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Severe Local Windstorms: A Meteorologist's Perspective

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ABSTRACT

The goal of this paper is to provide an overview of the meteorology associated with damaging winds at the surface, and a brief description of how to forecast such events. The style is suitable for non-meteorologists. First, the paper introduces weather systems that tend to produce damaging winds, from the large scale (cyclones) to the smaller scale (thunderstorms, mountain waves). The point is made that damaging winds can be produced in a wide variety of ways and across a range of spatiotemporal scales. Next, the multi-day prediction of such events requires computer models that are hemispheric or global in their domain size, as forcing mechanisms on day 1 of a prediction are often displaced thousands of kilometers from the final wind event on day 7, say. Inevitable errors in such predictions suggest an ensemble approach that predicts a distribution of plausible events, rather than a single outcome. Finally, an attempt is made to relate the wind field output from weather prediction models to actual winds to be expected at a building level. The ACCESS model at the Australian Bureau of Meteorology produces a gust field that better estimates such wind strengths compared to the standard averaged 10 m winds, but great variability exists in near-surface vertical wind profiles that complicate any estimate of building-level winds.

1. Introduction

Operational meteorologists predict wind speeds near the surface as part of generating forecasts and warnings. Such output generally extends over 10s to 100s of kilometres in space and 30 minutes to many hours in time and is therefore quite non-specific if an estimate of future wind speeds at specific locations is desired. One of the main goals of this paper is to introduce a range of physical mechanisms that produce most of the observed damaging surface winds and provide the wind engineering community with some insight into why weather forecasting is practiced on relatively large scales, and how numerical weather prediction or NWP models aid in the production of such forecasts.

The prediction of damaging surface winds in meteorology is a challenging problem as a whole variety of mechanisms can result in such winds. Further, near-surface winds often exceed the damaging threshold only over small areas and for relatively short periods of time, which enhances the uncertainty in their prediction. Ensembles, here these are multiple runs of the same NWP model starting with slightly different initial conditions, have become popular tools for the estimation of these uncertainties as they provide more reliable estimates of likely values instead of a single deterministic value that has an unknown error attached to it.

Section 2 describes weather systems that are likely to produce damaging winds. Section 3 provides some comments of how meteorologists predict such winds, and Section 4 adds some concluding thoughts to the topic.

2. Weather systems that can produce damaging winds

Nature produces strong surface winds through a wide range of physical processes that span scales from hundreds of kilometres down to tens of metres. This section lists a number of these processes that account for the majority of the damaging wind events.

On the large or synoptic scale, extra-tropical and tropical cyclones are well-known environments for the production of strong winds. Fig. 1 shows an example of the appearance of extra-tropical cyclones in visible satellite imagery. These cyclones draw their energy from large-scale horizontal temperature differences between polar and tropical air masses, a setup known to meteorologists as *baroclincity*. Extra-tropical cyclones predominantly affect the southern half of Australia and all of New Zealand.

Fig. 1. MODIS visible image of two extra-tropical cyclones over southeast Australia on 24 June 2014 at 0015 UTC. Note the fair amount of clear skies close to the respective low centres, a feature that visually distinguished extra-tropical from fully formed tropical cyclones. The scale is approximate only.

Most tropical cyclones tend to be smaller in scale when compared to their extra-tropical counterparts, with wind fields that surround the low centre (or "eye") in a more symmetrical fashion (Fig. 2). Their main energy source, in contrast to extra-tropical cyclones, is the latent heat stored in very warm ocean surface waters (sea surface temperatures in excess of ~26^{o}C). Tropical cyclones mostly affect the northern coastlines of Queensland, the Northern Territory and Western Australia, but do influence regions further south where their main impact shifts to heavy rainfall.

