the measurement of gustiness at routine wind stations - a review

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Abstract

Many meteorological stations observe wind gusts on a routine basis. The measuring procedures, however, are far from uniform. Some stations measure "instantaneous gusts" with fast response equipment, whereas other stations report the fastest mile. In this report it is tried to unify the observation practice by formulating specifications for the measurement of wind gustiness. The user requirements are reviewed and the consequences for the measuring system are discussed. Two aspects play an important role in this problem. First of all it is important to observe wind extremes in a uniform way and such that the results can be used directly in wind load studies. Secondly, gustiness measurements, can be used to characterize the exposure error of wind stations. The gustiness of the wind is a measure of the turbulence intensity which is directly related to the roughness of the upstream terrain. This information enables the correction of mean wind observations for local perturbations. Application of such procedures would greatly enhance the quality of surface wind observations over land. The best gustiness parameters for this application are the standard deviation of wind speed and wind direction. It is therefore recommended to measure these parameters on a routine basis with the new generation of wind measuring systems.

1. Introduction

At its 9th session, the Commission for Instruments and Methods of Observation concluded that upgraded specifications for the measurement of wind gustiness were urgently needed. The WMO-Guide to Meteorological Instruments and Methods of Observation (WMO-8, 1983) does not provide sufficient guidelines to guarantee compatible measurements, resulting in considerable discrepancies between data sets from different locations.

The basic problem is the lack of definition and uniformity of the observed wind gusts. Slowly responding wind measuring systems measure weaker gusts than quickly responding systems. Until now, WMO does not specify the duration of the gusts that should be measured and even with a specified duration it would be useless without a proper definition of the term "duration". The actual situation has resulted in important differences between observational practices in different institutes and countries. In the USA for instance, extensive climatology exists of the "fastest mile" (Simiu et al., 1979) whereas "instantaneous" gusts are archived in the UK (Collingbourne, 1978) and in New Zealand (Bowen, 1981). By instantaneous gust is meant the maximum excursion of the pen trace on a recorder and it is often called the 3 s gust (cf. Jackson, 1977). These differences are mainly caused by the technical possibilities of the equipment rather than by a motivated choice.

A number of reasons exist to improve the situation described above. First of all it is difficult to use measurements (e.g. 3 s gusts) without knowing what they exactly mean. Even a description as "the fastest mile" can be misleading if it is not realised that the equipment measures non-overlapping wind displacements of 1 mile. If an overlap of two recorded miles is considered, even a "faster mile" might occur than the fastest mile that is recorded.

Secondly the range of applications of gustiness measurements has broadened. Extreme wind speed data are not only used for warnings and load studies, but the variability of the wind is also an important parameter in application areas as air pollution modelling and wind energy. In general it can be stated that the gustiness of the wind or the turbulence intensity is useful where some form of Monin Obukhov similarity is used e.g. to extrapolate the wind profile, to estimate diffusion

coefficients or to apply exposure correction for the wind station.

Another reason for improving the specifications for wind measuring systems is the automation of observation methods. More and more classical wind recording devices are replaced by microprocessor systems which take samples from the anemometer and windvane signal, do some sort of data reduction and send the results to a storage device. Such systems are very powerful and can still be reasonably cheap, if they are mass produced on the basis of generally accepted specifications.

This report reviews the actual situation with respect to gustiness measurements. The requirements of different users of wind data are investigated and finally recommendations are made for specifications of new wind measuring systems. It is tried to provide specifications that can be implemented easily with modern technology. On the other hand, the data reduction is choosen in such a way that many applications can be served with the same data.

The specifications for mean wind speed and direction as they exist now in the WMO-Guide to Meteorological Instruments and Methods of Observation (WMO-8,1983) are only partially discussed. Observation height, averaging interval for mean wind speed and minimum requirements for exposure are widely accepted and only very convincing arguments can be used to change them. The emphasis in this report is on the measurements of gustiness at standard synoptic or climatological stations.

2. The needs of wind-data users

In this chapter the actual use of gustiness and the possible re-
quirements in future will be discussed. Gustiness should be interpreted
here as wind variability. In most cases the gustiness is quantified by
means of the standard deviation of wind speed and/or direction and the
maximum gust in a given time interval.

2.1 Requirements for weather forecasting

Wind speed and wind direction averaged over the last 10 minutes of
each hour are standard observations and are exchanged on a global basis
by means of SYNOP and SHIP bulletins. This information is used by
meteorologists together with other information to obtain a complete
picture of the weather situation. Wind extremes are usually reported in
strong wind cases and exchanged on a regional basis only. They are used
to describe the weather situation and for warning purposes. So far wind
information is used in a rather qualitative way and differences in gusts
due to differences in the response characteristics of the equipment will
hardly be noticed by the meteorologists, also because wind stations show
considerable departures due to exposure problems. For ship, platform and
buoy observations at sea the situation is slightly different; exposure
problems related to inhomogeneous surface vegetation and topography do
not exist here. However, wind measurements above sea are often contami-
nated by the flow distortion and made at non-standard observation
heights (see Dobson, 1981 for a review).

Observations are the starting point for forecasting systems, and
data assimilation is the initial step in all models. Although the two
wind components are part of the set of dependent variables for which
initial conditions are needed, surface wind observations are hardly used
in forecast models. The initial conditions for the surface wind are
derived from model assumptions, upper air observations and pressure
measurements. We quote from the research manual, describing the global
model in operation at the European Centre for Medium and Longe Range
Weather Forecasting (ECMWF, 1986): "Winds from ships are used, winds
from land stations are not used". No reason is given but the argument is
clear from an enquete among modellers by Pailleuse (1986). He concludes

in a discussion about accuracy of observations: "Users have difficulties
with surface wind observations. The problem is more related to the
representativeness of the measurement than to its accuracy (how to get
rid of the local effects in a large scale analysis)".

With the increase of computer power it has been possible to reduce
the resolution in global forecast models. Limited area models describe
even more detail. This has implications for the resolution of input
data; fine mesh models require an initial wind field that is independent
of the pressure analysis, because the geostrophic relation is no longer
valid on the smallest scale (cf. Lorenc, 1981: Cats, 1980, 1984;
Nordlund, 1976). However, it is well known that wind observations from
land stations are contaminated by perturbations related to non represen-
tative upstream roughness, distinct obstacles or topographic effects.
The horizontal length scale of these perturbations ranges from 100 m to
several kilometers. All these scales are subgrid, even for the most de-
tailed limited area models. In the context of an analysis scheme Lorenc
(1981) distinguishes two parts in the observation variance, namely (i)
pure observation errors and (ii) variations on scales smaller than those
that are resolved by the analysis scheme. The latter perturbation, which
can be interpreted as an exposure perturbation or as representativeness
error, can not be neglected for most wind stations above land. On the
other hand, techniques are available now to correct wind measurements
for local roughness effects (cf. Wieringa, 1976, 1986) and for low
topography (cf. Bowen, 1983; Taylor and Lee, 1984). Cats (1984) shows
that the observation error in a wind analysis scheme can be reduced to
about 1 m/s by applying appropriate exposure corrections.

With respect to the use of wind data in operational forecasting, we
conclude that the averaged wind speed, wind direction and peak gust are
sufficient. However, representativeness errors limit the quantitative
use of wind data in analysis schemes for global or limited area models.
Given the tendency towards higher resolution models, there is a need to
correct for representativeness errors. As will be shown in chapter 3
these corrections can easily be applied if sufficient station informa-
tion is available. One of the parameters that is needed is the station
specific upstream roughness length, and this can be derived from
gustiness observations.

2.2 Air pollution modelling

Air pollution modelling relies heavily on meteorological input data. Dilution and plume rise depend on wind speed at stack height; dispersion and long range transport depend on turbulence characteristics and on the wind field over the area where the pollutant is dispersed. Most papers on air pollution modelling stress the importance of high quality meteorological observations (cf. Sivertson, 1978; Hanna 1982; Irwin et al., 1985; Van Dop, 1986). We limit ourselves here to wind observations at a standard height of 10 m and parameters that are related to these observations.

Hanna et al. (1977) recommend to archive one hour averages of wind speed and wind direction from the National Weather Service stations in the USA. Additional measurements of the roughness length z_0, the friction velocity u_* and the standard deviation of wind direction σ_θ would be required. Hoffnagle et al. (1981) recommend wind speed, direction, the inverse of wind speed, standard deviation of speed and direction, averaged over 3 minutes or one hour dependent on the application. Sivertsen (1978) proposes wind speed, direction with standard deviations averaged over 5 minute intervals. Mehta and Cermak (1979) conclude in a summary of needs for atmospheric diffusion, that direction and speed are necessary with averaging intervals from 10 to 60 minutes. Also the extrapolation of wind profiles to stack height and the spatial correlation is considered to be important. The importance of an accurate extrapolation scheme is also stressed by Turner (1979). It is shown by Holtslag (1984) that wind at stack heights can be derived from standard observations, provided that an accurate z_0-table exists for this station.

