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Article

Mean gust factors in complex terrain

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Abstract

Gust factors are analyzed for wind speeds greater than 10 m/s in a large set of data from automatic weather stations in the complex terrain of Iceland. The mean gust factors appear to be independent of the static and dynamic stability of the atmosphere, suggesting that gravity wave dynamics may compensate for the damping of turbulence in stably stratified flows. The mean gust factor depends however on wind speed and nearby topography and decreases regularly with increasing wind speed and station altitude. High mountains close to the weather stations give strong downstream wind gusts. In a subset of the data, containing only statically stable flows, mean gust factors of 1.6 or more may be obtained if an upstream mountain rises at least 200 m above the weather station and the distance to the mountain is less than 10 times its height above the station.

Zusammenfassung

Faktoren für Windböen mit Windstärke größer als 10 m/s werden in einer großen Datenmenge von Messungen automatischer Wetterstationen für das komplexe Terrain von Island analysiert. Die mittleren Böenfaktoren scheinen von der statischen und dynamischen Stabilität der Atmosphäre unabhängig zu sein, was darauf hindeutet, daß Schwerewellendynamik die Dämpfung der Turbulenz in stabil geschichteten Strömungen kompensieren kann. Der mittlere Böenfaktor hängt jedoch von der Windgeschwindigkeit und von der nahe gelegenen Topographie ab und verringert sich gleichmäßig bei Zunahme der Windstärke und der Stationshöhe. Hohe Berge nah an den Wetterstationen bewirken starke, abwärts gerichtete Windstöße. In einer Teilmenge der Daten, mit statisch stabiler Strömung, können mittlere Böenfaktoren von 1,6 oder mehr erreicht werden, wenn ein stromaufwärts gelegener Berg sich mindestens 200 m höher als die Wetterstation erhebt und seine Distanz kleiner als seine 10-fache Höhe über der Station ist.

1 Introduction

Temporal variability of wind speed is an important factor describing the wind climate. Low frequency variability is described by the mean wind speed, where the wind speed is generally averaged over a period of 10 minutes, although this period can vary with institutes and the intended use of the wind data. Variability within shorter periods of time is however also of great importance. Fluctuations in wind speed at this scale are usually characterized as “gustiness” and they are generally described by the ratio of near-instantaneous wind speed to the mean wind speed, often called gust factor. Values of the gust factor at 10 metres height over open land are typically 1.2–1.6 (ÁGÚSTSSON and ÓLAFSSON, 2002; NAESS et al., 2000), but varying anemometer heights and averaging periods make comparison with the existing litterature difficult (BRASSEUR, 2001; DAVIS and NEWSTEIN, 1968; MITSUTA and TSUKAMOTO, 1989).

Wind gusts are associated with turbulence which is primarily found in the atmospheric boundary layer, close to the surface of the earth. Here, low static stability and large vertical windshear due to surface friction give rise to turbulent motion. Turbulence can also be found at upper atmospheric levels, such as in deep convective cells and regions of windshear close to the upper tropospheric and stratospheric jets. In regions of high mountains, large amplitude gravity waves may form if the atmosphere is stably stratified. These waves can propagate far above the surface of the earth and they can produce significant turbulence, as a result of either local windshear or local convective instability due to wave breaking. Turbulence or gustiness at the surface of the earth has also been observed in connection with large amplitude gravity waves (e.g. CLARK et al. (1994)). In such cases, the gustiness is associated with severe downslope windstorms and the pulsating motion that is brought down to the surface of the earth has been suggested to be a result of wave breaking aloft, (CLARK and FARLEY, 1983; SCINOCCA and PELTIER, 1989; PELTIER and SCINOCCA, 1990). Major windgust events do in fact often occur in windstorms close to mountains, for instance in downslope windstorms. Two well known examples of very gusty mountain weather events, that have been studied and modelled, are the 9 January 1989 Boulder windstorm (CLARK et al., 1994) and the 12 October 1996 windstorm in Northern Norway, (GRØNÅS and SANDVIK, 1999). In the event in Norway, 30 m high power pylons broke down in a short, narrow, valley. It is argued that gusts in excess of 50 m/s were responsible

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for the damage, although the mean wind may have been as low as 25 m/s, which gives a gust factor close to 2. In the Boulder event the mean wind was close to 30 m/s with indications of very strong gusts. Gusts in the Boulder windstorms do in fact easily exceed twice the mean wind speed (DURRAN, 1990). Wind gust events of similar magnitude have been observed in the SNEX experiment in W-Iceland, (ÓLAFSSON et al., 2002a,b). For further reading on turbulence and gustiness in the atmospheric boundary layer, the reader is referred to STULL (1988) e.g. chapter 5.

