Summary of changes made into the manuscript.

Reviewer 1.

The first comment is related to calculation of weighting factors *"p. 4, l. 14: the rationale behind the weighting factor should be explained"*

5

In our work we first interpreted the terrain cover available from CORINE database to surface roughness values using the same methods as used e.g. in the Wind Atlas (Tammelin et al. 2013). We are interested in very high resolution spatial variation of wind speed in typically highly variable terrain mosaic composed of forests, fields, lakes, clear cut areas etc. The detailed structure of wind flow in this kind of heterogeneous terrain is very complex (e.g. Dupont&Brunet, Forestry, Vol. 81, No. 3,

10 2008. doi:10.1093/forestry/cpn006); one dominant feature being rapid deceleration of wind when wind encounters forest edge. The main wind damage are found typically within distance less than 50 m from the forest edge (Peltola ret al 1999b). In integration of the so called effective roughness we have applied normal distribution having variance 150 m. With these assumptions the weighting of each grid is as demonstrated in Fig. A2 added into the manuscript. The weight of the closest grid square is about 11 % and the furthest grid square located 500 m upwind has the weight of 0.04 % only. With no doubt, this

15 formula is a simplification of a very complex issue as the exact impact of roughness elements on wind flow depend beside terrain properties also on the characteristics of prevailing air flow. However, when aiming in computationally light applications all these issues cannot be taken into account and the approach selected here gives a realistic interpretation of the complicated issue. In addition to the Figure A2, we also have added explanatory text.

20 The next comment, *"p. 6, l. 33-34: the authors use 12 m/s as a wind speed likely to cause damage. Given the availability of the HWind model, it would seem interesting to provide examples of stands that would be vulnerable to such wind speeds. The same applies at l. 39. I believe the paper could be strengthened if this section was somewhat expanded."*

Simulations using HWind would really give additional value for the study. Unfortunately for this study and for the Pyhätunturi

25 test-area we did not have all the needed forest data. However, in our next studies we plan to expand our studies to cover whole country is respect of wind climate and apply HWind model for another test areas where we have needed detailed forest characteristics data. We have added text explaining the issue into the manuscript.

The third comment relates to accuracy of weather station data *" p. 7, l. 28-29. The authors point out some potential imprecisions*

30 *of weather station data. It would be interesting to know to what extent this problem is present in the data base."*

FMI has a three stage quality control system, first check is done at the observation station site checking the main instrument malfunctions, and next check is done before storing the data to database. This check includes e.g. comparison with the extreme values and temporal and spatial consistency. The final step is the manual quality control for those values that did not pass

35 earlier steps. The quality control ensures that the values stored in database are realistic can have occurred. However, quality control does not guarantee that the measurements are exactly correct. As well, quality control does not ensure the homogeneity of observations. The changes at measuring site and changes in instrumentation as well as, the changes of the height of anemometer installation can lead to discontinuations, break points, in observational time-series. These break points are relatively common also in wind observational time series like studied by Laapas and Venäläinen (2017). We have added text

40 about the reliability of wind observations.

Next comments:
"p. 13: please provide units with column headings". We have edited the table.
"p. 19: the title of the y axis should be changed since it represents 10 year return levels of maximum wind speed for two

45 *different approaches"*. We have edited Figure 6. and also added text about the challenges wind multiplier approach seem to have in simulation of conditions for small open island stations
p. 22: it is mentioned that the figure includes only values > 11.4 m/s. Do you mean that the graphs were truncated at this value or that the whole statistics did not consider lower values? The whole statistics did not consider lower values. This was done because we were interested in high wind speed values and the direction distribution of these strongest winds. We have added

50 explanatory text.

Reviewer 2.

55 The first comments is related to the <u>Title</u>
"The title includes a bit more promises than actually addressed in the body of the manuscript – for risk management an assessment of potential future changes is necessary. Investigations about future scenarios are however not addressed in this study. Therefore I suggest to modify/correct the title for this missing part of the analysis."

60 The Title is "Estimation of the high-resolution variability of extreme wind speeds for a better management of wind damage risks to forest-based bioeconomy". If needed, we can shorten the title and make it more general e.g. "Estimation of the high spatial resolution variability of extreme wind speeds for forestry applications"

The next comment is related to Abstract. *"The abstract is very extensive – At the end of the review the authors find a suggestion for a shortened version with focus on the very background and the most important findings."*

5   We have edited the Abstract.

Introduction
The comment: *"p1. l. 5: could you please add a few examples from the papers you cite which specific risks are impacting on the forests in Finland."*

10

The foreseen risks include increased wind throw risk due reduced soil frost period and depth. As well, drought may have negative impacts especially in southern Finland spruce forests. Related to drought, forest fire danger will increase. During winter season heavy snow loads will decrease in the southern but increase in the northern Finland. We have edited the text taking into account the comment.

15

Comment: *"p2. l. 35ff: The authors should add one or two sentences on the drawbacks of reanalysis data sets when the network of stations used for assimilation changes in space and time affecting the temporal and spatial covariance patterns."*

We have added text about the factors affecting the accuracy of re-analyzed data.

20

Comment: *"p3. l. 1ff: In my opinion the authors could improve the intro by adding a short paragraph on their downscaling cascade from large to their localized scale. I guess that at least three levels of complexities are involved. An important issue in this context is that a consistent approach is desirable where the subsequent downscaling steps comprise over the at least as complex structure as the preceding. For instance, given the assimilated or GCM derived large-scale circulation shows too*
25   *strong biases (e.g. blocking frequencies) also the following steps do not compensate this shortcoming but inherent the information from the boundaries. This should at least be kept in mind to consistently interpret results and according uncertainties. "*

There are many challenges when downscaling to this high resolution. The coarse resolution characters of re-analyzed data
30   contain inaccuracies. This is concreate especially if we are looking specific weather events. Fortunately the mean and as well, return levels are not as much dependent on imperfectly simulated cases as if we were making cases-studies of e.g. on some disastrous event. However, if the model contain systematic biases then the downscaling we have applied is not able to correct them. The importance of small scale spatial variation is demonstrated in our study; the coarse scale ERA Interim based spatial variation of e.g. 10-year return level of maximum wind speed for the area covering the whole Finland is less than the simulated
35   high resolution spatial variation within the small test area. We have added text.

Material and methods
The next comment related to Material and methods chapter, 2.2 Estimation of return level for regional maximum wind speeds
40   *"p4 l. 1ff: I assume that also a seasonal component is into the variability of maximum wind speeds. The authors could add some information which processes drive maximum wind speed during different seasons (e.g. frontal based cyclonic maximum wind speed in cold fronts during winter half year vs. wind gusts originating from thunder storms that are operating during the summer seasons)."*

45   We will add text about the reasons for the occurrence of high wind speeds.

Comment: *"Another important information relates to the temporal basis. As much as I could infer authors use maximum monthly wind speeds. Using maximum daily wind data would provide a better statistical basis. However, in this case one also needs to account for the effect of serial correlated data.*
50   *A third issue involved in the analysis of extremes relates to the procedure of averaging – Are the values used for comparisons based on 6(x)hourly means or are they related to certain reading hours, i.e. instantaneous measurements without any temporal averaging ? This could for instance explain already part of the differences between ERA40 and observations. Given the comparable short length of the observational basis with the high value of return period it might also be useful to calculate shorter term return period, i.e. two and five years."*

55

In case of the re-analyzed coarse resolution data we have used 6-hourly data and the parameter was instantaneous 10-minute wind speed. When calculating the return levels we have applied the GEV approach that fits the extreme value distribution based on the annual maximum values. The same approach was used also for station data but now the parameter was the 3-hourly (synoptic) instantaneous 10-minute wind speed. In this sense the observational values are not exactly the same as
60   reanalyzed data and this may create some systematic difference. However, when we finally use the annual maximum values as the bases for fitting the distribution this may reduce the bias. We can add discussion about this into the text. It is true that the estimation of e.g. 50-year return levels based on 30-years of data leads to large uncertainty in estimates. The shorter return periods like two and five years could be estimated more accurately but from the point of forestry planning activities the longer

return periods are interesting and that is why we have demonstrated the applicability of the method with 10-year return level. We have added text.

Discussion and conclusion

Comment: *"How do other climate change studies (e.g. Bärring et al. 2017) addressing other climatic variables compare to changes that are potentially controlled by changes in extreme wind speeds?"*

Bärring et al. (2017) examined climate change impacts on temperature and precipitation related indices relevant from the point of the Scots pine transfer functions. Their study is an interesting example on how climate change may influence on forestry. The importance of climate change impact studies is emphasized by the long rotation period of 50-100 years from forest cultivation to final harvesting in Scandinavia. Bärring et al. (2017) found clear signal in temperature related indices but minor in precipitation and future climate is in that sense more favorable for forest growth. Bärring et al. (2017) did not study possible changes in wind climate that might influence on wind throw risks. There are other studies like Nikulin et al. (2011); Pryor et al, 2012; Outten&Esau, 2013) that indicate no clear signal in the occurrence of extreme winds in Scandinavia. We have added discussion and references to Bärring et al. (2017) and other relevant literature into the manuscript into the Introduction chapter.

Figure and Tables:
Comment: *"In general, on the small scale geographic information is missing at borders. It would also be helpful to include an inset covering the large scale surroundings. In addition, each map should have its own frame with lat/lon coordinates."*

There is information about the land use in Appendix, Figure A2. There exist detailed photos available e.g. in the Finnish National Surveys web service (https://asiointi.maanmittauslaitos.fi/karttapaikka/?lang=en) or Google Maps, we could add links to these services, however, we are hesitant to add these photos e.g. due to the copyright restrictions. We have added new information and the co-ordinates; this will improve the reading of manuscript.

Comment: *"Table 1: Please include the length of the individual meteorological recordings to better visualize the robustness in the estimation of the 10yr return period. If the length between the ERA40 and the meteorological station varies then only the common overlap period should be used. Another question is whether the direction of strongest wind direction is the same for both, the ERA40 data set and the meteorological observations, respectively."*

We have continued the analyses in the way that the analyses have been made for all wind directions. The table has been edited accordingly and the length of time-series have been added.

Comment: "*Appendix Figure 1: For the comparison a similar basis should be used. Obviously the ERA40 data are based on maximum monthly wind speed whereas the boxplot is based on 10min readings. Again, it would be important to know the averaging procedure, especially for the Era40 interim data set.*"

ERA data is 6-hourly data and we have added a box plot that is drawn using that data.

Estimation of the high spatial resolution variability of extreme wind speeds for forestry applications ~~Estimation of the high-resolution variability of extreme wind speeds for a better management of wind damage risks to forest-based bioeconomy~~

Ari K. Venäläinen[1], Mikko O. Laapas[1], Pentti I. Pirinen[1], Matti Horttanainen[1], Reijo Hyvönen[1], Ilari Lehtonen[1], Päivi Junila[1], Meiting Hou[2], Heli M. Peltola[3]

[1]Climate Service Centre, Finnish Meteorological Institute, Helsinki, FI-00101, Finland
[2]China Meteorological Administration Training Centre, Beijing 100081, China
[3]School of Forest Sciences, University of Eastern Finland, Joensuu, FI-80101, Finland

Correspondence to: Ari K. Venäläinen (ari.venalainen@fmi.fi)

Abstract The bioeconomy has an increasing role to play in climate change mitigation and the sustainable development of national economies. In a forested country, such as Finland, over 50% of its current bioeconomy relies on the sustainable management and utilization of forest resources. Wind storms are a major risk that forests are exposed to and high spatial resolution analysis of the most vulnerable locations can produce risk assessment of forest management planning. ~~Coarse spatial resolution estimates of the return levels of maximum wind speed based, e.g., on reanalysed meteorological data or climate scenarios can be downscaled to forest stand levels with the help of land cover and terrain elevation data.~~ In this paper, we examine the feasibility of the wind multiplier approach for downscaling of maximum wind speed, using 20 meter spatial resolution CORINE-land use dataset and high resolution digital elevation data. A coarse spatial resolution estimate of the 10-year return level of maximum wind speed was obtained from the ERA-Interim reanalysed data. <u>Using a geospatial re-mapping technique the</u>~~These~~ data were downscaled to 26 meteorological station locations to represent very diverse environments<u>.</u> ~~:~~ ~~Open Baltic Sea islands, agricultural land, forested areas, and Northern Finland treeless fells.~~ Applying a comparison, the downscaled 10-year return levels ~~explained~~ <u>represent</u> ~~77~~<u>66</u>% of the observed variation among the stations examined. In addition, the spatial variation of wind multiplier downscaled 10-year return level wind was compared with the WAsP- model simulated wind. The heterogeneous test area was situated in Northern Finland, and it was found that the major features of the spatial variation were similar, but in the details, there were relatively large differences. ~~However, for areas representing a typical Finnish forested landscape with no major topographic variation, both of the methods produced very similar results. Further fine-tuning of wind multipliers could improve the downscaling for the locations with large topographic variation. However, the current~~ <u>The</u> results ~~already~~ indicate that the wind multiplier method offers a pragmatic and computationally feasible tool for identifying at a high spatial resolution those locations having the highest forest wind damage risks. It can also be used to provide the necessary wind climate information for wind damage risk model calculations, thus making it possible to estimate the probability of predicted threshold wind speeds for wind damage and consequently the probability (and amount) of wind damage for certain forest stand configurations.

1 Introduction

The forest-based bioeconomy plays an important role in climate change mitigation (Kilpeläinen et al., 2016), and in a forested country like Finland, over 50% of the current bioeconomy there relies on the sustainable management and utilization of forest resources. In Scandinavia forest grow relatively slowly and it takes typically 50-100 years from forest cultivation to final
5 harvesting. During this long period the projected climate change (Ruosteenoja et al., 2016) may largely alter the growing conditions, and thus affect the survival and productivity of forests (Kellomäki et al., 2008; Bärring et al., 2017). For example, according to Bärring et al. (2017) in Scandinavia the vegetative growing period may extent by around one month by 2050 compared to current climate. A warming climate is expected to increase the volume of growing stock of Finnish forests due to increasing forest growth (see e.g. Kellomäki et al., 2008). However, warming is also expected to increase certain risks to
10 forests. Drought may have negative impacts especially in southern Finland for Norway spruce forests (Ruosteenoja et al., 2017; Kellomäki et al, 2008). Related to drought, forest fire danger will increase (Lehtonen et al., 2016b). During winter season heavy snow loads will decrease in southern but increase in northern Finland (e.g. Kellomäki et al., 2008, 2010; Peltola et al., 2010, Gregow et al., 2011; Lehtonen et al., 2016a, b). In the past few decades, wind storms have damaged a significant amount of timber and caused large economic and ecological losses in forestry from central to Northern Europe (Schelhaas et al., 2003;
15 Gregow, 2011, 2013; Reyer et al., 2017). In Finland, strong winds have damaged over 24 million m^3 of timber in different winter and summer storms since 2000 (e.g. Gregow, 2011; Zubizarreta-Gerendiain et al., 2016). During the coming decades, the risk of wind damage to forests is expected to increase, although the frequency and severity of the storms may not increase. (Nikulin et al., 2011; Pryor et al., 2012). This increase is due to the shortening of the frozen soil period, which currently improves tree anchorage during the windiest season of the year from late autumn to early spring (Peltola et al., 1999a;
20 Venäläinen et al., 2001; Kellomäki et al., 2010; Gregow et al., 2011).

In addition to the properties of wind (e.g. speed, direction, gustiness and their duration), the stand and site characteristics affect largely the vulnerability to wind damage (Peltola et al., 1999b; Gardiner et al., 2016). In Finnish conditions, mature stands adjacent to newly clear-cut areas or recently heavily thinned stands are especially vulnerable to wind damage (e.g., Laiho,
25 1987; Zubizarreta-Gerendiain et al., 2012). Risks to these forests may be decreased by proper forest management and planning for the spatial and temporal patterns of cuttings in forested areas (Tarp and Helles, 1997; Meilby et al., 2001; Zeng et al., 2004, 2007a; Heinonen et al., 2009; Zubizarreta-Gerendian et al., 2016). Several mechanistic models that have been built in recent decades allow the prediction of threshold wind speeds that can uproot or break trees under alternative forest stand configurations (e.g. Peltola et al., 1999b, 2010; Gardiner et al., 2000, 2008; Byrne and Mitchell, 2013; Seidl et al., 2014;
30 Dupont et al., 2015). Consequently, based on these predicted threshold wind speeds it will be possible to predict the probability (and amount) of wind damage based on local wind characteristics if sufficient knowledge about the local wind climate is available (e.g. Gardiner et al., 2008; Blennow et al., 2010; Zubizarreta-Gerendian et al., 2016).

