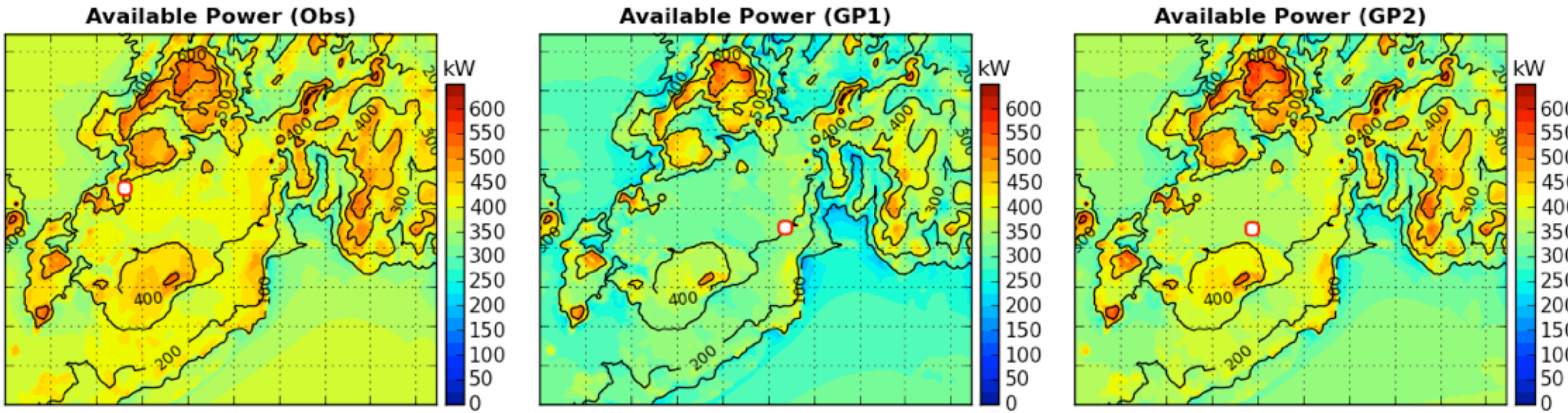
ThinkGeoEnergy - http://www.flickr.com/photos/thinkgeoenergy/4473297657/

Hellisheiði – Speed and Power Density (55 mAGL)



Hellisheiði – Average Available Power (55 mAGL)

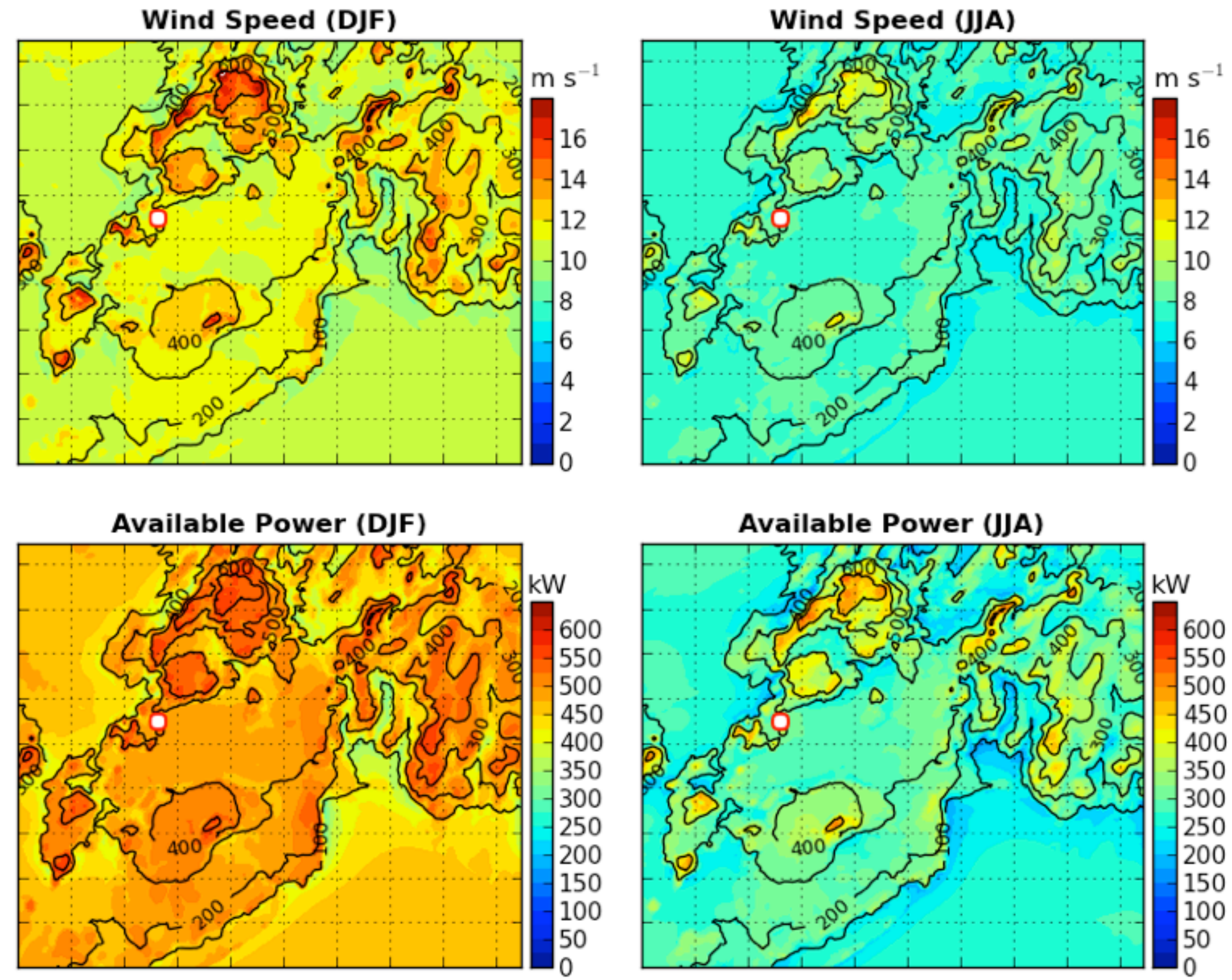
Based on Enercon E44 (900 kW) wind turbine



