Met Office

Current gust forecasting techniques, developments and challenges

Peter Sheridan

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Outline

- Introduction
- “Physically-based” boundary layer gust algorithms for NWP
- (Deep) convective gust methods
- Empirical gust forecasting: statistical and machine learning methods
- Implications of (sub-)mesoscale phenomena for gust forecasting
- Focus on recent research

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What is a gust?

Maximum 3 second average wind at a given height AGL within some period (e.g. 10 minutes, 20 minutes,1 hour)

Why do we care? – Brief, intense gusts are mostly responsible for the damage caused by winds, compared to the sustained wind

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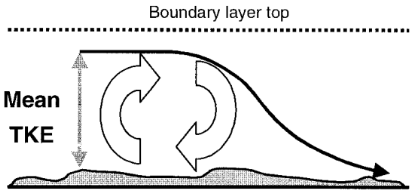
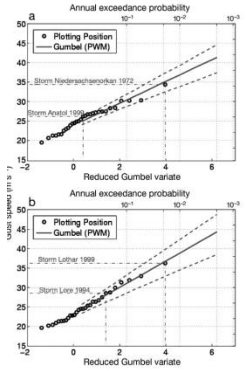
Summary of techniques

Forecasting gusts using NWP requires some form of treatment applied to the NWP fields to interpret the turbulence likely experienced at the surface under the modelled conditions

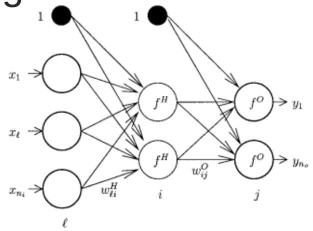


Physical parametrisations – “fundamental” appraisal of boundary layer turbulence, mesoscale controls (versatile)



Statistical methods – construction of statistical models (regression, extreme value modelling; data driven, climatology)

Machine learning (neural nets, Support Vector methodologies, regression tree methods)



For highly convective situations, separate (physically based) approaches exist

“New” to NWP

With increasing model resolution, resolved small scale dynamics emerge

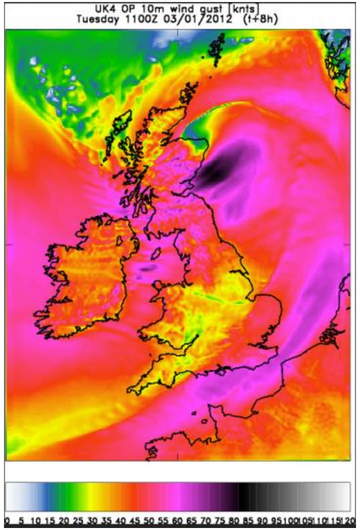
Eddies or shallow convection:

- source of gust partially resolved; techniques developed for coarse models assume perturbations are sub-grid, become overactive

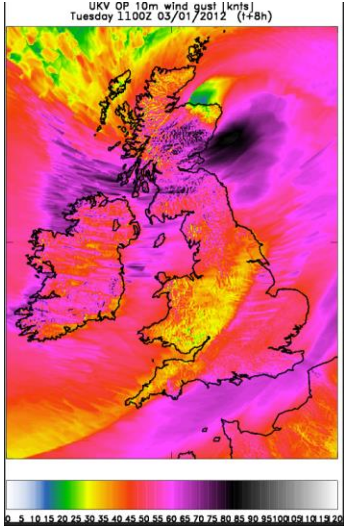
Mountain waves, sting jets:

- associated with severe gusts, may not conform to physical models envisioned in gust techniques

4km model



1.5km model



Boundary-layer turbulence gust diagnostic

MetUM gust diagnostic, following Panofsky *et al.* (1977), Panofsky and Dutton (1984), Beljaars(1987):

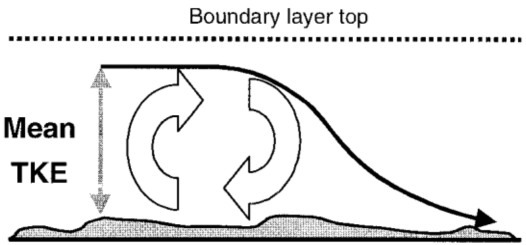
$$u_g = |u| + \sigma(1/k)\log\left(\frac{5\exp(kc_{ugn}) + z_{0m\_eff}}{5 + z_{0m\_eff}}\right) \quad (1)$$

$$\sigma = 2.29u_* \qquad (\mathcal{L} > 0)$$
$$\sigma = 2.29u_*\left(1 - \frac{z_i}{24\mathcal{L}}\right)^{1/3} \qquad (\mathcal{L} < 0) \quad (2)$$

Based on modified Monin-Obukhov similarity theory for convective BL turbulence using mixed layer depth, z_i, as vertical spatial scale, empirically fit. z_i =0 applies in stable conditions

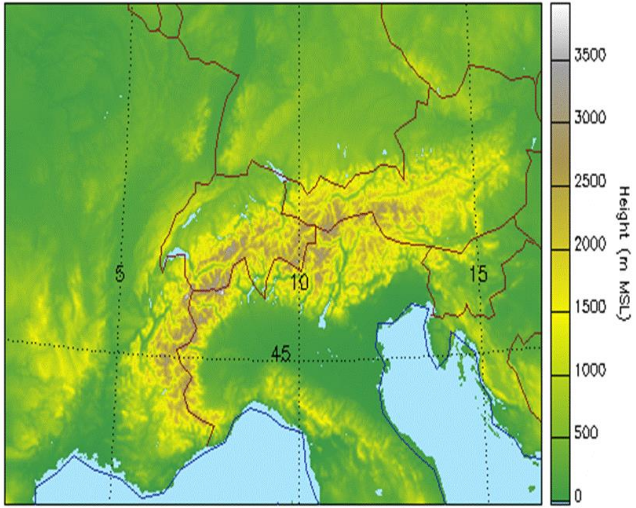
(Equivalent method used in ECMWF model)

Also physically-based, Brasseur (2001) "Wind Gust Estimate" method treats downward momentum transport from levels for which TKE is sufficient to overcome intervening bouyant inhibition

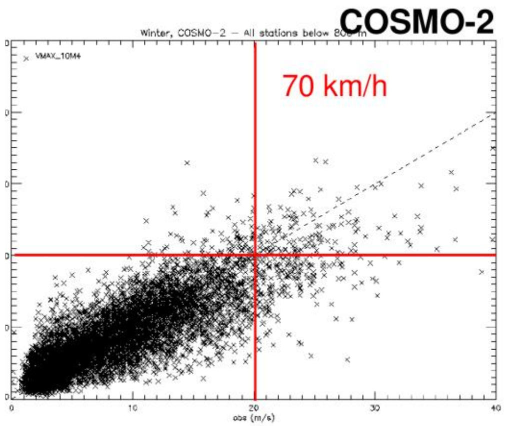


Verification example

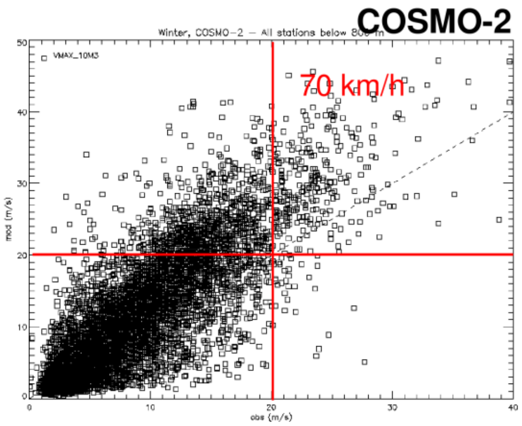
Schubiger *et al.* (2012) – COSMO-2 model (NB augmented with convective gust, amplification of large gusts)



M-O based gust



Brasseur WGE



Convective gust estimation

Nakamura *et al.* (1996) method, based on physical appraisal of momentum processes in deep convective storms: downdraft temperature deficit, precipitation loading, downward momentum transport (system speed and induced surface pressure gradients not treated)

COSMO regional model: $U_g = \sqrt{U(T_w = 0)^2 + 0.2 \int_H^0 2g\frac{\Delta\theta}{\theta}dz}$

Was once tested in Met Office nowcasting system: $U_g = 0.67\sqrt{U^2_{T_w=0} + \frac{gH_{T_w=0}T_{deficit}}{T_{mean}} + \frac{2gH_{T_w=0}P_{max}}{(5)(60)(60)}}$

ECMWF IFS model: simpler method based on momentum transport in deep convection,

$$C_{\mathrm{conv}}\max(0, U_{850} - U_{950}) \qquad C_{\mathrm{conv}} = 0.6$$

Schemes are useful for conceptual understanding, attribution, but also applicable in coarse resolution models for weather and climate (with the caveat that they carry significant uncertainty)