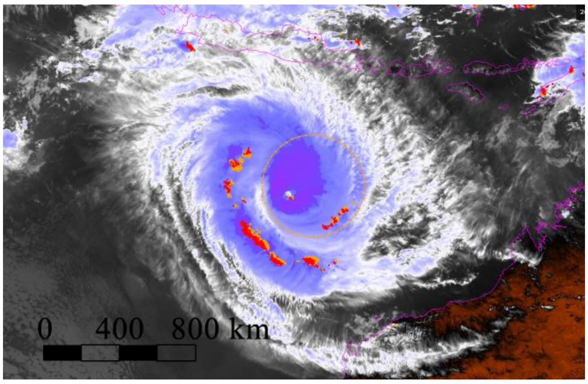
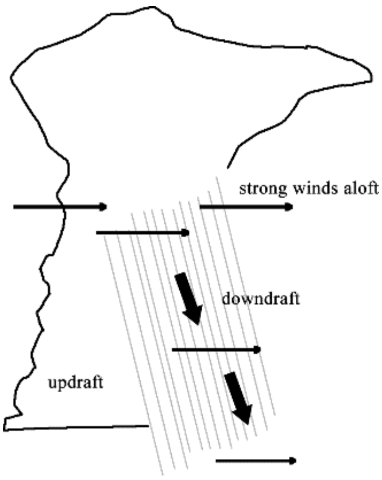


Fig. 2. Tropical cyclone Marcus off the northwest coast of Australia on 21 March 2018 at 05:40 UTC. Note the central dense overcast and the overall compact nature of the storm when compared to Fig. 1. The red and amber specs mark total lightning strikes.

On a smaller scale (kilometres to tens of kilometres), thunderstorms can produce a range of hazards such as large hail, damaging winds, heavy rainfall and tornadoes. The wind production is either associated with downdrafts or with storm-scale rotation. Fig. 3 shows three distinguishable physical mechanisms of how a downdraft can produce strong surface winds.



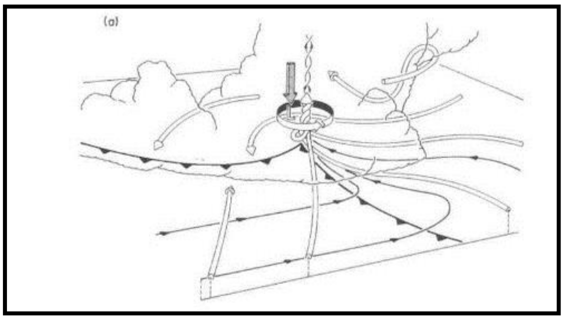


Fig. 3. Overview of three separate mechanisms how thunderstorm downdrafts can produce damaging winds at the surface. Top: a wet microburst on 27 January 2015; Middle: conceptual model of downward transport of horizontal momentum; Bottom: downward acceleration of downdraft air by a low-level mesocyclone (storm-scale rotation centre; from Fig. 13 in Klemp 1987).

A very common type of downdraft in Australia is the microburst. A wet microburst is shown in Figure 3 (top) and shows a rain-filled volume of negatively buoyant air descending towards the surface where it builds a dome of cool air, the "cold pool." This mass of relatively dense air then accelerates radially outwards as a gravity current (Benjamin 1968) to generate often strong horizontal flow (much like water spreading from a downward-pointed garden hose). A second mechanism for the creation of strong surface winds underneath a downdraft is the downward transport of large horizontal momentum. This setup is more common during the cool season in Australia where stronger flow aloft supplies a reservoir of horizontal momentum, and fast-moving storms can add to the final deposition of horizontal momentum near the surface. A less well-known third mechanism for the creation of a strong downdraft is related to the presence of rotating airflow in the lower parts of a thunderstorm (Markowski and Richardson 2014). If such rotation is maximized in the low levels of a thunderstorm, a storm-scale low pressure centre is collocated with it. This storm-scale low can then become instrumental in accelerating a downdraft by drawing in air from above due to pressure gradient forces. In thunderstorms that contain rotating air flows (supercells, see below) the “rear-flank downdraft” or RFD is most likely to be affected by such storm-scale low pressure centres. Within RFDs the wind speeds are not solely driven by thermodynamic processes such as evaporating droplets, but also by accelerations linked to these storm scale lows. As a consequence, RFD wind speeds in stronger rotating storms can easily exceed damaging thresholds. For a review of RFDs see Markowski (2002).

