Review of techniques and research for gust forecasting and parameterisation

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Abstract

Numerous techniques are used by national met services and researchers to predict wind gusts based on output from large scale forecasts. For forecasting purposes, severe gusts are most often divided into those originating in convective, and in non-convective environments. The former are generally associated with convective downdrafts and the vertical mixing associated with deep convection, and attempts to parameterise them focus on representing these mechanisms. The latter are typically associated with transport of turbulence within the boundary layer, using measures of TKE, boundary layer wind, and in some cases stability to estimate surface gust. Perhaps the most sophisticated of these is the widely used "Wind Gust Estimate" method of Brasseur (2001). Convective and non-convective gust parameterisations operate exclusively.

Contrasting with these physically/heuristically-based parameterisations are empirical/statistical models generally derived from the variation of the behaviour of observations with different static and meteorological factors. Here, a number of predictors are usually tested in regression formulae to model the overall gust behaviour without specific reference to gust-producing mechanisms, though some account of these may be implicit in the choice of predictors.

Various orographic flow phenomena such as downslope winds, mountain waves, flow channelling, rotors, wakes are not treated explicitly in gust parameterisations. Again they may perhaps be present implicitly in statistical models trained using observations within orography, or in physically/heuristically-based models insofar as the source NWP model is able to represent terrain-affected airflow. Nevertheless, scope exists for building in new parameterisation components which deal more directly with mountain-induced effects.

1 Introduction

Wind gusts, when severe, represent hazards to property, people and transport. The processes leading to their formation, such as boundary-layer turbulence, deep convection, mountain waves and wake phenomena are generally not resolved in NWP models, so frequently parameterisations and diagnostic formulae are used to predict gusts based on more coarse grained output from NWP and/or limited observations. Gusts are, however, chaotic and difficult to predict, often the result of a combination of processes which may not be fully understood. Hence much effort is ongoing to develop viable techniques.

The current state of gust forecasting naturally divides along several lines:

(i) convective and non-convective gusts;

(ii) statistical models trained using observations, and physical/heuristic models designed around transport processes;

(iii) routine, established operational forecasting techniques used by met services, and research into gust forecasting and turbulence.

(i) depends on the existence or otherwise of deep convection, (ii) represents different approaches/philosophy when modelling gusts, (iii) the difference between practical solutions and development research.

This review first covers physical/heuristic models of convective and non-convective gusts, of the kind which met services have so far used for gust forecasting, in section 2, including the gust diagnoses used in the Met Office operational suite. Then, the topic of statistical and empirical gust models, which form an area of relatively new development, is discussed in section 3. Subsequently orographic flow processes in stable flow which contribute to gustiness, but which are unresolved by NWP models and not treated explicitly by current gust models, are summarised in section 4. A summary and possible directions for future work are given in section 5. The details included are derived from published papers, reports, conference presentations and material from the web at the time of writing (April 2011).

2 Physical/heuristic models

These models are based on some hypothesis about the process involved in gust formation, such as turbulent vertical transport within the boundary layer, or downdrafts within deep convection, and informed by the general body of practical field experience. The discussion is not exhaustive of all models or Met services, but takes in a broad selection.

2.1 Non-convective

Models of wind gust in non-convective conditions rely on estimates or calculations of boundary layer turbulence and vertical transport of momentum. The effects of this are expressed in different ways for different models. A summary of the different gust models that have been used with different NWP models / by different groups (whether operationally or otherwise), relevant formulae and references is given for non-convective gusts in Table 1.

The first group of users, including the MetUM, in Table 1 use the relationship of near-surface wind variability to u_* (or equally, drag coefficient C_D) after Panofsky *et al* (1977) and Panofsky and Dutton (1984). The MetUM and ECMWF/AEMET gust diagnostics also take into account variations in BL stability. The Met Office Virtual Met Mast (VMM) calculates mean wind using a correction to remove the effect of orographic roughness on the near-surface wind, and to account for difference in height between the (4km resolution UK) model surface and the true surface. In recent versions mean wind is first calculated using a 3-D linear turbulent flow theory (Wilson *et al*, 2010) which predicts direction dependence due to the surrounding topography; a u_* based approach is then used to determine gusts (Wilson and Vosper, 2011). Note the COSMO-EU diagnostic is the maximum of the non-convective and the convective gusts (see later) output.