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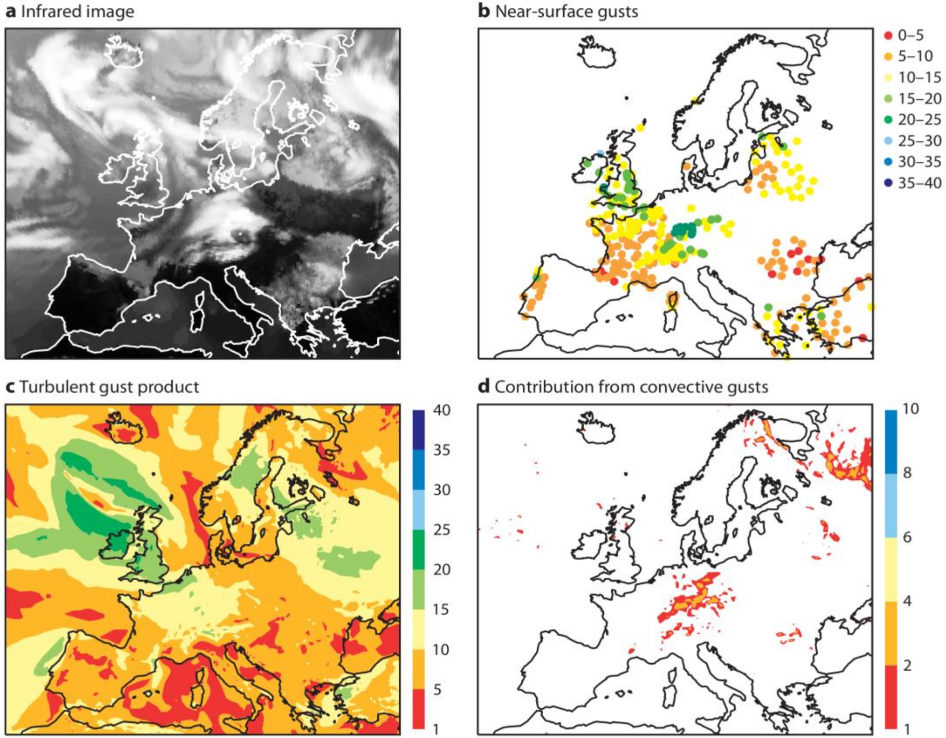


Figure 2 Same as Figure 1, but with the satellite image for 12 UTC on 25 June 2008, and the gusts observed and modelled between 12 and 15 UTC.

Case study: ECMWF IFS (Bechtold and Bidlot, 2009)

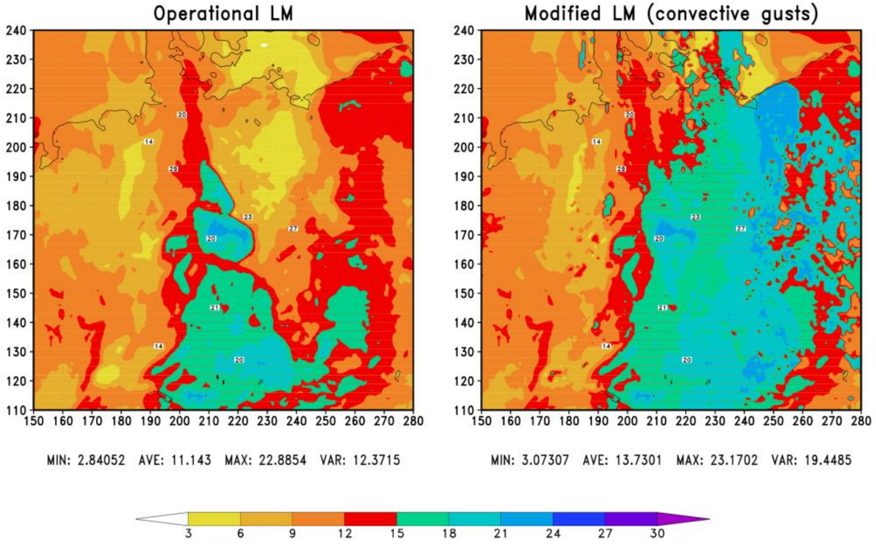


Figure 3: Comparison of 10-m gusts (m/s) on 9 July 2002, 00 UTC + 37h-42h, as forecasted by the operational LM and by the modified LM using the new parameterization of convective gusts. The numbers in the maps are observations.

Case study: COSMO LM (Schulz and Heise, 2003)

Statistical methods

Typically focussed on climatological timescales in terms of threshold exceedance probability or return time, for instance for modelling damage/financial loss, avoiding/amplifying brute-force dynamical modelling

Techniques include:

Extreme value statistics focussed on individual meteorological stations/numerical model grids to provide location-specific/mapped guidance products

Models of wind distribution as function of predictor variables (e.g. Generalised Linear Models)

Model Output Statistics (MOS) – refers to e.g. multiple regression of observations in terms of NWP predictor variables to remove bias; can be applied to data subsets for a set of tailored models; fundamentally applies to weather at point locations, but gridded “analyses” also employed

Statistical modelling example

Hofherr *et al.* (2010) – extreme value (Gumbel) analysis based on 1km resolution simulations of worst annual storm, for 30 years in Germany, employing a number of “shortcuts”

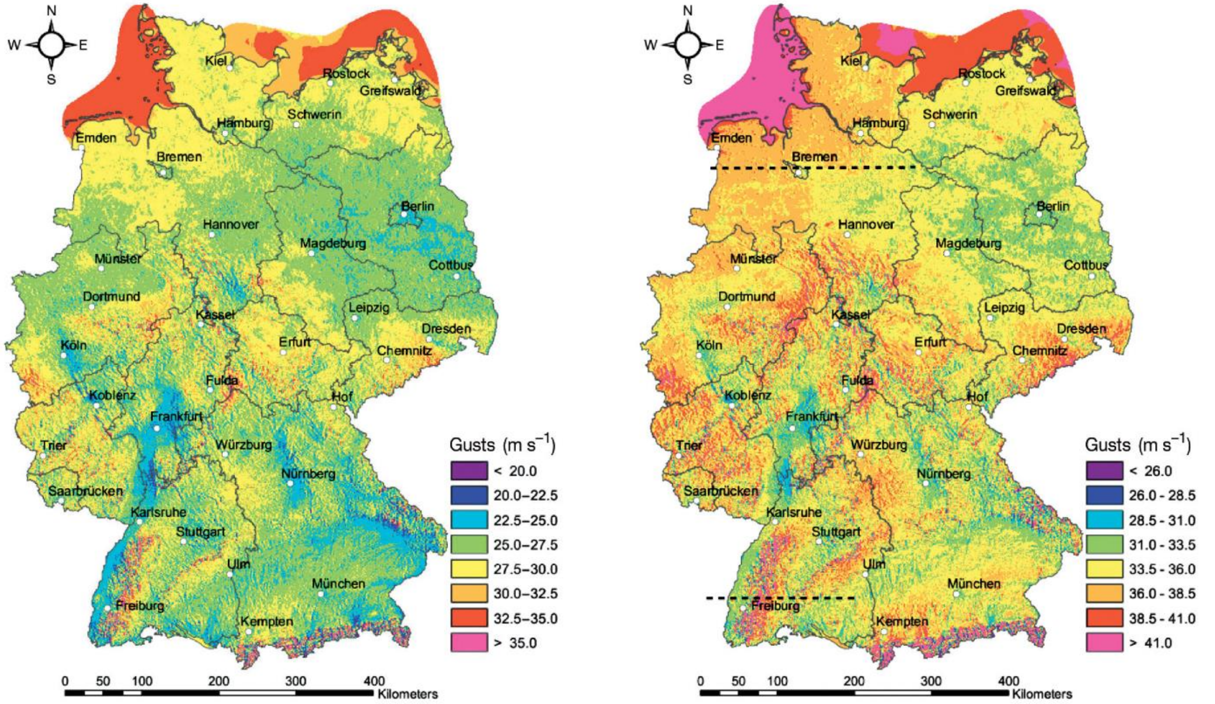
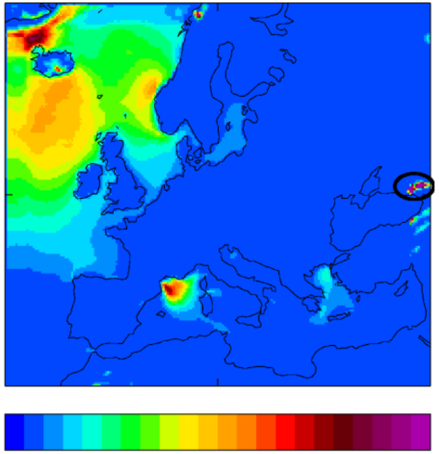


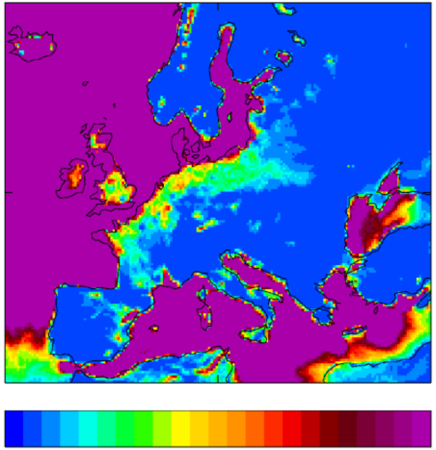
Fig. 4. Maximum wind speeds in Germany on a 1 × 1 km grid, with an exceedance probability of p = 0.5 (return period 2 yr; left) and p = 0.05 (return period 20 yr; right). The dashed lines indicate the position of the cross-sections shown in Fig. 6