Fig. 4. shows the presence of a vortex (mesocyclone) associated with a thunderstorm near Kurnell in eastern Sydney. Storms that show persistent and deep rotation of this nature are known as supercells (Burgess et al. 1982) which produce a disproportionate amount of damage inflicted by thunderstorms and almost all the high-end thunderstorm damage observed. Mesocyclones form when a strong updraft reorients into the vertical the horizontal circulation tendencies that are inherent in a wind profile that is vertically sheared, i.e. where the wind changes direction or speed with increasing height (Rotunno 1981).

In some environmental conditions mesocyclones can extend downward into the low levels of a supercell. Such low-level mesocyclones are most common when the storm environment contains low-level vertical wind shear, i.e. the wind field in the lowest ~1 km AGL changes direction or speed with height. A circulation can even develop near the ground if the storm's cold pool is of an intermediate intensity. In such a case the low-level flow that initially rises over the forward flank cold pool of the storm can acquire some rotation but simultaneously remain sufficiently buoyant to 'connect' with the aforementioned low-level mesocyclone to result in tornado formation (Markowski and Richardson 2014). Tornadoes are capable of producing the strongest winds on earth, with some Doppler radar measurements suggesting winds near the ground that exceed speeds of 135 m s^{-1} (486 km hr^{-1}; Bluestein et al. 2015). Within Australia, thunderstorms are particularly common along the eastern coastal and northern coastal areas, as areas further inland (by "inland" I mean 100s of km inland) are often moisture-limited. Supercells are most common in the southeast and east of the continent where the juxtaposition of moist boundary layer air and deep vertical wind shear is most common.

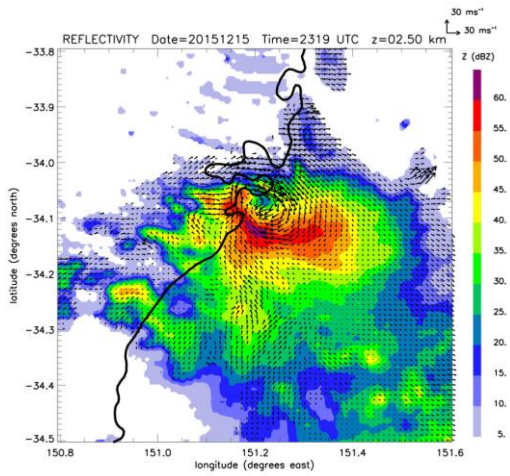


Fig. 4. A dual-Doppler synthesis of the horizontal wind field near 2.5 km above the ground (AGL) at 2319 UTC on 15 December 2015 over Kurnell (Sydney). The depicted supercell was tornadic at the time, but the circulation shown is the parent mesocyclone.

A final mechanism that is capable of creating winds exceeding 50 m s^{-1} can occur when stably stratified flow is forced across a mountain barrier by strong flow orthogonal to a mountain barrier in the presence of an inversion near mountain-top level (Fig. 5). Strong winds in such setups occur on the downwind side of the barrier and can be associated with a hydraulic jump further downstream as well as breaking mountain waves aloft.

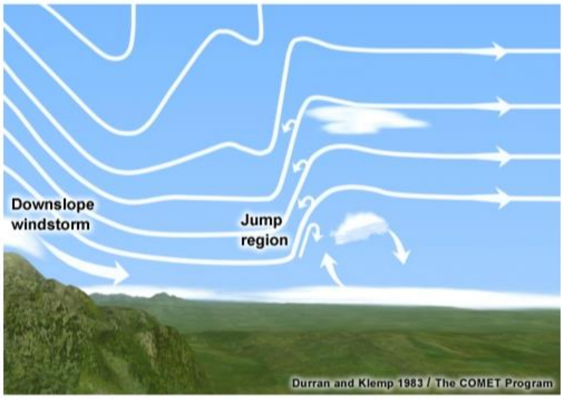
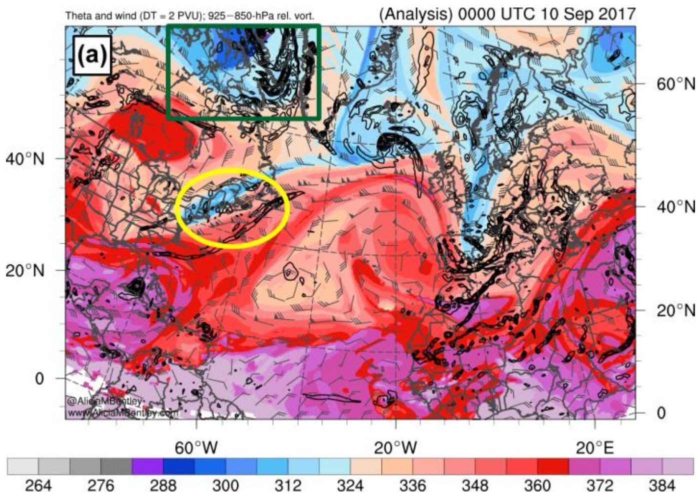