In extreme weather events, gusts are the main cause of damage to structures and vegetation. Aloft, turbulence is also a potential hazard for aviation. Understanding and predicting turbulence and wind gusts is therefore of great concern. The hazard associated with gusts has led to several attempts to construct a system for gust prediction. Statistical methods using empirical gust factors (e.g. JUNGO et al., 2002; WEGGEL, 1999), as well as methods based on the parameterization of turbulence in numerical weather prediction models (e.g. BRASSEUR, 2001; GOYETTE et al., 2003; NIELSEN and PETERSEN, 2001) provide helpful guidance for operational gust forecasting.

Mean gust factors have also been studied in observational data by several authors. Some studies show a clear and negative correlation between wind speed and the gust factor (DAVIS and NEWSTEIN, 1968), while in other datasets this may not be as clear for all wind speeds (MITSUTA and TSUKAMOTO, 1989; NAESS et al., 2000). The study of DAVIS and NEWSTEIN (1968) showed no obvious connection between atmospheric static stability and the gust factor, but to our knowledge no extensive study has been made of the connection between mean gust factors at several stations and the vertical windshear, the height and distance to nearby topography.

In Iceland, there is a large and growing number of automatic weather stations that measure both the speed and the direction of the wind. Many of these stations have been active for more than 5 years and considerable information on the wind climate is stored in the data from these stations. Most of the automatic stations are located in coastal areas, but still many are located inland or in the mountains. The weather stations belong to different institutes, but the observations are of similar standard and comparable. In this study, data from selected automatic weather stations has been collected and is used to investigate mean gust factors. The gust factors are calculated and compared to the static and dynamic stability of the airmass, wind speed, station altitude and the topography surrounding the stations.

The results will hopefully improve the wind climate description of regions that are similar to Iceland with respect to terrain and climate. Such a step towards a more detailed analysis of the winds is of great value for estimating wind-stress on structures and for risk assessment in the context of weather and climate (ÞORSTEINS, 1999) The outcome of this study may also be of some guidance for gust forecasts.

In the next section of this paper, the observations and topographic data are described. Section 3 shows the results of the statistical study on the connection of the mean gust factor with some atmospheric and topographic parameters The final section includes a summary and a discussion of the results, as well as concluding remarks.

2 Data

2.1 Wind observations

The wind data used in the study was collected from the 36 automatic weather stations shown in Fig. 1. Most parts of the study use only data from 13 stations in Southwest Iceland, which are all located inside the domain delineated in Fig. 1. Three of the stations in Southwest Iceland, Bláfjöll, Ölkelduháls and Hellisskarð are located in the mountains (approx. 400–500 m above sea level). In other parts of Iceland, Brú, Kárahnjúkar, Eyjabakkar, Vatnsfell and Setur qualify as high altitude stations (approx. 500–600 m.a.s.l.) while other stations are located at relatively low altitudes.

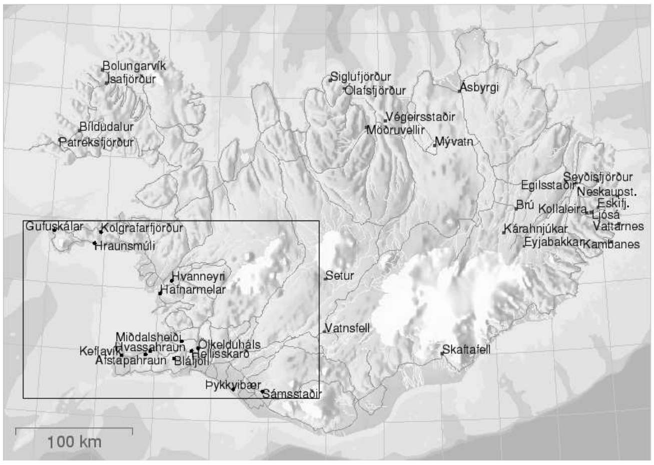

Figure 1: Weather stations used in the study. Delineated domain includes stations considered in Southwest Iceland.

All the automatic weather stations measure wind at 10 metres above ground level and use a 10 minute averaging period.[1] The mean wind speed, f, maximum 3 second gust, f_g, and wind direction, d, were collected from the years 1999, 2000 and 2001. In order to limit the volume of data, only observations with $f > 10$ m/s were considered. The practical value of knowledge on

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[1] Young anemometers from Campbell Scientific are used at all stations except one which uses equipment of similar standard.

gust factors is in most context only important for wind speeds above these limits.

The average number of observations for each station is roughly 4000 The data has been checked for errors at the Icelandic Meteorological Office.