It is obvious that all possible air pollution applications and wishes of users add up to a quite unworkable data reduction scheme, requiring a large number of parameters to be derived from the wind signal with different time intervals. The main requirements in air pollution modelling are representative wind fields and diffusion coefficients. Also a clear tendency can be recognized to put data and modelling techniques in the framework of similarity theory (cf. Irwin, et al. 1985). It appears therefore appropriate to organize the wind measurements in such a way that (combined with other measurements) similarity

parameters can be derived. This means that not only wind speed and wind
direction averages are needed but also standard deviations. The latter
can be translated into friction velocities (or aerodynamic resistances
as shown by Hicks et al., 1985) or can be used to construct a station
specific roughness table (Beljaars, 1987a).

The fluctuations in wind direction are mainly responsible for
lateral plume dispersion. The standard deviation of wind direction or
the standard deviation of the lateral velocity components, is therefore
proposed in many studies as standard input for plume width models (cf.
Skibin, 1972; Turner, 1979; Irwin et al., 1985; Hoffnagle et al., 1981;
Sivertsen, 1978; Gryning et al., 1987). Although the optimal averaging
time depends on the downstream distance from the pollutant release
point, routine measurement of 10 minute averages of the standard devia-
tion of wind direction would of great advantage to the air pollution
community.

The averaging time as proposed by different air pollution modellers
varies from 1 minute to one hour. This has to do with the time scales
that are involved at different stages of the plume dispersion after
release. Too many data have to be archived when 1 minute averages are
considered. Here again it appears appropriate to relate diffusion and
plume meandering to the spectrum of turbulence, that can be expressed by
means of empirical functions in the characteristic parameters of the
atmospheric boundary layer (friction velocity, heat flux at the surface,
mixing layer height etc., cf. Højstrup, 1982; Kaimal, 1978). Routine
observations should be sufficient to estimate these characteristic par-
ameters. The averaging time should be such that the turbulent fluctua-
tions are smoothed out in the averages and that the standard deviations
cover the entire three dimensional turbulence spectrum. An averaging
time of 10 minutes is appropriate in this sense, because it is compat-
ible with the spectral gap that separates turbulent fluctuations from
time evolution, e.g. diurnal changes etc. (cf. Fiedler and Panofsky,
1970). In contrast to weather forecast applications, where only the last
10 minute interval of each hour is used, it would be desirable to have
continuous monitoring of the wind by means of 10 minute averages. Rela-
tively small time scales are involved in plume dispersion, but also the
mesoscale meandering from one 10-minute interval to the next is
important.

2.3 Wind climatology

A climatological database for wind will always be a working compromise. It is practically restricted by the available means of observation and by the limitations in capacity to process data and to store them. On the other hand, it should contain all the essential information to give an adequate description of the wind climate and accomodate as much as possible the requirements of potential users of climatological data. Three groups of applications are distinguished, namely wind energy studies, air pollution modelling and wind loading. Air pollution modelling will not be discussed here, since its climatological requirements are similar to those for on-line use and have been discussed in the previous section.

The main requirement for wind energy feasibility studies is a continuous record of wind speed averages. The energy potential can easily be derived from such a record. Mehta and Cermak (1979) also mention fluctuations, profiles and spatial correlations for which climatological information would be needed. The need for profiles or methods to extrapolate from standard observation height is obvious, since most modern windmills have hub heights much larger than 10 m. Methods are available now to estimate wind profiles from routine weather observations viz. the wind at 10 m height, the terrain roughness and cloud cover (Holtslag, 1984). The type of turbulence information needed for dynamic load estimates on turbine blades is very specific and can not be expected to be available in standard climatological databases. Experiments have to be done to relate the turbulence parameters needed in wind energy applications to boundary layer similarity parameters. Hence climatological information is only needed for the similarity parameters.

Probably the most important application of wind climatology is the estimation of extreme loads on buildings and constructions. No standard practice seems to exist for this problem. Davenport (1982) describes the wind loading process as a chain of interconnected components going from wind climate via terrain influence, aerodynamic and mechanical response to safety and comfort criteria. Davenport distinguishes wind climate and wind structure, where the wind climate is determined by the large scale weather patterns. In this view wind climatology should be based on averages; Davenport prefers 10 to 15 minute averages. Turbulent fluctuations

with time scales of less than 10 minutes are considered to be part of
the local wind structure. Also inhomogeneous effects such as changing
surface roughness, local obstructions and hills are seen as part of the
wind structure.

The wind climate based on averages over 10 minutes is sufficient
for such an analysis. The structure and turbulence characteristic can be
determined from knowledge about the surface roughness in homogeneous
cases, and from roughness and elevation maps in weakly inhomogeneous
cases. In situations with strong inhomogeneous flow (e.g. near hills or
in city centres with tall buildings) a wind tunnel test with an appro-
priate model is needed for accurate modelling. In such an experiment the
wind tunnel flow produces the turbulence structure; the averaged upper-
level wind is needed as a boundary condition. The latter can be derived
by extrapolating station winds with help of a specified station rough-
ness. This technique can be supplemented by upper air wind observations
from pibal or rawinsonde balloons (Davenport, 1967).

The type of analysis described above only works in cases, where a
distinct spectral gap exists between the wind climatology of say 10
minute averages and the structure of turbulence. This is appropriate for
e.g. the Dutch situation, where storm depressions are responsible for
the extreme wind climatology (cf. Rijkoort and Wieringa, 1983). Such
storms have horizontal scales of the order of 100 km and are well repre-
sented by 10 minute averages even if they are measured once per hour
only. The gusts can easily be calculated by making assumptions about the
terrain roughness and by applying an appropriate gust model. Formally
this is only valid for homogeneous terrain, but in so-called complex
terrain we have a problem anyway: the location of the wind station does
not necessarily have the same wind climate as the site where we need the
information, due to differences in terrain roughness and surface eleva-
tion.

Climatology of wind averages is not sufficient in cases where the
duration of a strong wind event (e.g. a thunderstorm) is equal to or
smaller than the averaging time. The pressure field that is driving the
wind is very unstationary and inhomogeneous and the separation of scales
can not be justified. Davenport (1982) proposes to solve this problem by
considering small scale events as thunderstorms, hurricanes and
tornadoes separately. Georgiou et al. (1983) estimate return periods of

gusts by applying a Monte Carlo method to the model parameters of tropi-
cal cyclones. Gomes and Vickery (1978) apply this method to thunder-
storms, tornadoes and hurricanes. The model for thunderstorms requires
continuous monitoring of wind gusts, and Vickery (1979) recommends to
record 2 to 3 second gusts for this application (see also Bowen, 1981).
The reason is that this duration accomodates as much as possible wind
loading studies; a storm gust duration of a few seconds corresponds to a
"wind run" (gust duration multiplied by average velocity) of the order
of 100 m. This is sufficient to engulf structures of ordinary size and
to let them "feel" the full load of a potentially damaging gust. Mackey
and Ko (1975) conclude from a detailed analysis of gust data, that
buildings with a height of 30 m respond to 3 s gusts whereas 50 m high
buildings give full response to 15 s gusts. It is impossible of coarse
to accomodate all potential users, but gusts with a duration of a few
seconds appear appropriate for many applications, particulary because
methods are available to rescale gusts to other durations (Wieringa,
1973; Beljaars, 1987b).

In summary it can be stated that most risk studies need wind aver-
ages only. It is important of course to eliminate station-specific per-
turbations; exposure correction should be applied if possible. To esti-
mate the turbulent fluctuations it is also necessary to determine the
roughness length of the terrain for which the risk study is carried out.

All this applies when the length scales of the weather systems,
that are responsible for extreme winds, are large compared to the turbu-
lence scales. This is not the case for thunderstorms, hurricanes and
tornadoes. Tornadoes are very small scale and infrequent and are unlike-
ly to hit any wind station. Anyhow, the wind station will probably not
survive such an event. Thunderstorms however, are much more frequent; it
is important to record peak gusts as well as averages for this type of
event. Moreover it is already common practice in many climatological
services to archive peak gusts (e.g. Collingbourne, 1978) and users such
as insurance companies make use of these data. Also Mehta and Cermak
(1979) recommend to measure and archive 2 to 3 second gusts in a review
of user needs.

3. Exposure correction

A common problem in all the applications described in chapter 2 is
the representativeness of wind data. Wind measurements are often per-
turbed by very local effects from buildings, vegetation and topography.
Although meteorological networks are designed to measure inhomogeneities
on a synoptic scale or even meso scale, we would like to remove the
effect of the smallest scales. It is very unlikely that weather forecast
models will be routinely available, that describe details of the flow
with a resolution smaller than 10 km on a prognostic basis. Moreover
this would require initial data with the same resolution and a high
network density, which is just not feasible. It is therefore important
that users of wind data have tools and station-specific information to
remove the complex terrain effects on scales smaller than about 10 km.
Applicability of wind measurements would be greatly enhanced if station
information of this type would be available. WMO should encourage the
national services to provide such information and publish it in such a
way that all users of wind data have access to it.

