APPENDIX II

World Meteorological
Organization

GUIDELINES FOR CONVERTING BETWEEN VARIOUS WIND AVERAGING PERIODS IN TROPICAL CYCLONE CONDITIONS

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GUIDELINES FOR CONVERTING BETWEEN VARIOUS WIND AVERAGING PERIODS IN TROPICAL CYCLONE CONDITIONS

by

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Executive Summary

This report documents the basis of recommendations for converting between wind speeds having different time averaging periods under tropical cyclone conditions. The report was commissioned in response to a request arising from the Fourth Tropical Cyclone RSMC's Technical Coordination Meeting in Nadi (Fiji), November 2002. Accordingly, a review has been undertaken of past and contemporary theory and data relevant to the issue of wind averaging periods and conversions under tropical cyclone conditions both over the open ocean and in coastal situations. The important physical and statistical aspects of the problem are identified and an example from a severe tropical cyclone is used to demonstrate the practical manifestation of those matters.

It is concluded that the accurate measurement of wind speed fluctuations, especially under tropical cyclone conditions, is a difficult and demanding activity that will always result in scatter from even the most careful analyses, and the available data and some theories show many inconsistencies. Clearly there are still significant gaps in our understanding of atmospheric turbulence characteristics under strong wind conditions. However, because the forecasting of tropical cyclones is an already difficult task, a simplified approach has been recommended that should nevertheless lead to an increase in consistency of quoted and forecast winds. An existing mathematical model of wind over-land in extra-tropical conditions has been adapted for this purpose and nominally calibrated against a wide range of assembled tropical cyclone data. The recommended procedure is seen as a practical interim solution until such time as increased data collection and analysis provides a more definitive description of the near-surface wind turbulent energy spectrum in various situations under tropical cyclone conditions.

The review has specifically highlighted the need to distinguish clearly between randomly sampled estimates of the mean wind speed based on any chosen averaging period and the peak gust wind speed of a given duration within a particular observation period. It is particularly noted that mean wind speed estimates should not be converted between different averaging periods using gust factors – only gust wind speeds.

Differences between the recommended conversion factors specified here and those previously specified in the WMO (1993) Global Guide are reasonably significant in a number of ways. Firstly, the present analysis considers a wider range of averaging periods and exposures, focusing on cases of specific concern for tropical cyclone forecasting. Secondly, the magnitudes of the equivalent conversion factors are different from those in the present Global Guide. Also, converting between agency estimates of storm-wide maximum wind speed (*Vmax*) is seen to require special considerations and the recommendation provided here is necessarily a function of the exposure. Accordingly, the review recommends an at-sea conversion between the so-called 1-min "sustained" estimate of peak storm intensity and the 10-min average wind speed estimate of 0.93, rather than the "traditional" value of 0.88, which has been shown here to be associated more with an off-land exposure. This implies that current practice has underestimated the at-sea 10-min average *Vmax* by about 5%, relative to an equivalent 1-min value. However, it is also strongly recommended that the "Dvorak-related" intensity estimation techniques be re-calibrated based on a more rigorous and consistent treatment of wind-averaging issues.

It is recommended that the WMO regional associations and panels work towards revising and standardising their wind terminology, definitions and associated use of averaging periods in the various operational plans (e.g. as summarised here in Appendix A). This will assist in ensuring that the historical record contains more consistent measurements and/or estimates that can be reliably transformed or converted for assisting in further development of the science.

The continued expansion and improvement of quality automatic weather station (AWS) surface networks and research-standard specialist facilities is strongly encouraged in order to gather the necessary information for future reviews.

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1 Introduction

This guideline has been prepared to provide a technical reference for best practice application of wind averaging conversion factors under tropical cyclone conditions. This issue arose from an IWTC-IV recommendation in 1998 (4th International Workshop on Tropical Cyclones) and a Working Group was formed at the Fourth Tropical Cyclone Regional Specialised Meteorological Centre's (RSMC) Technical Coordination Meeting in Nadi (Fiji), November 2002, to coordinate the present study. It is expected that the recommendations here will be incorporated into an update of the Global Guide for Tropical Cyclone Forecasting (WMO 1993).

1.1 Scope

The present study scope[1] was to: *Undertake reviews and assessments leading to the recommendation of suitable conversion factors between the WMO over-water +10 m standard 10 min average wind and 1 min, 2 min and 3 min "sustained" winds in tropical cyclone conditions.*

The study does not consider matters relating to the choice of wind speed thresholds used by various agencies when defining tropical cyclone intensities, nor does it consider the vertical structure of the wind within tropical cyclones, other than where such structure is especially relevant to the issue of wind speed conversion factors. However, some agency-specific definitions and usage are discussed within the context of a desire for increased standardisation of nomenclature and technical clarity. In support of this, Appendix A provides a summary of existing practice as documented in the five WMO tropical cyclone regional associations.

1.2 Approach

The report firstly addresses the theoretical background to a simple statistical model of the near-surface wind environment. This provides a review of the fundamental issues needing consideration, leading then to the specific case of tropical cyclones. The development is supported by reference to numerous case studies and an example tropical cyclone wind dataset is included to assist in practical application. Only basic mathematical developments have been included and the interested reader is referred to the relevant texts for further detail.

Using a variety of existing methods and data, recommendations are then made as to the appropriate method to be used for deriving wind averaging conversion factors for tropical cyclone conditions. The aim has been to provide a broad-brush guidance that will be most useful to the forecast environment rather than a detailed analytical methodology. Notwithstanding this, accurate wind prediction and measurement under all conditions (not just tropical cyclones) is a very difficult and challenging problem that requires careful consideration of a number of important matters. It is therefore not the intention of this review to discourage in any way the positive and increasing move towards better and more extensive insitu measurement of tropical cyclone winds in all types of environments. In particular, post analysis of tropical cyclone events should seek to use the highest possible site-specific analytical accuracy for estimating local wind speeds. This would include consideration of local surface roughness, exposure and topographic effects when undertaking quantitative assessments of storm impacts.

An extensive bibliography on the subject of wind measurement and conversion is included to assist with future research efforts. For the interested reader, Appendix B provides an overview of the historical development of scientific studies of the wind with special reference to tropical cyclones.

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[1] While the study scope did not specifically address the issue of near-instantaneous wind "gusts", the authors considered it necessary to include the full range of wind variability in the assessment. Also, the scope was later extended by the client in requesting some nominal "in-land" exposure guidance.

1.3 Wind Averaging Conventions and Gust Factors

The WMO standard for estimating the mean wind is the 10-min average. This has the advantage of averaging over a period that is typically sufficiently long to incorporate most of the shorter period fluctuations in natural wind (turbulence) but is sufficiently short to be normally regarded as representing a period of near-constant background mean wind. Dobson (1981), for example, provides background and a practical guide for marine conditions from the WMO perspective.

Although any period of time can be chosen for averaging the wind speed, shorter periods of averaging will typically produce more erratic values than the 10-min average. For example, ten 1-min averages taken during a 10-min period will produce values that lie both above and below the 10-min mean value. Any single 1-min random sample is an equally valid (unbiased) estimate of the mean wind but it is likely to be higher or lower than the true mean wind. Hence, while one estimate of the mean wind is (statistically) as good as another, in practice, mean winds measured over shorter periods will possess greater variance and will therefore be “less reliable”. Alternatively, if there was no turbulence in the wind, then all averaging periods would yield the same true mean wind speed.

The practice of “converting” between wind speeds that are obtained from different wind averaging periods (e.g. 10-min, 1-min, 2-min, 3-min etc) is only applicable if the shorter averaging period wind is regarded as a “gust”, i.e. the highest average wind speed of that duration within some longer period of observation. This results in a high-biased estimate of the mean wind. For example, while the 3-sec average is typically acknowledged as a “gust”, this is only true if it is the highest 3-sec average within a period. If the 3-sec average is effectively a random sample, then it is an estimate of the true mean. The lowest 3-sec average is conversely a “lull” (low-biased). The “maximum 1-min sustained” wind, as used predominantly in US territories, refers to the highest 1-min average within a period of observation and is therefore also a gust relative to the estimated mean wind over that same period. Even a 10-min average wind can be a gust if it is the highest 10-min average observed within, say an hour, assuming that the mean wind is constant over that one hour period. It is important that all wind speed values be correctly identified as a mean or a gust.

Hence, wind speed conversions to account for varying averaging periods are only applicable in the context of a maximum (gust) wind speed of a given duration observed within some longer interval. Furthermore, the conversions are always relative to the mean wind speed and only applicable if the wind flow is steady (or stationary). Accordingly, there is no basis for converting any estimate of the mean wind speed (based on randomly sampled 1-min, 2-min, 3-min, etc averages) to any other estimate of the mean wind speed (e.g. based on a 10-min average). Mean wind speed estimates cannot be converted as they are all equivalent measures of the true mean wind but with differing variance. Section 2 specifically addresses this issue. Simply measuring the wind for a shorter period at random will not ensure that it is always higher than the mean wind. Hence, a visually estimated wind, taken for practical reasons over a short period, is statistically equivalent to an instrumented measure over the same or a longer period. The mean wind estimate is therefore always of critical importance and should be based on the longest practical interval that can be regarded as stationary. In practice, the 10-min average generally satisfies this requirement. Once the mean wind is reliably measured or estimated, the effects of turbulence in typically producing higher but shorter-acting winds of greater significance for causing damage can be estimated using a “gust factor”.

The “gust factor” is then a theoretical conversion between an estimate of the mean wind speed and the expected highest gust wind speed of a given duration within a stated observation period. In order for a gust factor to be representative, certain conditions must be met, many of which may not be exactly satisfied during a specific weather event or at a specific location. Hence, isolated comparisons of measured mean winds and their associated gusts may show differences from the theoretical values. Theoretical gust factors are applicable only in a statistical sense and the semi-empirical theories available are based on many sets of observations. However, theoretical gust factors are still extremely useful for making forecasts of the most likely gust wind speed that will accompany the forecast mean wind speed within a specific period of observation, and at the same height above the surface. From the observational perspective, the aim is to process measurements of the wind so as to extract an estimate of the mean wind and its turbulence properties. From the forecasting viewpoint, the aim is, given a specific wind speed metric derived from a process or product, to usefully predict other metrics of the wind.

There are two specific assumptions that apply for the theoretical estimation of gust factors:

(a) Turbulent Flow with a Steady Mean Wind Speed

If the mean wind is not steady within the period of the observation, then the observed gust is likely to deviate from the expected gust obtained from the statistical theory. In fact, if the mean wind trends either upward or downward during the period, then the observed gust is likely to yield a gust factor higher than predicted by theory. Non-steadiness in the mean wind over the observation period is one typical reason why there will likely be scatter in observed gust factors during actual events. In statistical terms we require the wind record to be “stationary”.