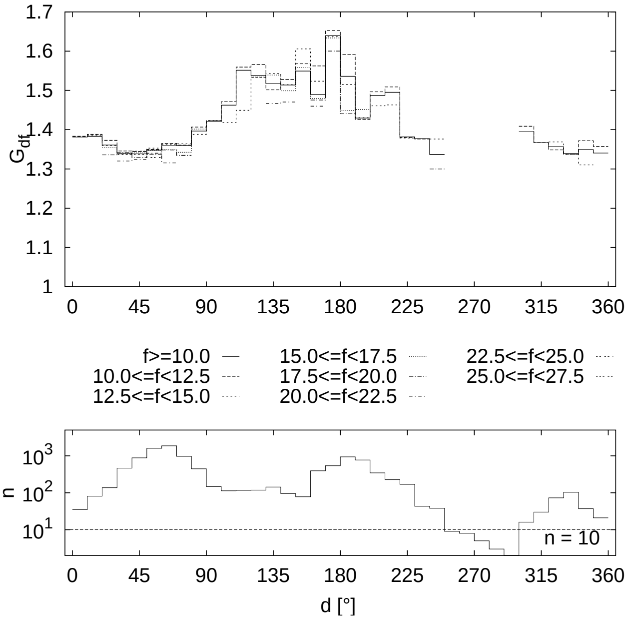

Figure 2: Data from the automatic weather station at Gufuskálar. Upper graph shows the mean gust factor, G_{df}, as a function of wind direction, d. The lower graph shows the number of observations, n, in each interval in d and a horizontal line where $n = 10$. Note the logarithmic scale in the lower graph and that for clarity no units are shown for f (m/s).

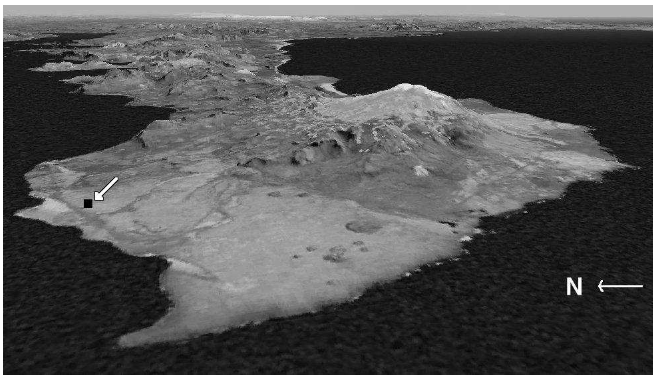

Figure 3: The topography around the automatic weather station at Gufuskálar, West Iceland The location of the station is shown with a black dot The snow-capped mountain is Mount Snæfellsjökull, 1446 m.a.s.l.

2.2 Observations of the vertical profile

Radiosoundings from the Keflavík upper-air station in Southwest Iceland (WMO no. 4018) are used to determine the vertical structure of the airmass. The soundings are made every 12 hours, and the vertical structure of the atmosphere at a certain time is determined from the sounding which is closest in time, at most 6 hours earlier or later. The soundings are considered to represent well the static stability and vertical shear of the airmass over Southwest Iceland. Their reliability would be questionable for more distant locations, which are therefore excluded in this part of the study.

The layer between 925 and 850 hPa is chosen to represent the static stability and windshear in the lower troposphere. This is the core of the airmass that impinges the terrain. All the stations are well below the 850 hPa level and this level is in general above the top of the boundary layer over the lowlands. Close to the surface of the earth, there can be large spatial variability in wind and temperature and close-to-surface observations in Keflavik may not be representative for a large area. Therefore a lower limit for the calculations is defined at 925 hPa.

Apart from the study of the connection between the vertical profile of the atmosphere and gust factors, only cases where the difference in temperature between the 925 hPa and 850 hPa levels is less than 4 K are considered. This corresponds roughly to the wet adiabatic lapse rate, and excludes statically unstable and near neutral situations. It is then less likely that the study on the connection of mean gust factors with topology and wind speed will be masked by gust factors of gusty winds traditionally associated with statically unstable airmasses.

The static and dynamic stabilities of the airflow are determined from the radiosoundings. The Brunt-Väisälä frequency, N, can be considered to represent the static stability of the airmass in the lower troposphere, while the dynamic stability is represented by the Richardson number R_i. For the layer between the 850 hPa and 925 hPa levels, the Brunt-Väisälä frequency is given by

$$N = \sqrt{\frac{g\Delta\theta}{\theta_{avg}\Delta z}} \tag{2.1}$$

and the Richardson number by

$$R_i = \frac{g\Delta\theta\Delta z}{\theta_{avg}(\Delta U)^2}. \tag{2.2}$$

The acceleration of gravity, mean potential temperature, mean wind speed and mean altitude are given by g, θ, U and z, respectively Here ΔU, $\Delta\theta$ and Δz are the difference in U, θ and z between the 850 hPa and 925 hPa levels, and θ_{avg} is the vertical average of θ.