Hellisheiði – Seasonal Differences (55 mAGL)

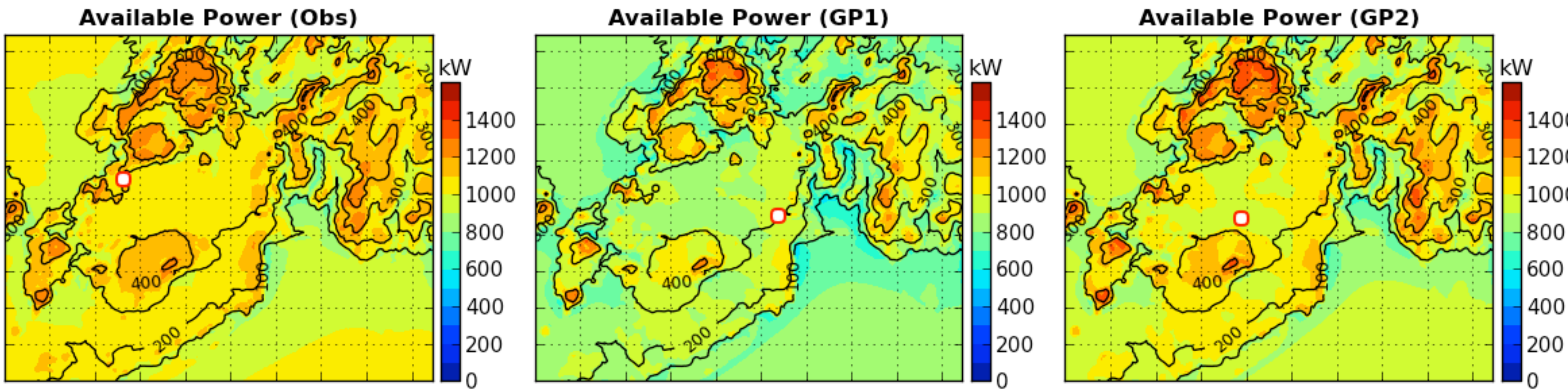
Based on Enercon E44 (900 kW) wind turbine

- Average wind speeds on plateau:
  - Winter: 10 - 12 m s^{-1}
  - Summer: 7 - 9 m s^{-1}
  - Winter / summer ratio: ~ 1.375
- Average available wind power on plateau:
  - Winter: 450 - 550 kW
  - Summer: 250 - 350 kW
  - Winter / summer ratio: ~ 1.667
- Relative wintertime increase in available power is ~ 120% of increase in wind speed; combined effect of higher cubed wind speeds, and higher air density; limited increase due to turbine inefficiencies



Hellisheiði – Average Available Power (67 mAGL)

Based on Vestas V80 (2 MW) wind turbine



Increase in blade length by factor of 1.8, plus small increase in hub height, leads to increase in available power by factor of ~ 2.4, rather than factor of $1.8^2 = 3.2$, as for energy flux through area swiped by rotor blades

Summary and Outlook

- Overall, wind energy potential of Iceland is highly competitive with other Western European countries; annual wind conditions are not a limiting factor for wind energy production
- At 50 – 70 mAGL, the annually average available power (theoretical potential) is approximately half the maximum output of typical small wind turbines (Enercon E44 ~ 400 - 500 kW; Vestas V80 ~ 1000 - 1200 kW)
- Seasonal cycle: winter wind speeds higher than in summer, leading to increased available power by about a factor of 1.7 for Enercon E44; well-timed with reduced streamflow and increased residential electricity demands
- Two Enercon E44 (55 m hub height), located in valley at 250 mASL in southern Iceland, operational since 14 Feb 2013, have experienced no downtime due to icing; on summits and ridges, extreme winds and icing might be a problem
- Ongoing and future Work:
  - Extension of wind energy potential assessment to offshore region around Iceland (ongoing; next presentation)
  - Detailed regional wind analyses using WAsP for different customers (ongoing)
  - Analyse actual production data from two Enercon turbines, in comparison with WAsP estimates

Journal Article (ScienceDirect, open access)

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Contents lists available at ScienceDirect

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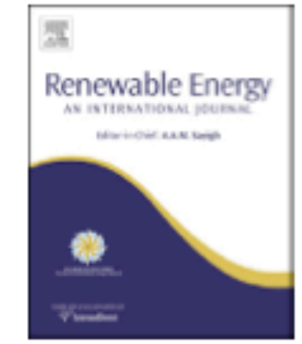
journal homepage: www.elsevier.com/locate/renene



ELSEVIER

The wind energy potential of Iceland

CrossMark

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A R T I C L E I N F O

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Mesoscale modelling

A B S T R A C T

Downscaling simulations performed with the Weather Research and Forecasting (WRF) model were used to determine the large-scale wind energy potential of Iceland. Local wind speed distributions are represented by Weibull statistics. The shape parameter across Iceland varies between 1.2 and 3.6, with the lowest values indicative of near-exponential distributions at sheltered locations, and the highest values indicative of normal distributions at exposed locations in winter. Compared with summer, average power density in winter is increased throughout Iceland by a factor of 2.0–5.5. In any season, there are also considerable spatial differences in average wind power density. Relative to the average value within 10 km of the coast, power density across Iceland varies between 50 and 250%, excluding glaciers, or