(b) Constant Surface Features

The statistical theory of gust factors assumes that the turbulent boundary layer is in equilibrium with the underlying surface roughness. This equilibrium assumption requires an extended constant roughness fetch for many kilometres and so if there are varying roughness conditions on a fetch, or if the direction of winds is changing during the observation period, then this will also potentially alter the expected gust factors. Likewise wind gusts measured on hills and slopes are likely to deviate from the theory.

Also, as gust factors are normally expected to increase towards the surface as a result of increasing mixing, the nominated factor is only applicable between the mean wind speed and the gust wind speed at the same height (e.g. +10 m) above the surface.

1.4 Recommended Procedure for Wind Speed Conversion

Wind speed conversions are possible only in the context of a maximum (gust) wind speed of a given duration observed within some longer interval, relative to the true mean wind speed. To ensure clarity in the description of wind speed, a nomenclature is introduced that will clearly describe and differentiate a gust from a mean, as follows:

It is proposed that an estimate of the true mean wind V should be explicitly identified by its averaging period T_o in seconds, described as V_{To} , e.g.

V_{600} is a 10-min averaged mean wind estimate;

V_{60} is a 1-min averaged mean wind estimate;

V_3 is a 3-sec averaged mean wind estimate.

Likewise, it is proposed that a gust wind should be additionally prefixed by the gust averaging period τ and be described as $V_{\tau,To}$, e.g.

$V_{60,600}$ is the highest 1-min mean (gust) within a 10-min observation period;

$V_{3,60}$ is the highest 3-sec mean (gust) within a 1-min observation period.

The “gust factor” $G_{\tau,To}$ then relates as follows to the mean and the gust:

$$V_{\tau,To} = G_{t,To}\, V$$

where the true mean wind V is estimated on the basis of a suitable sample, e.g. V_{600} or V_{3600}.

On this basis, Table 1.1 provides the recommended near-surface (+10 m) conversion factors $G_{\tau,To}$ between different wind averaging periods, where the duration τ of the gust observation is referred to a base reference observation period T_o and there is an estimate available of the true mean wind V.

Table 1.1 Recommended wind speed conversion factors for tropical cyclone conditions.

Exposure at +10 m		Reference Period T_o (s)	Gust Factor $G_{\tau,To}$				
Class	Description		*Gust Duration* τ *(s)*				
			3	*60*	*120*	*180*	*600*
In-Land	Roughly open terrain	3600	1.75	1.28	1.19	1.15	1.08
		600	1.66	1.21	1.12	1.09	1.00
		180	1.58	1.15	1.07	1.00	
		120	1.55	1.13	1.00		
		60	1.49	1.00			
Off-Land	Offshore winds at a coastline	3600	1.60	1.22	1.15	1.12	1.06
		600	1.52	1.16	1.09	1.06	1.00
		180	1.44	1.10	1.04	1.00	
		120	1.42	1.08	1.00		
		60	1.36	1.00			
Off-Sea	Onshore winds at a coastline	3600	1.45	1.17	1.11	1.09	1.05
		600	1.38	1.11	1.05	1.03	1.00
		180	1.31	1.05	1.00	1.00	
		120	1.28	1.03	1.00		
		60	1.23	1.00			
At-Sea	> 20 km offshore	3600	1.30	1.11	1.07	1.06	1.03
		600	1.23	1.05	1.02	1.00	1.00
		180	1.17	1.00	1.00	1.00	
		120	1.15	1.00	1.00		
		60	1.11	1.00			

Some example applications of the above recommendations are as follows:

- To estimate the expected “off-land” 3-s peak gust in a 1-min period, multiply the estimated “off-land” mean wind speed by 1.36
- To estimate the expected “off-sea” 3-s peak gust in a 10-min period, multiply the estimated “off-sea” mean wind speed by 1.38
- To estimate an “at-sea” 1-min peak gust in a 10-min period, multiply the estimated “at-sea” mean wind speed by 1.05

Note that the above examples deliberately do not distinguish between estimates of the mean wind speed based on different durations of observation. Similarly, it is not possible to convert from a measured gust back to a specific time-averaged mean wind – only to the estimated true mean speed. Hence:

- To estimate the “off-sea” mean wind speed given only a peak observed gust of 1-min duration ($\tau = 60$ s) measured in a 10-min period ($T_o = 600$ s), multiply the observed 1-min gust by (1/1.11) = 0.90

Also, it is not appropriate to use ratios of the $G_{\tau,To}$ values to infer relationships between different reference periods, e.g. $G_{3,600}$ / $G_{3,60}$ is not equal to $G_{60,600}$. All conversions between gusts must be referenced via the estimate of the applicable mean wind speed, which in stationary conditions does not depend upon the observation period.

1.5 Converting Between Agency Estimates of Storm Maximum Wind Speed

The concept of a storm-wide maximum wind speed *Vmax* is a metric of tropical cyclone intensity used by all agencies and is often used to classify storms according to a simplified intensity scale (e.g. the Saffir-Simpson scale in the USA context). Such a metric conceptually has an associated spatial context (i.e. anywhere in the storm) and a temporal fix context (at this moment in time or during a specific period of time). While it may be expressed in terms of any wind averaging period it remains important that it be unambiguous in terms of representing a mean wind or a gust.

Because the development of tropical cyclone intensity estimation methodologies has been dominated by the Dvorak (1975, 1984) method and associated Atkinson and Holliday (1977) pressure-wind relationship for the past 30 years, the so-called maximum 1-min "sustained" wind has become the defacto standard in terms of obtaining an initial estimate of the storm maximum wind speed. Accordingly, agencies that prefer the standard 10-min averaged wind have traditionally applied a wind-averaging conversion (refer Appendix A) to reduce the maximum 1-min wind value. Leaving aside that Dvorak is silent on the issue of wind averaging and only refers to the "maximum wind speed" or MWS, Atkinson and Holliday (1977) does represent an intention to recommend a peak 1-min gust via the use of the Sissenwine et al. (1973) methodology, which is referenced to a 5-min observation period. Technically, this implies a gust wind speed of $V_{60,300}$. Recently the original analysis of the Atkinson and Holliday data has also been questioned (Harper 2002; Knaff and Zehr 2007), which relates to the overall accuracy of the wind speed estimates themselves.

Assuming that one is satisfied that the starting estimate of the storm maximum wind speed is accurate for the intended purposes, it may be converted to other wind speed metrics in accordance with the recommendations presented here. However, in practice this typically involves converting from the maximum 1-min "sustained" wind (a gust but without a stated observation period) to the highest 10-min wind speed in the storm. As noted in the previous section, it is technically not possible to convert from a gust back to a specific time-averaged mean wind – only to the estimated true mean speed. Accordingly, in Appendix E, a practical argument is made for nominal conversion between, for example, $Vmax_{60}$ and $Vmax_{600}$ values via the hourly mean wind speed reference, and the recommendations are summarised in Table 1.2. This approach should be regarded as an interim measure until a more robust and recoverable process is developed for estimating the storm maximum wind speed metric. It can be noted that the recommended conversion for at-sea exposure is about 5% higher than the "traditional" value of 0.88, which is seen to be more appropriate to an off-land exposure.

Table 1.2 Recommended conversion factors between agency estimates of maximum tropical cyclone wind speed *Vmax*.

$Vmax_{600}=K\ Vmax_{60}$	At-Sea	Off-Sea	Off-land	In-Land
K	0.93	0.90	0.87	0.84

1.6 The Impact of Modelled Winds and New Instrumentation

This study deals primarily with "conventionally" measured wind estimates from a fixed height near the surface. However, winds derived from numerical models, remote sensing instruments (SFMR, Doppler radar) and moving platforms (aircraft, GPSdropwindsondes) also need to be correctly assimilated into the framework of mean and turbulent components. While the detail of this is outside of the present scope it is noted that winds from numerical models, unless including an explicit eddy representation, should be regarded as mean wind estimates over space and time.

2 The Nature of the Near-Surface Wind

This chapter introduces the essential concepts of variability in the surface winds, explains the importance of the true mean wind and how to interpret and estimate winds that are obtained from different samplings of the mean wind over different periods of time.

2.1 The Mean Wind

While the term "wind speed" in common or colloquial use can occasionally be misused, it is generally accepted to be the *mean* or *average* wind, with reasonably widespread public recognition of, and respect for, the co-existence of the temporarily higher "gust" and lower "lull" winds. Additionally, only the longitudinal or along-wind component is normally acknowledged in the common-usage framework. However, in professional usage, it is well understood that the presence of turbulence over a range of time and space scales causes a degree of unsteadiness in any wind sample and, depending on how that is measured, the wind magnitude will present as a fluctuating time history. In addressing the basic concepts it is useful to consider only the longitudinal component and ignore for the moment that the fluctuating component is actually a vector quantity in the three independent spatial dimensions.

For the purpose of this review, it is assumed that the mean near-surface (< 100 m) wind speed V over land and sea in "strong" wind conditions (> 17 m s^{-1}) typical of tropical cyclones can be well approximated by an equilibrium form of the logarithmic boundary layer profile under neutral stability conditions (e.g. Lumley and Panofsky 1964, Powell et al. 2003):

$$V(z) = \frac{u_*}{k} \ln\left(\frac{z}{z_0}\right) \approx V_{To}(z) \qquad (1)$$

where V_{To} = the mean wind speed (m s^{-1}) averaged over a period of T_o (s)
u_* = a scale parameter, the so-called friction velocity (m s^{-1}) = $\sqrt{\tau_s / \rho_a}$
τ_s = the surface shear stress (N m^{-2})
ρ_a = air density (kg m^{-3})
k = von Karman's "constant" (0.41)
z_o = a scale parameter, the representative surface roughness length (m)
z = elevation above land or mean sea level (m); for $z > z_0$
(this term is sometimes replaced by $(z - d)$ where d is a displacement height above a rough wall boundary layer such as a dense forest.)

The form of Eqn 1 is shown graphed in Figure 2.1 as the "mean wind". This is a steady-state simplification of the real condition that extensive observational and theoretical work has demonstrated to be a very good approximation under neutral stability conditions, suitable to enable development of a practical model of the near-surface wind. The theoretical basis is that the profile is formed and maintained by a process of frictional dissipation and mechanical mixing between the wind in the free atmosphere and the land or sea surface. The boundary layer is often subdivided into the surface or constant stress layer, in which the logarithmic profile applies, and the outer or mixed layer. Buoyancy forces in the surface layer are typically assumed negligible on the basis that the mechanical mixing in the strong winds typical of tropical cyclones is sufficiently vigorous to overcome density differences[2]. Also, convectively-driven phenomena such as downbursts or gust fronts and flow instabilities such as boundary layer rolls are excluded (a later section addresses the

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[2] This remains a reasonable yet not wholly justifiable assumption that in time may be superceded as more near-surface data becomes available.

potential significance of this in the context of tropical cyclones). In particular, effective changes in actual surface roughness will vary continuously in many land environments due to directional wind shifts, and rarely be constant for more than a few kilometres. Although a constant upwind roughness domain (fetch) of many tens of kilometres is required to ensure that the profile is in equilibrium over its full height, response to roughness changes is achieved much more quickly at lower elevations, e.g. at the standard reference height of 10 m above ground level (AGL). Also, it is assumed here that the surface is essentially flat and that the flow is therefore free of topographic influences that would lead to local accelerations. Many texts describe procedures suitable for adequately adjusting the above theoretical wind profile for specific situations (e.g. Cook 1985; ESDU 2002a,b; Holmes 2001; ANSI 1996; Standards Australia 2002a), which are essential when comparing readings between differently sited anemometers. Powell et al. (1996) provides specific advice in regard to landfalling tropical cyclone conditions.