Research indicates that the onset of turbulence occurs for R_i smaller than 0.25, but as R_i is here calculated for a finite layer, as opposed to a local point, this critical value is greater and possibly 10–50 times as big For $R_i > 10$ there is empirical evidence for non-turbulent flows (STULL, 1988, p. 177).

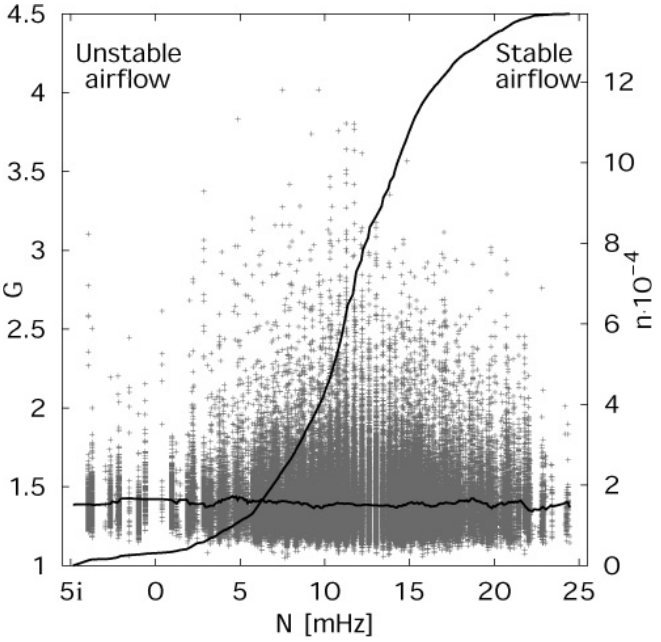

Figure 4: Data from stations in Southwest Iceland Points show individual observations of *G* and horizontal line the average value of *G* The rising line shows the accumulated number of observations, *n*, and *N* is the Brunt-Väisälä frequency. Note the change from imaginary to real numbers on the horizontal axis.

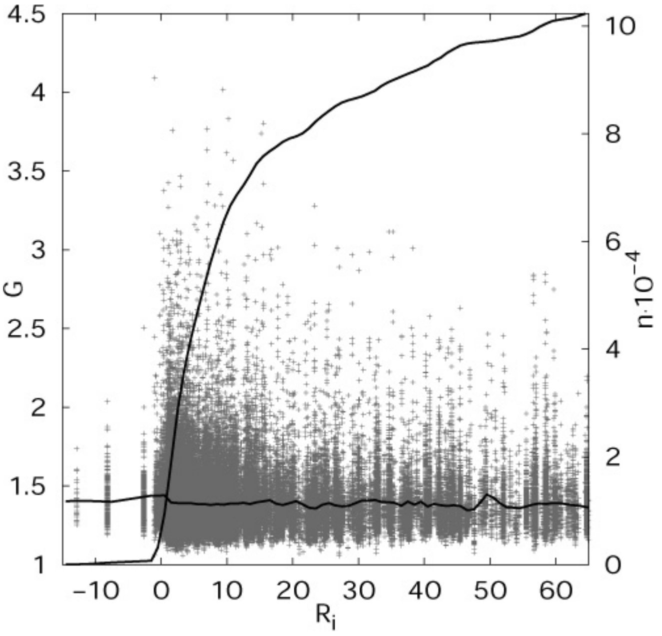

Figure 5: Data from stations in Southwest Iceland. Points show individual observations of *G* and horizontal line the average of *G*. The rising line shows the accumulated number of observations, *n*, and R_i is the Richardson number.

2.3 Topographic data

Topographic maps and photographs of the stations were used to find directions, d_m, from the stations to nearby hills and mountains. The height of a mountain above a weather station, H, and the distance, D, to the mountain are also determined for each station for mountains up to 20 km away from the station. Due to the complex topology at many of the stations, up to several d_m, H and D are defined for each weather station.

3 Calculation of gust factors

The gust factor G is defined as $G = f_g/f$. For each station, the mean gust factor G_f is calculated for 2.5 m/s intervals in wind speed. A mean gust factor G_d is also calculated for each wind direction with 10 ° intervals. Finally, the mean gust factor G_{df} is calculated by splitting G_d into wind speed categories with 2.5 m/s intervals. No G_f, G_d or G_{df} are calculated for fewer than 10 observations.