Jess Standen (2012)

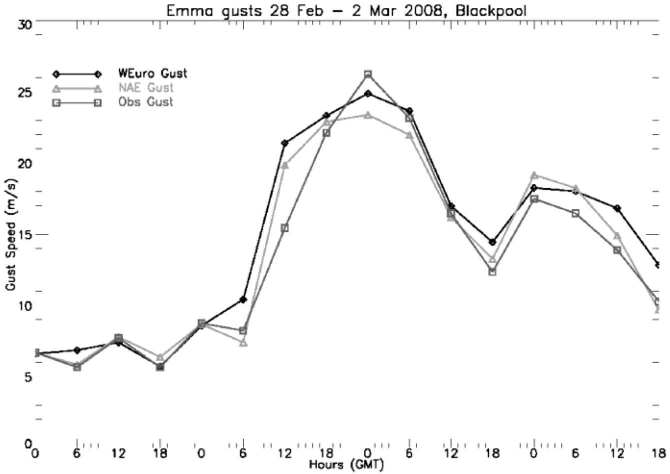
Counter example – gridded gust database



(a) Points that Exceed the 25m/s Threshold on a scale 0-20000



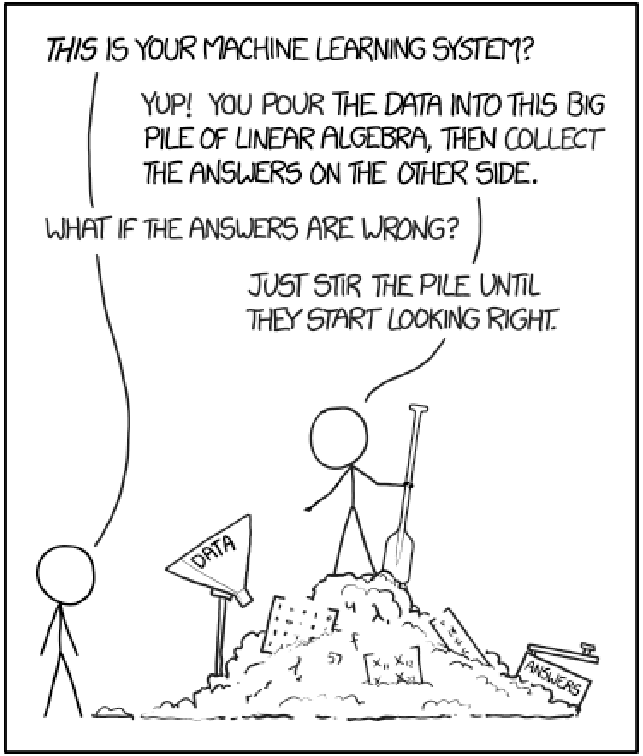
(c) Points that Exceed the 25m/s Threshold on a scale 0-200



1979-2012 (> 30 years data) single 25km resolution model driven by ERA-interim

http://www.europeanwindstorms.org/ footprints, characterisation of 50 storms (Roberts *et al.* 2014)

Machine learning



Machine learning

Applied frequently to wind modelling (sustained rather than gust)

Accommodates non-linear relationships to predictors

Application to gust forecasting fairly nascent; could be extended to gusts using physically-based methodology?

Artificial Neural Network (ANN) methods

Support Vector Machines/Regression (SVM/SVR)

Classification and regression tree methods, and others....

Similar goal to statistical modelling: optimisation; but iteratively improved, more nuanced

Numerous applications in gust detection/mitigation as part of control systems for flight/turbines

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Jung *et al.* (2016a,b)

Use machine learning* to optimise parameters of an extreme value model for gridded gust climatology derived from station data; applied to forest damage SW Germany

Predictors: elevation, aspect, curvature, slope, exposure index, local and fetch surface properties, monthly median U(850hPa), latitude, longitude

*LSBoost: method of weighted combination of simple regression trees ("weak learners") to create a "strong" prediction

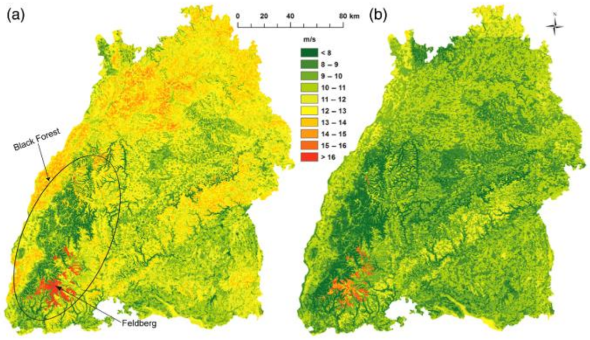
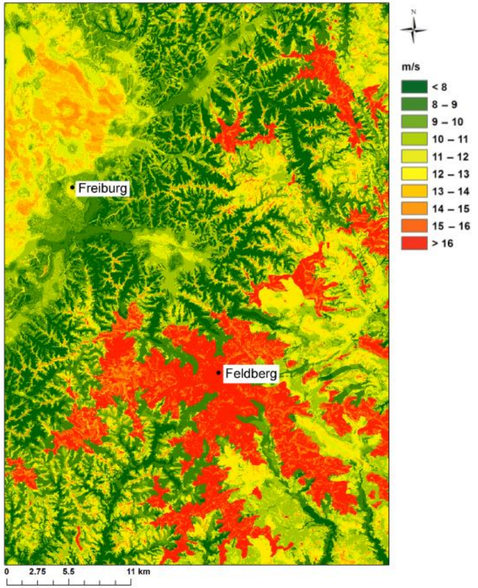


Figure 5. Map of $U_{max,mod}$-values ($F_{distr} = 0.75$) in (a) January and (b) July (50 × 50 m grid).



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(sub-)Mesoscale phenomena (100m-50km)

Convective cells and rolls

Largest BL eddies

Sting jets

Lee waves/rotors

Terrain variation – exposure and sheltering at small scales

} horizontal anisotropy ⇒ depend on surrounding model columns

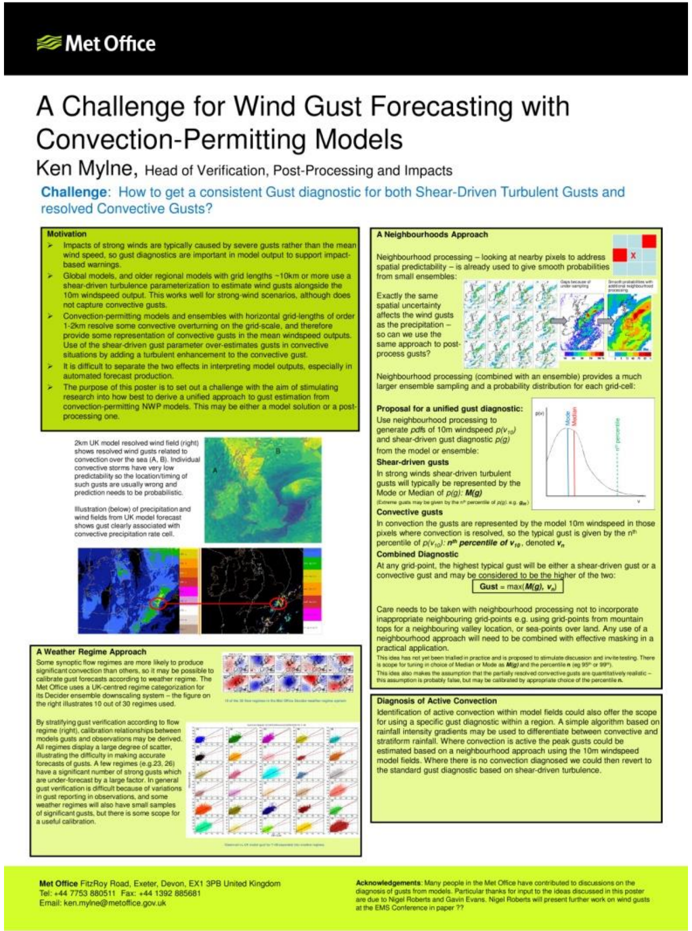
"Grey zone": these phenomena now permitted (but not fully resolved) in high resolution operational NWP

⇒ NWP wind input into gust methods no longer represents a "mean" but contains some representation of gust: this error is propagated through the gust computation ⇒ potentially gross overestimation

⇒ Physical underpinning of turbulent gust modelling may not be appropriate

Poster:

Ken Mylne, P85



Possible approaches:

1) Neighbourhood approach to capture resolved wind maxima (e.g. convective gusts)

Combine with parametrised shear driven gusts away from these spikes (e.g. by using neighbourhood mode/median)

OR

2) Diagnose convective areas and use neighbourhood resolved wind maxima or parametrised gusts accordingly