Fig. 5. Schematic of a downslope windstorm from http://www.meted.ucar.edu/mesoprim/mtnwave/frameset.htm and originally based on Durran and Klemp 1983)

3. Prediction and predictability of damaging winds

Most operational weather predictions beyond a few hours are based on physically based numerical weather prediction or NWP models. The Bureau of Meteorology utilizes ACCESS (Australian Community Climate and Earth System Simulator; Puri et al. 2013) as its NWP model. ACCESS is based on and closely tied to the Unified Model of the UK Met Office. With a view towards the required domain size of such models, Fig. 6 shows an example from the North American GFS model of how a 7-day weather forecast for Northern Russia (green rectangle region in Fig. 6b) specifically requires knowledge of the state of the atmosphere west of Greenland and southeast of Newfoundland (green rectangle and yellow ellipse in Fig. 6a). Airstreams associated with the cold temperature trough west of Greenland and the frontal zone around Newfoundland at 0000 UTC 10 September 2017 after ~5 days combined to spin up the cold core cyclone at 0000 UTC 17 September 2017 in extreme northern Russia.



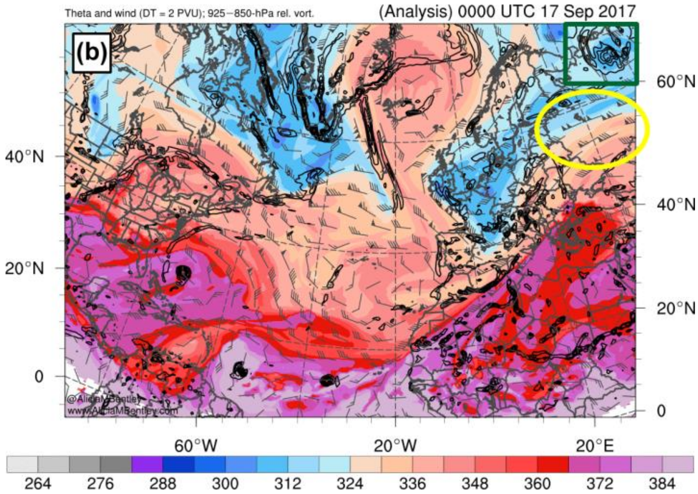


Fig. 6. Potential temperature on the tropopause (shaded), winds on the tropopause (grey barbs) and the 925-850 hPa layer mean vertical vorticity (solid black contours) from the GFS NWP model at 0000 UTC 10 September 2017 and 7 days later, at 0000 UTC 17 September 2017. See text for description of the evolution of the fields between these two times. The tropopause marks a zone ~7-18 km AGL below which the atmosphere supports deep convective overturning.

This example demonstrates that weather forecasts with lead times of a week require computational domains that, for this case, span at least half a hemisphere. In some weather patterns disturbances move a lot faster than is the case for this example, so in general weather forecasts out to one week actually require global models to ensure that the relevant initial conditions are captured.

Apart from the fundamental setup requirements for NWP models, a second more fundamental concept for forecasting strong surface winds is a focus on forecasting environments rather than directly forecasting the field of interest (such as wind) if the underlying model is a "large-scale" model with horizontal grid spacings greater than ~4 km where deep convection is “parameterized” rather than explicitly resolved. To predict the probabilities of damaging winds due to thunderstorms, meteorologists do not interrogate the model 10 m AGL wind field, but inspect the likelihood of thunderstorm-conducive environments instead.