3.1 Gust factors at the Gufuskálar automatic weather station

Fig. 2 illustrates the directional dependence of the gust factor at the weather station Gufuskálar (7 m a.s.l.). The Figure shows how G_{df} and the number of observations, n, vary with wind direction, d. Altough there appears to be little or no dependence of the mean gust factor on the stability of the atmosphere (see section 3.2), this may not necessarily be valid for individual stations. Therefore only statically stable situations, according to radiosoundings at Keflavík, are considered here

The important and most apparent feature in Fig. 2 is that southerly winds show much higher gustiness and more variability with wind speed, than do other wind directions (for a more detailed figure, see ÁGÚSTSSON and ÓLAFSSON (2002)).

Fig. 3 sheds some light on the cause of the variable gustiness, as it shows the topography around the weather station at Gufuskálar. The station is marked with a black dot and an arrow. To the north and west of the station, there is flat land and open sea further away, while to the south, there is a high mountain (Mount Snæfellsjökull, 1446 m a.s.l.). Turbulent eddies and/or gravity waves, created by the flow-mountain interaction, presumably contribute to the observed gustiness.

3.2 Gust factors and the vertical structure of the atmosphere

Fig. 4 shows the observations from the stations in Southwest Iceland plotted against the Brunt-Väisälä frequency, N, as given by equation 2.1. The figure reveals very little dependence of the mean gust factor on the static stability of the airmass, as it remains close to 1.4 for unstable as well as very stable air.

In Fig. 5, data from stations in Southwest Iceland is plotted against the Richardson number, R_i, given by equation 2.2. Fig. 5 shows a very slight decrease in the mean gust factor as the dynamic atmospheric stability increases. In the interval of R_i, shown in Fig. 5 (including more than 80% of the observations), there is a decrease of approximately 0.05 in the mean gust factor.

3.3 Gust factors and wind speed

The average of G_f, for all automatic weather stations in Southwest Iceland, is plotted as a function of mean wind speed, f, in Fig. 6. Only statically stable situations are considered.

For low and moderate wind speeds, Fig. 6 shows the gust factor decreasing regularly with increasing wind speed. With f between 10 and 22 m/s, there is a reduction of about 0.03 in the mean gust factor for every 5 m/s increase in mean wind speed The irregular behaviour of the mean gust factor at higher wind speeds is presumably related to a limited number of data points.

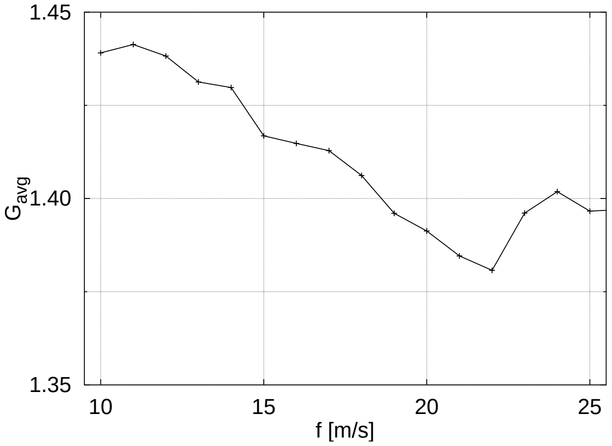

Figure 6: Average of G_f for stations in Southwest Iceland, shown against the mean wind speed, f.

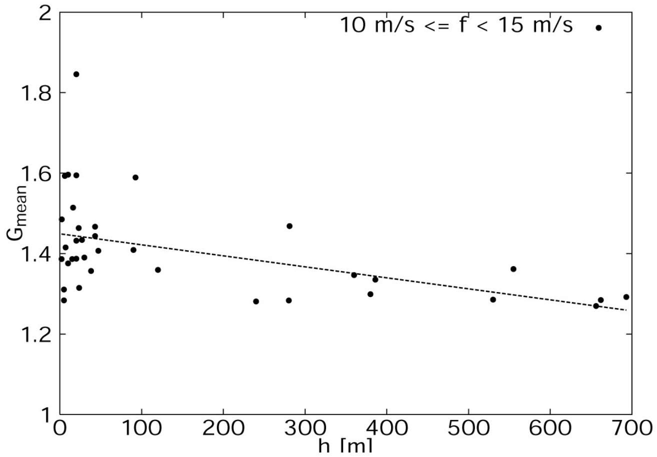

Figure 7: Data from all weather stations Average of G_f, for windspeeds, f, between 10 m/s and 15 m/s, is plotted against station altitude, h.

3.4 Gust factors and station altitude

Fig. 7, station altitude is compared to the mean gust factor in statically stable situations. To limit the bias due to mean wind speed growing with altitude, only observations with mean wind speeds between 10 m/s and 15 m/s are considered. As most of the stations in Southwest Iceland are located at low altitudes, data from all stations in Fig. 1 is used. The sloping line is the best fit to the data using the least squares method and serves to highlight a possible trend in the data.