The second group, which includes the algorithms used in the Met Office NIMROD and UKPP systems, represent the simple tactic of searching upwards, either to the first stable layer, the boundary layer top (often amounting to the same thing), or some set level to determine heights from which momentum may be transported to the surface. This is based on the argument that beneath these heights, there is essentially no obstruction to downward mixing of momentum. The gust diagnostic then reflects the maximum wind encountered within these levels.

In the third group, the turbulence intensity, which often forms the basis of the model of boundary layer vertical mixing in these models, decides the strength of the gust, based on the obvious reasoning that gusts directly represent the degree of turbulence in the boundary layer. Of the latter group, the boundary layer stability is also taken into account in the KNMI HIRLAM method, via the normalised gust, g, which reflects an assumed stability-dependence of the turbulence spectrum (Schreur and Geertsema, 2008).

The fourth and largest group uses the “Wind Gust Estimate” (WGE) method of Brasseur (2001). This is similar to the second group, except with a more intelligent selection of the level from which momentum may be transported to the surface. Qualifying levels must satisfy,

$$\frac{1}{z_{parcel}} \int_{z_{parcel}}^{0} E(z)dz \geq \int_{z_{parcel}}^{0} g\frac{\Delta\theta_v(z)}{\Theta(z)}dz \quad (1)$$

i.e. TKE must be large enough to overcome any intervening bouyant inhibition. Hence this method also has something in common with ‘group three’ in Table 1, in particular the KNMI HIRLAM method, which is based on similar information. The WGE method is argued to be more ‘physically based’ than the other non-convective gust prediction methods; also limits are offered to bound the estimate of gust provided. The bounding limits are determined, for the lower bound, by using a local instead of vertically averaged measure of TKE in the above equation, and for the upper bound, as simply the maximum wind within the boundary layer.

A number of authors have cited the usefulness of WGE (e.g. Olafsson and Agustsson (2007), Agustsson and Olafsson (2009), Goyette *et al* (2003), Nilsson *et al* (2007), Adams (2004), Cheung *et al* (2008), Szeto and Chan (2006), Chan (2011), Chan *et al* (2011)), but only limited comparisons with other techniques have been published (Brasseur (2001) find some improvement relative to a rudimentary local gust factor determined from observations, while Brasseur (2001) and LaCroix (2002) find comparable behaviour to the standard ‘surface-layer-deflection’ (SL) method used in the AFWA MM5 configuration (Table 1), a method which is unlikely to be the strongest of those listed). Also, there is some suggestion that the algorithm may have a tendency to overestimate gusts (Pinto *et al*, 2009).

Only one (regional) climate model is included in Table 1. Rockel and Woth (2007) discuss a multi-model ensemble of RCMs, of which only two diagnose gusts. The diagnostics described are rather simple, but clearly eessential. The authors not only recommend use of (preferably more sophisticated and physically based) gust parameterisations, but also highlight problems simulating extremes in mountainous areas where topography may be poorly resolved compared to NWP models, suggesting the need to account for sub-grid orography.