Two types of perturbation are distinguished, namely perturbations
related to a variable upstream terrain roughness and topographically
induced perturbations. Both types will be discussed in the next sec-
tions. It will be assumed that both perturbations are small and that the
anemometer is mounted acceptably free from direct interference from e.g.
buildings or vegetation. The guide for meteorological observations (WMO,
1983) specifies a minimum distance of 10 obstacle heights between the
nearest obstacle and the anemometer. This specification should be seen
as a minimum requirement; an anemometer that is e.g. only 100 m away
from 10 m high trees cannot be considered to be well exposed.

3.1 Topographic perturbations

In this section we limit ourselves to situations where the pertur-
bations due to topography are small and the local flow is still mainly
determined by the large scale pressure field. If the topography domi-
nates the local flow, as in cases with recirculation and katabatic
winds, the wind measurements hardly contain any "representative" infor-
mation and can not be generalized easily.

A number of experimental studies (e.g. Bradley, 1980; Jenkins et al., 1981; Taylor and Teunissen, 1985) and theoretical studies (e.g. Jackson and Hunt, 1975; Mason and Sykes, 1979) have been devoted to the flow over low hills, and workable models are becoming available now for neutral conditions (cf. Taylor et al., 1983; Beljaars et al., 1987). Although the condition of neutral flow seems rather restrictive, it still gives useful information for climatological applications where the emphasis is on strong wind cases (in strong winds over land, the stability will be close to neutral in the surface layer). The restriction to neutral flow simplifies the model and reduces the number of input parameters needed to run the model.

High resolution models such as those by Taylor et al. (1983) and Beljaars et al. (1987) compute the flow over low hills with arbitrary shape and cover an area of say 10 x 10 km. The output of such models can be the ratio of the wind speed at a particular anemometer location and the area-averaged wind at the same height, i.e. the model computes the correction needed for a wind station to make it representative for a large area. Such ratios should be calculated as a function of wind direction and be available as a correction table for the wind station. Although the technique of computing flow perturbations in complex terrain is available, it is still fairly complicated and probably not feasible yet for most meteorological services. However, with the increasing power of personal computers, this type of modelling will become more accessible. The necessary input consists of a digitised map of surface elevation surrounding the wind station.

For simple topographic features (two-dimensional hills or bell-shaped three-dimensional hills with horizontal dimensions up to to 1000 m) guidelines exist to estimate the corrections for a wind station at the top of the hill (see Bowen, 1983; Taylor and Lee, 1984). Flow over more complex and larger scale topography can be analysed by means of meso scale models (cf. Walmsley, 1983 for a review). The complexity of such models ranges from very simple in the mass-consistent approach (e.g. Sherman, 1978) to very complicated in models that solve the full set of conservation equations (see Pielke, 1984).

Whatever method is used to estimate exposure corrections, it would be an important step forward if such corrections became available for all wind stations. Reid (1987) shows for a practical situation that wind

speed corrections on a mountain can be calculated with an accuracy of about 1 m/s. WMO should encourage the computation and estimation of such data and publish the results in well-disseminated documents.

The conclusion we draw here is that the corrections due to changes in surface elevation are important and should be calculated. The only information that is needed is a detailed topographic map of the wind station surroundings. No additional measurements are needed for this.

3.2 Perturbations due to roughness changes

The direct surroundings of a wind station do not necessarily have the same surface characteristics as the whole area for which the wind measurement is supposed to be representative. In the extreme case of e.g. a big forest one would deliberately choose a non-representative open area to locate a wind station. The reason is very simple: at a measuring height of 10 m the anemometer would receive no "signal" at all in the middle of a forest.

It is clear that most wind stations suffer from "representativeness errors" caused by inhomogeneities in surface cover; really uniform terrain hardly exists. These errors can be avoided by choosing a measuring height that is large compared to the perturbing roughness elements (houses, trees etc.), leading to a roughness dependent measuring height. In some countries, e.g. the United Kingdom, anemometers are subjectively placed at the "effective height" where the wind speed is estimated to be equivalent to the wind at 10 m height over open country (cf. Collingbourne, 1978). When it is assumed as a working hypothesis, that the measuring height should be 100 times the roughness length, then a 100 m mast would be needed above forest and a 3 m mast would be sufficient above grassland. Departure form the standard height of 10 m is also suggested in the WMO guide for observations (WMO, 1983) for situations with poor exposure. However, terrain roughness estimations are very difficult to make and the resulting measuring height would be quite arbitrary. Moreover the roughness length of the upstream terrain will in general vary with the wind direction. Due to these practical problems it is believed that a roughness-dependent measuring height would deteriorate the representativeness of the wind observations rather than improve it.

The alternative is to prescribe a standard measuring height (10 m)

and to apply a correction, that depends on the wind direction and is different for each station. The standard observation height of 10 m is widely accepted now and it would not serve the cause of standardization to change it.

A consistent approach to deal with roughness inhomogeneities would be to treat the perturbations equivalent to the topographic perturbations, namely by applying a high resolution model. Such models exist and will soon be available in personal computer versions (cf. Walmsley et al., 1986; Beljaars et al., 1987). An example of representativeness computations is presented by Walmsley and Salmon (1986). They determined the corrections needed for a wind station on an island such that the wind observation can be interpreted as if it was made over sea. In this particular case the roughness length distribution is well defined and relatively easy to determine. A comparable procedure is followed by Jensen et al. (1984) for the European wind atlas. They made an subjective estimate of the terrain roughness up to 5 km from the different wind stations for all wind directions. A multiple internal boundary layer analysis is employed to determine the effect on the wind profile. For most land situations, however, it is very difficult to make an accurate map of the roughness length distribution. The contribution of scattered obstacles to the overall roughness length is difficult to estimate and requires a great deal of judgement experience.

An alternative approach is proposed by Wieringa (1976), who derives the roughness length of the upstream terrain from the wind gusts observed at the windstation. The advantage is that no inconsistency can exist between the roughness length as used for exposure correction and the roughness length that is felt by the wind as it approaches the anemometer. A subjective terrain classification is not needed now. The exposure correction is made by extrapolating the measured wind up to 60 m height, making use of the known roughness length in the logarithmic profile.

$$\frac{U_{60}}{U_{10}} = \frac{\ln \frac{60}{z_o}}{\ln \frac{10}{z_o}}, \qquad (3.1)$$

where U_{10} is the observed wind speed at 10 m height, z_o is the roughness length of the upstream terrain and U_{60} the extrapolated wind at 60 m height. For an optimal exposure correction, we would like to choose the extrapolation height as large as possible (far away from the perturba-

tions), but the height depends on the upstream length for wich z_0 in (3.1) is representative. If z_0 is representative for a large upstream area, the extrapolation height should be large; if the roughness length corresponds to a small area extrapolation is only justified to low heights. The horizontal and vertical dimensions are coupled by means of the internal boundary layer concept. Two arguments can be give for choosing 60 m in (3.1): (i) Expression (3.1) has proven to work well in a climatological application (cf. Wieringa, 1986) and (ii) by considering memory effects in turbulence it can be shown that the extrapolation height should have about this magnitude if z_0 is derived from gustiness measurements (Beljaars, 1987a).

It should be noted that logarithmic extrapolation can only be justified in neutral stability conditions. For strong winds this is often a reasonable approximation particularly when the extrapolation is used to construct a homogeneous wind field from different stations.

Wieringa (1980) shows that homogeneous wind fields can be constructed in the neutral approximation for wind speeds larger than 3 m/s. If homogeneity from station to station is not sufficient but also the absolute wind speed at larger heights, e.g. 60 m, is needed, then the stability corrections should be included in equation (3.1). The stability corrections to the logarithmic profile are well documented now (cf. Panofsky and Dutton, 1984) and can even be estimated from routine observations of cloud cover, wind speed and temperature (cf. Holtslag, 1984; Holtslag and Van Ulden, 1983).

The main problem with (3.1) is that an accurate estimate of z_0 is needed, corresponding to the terrain upstream of the anemometer. In principle it would be possible to survey the terrain and estimate z_0 on the basis of empirical classification (Van Dop, 1983; Wieringa, 1980, 1986). This requires experience and entails at least a factor-two uncertainty in z_0. The problem of averaging in inhomogeneous situations is also not yet completely solved (Taylor, 1987). The most accurate way to estimate the z_0-value, that is "seen" by the anemometer, is to use the information provided by the anemometer itself.

The surface stress as seen by the anemometer can be estimated by applying similarity arguments to the measurements of horizontal velocity fluctuations. This method is used by Hicks et al. (1985) to estimate the aerodynamic resistance for dry deposition of pollutants, although they ignore the scaling of horizontal fluctuations as a function of z_i/L,

where z_i is the inversion height and L the Obukhov length. To avoid the
problem of stability corrections we limit ourselves to near neutral
flow. For neutral flow the logarithmic profile can be rewritten as (cf.
Lumley and Panofsky, 1964 or Panofsky and Dutton, 1984)

$$U = \frac{\sigma_u}{2.2 \ \kappa} \ln \frac{z}{z_o} ,$$
(3.2)

The ratio σ_u/u_* is assumed to be 2.2 which is the neutral value proposed
by Panofsky et al. (1977) adapted for an averaging time of 10 minutes
(the corresponding high pass filter causes a reduction of 4%). Since
equation (3.2) is only valid in neutral situations, we limit ourselves
to strong wind cases (U > 6 m/s) to derive z_o-values. At least 20
measurements of U/σ_u are statistically necessary to determine a reason-
ably accurate z_o-value. This procedure has to be repeated for all wind
directions, say in 30 degree sectors, and different seasons, e.g. if the
foliage disappears in the winter season. The z_o-table created in this
way is station-specific and only needs an update, if the station is
moved or if the surface situation (vegetation, buildings etc.) changes
considerably.

