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Challenges in modelling stochasticity in wind

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SUMMARY

This article is an attempt to summarize some of the existing problems in stochastic aspects of wind. Different types of wind are listed with their specific properties. For most of them no statistical model or stochastic process has been constructed as yet. At the same time, existing problems with data are very diverse and possible improvements are proposed. For example, the quality of wind speed and wind direction data might be upgraded by a careful inclusion of measurable covariates while developing models. Other problems are dealing with extreme winds that can hardly be measured accurately. In this connection, interesting and important questions for insurance companies and for construction engineers can be tackled by applying extreme value theory. This incomplete overview hopes to encourage stochasticians to put more interest in wind problems. At the same time it is hoped that meteorologists will help them with high quality data, needed in the verification of the offered models.

KEY WORDS: wind types; data quality; extremal wind; wind models; wind velocity; wind power; wind pressure

1. INTRODUCTION

A thorough search through scientific libraries revealed that there are a reasonable number of publications concerning wind and statistics. Reading through these books and articles, we realized that there still seem to be a lot of unsolved problems in wind modelling. This idea has led to the organization of an HSSS research kitchen entitled 'Stochastic modelling of wind', held in Leuven, Belgium, during the period 29 September–3 October 2000. The results of discussions between the eight participants are given in the succeeding four sections. First, different types of wind, each with their specific properties and difficulties are mentioned. Secondly, a number of comments are made that can help improve the quality of wind data. In a third part we focus on extreme winds and their specific problems. In the final section, stochastic modelling of wind speed, wind direction and derived quantities are discussed in some detail.

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2. DIFFERENT TYPES OF WIND

For most human beings, wind is considered the most random quantity that they experience in daily life. For a probabilist, it becomes a challenge to translate physical and random properties of wind in stochastic rather than in deterministic equations. Wind as such is a mixture of different types of wind. Each wind type (e.g. large scale extra-tropical storms, windstorms, tropical cyclones, tornadoes) has its own, different physical structure and satisfies the Navier–Stokes equations with different parameters and/or boundary conditions. It is desirable to look for stochastic analogues for most if not all of these different types. At a later stage, these models can then be combined into a mixed model where the frequencies of the different types are used as mixing variables for the general *wind*. For a first attempt in this direction, see Breckling (1989). For general background on wind we refer to Simiu and Scanlan (1996).

Among the different types we mention the following:

(i) *Breezes*: Breeze applies to coastal regions where during the day a wind flow is caused by the warming of the coast, while during the night the temperature gradient is in the other direction. The flip-over of the wind in the early morning and in the late afternoon happens rather suddenly. Probably, the stochastic modelling of breeze is not too difficult. In a first attempt one might take a fixed wind speed distribution; the directional process is simple as it can be developed from a two-point circular model. Moreover, the physical laws underpinning the breeze are very well known. For cities close to large water areas, breeze is fundamentally important in connection with air pollution.

It is interesting to remark that also *monsoons* have a similar behaviour but spread over a year rather than over a day.

(ii) *Rain storms*: Due to complex temperature variations in the lower atmospheric layers, the resulting wind model is much more complicated. The wind speed and the directional component are very much dependent on each other. Therefore, proper modelling is very complicated. Moreover, few data are available to check such models on their accuracy.

(iii) *Tornadoes*: Tornadoes are often mentioned in the literature because of their impact and news-value. Usually, statisticians think of tornadoes as belonging to the realm of *extremal statistics*, but this is often not the case. At least, there are a number of elements that have nothing to do with extremes as such. Thom (1963) wrote the first substantial paper on the subject. Tornadoes are caused by internal vortex motions within huge clouds. That there is a lot of stochasticity in tornadoes is clear. We mention, with Thom, the striking point of the tornado, the direction it takes, its path length and path width. The latter two are the key ingredients for the area swept by a tornado. However, no attempt has been made to do any stochastic modelling of a tornado as a stochastic item.