Model/system	Met service	formula	references	notes
MetUM	Met Office	$U_g = U + \sigma f(\kappa, c_{ugn}, z_{0m\_eff})$	Panofsky and Dutton (1984)	$\sigma \sim u_*$, depends on mixed layer details
VMM	Met Office	$U_g = U + C\sigma$	Wilson *et al* (2010), Wilson and Vosper (2011)	$\sigma \sim u_*$
IFS/HIRLAM	ECMWF/AEMET	$U_g = U + c_{ugn1}\sigma$	IFS documentation CY33R1:IV:3.12.4	$\sigma \sim u_*$, depends on mixed layer details
			Beljaars (1987), Panofsky *et al* (1977)	$c_{ugn1} = 7.71$
			Calvo and Morales (2009)*, Calvo *et al* (2010)*	(formerly function of z_{0m_eff})
			Della-Marta *et al* (2009)*	
COSMO-EU	DWD	$U_g = U + \alpha 2.4\sqrt{C_D}U$	Panofsky and Dutton (1984), Schulz (2008)	$u_* \sim \sqrt{C_D}U$
MM5/WRF	-	$U_g = U + c_{ugn1}\sqrt{C_D}U$	Simon *et al* (2011)*	LGUST parameterisation
NIMROD/UKPP	Met Office	$U_g = (0.89 - 0.002U_{max})U_{max}$	Ashton (2004)*	U_{max} - max model wind 0-1km
ATWIS	RWIC	$U_g \sim U(z_{BL\_top})$	James and Block (1998)	Re-based turbulence threshold
MM5	AFWA	$U_g = U(z_{stable})$	LaCroix (2002)*	Often defaults to BL top
WRF	-	$U_g = f(U_{BL\_top}, z_{BL\_top})$	http://forum.wrfforum.com /viewtopic.php?f=8&t=948	
HIRLAM	KNMI	$U_g = U + gr_\sigma\sqrt{2E}$	Schreur and Geertsema (2008)	g - normalised gust for given probability
			Calvo and Morales (2009)*, Calvo *et al* (2010)*	E - turbulence intensity
				r_σ - anemometer sampling factor
ARPEGE/ AROME/ ALADIN	Meteo-France	$U_g = U + 3.5\sqrt{E(20m)}$	Seity *et al* (2010)*, Calvo and Morales (2009)*	E - turbulence intensity
			Calvo *et al* (2010)*	Max U_g over 1 hr used
MM5	AFWA	See discussion	LaCroix (2002)*	WGE method
			Agustsson and Olafsson (2009)*	
WRF	-	See discussion	Agustsson and Olafsson (2009)*	WGE method
			Simon *et al* (2011)*	
RAMS	HKO	See discussion	e.g. Chan *et al* (2011)*	WGE method
GEM-LAM	CMC	See discussion	Higuchi *et al* (2008)*	WGE method
CRCM	EC	See discussion	Goyette *et al* (2003)*, Nilsson *et al* (2007)*	WGE method
ALAPS	Antarctic CRC	See discussion	Adams (2004)	WGE method
LM	MeteoSwiss	See discussion	Walser *et al* (2006)	WGE method

Table 1: Gust parameterisations/diagnostics used in different models and/or by different national met services. These may feature in NWP models, nowcasting systems, or simply ad hoc methods. Methods have been grouped in terms of similar bases. Original references or references which provide the basis for a given scheme are included where possible, and other appearances of each scheme in the literature are also given (* - not original reference). U refers to the 10m wind. The Advanced Transportation Weather Information System (ATWIS) is run by the Regional Weather Information Centre (RWIC) operating in Dakota.

2.2 Convective

Physical/heuristic convective gust models revolve around basic concepts concerning air motion within convective cells. Downdrafts possess vertical momentum which, on approaching the ground, is deflected to the horizontal. These downdrafts are considered to be driven by negative bouyancy as a result of (i) latent cooling, due to melting of frozen precipitation as it descends through the freezing level, and evaporation/sublimation from falling precipitation, and (ii) loading of the air with precipitation (similar to e.g. dust in pyroclastic flows). In addition, these downdrafts also transport parcels with large horizontal momentum from high levels to the surface, further enhancing gust strength. Surface winds may also be accelerated by pressure perturbations induced by the convective or frontal system. Lastly, the momentum of the system itself may contribute to the precise magnitude of gusts.

Different convective gust models are summarised in Table 2. Since this review was motivated originally by the requirement to better predict orographically-induced gusts during stable (i.e. non-convective) conditions, only a handful of operationally used convective gust parameterisations have been listed.