Alternatively, if σ_u-measurements are not available, peak-gusts
combined with wind averages measured over the same time intervals can be
used to estimate σ_u. The relation between peak-gusts and standard devia-
tions is discussed more extensively in chapter 5 (see also Beljaars,
1987) and turns out to be well behaved and predictable, provided that
exact information on filtering by the measuring chain is available. Very
often peak-gusts are measured over the last hour whereas the wind aver-
age is taken over the last 10 minutes of the hour. This incompatibility
can be solved by estimation of the hourly average by means of
$U = (5/12)U_{i-1} + (7/12)U_i$, where U is the estimate of the hourly average
of hour i and U_i and U_{i-1} are the wind speed over the last 10 minutes of
hour i and i-1 respectively. The derivation of z_o from peak gusts has
been applied extensively by Wieringa (1986) and can be regarded as a
"poor-mans version" of the standard deviation method.

The conclusion we draw here is that knowledge about the upstream
roughness length of a wind station is important for many applications
and that this parameter can most easily be derived from the standard
deviation of the wind speed. It is believed that roughness lengths
determined in this way are more accurate than those derived from a
subjective survey of the terrain.

4. Definition of wind parameters to be recorded

The selection of relevant wind climatology parameters has been sub-
ject of a Workshop on Wind Climate (Mehta, 1979; see also Peterson and
Mehta, 1980). The summary of recommendations, as given in the proceed-
ings, is used here as a starting point for the discussion (see Table
4.1). Many users of climatological and on-line wind data were repre-
sented. Although operational meteorologists and weather forecast
modellers did not take part in this workshop also their needs are
reasonably covered by table 4.1. A general problem that was recognized
in this workshop was the representativeness of the observation and the
need to extrapolate the wind to larger heights. In accordance with the
conclusions of the previous chapter we supplement the table of par-
ameters with the required station information in table 4.2.

Table 4.1 Parameters to be recorded every 20 minutes
according to Mehta (1979)

Parameters	Application
1 Averaged speed and direction (from components)	Windenergy, pollutant dispersion, forces on structures, agriculture, aviation.
2 Peak speed/direction (2 second gust)	forces on structures
3 Fastest one minute (speed/direction)	wind turbines, forces on structures
4 Fastest mile (speed/direction)	continuity with previous data
5 Standard deviation of fluctuations (speed/direction)	pollutant dispersion

Table 4.2 Station information required for many
applications

Parameter   Application

z_0 as a function of wind direction   exposure correction;
(30 degree sectors) and season   extrapolation of wind

map of surface elevation   exposure correction

The extensive list of parameters in table 4.1 appears sufficient for most applications and also contains the necessary information to construct the roughness table. However, no attempt is made to limit the number of parameters and to keep the procedures and parameters compatible with the actual observation practice (see also the comments by Readings et al., 1982). Computation and storage of all the proposed parameters is not feasible for most operational wind stations. Many climatological services will have difficulties with a change from 3 numbers per wind station each hour (speed and direction averaged over the last 10 minutes and the peak gust) to 8 numbers per 20 minute interval. Not every institute will be able to cope with this large amount of data. A compromise is needed here.

We will discuss the data reduction aspects and the different parameters of table 1 to see if these parameters are really needed or can be derived from other information.

- Averaging time

The averaging time of 20 minutes as proposed by Mehta (1979) is quite arbitrary (cf. Readings et al., 1982). Averaging times from 10 to 30 minutes are acceptable because in this way an appropriate distinction is made between turbulence and diurnal or synoptic changes (see Fiedler and Panofsky, 1970 for a discussion of different time scales in the atmospheric boundary layer; see also Baer and Withee, 1971). The turbulence is smoothed out sufficiently and the successive averages give a description of the evolution of the mean flow. An averaging time of 10

minutes is still preferable for two reasons: (i) Averaging over 10 minutes is common practice right now (ii) standard deviations calculated over 10 minute intervals don't need trend correction, which is important in order to keep the data reduction as simple as possible.

- Averaging of wind components verses scalar averaging

Traditionally wind speed and wind direction are averaged independently. The wind speed is the magnitude of the horizontal wind vector here. We will call this scalar averaging, with the scalar average as the result. The popularity of this type of averaging is related to its simplicity. Most anemometers and vanes produce signals proportional to the horizontal wind speed and the wind direction respectively. Averaging wind direction and computation of its standard deviation can pose problems when the direction is fluctuating through north where a discontinuity of 360 degrees is present (the gap problem). A number of methods exists to solve this problem (Verrall and Williams, 1982; Skibin, 1984; Nelson, 1984; Yamartino, 1984; see Turner, 1986 for a review). The simplest algorithm for microcomputer-based data reduction schemes is probably that where successive samples are compared. If the difference is larger than 180 degrees, then 360 degrees is subtracted from the last sample; if the difference is smaller than -180 degrees, then 360 degrees is added. The resulting record is continuous so that no need exists to store the entire data sequence. Standard single pass methods for the average and the standard deviation can be used now.

The alternative for scalar averaging is averaging over the two horizontal wind components. For the usual anemometer/vane system this implies the computation of the two components for each sample. The gap problem does not exist for this type of averaging. From the macroscale meteorological point of view component averaging is better than scalar averaging, because it results in a more direct measure for the air mass motion.

The difference between the scalar average of the horizontal wind and the component average is generally small (between 1 and 4%; cf. Businger et al., 1971). The difference is in first approximation proportional to the variance of the lateral velocity fluctuations devided by

the mean wind speed (Frenkiel, 1951; Skibin, 1973). The correction can be calculated, if the standard deviation of the wind direction fluctuations is measured. Also the standard deviation of the wind components can be related to the standard deviation of the horizontal speed and the direction (Ackerman, 1983) with acceptable accuracy. This implies that component averaging and scalar averaging are approximately equivalent, except for extremely weak winds ($<$ 2 m/s). In the latter case the turbulent fluctuations are of the same order as the mean wind; the air mass moves back and forward and the averaged components may even be close to zero. The scalar wind (the averaged magnitude of the horizontal vector) does not approach zero when the wind is fluctuating, as in the case of convective situations. Whatever method is used, the detected air motion will not be representative for a large area. The fundamental advantage of component averaging is therefore of limited value. Although weak wind situations can be very important in e.g. air pollution episodes, it can be concluded that vector-averaged winds give only slightly better information about regional motion of air masses than scalar-averaged winds.

From the technical and operational point of view, scalar averaging is preferable for a number of reasons. First of all the wind speed and wind direction can be treated separately. When one sensor drops out the other is still operating. Secondly, the datareduction is simpler than in the case of component averaging. Even manual averaging from strip chart records is reasonably accurate, whereas complicated sine and cosine computations have to be done for component averaging. Finally, scalar averaging is compatible with common usage.

We conclude here that component averaging would be preferable from the fundamental point of view, but that scalar averaging is as valuable for most applications and much easier to implement.

- Peak speed and direction (gusts)

It was concluded in section 2.3 that 2 to 3 second gusts should be measured and archived for wind load applications. This time scale should be seen as a rough indication; a workable definition of "gust duration" will be formulated in chapter 5.

With respect to peak gusts Cermak (1979) proposes to archive the daily wind extreme for each wind direction sector of 22½ degrees. The

direction information is important, because in a given configuration of constructions or buildings the sensivity to wind load depends on the direction of the load. In practice however it is much easier to measure the same parameters for all measuring intervals. If wind extremes are archived for all ten minute intervals or even each hour then it is generally sufficient to have the averaged direction of the same interval instead of the instantaneous direction measured at the occurrence of the gust. This means that only the extreme horizontal speed has to be archived (no corresponding direction). The wind direction averaged over 10 minutes gives sufficient information on the direction distribution of wind extremes.

- Fastest mile and fastest minute

The existence of extensive records of the "fastest mile" is related to the technical possibilities of certain wind recording systems. The fastest mile was particularly popular in the USA where the observations were done with chronograph recorders. With the deployment of electronic wind recording systems, the fastest mile is often replaced by the "fastest minute" (cf. Simiu et al., 1979). The use of "fastest mile" information in studies is only inspired by the availability of a particular type of recorder (Peterka, 1979).

From the fundamental point of view it is difficult to justify the use of "fastest mile" data. The length scale, for which the wind extreme is measured, is at least one order of magnitude larger than the size of constructions for which load estimates are needed, and as averaging scale one mile or one minute is not large enough compared to the turbulence scales to arrive at stable averages. Therefore little reason exists to incorporate the fastest mile or the fastest minute in a climatological data base. For countries that already have long records of the "fastest mile" it is important to create sufficient overlap to enable comparison with other parameters.