The Figure indicates that the mean gust factor decreases with station altitude. As station altitude generally grows further inland, the figure also indicates that gustiness is on average lower at inland stations.

3.5 Gust factors and surrounding topography

At each weather station, the gust factor of wind blowing from the direction d_m of a nearby mountain is defined as G_m. The value of G_m is equal to G_d for the 10° interval in d that includes d_m. It is assumed that for most of the data, the wind direction at the weather station correctly indicates where the airflow is coming from.

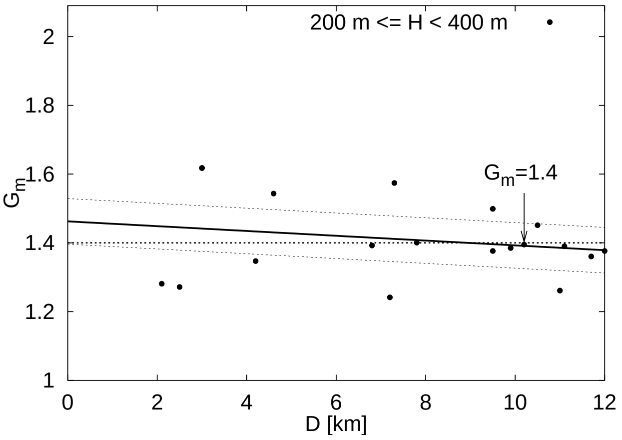

Figure 8: Mean gust factor, G_m, for wind blowing off a mountain of height H and in the distance D.

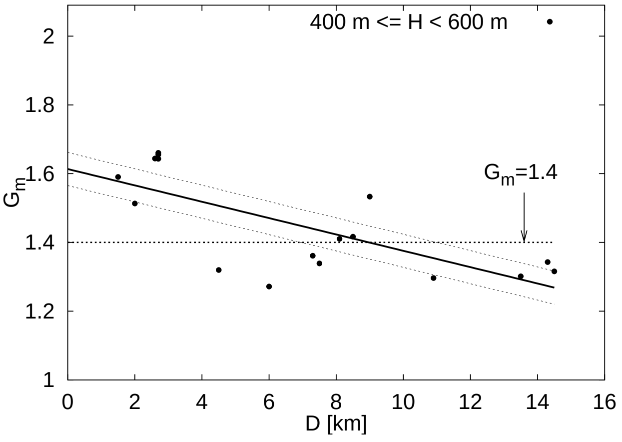

Figure 9: Mean gust factor, G_m, for wind blowing off a mountain of height H and in the distance D.

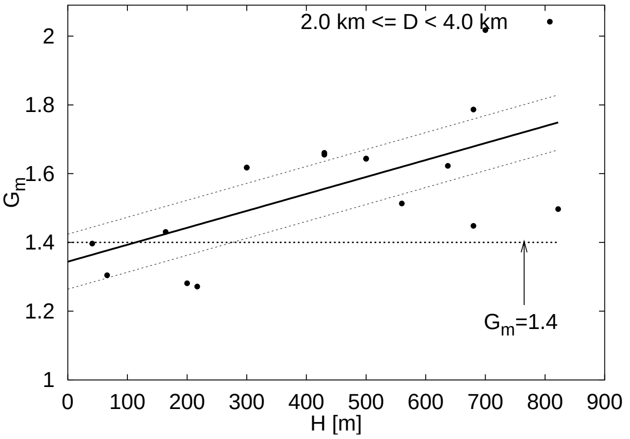

Figure 10: Mean gust factor, G_m, for wind blowing off a mountain of height H and in the distance D.

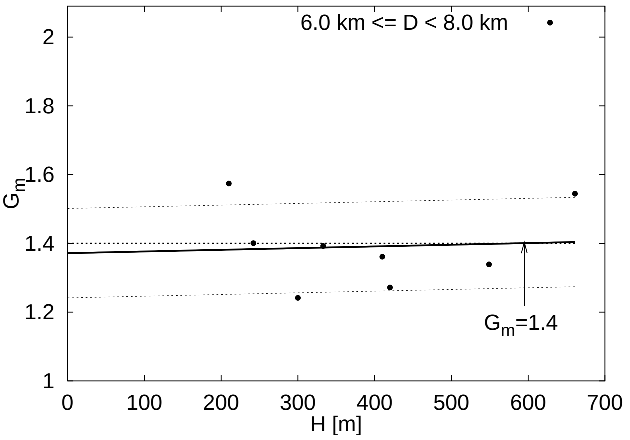

Figure 11: Mean gust factor, G_m, for wind blowing off a mountain of height H and in the distance D.