The Nakamura *et al* (1996)-based scheme used by the Met Office is a fairly typical method dealing with some of the above physical concepts. The three terms in the equation in the first line of Table 2, calculated using model profile data, represent the momentum of the parcel at the top of the downdraft, the latent heat-induced negative bouyancy of the air, and the precipitation loading effect. $T_{deficit}$ is the difference between the T_{mean} and $T_{surface}$. The top of the downdraft is considered to be the highest out of 500m and $H(T_w = 0)$. This assumption, consistent with the much earlier Fawbush and Miller (1954) technique for non-frontal convection (Met Office 1993, Forecasters' Reference Book), may be flawed: Nakamura *et al* (1996) state that the downdraft may originate at higher levels if driven by sublimation, and suggest instead that a standard height above cloud base be used for better accuracy and to avoid spurious seasonal variations (the above limit of 500m was introduced to try and address this). Pierce *et al* (1996) cast doubt on the predictive skill of the algorithm and Ashton (2004) advises care in using the latest, improved version which still retains substantial RMS and bias errors (Hand, 2000). The COSMO-EU diagnostic is also based on Nakamura *et al* (1996). Holleman (2001) proposes using the NIMROD gust algorithm at KNMI, with modifications using upper air and radar observations for nowcasting purposes.

Two older techniques, termed 'T_1' and 'T_2', based on Fawbush and Miller (1954), are still a common rule of thumb, for instance with aviators, though only thermal downdraft potential is treated. The Fawbush and Miller (1954) technique depends on the difference between the wet bulb potential temperature at the $T_w = 0$ level and the predicted maximum temperature at the surface (a measure of potential negative bouyancy). It also forms part of the basis for the technique of Bartha (1994), used in the MEANDER nowcasting system (Simon *et al*, 2011). In the latter, standard radar reflectivity output and surface pressure gradient also supplement the information used to diagnose gusts. Steen (1999) also reviews some early convective gust forecasting techniques.

The WINDEX method (McCann, 1994) is based on a vertical momentum equation for convective downbursts which takes account of downdraft potential due thermal, precipitation loading and pressure perturbation effects, with empirical modifications. Kuhlman (2006) compares WINDEX with the T_1 and T_2 methods for a two month period in areas of the US, finding T_1 and WINDEX perform comparably, better than T_2 (Kuhlman provides a full description of the techniques and reproductions of convective dynamics diagrams from Wakimoto (2001)). Meanwhile the Naval Aerographer (http://www.tpub.com/weather3/6a-21.htm, "Calculations of Convective Wind Gusts") suggests use of T_2 for frontal thunderstorms and prefrontal squalls, and T_1 for airmass thunderstorms. Geerts (2001) finds that WINDEX is significantly improved by a further term to account for horizontal momentum transport (from a nominal 500mb level), and rescaling, resulting in the "GUSTEX" method.

Bukharov *et al* (2008) describes a method based on the nearest standard level wind ('principal wind speed component'), and contributions for isobar curvature, vertical momentum exchange and a basic treatment of thermal and precipitation induced downdraft potential. The vertical momentum exchange is considered relatively local (based on the nearest standard level). All terms are based on NWP except for the thermal part of the downdraft term, which is derived from satellite data.

The ECMWF algorithm (Bechtold and Bidlot, 2009) takes a similarly local approach to vertical momentum exchange, based on the shear forecast at low levels, only applying the algorithm where deep convection is diagnosed within the NWP model. The authors state that this is found to produce better results than downdraft-based models. Though this simple approach is somewhat empirical, it is included here for completeness and comparison with the other current operational methods.

A number of research studies look for the (dominant) origins of severe convective gusts. Kuchera and Parker (2006) compared analysis vertical profiles (from NCEP Rapid Update Cycle, RUC) against reports of damaging wind, looking for skill in different profile parameters for predicting the damage occurrences. They found the best skill for a combination of the wind at the top of the convectively unstable layer and a downdraft CAPE parameter derived from the level of minimum equivalent potential temperature aloft (Table 2). They also found that wind blowing from warm to cold over a front, or blowing along the line of convective development diminishes damaging wind occurrence. In the former case, bouyant parcels rise over stable, colder air and convection is relatively isolated from the surface at higher levels. In the latter, the system tends to slow and thus additivity between descending gusts and system speed results in smaller values. Mahoney and Lackmann (2009) study rear-inflow jets in "realistic" idealised 3D simulations of mesoscale convective systems, showing that downward momentum transport associated with these jets dominates the production of wind extremes. Other authors take a more detailed view of convective system structure in estimating gust potential. Kwon and Kareem (2009) describe research around a gust-front model containing time dependent, height-varying mean and fluctuating wind terms at a given location, developing a 'gust front factor' relating to the enhancement of boundary layer gust magnitude by convective gust fronts. The physical basis of different gust front models may vary in rigour, but they essentially rely on the concept of a gravity current (e.g. Qian *et al* (1998)).