An estimation of the frequency of extreme weather events, like extreme wind speeds, can be accomplished by utilizing extreme
35 value analyses (EVA) methods. These methods enable , making possible to fit their statistical distribution (e.g., Gumbel, Frechet or Weibull distribution) into observations that offer the best estimate of the occurrence probability of the most extreme values of the studied phenomena (e.g. Coles, 2001). The software package, Extremes Toolkit, developed by the National Center of Atmospheric Research (NCAR) is a widely used example of a tool that can be utilised to produce such a statistical distribution (Gilleland and Katz, 2011). For an accurate estimation of the probability of the occurrence of very extreme events
40 with long return periods (e.g., 50 to 100 years), observations over many decades are needed. Additional difficulty to gain an accurate estimation of return levels of extreme wind speeds and wind gusts is caused by a lack of homogeneous wind observation time series due to changes in the measuring conditions and instruments (Laapas and Venäläinen, 2017). One possibility of assessing the return levels of extreme wind speed in coarse resolution is to use reanalysed datasets (e.g., Dee et

al., 2011), which are produced by assimilating all available observations in a systematic way. The benefit of these data sets is that they offer consistent spatial and temporal resolution over several decades (and hundreds of variables). Reanalysed data sets are also relatively straightforward to handle from a processing standpoint. Although the quality of this data varies from location to location and from variable to variable, the scale of the magnitude of extreme wind for a coarse spatial scale can

5 indeed be estimated based on them (e.g., Brönniman et al., 2012). From the point of local effects, the ERA-Interim dataset has a relatively coarse spatial resolution of approximately 80 km and detailed spatial variation cannot be taken into account in such a coarse grid. As well, the continuous change in the availability of reliable observational data creates limitations and must be taken into account especially if trend analyses of a change of e.g. wind are made (Dee et al., 2011).

10 The high resolution spatial variation of extreme wind speed that is affected by topography and surface characteristics (e.g., Wieringa, 1986) can be considered by applying spatial statistical tools (e.g. Etienne et al., 2010; Jung and Schindler, 2015). Additionally, complex airflow models like WAsP (Mortensen, 2015) and WindSim (http://www.windsim.com/), typically applied for wind power potential predictions, can be used for this purpose. One example of exposure estimation is the Detailed Aspect Method of Scoring (DAMS), which takes into account the local wind climate, elevation, aspect and topographic

15 exposure (Quine and White, 1993; Hale et al., 2015). DAMS is used in the ForestGALES (http://www.forestry.gov.uk/forestgales) for estimating the probability of wind speeds that cause damage. GIS- based methods for mapping the most wind damage prone areas have also been introduced (e.g., Talkkari et al., 2000; Zeng et al., 2007b; Schindler et al., 2012; Ruel, 2002). A pragmatic and computationally very feasible approach to use to estimate the return levels of extreme wind speeds for large geographical areas with very high spatial resolution is the wind multiplier approach. In this

20 approach, regional wind speeds obtained, e.g., from the reanalysed data (or climate change scenario), are downscaled to local wind speeds to consider the local effects of land cover and topography (e.g. Jones et al., 2005; Cechet et al., 2012; Yang et al., 2014). By applying GIS-tools to detailed land-use data and digital elevation maps, it is also very straightforward to produce the required multipliers.

25 In this study, we evaluated the applicability of the wind multiplier approach for an estimation of the high-resolution (20 m) variability of extreme wind speeds in Finnish forested landscapes, employing CORINE- land use and high resolution digital elevation data. First we calculated the return levels of extreme wind speeds using the ERA-Interim reanalyses dataset to each coarse resolution grid box and for eight wind directions (cardinal and sub-cardinal). Based on the elevation data, the wind multiplier depicting the effect of orography on wind speed was processed. Likewise the multiplier depicting the effect of terrain

30 properties on wind speed was processed for each 20 m grid square. More specifically,Thereafter, wind multipliers were used to provide quantitative estimates of local wind conditions relative to the regional wind speeds in our 20 km x 20 km test area located in northern Finland and for 26 meteorological observing stations with various surface characteristics in different parts of the country, as well. The data processing was done using standard Python, QGIS, and ArcGis- software routines. The work was motivated by the fact that full-filling of the increasing needs of forest biomass for the growing forest-based bioeconomy

35 will require also increasing area of wood harvesting intensity in thinneding and clear cut final felling areas (Heinonen et al, 2017), thus potentially increasing the wind damage and other risks to these forests. Having reliable high-resolution information on extreme wind speeds expected over forested landscapes will enhance both forest management and planning. The method gives a detailed estimate of the exposure of forest to wind damage. However, it is good to notice that if the coarse resolution data that is been downscaled is biased, then the downscaled data will be biased too. For example, climate scenarios that often

40 contain biases must be bias corrected prior to downscaling.

2 Material and methods

2.1 The wind multiplier approach

The wind multiplier approach used here follows the one presented in AS/NZS 1170.2 (2011) and Yang et al. (2014), where terrain properties are taken into account when assessing local maximum wind speeds (see Eq. 1). The return level of regional maximum wind speed (V_R) in an open terrain at a 10 meter height is downscaled into site specific maximum wind speed (V_{site}) as follows:

$$V_{site} = V_R \times M_Z \times M_s \times M_h \times M_d \qquad (1)$$

Where the three wind multipliers used are the terrain/height multiplier (M_z), shielding multiplier (M_s) and topographic (hill-shape) multiplier (M_h). The impact of wind direction is taken into account using a fourth factor (M_d). In our study, we use a 20 m x 20 m grid, which is in line with the CORINE Land Cover 2012 dataset. It provides information on land cover and land use in 2012, and its changes from 2006 to 2012 (based on the European Gioland 2012 project). Our interest is forested landscape (including practically no buildings or other similar obstacles); therefore, the shielding factor was not considered. The return levels of winds speeds (V_R) were also defined separately for the eight cardinal and intercardinal wind directions. Thus, there was no need to calculate the direction multiplier (M_d).

2.2 Estimation of return level for regional maximum wind speeds

The regional scale return levels of maximum wind speeds were calculated using the ERA-Interim dataset (Dee et al., 2011) and the Generalized Extreme Value method (GEV) (e.g. Coles, 2001). This method estimated the 10-year return level of maximum wind speed as, for example, in inland Finland at below 12 ms^{-1} and on open sea at even around 24 ms^{-1} (Fig. 1). The values are given as grid box averages, each covering an area of $0.75° \times 0.75°$ and the time period used for the calculation of return levels covered years 1979-2015. The maximum wind speed dependence on wind direction was estimated by making the calculations wind direction wise (Fig. A1). The parameter we analysed was 10 minute instantaneous wind speed available with six hour interval. The GEV distribution is based on the block maxima approach, i.e. we have maximum values for the selected block, in our cases year, and the distribution is fitted to this data (Coles, 2001). In northern Europe like in Finland the cause for the high wind speeds vary from season to season. During summer the extreme wind speed values are typically associated with convective weather phenomena whereas during winter season they are caused by large synoptic scale wind storms. As we use only the annual maximum wind speed in the return level calculations we have not paid attention on the cause of the extreme wind speed.

2.3 Estimation of the impact of terrain roughness on maximum wind speeds

In AS/NZS 1170.2 (2011) for elevations below 50 m, 1000 m fetch was used when the surface roughness impact was estimated. In this study, we applied a somewhat different approach. First, each CORINE-land use class was interpreted to roughness lengths following the technique applied in the production of the Finnish Wind Atlas (Tammelin et al., 2013). We were interested in this work in very high resolution spatial variation of wind speed in typically highly variable terrain mosaic composed of forests, fields, lakes, clear cut areas etc. The detailed structure of wind flow in this kind of heterogeneous terrain is very complex (e.g. Dupont and Brunet, 2008). One dominant feature is rapid deceleration of wind when wind encounters forest edge. In Finnish conditions the main wind damage are found typically within one to two mean stand heights from the upwind forest edge (Peltola et al., 1999b). When estimating the impacts of upwind conditions on wind speed in the location that was of interest, we used 500 m fetch to calculate the effective roughness (z_{eff}). As the conditions close to the place of interest have a larger importance than the values at a further distance, each 20 m grid cell did have a weighting factor *(we)*, which was presumed to follow normal distribution (Eq. 2), having variance of 150 m. With these assumptions the weighting of each grid is as demonstrated in Fig. A2. The weight of the closest grid square is about 11 % and the furthest grid square

located 500 m upwind has the weight of only 0.04 %. With no doubt, this formula is a simplification of a very complex issue as the exact impact of roughness elements on wind flow depend, beside terrain properties also on the characteristics of prevailing air flow. However, when aiming in computationally light applications all these issues cannot be taken into account and the approach selected here gives a realistic interpretation of the complicated issue. ~~When estimating the impacts of upwind conditions on wind speed in the location that was of interest, we used 500 m fetch to calculate the effective roughness (z_{eff}). As the conditions close to the place of interest have a larger importance than the values at a further distance, each 20 m grid cell did have a weighting factor (we), which was presumed to follow normal distribution (Eq. 2).~~

$$we_i = \frac{1}{\sigma\sqrt{2\pi}}\, e^{-\frac{1}{2}\left(\frac{x_i-\mu}{\sigma}\right)^2} \qquad\qquad (2)$$

where σ is the variance defining the shape of distribution and in our case (150), x is the fetch, and μ is the location and in this case zero. Thus z_{eff} was calculated as

$$z_{eff} = \sum_{i=1}^{25}(we_i \times z_{oi}) \qquad\qquad (3)$$

where z_{0i} is the surface roughness length of ith ~~grid~~ 20 m grid ~~c~~cell. The final step to calculate the surface roughness dependent multiplier (M_z) was to use the estimates given in Tables 3.2 and 3.3 by Yang et al. (2014). This step led to an estimate given in Eq. 4.

$$M_z = -0.056\ln(z_{eff}) + 0.7715 \qquad\qquad (4)$$

The multiplier were defined for eight directions (cardinal and intercardinal), using the GDAL raster utility programs.

In ERA-Interim analyses, a roughness length for each grid cell is presumed. To normalize the roughness length of the ERA-Interim data into a reference roughness, we multiplied the ERA-Interim wind speed values by $1/M_z$ (Eq. 4), using the ERA-Interim grid cell roughness length as the value of z_{eff}.

The values of Z_0, Z_{eff} and M_z in the case of sharp roughness change between forest and lake are demonstrated in Fig. 2. When the wind comes from an open lake (z_0=0.0004 m) to dense forest (z_0=1.4 m), ~~then~~ the multiplier M_z changes from 1.21 to 0.75 within a distance of 300 m and to 0.80 within a distance of 80 m. The change is very rapid, demonstrating the strong slowing of wind speed within a dense forest during the first tens of meters. This rapid change is demonstrated in the case when the most vulnerable forest edges are studied; the wind throw risk is largest within approximately 20-30 m from the upwind edge of a clear cut area (e.g. Peltola et al. 1999b). The acceleration of wind speed from forest to open water surface is not as rapid as the slowing; the change of M_z from the minimum value of 0.75 to maximum takes about 500 m (Fig. 2). This rate of acceleration is quite close to the values introduced by Venäläinen et al. (1998). The land-use map and ~~T~~the values of Z_{eff} and M_z for the Pyhätunturi-fell area for northwesterly winds are given in Fig. A3~~.~~ and Fig A4, respectively.

2.4 Estimation of the impact of topography on maximum wind speeds

The topographic multiplier M_h was taken as the larger of the two estimates M_{h1} and M_{h2} (Eq. 5).

$$M_{h1} = 0.4343 \times \ln(H_{eff}) \qquad \text{for } M_{h1} < 1, M_{h1} = 1 \qquad\qquad (5a)$$

$$M_{h2} = 0.913 \times e^{0.0008H_{msl}} \qquad\qquad (5b)$$

M_{h1} simulates the impact of small scale topographic variation that is typical in Finland. H_{eff} is calculated as the difference between the place of interest and the median elevation of 1000 m distance upwind from the location of interest (see Fig. 3). The logarithmic shape follows that of logarithmic wind law in the case of surface roughness of one meter that is typical for a forest and wind speed 15 ms^{-1} at an elevation of 10 m. The other multiplier M_{h2} simulates the general increase of wind speed as a function of elevation. The shape of Eq. 5b is based on an estimate of the dependence of a 50- year return level of maximum wind speed on elevation, defined by using wind measurements made at observing stations located at different elevations (not

published). Finland is a rather flat country, and most of the country is located below an elevation of 200 meters above sea level. Multiplier M_{h2} is thus larger than M_{h1} at only very rare locations in the entire country. The topographic wind multiplier M_h was calculated using the digital elevation data obtained from the Finnish National Data Survey. The data was 25 m spatial resolution raster data re-sampled to 20 m resolution. The data was first smoothed by replacing each pixel with the average of its 3×3 neighborhood, ~~and done~~ to filter out the very small scale noisy features the data might contain. The processing was done by utilizing the R package 'raster'. H_{eff} was then calculated in the eight directions of the wind, using Python and the GDAL routine.

An example of the change of topographic multiplier in the case of a transection reaching over the roughly 500 m high Pyhätunturi (Fig. 5) fell in Northern Finland in case of north-westerly wind is given in Fig. 4 and Fig. A~5~4. As this place is located at a relatively high elevation, the purely on elevation dependent M_{h2} dominates, and only in the case of a steep hill slope around the location interval 11655 m-13405 m (Fig. ~5~4) does the multiplier M_{h1} get larger values than M_{h2}. The approach used in this study is also simpler than the one described in AS/NZS 1170.2 (2011). Still, as the terrain in Finland is relatively flat, the main impact of these relatively small scale topographic variations can be taken into account even with the schema utilized here.

2.5 Verification tests

The first verification tests were done by utilizing wind measurements made at 26 observing stations in Finland~;~ ~, and of these,~ 23 of these stations belong to the observation network maintained by the Finnish Meteorological Institute (FMI) and represent conditions ranging from open sea to agricultural land, forests, and open hill areas. More detailed analyses were made in Northern Finland (67.02204° lat, 27.2184° lon) for the Pyhätunturi –fell test area, with an elevation range of 148 – 526 m above sea level (Fig 5, Fig. A~3~2). In addition to the forests, other terrain types included open tundra, agricultural fields, lakes, and ski slopes. The test area had both larger topographic variation and spatial variation of wind speeds than the typical Finnish landscape and in that sense represented more challenging conditions than those expected in most of the rest of the country. This Pyhätunturi –fell test area was also used in the EU- funded MOWIE project, where three 10-m tall wind-measuring masts were installed at a range of elevations above the mean sea level: 470 m (MM1), 419 m (MM2) and 408 m (MM3). In addition, there was a permanent observing mast (FMI station number 7708) on the telecommunication mast (TM) at an elevation of 61 m above the surface at the top of the hill (see Fig. 5). All wind speed measurements were corrected to 10 meter high values by applying the logarithmic wind law. Wind climate simulations for this same area have earlier been made utilizing the Karlsruhe Mesoscale Model (KAMM) and WAsP by Frank et al. (1999). An airborne detailed photograph of the area is available e.g. from the Finish Land Survey's map service (https://asiointi.maanmittauslaitos.fi/karttapaikka/?lang=en).

Based on the measurements made at the observing stations, 10 year- return levels of maximum wind speeds were calculated for each location and compared with return period values obtained for the station locations using the wind multiplier approach and the ERA-Interim maximum wind speed estimates. The return levels were calculated using the same GEV approach as in the case of ERA-Interim data. The observations were 10 minute winds speed measured after every three hours and the annual maximum values was filtered from this data. In this sense the observational values are not exactly the same as reanalyzed data and this may create some systematic difference. However, when using the annual maximum values as the bases for fitting the distribution this may reduce the bias. For stations MM1, MM2 and MM3, there was only two years of data available, a short period to estimate even 10-year return levels. Therefore, to have the extreme value analysis be as robust as possible, for these stations, we applied the Block Maxima approach (e.g., Coles, 2001) to the monthly maximum values, using the R package extRemes (Gilleland and Katz, 2016). For most of the other station locations, the data used for the extreme value analyses covered the years 1979-2015 that is the same period as used in case of ERA-Interim data.

For the Pyhätunturi –fell area, we also compared a spatial variation of high wind speed as simulated by the WAsP- package with a wind multiplier downscaled wind. The area was slightly smaller (Fig. 5) due to the availability of terrain information needed for a WAsP simulation. In the WAsP simulation, the geogstrophic wind speed was expected to be 39 ms^{-1} from north-

5 west. This geogstrophic wind speed leads to approximately 26 ms^{-1} winds at the top of the Pyhätunturi –fell, which is roughly the 10-year return level maximum wind speed (see Table 1). For a comparable wind multiplier downscaling, the coarse scale north-westerly wind 12.7 ms^{-1} was used as the basis in the calculation. In this way the maximum wind speed was the same in both simulations.

3 Results

10 **3.1 Comparison of measurement-based return levels to those based on a wind multiplier approach**

A comparison of the ERA-Interim and wind multiplier- based assessment of 10-year return levels of wind speed to the estimates based on measurements for the test locations (Table 1, Fig. 6) revealed that for these locations and representing different kinds of terrain and elevations, the wind multiplier approach improved the local wind speed return level estimates remarkably (R^2 = 0.7~~6~~66). There was ~~also no clear~~a small bias in the estimates, the mean difference being -1.2 ~~0.13~~ ms[-1] and the RMSE error

15 4.09~~3.31~~ ms[-1]. According to the comparison, the wind multiplier approach tends to underestimate the wind speed on station located at small Baltic Sea islands, i.e. according to the measurements there is less deceleration of wind speed on these island than predicted by the method (Fig. 6). This indicates that the method exaggerates the impact of change of surface roughness on wind speed in these rather specific conditions. As we are interested in inland and mainly forested landscape, this is not a crucial issue. However, further development of the method is needed in order to be able to simulate also the coastal and island

20 conditions. The largest differences were found in the case of Station No. 9004, which is located at an elevation of 1004 m above sea level, i.e. almost at the highest point in Finland. The anemometer at this station is also located at the edge of a steep slope, thus leading to a high topographic multiplier value.