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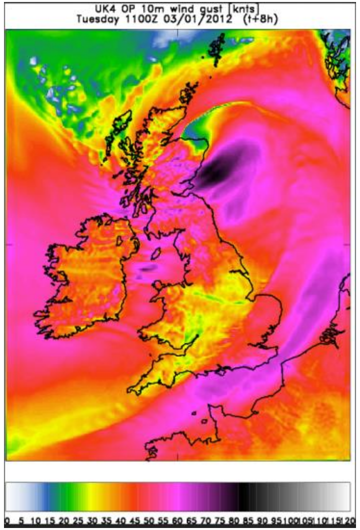
Convective cells

e.g. N Atlantic cold air outbreaks, cells small ~ BL depth, but large enough to be permitted in UKV, mimicking behavioural aspects of real cells – such as cold downdrafts

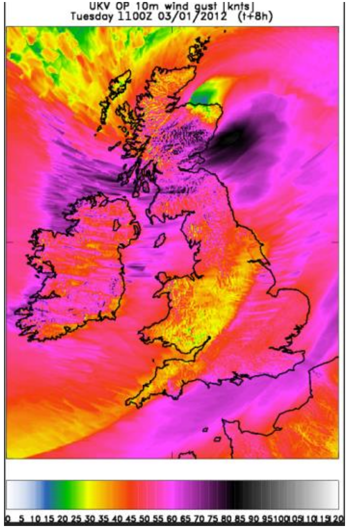
⇒ pattern of modelled surface wind already reflects some or all of gust amplitude

Gusts likely to be roughly collocated with convective showers and vertical instability (broadly columnar)

4km model



1.5km model



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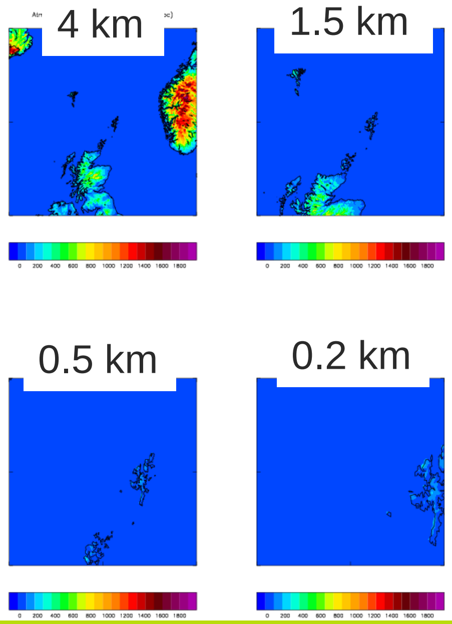
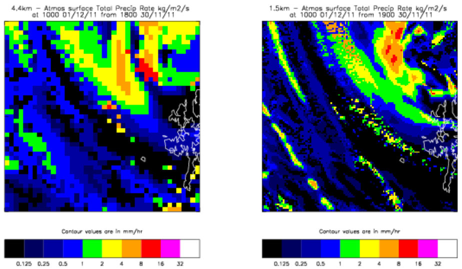
1 December 2011

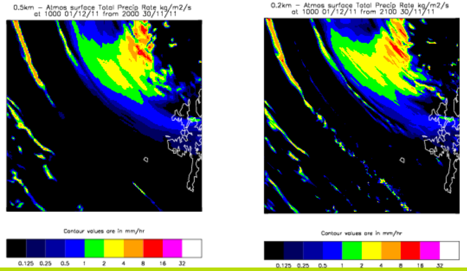
Cold air outbreak, Atlantic west of Scotland, leads to small scale convection

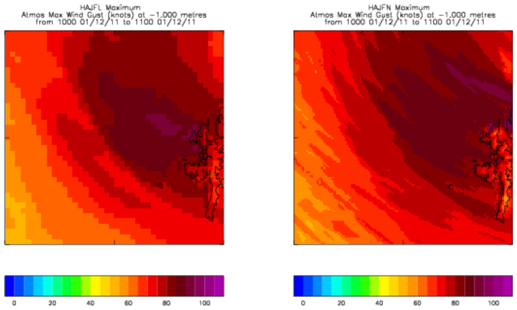
MetUM simulations at 4km, 1.5km, 0.5km, 0.2km resolution



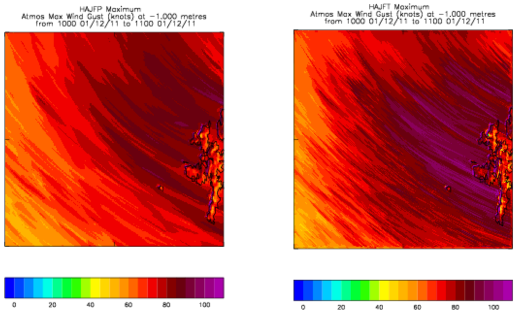


Precipitation rate





Max hourly 10m gust



(Mark Weeks, Met Office)

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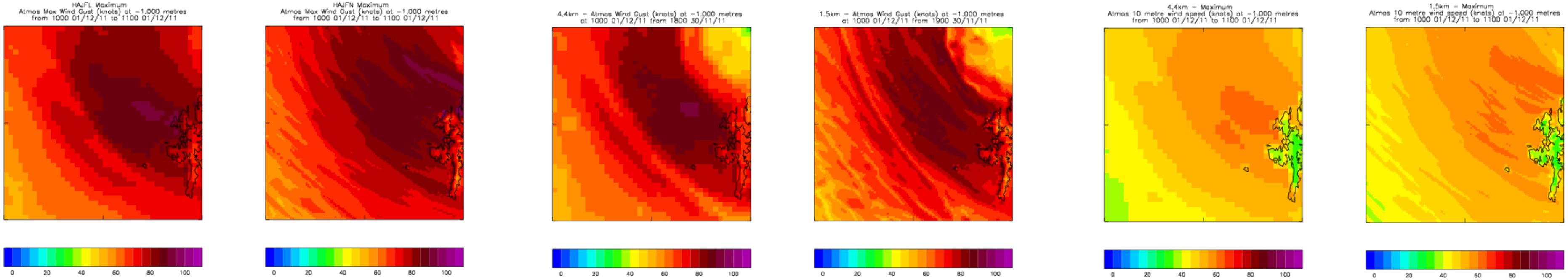
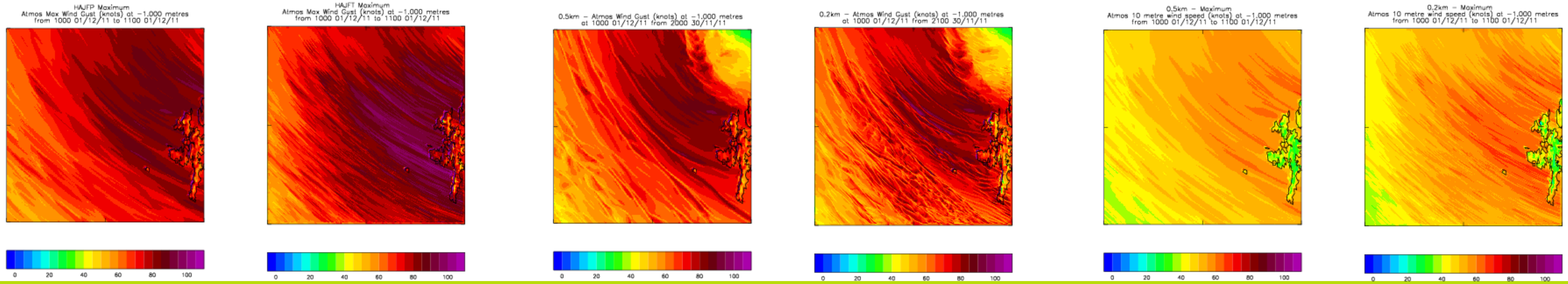
Max gust vs. other measures