Evans *et al* (1995) describe a gust front model component of a cumulus parameterisation illustrating its dependence on system/downdraft speed. Zeng *et al* (2010) studied observed gust 'wavepackets' accompanying the passage of a cold front. They decomposed the variation of wind into mean quasi-stationary flow, coherent gust flow ($\sim$ 1-20 minute fluctuations dominated by anti-correlated vertical and horizontal components) and isotropic turbulence. They found that flux of momentum to the surface is mainly through the mean term, but with the coherent gust and turbulent terms contributing substantial, roughly equal amounts.

Model	Met service	formula	references	notes
MetUM/ NIMROD/ UKPP	Met Office	$U_g = 0.67\sqrt{U_{T_w=0}^2 + \frac{gH_{T_w=0}T_{deficit}}{T_{mean}} + \frac{2gH_{T_w=0}P_{max}}{(5)(60)(60)}}$	Nakamura *et al* (1996) Ashton (2004)*	P_{max} - maximum precip rate T_{mean} - mean T up to $H_{T_w=0}$ $P > 0.1$mmhr^{-1}
COSMO-EU	DWD	$U_g = \sqrt{U(T_w=0)^2 + 0.2\int_H^0 2g\frac{\Delta\theta}{\theta}dz}$	Nakamura *et al* (1996) Schulz and Heise (2003)	no ppn loading
MM5	AFWA	$U_g = 5*$ $\sqrt{(H_{T_w=0}MIN(q_{1km},1)(\Gamma^2 - 30 - q_{1km} - 2q_{T_w=0}))}$	McCann (1994) Kuhlman (2006)*	WINDEX method ; Γ - lapse rate
-	-	$U_g = 0.6U_g(WINDEX) + 0.5U(500mb)$	Geerts (2001)	GUSTEX method
MEANDER	Hungarian Met Service	See discussion	Bartha (1994) Simon *et al* (2011)*	Nowcasting
-	-	$U_g = U_1 + \delta U_R + \delta U_{exch} + \delta U_{conv}$	Bukharov *et al* (2008)	U_1 - 'principal wind speed component'
RUC	AFWA	$DMGWIND = (WINDINF/8)(DCAPE/800)$	Kuchera and Parker (2006)	$WINDINF$ - max wind over unstable layer
IFS/INCA	ECMWF/ ZAMG	$U_g = max(0, U(850mb) - U(950mb))$	Bechtold and Bidlot (2009) Simon *et al* (2011)* Calvo and Morales (2009)* Calvo *et al* (2010)*	

Table 2: As Table 1, but for convective gust parameterisations.

3 Statistical/empirical models and related observational studies

A large proportion of gust models place little emphasis on a physical mechanism for the understanding of gusts, either relying on established empirical observations, or performing regressions based on observed gusts in different locations under different conditions. Previously, these might represent simple gust factors at a site (the average ratio between peak wind and mean wind within a given time interval), determined empirically or based on simple assumptions concerning the surrounding environment (Met Office 1993 Forecasters' Reference Book). More recently, however, in parallel with the advent of GIS, such methods tend to take inputs in the form of mapped model data (variables successfully trialed as predictors and with some intuitive connection to wind behaviour) and terrain/land use characteristics, and result in mapped products on the same grid. Due to their use of regression methods, and probabilistic treatment of gusts, these are often termed statistical models. Statistical models are well suited to predicting the probability of gusts exceeding some threshold.

The statistical approach has advantages and disadvantages. For instance, since it is not constrained by a particular physical process model, it has a good chance of capturing the net effect of all relevant processes to some extent, insofar as they are represented by the variation of the predictor variables. However, the absence of a physical process understanding may mean that they are more difficult to evaluate meaningfully and improve.