At the four Pyhätunturi -fell stations, the wind multiplier estimates were close to the measurement- based estimates with the

25 exception of Station MM1. The estimate based on measurements made at MM1 (29.6 ms^{-1}) was ~~almost~~ about 5~~7~~ ms[-1] higher than the return level estimate calculated for the telecom mast at the same height ~~(the TM value at an elevation of 61 m was roughly the same as the value at Station MM1)~~. The difference between MM1 and MM2 was about 3 ms^{-1}. The return level estimates for Stations MM1, MM2 and MM3 were based on two years of measurements and led also to a high degree of uncertainty. For example, for Station MM1, the estimated 95% confidence levels were 23.1 ms^{-1}… 36.1 ms^{-1}. The

30 corresponding estimate of the telecom tower based on 19~~0~~ years of measurements was more robust with 95% confidence levels, i.e., 21.5~~8~~ ms[-1]… 2~~7~~4.6~~7~~ ms[-1].

3.2 Spatial variation of maximum wind speeds

The spatial variation of 10-year return levels of wind speeds within the roughly 4000 km[2] Pyhätunturi test area was large. The lowest values for the 10-year return level were around 9.2 ms^{-1} and the highest on top of the Pyhätunturi-fell were

35 approximately 26.5 ms^{-1} (Fig. 7). A crude approximation indicates that mean 10 min wind speed exceeding 12 ms^{-1} can uproot or break a tree during unfrozen soil conditions (Peltola et al., 1999b; Zubizarreta-Gerendiain et al., 2012). When we looked at the spatial variation of a 10-year return level of wind speed inside the test area, we can see areas having wind speeds higher than the threshold of 12 ms^{-1} found on local topographic formations, at the edges of open terrain, and at high elevation locations. At a total 23.8% of grid squares, the 10-year return level wind speed reaches the threshold and if we look only at the forested

40 area, then we end up with 22.8 %. This statistic means that approximately 20% of the area is exposed to wind speeds that can

lead to forest damage. The exact value depends, however, on several factors including tree and stand characteristics. The next step is to use a wind-throw risk models like e.g. HWIND (Peltola et al., 1999b) to simulate the threshold wind speeds needed for wind damage and further to estimate the probability of occurrence of such winds and the amount of damage, respectively. Unfortunately, in this work we do not have available the needed forest inventory data for the test area enabling the simulations.

5 However, this work will be done in future studies using forested areas with sufficient data.

In a qualitative comparison, the wind multiplier approach and a WAsP simulation produced the same dominant features of spatial variation of maximum wind speed; maximum values were found at treeless fell-top areas (Fig. 8). One interesting feature was the case of the WAsP- simulation for the acceleration of wind at the forest-lake edge; it was immediate, and so

10 was the deceleration on the opposite shore. In such a case of wind multiplier simulation, the impact of roughness change is reflected a longer distance, as can be seen in the case of the Lake Pyhäjärvi. On top of the fell, the wind speed was adjusted to approximately the same 26 ms^{-1}. On the lee side of the top of the fell, the wind multiplier simulations indicated a more rapid deceleration of wind speed than WAsP, while on the side to windward, the wind multiplier gave higher wind speeds. With no proper measurements, we could not decide which reflected the real conditions better. In the case of canyons like Pyhäkuru and

15 Pikkukuru (Fig. 8) WAsP is more capable of predicting higher wind speed values than the wind multiplier and obviously reflect the prevailing conditions better. For most of the lower elevation areas, the difference between the two simulations was small, and with these input wind speeds, the prevailing difference is on the scale of 1 ms^{-1}; wind multiplier giving systematically higher wind speeds (Fig. A65). By scaling wind multiplier input wind speed lower the bias could have been adjusted to zero.

4 Discussion and conclusions

20 ### 4.1 Reliability of tested method

The wind multiplier method has been used earlier to estimate the design values of buildings and other constructions (AS/NZS 1170.2, 2011) and assessment of wind damage risk (Yang et al., 2014). Based on our study, the wind multiplier method is very capable of identifying the locations having the highest extreme wind speeds in Finnish conditions. This is true despite the fact that this approach is much simpler than the dynamical models. The method seem to underestimate wind speeds at small islands

25 located on open sea and this issue has to be taken into account in case high spatial resolution assessment of extreme wind speeds are calculated to such conditions. The wind multiplier approach is also easily transferable to any location with needed terrain information and is an interesting and easily applicable alternative to use to assess the exposure of terrain.

How precise each grid square estimate is depends on several external factors. First, we must have an estimate of the coarse

30 scale return levels of the extreme wind speeds. Reanalysed data gives such a coarse estimate. If the reanalysed data is compared to in situ measurements in certain wind storm event, it is easy to find large differences between them. As well, the return levels of wind speed calculated using ERA-Interim grid values can be quite different from the value based on point measurements, but downscaling the grid value to the point using the wind multiplier approach improves the estimate substantially, as we demonstrated in Fig. 6. It is also good to remember that although the wind measurements made at meteorological stations can

35 go through several quality control steps, they msy still may contain erroneous values. FMI has a three stage quality control system. First check is done at the observation station site checking the main instrument malfunctions. The next check is done before storing the data to database. This check includes e.g. comparison with the extreme values and temporal and spatial consistency. The final step is the manual quality control for those values that did not pass earlier steps. The quality control ensures that the values stored in database are realistic and can have occurred. However, quality control does not guarantee that

40 the measurements are exactly correct. As well, quality control does not ensure the homogeneity of observations. The changes at measuring site and changes in instrumentation as well as, the changes of the height of anemometer installation can lead to

11

discontinuations, break points, in observational time-series. These break points are relatively common also in wind observational time series like studied by Laapas and Venäläinen (2017). ~~As well, the measured values used here have not been homogenized, and e.g., changes in anemometer location and terrain properties may influence the values.~~ In that sense the return periods based on measured values (Table 1, Fig. 6) contain ~~several~~ uncertainties that are wise to remember when the comparison is fully valued.

The simple visualization and comparison of the spatial variation in wind speed at Pyhätunturi –fell was done by applying WAsP and, on the other hand, by applying wind multipliers. These demonstrate that the main features of spatial variation of an extreme wind field produced by these two different methods are very similar. A profound analysis on the exact accuracy of the simulations is not possible, however, based on the available measurements; it would require much more detailed and reliable wind measurement data. However, by fine- tuning the wind multipliers, it is possible to achieve results that are closer to WAsP simulation. Pyhätunturi is not a typical Finnish forested landscape due to its high topographic variation. In those parts of the test area that exemplify a more typical landscape with only relatively small topographic features these two methods give quite similar results. It is also good to remember, that as we are summarizing all wind directions (Fig. 7) the importance of lee -side wind simulation accuracy is not as crucial as having accuracy for the windward size having the highest wind speeds.

The wind multiplier method itself is also relatively easy to apply. The calculation of surface roughness and topographic multipliers can be done using routine GIS tools, and these calculations can be done for large areas like, e.g., the whole country. Similarly, this method could be used to assess the risks to forests that are related to forest management and planning with relatively little extra effort. Further, climate change impact assessments can be done with high spatial resolution when the return levels of maximum wind speed are calculated using climate scenarios instead of only reanalyzed data.

One challenge of the method is the accuracy of surface roughness information in the CORINE-dataset; it is updated approximately every six years and thus does not represent real-time land use conditions for all locations. For example, forest clear-cutting changes the roughness conditions very dramatically. Thinning affects it less. More frequent updates to surface conditions could be obtained from satellite measurements. As an example, the European Space Agency's (ESA) satellite Sentinel-2 (http://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Sentinel-2) is producing high spatial resolution, at best 10 m, data describing the earth surface properties. Because of the development of satellite-measured data handling methods, the data can provide new possibilities for updating the surface state with a higher frequency than, e.g., the CORINE-data is updated. Use of up- to -date airborne laser scanning data, if available (e.g., Kotivuori et al., 2016), can also offer a viable means to provide very detailed information on forest properties and thus also offer information on surface roughness conditions.

4.2 Conclusions

The rapidly growing, forest-based bioeconomy calls- for increasing wood harvesting intensity, which means an increase in thinning and a final felling area. This ~~circumstance~~ will increase the wind damage risks <u>to forests</u> especially at the upwind edges of new clear~~ed~~ felling areas and <u>in recently</u> thinned stands that have not yet been acclimated to increasing wind loading. Thus proper risk assessment is a clear pre-condition for a sustainable forest-based bioeconomy. This study demonstrate<u>d</u>~~s~~ a useful tool to use for forest management and planning.

12

The tested wind multiplier method is very capable of identifying the locations (at high-resolution) having the highest extreme wind speeds and could well support the precise assessment of wind damage risks to forests. It can also be used to provide needed wind climate information for wind damage risk model calculations,. tThus, it would make ing it possible to estimate the probability of predicted threshold wind speeds for wind damage, and consequently the probability (and amount) of wind damage under certain forest stand configurations. Accurate estimation of the spatial variation of the return levels of extreme wind speed with very high spatial resolution over the whole country or even over larger areas like Fennoscandia are possible in the future using this approach. A high resolution estimation of climate change impacts on forest wind damage risks to forests is also feasible using this approach.

References

AS/NZS 1170.2:. Structural design actions, Part 2: Wind actions, Australian/New Zealand Standard, 2011.

Blennow, K., Andersson, M., Sallnäs, O., and Olofsson, E.: Climate change and the probability of wind damage in two Swedish forests. For. Ecol. Manag., 259, 818–830, doi:10.1016/j.foreco.2009.07.004, 2010.

Brönnimann, S., Martius, O., von Waldow, H., Welker, C., Luterbacker, J., Compo, G.P., Sardeshmukh, P.D., and Usbeck, T.: Extreme winds at northern mid-latitudes since 1871, Meteorol. Z., 21(1), 13–27, doi:10.1127/0941-2948/2012/0337, 2012.

Byrne, K., and Mitchell, S.: Testing of WindFIRM/ForestGALES-BC: a hybrid- mechanistic model for predicting windthrow in partially harvested stands. Forestry, 86, 185–199, doi:10.1093/forestry/cps077, 2013.

Bärring, L., Berlin, M., and Gull B.A.: Tailored climate indicators for climate-proofing operational forestry applications in Sweden and Finland, Int. J. Climatol., 37, 123-142, 2017.

Cechet, R., Sanabria, L., Divi, C., Thomas, C., Yang, T., Arthur, W., Dunford, M., Nadimpalli, K., Power, L., White, C., Bennett, J., Corney, S., Holz, G., Grose, M., Gaynor, S., and Bindoff, N.: Climate Futures for Tasmania: Severe wind hazard and risk technical report. GA Record 2012/43, 2012.

Coles, S.: An introduction to statistical modeling of extreme values. Springer-Verlag, Lontoo. 204 pp., 2001.

Dee, D., Uppala, S., Simmons, A., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hersbach, H., Hólm, E., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A., Monge-Sanz, B. M., Morcrette, J., Park, B., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N., and Vitart, F.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Quart. J. R. Meteorol. Soc., 137, 553– 597, 2011.

Dupont, S., and Brunet, Y.: Impact of forest edge shape on tree stability: a large-eddy simulation study, Forestry, 81(3), 299-315, doi:10.1093/forestry/cpn006, 2008.

Dupont, S., Ikonen, V.-P., Väisänen, H., and Peltola, H.: Predicting tree damage in fragmented landscapes using a wind risk model coupled with an airflow model. Can. J. For. Res., 5, 1065–1076, doi: 10.1139/cjfr-2015-0066, 2015.

Etienne, C., Lehman, A., Goyette, S., Lopez-Moreno, J.I., and Beniston, M.: Spatial Predictions of Extreme Wind Speeds over Switzerland Using Generalized Additive Models. J. Appl. Meteorol. and Climatol., 49(9), 1956-1970, 2010

Frank, H., Petersen, E., Hyvönen, R., and Tammelin, B.: Calculation on the wind climate in Northern Finland: The importance of inversion and roughness variations during the season. Wind Energy, 2, 113-123, 1999.

Gardiner, B., Peltola, H., and Kellomäki, S.: Comparison of two models for predicting the critical wind speeds required to damage coniferous trees. Ecol. Model. 129,1-23, 2000.

Gardiner, B.A., Byrne, K., Hale, S., Kamimura, K., Mitchell, S.J., Peltola, H., and Rue, J.C.: A review of mechanistic modelling of wind damage risk to forests. Forestry, 81(3), 447–463, doi: 10.1093/forestry/cpn022, 2008.

Gardiner, B., Berry P., and Moulia, B.: Review: Wind impacts on plant growth, mechanics and damage. Plant Science, 245, 94–118, doi: 10.1016/j.plantsci.2016.01.006, 2016.

Gilleland, E. and Katz, R. W.: New software to analyze how extremes change over time. Eos, 92.2., 13—14, 2011.

Gilleland, E. and Katz, R. W.: extRemes 2.0: An Extreme Value Analysis Package in R. Journal of Statistical Software, 72(8), 1-39, doi:10.18637/jss.v072.i08, 2016.

Gregow, H: Impacts of strong winds, heavy snow loads and soil frost conditions on the risks to forests in Northern Europe. Finnish meteorological Institute Contributions, 94:178 pp., 2013.

Gregow, H., Peltola, H., Laapas, M., Saku, S., and Venäläinen, A.: Combined occurrence of wind, snow loading and soil frost with implications for risks to forestry in Finland under the current and changing climatic conditions. Silva Fennica, 45(1), 35–54, doi: 10.14214/sf.30, 2011.

Hale, S., Gardiner, B., Peace, A., Nicoll, B, Taylor, P., and Pizzirani, S.: Comparison and validation of three versions of a forest wind risk model. Environ. Modell. Software, 68, 27-41, http://dx.doi.org/10.1016/j.envsoft.2015.01.016, 2015.

Heinonen, T., Pukkala, T., Ikonen, V-P., Peltola, H., Venäläinen, A., and Dupont, S.: Integrating the risk of wind damage into forest planning. For. Ecol. Manage., 258, 1567–1577, doi:10.1016/j.foreco.2009.07.006, 2009.

Heinonen, T., Pukkala, T., Mehtätalo, L., Asikainen, A., Kangas, J., and Peltola, H.: Scenario analyses for the effects of harvesting intensity on development of forest resources, timber supply, carbon balance and biodiversity of Finnish forestry, For. Policy Econ., 80, 80-98, 2017.

Jones, T., Middelmann, M., and Corby, N. (eds.): Natural hazard risk in Perth, Western Australia, Comprehensive Report, Geoscience Australia, 352 p., 2005.

Jung, C. and Schindler, D.: Statistical Modeling of Near-surface Wind Speed: A Case Study from Baden-Wuerttemberg (Southwest Germany). Austin J Earth Sci., 2(1), 1-11, 2015.

Kellomäki, S., Peltola, H., Nuutinen, T., Korhonen, K., and Strandman, H.: Sensitivity of managed boreal forests in Finland to climate change, with implications for adaptive management. Phil. Trans. R. Soc. B, 363, 2341–2351, 2008.

Kellomäki, S., Maajärvi, M., Strandman, H., Kilpeläinen, A., and Peltola, H.: Model computations on the climate change effects on snow cover, soil moisture and soil frost in the boreal conditions over Finland. Silva Fennica, 44(2), 213–233, 2010.

Kilpeläinen, A., Torssonen, P., Strandman, H., Kellomäki, S., Asikainen, A., and Peltola, H.: Net climate impacts of forest biomass production and utilization in managed boreal forests. GCB Bioenergy, 8, 307–316, 2016.

Kotivuori, E., Korhonen, L., and Packalen, P.: Nationwide airborne laser scanning based models for volume, biomass and dominant height in Finland. Silva Fennica, 50(4), http://dx.doi.org/10.14214/sf.1567, 2016.

Laapas, M. and Venäläinen, A.: Homogenization and trend analysis of monthly mean and maximum ~~time series of~~ wind speed time series in Finland, 1959-2015. Int. J. ~~Climatol.~~ Climatol., DOI:10.1002/joc.5124, ~~(submitted)~~, 2017~~6~~.

5   Laiho, O. :Metsiköiden alttius tuulituhoille Etelä-Suomessa. Folia For., 706, 1–24 (Susceptibility of forest stands to wind throw in Southern Finland. In Finnish with English summary), 1987.

Lehtonen, I., Kämäräinen, M., Gregow, H., Venäläinen, A., and Peltola, H.: Heavy snow loads in Finnish forests respond regionally asymmetrically to projected climate change, Nat. Hazards Earth Syst. Sci., 16, 2259-2271, doi:10.5194/nhess-16-2259-2016, 2016a.

10 Lehtonen, I., Venäläinen, A., Kämäräinen, M., Peltola, H., and Gregow, H.: Risk of large-scale forest fires in boreal forests in Finland under changing climate. Nat. Hazards Earth Syst. Sci., 16, 239-253, doi:10.5194/nhess-16-239-2016, 2016b.

Meilby, H., Strange, N. and Thorsen B.J.: Optimal spatial harvest planning under risk of windthrow. For. Ecol. Manag., 149(1–3),15–31, 2001.

Mortensen, N. G.: Planning and Development of Wind Farms: Wind resource assessment using the WAsP software. DTU
15 Wind Energy. (DTU Wind Energy E; No. 70(ed.2)), 2015.