Max hourly 10m gust

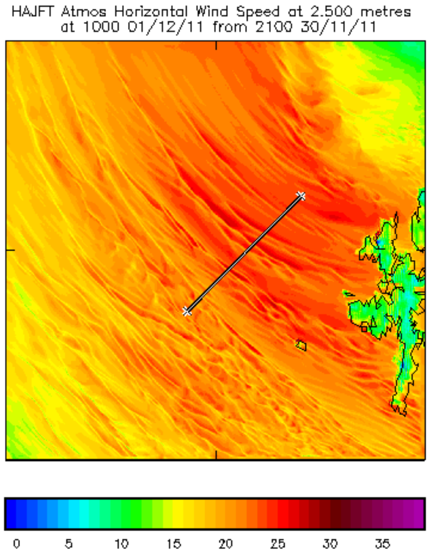
Instantaneous 10m gust

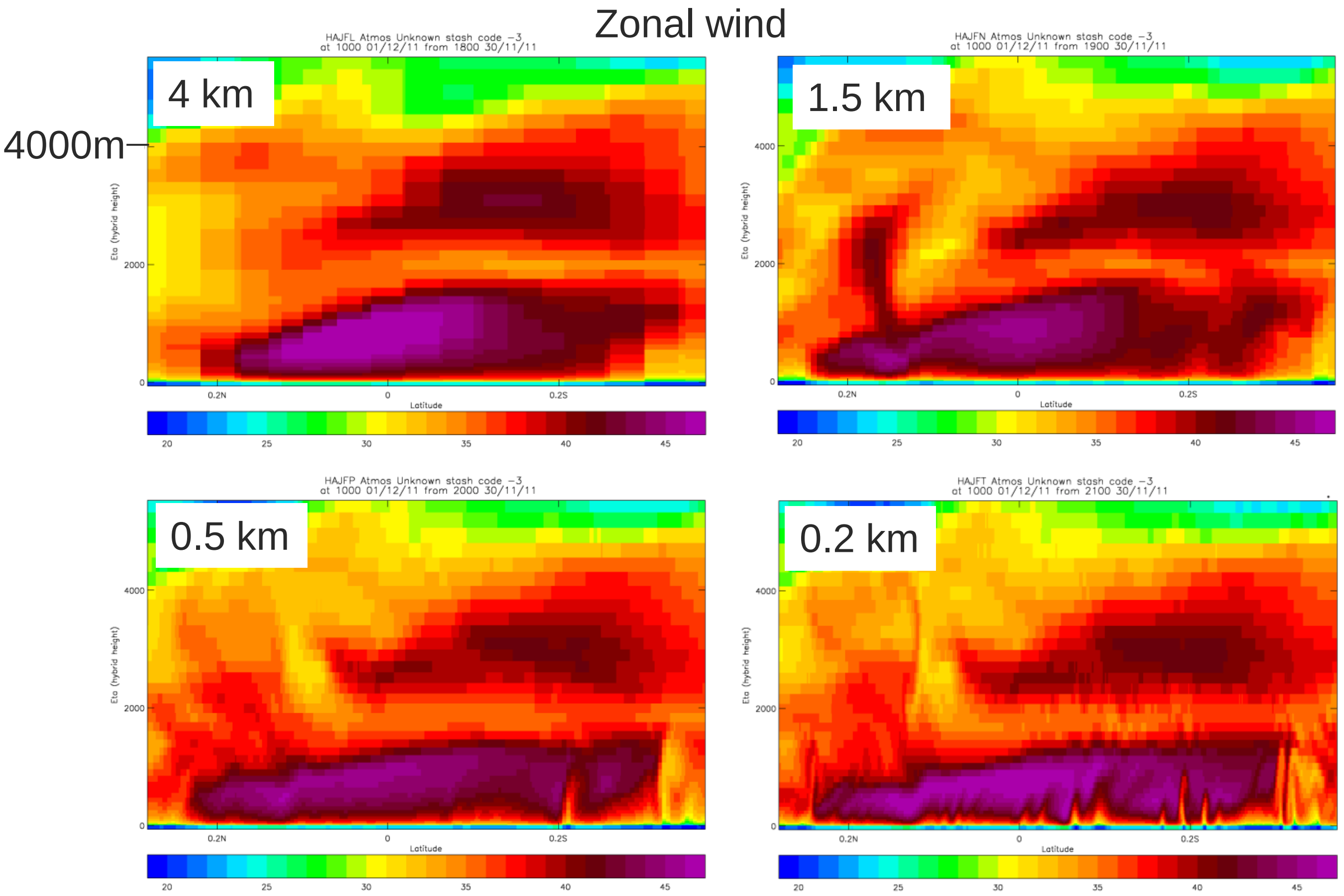
Max hourly 10m wind



(Mark Weeks, Met Office)

Vertical sections





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Sting jets

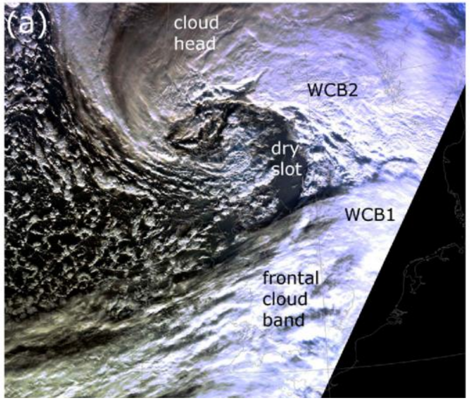
Descent from cloud head behind cold front

Distinct from Warm and Cold Conveyor Belt jets

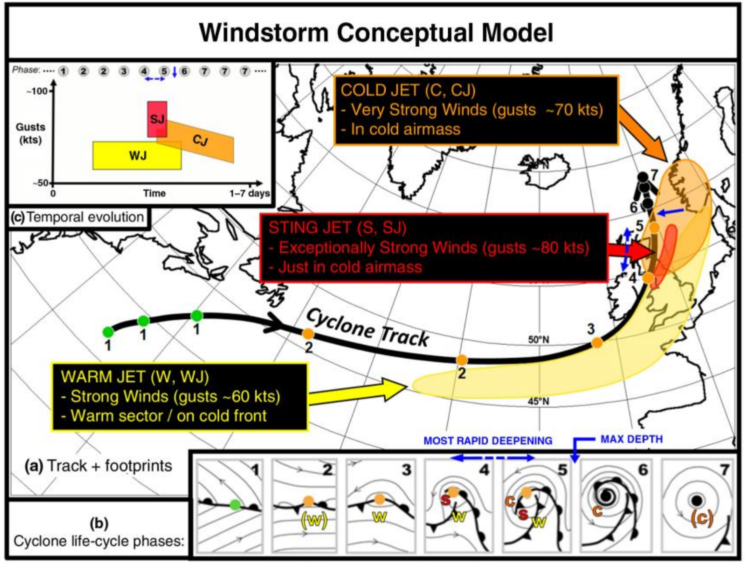
Associated with local slantwise CAPE

Assisted by evaporation from cloud head

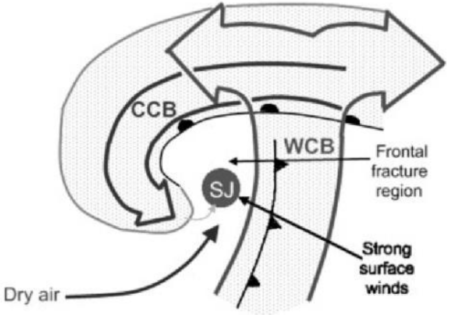
Transport of momentum to surface depends on low level stability; can be due to release of conditional instability (⇒ accompanied by precipitation)



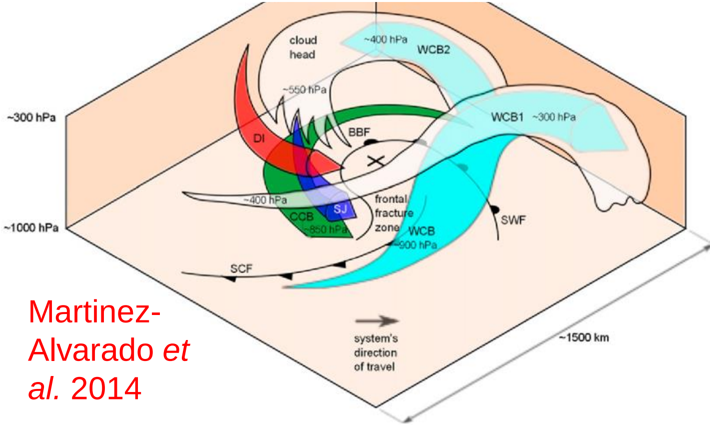
Martinez-Alvarado *et al.* 2014



Hewson and Neu 2015

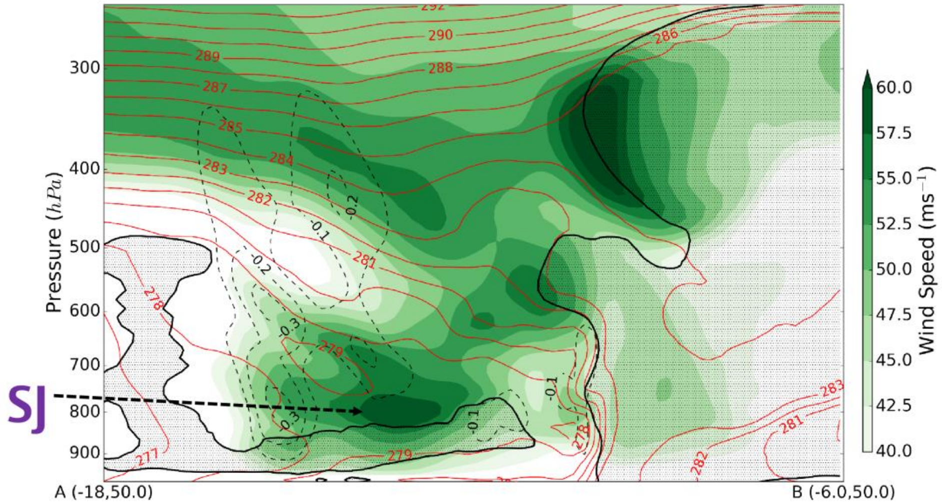


Baker *et al.* 2015



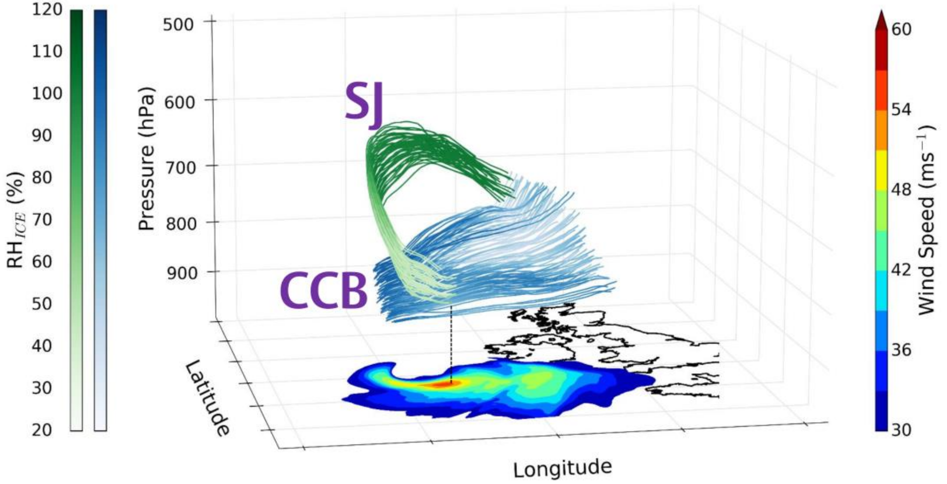
Martinez-Alvarado *et al.* 2014

Windstorm Tini, 12 Feb 2014 (Volonté *et al.* 2017)