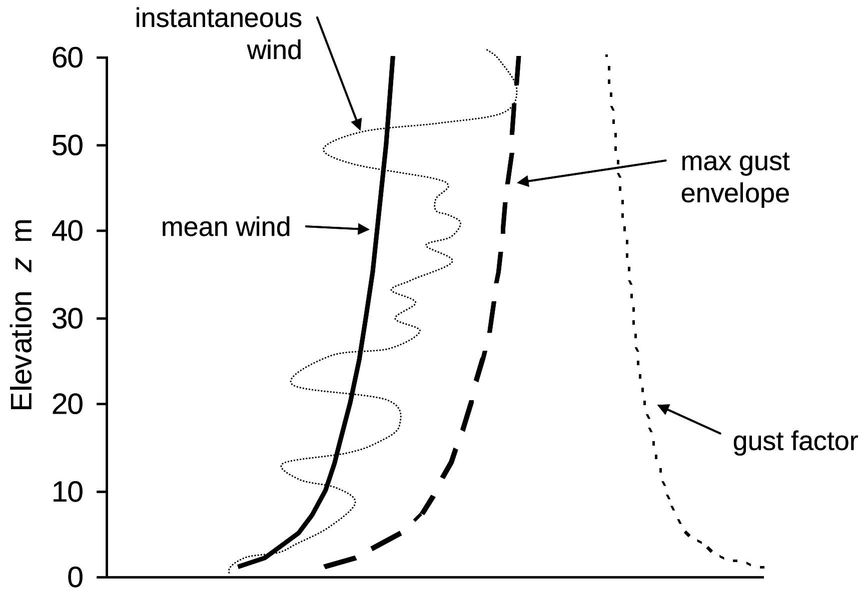

Figure 2.1 A traditional schematic view of the near-surface vertical profile of strong winds.

The application of Eqn 1 then requires the specification of u_* and z_o, which are used to scale the speed and the height respectively. In practice, u_* can be expressed in terms of a surface drag coefficient C_{10} referenced to the standard reference height of +10 m for neutral stability conditions, e.g.

$$C_{10} = \frac{\tau_s}{\rho_a V_{To}^2(10)} = \frac{u_*^2}{V_{To}^2(10)} \qquad \text{for large } T_o\text{, typically 10 min} \qquad (2)$$

Combining Eqn 1 and 2 allows u_* to be eliminated, leaving:

$$C(z) = \left[\frac{k}{\ln(z/z_o)}\right]^2 \qquad (3)$$

noting that the drag coefficient is a function of height.

To complete the above simplified model of the near surface wind we require an estimate of the surface roughness length z_o. In the case of winds over water, the surface roughness is clearly dependent on the wind speed, whereby ripples and then increasingly larger surface waves will be generated, subject to depth, fetch and wave age considerations. The exact dependence of wind speed and the effective surface roughness over the ocean has been subject to much investigation (e.g. Large and Pond 1981, Fairall et al. 2003) but always limited by difficulties in obtaining reliable data, especially at high wind speeds typical of tropical cyclones. Notwithstanding significant advances in understanding and amassing of much improved data sets over the open ocean, the dimensionally-based Charnock (1955) hypothesis that was originally based on lake data is still widely applied, namely:

$$z_o = \frac{\alpha u_*^2}{g} \tag{4}$$

with α being an empirical coefficient derived from measurements, typically found to be in the range 0.01 to 0.03 (e.g. Garratt 1977). The drag coefficient determined by combining the Charnock relation with (3) is quite consistent with empirical estimates of the surface drag coefficient over the ocean, for example after Large and Pond (1981):

$$10^3\, C_{10} = 0.49 + 0.065\, V_{To}^2 \qquad \text{for} \quad 11\,\mathrm{m\,s^{-1}} \le V_{To} \le 26\,\mathrm{m\,s^{-1}} \tag{5}$$

However, there has long been speculation that under more extreme wind conditions the drag coefficient and the surface roughness may reach some type of limiting condition due to wave breaking, flow separation and the like. A number of recent studies present strong evidence for this effect, e.g. Powell et al. (2003) analysed GPS sonde data within hurricane eyewall regions, Donelan et al. (2004) undertook laboratory wind-wave experiments and French et al. (2007) performed direct flux measurements from low flying aircraft within hurricanes. The extent to which the surface waves themselves might modify the lower logarithmic surface layer remains open (e.g. Jansen 1989, Large 1995) until more full scale data becomes available.

To illustrate the range of sea surface roughness descriptions that has emerged over time, Figure 2.2(a) presents surface drag coefficients and Figure 2.2(b) the equivalent roughness relationships. Garrett (1977), Large and Pond (1981), Andersen and Løvseth (1992) represent typical fixed-Charnock α forms that have been extrapolated here to higher wind speeds, while Fairall et al. (2003) incorporates a variable α. In contrast to these trends, the latest investigations targeting tropical cyclone conditions in the open ocean suggest significantly lower overall roughness values are applicable. In respect of conditions closer to land in shoaling wave environments it is likely that the roughness is greater, as suggested by Andersen and Løvseth (1992), but there has been little detailed analysis of wind-wave interaction in this environment.

The appropriate z_o for application over the ocean or on land therefore needs to be estimated for specific conditions, typically over space and time. On land, a number of guideline roughness classifications have been devised based on detailed site specific measurements and calibrations (e.g. Wieringa (1992) and Wieringa et al. (2001)). Table 2.1 presents a modified version of these that has been further interpreted here to describe features more likely in tropical cyclone regions and also made consistent with the oceanic conditions noted above.

In the developments and discussion that follow, attention is focused on the “smooth to open” classification over nearly flat land or coastal sea with a surface roughness length z_0 of nominally 0.03 m. This is almost universally acknowledged as “standard exposure” on the basis that the vast majority of all land wind measurements have been obtained from airports and it is also deemed representative of rough coastal seas (e.g. Standards Australia 2002a[3]; Vickery and Skerlj 2000). Also, only the standard reference height of +10 m is now considered. For conversion of the subsequent recommendations to other roughness regimes and elevations, the interested reader is referred to the nominated texts.

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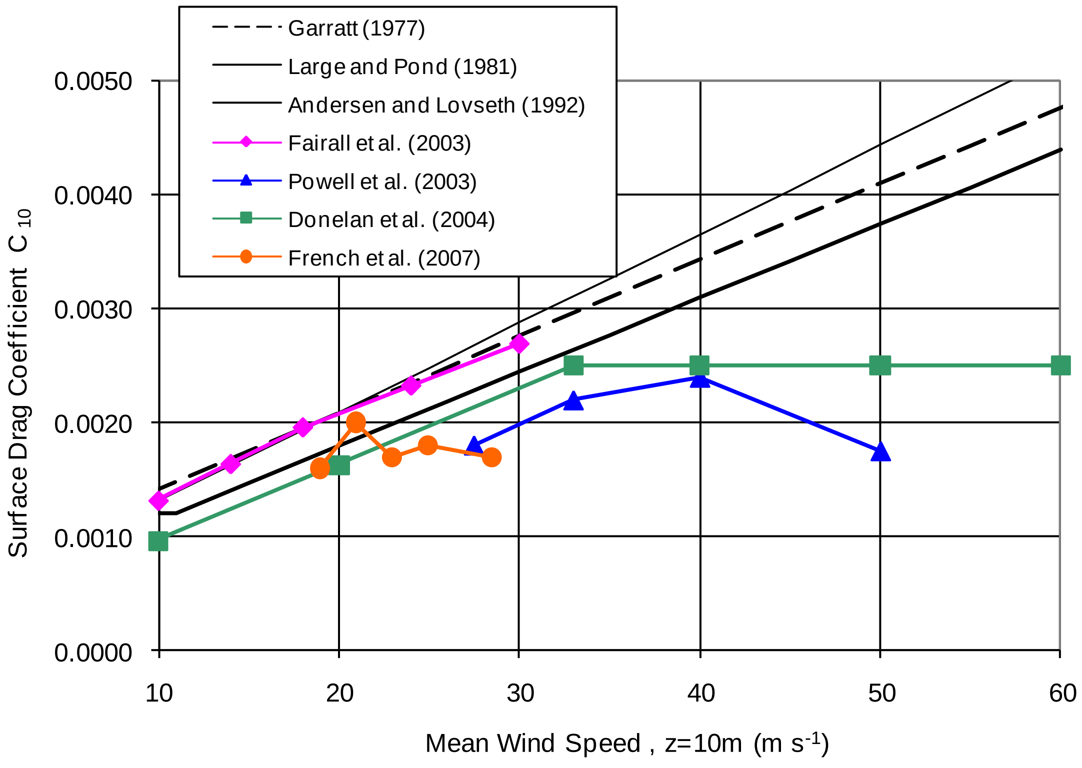
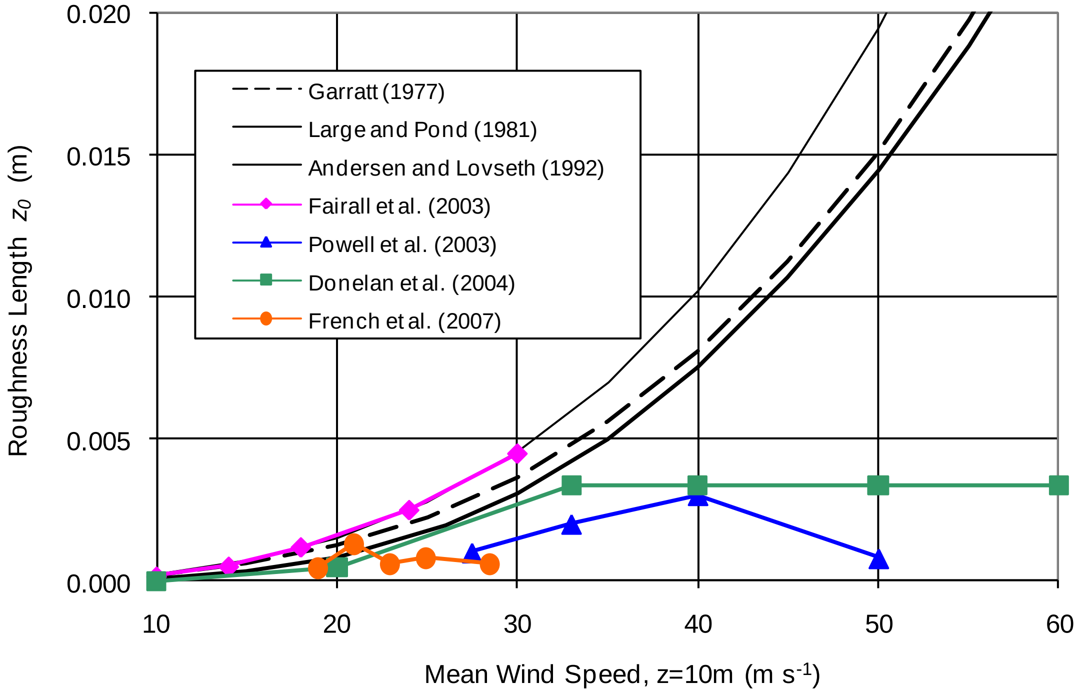
[3] The Australian/New Zealand wind loading standard uses 0.02 m but this is functionally similar.