Measurements of wind speeds in tornadoes do not exist. The Fujita scale is used to define the intensity of a tornado. The scale is based on tornado-induced damage description. For example, if a tornado destroys roofs, it has a Fujita scale of 2, independently of how the roof was constructed. Spatially, this type of *quality* scale definition is not very useful as no *quantification* corresponds to it. A table with the different scales is found on the internet at the following site: http://www.tornadoproject.com/fujitascale/fscale.htm#fscale table. Also note that the scale is hard to use for tornadoes at sea or in open land without buildings.

(iv) *Hurricanes*: Because of their often spectacular side effects, the understanding of hurricanes by statistical methods has gradually grown since Russell (1968) investigated their effects for the coast of Texas. Since then there have been a couple of detailed attempts made to model hurricanes. Among the geographical elements the rate of hurricane occurrence in a region and the co-ordinates of the landfall are stochastic. More importantly, the hurricane itself has a number of characteristics that are stochastic in nature: pressure distribution within the hurricane, the shape of its boundary, and its motion expressed in terms of speed, direction and strength.

In recent years, scientists have come to the conclusion that an appropriate model for the maximal wind speed during a hurricane should have an upper limit. This is due to the physical reality proved by Emanuel (1988) that hurricanes have finite maximum intensity. This is good news. On the other hand, the value of the upper limit may still be enormous. Astronomers have found that on Mercury there are wind speeds of a few thousands miles per hour.

(v) *Wind gusts*: Wind gusts are defined in opposition to mean winds and represent fluctuations associated with atmospheric flow turbulence. A gust measurement only has a meaning when information about the measurement system is available. In practice, gust data are deviations from the average wind speed and depend on the resolution used. See Verkaik (1998, 2000).

(vi) *Geostrophic wind*: The geostrophic wind is in the first case defined as the wind speed computed from the pressure gradient assuming geostrophic balance. According to Breckling (1989),

$$G = \vec{k} \times \frac{1}{\rho f} \operatorname{grad} p$$

where $\vec{k}$ is a vertical unit vector, ρ is the atmospheric density, $f = 2\Omega \sin \phi$, the Coriolis parameter (positive in the northern and negative in the southern hemisphere), Ω is the angular velocity of the earth's rotation, ϕ is the latitude and p is the pressure. This equation only yields a good estimate of the actual wind above the planetary boundary layer when the curvature of the isobars is negligible. If the curvature is important, the equation becomes

$$\frac{G^2}{R} = \frac{1}{\rho} \operatorname{grad} p - fG$$

where R is the radius of curvature.

A spatial stochastic model for the geostrophic wind has been suggested by Breckling (1989), where the pressure at a site is modelled by a weighted mixture of pressure systems in the neighbourhood.

(vii) *Jet stream*: Although physical models are available, it appears that few if any associated statistics or statistical models have been developed so far.

(viii) *Residual wind*: This could be defined as the *left over* wind after subtraction of all the previous types. Even here one should distinguish between weak, moderate and extreme windstorms. The Weibull distribution is most often considered a good approximation for the speed of this usual wind. Because of the mere fact that most of the previous wind types have a relatively short life length, this Weibull part will dominate in the ultimate mixture model.

A general remark on wind types is the following. It is advisable to make a distinction between *turbulence* related processes and processes of the *mean flow.* Since in turbulence there are no deterministic methods, most results from the past decades are formulated within a statistical context. Although turbulence in itself largely remains an unsolved problem, we do know a great deal about its statistics. One pleasing aspect of turbulence is that it behaves the same all over the planet. This is not the case for average winds, where every part of the world has its own special breezes and storms. However, it might be difficult to discriminate between the two. Meteorologists like to believe that there is a spectral gap, a definite distinction in time scales between turbulence and mean flow (somewhere around 30 min); however, in practice, trends in the mean flow often veil this potential spectral gap.