Field observations have been used to study gust factors, often with the focus on how these factors are affected by surrounding terrain. For instance, Agustsson and Olafsson (2004) show a direction dependence in the gust factor at a location adjacent to a large, isolated mountain. The gust factor varies between 1.4 and 1.6 for mean wind speeds greater than 10ms^{-1}, with larger values related to upstream disturbance created by the mountain. A similar effect occurs for other stations depending on mountain height and distance. Little dependence is found on stability (N, R_i), possibly due to the compensating effect of enhanced mountain effects, combined with decreased downward momentum mixing, with increasing stability. A deficiency of using gust factors to derive gust forecasts from the mean wind is that they typically decrease with increasing windspeed (Agustsson and Olafsson, 2004), but this decrease is not generic (Naess *et al*, 2000). However, they are a standard measure used by wind engineers in assessing the vulnerability of standing structures. Typical mean values of gust factors seem to lie generally between 1 and 2 (Met Office 1993 Forecasters' Reference Book, Naess *et al* (2000), Agustsson and Olafsson (2004)).

Barrett and Short (2008) developed a tool to predict peak wind strength by using observations at the Kennedy Space Centre/Cape Canaveral tower network and soundings. The most successful combination of predictors proved to be the maximum wind up to 3000ft and the surface inversion strength and depth. The latter reflects the decoupling of surface winds from the flow aloft by strong near-surface stability.

Gray (2003) describes a statistical approach to convective gust forecasting, using the Met Office

LEM, with initialisation and lateral boundary conditions provided by two series of typical radiosonde profiles for convective conditions and driven by a prescribed surface heating function, to simulate convection. After finding that the Nakamura *et al* (1996) method predicts the peak near-surface wind in the domain well, Gray goes on to fit Gaussian functions to the distributions of perturbation gusts (calculated for individual grid points within a given time window) in each simulation at different times. Gray finds empirical relationships of these distributions' mean and standard deviation to the product of the maximum gust and the mean wind, and the maximum gust, respectively. Given the maximum gust and the mean wind may be gained from NWP and gust diagnostics, a forecast of the distribution of gusts may be made, and thus of probabilities that different thresholds are exceeded.

Friedrichs *et al* (2009) describe the use of Generalised Linear Models (GLMs) to describe the behaviour of winds detected by 139 stations of the DWD observation network. GLMs involve the assumption that the probability of different values of the dependent variable (i.e. gust) conforms to an exponential-type distribution (e.g. Poisson) whose mean is a linear function of the predictor variable. Friedrichs *et al* (2009) also compare the use of Generalised Extreme Value (GEV) distributions to model the behaviour of gusts. A GEV distribution represents the distribution of maxima of a sequence of independent, identically distributed random variables, and hence is suited to modelling gusts (the extreme value wind measurements within a given time period). The aim is to obtain, for a given mean wind, a probability distribution for the gust strength, and therefore the probability that some threshold is exceeded. Both types of model are tuned by regression against observations. Using a Brier score with only the mean wind as predictor, it is found that GEVs of gust perturbation offer the best combination of stability (reproducibility for different training periods) and skill. Adding further predictors to this method such as CAPE and DCAPE (downdraft CAPE), winds at different levels, the best results are found using the mean wind and the highest gust measured in the surrounding 100km. From the point of view of forecasting, using ECMWF model 10m wind offers generally comparable skill; CAPE, DCAPE and winds at different levels make little relative impact as predictors.