Nikulin, G., Kjellström, E., Hansson, U., Strandberg, G. and Ullerstig, A.: Evaluation and projections of temperature, precipitation and wind extremes over Europe in an ensemble of regional climate simulations. Tellus, 63a, 41-55, DOI: 10.1111/j.1600-0870.2010.00466.x, 2011.

20 Peltola, H., Kellomäki, S., and Väisänen, H.: Model computations on the impact of climatic change on the windthrow risk of trees. Clim. Change 41: 17–36, 1999a.

Peltola H, Kellomäki S, Väisänen H., and Ikonen V-P.: A mechanistic model for assessing the risk of wind and snow damage to single trees and stands of Scots pine, Norway spruce and birch. Can. J. For. Res., 29, 647–661, 1999b.

Peltola H., Ikonen, V-P., Gregow, H., Strandman, H., Kilpeläinen, A., Venäläinen, A., and Kellomäki, S.: Impacts of
25 climate change on timber production and regional risks of wind-induced damage to forests in Finland. For. Ecol. Manage., 260(5), 833-845, 2010.

Pryor, S., Barthelmie, R., Clausen, N., Drews, M. MacKellar, N. and Kjellström, E.: Analyses of possible changes in intense and extreme wind speeds over northern Europe under climate change scenarios. Clim. Dyn., 38(1-2), 189-208, DOI: 10.1007/s00382-010-0955-3, 2012.

30 Quine, C.and White I.: Revised Windiness Scores for the Windthrow Hazard Classification: the Revised Scoring Method. Edinburgh, UK: Forestry Commission; 1993. Forestry Commission Research Information Note 230, 1993.

Reyer, C., Bathgate, S., Blennow, K., Borges, J., Bugmann, H., Delzon, S., P Faias, S., Garcia-Gonzalo, J., Gardiner, B., Gonzalez-Olabarria, R.M., Gracia, C., Hernández, J.G., Kellomäki, S., Kramer, K., Lexer, M.J., Lindner, M., van der Maaten, E., Maroschek, M., Muys, B., Nicoll, B., Palahi, M., Palma, J.H.N., Paulo, J.A., Peltola, H., Pukkala, T., Rammer,
35 W., Ray, D., Sabaté, S., Schelhaas, M.-J., Seidl, R., Temperli, C., Tomé, M., Yousefpour, R., Zimmermann, N.E., Hanewinkel, M.: Are forest disturbances amplifying or canceling out climate change-induced productivity changes in European forests? Environmental Research Letters, 12:034027 https://doi.org/10.1088/1748-9326/aa5ef1, 2017.

Ruel, J.-C., Mitchell, S. and Dornier, M.: A GIS based approach to map wind exposure for windthrow hazard rating. NJAF 19(4), 183-187, 2002.

Ruosteenoja, K., Jylhä, K., Kämäräinen, M.: Climate projections for Finland under the RCP forcing scenarios. Geophysica, 51(1-2), 17-50, 2016.

Ruosteenoja, K., Markkanen, T., Venäläinen, A., Räisänen, P., Peltola, H.: Seasonal soil moisture and drought occurrence in Europe in CMIP5 projections for the 21st century. Climate Dynamics, doi: 10.1007/s00382-017-3671-4, 2017.

Schelhaas, M–J., Nabuurs, G-J., and Schuck, A.: Natural disturbances in the European forests in the 19th and 20th centuries. Global Change Biol., 9, 1620–1633, 2003.

Schindler, D., Grebhan, K., Albrecht, A., Schönborn, J., Kohnle, U.: GIS-based estimation of the winter storm damage probability in forests: a case study from Baden-Wuerttemberg (Southwest Germany). Int. J. Biometeorol,, 56, 57–69, 2012

Seidl, R., Rammera, W., and Blennow, K.: Simulating wind disturbance impacts on forest landscapes: Tree-level heterogeneity matters. Environ. Modell. Software, 51, 1–11, 2014.

Talkkari, A., Peltola, H., Kellomäki, S. ,and Strandman, H.: Integration of component models from tree, stand and regional levels to assess the risk of wind damage at forest margins. Special Issue Wind and other abiotic risks to forests, For. Ecol. Manage., 135(1-3), 303-313, 2000.

Tammelin, B., Vihma, T., Atlaskin, E., Badger, J., Fortelius, C., Gregow, H., Horttanainen, M., Hyvönen, R., Kilpinen, J., Latikka, J., Ljungberg, K., Mortensen, N. G., Niemelä, S., Ruosteenoja, K., Salonen, K., Suomi, I., and Venäläinen, A.: Production of the Finnish Wind Atlas. Wind Energ., 16, 19–35, doi:10.1002/we.517, 2013.

Tarp, P. and Helles, F.: Spatial optimisation by simulated annealing and linear programming. Scand. J. of For. Res., 12, 390–402, doi:10.1080/02827589709355428, 1997.

Venäläinen, A., Heikinheimo, M., and Tourula, T.: Latent heat flux from small sheltered lakes. Boundary Layer Meteorol., 86:3, 355-377, 1998.

Venäläinen, A., Tuomenvirta, H., Heikinheimo, M., Kellomäki, S., Peltola, H., Strandman, H., and Väisänen, H.: The impact of climate change on soil frost under snow cover in a forested landscape. Climate Research, 17, 3-72, 2001.

Wieringa, J. : Roughness-dependent geographical interpolation of surface wind speed averages. Q.J.R. Meteorol. Soc., 112: 867–889. doi:10.1002/qj.49711247316, 1986.

Yang, T., Nadimpalli, K., and Cechet, R.P.: Local wind assessment in Australia: computation methodology for wind multipliers. Record 2014/33, Geoscience Australia, Canberra, http://dx.doi.org/10.11636/Record.2014.033, 2014.

Zeng, H., Peltola, H., Talkkari, A., Venäläinen, A., Strandman, H., Kellomäki, S., and Wang, K.: Influence of clear-cutting on the risk of wind damage at forets edges. For. Ecol. Manage., 203, 77-88, Doi: 10.1016/j.foreco.2004.07.057, 2004.

Zeng, H., Pukkala, T., and Peltola, H.: The use of heuristic optimisation in risk management of wind damage in forest planning. For. Ecol. Manag. 241, 189–199, doi:10.1016/j.foreco.2007.01.016, 2007a.

Zeng, H., Talkkari, A., Peltola, H., and Kellomäki, S.: A Gis-based decision support system for risk assessment of wind damage in forest management. Environ. Modell. Software, 22,1240-1249, 2007b.

Zubizarreta-Gerendiain, A., Pellikka, P., Garcia-Gonzalo, J., Ikonen, V-P., and Peltola, H.: Factors affecting wind and snow damage of individual trees in a small management unit in Finland: Assessment based on inventoried damage and mechanistic modelling. Silv. Fenn., 46(2), 181–196, doi:10.14214/sf.441, 2012.

Zubizarreta Gerendiain A., Pukkala T. and Peltola H.: Effects of wind damage on the optimal management of boreal forests under the current and changing climatic conditions. Can. J. For. Res., 2016 (in Press).

Table 1. 10-year return levels of maximum wind speed (ms⁻¹) as estimated directly from ERA -Interim data, downscaled to station locations using the wind multiplier approach, and calculated based on measurements for the station locations given in Fig.5. The observations are corrected to represent 10 m wind speed by applying logarithmic wind profile. The other variables

5 included are the wind multipliers (M$_z$, M$_{h1}$, M$_{h2}$), surface roughness, sStation elevation above sea level (H$_{msl}$m) and local topography (H$_{eff}$) and estimated direction of strongest winds (Dir.).has been included into the table.

Observation period	Station number	Elevation (m)	ERA-Interim (ms⁻¹)	Wind multiplier (ms⁻¹)	Observations (ms⁻¹)
1979-2015	1	1	20.0	17.1	15.6
"	2	9	19.7	16.6	21.5
"	3	8	20.0	17.3	22.3
"	11	11	20.0	17.3	17.7
"	101	5	20.1	16.7	21.8
"	103	6	16.9	20.1	12.3
"	301	51	17.7	15.4	16.2
"	302	10	19.1	14.8	20.1
"	1201	104	16.0	12.4	12.7
"	2710	93	13.7	12.6	12.8
"	3601	99	13.8	12.6	14.1
"	3801	121	13.6	12.7	12.1
"	6801	264	13.9	14.1	12.8
"	8601	240	13.5	14.6	18.7
"	9003	480	19.9	22.6	21.6
"	9603	107	18.7	14.8	20.1
"	9705	121	15.1	12.5	16.5
1997-2015	7708(TM)	491	12.3	22.8	24.5
"	8307	760	14.4	29.1	33.4
"	8308	565	14.4	23.1	23.9
"	8607	437	14.1	20.7	22.2
"	9004	1003	19.9	44.0	33.9
2003-2015	8312	347	14.4	17.4	13.6
2008-2010	7708(MM1)	470	12.3	22.5	29.6
"	7708(MM2)	419	12.3	23.8	26.2
"	7708(MM3)	408	12.3	19.9	22.2

Station number	ERA InterimERA-Interim	Wind multiplier	Measure-ments	z$_{eff}$	M$_z$	H$_{msl}$	H$_{eff}$	M$_{h1}$	M$_{h2}$	Dir.
1	20.0	18.4	15.6	0.07	0.920	1	10	1.000	0.914	s
2	19.7	17.3	21.0	0.16	0.874	9	10	1.000	0.920	sw
3	20.0	20.5	21.0	0.01	1.029	8	10	1.000	0.919	s
11	20.0	16.9	17.3	0.27	0.845	11	10	1.000	0.921	sw
101	20.1	22.6	21.8	0.2	0.862	5	20	1.301	0.917	nw
103	16.9	13.8	14.0	0.44	0.817	6	10	1.000	0.917	s
301	17.7	17.6	15.9	0.02	0.991	51	10	1.000	0.951	sw
302	19.1	18.2	20.1	0.5	0.810	10	15	1.176	0.920	w
1201	16.0	14.4	12.4	0.1	0.900	104	10	1.000	0.992	sw
2710	13.7	12.5	12.8	0.08	0.913	93	10	1.000	0.984	s

3601	13.8	13.7	14.1	0.02	0.991	99	10	1.000	0.988	nw
3801	13.6	13.2	12.1	0.03	0.968	121	10	1.000	1.006	se
6801	13.9	15.2	12.8	0.03	0.968	264	10	1.000	1.128	w
7708(TM)	12.3	22.0	22.6	0.18	0.868	491	116	2.064	1.352	e
7708 (MM1)	12.3	22.3	29.6	0.19	0.865	470	130	2.100	1.330	e
7708 (MM2)	12.3	24.4	26.2	0.1	0.900	419	160	2.200	1.277	e
7708 (MM3)	12.3	22.0	22.2	0.05	0.939	408	80	1.900	1.265	e
8307	14.4	30.9	34.8	0.076	0.916	760	220	2.342	1.677	sw
8308	14.4	25.8	24.7	0.049	0.940	565	80	1.903	1.435	ne
8312	14.4	17.4	15.0	1.39	0.753	347	40	1.602	1.205	sw
8601	13.5	17.1	18.7	0.0004	1.210	240	11	1.041	1.106	n
8607	14.1	24.7	23.2	0.128	0.887	437	97	1.987	1.295	sw
9003	19.9	21.8	19.7	0.44	0.817	480	10	1.000	1.340	s
9004	19.9	45.6	33.9	0.06	0.929	1003	294	2.468	2.037	sw
9603	18.7	22.1	21.0	0.26	0.847	107	25	1.398	0.995	nw
9705	15.1	12.2	16.5	0.53	0.807	121	10	1.000	1.006	nw
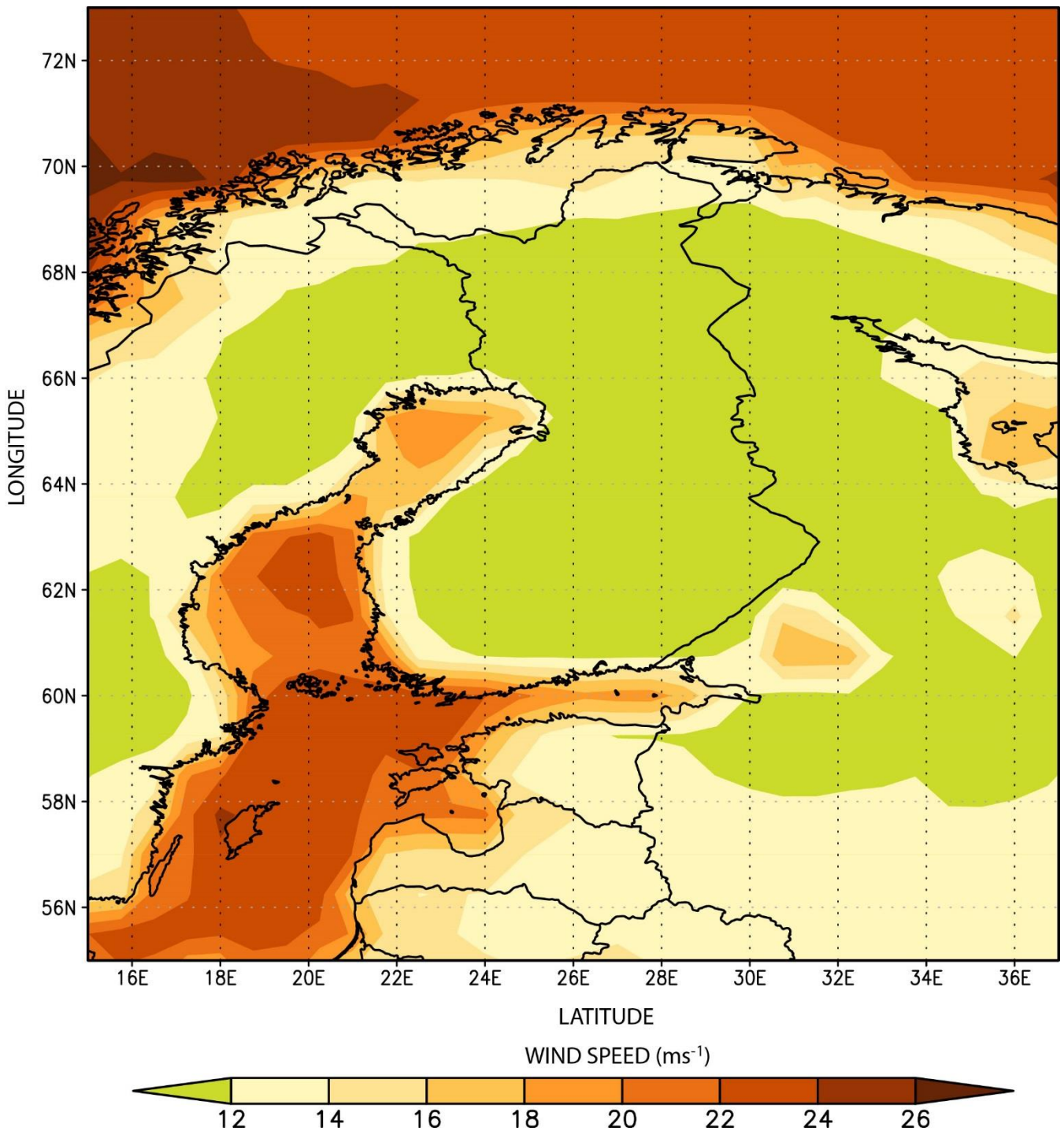
Figure 1: 10 –year return level of maximum wind speed calculated using ~~ERA Interim~~ERA-Interim 1979-2015 data and the GEV-analysing approach.
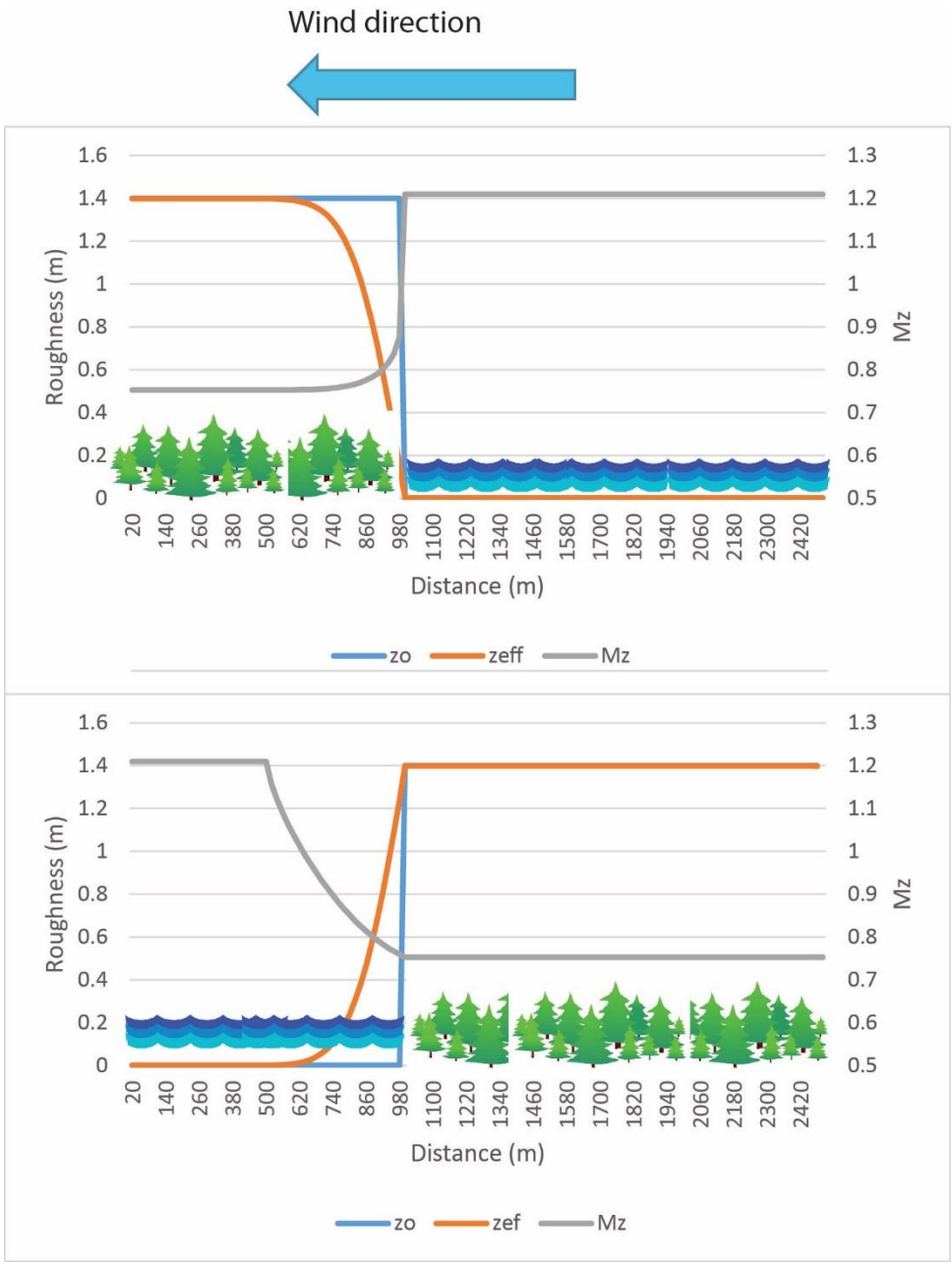
Figure 2: The value of surface roughness lengths z_0 and z_{eff} and the surface roughness dependent wind multiplier (M_z) in cases where wind is from lake to forest (upper figure) and from forest to lake (lower figure).