The behaviour of G_m as a function of mountain height above the weather station, H, and distance to mountain from weather station, D, was investigated. Fig. 8 and 9 show G_m as a function of D for two discrete intervals in H. The data used is from the stations in Southwest Iceland and only statically stable situations are considered. Each dot on the graphs corresponds to wind coming from the direction of a certain mountain at one of the stations. For clarity four straight lines are drawn on each graph. A horizontal line is drawn at $G_m = 1.4$, and serves as a first estimate for the mean gust factor of the airflow. The three sloping lines serve to highlight a possible trend in the data. The central line is the best fit to the data points, according to the method of least squares, and its error estimate is bounded by the upper and lower sloping lines.

In Fig. 10 and 11, G_m is plotted as a function of mountain height, H, for two discrete intervals in distance to mountain, D. The Figures are similar to Fig. 8 and 9, and the same data is used.

Fig. 8–11 and similar figures for other mountain heights and mountain distances, show the same behaviour. The Figures indicate that the downstream gust factor decreases as the distance to the mountain increases. It is also seen that the downstream gust factor increases for increasing mountain height and the influence of the mountain extends further downstream as the mountain gets higher. At short distances, mountains as low as 200 m appear to be able to have a strong effect on the mean gust factor. A more detailed analysis on the connection between the gust factors and surrounding topography is given in ÁGÚSTSSON and ÓLAFSSON (2002).

An attempt to summarize the effect of topography is made in Fig. 12, where the mean gust factors are plotted against distance from mountain and mountain height. Data from all stations in Fig. 1 is used, although still only statically stable cases are considered.

Not unexpectedly, mean gust factors greater than 1.6 are only found in the upper left corner of Fig. 12. All have a mountain rising at least 200 m above the station and not further away than 10 times the mountain height above the station. Lower mean gust factors scatter all over the figure, but there is a trend towards higher density of low-G at the lower end of the figure.

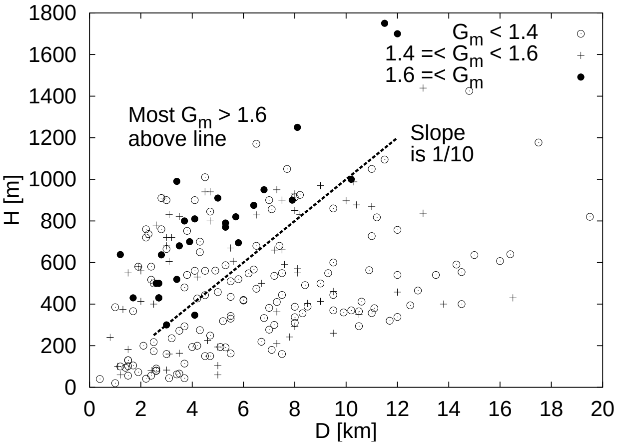

Figure 12: Three series of the mean gust factor G_m, plotted against mountain height, H, and distance to mountain, D Only one mean gust factor lower greater 1.6 is found below the black line with slope 1/10.

4 Summary and concluding remarks

A large collection of data from automatic weather stations has been analyzed in an attempt to investigate gust factors and parameters influencing the gust factors. Only data with mean wind speed greater than 10 m/s has been considered in this study.

The average gust factor in the dataset is close to 1.4, and appears to be independent of the static atmospheric stability and only slightly decreasing with increasing dynamic atmospheric stability. The independence of the gust factor of the static stability agrees with DAVIS and

NEWSTEIN (1968), although their dataset was obtained from only one location. The physical explanation of the gusts at different ends of the stability curve may however be quite different. In unstable air, turbulent eddies can give strong gusts, while in a stable airmass there is less turbulence, except where the airflow interacts with topography. In such a case, strong gusts can be produced, in particular downstream of mountains. The data in this study suggests that the gust-producing effect of topography in statically stable flows may compensate for damping of gusts by atmospheric stability.

An attempt has been made to create a parameter space for high mean gust factors in stably stratified flows, where mountain height and distance from the weather station are key parameters. Accordingly, to obtain a mean gust factor of 1.6 or more, it is necessary but not sufficient for upstream mountains to rise at least 200 m above the weather station and not be further away than 10 times the height of the mountain over the station.

Finally, the data indicates a regular decrease in the gust factor for increased wind speed and station altitude. The reduction of gust factor in stable flows is about 0.03 for every 5 m/s increase in 10 min mean wind speed for the wind speed range between 10 and 22 m/s. Although no such correlation in seen in the study of NAESS et al. (2000), other studies (DAVIS and NEWSTEIN, 1968; WEGGEL, 1999) show similar results, but their data does not allow for a quantitative comparison with the results of this paper. In weak to moderate winds, MITSUTA and TSUKAMOTO (1989) observe a similar reduction of the mean gust factor with increasing wind speed, and propose that it is due to a relative decrease of turbulence energy with regard to mean wind energy.