3. THE QUALITY OF WIND DATA

One of the most frustrating aspects of current wind studies is the profound gap between the model builders and the data providers. Many statisticians seem to only care about the statistical models they have developed. They do hardly worry about the data they have acquired from meteorologists in their vicinity. Even worse, they often do not understand the practical problems in which these data need to be applied such as wind energy. On the other hand, it cannot be denied that the quality of the data provided is not always satisfactory. This fact may be at the origin of the lack of interest in stochastic models for wind problems. In what follows a non-exhaustive list of suggestions related to the quality of wind data is given. The general theme might be that data should be given to the statisticians in their roughest form without any preliminary manipulation.

(i) First of all, data providers should indicate to the statistician the *error bands on the measurements*:
   (a) It should be noted that most measurements are time dependent and therefore so are the errors.
   (b) Measurements and the attendent errors are dependent upon the geographical location. For example, measurements at sea are usually very crude and hence have wide variability.
   (c) The quality of the data is different from station to station. While some stations provide first class data, others are notorious for the low quality of the data they provide.
   (d) Time series coming from one particular location may be unreliable because of changes in the measurement environment. For example, the construction of buildings in the neighbourhood of anemometers affects the quality of the measurements. In some instances the presence of trees or their growth or their cutting down is not indicated. In other cases, problems are caused by the undocumented displacements of the anemometers.
   (e) A further point is that a controversial topic such as *climate change* can hardly be tackled by using wind data, particularly if the measurement errors are not given. Data are often contaminated so that a suspected trend may be fully explained by measurement errors.

(ii) NCEP provides climatological data on a global scale from a re-analysis project. These data are today the most important source for carrying out wind climatological studies on meso-scale for wind energy purposes. Here is a caveat in that NCEP data do not seem to fit ground based data very well for European rainfall data. Fortunately, recent comparisons of NCEP wind speeds with wind data from the Netherlands indicate far better agreement than for rainfall. An analysis of such data may be useful for studying *large-scale wind fields*.

(iii) Basic measurements are usually *tick by tick data*. Most stations do not provide these raw data but rather some derived set, usually averaged. In the past this attitude could be defended by invoking the lack of storage place on the handling equipment. However, present capabilities should allow storage of large sequences of data, measured at the finest possible resolution. It should be the duty of the statistician to inform the data providers what kind of averaging is adequately representing the necessary features of the data. For example, statisticians should have access to the original data to take maxima over 10 min, over 1 h or daily. The situation is similar to that in financial markets where tick by tick data are available; they show some of the small scale stochasticity or volatility which is hidden as soon as averages are taken.

(iv) A further remark is that proper data collection may be crucial for specific wind types:

(a) For example, *rain storms* usually last for about 1 h. How can one rely on daily averages to say anything sensibly about such storms? If a certain region is usually hit by four 1 h storms in a year, the storm part in the measurements uses only 4 h out of the 9000 h of wind measurements and will be averaged out.

(b) There are simply no data for *tornado wind speeds*. The reason is that tornado sizes as well as anemometers are extremely small and the probability that a tornado passes by an anemometer is close to zero. Secondly, if a tornado hits an anemometer, it is blown away and no recording is available.

(c) A fortiori, *hurricane data* are even more scarce than tornado data.

(v) Last but not least, most of the illustrating data used in the statistical literature on wind suffer from a variety of defects:

(a) In most cases, dependence on *height* is empirically treated. By using a loading factor, extrapolations are made to determine wind speeds at different heights. However, the correctness of this procedure is doubted, as shown by the wide variety of such loading procedures in operation.

(b) Data from the same station are sometimes given with different *time resolutions*. It is more than a matter of calibration to use such data in the same statistical analysis.

(c) Due to the inertia of anemometers, *calms* are censored from the measurements. Nevertheless, these very low wind speeds are crucial in the study of the effect of wind on air pollution. Also, a minimum of ventilation is needed to make damped rooms livable.