5
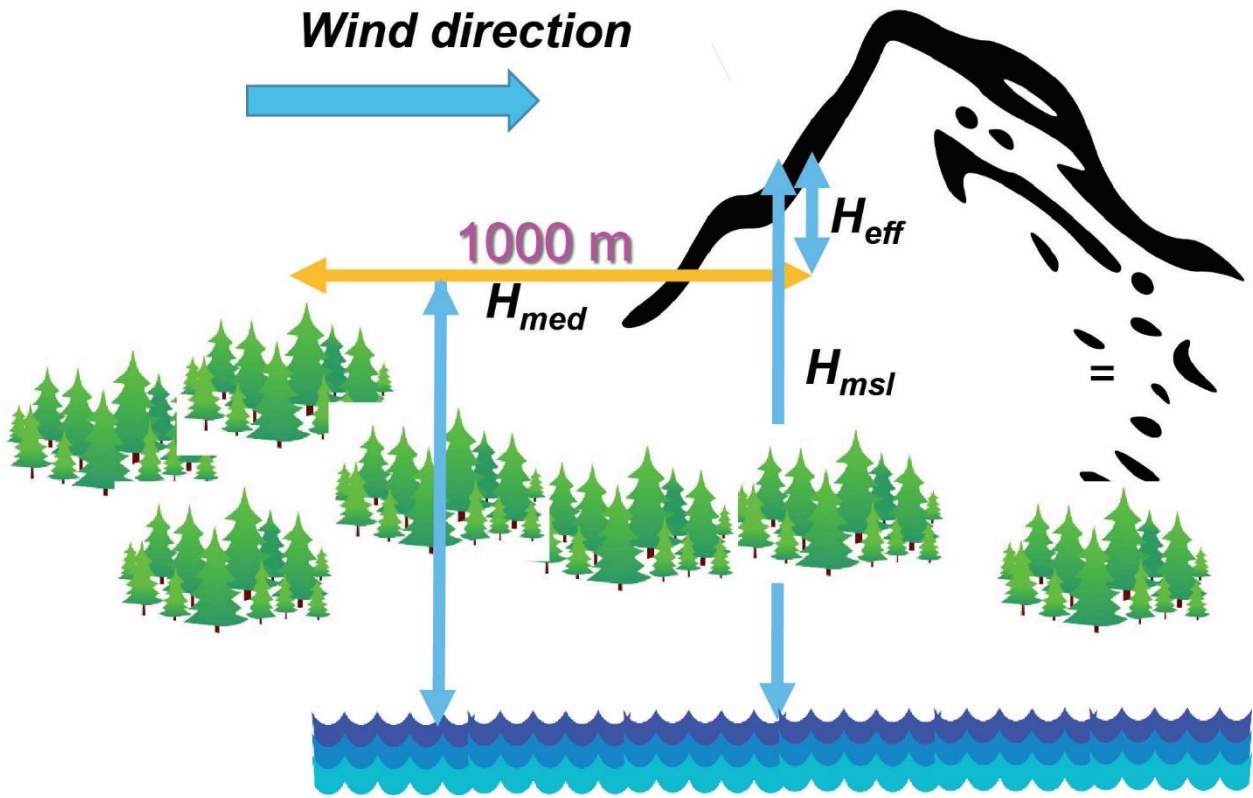
Figure 3: A visualization of the calculation of the topographic multiplier M_h.
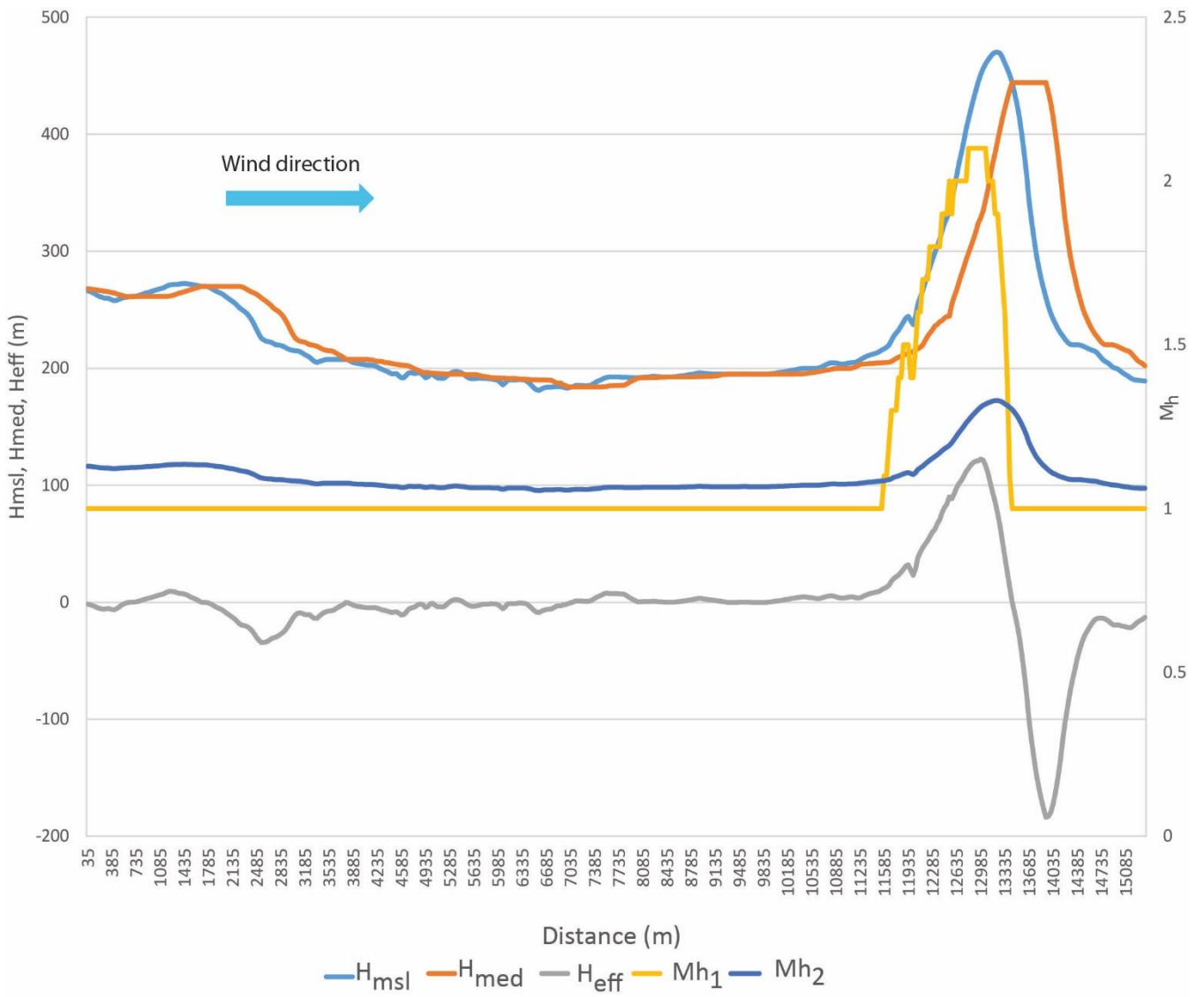
Figure 4: Variations of elevation (Hmsl), median elevation (Hmed), and the effective elevation (Heff) (left axis) and topographic multipliers Mh1 and Mh2 (Eq. 5, Fig. 3) (right axis) along a transection from northwest to southeast (the black line in Fig. 5) crossing the Pyhätunturi- fell in Northern Finland.

5
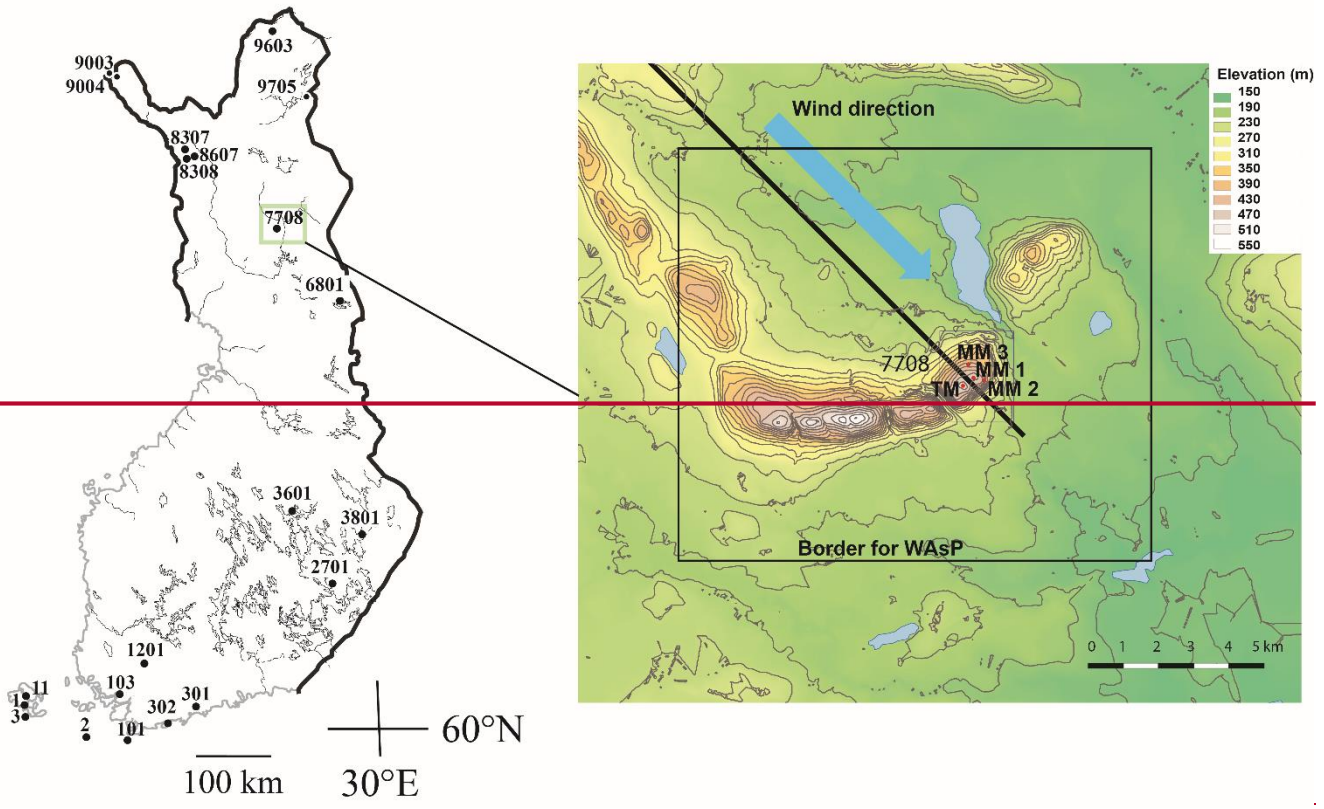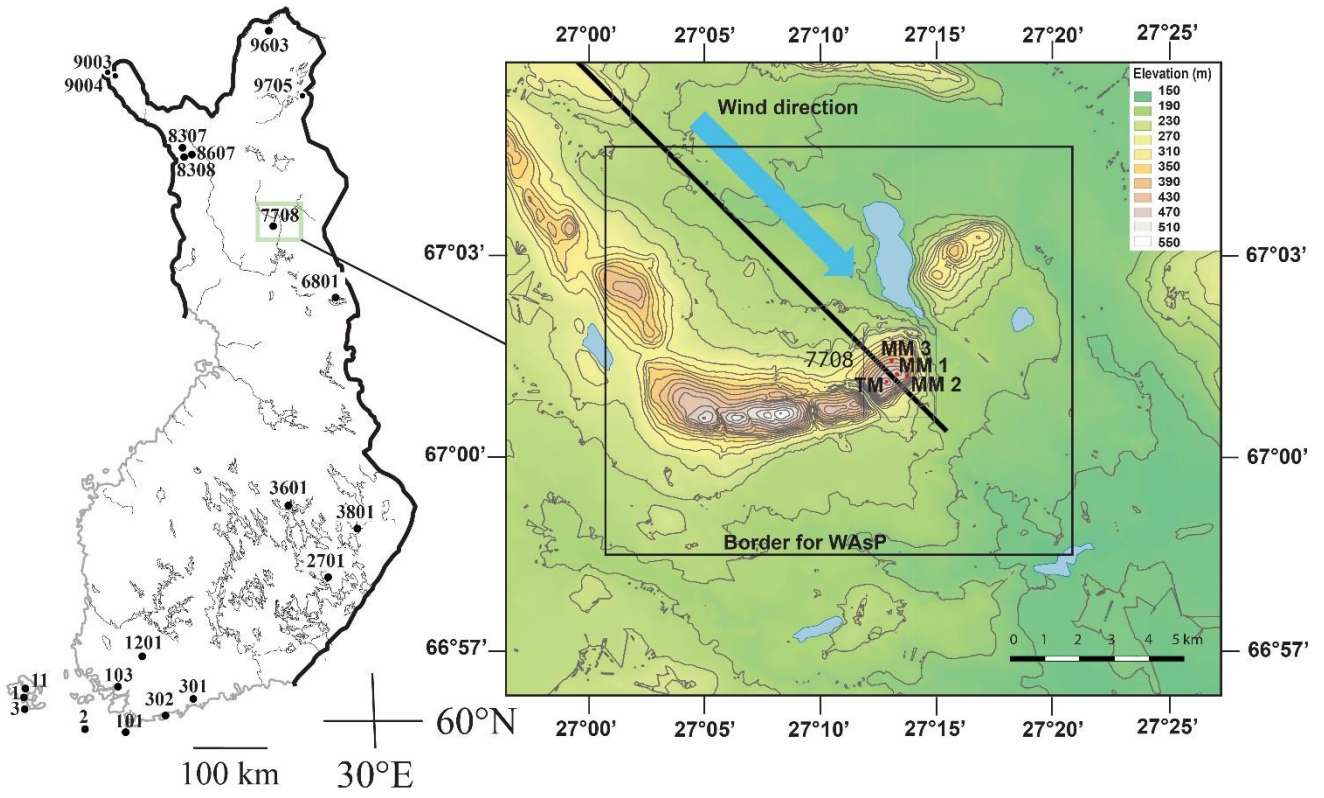
Figure 5: The meteorological stations used in the analyses (see Table 1, Fig. 6) and the topography of the Pyhätunturi -area located in Northern Finland. The black northwest direction line in the Pyhätunturi figure indicates the transection analysed in Fig 4; the black square indicates the border of the WAsP -simulation.