(a) Surface Drag Coefficient



(b) Roughness Length

Figure 2.2 Example oceanic surface drag coefficients and roughness lengths.

Table 2.1 Representative terrain classes and roughness classifications for tropical cyclone applications (adapted from Wieringa et al. 2001).

Terrain Class	**Terrain Description**	**Roughness Length z_0 (m)**	**Surface Drag Coefficient C_{10}**
Sea	Open sea conditions for all wind speeds, exposed tidal flats, featureless desert, tarmac.	0.0002 – 0.005	0.001 – 0.003
Smooth	Featureless land with negligible vegetation such as wide beaches and cays, exposed reefs.	0.005 – 0.03	0.003 – 0.005
Open	Nearshore water for winds > 30 m s^{-1}, level country with low grass, some isolated trees, airport surrounds.	0.03 – 0.10	0.005 – 0.008
Roughly Open	Low crops, few trees, occasional bushes.	0.10 – 0.25	0.008 – 0.012
Rough	Lightly wooded country, high crops, centres of small towns.	0.25 – 0.5	0.012 – 0.019
Very Rough	Mangrove forests, palm plantations, metropolitan areas.	0.5 – 1.0	0.019 – 0.032
Closed	Mature regular rainforests, inner city buildings (CBD).	1.0 – 2.0	0.032 – 0.065
Skimming	Mixture of large high and low-rise buildings, irregular large forests with many clearings.	> 2.0	> 0.065

2.2 Measuring the Mean Wind

Here, we briefly consider some of the statistical issues in measuring the mean wind. We assume that the actual wind is the sum of a mean wind and some turbulence, and the aim is to process measurements of the wind so as to extract an estimate of the mean wind. The emphasis is on issues associated with this averaging, rather than with the positioning and logging of anemometers, although these are of importance also. For simplicity, we assume that the instruments in use are free from systematic biases, or at least, that any such biases are removed.

To begin with, assume an ideal anemometer that provides instantaneous point measurement of the wind, and an unchanging synoptic situation. If the anemometer was interrogated at a suitable frequency and these data collected over some period, then their mean over that averaging period could be calculated. Assuming that the wind sampled during the averaging period was effectively a random sample, then the sample mean would be an unbiased estimate of the true mean wind at that point. “Unbiased” is meant in the statistical sense; that is, the expected value of the sample mean is equal to the true mean. In practice, a random sample can be achieved by choosing the averaging period before the measurements are taken; e.g. the last 5 minutes of the hour.

The finite sample implies that there is inevitably a degree of uncertainty in the sample mean. The variance of the sample mean is (Lumley and Panofsky 1964):

$$\sigma_{\bar{u}}{}^2 = 2\sigma_u{}^2 \frac{T_u}{T_o} \qquad (6)$$

where σ_u is the wind variance, T_u is the integral time scale for that wind component, and T_o is the averaging period. Turbulence is correlated in space and time, so increasing the frequency of measurement does not result in a proportional increase in the amount of independent information. The spatial and temporal correlation scales of turbulence may be measured by the turbulence integral length and time scales, which typically depend upon the wind speed, surface roughness, height above the surface, and stability. If we interpret samples taken at an interval of $2T_u$ as being effectively independent, giving $T_o/(2T_u)$ independent samples, then this formula reduces to the well-known result that the variance of the sample mean for independent samples is inversely proportional to the sample size. The rate at which the anemometer is sampled is assumed to be at least as frequent as $2T_u$, but does not otherwise enter into consideration.

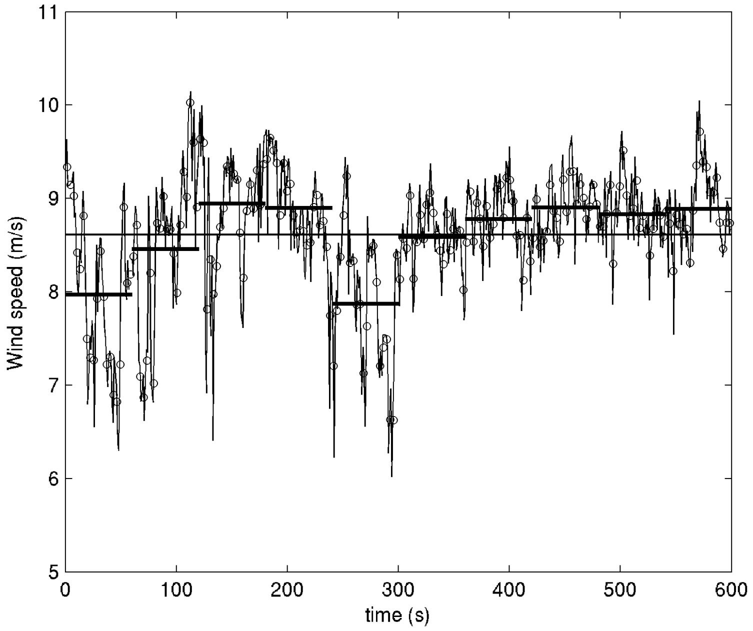


Figure 2.3 Measuring the mean wind.

By way of illustration, Figure 2.3 presents 10 minutes of sonic anemometer data measured at North West Cape, Western Australia, at 42 m height. The thin curve is the 1-s mean wind derived from sonic 10 Hz measurements, the open circles are the 3-s mean wind speeds. Thick horizontal bars show the 1-min mean wind speed and the thin horizontal line is the 10-min mean wind speed.

Thus the difference between 1-s, 3-s, 1-min and 10-min observed means is solely that the longer averaging period leads to the sample mean being a more accurate estimate of the true mean. Provided that the sampling is random, the expected values for each averaging period are equal, and individual realisations will be both greater and less than the true mean. Note however that if a 10-min sample is subdivided into ten 1-min samples, the mean of each calculated, and the largest of these 1-min means is chosen, then this is no longer an unbiased estimate of the true mean, since the sampling is not random. Such a measurement is, in fact, termed a gust (refer 2.4 for definition).

We have so far assumed an ideal, instantaneous response anemometer. Real anemometers implicitly apply some averaging, due to e.g. the mechanical inertia of cups, or the finite signal path length in a sonic anemometer. While there are numerous historical references dealing with the filtering effects of anemometers (e.g. Deacon 1955, Wieringa 1973, Greenway 1979, Beljaars 1987, Wieringa 1996) it seems rare for manufacturers to publish instrument response characteristics. It can be shown that the best way to describe a cup anemometer's response is in terms of a distance constant, which represents the wind-sample required to respond to a stepped change in speed (e.g. Kristensen 1993). A typical cup anemometer may have a distance constant of the order of a few to a few 10's of metres, which implies that information on smaller space scales is filtered out. The corresponding time constant may be found by dividing the distance constant by the mean wind speed, so such anemometers have an inherently faster response in high winds. If the averaging period is much longer than the filter time scale, then the filtering provided by the anemometer can be ignored, but it has to be considered when the two are comparable. This topic will not be further discussed here, but should be of significant concern where long-term climatological measurements are interrupted by inevitable changes in instrumentation. The Dines pitot-tube recorder, for example, which has been in worldwide use throughout the 20th century, and is widely credited with the ability to accurately measure a "2 to 3 s" gust (Sanuki 1952, Whittingham 1964, Deaves and Harris 1978), is rapidly being replaced by more compact self-contained cup and propeller anemometer systems that have different response characteristics.

Our other key assumption is that the true mean wind is in fact steady. If this is not the case, then more sophisticated processing will be necessary to remove the turbulent part of the signal, as otherwise the trend in the mean wind may bias the sample mean away from the true mean. For example, a 10-min mean measured during the passage of a sharp eyewall wind maximum of a fast-moving storm may reduce the amplitude of the true mean wind maximum. In practice, averaging periods are chosen as a compromise between minimising sampling errors, reducing the errors due to non-stationarity, and (for non-electronically logged systems) observer patience. Values of the order of 10 minutes are typically many times the integral time scale, but short enough that nearly all meteorological phenomena of operational interest can be considered stationary.

We close with two remarks. Firstly, the interaction between a mechanical anemometer and turbulence is nonlinear, which may lead to upward biases of the order of a few percent in measured mean winds. This phenomenon is known as "overspeeding" and is analysed in significant detail for cup anemometers by Kristensen (1993). Secondly, remotely-sensed wind measurements often involve 2-dimensional averaging rather than the 1-dimensional averaging of an anemometer. For example, scatterometer data might be representative of a nominal 25-km square of the ocean surface. Such measurements almost always sample many more integral scale's worth of wind than a line average, not least because the integral length scale perpendicular to the wind direction is several times less than that parallel to it. Thus such wind measurements may have relatively low variance, although they may also contain significant biases due to factors not taken into account in the retrieval, such as heavy rain in the case of a scatterometer.

2.3 Representing the Fluctuating Wind

Following Reynolds (1895) (see also e.g. Garratt 1992; Kaimal and Finnegan 1994; Holmes 2001), the instantaneous (longitudinal) wind $V(t)$ can be simply represented as the sum of the mean wind V_{To} and a fluctuating component $u(t)$ about the mean such that:

$$V(t) = V_{To} + u(t) \tag{7}$$

and the variability can be summarised by calculating the standard deviation (or root-mean-square) of the fluctuating component about the mean:

$$\sigma_u = \sqrt{\frac{1}{T_0}\int_0^{To}\left(V(t) - V_{To}\right)^2 dt} \tag{8}$$

A non-dimensional form of this variability relative to the mean is simply the coefficient of variation, which is termed the turbulence intensity in this context:

$$I_u = \frac{\sigma_u}{V_{To}} \tag{9}$$

Based on the many detailed measurements made over land in high latitudes from large scale depression systems, a common simplifying approximation to the magnitude of turbulence fluctuation for land-based wind engineering applications is given by:

$$\sigma_u = 2.5u_* \tag{10}$$

This provides an order of magnitude estimate only of this complex relationship (e.g. refer Lumley and Panofsky (1964) for more detail) that conveniently removes u_* and k when combining with Eqn 1. This then provides an approximate indication of the variation in turbulence intensity with surface roughness and height, namely:

$$I_u = \frac{1}{\ln(z/z_o)} \tag{11}$$

which it should be noted, implicitly assumes that σ_u, the standard deviation of the wind speed fluctuation about the mean, is actually constant with height[4].