(d) In many instances, when a specific model does not seem applicable, statistical techniques are employed as *corrections* to get better fits. This corrected model is then used when performing even more corrections. Current software should be able to use the raw data.

(e) *Rounding off* of data leads to unwanted inaccuracies. From the statistical point of view it is deplorable that most wind speed measurements are expressed in miles, knots or kilomet while the instruments usually give a much higher resolution. The subsequent loss of precision is obvious. The effect on parameter estimation in any kind of wind speed distribution is evident. Also, the conversion from kilomet to miles or to knots adds to the inaccuracy of data. This applies both to mean and to maximal wind speeds.

(f) *Wind rose* recordings unnecessarily limit the information on the wind directions. By aggregating data to 16, 12 or even 8 sectors, a lot of valuable information is lost.

(g) The grouping of data by *seasonal aggregation* is deplorable. For example, meteorologists state that 2-month seasons are convenient for Western Europe. However, the convenience of grouping meteorological data over sections of 2 or 3 months does not take into account the *stochastic* beginnings of seasons.

4. PROBLEMS RELATED TO EXTREMAL WINDS

It is not surprising that extremal winds are responsible for a major role played by statistics in wind studies. For example, the key question raised by the engineer is, ‘How can buildings perform safely without being overly expensive? How do you find an equilibrium between *safety* and *economy*?’

Obviously, extremal winds are a potential danger. Among the more specific questions we mention the following:

(i) The protection of buildings against *hurricanes* poses difficult problems. Physically a hurricane can only develop if the water temperature over a large expanse of ocean is at least 26.5°C. However, there are a vast number of stochastic elements that need to be modelled as mentioned in Section 2 (iv). For example, the difference between atmospheric pressure at the centre and at the periphery of a hurricane is usually modelled by a log-normal or Weibull distribution. While the maximal wind speed during a hurricane should have an upper limit, this maximum seems to depend on the surface temperature of the sea, as for warmer seas the maximum increases. One can surmise that a similar analysis will be possible for storms at mid-latitudes. In that case perhaps the temperature gradient of the polar front limits the speed.

Different methods exist to predict the number of hurricanes in an upcoming year, which is often assumed to be Poisson distributed. The highly regarded work by Gray *et al.* (1992) does not provide standard deviations on the predictions. There remains the issue of whether the number of hurricanes is well modelled by a Poisson process which assumes independence over non-overlapping time intervals. There are tests that can be used to check this independence, and such a test should preferably be non-parametric.

(ii) A critical question for the structural engineer is whether in other cases there exists an upper bound on the wind speed, i.e. whether there exists a *maximum wind speed*. Supersonic wind speeds will probably never occur. Nevertheless, a physical proof for an upper limit as in the hurricane case does not yet exist. When studying possible fatigue effects in structures, it might be more important for a safety engineer to take into account all (possibly even very low wind speeds) rather than only extremes due to the high number of load cycles produced by these low speeds.
(iii) Probability distributions fitted to extreme wind speeds by the peaks over the threshold method often lead to a Gumbel distribution, but if a large number of Gumbel distributed numbers are simulated, the Fréchet distribution often seems to fit better. Perhaps the reason for this discrepancy might be unnoticed dependencies in the simulation process where very large values can trigger off subsequent large values.
(iv) Buildings must be designed in accordance with building codes to safeguard them from adverse wind effects. In particular, nuclear reactors and other special structures must withstand *tornado effects*. An open problem is the stochastic modelling of the path of a tornado. At the moment, predictions about the path are based on historical data. One possible line of attack would be to combine the well-understood physical laws with stochastic calculus to model such a path, keeping in mind the distribution of the pressure systems in the neighbourhood of the striking point. But then again, a tornado path might remain unpredictable because of the effect of disturbing factors. The total lack of data in this respect remains a disarming fact.
(v) One way of expressing the probabilistic uncertainty in extreme wind situations is in terms of *return periods* (Smits, 2000). In structural engineering, return periods of 50 years are usually considered. This of course does not mean that the object is only safe for just 50 years. Therefore, wind loads (Macke and Bucher, 1997; Simiu and Heckert, 1998) are multiplied by a *safety factor*. This means that the return period of the wind causing structural collapse remains unknown. There is definitely a need for confidence intervals on these return periods. Another disadvantage is the lack of meaning of the whole safety concept in the presence of a non-stationary climate. It would be more relevant to give a probability of failure within the lifetime of a structure.