24

5
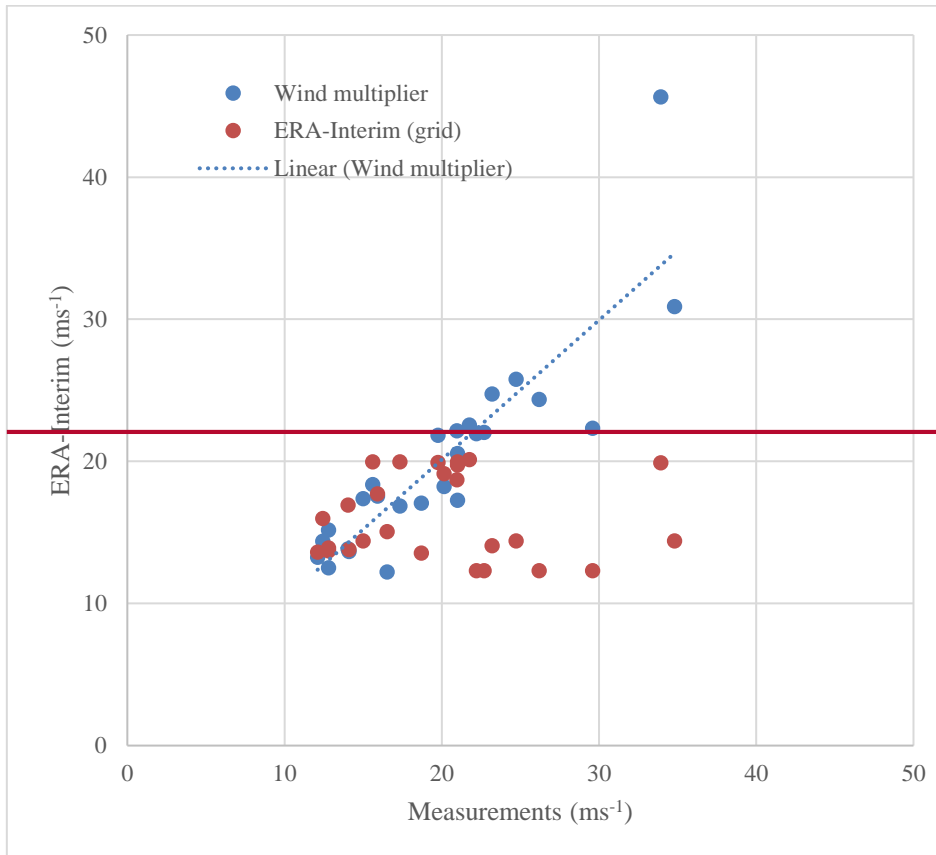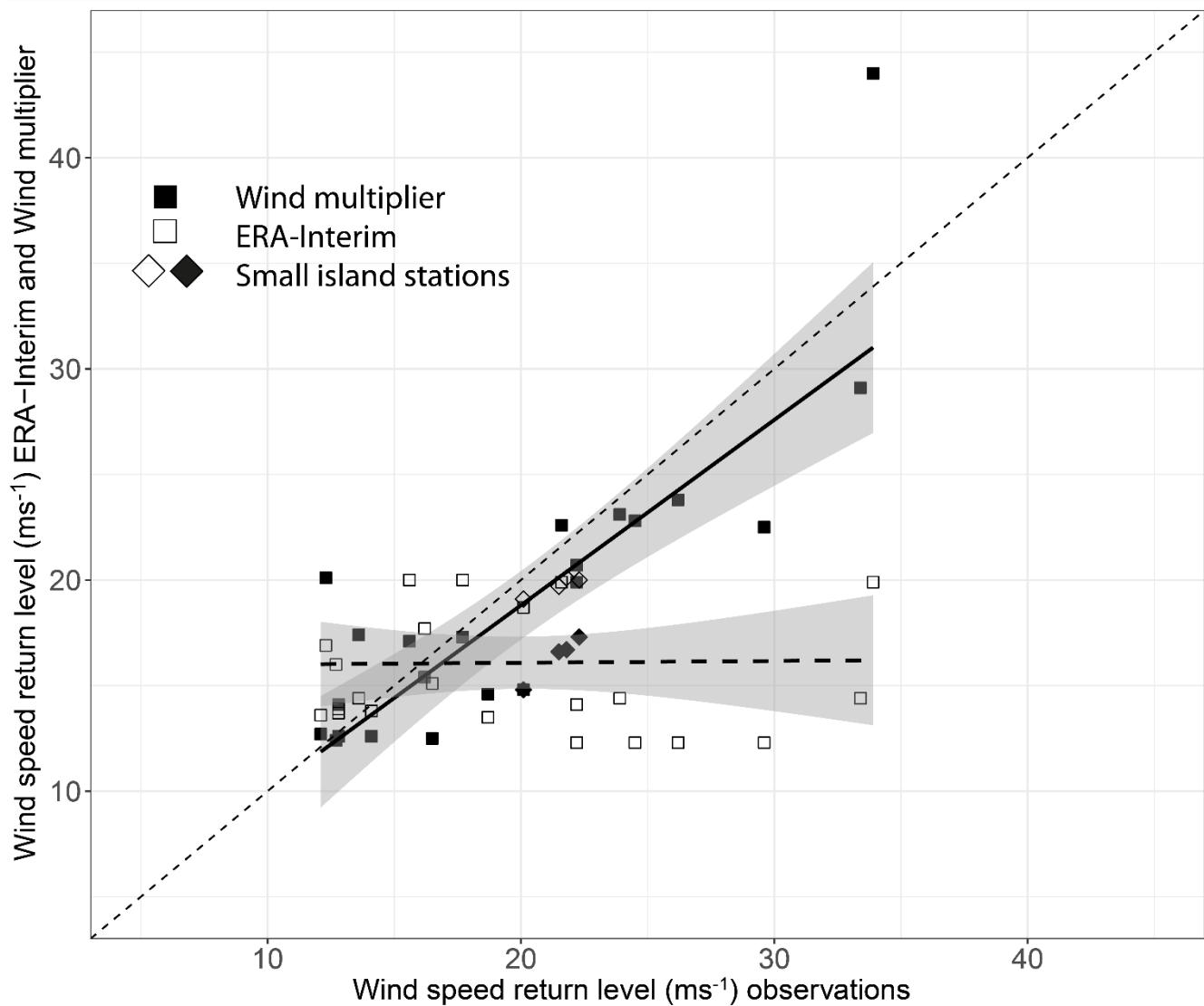
Figure 6: Comparison of 10-year return levels of maximum wind speeds, as calculated, based on observations and by utilizing the wind multiplier method (Eq. 1) and the ERA-Interim dataset for the 26 measuring sites (Fig. 5). Return levels taken directly from the ERA-Interim dataset with no wind multiplier correction ~~(grid)~~ are included in the visualization. The shaded areas are 95% confidence levels for the linear trend lines depicting the dependence between the datasets. The diamond shape symbols indicate that the station is located on small Baltic Sea islands.
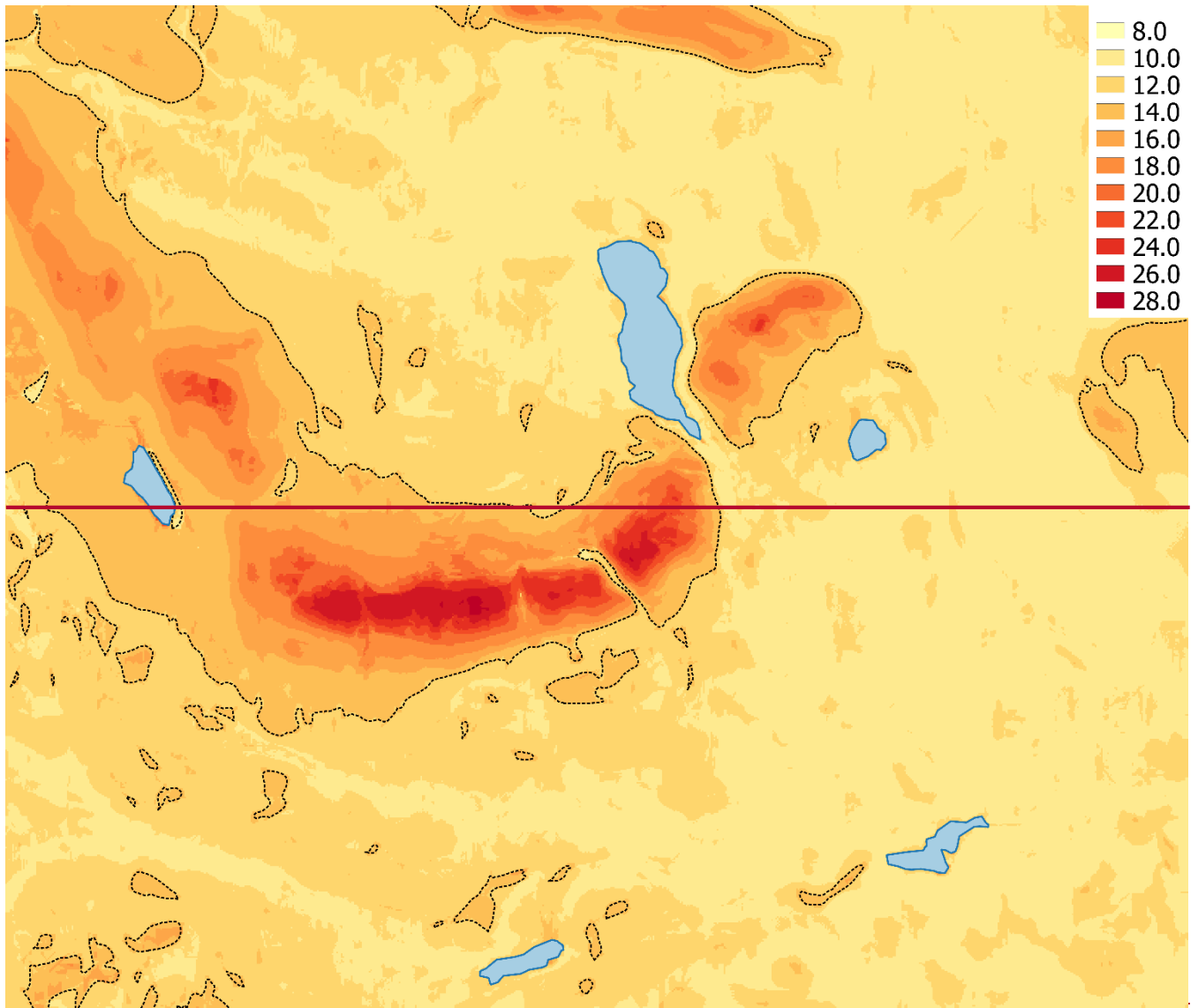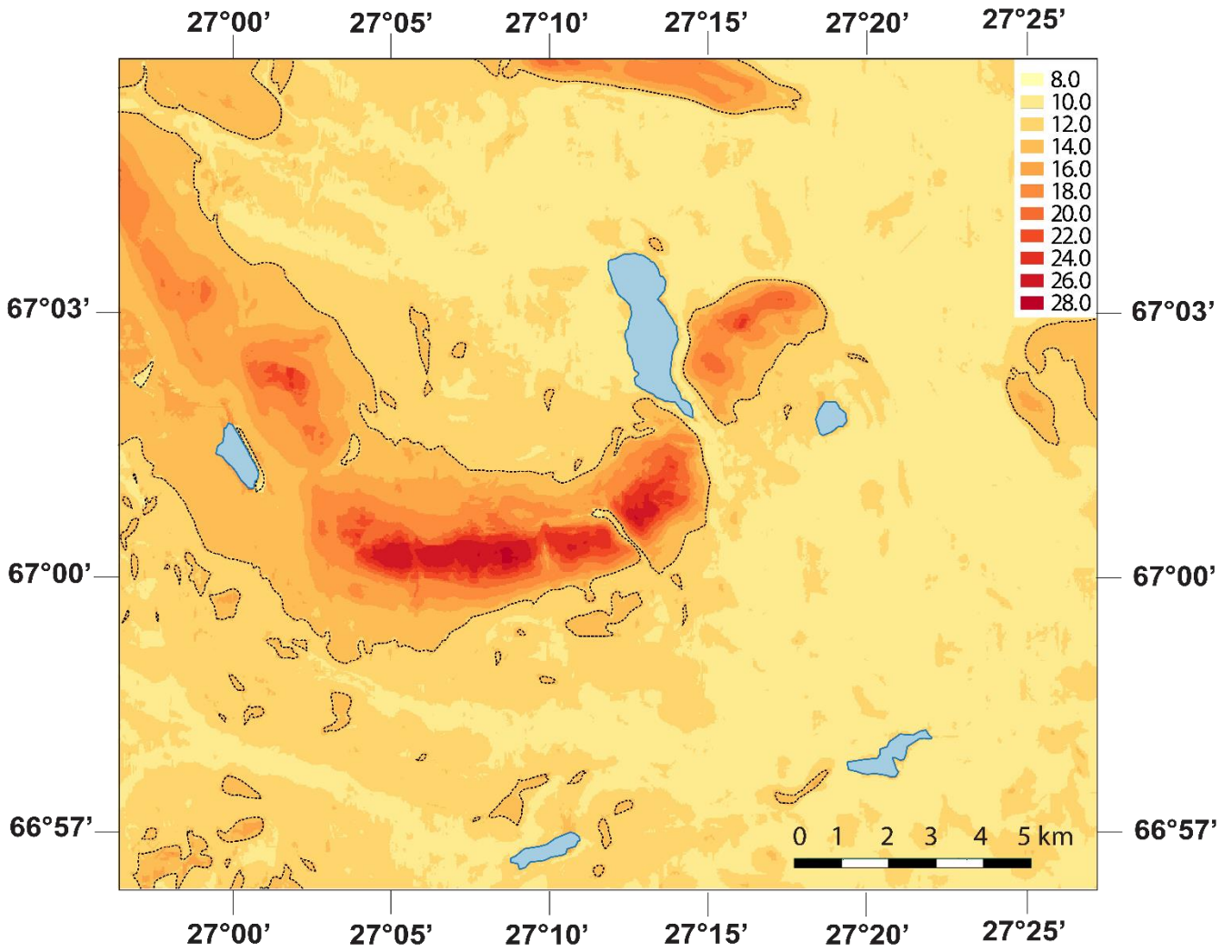
Figure 7: 10-year return levels of maximum wind speed (A) calculated using the wind multiplier method (Eq. 1) and the ERA-Interim dataset for the Pyhätunturi test area (Fig. 5). The values where wind speed exceeded 12 ms^{-1} are indicated by a black dotted line.

5
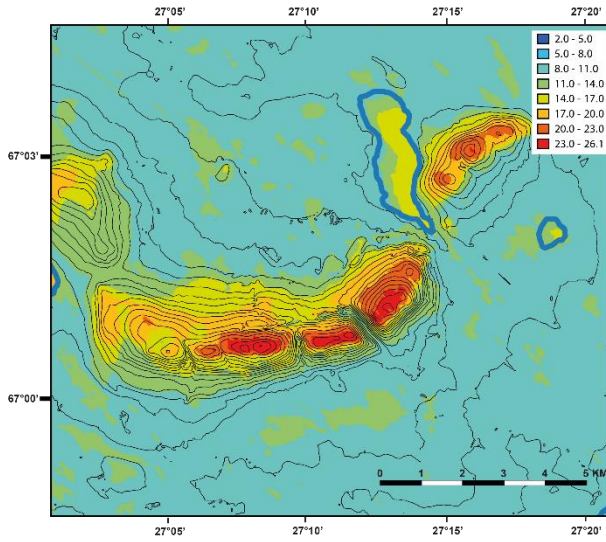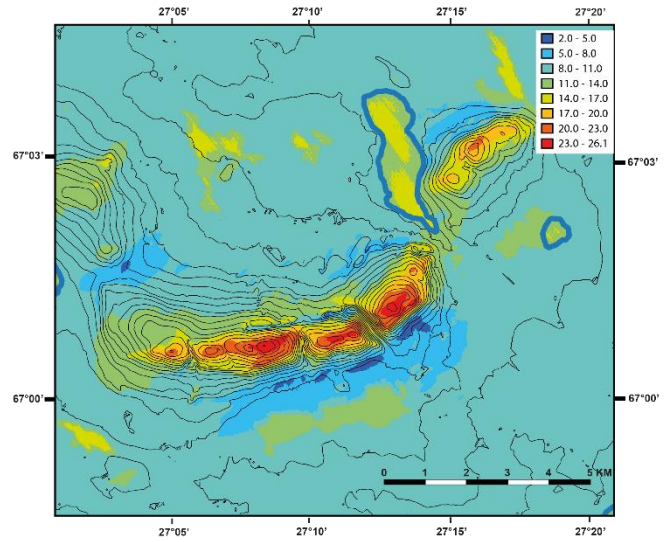
Wind multiplier
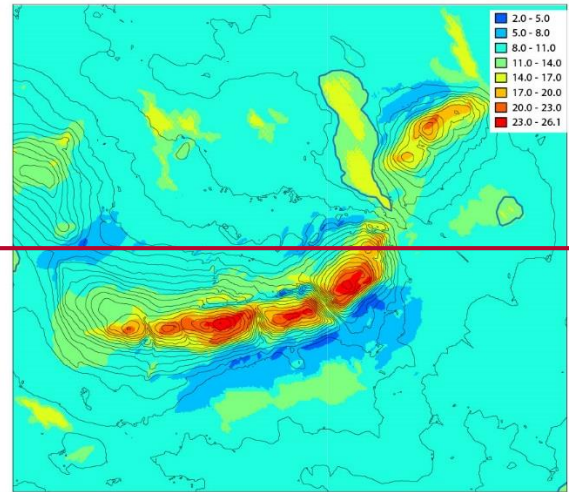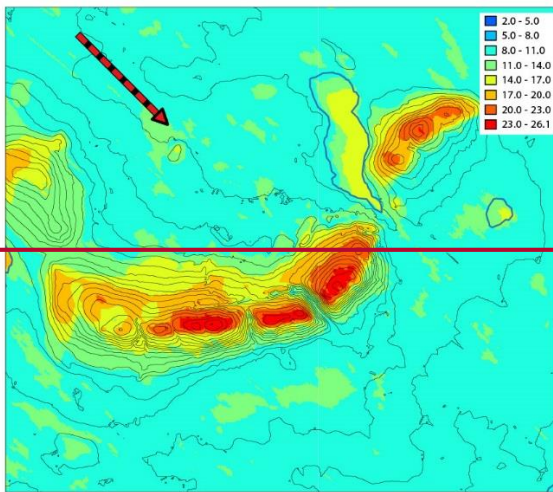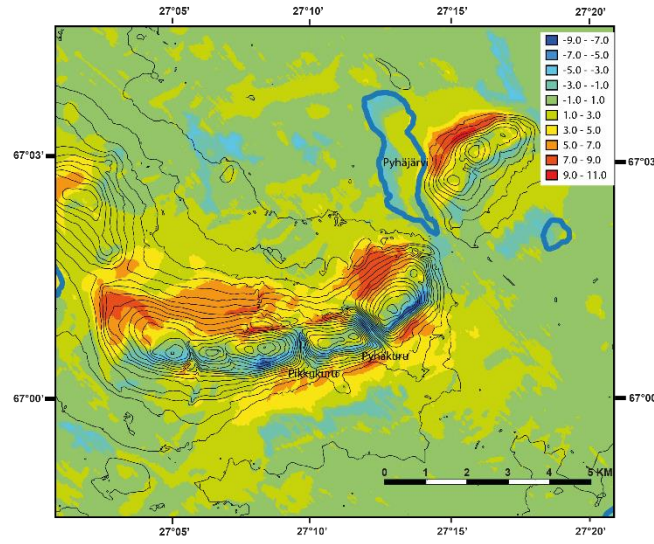
WAsP