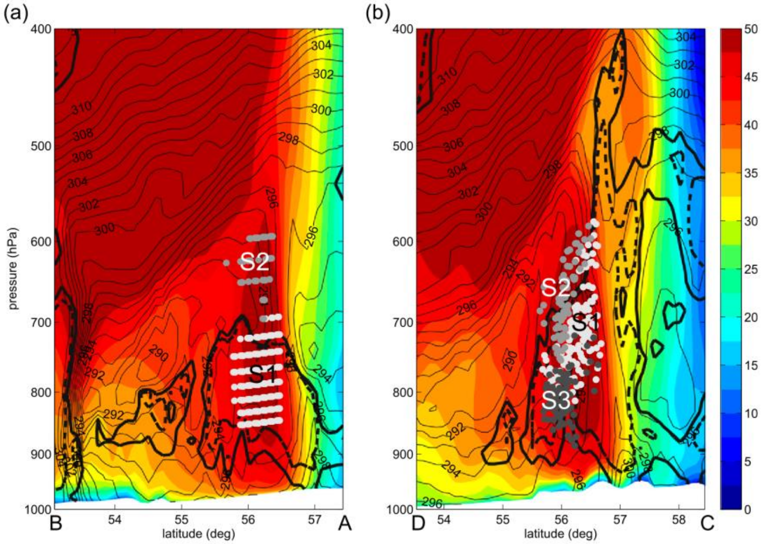


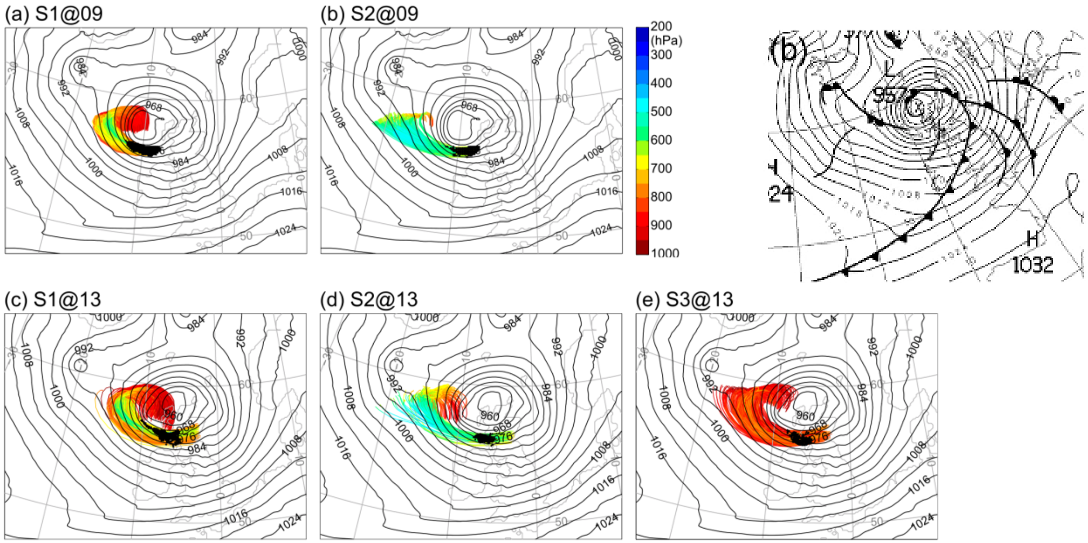
12 km hoz. resolution MetUM, 70 levels

(SJ missed at 25 km resolution)



St Jude's day, 27-28 Oct 2013 (Martinez-Alvarado 2014)





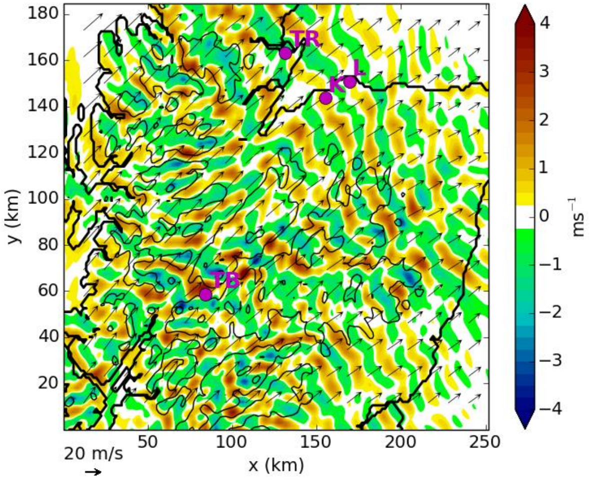
Sting-jets

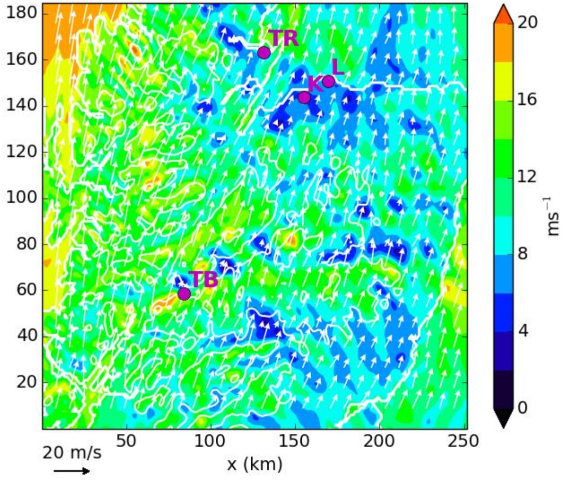
Potential disconnect between origin, footprint of the jet and precipitation – highly non-columnar, not simple to diagnose (approach (2))

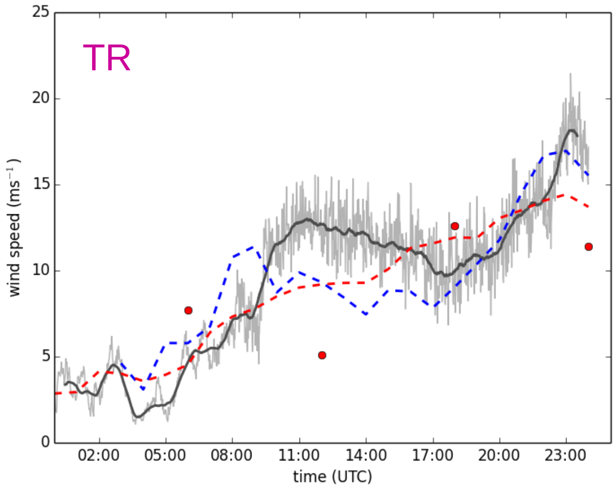
Sting jet precursor developed by Martinez-Alvarado *et al.* 2012 and Hart *et al.* 2017 $\Rightarrow$ potential to attribute (somewhat involved; imperfect)

Lee waves and rotors

Acceleration/deceleration pattern of wind phase locked with lee wave pattern aloft







(Met Office UKV, Sheridan et al. 2017)