- Standard deviation of fluctuations (speed/direction)

Standard deviations of wind speed and direction are the simplest and most general parameters to characterize the turbulence intensity. It

has been shown in chapter 2 that measurement of these parameters opens the way to the boundary layer similarity approach where empirical scaling laws are applied. An indirect, but at least as important application is the derivation of station-specific roughness lengths (see also chapter 2 and 3). Standard deviations of speed and direction are therefore recommended as standard parameters to be derived from automatic wind stations.

We conclude this chapter with a list of parameters that should be the result of a data reduction or observation procedure. Minimum requirements and recommendations are distinguished. The minimum list consists of those parameters that have to be provided by every station; the recommendations are primarily for new automatic stations.

Minimum requirements:
- Wind speed and direction averaged over the last 10 minutes of each hour.
- Peak gust over the last hour.

Recommended:
- Wind speed and direction averaged over 10 minute intervals for all intervals.
- Peak gust for all ten minute intervals.
- Standard deviation of wind speed and wind direction for all ten minute intervals.

5. The measurement of gustiness

Three gustiness parameters are discussed in this chapter, namely (i) the peak gust of the horizontal wind, (ii) the standard deviation of the horizontal wind and (iii) the standard deviation of the wind direction. Each of these parameters imposes its own restrictions on the measuring chain. The standard deviations require a system with as little filtering as possible, whereas the gust measurement needs filtering to arrive at the desired gust duration. Ideally we need separate systems for the different parameters, where each system is fully adapted to the parameters it has been designed for. Such a complex configuration is not feasible for standard wind observations. We therefore have to compromise; the system parameters (time constants, sampling frequency etc.) have to be choosen such that the gusts have the desired duration and the standard deviations can still be corrected with reasonable accuracy.

The main conflict of requirements is related to filtering in the measuring chain; the gust measurements need filtering, whereas the standard deviations are perturbed by filtering. The theoretical description of the effects of filtering on observed gust is reviewed in section 5.1. Until now the expression "gust duration" has been used without a clear definition. Intuitively "gust duration" specifies the width of a pulse in the time evolution of the wind. A clear definition is given in section 5.2, where it is also shown that the gust duration can be interpreted as a characteristic of the measuring chain. Measurement of the standard deviation of wind speed and direction are discussed in 5.3, and finally recommendations are made for an optimal wind measuring system in section 5.4.

5.1 Peak gust measurements

The main problem in relation to peak gust measurements is the dependence of observed peaks on filtering in the measuring chain. A fast measuring system can trace the highest peaks in the wind signal, whereas a slowly responding system smoothes the extremes. It depends on the application whether we are interested in narrow spikes; it has been shown in section 2.3 that only gusts with a certain duration cause damage to objects of a certain size. The extent of time that an extreme has to

persist in order to cause any damage depends on the size of the object on which the wind load is exercized (Mackey and Ko, 1975).

A number of studies exists in which gusts are analysed and compared with theory (e.g. Davenport, 1964; Greenway, 1979; Frost and Turner, 1982; Wood, 1983; Healy, 1985; Beljaars, 1987b). Most of them consider continuous wind records and use the extreme value theory developed by Rice (1944, 1945). The sampling process or analog to digital conversion is discussed by Beljaars (1987b).

According to Rice's theory, the height of a peak in a stochastic signal is related to the variance of the signal and the variance of its first derivative. Both parameters can be derived from the wind spectrum which is well documented now (cf. Olesen et al., 1984 and Kaimal, 1978). Anemometers, signal transmission lines and recording systems can easily be represented by filters enabling the computation of the spectrum at the end of the chain. (See Otnes and Enochson, 1978 for standard system theory). So an empirical expression for the wind spectrum combined with standard signal analysis techniques lead to a simple theory for gusts (Davenport, 1964; Beljaars, 1987b). An extensive comparison with data of various origin and nature (taken over land and water under stationary and unstationary conditions) is presented by Beljaars (1987b). A few results are summarized here.

Fig. 5.1 depicts the elements in an experimental measuring chain that consists of an anemometer with a response length of 2.2 m, producing an analog voltage that is sampled with a frequency of 2 Hz. All the basic samples are stored on magnetic tape. Digital filtering is applied afterwards by averaging over N samples where N can be chosen.
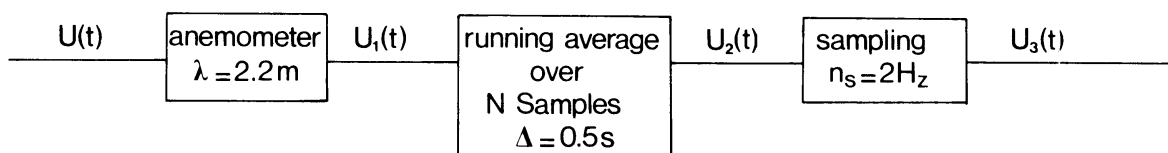

Fig. 5.1 Measuring chain with anemometer (response length λ = 2.2 m) , digital filter consisting of an averaging procedure over N samples and sampling with frequency n_s = 2 Hz.

The new filtered data record has the same number of samples, since a running average has been taken. The total process, i.e. measurement and computation, can be represented by the chain in Fig. 5.1. The normalized gust magnitude $(U_{max3} - \bar{U})/\sigma_1$ has been determined for every 10 minute interval, where U_{max3} is the observed extreme value at the end of the chain, $\bar{U}$ is the mean value of the wind and σ_1 is the standard deviation of the wind just after the anemometer. All three parameters correspond to the same 10 minute interval. The standard deviation σ_1 has been used because it is the measurable quantity that is close to the standard deviation of the wind σ. Parameter σ_1 has been computed from the basic samples without averaging. The individual values of the normalized gust magnitude are averaged over a number of 10 minute intervals, a procedure that is represented by $< >$.
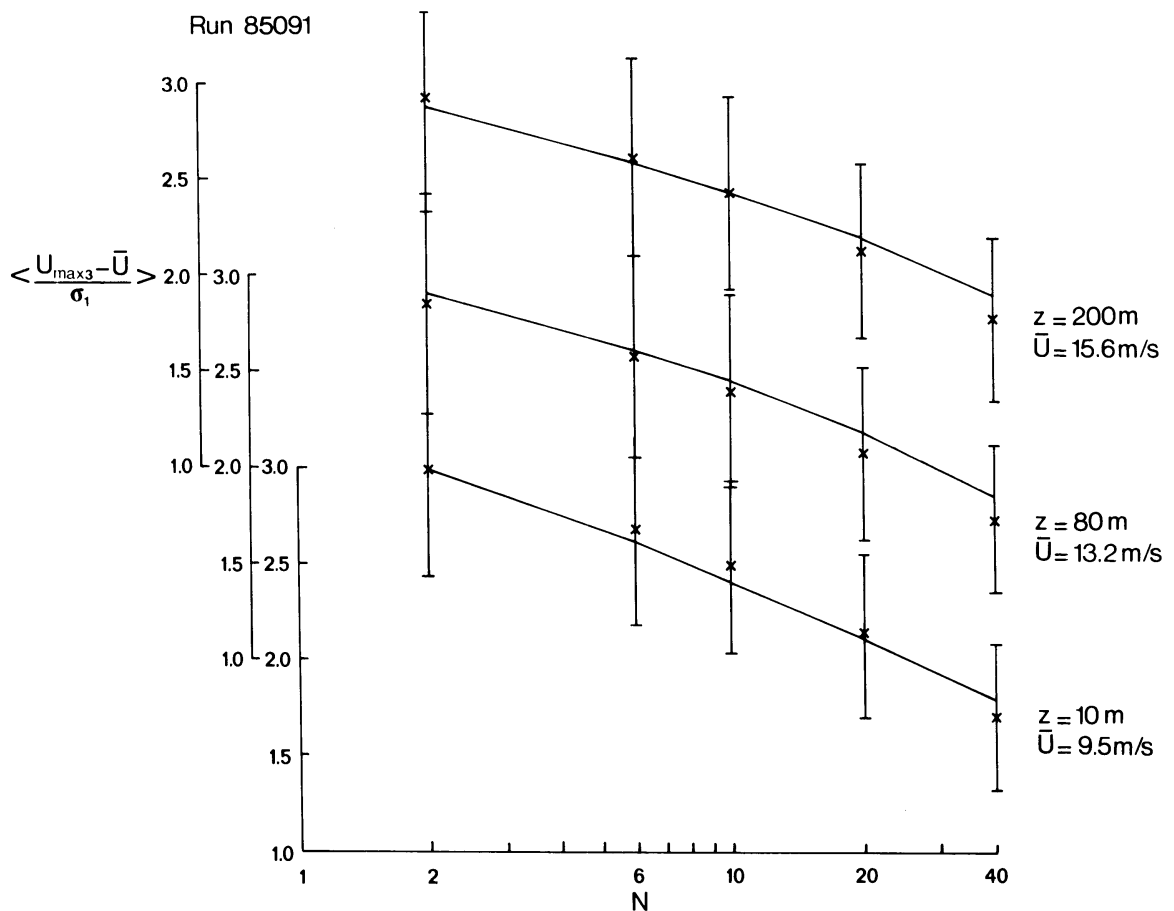

Fig. 5.2 Normalized gusts, with error bars indicating the standard error of this quantity, as measured with the measuring chain of Fig. 5.1 for three measuring heights at the Cabauw tower in the Netherlands.