Etienne *et al* (2010) use Generalised Additive Models (GAMs) to model regional wind extremes in Switzerland from a climatological point of view. GAMs are an extension of GLMs, whereby the response function for the dependent variable (gust) need not be confined to a simple linear function. The study focuses on the 98th percentile of daily maximum winds, found to be a convenient analogue to days with damaging winds. Observations from seventy stations are used. Etienne *et al* (2010) employ GIS topography data - location, elevation, slope and slope orientation, curvature (resolved into along slope and transverse components) and landform category (e.g. canyon, midslope drainage) calculated on a range of scales from 50m to 2000m. Different combinations of these predictors are studied; combinations of predictors are only permitted if their mutual correlation coefficient is sufficiently small. A combination of curvature, slope, landform and elevation at 1km scale is found to give the best results. Predictor characteristics show the highest wind extremes correspond to high elevations, exposed landforms, shallow slope values, and negatively curved (convex) surfaces. The authors remind that their method only takes into account static factors; complex terrain flow processes emerge from multiple static and dynamic factors on a range of scales, and cannot be tagged simply to terrain characteristics.

Sallis *et al* (2011) explore different machine learning approaches, including neural networks, for predicting gusts based on simple meteorological variables. The best performer is found to be a simple classification and regression tree (CART, has some features in common with a GAM). Some tests are performed with 30min lagged data to test prediction of future gusts based on present observations; significant skill remains at this lead time. Sallis *et al* (2011) use an unusually specific definition of gust, corresponding to standard US weather observing practice, concerning peak wind, wind variability and rate of acceleration, and duration; it is prediction of this, rather than some threshold exceedance, which is tested. In a similar vein, Kretzschmar *et al* (2004) evaluate the potential of neural network classifiers based on lagged wind/gust data and ECMWF analysis data from 24 hr previous to predict gusts finding benefits from inclusion of both kinds of data.

Sanabria and Cechet (2010) fit the behaviour of wind extremes at Sydney Airport to a Generalised Pareto Distribution (GPD, similar to a GEV distribution, but applying to a range of values close to the extreme, rather than the extreme value alone) in order to compare this to a newly developed Monte Carlo technique: using observations to develop gust factor distributions for different mean wind categories (ignoring as trivial, data where mean wind is below 5 ms^{-1}), these distributions are sampled in a Monte Carlo process, with care to ensure the same overall distribution of peak wind strengths. This produces over 2500 effective years of data which compare well statistically to the original dataset and can be used to estimate bounds upon long return periods for different wind extremes. The Monte Carlo process is justified by citing that the use of the gust factor, which relates turbulence to mean wind, represents the physical process of gust formation by transport of turbulence from higher levels. As an aside, the authors highlight the deficiency of typical anemometer instruments, developed to measure mean winds, in detecting the true intensity of the extreme, short-lived gusts typically associated with damage. The technique has been applied to output from high resolution climate models, where hazardous wind occurrences were found to increase under climate change as a function of emmissions (Sanabria and Cechet, 2011). Sanabria and Cechet (2007) attempt to directly account for the process producing the gust by grouping data according to past/present weather type at the time, so that return periods for gusts with different sources may be determined.

Glahn and Dallavalle (2006) discuss gridded Model Output Statistics (MOS) products under development at NWS. MOS involve a (here multiple linear) regression between model and observational data to correct empirically for differences in local detail. Rudack (2006) describes the application of this technique to gusts. Using predictors (for mean and gust wind) including model u, v and wind speed at the 10-m, 925-mb, 850-mb, 700-mb, and 500-mb, relative vorticity, relative humidity and some wind speed observations (at short lead times), along with the first and second harmonics of the day to account for the seasonal variation of wind gusts throughout each 6-month season. Also added specifically for gusts are the gust speed observed 3 hours after initial model time, the difference between the GFS 850-mb temperature forecast valid at a specific projection time and 12 hours later, a BL mixing potential parameter, and the ratio between the 925-mb and the 10-m model wind speeds. The prediction equations developed are "regionalised", applying to a number of stations in a region. Within the interpolation inherent in the approach the "lapse rate" of different variables is taken into account (i.e. the simple height dependence). In a separate effort, Cook *et al* (2008) describe a method using of mixed layer momentum transfer to forecast gusts, carried out through the NWS "BUFKIT" profile analysis platform, with good results for the NAM model.

Connor *et al* (2003) describe a 'stratified' (according to synoptic wind direction) MOS technique for predicting the detailed wind field in Sydney Harbour based on typical standard level meteorological variables, local lapse rates, land-sea thermal contrast and other derived variables. They also develop a gust prediction technique, citing the surrounding complex terrain as a likely source of turbulence. The optimal technique found involves a nonlinear regression in terms of the stratified-MOS-predicted mean wind speed and direction which explains 98% of the observed variation of gusts.