The accurate measurement of turbulence intensity requires high response instrumentation, reasonably high speed sampling (> 5 Hz depending on height and wind speed etc) and is also sensitive to the choice of T_o (e.g. refer Schroeder and Smith 2003), which can make inter-comparisons more difficult. Normally, T_o is chosen to be hourly in synoptic environments and usually not less than 10 min (refer Section 2.5 also). Hence reference here to I_u implies a base reference $T_o \geq 600$ s.

The capability to accurately measure I_u is normally only available at purpose-built research-grade facilities. Accordingly, due to the sparse occurrences of tropical cyclones, there are relatively few estimates available of the turbulence intensity in those conditions. Recently, the development of mobile instrumented towers in the US (e.g. Schroeder et al. 2002, Masters et al. 2005) has lead to a greater capture rate of tropical cyclone conditions. Partly due to this lack of comparative data, there has been much debate about the possible differences between tropical and extra-tropical turbulence intensities (e.g. Wilson 1979, Melbourne and Blackman 1982, Ishizaki 1983, Krayer and Marshall 1992, Black 1993, Sharma and Richards 1999, Paulsen and Schroeder 2005, Vickery and Skerlj 2005).

Acknowledging for the moment that there may be reasons for differences between tropical and extra-tropical conditions, the collective I_u values near the earth's surface appear similar in order-of-magnitude terms for equivalent exposures. However, even small differences of the order of 10% could be important in structural assessments. In closing, it is noted that Eqn 11 yields a typical value for I_u of about 0.17 for z = 10 m and for standard exposure with a z_0 of 0.03 m.

2.4 The Concept of the Gust Wind Speed and the Gust Factor

Extending the preceding discussion, the instantaneous wind can, in simple terms, be considered as the superposition of a range of eddy sizes and speeds within the air flow, moving along at the mean speed. Hence, assuming that the scale and strength of these eddies are largely independent and random, the Gaussian statistical distribution is typically used to describe the expected variation in sampled speeds, namely:

$$f_u(u) = \frac{1}{\sigma_u \sqrt{2\pi}} e^{\left[-0.5\left(\frac{u - V_{To}}{\sigma_u}\right)^2\right]} \tag{12}$$

gives the probability *density* of the instantaneous wind based solely on the specified mean speed V_{To} and the standard deviation σ_u ; whereby $f_u(u).du$ is the probability that $V(t)$ will lie in the interval u_o+du for $u=u_o$ (Holmes 2001).

The statistical variability of the natural wind has been shown by numerous studies to be reasonably well modelled by the Gaussian assumption. Some examples of this under tropical cyclone conditions include Powell et al. (1996) during Hurricane *Bob* and Schroeder and Smith (2003)

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[4] This is an assumption of convenience here to illustrate the principal observation that turbulence intensity is expected to decrease with height but it is far from certain that σ_u does not also reduce with height in tropical cyclone conditions.

during Hurricane *Bonnie*, while Paulsen and Schroeder (2005) compares some limited tropical and extra-tropical datasets.

While the measurement of a gust is seemingly straightforward, being the highest average speed recorded within a specified period, a statistical definition is required for predictive purposes. Following Kristensen et al. (1991) we define the expected maximum gust V_τ as:

The wind speed averaged over a duration of τ *seconds which, on average, is exceeded once during the reference period* T_o.

Kristensen et al. (1991) discuss some consequences of this definition:

- the expected gust is the mode (the most probable value) of the probability distribution,
- the probability of not exceeding the expected gust is $e^{-1} = 0.37$,
- the probability of exceeding the expected gust exactly once is $e^{-1} = 0.37$, and
- the probability of exceeding the expected gust twice or more is $1 - 2/e = 0.26$.

The expected gust wind speed is then typically modelled as:

$$V_\tau = V_{To} + g_{\tau,To}\,\sigma_u \tag{13}$$

where $g_{\tau,To}$ is termed the peak factor, representing the number of standard deviations that the maximum gust speed's magnitude is statistically expected to lie above the mean speed over the period T_o, consistent with the selected gust duration τ. This is often expressed relative to the mean wind reference magnitude in terms of a gust factor G and the turbulence intensity:

$$G_{\tau,To} \quad = \quad \frac{V_\tau}{V_{To}} \quad = \quad 1 + g_{\tau,To}\, I_u \tag{14}$$

Using this approach, it remains to select appropriate values for turbulence intensity I_u and obtain a statistically based estimate of $g_{\tau,To}$ to arrive at recommended values for $G_{\tau,To}$ for tropical cyclone conditions. However, there still remain a number of issues that need consideration, and the determination of g has been subject to some historical debate. A number of slightly different formula for g have been proposed (e.g. Davenport 1964, Wieringa 1973, Forristall 1988, Mitsuta and Tsukamoto 1989) and some alternate statistical theories offered (e.g. Bergstrom 1987, Kristensen et al. 1991, Boettcher et al. 2003), which can be shown to be approximately equivalent within a range of assumptions (Kristensen 1993).

The most complete theoretical description available that satisfies the present scope requirements is summarised by ESDU (2002b), which is based on the original statistical approach by Davenport (1964) as augmented by the analyses of Greenway (1979, 1980) and Wood (1983). This approach considers the sampling of independent gust episodes from a pre-determined spectrum of the natural wind (the von Karman form), which relies on estimating the mean zero-crossing frequency associated with the spectra relevant to the chosen averaging period and gust duration. Then, with the assumption of a Gaussian parent distribution, this can be shown to produce an Extreme Value Type I (or Gumbel) distribution for the maximum gusts and the mean of this distribution is then taken as the expected value. As noted above, Kristensen et al. (1991) takes a slightly different view and chooses the mode of the distribution, which will always be less than the mean due to the positive skewness, but the results are almost indistinguishable. Because of the probabilistic nature of the gust, gust measurements will always have some scatter about the expected gust value, even if the forecast is perfect and all the assumptions are justified.

2.5 The Relevance of the Spectral Gap and the Need for Stationarity

If we wish to accurately know the expected deviation of wind speed from a time-averaged mean condition, then it is important that the reference used for the mean is stable, well defined and not subject to trends that would otherwise interfere with, for example, the ergodic hypothesis (Lumley and Panofsky 1964). This is achieved by focussing on the relevant subset of eddy time and space scales and choosing a reference position that is sufficiently homogeneous and stationary to be suitable for this purpose.

One of the earliest investigations into the range of naturally occurring turbulent wind scales was documented by Van der Hoven (1957), who constructed a broad energy spectra based on almost one year of wind measurements, using varying averaging periods, obtained from a 125 m tower at Brookhaven National Laboratory. The data was pieced together in as consistent a manner possible for the times and spectrally analysed, including some high frequency data collected during the passage of Hurricane *Connie*. A schematised reproduction of this original spectrum is given in Figure 2.4, which shows that the measured wind energy was not equally distributed across all frequencies but rather indicated preferences for certain scales. Spectral energy peaks were clearly identified at periods of 4 days, 12 h and near 1 min. between these prominent energy peaks, a "spectral gap" was identified with a minimum energy occurring around about 1 h. The spectral peaks indicate time scales at which most energy is being generated, which are then transferred to other scales by a cascade process. Frequencies where there is little or no energy present are known as "spectral gaps". It was found that the spectral gap was independent of the magnitude of the mean wind speed and was quite flat over the range from about 3 h to 20 min. This broadscale spectral behaviour has been identified consistently at other sites around the world both on land and at sea, although the details vary depending on height, the locally dominant processes and their energetics (the energy scale might vary). The most significant peak at 4 days is considered typically representative of the passage of weather systems at the synoptic scale, with the near 1-min peak, the second highest, attributed to mechanical and convective turbulence in the micrometeorological scale, with the intermediate peak representing the mesoscale range (e.g. Fiedler and Panofsky, 1970; Pierson, 1983) where diurnal and semi-diurnal processes also contribute. As described by Jensen (1999) the concept of a spectral gap offers an attractive separation of the atmospheric motions into a deterministic low-frequency part and the unpredictable turbulent part.

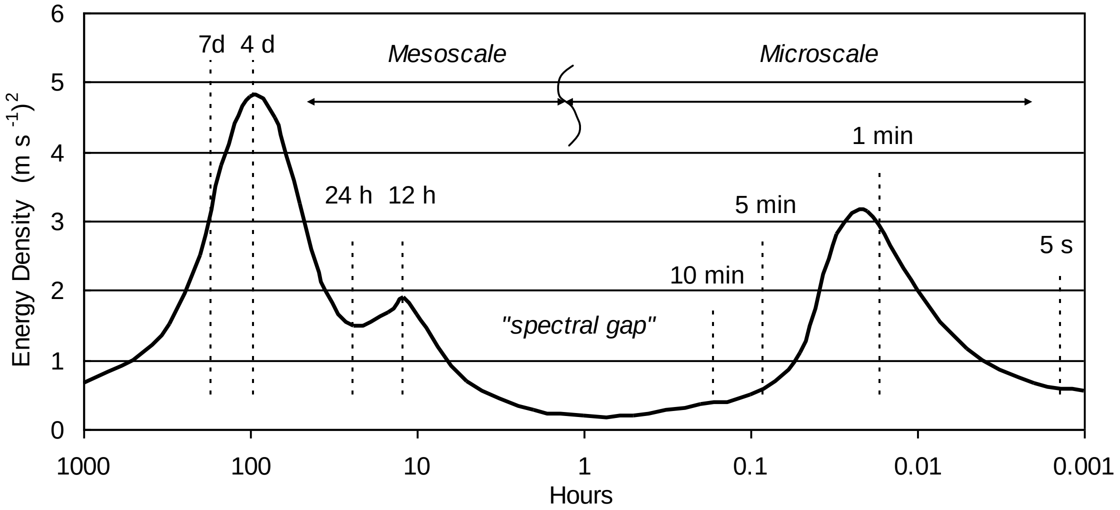

Figure 2.4 Schematic energy spectrum of near-ground wind speed after Van der Hoven (1957).