Detailed knowledge of the wind climate is of importance when hazards associated with strong winds are evaluated. Studies of the mean gust factor can give valueable information as to identify possible locations and situations where strong and gusty winds can be expected. Of no less importance is the knowledge of the maximum wind speed, but for determining the wind induced stress on structures, it is often necessary to know the strength and duration of the strongest wind gust. The strongest wind gust can though not be deduced from the mean gust factors, and a study of the maximum gust factors would therefore be a valuable next step towards a more detailed description of the wind climate.

Acknowledgements

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References

ÁGÚSTSSON, H., H. ÓLAFSSON, 2002: Hviðustuðlar. – Icelandic Meteorological Office, scientific report, 02022. Available in Icelandic at www.vedur.is/utgafa/greinarger dir/.

BRASSEUR, O., 2001: Development and application of a physical approach to estimating wind gusts. – Mon. Wea. Rev. **129**, 5–25.

CLARK, T. L., R. D. FARLEY, 1983: Severe downslope windstorm calculations in two and three spatial dimensions using anelastic interactive grid nesting: A possible mechanism for gustiness. – J. Atmos. Sci. **41**, 329–350.

CLARK, T. L., W. D. HALL, R. M. BANTA, 1994: Two- and three-dimensional simulations of the 9 January 1989 severe Boulder windstorm: Comparison with observations. – J. Atmos. Sci. **51**, 2317–2343.

DAVIS, F. K., H. NEWSTEIN, 1968: The variation of gust factors with mean wind speed and with height. – J. Appl. Meteor. **7**, 372–378.

DURRAN, D. R., 1990: Mountain waves and downslope winds. Atmospheric processes over complex terrain, W. BLUMEN Ed. – American Meteorological Society Monographs **23**, 59–81.

GOYETTE, S., O. BRASSEUR, M. BENISTON, 2003: Application of a new wind gust parametrization: Multiscale case studies performed with the Canadian regional climate model. – J. Geophys. Res. **108** (D13), 4374, 16 pp.

GRØNÅS, S., A. D. SANDVIK, 1999: Numerical simulations of local winds over steep orography in the storm over north Norway on October 12, 1996. – J. Geophys. Res. **104**, 9107–9120.

JUNGO, P., S. GOYETTE, M. BENISTON, 2002: Daily wind gust speed probabilities over Switzerland according to three types of synoptic circulation. – Int. J. Climatol. **22**, 485–499.

MITSUTA, Y., O. TSUKAMOTO, 1989: Studies on spatial structure of wind gust. – J. Appl. Meteor. **28**, 1155–1160.

NAESS, A., P. H. CLAUSEN, R. SANDVIK, 2000: Gust factors for locations downstream of steep mountain ridges. – J. Wind Eng. Ind. Aerodyn. **87**, 131-146.

NIELSEN, N. W., C. PETERSEN, 2001: Calculation of wind gusts in DMI-HIRLAM – Danish meteorological institute, scientific report, 01–03.

ÓLAFSSON, H., H. ÁGÚSTSSON, H. SIGURJÓNSSON, 2002a: Two cases of downslope windstorms observed during the Snæfellsnes experiment (SNEX) – Danish Meteorological Society, 23th Nordic Meteorological meeting. Available at http://www.vedur.is/fiv.

ÓLAFSSON, H., H. SIGURJÓNSSON, H. ÁGÚSTSSON, 2002b: SNEX – The Snæfellsnes experiment. – American Meteorological Society, 10th conference on mountain meteorology, P3.34, 400–401.

PELTIER, W. R., J. F. SCINOCCA, 1990: The origin of severe downslope windstorm pulsations. – J. Atmos. Sci. **47**, 2853–2870.

SCINOCCA, J. F., W. R. PELTIER, 1989: Pulsating downslope windstorms. – J. Atmos. Sci. **46**, 2885–2914.

STULL, R. B., 1988: An introduction to boundary layer meteorology. – Kluwer academic publishers, 670 p.

WEGGEL, J. R., 1999: Maximum daily wind gusts related to mean daily wind speed. – J. Struct. Eng. **125**, 465–468.

ÞORSTEINS, E., 1999: Hönnunargildi vindálags samkvæmt skilgreiningu ENV 1991-2-4. – Rannsóknastofnun byggingariðnaðarins, Reykjavík, Iceland, technical report 99–17.