A comparison of theoretical results with data is given in Fig. 5.2 for three measuring heights. The correspondence is satisfactory for most applications. It should be realized here that the theory has been derived for stationary situations and Gaussian turbulence. These conditions are not expected to be valid in situations with strong convection e.g. thunderstorms. The theory is therefore only meant to be used in the relative sense. When gusts are measured with a duration that is not compatible with the requirements of the application, the theory can be used to apply small corrections. The corrections convert measured gusts to hypothetical gusts, as if they were measured with a slower or more quickly responding measuring system. An example is given in Fig. 5.3.
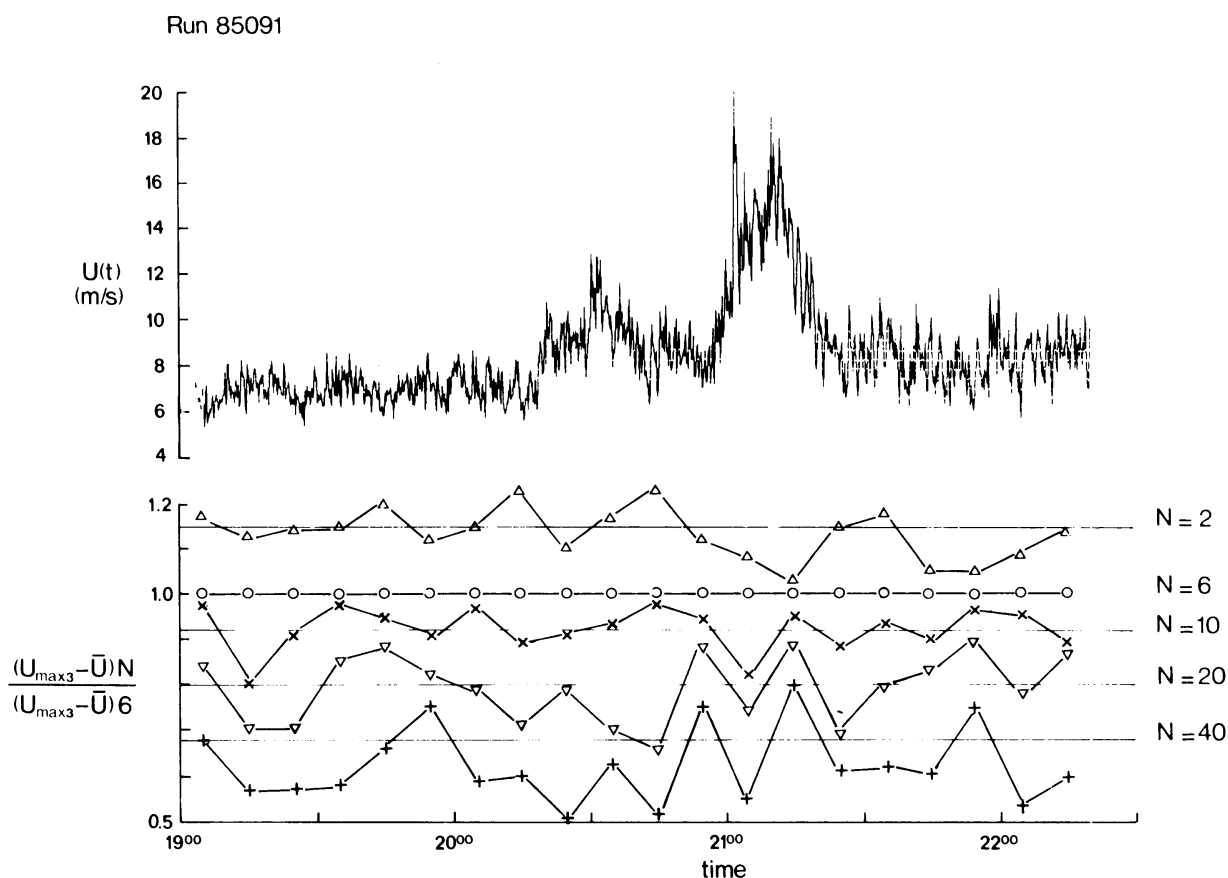
Run 85091

Fig. 5.3 The evolution of the wind signal (filtered for clarity) for run 85091 at 10 m height. The lower part of the figure shows the ratio of gusts obtained from the same reocrd after averaging over N and 6 samples respectively. The value of N ranges from 2 to 40 samples. Each 10 minute interval results in one value; the connection lines are added for clarity. The horizontal lines represent the model prediction.

For the experimental run with 2 Hz basic samples, normalized extremes
have been determined for different averaging times determined by N. Fig.
5.3 shows the ratio of normalized gusts measured with N = 6 (averaging
over 3 seconds) and with other values of N. Even for this very unsta-
tionary run the experimental results are well described by the theory.
The extreme winds between 21 and 22 hours are caused by a short shower.

5.2 Definition of the duration of gusts.

Until now we have used the expression "gust duration" in a
qualitative way to describe the persistence of wind extremes. Formally
speaking, an extreme value is only present during an infinitesimal short
time. Still there is an obvious difference between a sharp spike and a
wide peak. When we want to characterize this, we meet the difficulty
that peaks in wind records do not have a defined shape; wind records
have essentially a stochastic nature.

In specifications of wind instrumentation there is also a tendency
to confuse the gust duration with the sampling period. If the output of
the anemometer is sampled every second, many manufacturers will claim
that their instrumentation delivers "1-second-gusts". It will be shown
in this section that the sampling period is not the only relevant par-
ameter in a measuring system. Also the smoothing effects of anemometer
inertia, transmission lines, averaging procedures etc., should be
considered and can make the gust duration entirely different from the
sampling period.

We propose here to define the duration of gusts with the help of a
standard filter, namely a running-average filter. A running average
filter with averaging time t_o averages for each time the incoming signal
over the t_o preceeding seconds. When extreme values are measured after a
running average filter, we say the gusts have duration t_o. The advantage
of this definition is that we are sure that the observed extreme
persists in the wind signal during at least t_o seconds.

For arbitrary measuring chains the problem is more complicated,
because all the elements in the chain contribute to the total filtering.
Usual elements are anemometer, RC-filters, running-average filters and
analog-to-digital conversion units. (Counting of pulses from an
anemometer over non overlapping time intervals t_o should be seen as a

running-average filter with averaging time t_0 combined with sampling with frequency $1/t_0$). To define the duration of gusts of an arbitrary measuring chain, we make again use of the running average filter. We choose a hypothetical running average filter with an averaging time t_0 such that the same gust magnitude would have been measured (according to the theory) as with the chain under consideration. We say then that the chain measures gusts with duration t_0.

Definition

Gusts observed after a running-average filter have a duration that is equal to the averaging time of the filter. An arbitrary measuring chain with several elements (not necessarily running average filters) produces gusts with duration t_0, if a hypothetical running average filter with averaging time t_0 would have resulted in the same gust magnitude (according to the theory).

In this definition the gust duration is a characteristic of the entire measuring chain. An arbitrary measuring chain can be characterized with respect to wind extreme statistics by means of this single parameter. It is not trivial that a single parameter characterization is possible. In principle also meteorological parameters as inversion height, mean wind speed and boundary layer stability interfere through the input spectrum of the extreme value theory. However, it is shown by Beljaars (1987b) that these large-scale parameters only have minor effects. This means that, to a reasonable degree of accuracy a straightforward relation exists between the defined gust duration and the gust magnitude. This relation can be computed on the basis of the running-average filter and is depicted in Fig. 5.4. The symbol t_G is used for "gust duration" because it can be used for an arbitrary measuring chain. If the chain consists exclusively of a running-average filter, $t_0 = t_G$ by definition.