The presence of a spectral gap between the mesoscale and the microscale is therefore conceptually appealing as the averaging period over which a generally practical "mean" wind would be best calculated, as there is clearly much less variability (variance being the area under the curve in Figure 2.4) in measurements taken from that region of the spectrum. Any random sample averaged over such periods (say 3 h to 20 min) could be expected to have a relatively sharp probability density function when compared with a similarly sampled set of random values using (say) 1-min averaged speeds. This results in the mean value being largely independent of the actual length of the record. Averaging over such periods is therefore also consistent with the desire to have a statistically stationary sample free from longer scale trends. Wieringa (1973) for example, highlights the ready potential for overestimation of gust factors that occurs if stationarity is not adequately considered and data is not correctly de-trended.

Fordham (1985) however notes that the presence of a spectral gap does not necessarily guarantee quasi-stationary conditions but does indicate a higher probability than otherwise of finding data records which will pass some statistical test for stationarity. Also, the spectral gap may not always reliably occur in a specific situation, as noted by Dobson (1981). Ishida (1989), for example, found some intermittent energy peaks (15 min to 1 h) in high latitude buoy data which appear to be related to convective events. It might also be expected that similar intermittent energy features might be found in a tropical cyclone and Naito (1988) shows a significant peak near 1 h for various strong wind over-ocean datasets, including a typhoon, but a gap nearer 10 min. Powell et al. (1996a) shows that a near-coast spectrum from Hurricane *Bob* at least displays similar microscale behaviour to the Van der Hoven example, with a broad energy peak around 1 min and various sharper peaks at 30 s or less. Schroeder and Smith (2003) have identified more low frequency energy than expected in Hurricane *Bonnie* data but concede that this may be due to difficulties in obtaining good stationarity of records, without which low frequency energy artificially accumulates in the spectra. Some recent studies also highlight the possibility of boundary layer roll-vortices in tropical cyclones (e.g. Winslow and Wurman 1998, Foster 2005, Morrison et al. 2005) with periodicity of 5 to 10 min, suggesting averaging periods in excess of this might be desirable.

The likely presence of a spectral gap at or near the hourly averaged wind speed resulted in its broad adoption as the reference period of choice for statistical studies of smaller scale near-ground atmospheric turbulence. However, as more homogeneous data has become available over time, it has become increasingly clear that the large energy gap first identified by Van der Hoven is simply not as great as suggested in Figure 2.4 and may typically only be about a factor of two lower than the higher frequency peak energy level (e.g. Jensen 1999).

In situations such as tropical cyclones, where the phenomena of interest typically presents with relatively high space and time gradients near its centre, retreat to a slightly lower averaging period of about 10 min is desirable to avoid non-stationarity of the record. Even more transient atmospheric events such as thunderstorm downbursts or tornados naturally require suitably downscaled mean wind averaging periods (e.g. Orwig and Schroeder 2007). Figure 2.5 presents an example wind energy spectrum from Powell et al. (1996), annotated here to indicate the principal averaging times of interest and the nominal spectral gap. This specific example shows a sharp peak in variability near 30 s, before the high frequency tail decay commences at about 10 s. The energy present at 10-min cycling can be seen to have less than half the variability of that at 1-min cycling.

2.6 Convective Features, Convergence and Instabilities

Whether convective processes might play a more significant role in the tropical cyclone boundary layer than the more extensively sampled extra-tropical wind environments has been the subject of much conjecture (Melbourne and Blackman 1982, Ishizaki 1983, Krayer and Marshall 1992, Black 1993, Sharma and Richards 1999, Sparks and Huang 2001, Paulsen and Schroeder 2005, Vickery and Skerlj 2005).

In the extra-tropics, the role of convective versus mechanical sources has also been explored (e.g. Bradbury et al. 1994) but found to be sufficiently and identifiably separate as to not interfere with the traditional UK approach to building design, although it is noted that extreme gust factors are always caused by convection but extreme gusts might be due to either process. Young and Kristensen (1992) demonstrate quantitatively how the surface layer would be gustier in unstable than in stable conditions. Meanwhile, Brasseur (2001) has recently advocated a direct transport-of-momentum-from-gradient approach to forecasting of gusts but this theory has previously met with limited support relative to the purely mechanical approach (e.g. Baran 1992; Mahrt and Gibson 1992). In Australia, the convective event has always been known to dominate design wind speeds outside of cyclonic regions, but turbulence intensity has been based largely on UK approaches (Standards Australia 2002b).

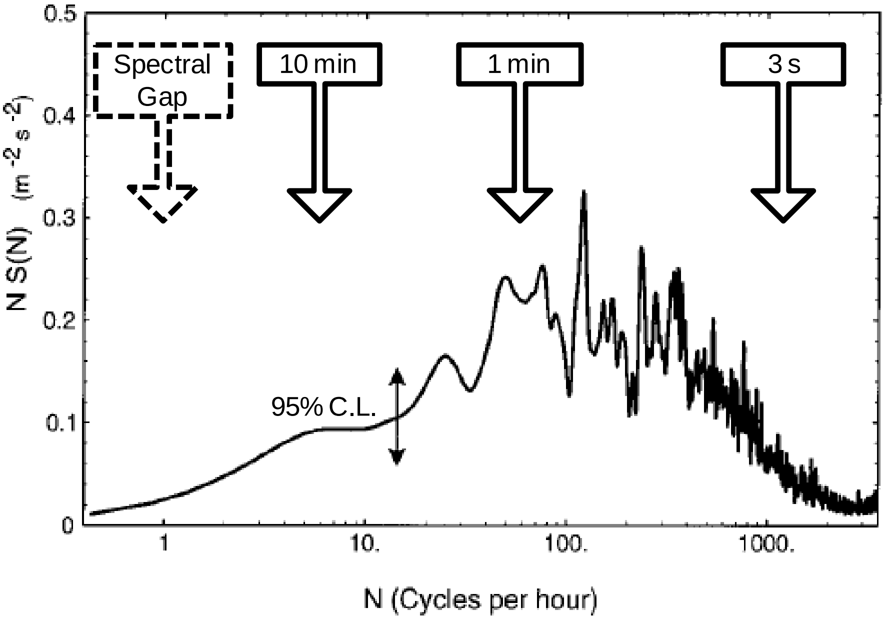

Figure 2.5 Example tropical cyclone wind energy spectrum after Powell et al. (1996).[5]

Clearly tropical cyclones are the result of the large-scale integration of convective processes and exhibit evidence of local convection (e.g. Powell et al. 1991). However, the separation of mechanical and convective processes from any near-surface wind record, at least in strong winds, is likely a difficult if not impossible process even with sensitive instrumentation. While there is no doubt that mechanical mixing near the ground is the dominant and pervasive process, the extent to which tropical convection acts to increase the vertical transport of momentum and enhance the turbulence intensity is yet to be fully quantified. Detailed measurements by Schroeder and Smith (2003) during *Bonnie* reported the possible signature of convection when some integral scales seemed to increase without changes in roughness and Paulsen and Schroeder (2005) reported up to a 6% increase in turbulence intensity between some equivalent tropical and extra-tropical exposures, the difference increasing with increasing roughness.

One of the first insights into the possible role of convective processes in tropical cyclones was provided by the coastal tower measurements of Wilson (1979ab) on the Western Australian coastline during the close approach of several storms. The vertical profiles of time history winds obtained from five anemometers (9 m to 390 m height) indicated a low level wind maximum near 60 m with a profile exhibiting shear levels higher than logarithmic. Above 60 m the profile showed clear evidence of longer period, apparently convective events associated with rainbands, which presented in the form of jets. After stratification into likely convective and non-convective subsets, the gust factor $G_{3,600}$ was found to decrease above the surface from a mean of about 1.4 at 9 m to 1.1 at 200 m for the mechanical case, but above 200 m the likely convective processes averaged 1.2 to 1.5. Wilson also noted that the surface wind gust consistently underestimated the mean wind at 390 m. Also, the surface gust was always less than the mean winds at 60 m, suggesting the mechanical

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[5] Powell Houston and Reinhold (1996): §FIG. 3. Spectral density plot of detrended fluctuations of the streamwise component of the wind at 20 m measured at the USACE Duck, North Carolina, pier for alongshore flow in 23 m s^{-1} mean winds during Hurricane Bob on 19 August 1991. Spectral estimates have been smoothed with a 20-point Hanning filter. Vertical axis is the product of frequency and spectral density, which has units of variance; horizontal axis is frequency expressed in cycles per hour on a logarithmic scale. The vertical line with arrows refers to the 95% confidence interval applied to an estimate of 0.1 m^2 s^{-2}. The area beneath the curve is proportional to the contribution of a given frequency band to the total variance.

mixing depth near the surface was small. It seems possible that the increased shear near the surface was influenced to some extent by the higher level transports.

Analytical and numerical modelling of the tropical cyclone boundary layer by Kepert (2001, 2002c) and Kepert and Wang (2001) has shown that a marked wind speed maximum is often present in the upper boundary layer. The boundary-layer depth is about 500 m at the radius of maximum winds (RMW), increasing to about 1.5 - 2 km at larger radii. These models do not include the effects of moist convection, demonstrating that this is not necessary for the generation of steady low-level jets. Examination of the near-surface wind profile in the numerical model shows that it is close to logarithmic up to at least 100 m height. Observational studies (Franklin et al. 2003, Powell et al. 2003, Kepert 2002b,c, Kepert 2006a,b, Bell and Montgomery 2008, Schwendike and Kepert 2008) have confirmed the presence of both the low-level wind maximum, and the near-surface logarithmic layer.

Black and Marks (1991) identified the presence of mesoscale vortices (e.g. Figure 2.6) circulating within the tropical cyclone eyewall region and later Willoughby and Black (1996) proposed that incursions into the boundary layer from such features could be responsible for locally high strips of damage in the landfall of Hurricane *Andrew*. Subsequently, Black et al. (1999) was able to document a possible example of such a feature recorded at Barrow Island, Western Australia, during the eyewall passage of Tropical Cyclone *Olivia* (925 hPa). In this case several unusually large surface gusts were recorded, the highest 3 s peak of 113 m s^{-1} being registered within a single record when the +10 m 5-min mean was 41 m s^{-1}, yielding $G_{3,300} = 2.75$. The other unusual $G_{3,300}$ gusts ranged from 1.6 to 2.6 within an overall storm mean of about 1.3. Section 3 here presents evidence of a potentially similar feature from the same region recorded in 1989 during Tropical Cyclone *Orson* (905 hPa). Other recent gust factor studies have reported little or no direct evidence of convective downdraft features in the vicinity of the eyewall (e.g. Sparks and Huang 2001, Vickery and Skerlj 2005) but these instances typically represent less energetic encounters. There is far too little data to make any firm recommendations, but there seems to be some limited and incomplete evidence showing that transient winds, not due to turbulence *per se*, may occur in tropical cyclone eyewalls with magnitudes in excess of double the otherwise prevailing mean wind.