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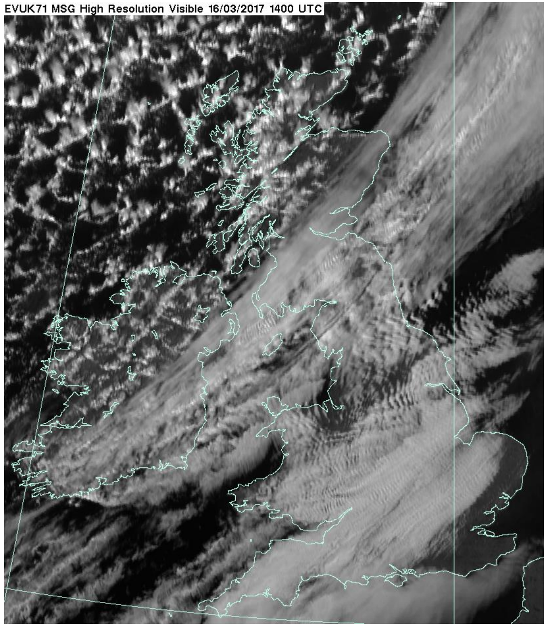
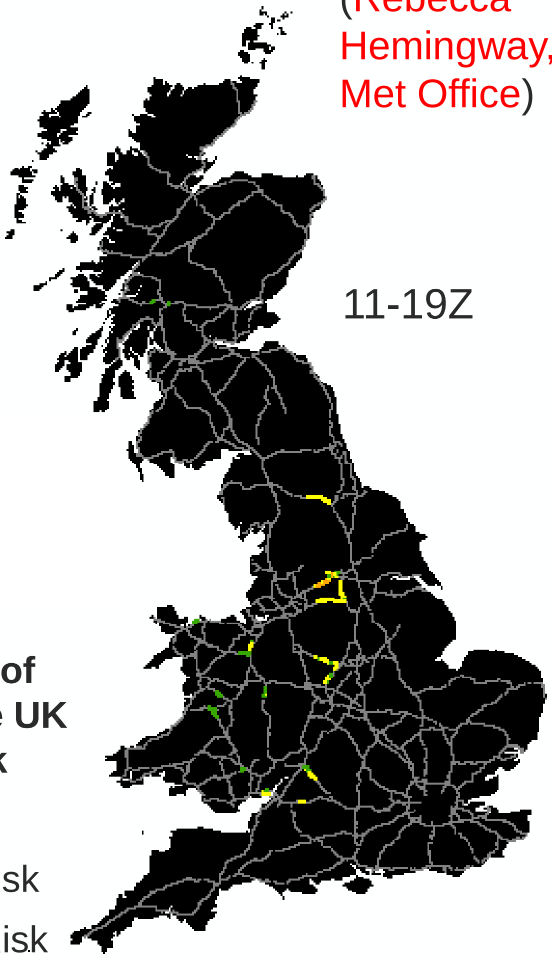
Vehicle OverTurning (VOT) Model

(Rebecca Hemingway, Met Office)

Lee Waves: 16th March 2017





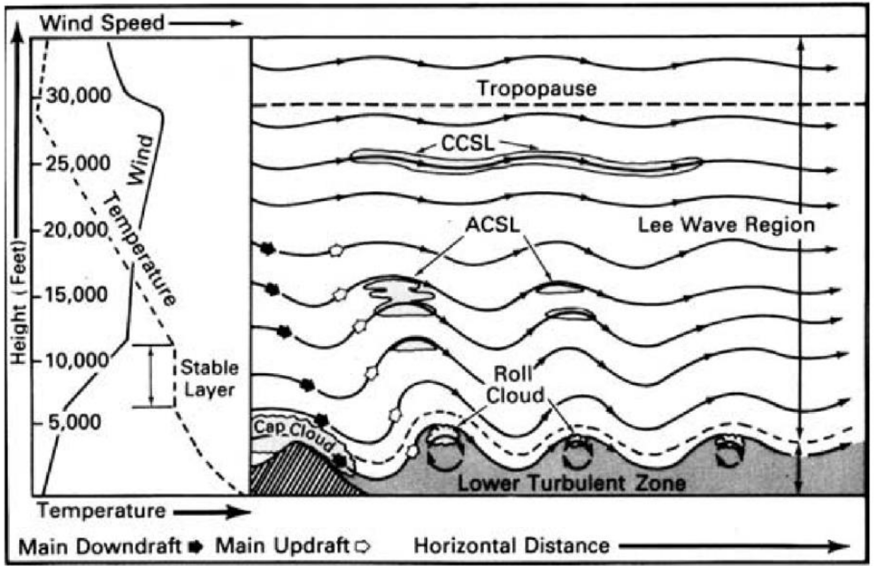
11-19Z

- VOT Model uses the 2.2km MOGREPS-UK wind gust and direction fields.
- It combines these, the Hazard, with information on Vulnerability and Exposure to determine Risk.
- Despite the hazard resolution lee waves are still seen in the model risk output.

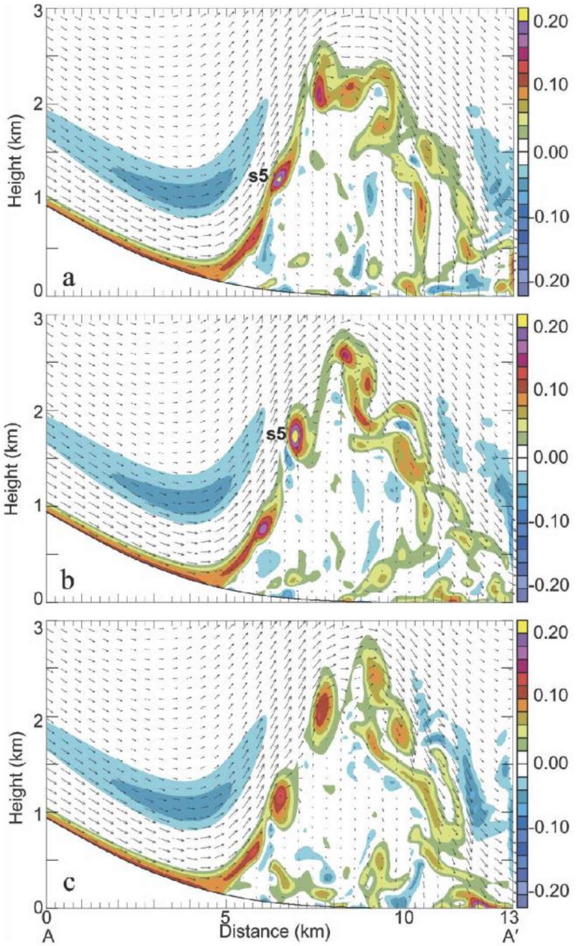
Maximum Risk of Disruption on the UK Road Network

- Low Risk
- Low - Medium Risk
- Medium - High Risk
- High Risk

Anatomy of lee wave/rotor system



Hertenstein and Kuettner (2005)



Doyle and Durran (2007)

Implications of lee wave/rotor system

In wave troughs/downslope windstorms strong winds may be steady

Certain areas favour gustiness (esp. flow separation region)

Under crests winds weak but may be gusty; strong shear zone in between has high uncertainty

→ not clear that turbulence statistics are the same as isotropic flow with the same mean profile

Current gust diagnostics treat each the same assuming only columnar influences

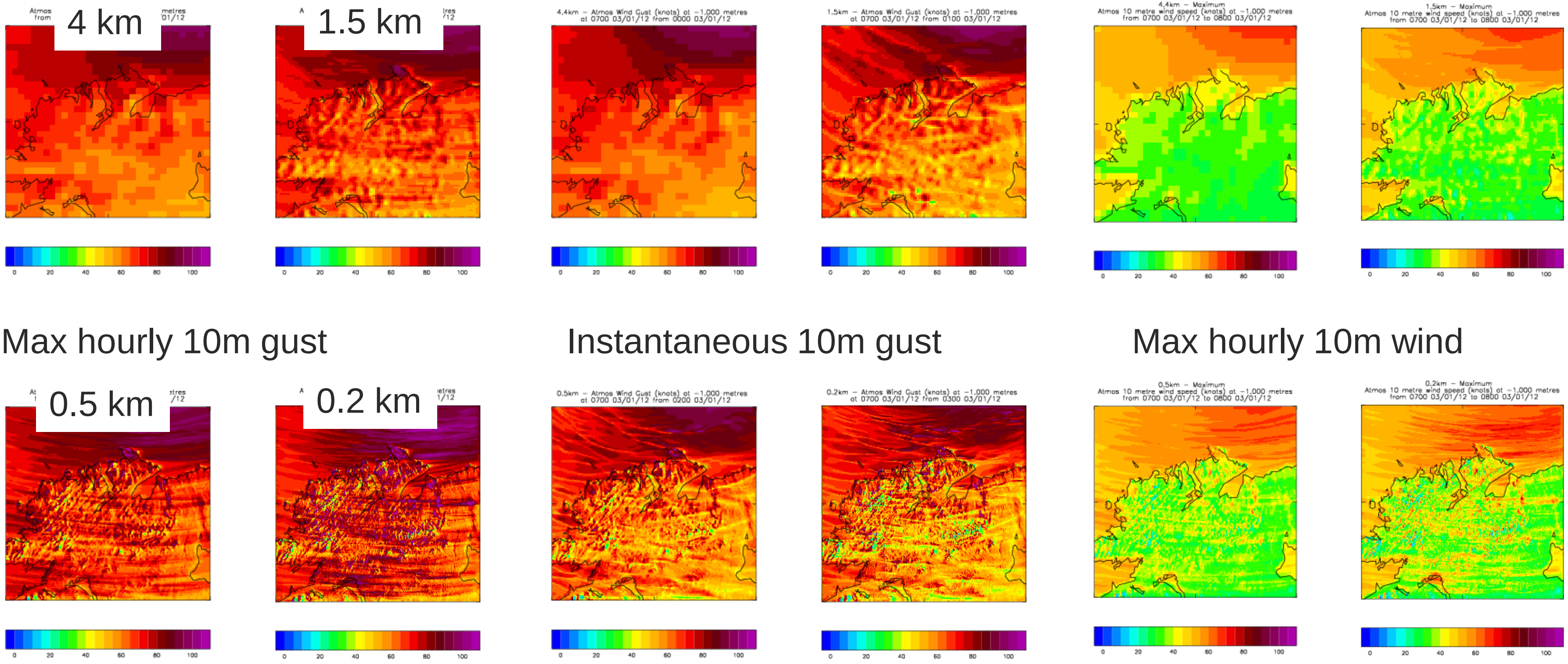
Effects of terrain

Validity of Monin-Obukhov theory over complex terrain

Direct effects on wind speed which propagate to parametrised gusts

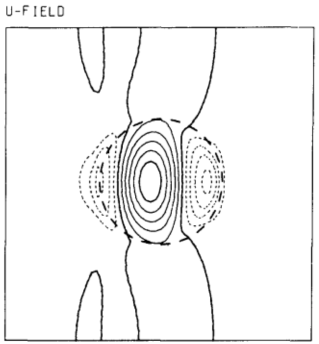
(Mark Weeks, Met Office)