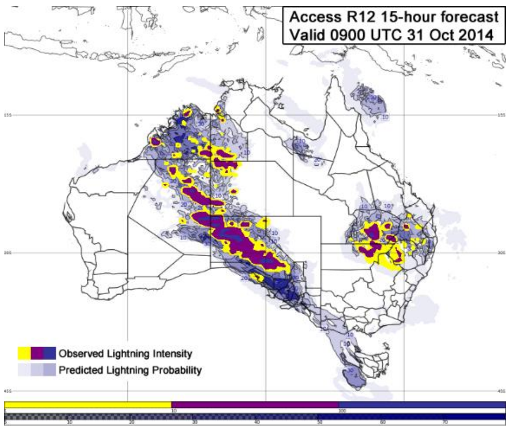


Fig. 7. ACCESS-R forecast of calibrated lightning probability ("Calibrated Thunder") with the corresponding observed lightning flash density overlaid.

Fig. 7 gives an indication that a frontal zone extending from western Tasmania through western South Australia and into the Kimberleys is expected to be conducive to the formation of thunderstorms and thus also marks an environment of enhanced surface winds through storm outflows. Such an "inference" technique is widespread in meteorological forecasting when models are not able to resolve the hazard of interest, or the model lacks sufficient skill to predict the hazard directly.

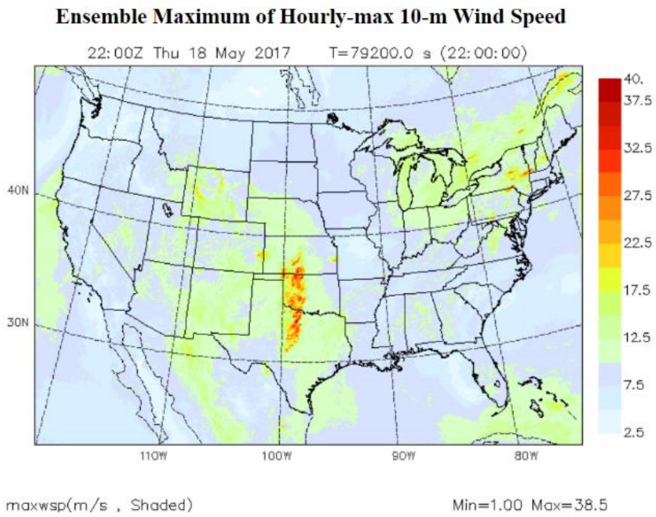


Fig. 8. Direct forecast of the 10 m AGL winds at 2200 UTC 18 May 2017 for the continental United States from the Center for Analysis and Prediction of Storms (CAPS) convection-allowing ensemble (source: http://www.caps.ou.edu/~fkong/spring17/20170518/max_wsp-15H.html). The winds shown are the hourly maximum winds maximised across all the CAPS ensemble members.

More recently, models that begin to resolve thunderstorms explicitly (with horizontal grid spacings less or equal to ~4 km) have been found to be quite skilful in predicting some convective hazards directly (Sobash et al. 2011). This is providing the possibility of direct 10 m wind gust forecasts by determining the maximum 10 m model wind speed at every dynamical time step over period of one hour (Kain et al. 2010). An example of the resulting hourly maximum wind speeds at 10 m is shown in Fig. 8.

One very important aspect in NWP-based wind forecasts is the proper acknowledgement of forecast uncertainties. The model initial conditions, its physical parameterizations and the model equations themselves all contribute to the resulting forecast error. A moderately successful tool for dealing with that error is the model ensemble, where various members of the ensemble start their integration from slightly different initial conditions, or with slightly different perturbations to their integration procedure, or both. Ensembles provide an estimate of the true model uncertainty through their degree of member disagreement on a solution. The uncertainty can be expressed in the form of weather scenarios or probabilistic forecasts, such as an exceedance probability for surface winds exceeding a fixed threshold value. More recent experience with convection-allowing models (CAMs) has shown progress in the prediction of strong surface winds, but it has also highlighted significant model uncertainty given winds are the “end product” of a very diverse range of complicated physical processes such as evaporation of droplets within downdrafts or the acceleration of flow through low pressure systems across various scales. A final example of an ensemble application, an ensemble track forecast of tropical cyclone Joaquin is shown in Fig. 9.