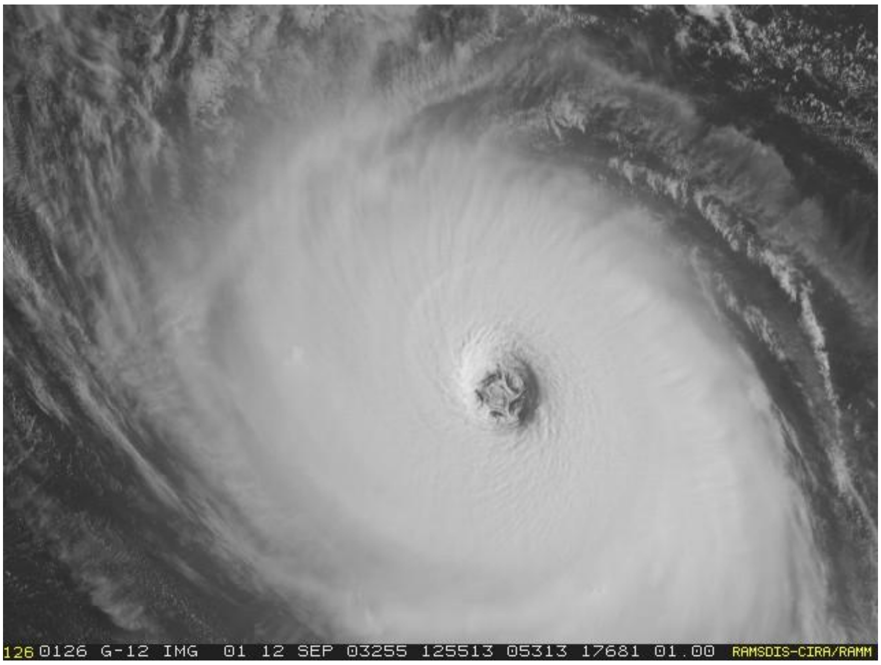

Figure 2.6 Mesovortices within the eye of Hurricane Isabel (2003).

Whether such features are simply isolated or form part of a deterministic framework, possibly even related to 2-D eyewall instability (e.g. Kossin et al. 2004) is yet to be determined. Certainly, highly energetic features are known to exist (Marks et al. 2008) and may penetrate to the surface.

The approach of tropical cyclones near elevated land has long been known to result in increased convergence of the low-level flows and undoubtedly leads to enhanced vertical transport of momentum, which is likely to enhance near-surface turbulence levels (e.g. Yeh and Elsberry 1993). However, Kepert (2002, 2006b) and May et al. (2008) also show that the process of landfall even over flat and relatively featureless land may lead to a substantial change in the near-surface winds due to changes in surface roughness interacting with the vortex boundary layer dynamics.

Taking the above arguments into account, and based on the evidence suggested from a number of near-coast measurements presented later, it is concluded that convective or at least non-mechanical turbulence processes probably play a more significant role in tropical cyclone turbulence intensities than in extra-tropical conditions. In respect of non-turbulent transients such as eyewall instabilities, these features are not presently considered in operational forecasts and warnings but the situation may change in the future as more data becomes available.

3 An Example Extreme Oceanic tropical Cyclone Wind Record

For illustrating some of the foregoing discussions on wind characteristics and averaging times it is instructive to examine a specific tropical cyclone wind record, which not only has a variety of parameters recorded but also shows how stationarity can be compromised during an eyewall passage.

Severe Tropical Cyclone *Orson* (BoM 1992; 905 hPa) passed directly over the North Rankin ‘A’ (NRA) natural gas production platform (19.5856°S, 116.1368°E) operated by Woodside Energy Ltd in March 1989 (refer Figure 3.1), 130 km offshore of the Western Australian coastline. Peak recorded winds were 62.3 m s^{-1} (10-min) and 66.4 m s^{-1} (1-min) at a level of +36.4 m above sea level. Two identically exposed anemometers[6] were automatically logged and the following wind speed parameters were electronically calculated and stored:

- Averaged 1-min wind speed every minute, V_{60}
- Averaged 10-min wind speed every 10 minutes, V_{600}
- Highest 3-s gust in each 10 minutes, $V_{3,600}$
- Highest 3-s gust in each hour and its time of occurrence, $V_{3,3600}$

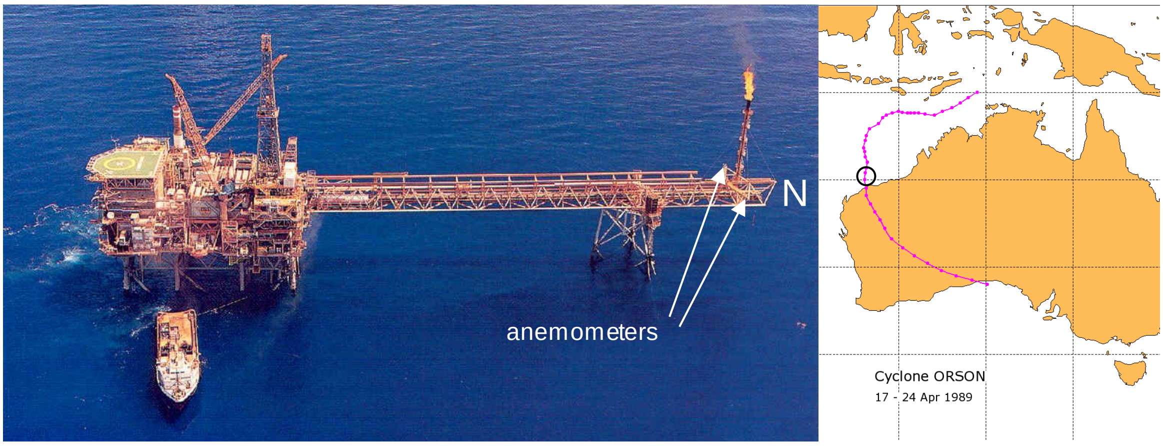

Figure 3.1 Location map and NRA facility during TC Orson.

Unfortunately both anemometers were destroyed during the eye passage, most likely due to the impact of lightweight debris that was stripped from the main structure. One anemometer failed at the time of the first eyewall encounter, the second instrument failed during the second, and the record of $V_{3,600}$ is incomplete due to transmission problems, thus illustrating the difficulty of reliably recording under such extreme conditions. The record here is from the eastern anemometer, which survived the longest and has the better exposure through the first eyewall passage. A nearby moored Waverider™ buoy also failed at a recorded significant wave height (H_s) of about 10 m and estimated single maximum wave heights were of the order of 20 m (Harper et al. 1993).

Figure 3.2(a) shows the time history variation of the indicated winds over a three hour period that includes the eye passage, where the more variable solid line is the continuously available V_{60}, which is lagged by the V_{600} dotted line reported each 10 minutes. The heavy stepped lines are the gust wind speeds $V_{60,600}$ (solid black) and $V_{3,600}$ (dashed red). The solid triangles are time-aligned $V_{3,3600}$ and considered suspect on either side of the eyewall. The only identifiable measure of the turbulence in the mean wind in this case is from V_{60}, being the highest frequency that was continuously recorded. As expected, any instantaneous value of V_{60} might be above or below the 10

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[6] The sensors were propeller-vane Qualimetrics Skyvane instruments, separated by about 30 m horizontally either side of a central cable-stayed flare tower on a cantilevered structure extending out over the ocean.

minute averaged V_{600} value for that interval and, although any single V_{60} is an unbiased estimate of the mean wind, it clearly will have a higher variance than any single V_{600} value and is therefore likely to have a greater associated error as an estimate of the true mean wind. Use of an hourly wind speed reference here would also clearly be unsuitable due to the rapid trends on that timescale. The observed gust $V_{60,600}$ can be seen to follow the peaks of V_{60} within each 10 minute interval. Note however the influence of non-stationary conditions on $V_{60,600}$ and $V_{3,600}$ whereby the peak gust is typically registered at the end of the interval when mean speeds are increasing, and at the beginning of the interval when mean speeds are decreasing.

$V_{60,600}$ is then plotted relative to the contemporaneous V_{600} as the gust factor $G_{60,600}$ in Figure 3.2(b). $G_{60,600}$ is relatively constant until the eyewall passage, averaging around 1.08, but then increases and becomes more erratic in the rapidly changing but lower speeds within the eye. Through the eyewall and eye regions, V_{600} clearly suffers extreme stationarity problems that result in the erratic $G_{60,600}$ values being of no specific consequence. Likewise, the observed gust $V_{3,600}$ in Figure 3.2(a) (when available) has been converted to the gust factor $G_{3,600}$ in Figure 3.2(b) and shows a similar behaviour, initially near-constant at about 1.23.

The extreme spike of $G_{3,600}$ within the eye is associated with a V_{600} of only 9 m s^{-1} and is not of practical interest, again because of non-stationarity. However, two of the three values of $V_{3,3600}$ shown (solid triangles), that are separately recorded by the data logging system, convert to equivalent $G_{3,600}$ values in excess of 2.0. The peak $V_{3,3600}$ of 132.6 m s^{-1} and its later companion of 91 m s^{-1} were originally discarded in the post-storm analysis as likely erroneous data spikes. However, the seemingly well-behaved values of V_{60} during the same period suggest that the logging system was functioning normally. Whether these data are valid or not cannot be determined. They are presented here only as increasing potential evidence for the transient phenomena discussed in Section 2.6. It can be noted that there were also two significant $G_{60,600}$ events for V_{600} values of 10 and 22 m s^{-1} probably associated with convective rainbands.

In Figure 3.3, a summary of the gust factor behaviour is presented for the period of about 2 days when V_{600} exceeded 10 m s^{-1} at the sensor height[7]. Figure 3.3(a) plots $G_{60,600}$ and the two values of $G_{3,600}$ as a function of V_{600}, showing that the mean values given by the superimposed lines (using a 5 m s^{-1} banding) do not vary appreciably but the scatter reduces as mean speed increases. The reason for this may relate directly to Eqn 6 whereby, assuming a constant eddy integral length scale, a larger number of samples at the higher wind speed improves the accuracy of the estimate. Note that this example analysis does not include a check for stationarity as the high frequency data was not recoverable, and all analyses are at sensor height.

Figure 3.3(b) then presents the same information but in the form of sample histograms and cumulative distributions (binned at 0.025 intervals for $V_{600} > 10$ m s^{-1}) for $G_{60,600}$ and $G_{3,600}$, where the modal values are 1.075 and 1.200 respectively, the medians are 1.08 and 1.22 and the means (s.d.) are 1.094 (0.097) and 1.237 (0.067).

This single example of extreme winds during a tropical cyclone serves to illustrate many of the principal theoretical wind averaging issues regarding stationarity, filtering, non-mechanical or convectively-generated turbulence, potential structure-related transients and the clear difference between measures of the mean wind and measures of gusts. It also demonstrates that interpreting gust factors measured under non-stationary conditions can be difficult.