K. Herring (Met Office internal reports, PostProc tickets 96, 364) describes a method which uses gust observations more directly, to modify model-based gust predictions. The modification acts at the nowcasting timescale; predictions converge with the model-based gust after six hours. A system based on this method was recently implemented in UKPP.

4 Unresolved orographic flow processes which lead to wind extremes

Few of the models so far discussed take account of surrounding topography in the calculation of gusts. The overall effects of the local terrain are implicit in statistical models tuned against observations, while gust factors and methods such as the VMM and stratified MOS technique of Connor *et al* (2003) (can) incorporate a direction dependence reflecting the surrounding landscape. Note also engineering standards take account of surrounding topography (Ngo and Letchford, 2008). None, however, attempt to specifically model orographic flow processes (associated with stable, or unstable flows) which are not resolved or represented in current NWP models. Such processes include lee waves, downslope winds and rotors (Doyle and Durran (2002), Vosper (2004), Mobbs *et al* (2005), Sheridan *et al* (2007), Doyle *et al* (2009)), Foehn (Mayr *et al* (2002), Zangl (2003)), Bora (Belusic *et al* (2004), Belusic *et al* (2007), Gohm and Mayr (2005)) and channeled flows (Whiteman and Doran (1993), Mayr *et al* (2007), Sheridan and Bedford (2010), Sheridan *et al* (2010)). Meanwhile, efforts at the Met Office to forecast lee waves and rotors and their effect on near-surface flow (Vosper (2003), Vosper (2004), Mobbs *et al* (2005), Sheridan *et al* (2007)) have resulted in the development of operational forecasting tools. There is also interest in accounting for such processes in road wind hazard risk products (P. Murkin, personal communication). Datasets from the Falklands Islands (Mobbs *et al*, 2005) and the Pennine hills (Sheridan *et al*, 2007) offer the possibility of a more detailed examination of the effect of lee waves and rotors on gust strength.

5 Summary and discussion

A wide range of approaches for the forecasting of gust strength exists, developed for routine forecasting or tailored to specific locales. These may be based on a specific treatment of the physical process of boundary layer mixing or convective vertical transport, or developed with a primary basis on statistical similarity to observations in relative ignorance of the underlying processes. It is not clear for general forecasting techniques if the degree of realism in the underlying science necessarily adds significantly to the accuracy of results (compare WGE (Brasseur, 2001) to the less sophisticated non-convective gust methods, or likewise the simple shear-based ECMWF convective gust formulation to other more physically-based treatments of convective flow structure). Statistical methods attempt to sidestep the need to directly address different atmospheric and orographic processes, while implicitly building in their effects within the overall response to predictor variables. There are clear advantages in this somewhat "blind" approach, though the degree of success seems to reflect the complexity of the model, its degree of local focus, and the extent to which care has been taken to account for physical processes that are expected to be important. For instance, in the scheme described by Connor *et al* (2003), 98% of the variation in gusts is explained using a system with a large number of predictors, including a stratification in terms of synoptic conditions, tuned to a small area (Sydney Harbour), and which takes account of the effect of the surrounding topography on turbulence. Such systems are harder to generalise since the whole process must be repeated for a new area. Meanwhile, simpler physically-based treatments have the advantages that they are based on reproduction of actual processes, which should be broadly applicable, while being relatively easy to understand, and therefore to improve. Statistical methods are well suited to predicting threshold exceedance, though Gray (2003) shows how a physical model can also be adapted to produce statistical predictions.

To date, models do not attempt to directly address specific orographic processes (such as lee waves or orographically generated convection). It is possible that the enhancement of the mean wind by these processes, and subsequent application of existing gust forecasting techniques, would be sufficient. Other suggestions for the future might involve synthesis between the advantages of statistical/empirical/mapped and physical approaches.

It is clear that methods of gust prediction based on model output have a crucial role to play in climate change projections as well as weather forecasting.

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