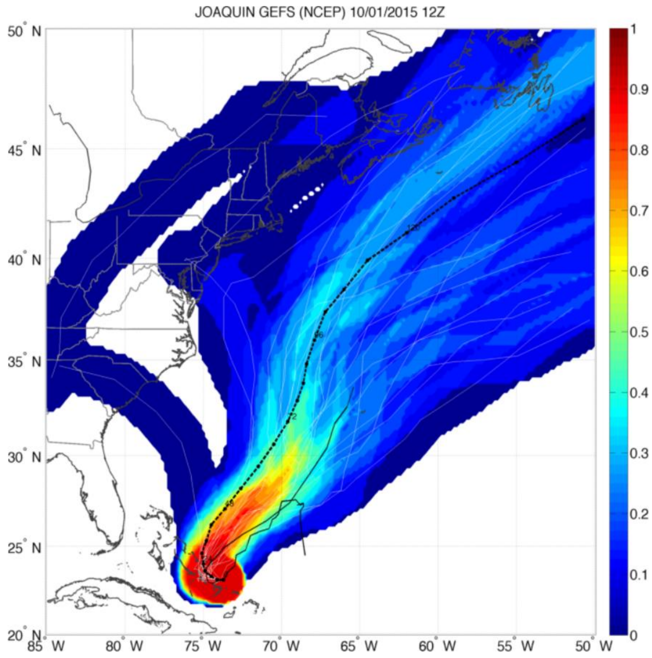


Fig. 9. Ensemble tracks for tropical cyclone Joaquin starting 1500 UTC 01 October 2015 based on the on the 21-member Global Ensemble Forecast System (GEFS) ensemble. The colour shading indicates member overlap where each member counts as "cyclone" a circular disk of radius 150 km around the storm centre. The dotted line is the deterministic operational Global Forecast System (GFS) track forecast, the solid smooth almost straight line the observed storm track. Courtesy of Brian Tang, SUNY Albany.

4. Conclusions

This paper provides a brief overview of operational meteorological wind forecasting suitable for a non-meteorological community. A range of natural processes can result in strong winds near the surface. Extra-tropical and tropical cyclones are the most common larger-scale environments that can produce damaging wind gusts on scales exceeding 100 km and many hours. On smaller spatial and shorter time scales, a range of physical processes associated with thunderstorms produce strong surface winds, from different types of downdrafts to storm-scale rotation from several kilometers in diameter (mesocyclones) down to tens of meters in diameter (smaller tornadoes).

Multi-day wind forecasts require weather prediction models with large (> 1000 km) domains, forecasts a week in advance or longer need to be computed on global domains. Often the wind is not utilized directly from the model by a forecaster, but the probability of damaging winds is inferred from a more skillful storm environment forecast, especially for thunderstorms. Modern weather forecasting increasingly includes a forecast error estimate to be attached to the forecast itself. Ensembles are widely utilized for the purpose of producing a distribution of forecasts that allows a usually probabilistic appraisal for the chance that a certain wind event might occur at a specific place.

As a concluding consideration, raw wind output from the ACCESS model comes in three categories. (1) The model outputs a 10-30 minute average wind field on each "model level" (currently at 2.5 m, 13.3 m, 33.3 m, 60.0 m, .. AGL for the 1.5 km ACCESS-C models). The exact averaging period is dynamically calculated by the model and depends on the altitude and boundary layer eddy size involving the individual model grid points. (2) An average 10 m wind is derived through extrapolation of the lowest model level wind distinguishing three different types of boundary layer vertical wind profiles (stable, neutral and unstable). (3) A wind gust is calculated from the 10 m average wind field by adding a turbulence variance term

$$U_g = U_{10m} + \sigma_u \frac{1}{\kappa} \ln(\frac{5e^{\kappa C} + z_{0m,eff}}{5 + z_{0m,eff}})$$

where U_g is the wind gust, U_{10m} is the average 10 m wind field, σ_u is the variance of the turbulent wind perturbations, $\kappa \sim 0.4$ is the von Kármán constant, C = 4 is a constant determined from turbulence spectra in Beljaars (1987), and $z_{0m,eff}$ is the effective roughness length (Wood et al. 2001). At face value it would seem sensible to explore the utility of the gust parameter U_g as a model-based proxy for the likelihood of wind damage.

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