For a given chain t_G can be determined by means of the extreme value theory (cf. Beljaars, 1987b). With the model and the known filtering elements we compute $(U_{max} - \bar{U}) / \sigma$, where U_{max} is the expected extreme at the end of the chain and σ is the unfiltered standard deviation of the wind speed. With help of the hypothetical running-average filter we determine such an averaging time that the same normalized gust magnitude is found. Fig. 5.4 can be employed here.
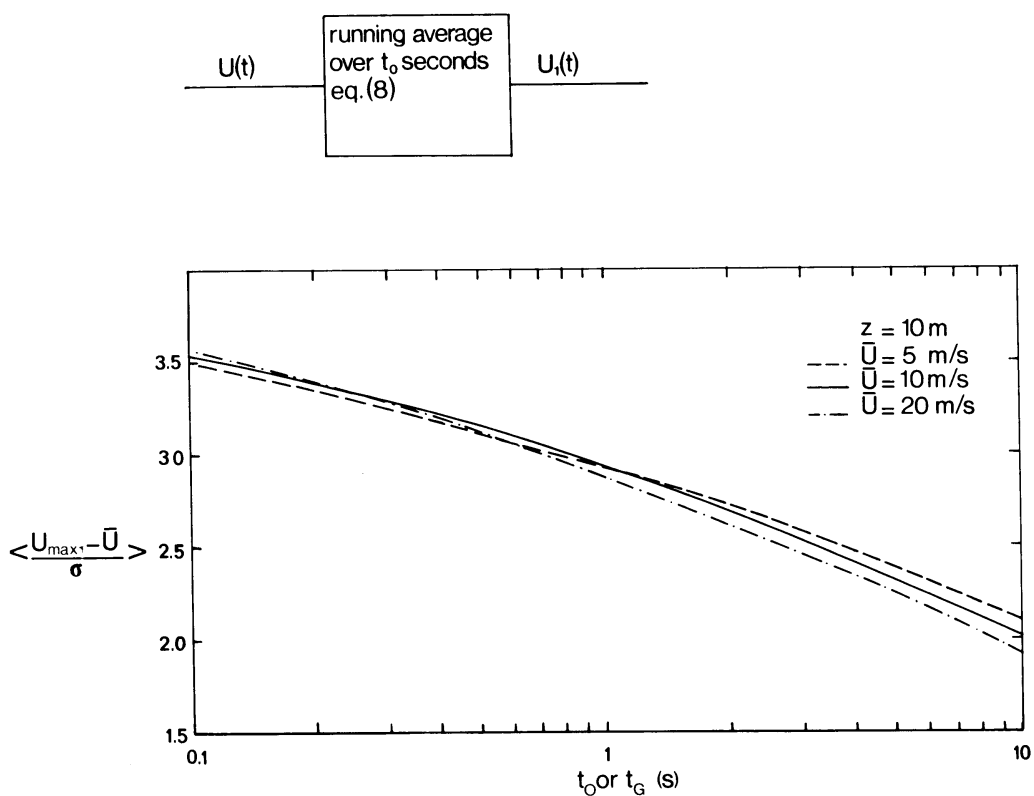
Fig. 5.4 Relation between normalized gust magnitude and gust duration.
According to the definition this is the theoretical curve for
the running average filter.

Two examples are given now of wind measuring systems that are
fairly common in practice. The first system is an anemometer producing a
fixed number of pulses per rotation, combined with a counter that is
read and reset every t_0 seconds. This can be simulated, as depicted in
Fig. 5.5, by a running average over t_0 seconds and sampling with

Fig. 5.5, by a running average over t_0 seconds and sampling with frequency $1/t_0$ Hz (non overlapping samples). The second system consists of an anemometer followed by an RC-filter and sampling. The theoretical results are expressed in terms of the gust duration instead of gust magnitude. These parameters are related according to the definition by means of the curve in Fig. 5.4.

It is clear from Fig. 5.5 that the response length of the anemometer only has a minor impact on the gust duration as long as the integration time of the running average filter is at least a few seconds. The filtering by the running average filter then dominates the filtering by the anemometer. The same can be concluded for the RC-filter with τ larger than 1 second.

Another important result is that the sampling part of the measuring chain can not be ignored. When the gust duration for non-overlapping samples ($n_s = 1/t_0$) is compared with that of the continuous record ($n_s = \infty$), we see that the sampling part adds about 50% to the gust duration. The physical explanation is, that by taking a finite number of samples of a continuous record the extreme in the continuous record will usually be "missed" by the sampler. This implies a smaller extreme value in the sampled data row and therefore also a longer gust duration according to the definition. All these statements should be interpreted in the statistical sense. This means that the extreme value distribution will be shifted to lower extreme values for the discretely sampled wind record.
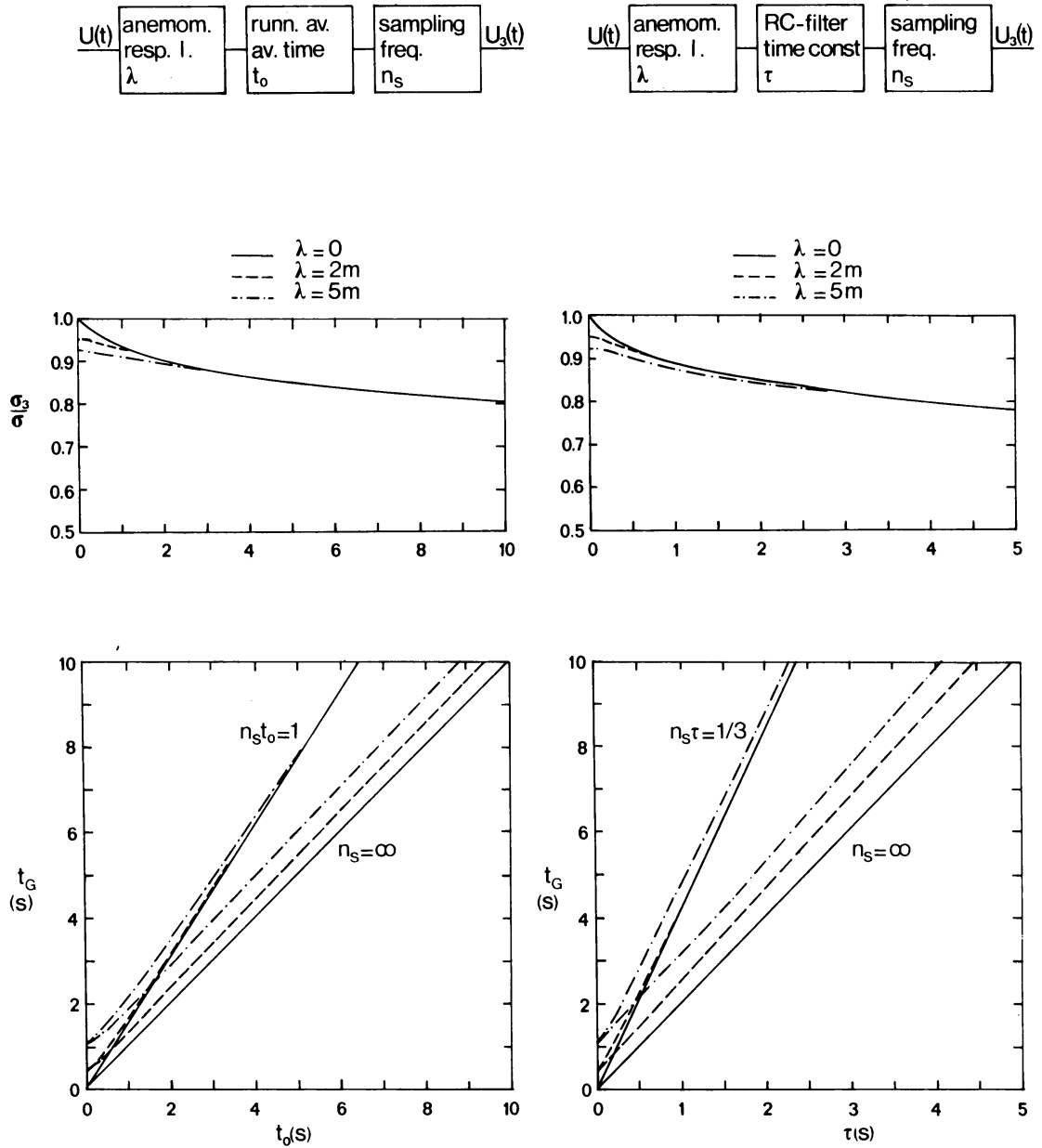
Fig. 5.5 Reduction of the standard deviation and the gust duration for
two different measuring chains (top part of the figure), as
calculated by the gust model (Beljaars, 1987b). These results
are valid for z = 10 m and measuring intervals of 10 minutes.
The model is not very sensitive for the exact values of L, z_i
and $\overline{U}$; the numerical values used for this figure
are $-\infty$, 1000 m and 10 m/s respectively.

5.3 Standard deviations

Filtering in the measuring chain reduces in general the standard deviation and should therefore be avoided (only wind vanes, having second-order response, amplify a portion of the spectrum). The horizontal wind fluctuations are damped by the anemometer, by the signal transmission and by the recording system. Sensor response has been extensively studied (e.g. MacCready and Jex, 1964; Macready, 1966; Wieringa, 1967; Kaganov and Yaglom, 1976; Busch and Kristensen, 1976; Wyngaard, 1981) and the dynamic properties of many current anemometer-vane systems is known (e.g. Mazzarella, 1972; Lamboley and Viton, 1977; Monna and Driedonks, 1979; Coppin, 1982; Lockhart, 1987). Two examples of wind measuring chains are given in Fig. 5.5 viz. a pulse counting system with averaging over non overlapping time intervals of t_o seconds and a system with a first order filter. It should be noted that sampling in these chains does not affect the measured standard deviations. Sampling is used in the sense of taking instantaneous readings of the signal at equidistant time intervals. In the system theory jargon we say: sampling does not bias the standard deviation estimates.

Negligible filtering would be the goal for detailed turbulence experiments; we would choose a fast sensor and avoid any filtering. In an operational environment it is necessary to use rugged anemometers and to measure gusts as well. For the latter it has been shown in section 5.2 that smoothing of the signal over a few seconds is required. The consequences are illustrated in Fig. 5.5; different averaging times and different RC-times are considered for the two chains respectively. Also three anemometer response lengths are considered. It is clear that for averaging times of a few seconds or RC-times of about 1 s, the response length of the anemometer has only a minor impact on the result. On the other hand the response length should not be too large to avoid over-speeding problems. Coppin (1982) concludes that the effects of over-speeding can be neglected at 10 m height for response lengths up to 5 m.