(vi) Another important problem is to find appropriate models for the number and the lengths of upcrossings of the wind speed over a given level. One notices undeniable internal dependencies between extremal winds that are close in time. On the other hand, sufficient time distances between these upcrossings make them stochastically independent. Extreme value methods for stationary sequences may prove to be useful. The availability of high quality data should prove to be an incentive to the extreme value specialist to investigate these problems statistically (Beirlant *et al.*, 1998). For the number of upcrossings, a Neymann–Scott process might point at a first attempt.

(vii) It can be a challenge to construct a mathematical model (based on Ito-equations) which gives a Weibull distribution for the wind speed population, provides a temporal correlation in accordance with measured wind speed data and is suitable for numerical studies of extremes over any given period of time. Extremes simulated this way might then be compared to available data.

(viii) Also connected to the lack of data quality is the modelling problem encountered by Rootzen and Tajvidi (1997) when they tried to find connections between the severity of a storm and *insurance losses* claimed afterwards. That no clear relation is found may be due to a variety of reasons:

(a) Wind data are very local, while insurance claims are usually aggregated.
(b) Wind atlases do not seem to give reliable prior information.
(c) There are many secondary factors that can be invoked to explain the losses. Perhaps it might help to look at secondary *covariates* such as the number of clients in one claim, or differences in resistances of the buildings. For example, heavy rainfall during a storm may cause more damage than wind pressure.

The remark in the last paragraph leads to a wide open problem: the modelling and use of *covariates* in wind studies at large. Apart from wind speed and wind direction, there is often a plethora of other physical quantities that are measured at the same location and at the same time. For example, measurements on rainfall, pressure, cloudiness, temperature or even wind vorticity are linked to wind speed and direction.

5. MODELLING WIND AND DERIVED QUANTITIES

We turn to a set of key questions for stochasticians. Denote the three components of the *wind velocity* at time t at the location (x, y, z) by $V_i := V_i(x, y, z, t)$, where i indicates one of the Cartesian co-ordinates. Using spherical wind co-ordinates $V(x, y, z; t) = \sqrt{(V_x^2 + V_y^2 + V_z^2)}$, $\Phi := \Phi(x, y, z; t)$, $\Theta := \Theta(x, y, z; t)$, one can write

$$\begin{cases} V_x &= V \quad \sin\Phi\sin\Theta \\ V_y &= V \quad \cos\Phi\sin\Theta \\ V_z &= V \quad \cos\Theta \end{cases}$$

The best studied quantity is the *wind speed* V. Another ingredient is the *wind direction*, which is determined by the quantity

$$\Phi(t) = \tan^{-1}\frac{V_x}{V_y}$$

Usually, the additional *latitude process* Θ (t) is forgotten.

(i) The first and most crucial problem is the modelling of this *velocity process*. There exist a number of papers (Bucher and Wall, 1992) where this process is modelled by a Gaussian process with drift. This compares well with similar situations in rain modelling where spatial modelling has been far more popular. The relevance of these models needs to be ascertained. For a more recent approach see Dellaportas *et al.* (2000).