Wind multiplier - WAsP
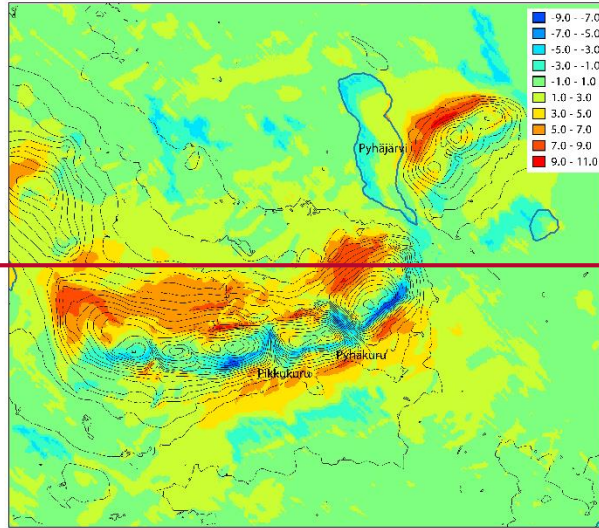
Wind multiplier   WAsP

Figure 8: Comparison of the spatial variation of wind speed as estimated, using the wind multiplier approach, calculated using the WAsP –programme. The last figure depicts the difference between the two methods. Wind direction is from the northwest and in the case of the wind-multiplier it is 12.7 ms^{-1}. For the WAsP simulation a geostrophic north-westerly wind of 39.2 ms^{-1} was assumed.

.

5

Measurements
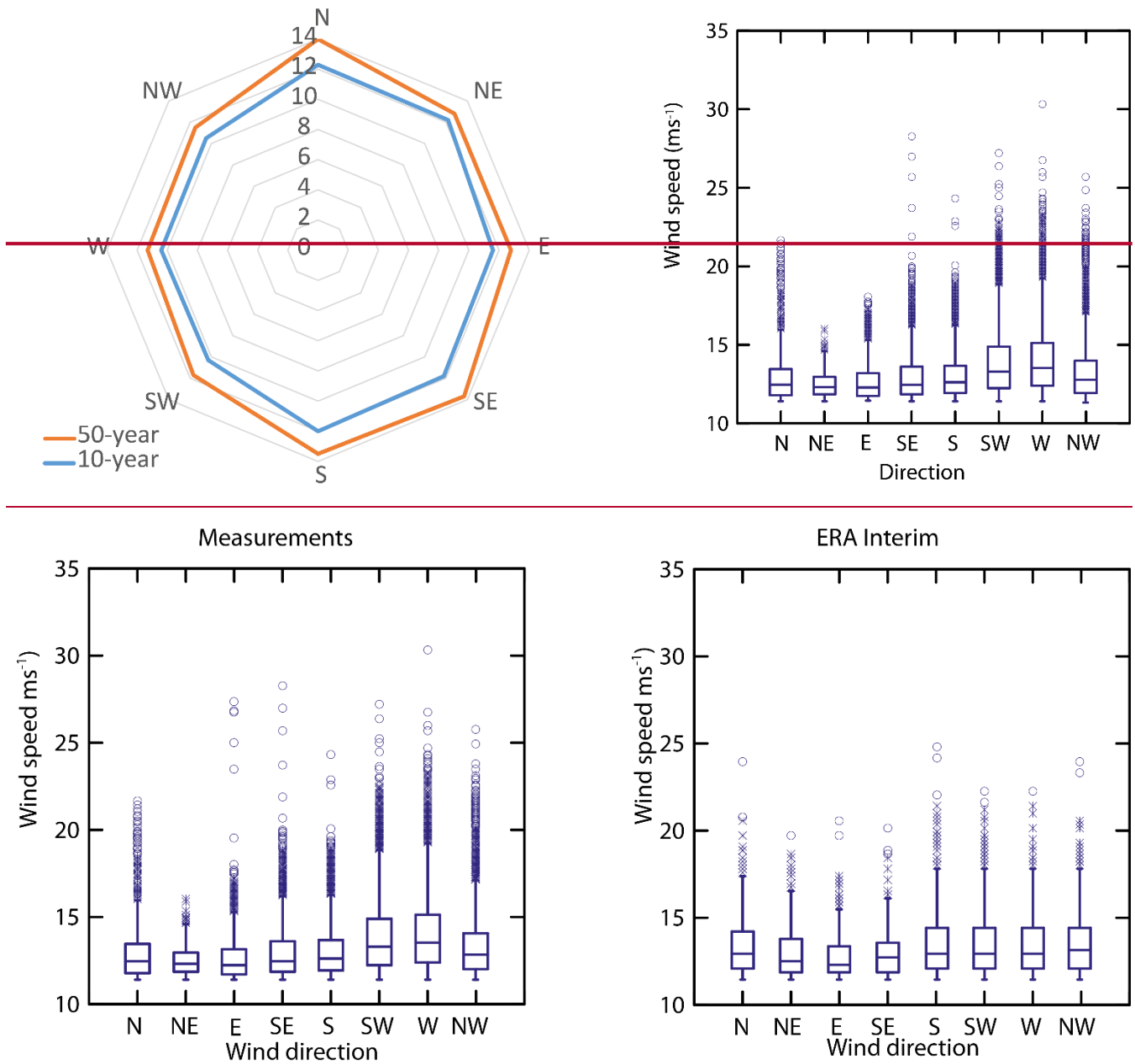
ERA Interim

Figure A11.: Wind speed distribution for the 10- and 50-year year return levels of 10 m height maximum wind speed as estimated from the ERA-Interim 1979-2014 dataset for the Pyhätunturi fell grid box. Box-plot depicting measured 10-minute wind speed

10 **values at the Pyhätunturi telemast station during years 1997-2016 and as taken from the ERA-Interim. The values measured at an elevation of 61 m were corrected to represent 10 m by applying logarithmic wind law. Only values that are 11.4 ms⁻¹ (corresponding value 15 ms⁻¹ at elevation of 61 m) are included into the analyses (right panel).**

15

5
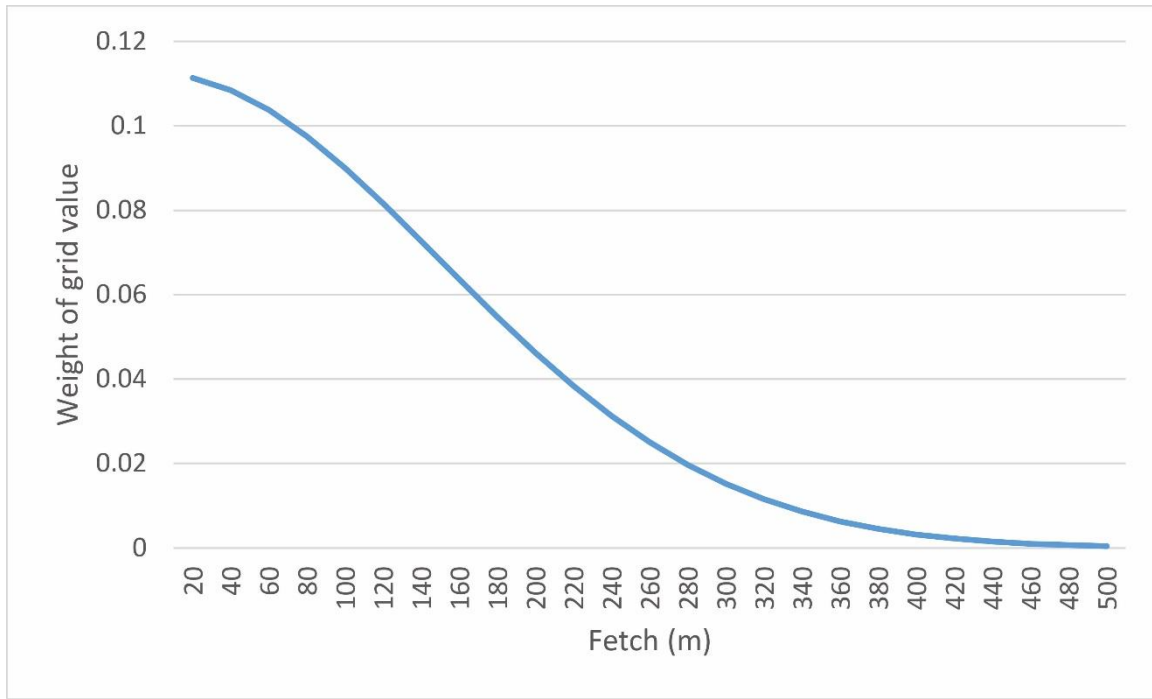
A2: The weight of each grid squares roughness on the effective roughness (z_{eff}) as a function of upwind distance as calculated using Eq. 2. in manuscript.

10

15

20
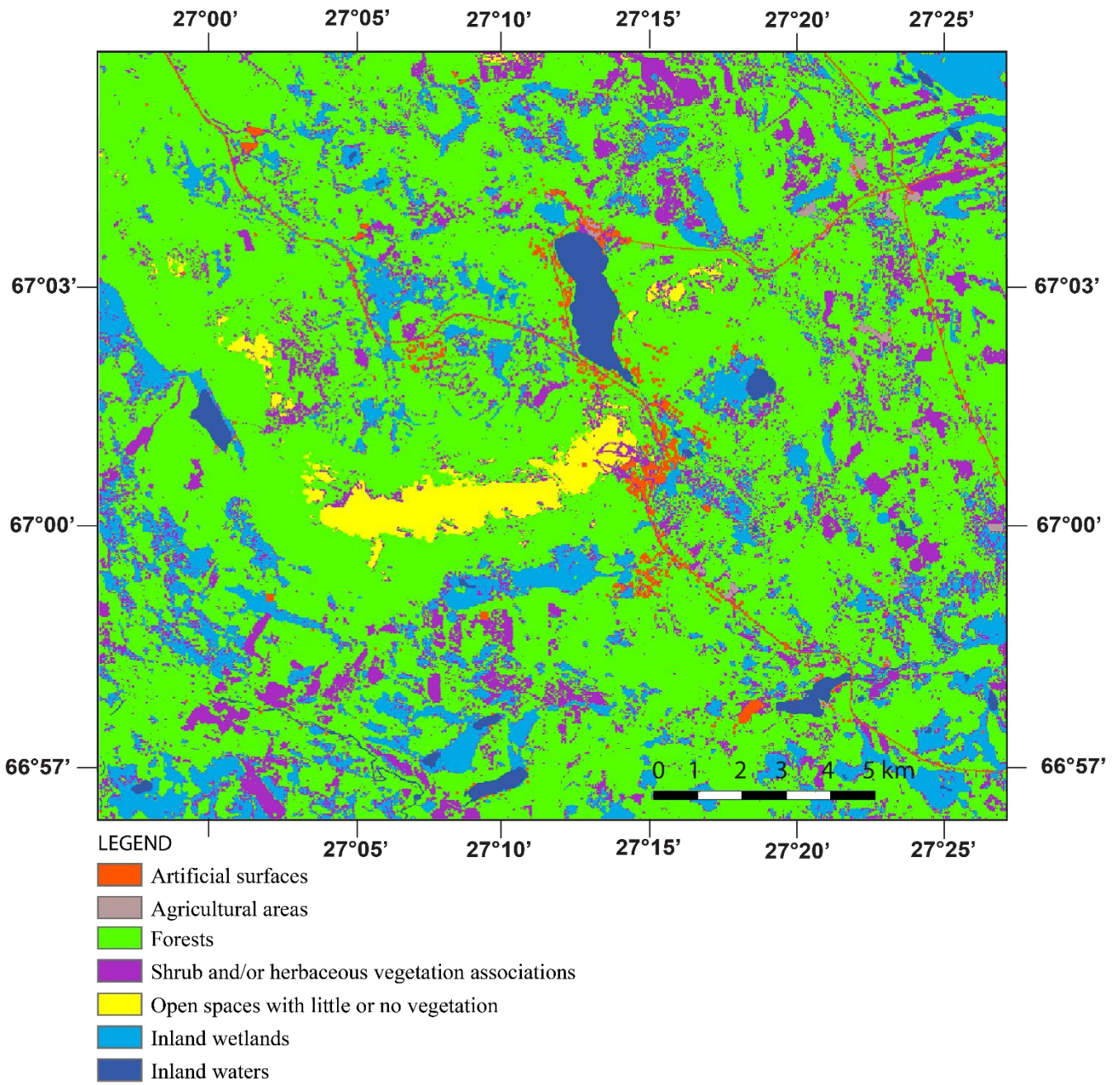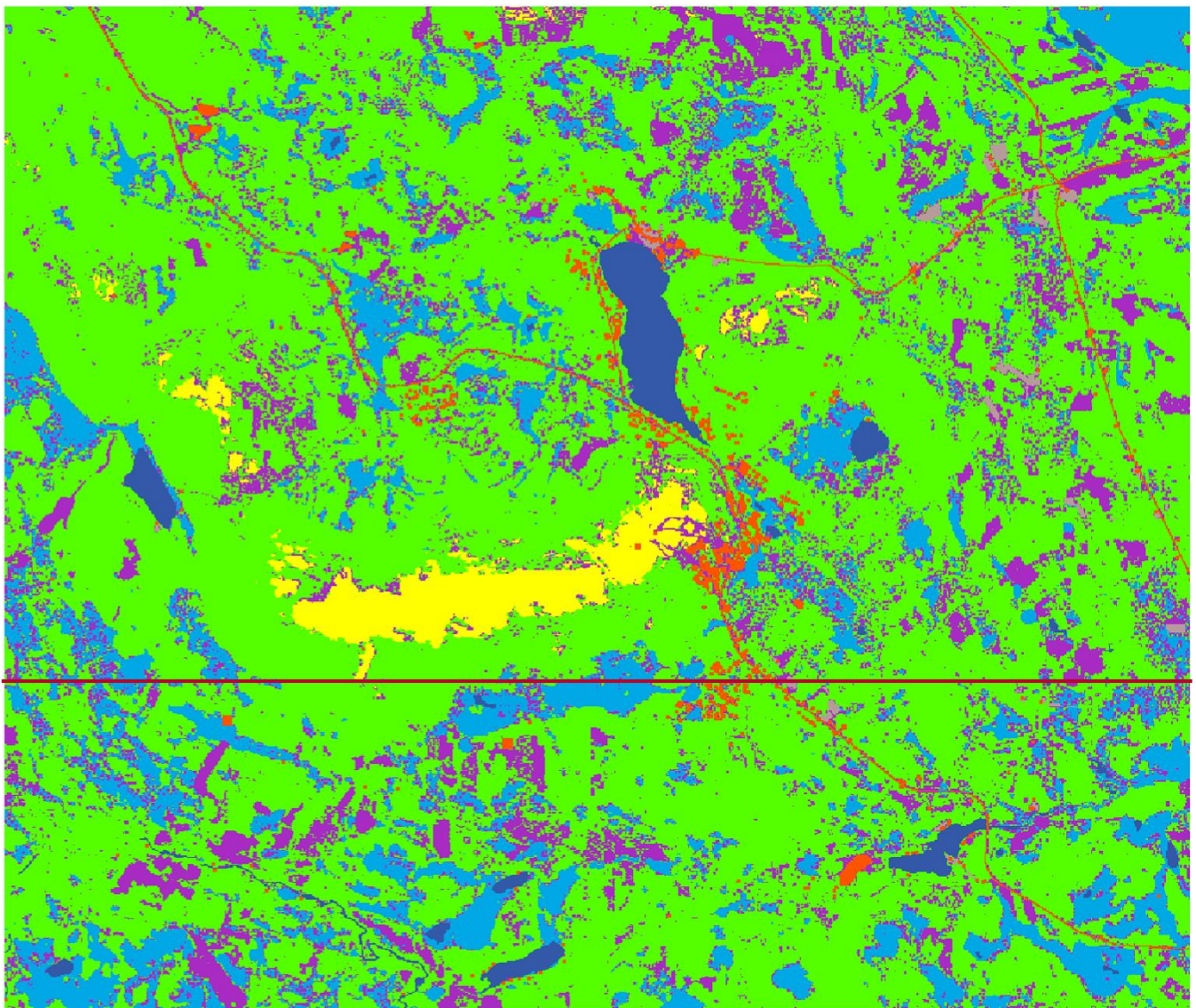
LEGEND