The same arguments apply to the wind vanes. Wind direction fluctuations are the result of the lateral velocity fluctuations. The spectra for longitudinal and lateral velocity fluctuations are equivalent except for the high frequency range where the lateral energy is 3/4 of the longitudinal energy (Kaimal, 1978). This implies that the reduction of the wind direction standard deviation can be roughly derived from the

same figure (Fig. 5.5). The behaviour of the vane is different from an anemometer; a wind vane has to be described by a second order response function whereas an anemometer obeys first order characteristics. The response is described by MacCready and Jex (1964) and Wieringa (1967). Mazzarella (1972) concludes in an inventory of specifications for wind instruments, that undamped wavelengths up to 10 m with damping ratios between 0.3 and 0.5 are acceptable for most air pollution studies.

Wind speed gusts and wind direction are synoptically reported in knots and units of 10 degrees respectively. Accuracy and resolution of the sensors should be better than these numbers. The standard deviations of the horizontal wind and the wind direction are considerably smaller and should be reported in smaller units. It is proposed to choose 0.1 m/s and 1 degree as unit for the standard deviations of speed and direction respectively. This resolution does not imply that the instrument should have the same resolution. Quantization noise, added to the signal due to finite resolution of the instrument (e.g. due to AD-conversion or a code disk in the wind vane) contributes only $\Delta^2/12$ to the variance, where Δ is the quantization resolution (cf. Otnes and Enochson, 1978). With a 7 bits code disk ($\Delta = 360/128 = 2.8$ degrees) we add only 0.66 degrees^2 to the total variance, which is quite acceptable.

5.4 Recommendations

We have to specify now the parameters in a wind measuring chain such that optimal results are obtained for different applications. For gust observations we need a system that produces gusts with a specified duration. Most applications demand for a duration of a few seconds, say 2 to 5 seconds. According to the results of Fig. 5.5, a pulse counting system would do the job for counting intervals of about 1 to 4 seconds. For systems with analog recording (approximately a first order filter), RC-times from 1 to 2 seconds would be appropriate. In case of additional analog to digital conversion with $n_s = 1/(3\tau)$ the RC-time should be in the range of 0.5 to 1.5 seconds.

Optimal standard deviation measurements require a system with as little filtering as possible. For routine use, however, we want a single system for gusts and standard deviations. This means that a compromise is needed for the optimal choice of system parameters. Since filtering

effects are most critical with respect to gust measurements, it is proposed to adapt the filter parameters to the requirements for gust observations and to accept the reduction in standard deviations. The gust duration we are interested in is of the order of a few seconds. For the two measuring chains depicted in Fig. 5.5 we propose 3 seconds for t_0 and 1 second for τ. The same figure shows the corresponding reduction of the measured standard deviation, which is about 10%. It is believed that such a reduction can be corrected with reasonable accuracy for most applications. It is clear that the correction can only be made if the details of the measuring chain are known and well documented.

6. Discussion and conclusions

The purpose of this study was to review the needs and requirements with respect to gustiness measurements at synoptic and climatological stations. The existing specifications for the observations of wind gusts do not guarantee uniform and exchangeable results that can be easily interpreted. Some stations measure for instance three second peak gusts (without clarity about the exact definition of this parameter); other stations record the fastest mile. It is well known that the magnitude of observed gusts depends strongly on the response characteristics of the wind measuring system, but no specifications exist for this.

The application areas of gustiness measurements are discussed in the chapters 2 and 3. It has not been attempted to propose specifications that meet with every possible application of wind measurements. Particular problems might need carefully prepared measuring campaigns and are beyond the scope of this study. Here we limit ourselves to users of wind data that need long-term climatology or information over a large area at a specific time.

One of the main shortcomings of the actual wind measurements at 10 m height is the lack of representativeness. This is felt by forecast modellers (they tend to exclude the land stations from their wind analysis schemes), by air pollution modellers and by engineers that need information at larger height. The situation can be improved by providing explicit information on the anemometer exposure. We assume that the anemometer location meets with the actual WMO-requirement of a minimum distance of at least 10 obstacle heights from the nearest obstacles. Additionally we need information on the surrounding topography and the upstream terrain roughness length. The topography can be derived from maps, and wind speed corrections for the anemometer location can be estimated for simple topographic configurations. The upstream roughness length can be determined by means of standard deviation measurements (or estimated from peak gust data, if standard deviations are not available). Such measurements are objective and considered to be more accurate than a classification of the terrain that surrounds the anemometer.

If wind measurements at 10 m height are supplemented with standard deviations or upstream terrain roughness lengths, these observations can be directly interpreted in the framework of Monin Obukhov similarity.

This would greatly enlarge the range of applications of routine wind data. It is therefore proposed to supplement the observation of average wind speed and direction with their standard deviations. The latter are also of direct use in air pollution studies.

A second shortcoming of the actual wind observation practice is the lack of uniformity in the gust observations. Short period wind extremes (gusts) play an important role in studies of wind load on buildings and constructions. Theory for wind extreme statistics assuming stationary and Gaussian wind patterns turns out to be reasonably accurate. A theoretical approach is probably sufficient in those climates where the damaging winds are the result of storm depressions. In many countries however, small scale systems like convective storms determine the extreme wind statistics. Direct gust measurements are therefore needed to provide fully representative information on peak gustiness.

The response characteristics of the measuring chain remain to be specified. The most damaging gusts are those that engulf the entire structure and have a dimension of the order of the size of this structure. In many cases this will be the order of 100 m. With strong wind this implies that the duration of the gust is of the order of a few seconds. If we say that we are interested in 3 second gusts we look for the "fastest 3 seconds" in the wind record. This is exactly the proposed definition for gust duration. A measuring system that meets exactly with this definition consists of an anemometer with a small response length and a running average filter that averages over the specified gust duration. Actual measuring chains can be characterized with respect to extreme value statistics by means of a gust duration in the sense, that a hypothetical running average filter with this averaging time would have produced the same gusts as the actual measuring chain.

We propose to choose the gust duration between 2 and 5 seconds. An exact number could have been specified here, but this would imply the readjustment or redesign of many existing systems. Besides, any particular value of the gust duration would be difficult to justify; based on the needs of wind load problems only an order of magnitude can be specified. For new systems that are equipped with analog filters we recommend a first order filter with a response time of 1 second in order to obtain gusts with the desired gust duration. If the analog signal is filtered it is recommended to take at least one sample every 3 seconds.

For systems with pulse counting we recommend counting over 3 second time intervals.

Without an exact specification of the duration of gusts, it is essential that the measuring stations are well documented. Each station has to provide precise information about the filtering characteristics and about the gust duration of the system in use. This enables the users of gust data to rescale the gust to another duration, if necessary. The station information which is very essential for the users of gust data should be incorporated in the WMO-station files.

All the parameters discussed above are based on 10-minute intervals. This makes the proposed data reduction scheme compatible with the existing practice. The integration time is also intermediate between the turbulence time scale and the time scale of changes in the mean wind. Users of wind climatology have maximum flexibility, when all 10-minute values are available. Dependent on their needs they can choose to block-average the available wind records. It is therefore recommended to store all ten minute results.

Not every wind station will be able to meet with these specifications and not every archive will be able to cope with the increased data flow. We therefore formulate minimum specifications that should be satisfied by every station and a hierarchy of recommendations. WMO should encourage members and manufactures to incorporate these recommendations in the equipment when it is renewed or modernized.

Minimum specification

Wind stations have to report every hour the mean wind speed and wind direction defined as the average over the last ten minutes. The minimum resolution for wind speed and direction are 0.5 m/s and 10 degrees respectively.

Recommendation 1

In addition to the wind speed and direction averages, it is recommended to report the maximum wind speed (gust) of the last hour (with a minimum resolution of 0.5 m/s). The equipment should be such that the recorded gusts have a duration between 2 and 5 seconds. For systems that

count anemometer pulses, we recommend counting over 3 second intervals. Where a first order filter is employed we recommend an RC-time of 1 second.

The filtering characteristics and the gust duration of the wind measuring system should be known exactly. This information should be incorporated in the WMO station files.

Recommendation 2

Systems with automatic data reduction are recommended to report the standard deviation of wind speed and wind direction over the last 10-minute interval of each hour. The standard deviation of wind speed should be reported with a minimum resolution of 0.1 m/s; the minimum resolution for the standard deviation of wind direction is 1 degree.

The standard deviation should be archived by the national services and analysed periodically in order to produce station specific roughness length tables. These tables contain the roughness of the terrain surrounding the anemometer per 30 degree direction sector, where a distinction is made between seasons, if necessary. These tables should be incorporated in the station files together with corrections for topographic effects.

Recommendation 3

With sufficient archiving space it is recommended to store the mean wind speed, the mean wind direction, the standard deviation of wind speed and direction and the gust for all 10-minute intervals. (Gusts are extremes over 10-minute intervals instead of hourly intervals as in recommendation 1.)

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8. Literature

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