Cyclone Ulli, 3 January 2012 (Similar to 1 Dec 2011 case)



Direct effect of terrain

Speed-up is expected, consistent with linear theory and numerous field campaigns (e.g. Mason and Sykes, 1979)



Implies care and selective masking in terms of terrain parameters (not just elevation) needed with neighbourhood methods

Speed-up of model wind may be realistic, though remains only partly resolved (cf. terrain)

Is the consequent amplification of the gust also realistic or further “error propagation”?

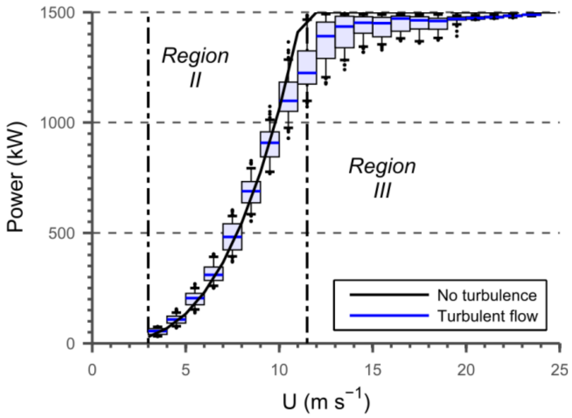
Depends on the gust method? – TKE-based methods (such as Brasseur 2001) may be less sensitive

Gust profile

Motivated by installation of increasingly large wind energy turbines (disc top >200m AGL; shear, uneven loading, loss of efficiency), but also applies to large buildings and forestry

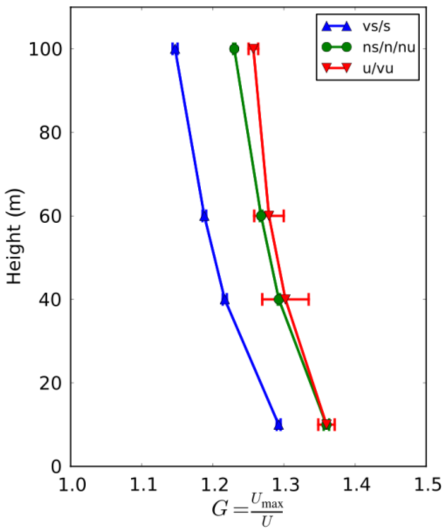
May be very different depending on the source of the gust

Time profile also of interest (Knigge and Raasch, 2016, LES)

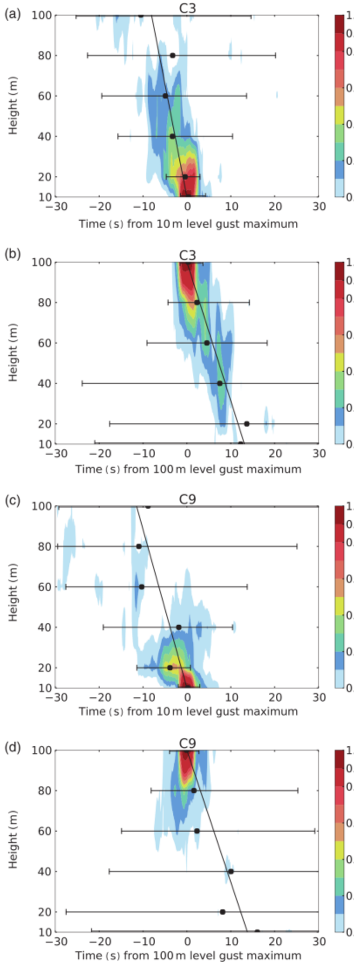


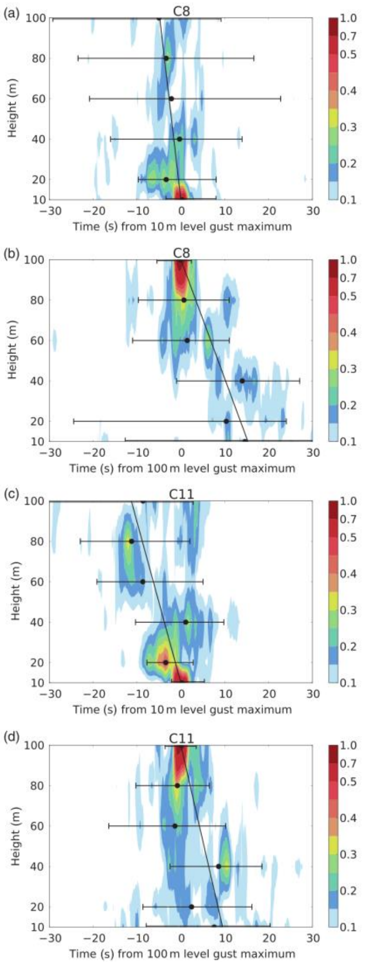
Clifton *et al.* (2013)

Suomi *et al.* (2015)



Stable

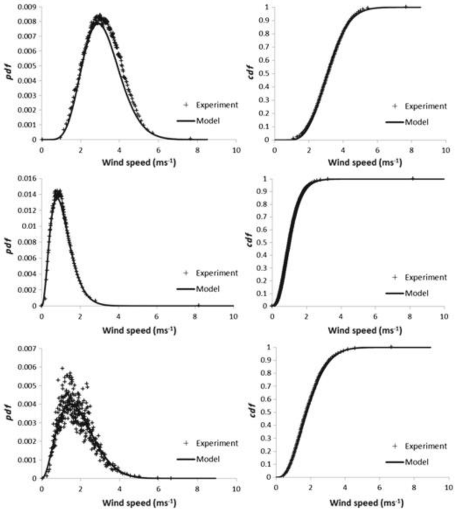


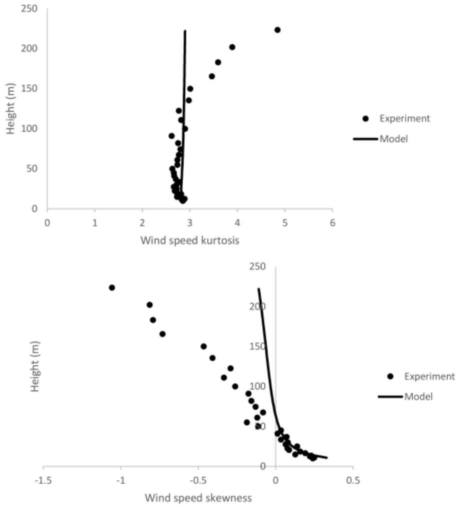


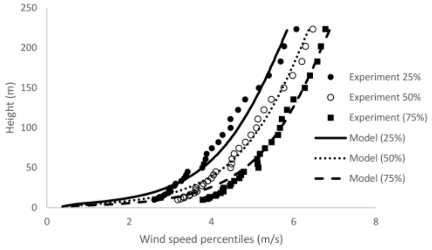
Unstable

Efthimiou *et al.* 2017

Wind modelled as beta distribution; employ extreme value analysis; DNS, wind tunnel data used to complete/validate the model, which can then be applied for any given height/time interval if mean wind and variance are known







Validation of statistical model

application to RANS model U, σ vs. tunnel

Met Office

Summary

“Physically-based” models – transparent, established theoretical basis; weather forecasting (not exclusively)

Statistical models – can be less transparent (black box), approximate, but provide comprehensive information; climatology, risk modelling (not exclusively)

Machine learning – increasingly ubiquitous; some applications in gust modelling or gust impact modelling/mitigation; can perform better than statistical techniques alone

Often powerful to combine approaches:

- statistical models based on high resolution simulations, or optimised using machine learning
- statistical climatologies built using gusts derived from physical parametrisations
- validation of gust models using LES, DNS, wind tunnels

Summary

“Grey zone” issues are emerging, as NWP models resolve wind phenomena responsible for gusts

$\Rightarrow$ stratify approach by gust source, or some robust accounting for this… (Ken Mylne, P85)

Growing research on height profile of gust partly due to increasing interest from urban and wind farm applications

Basic research on BL turbulence continues to be of importance!