- Artificial surfaces
- Agricultural areas
- Forests
- Shrub and/or herbaceous vegetation associations
- ![#FFFF00](Open spaces) Open spaces with little or no vegetation
- ![#3399CC](Inland wetlands) Inland wetlands
- ![#333399](Inland waters) Inland waters

LEGEND

⬛ (orange)	Artificial surfaces
⬛ (grey)	Agricultural areas
⬛ (green)	Forests
⬛ (purple)	Shrub and/or herbaceous vegetation associations
⬛ (yellow)	Open spaces with little or no vegetation
⬛ (light blue)	Inland wetlands
⬛ (dark blue)	Inland waters

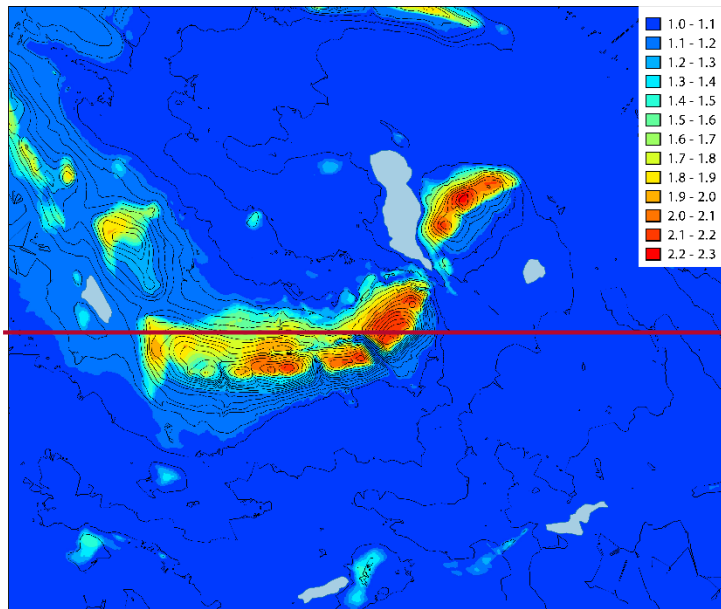**Figure A2A3: Land-use map for the Pyhätunturi-fell area based on the CORINE dataset.**
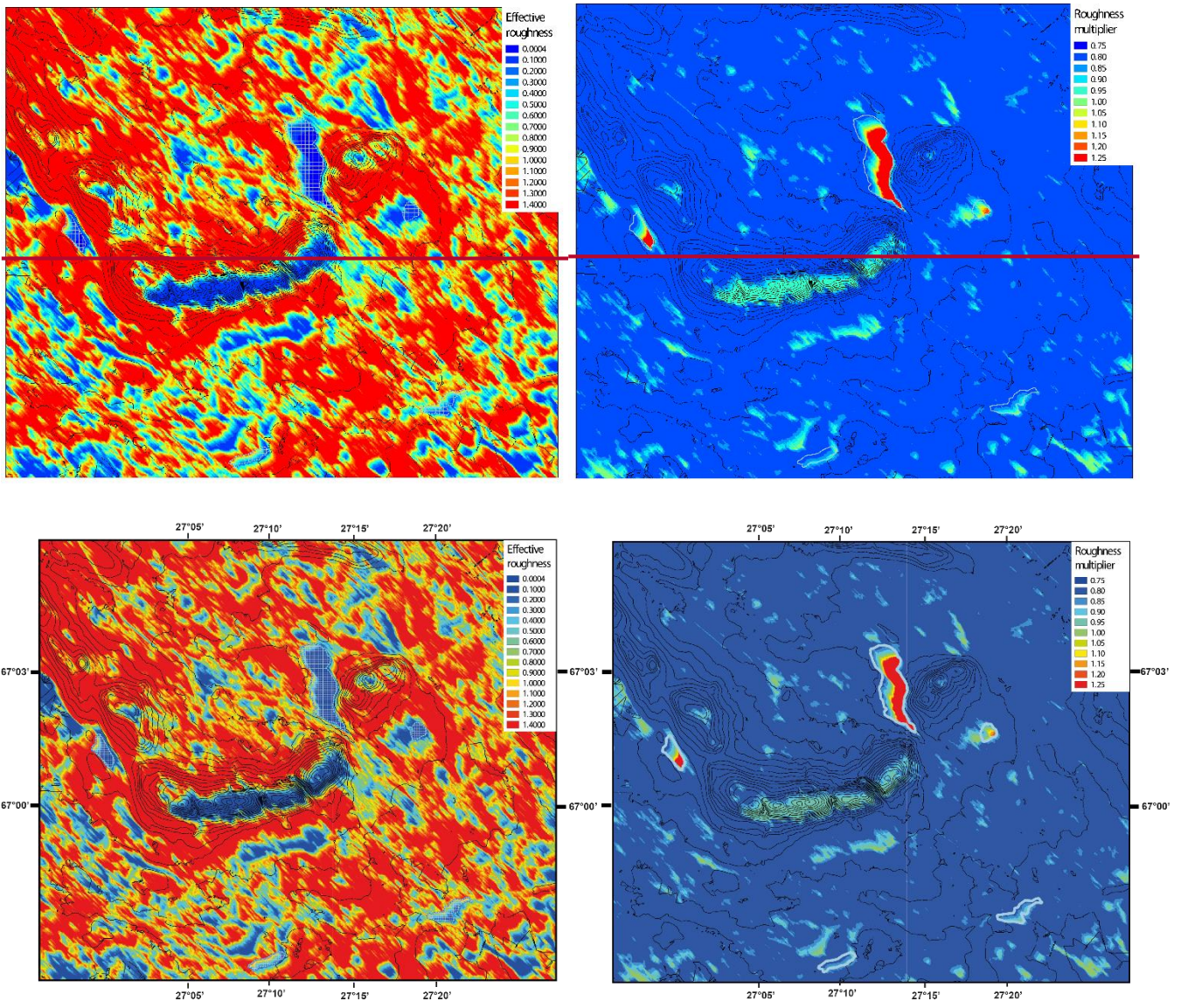
Figure A43 : Effective roughness (zeff, Eq. 4) and roughness dependent wind multiplier (Mz) calculated for the Pyhätunturi-fell area for northwesterly winds.
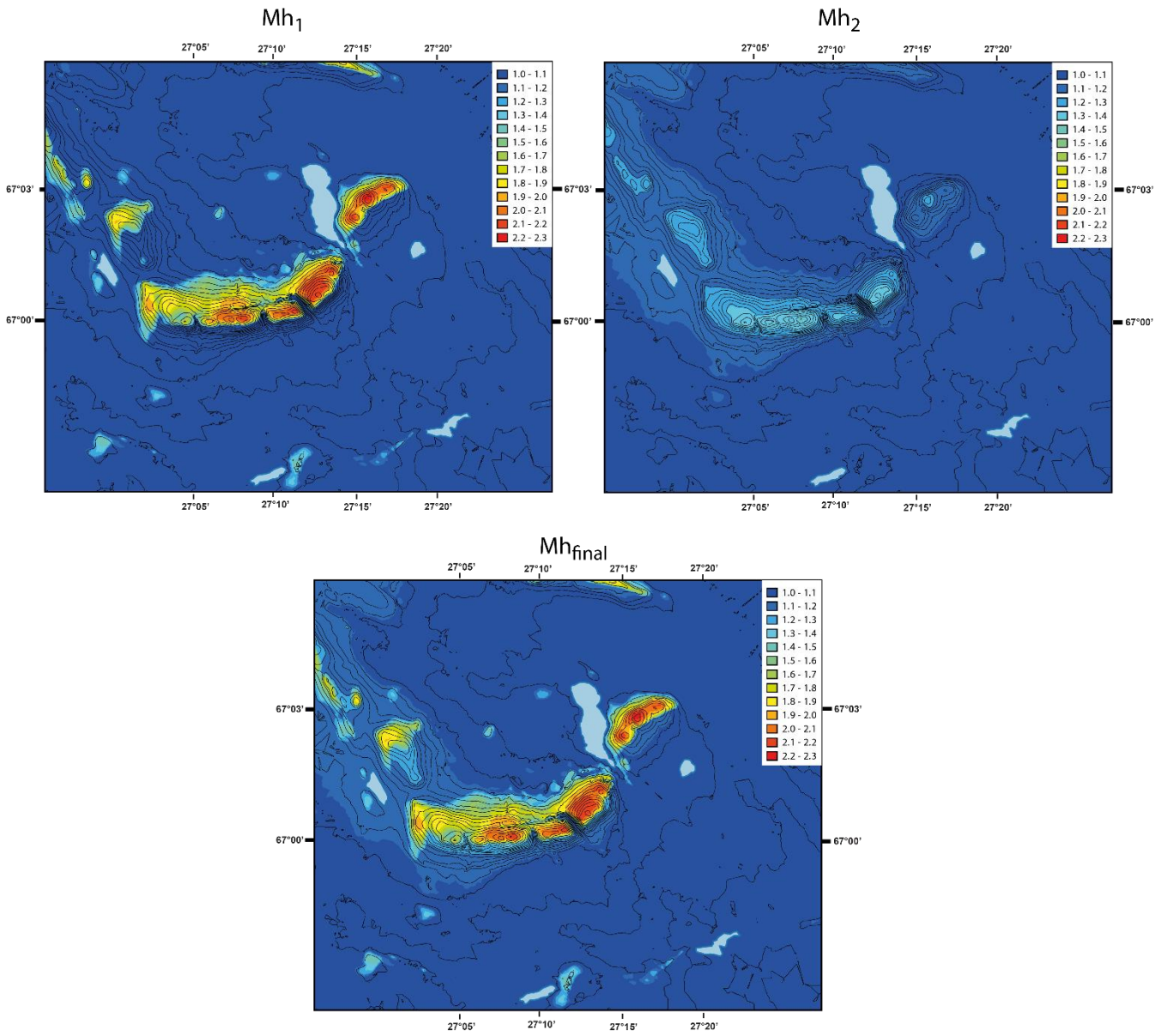
5

Mh₁

Mh2
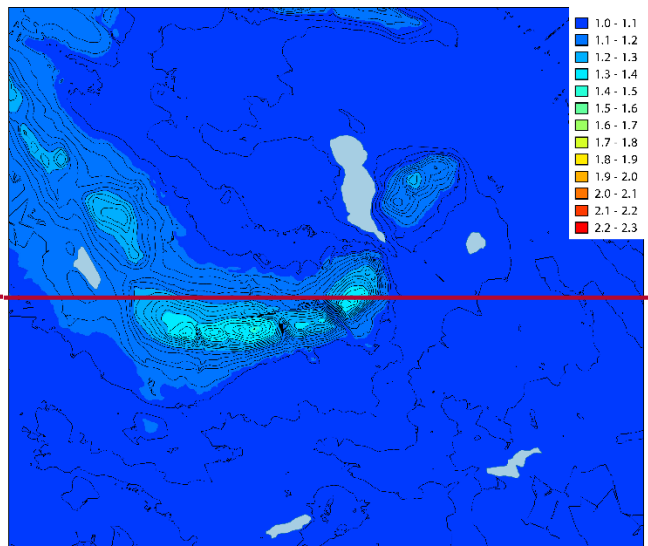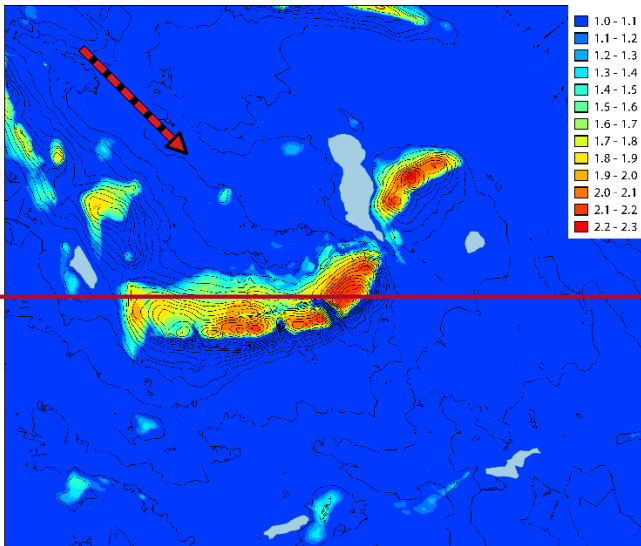
Mh_final

Figure A54: Topographic wind multipliers (Eq. 6) calculated for the Pyhätunturi-fell area for northwesterly winds.
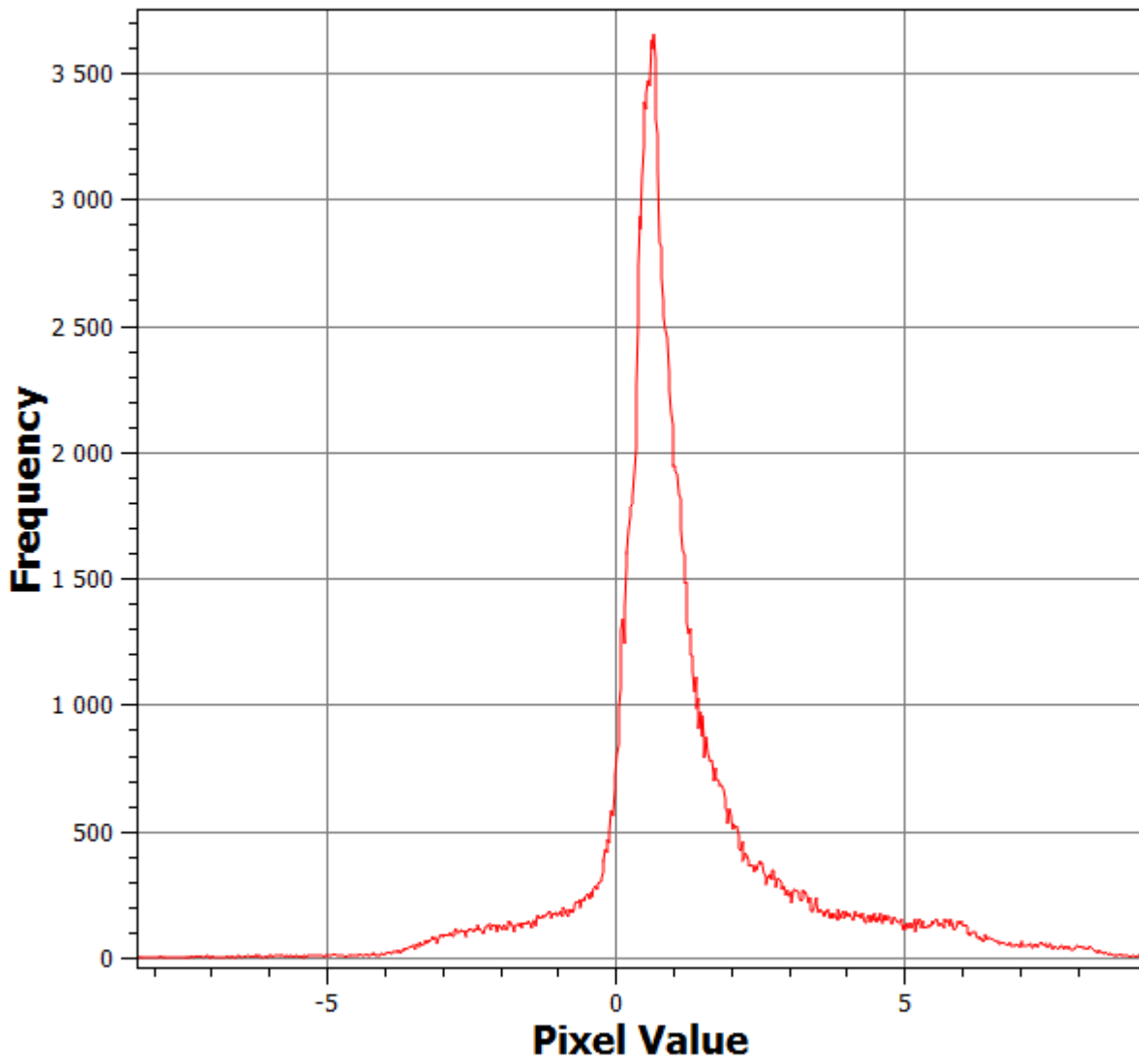
Figure A65: Histogram depicting the difference between the wind speed as estimated using the wind multiplier approach and as calculated using the WAsP –programme (see Fig. 8).