(ii) Secondly, once a model for the velocity process is accepted, the *wind speed process* $V(t)$ should emerge naturally. Is it true that an underlying Gaussian process results in Weibull marginals for the wind speeds? Most studies show that overall the Weibull distribution provides the best fit to wind speed data and there are theoretical reasons to use it indeed. If the velocity components of the speed follow a Gaussian law, then the speed follows a Rayleigh distribution which is a special case of the Weibull. This Rayleigh argument is valid only if the components are identically and independently distributed. It is doubtful that this is the case in reality. Perhaps the Weibull assumption only holds over short time fluctuations around, say, 10 min means. The effect of varying mean wind speeds and wind directions has to be accounted for in the distribution of the wind speed.

(iii) A third question is that hardly anything has been done to gain more insight into $\Phi(t)$, the *directional process*. Again the stochastic characteristics of this process need to follow from those of the basic velocity process. For example, what are the characteristics of the velocity process to obtain a directional process with von Mises or wrapped-normal marginals—two alternative models that seem to be preferred by practitioners? A good understanding of the velocity process will also give information on the neglected latitude process.

(iv) Why don't we look at wind as a *random field*? This kind of modelling is already familiar in rainfall models (Chandler, 1997). Such an approach would allow predictions for locations that cannot be reached in advance as for suspension bridges or high towers. A proper model should allow us to measure and model correlations between different locations.

(v) In connection with constructions mentioned in (iv), it has been remarked that *joint correlations* between wind speeds at different locations and distinct locations are modelled as products of correlations between wind speeds and correlations between locations. The reason for modelling space–time correlations as separable products of spatial and temporal correlation functions is that there really are very few tractable models that allow us to dispense with the assumption of separability. One such model is introduced and discussed by Brown *et al.* (2000). In this paper there are some useful references to follow up. Another remark is that the assumption of a separable correlation function is very much a matter of spatial orientation of points x and y with respect to the direction of the mean wind speed. In a perpendicular direction it appears to be reasonable, while along the wind direction a fully identical space–time correlation is dictated. A smooth transition model might be helpful.

(vi) Another important problem is the *simultaneous* modelling of wind speed and wind direction as a bivariate stochastic process. From this joint model the effect of wind direction on extreme wind speeds should emerge as a feature of the conditional distribution of the wind speed given the direction. Alternatively, correlations between wind speeds and directions could be investigated. To gain insight into *turbulence*, both speed and direction are necessary.

(vii) Without insight into the stochastic nature of the velocity process, no *predictions* can be made on any of its derivatives. We give two examples for which there exist stochastic models in the literature. Our point is that such models should follow from the underlying basic model for the wind velocity process:

(a) Knowing the velocity process, wind engineers may use it to derive the stochastic nature of *wind power*. The kinetic energy available for power use by a rotor is $\frac{1}{2}mV^2$, where $m = \rho FV$, with F the swept rotor area. Hence the energy itself is proportional to V^3. Classical stochastic calculus should give the characteristics of this velocity-derived process. If, for example, the Weibull distribution is a reliable model for V, then any power will also follow a Weibull law.

(b) In a very similar vein, *wind pressure* on buildings is calculated by the formula

$$P(t) = \frac{1}{2}\rho\, C_p(\theta(t))\, V^2(t)$$

where ρ is the air density, $V(t)$ is again the wind speed at time t, while C_p is a pressure coefficient which is, inter alia, a function of the perpendicular wind direction $\theta\,(t)$ at t. The latter element depends on the directional process. Again the Weibull law seems mathematically convenient, but this should follow from stochastic calculus. The role of the *aerodynamic admittance* has to be specified as well.

6. CONCLUSION

Drawing conclusions is easy: much work has been done, but still a lot of effort is necessary to solve even part of the many problems mentioned above. Tackling them could improve the existing wind modelling in many ways.

Below, just a few references are given. An attempt to obtain a complete list is contained in Kestens and Teugels (2001). It gives a gently annotated bibliography for the subject and can be found on the website http://www.kuleuven.ac.be/ucs/windkitchen.

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