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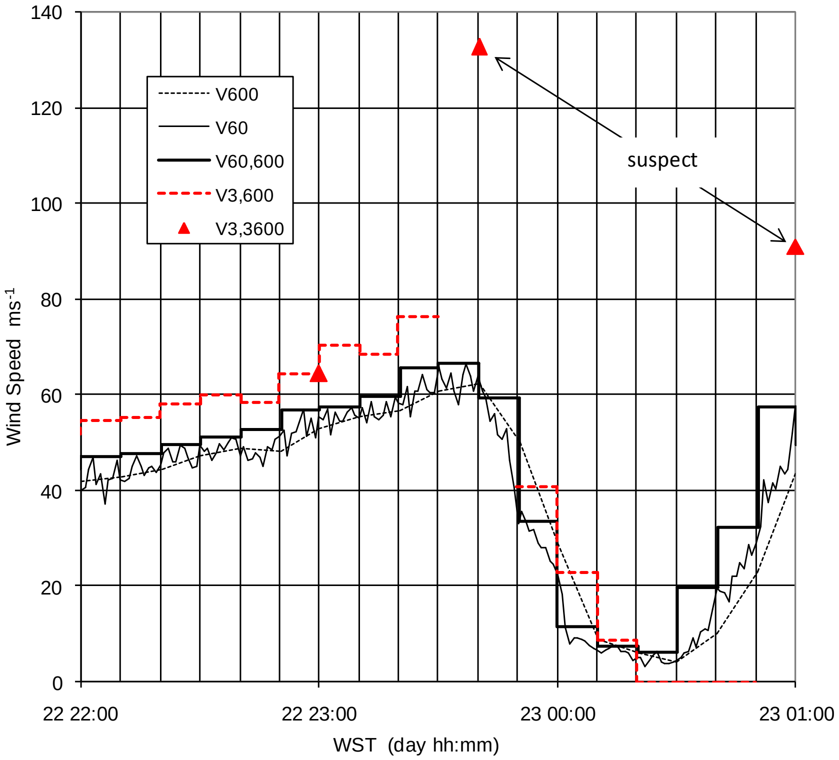
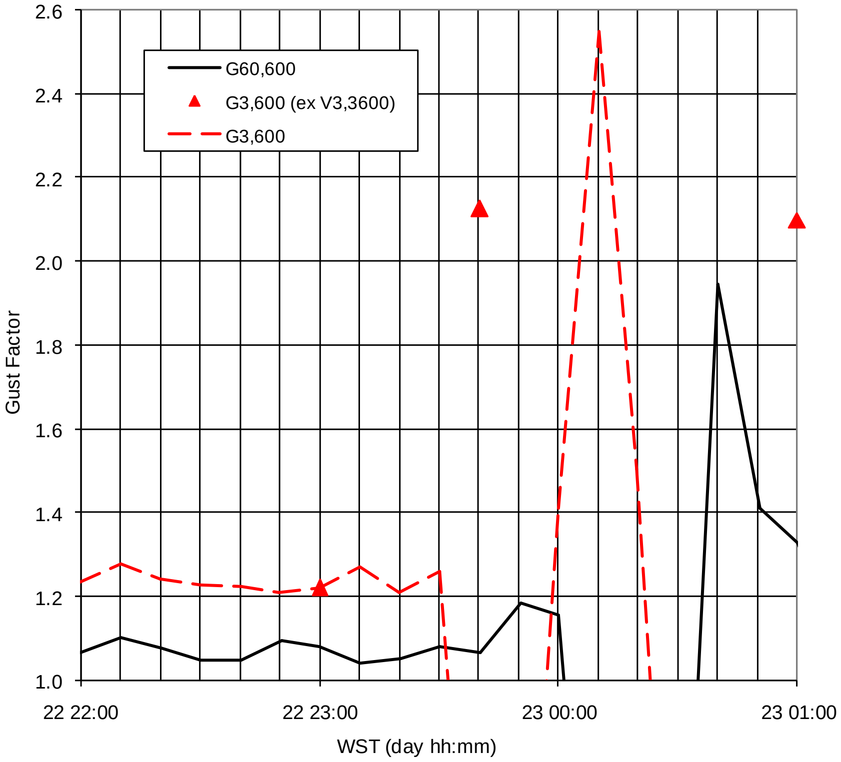
[7] While the present discussion seeks to avoid the equally complex issue of the vertical profile of wind speed, the adjustment factor from +36.4 m to +10 m would be of the order of 0.85 based on ISO (2003) or API (2002).

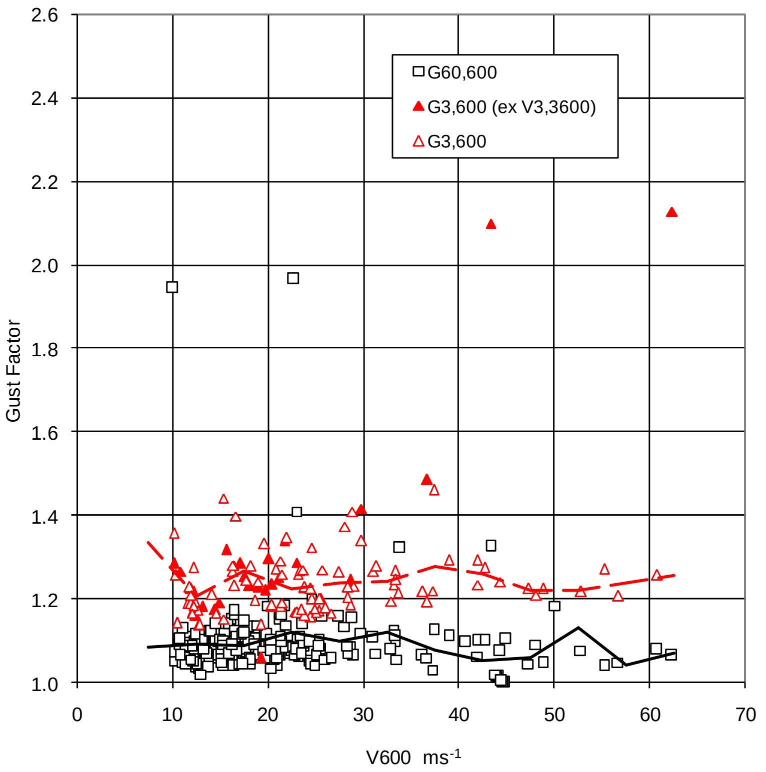


(a) Wind Speeds

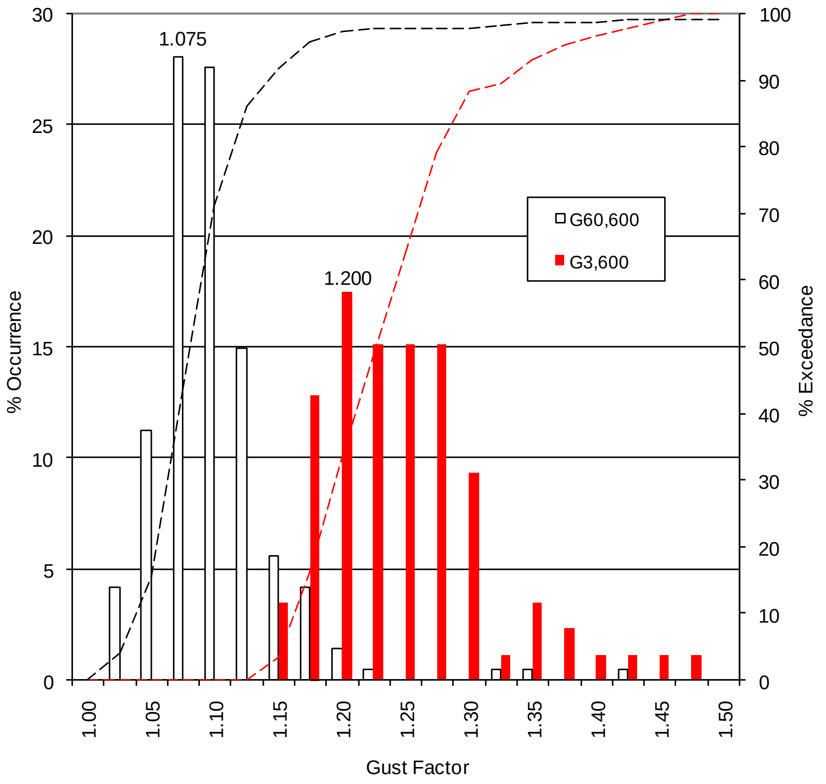


(b) Gust Factors

Figure 3.2 Time history of wind speed and gust factors during TC Orson (1989).



(a) Gust Factor Variability



(b) Gust Factor Distribution

Figure 3.3 Summary gust factor variability during TC Orson (1989).

4 A Compendium of Data and Theories

The approach taken here now is to begin to compare the available (limited) evidence from measurements of tropical cyclone conditions with the established gust theories that are derived from largely land-based extra-tropical conditions. As mentioned previously, the nominal land context is strong winds, typically $V_{To} > 17$ m s^{-1}, standard exposure with roughness length $z_0 = 0.03$ m and height $z = +10$ m. However, there are instances where the available data do not exactly represent this situation – some for obviously practical reasons – and some is reported within specific wind speed bands. Also, some information presented here is based on very extensive datasets that have been smoothed, while some is derived from only a few situations or is simply a recommendation in common usage. Some data is derived from high frequency studies and other data is mean and gust only from AWS sites, some strip-chart based. Attempts have also been made to present original data and thereby avoid simply repeating previous recommendations. Rather than attempt to individually correct each of the published values, which itself requires model assumptions and the like, the data has been logically grouped and clearly identified to hopefully illustrate the emerging trends.

Mindful of the need to provide broad guidance, the presentation of data and theory has been grouped here into three characteristic over-water wind-relative regimes or exposures that are likely to be of most interest to tropical cyclone forecasters and should capture what are believed to be the critical differences, namely:

- “off-land” - any land-based near-coastal exposure with offshore wind;
- “off-sea” - any land-based near-coastal exposure with onshore wind;
- “at-sea” - nominally > 20 km offshore.

Figure 4.1 a to d shows a summary of data and theories collected during this review, presented here in the context of gust factors relative to the “effective” hourly reference period, i.e. values of $G_{\tau,3600}$. Not all of the data collected (refer Appendix C for details and author cross-references) could be objectively presented in an hourly reference context but is used in the subsequent comparisons in Section 4.4. Figure 4.1a is a combination of all the information collected, unstratified by the above exposure classes and provided simply for completeness and comparison. By way of example, the uppermost curve presents the results by Schroeder and Smith (2003), where a peak 3-s gust duration ($\tau = 3$) within an hour yields a gust factor for $G_{3,3600}$ of about 1.72. The symbols and lines on the figures offer some consistency, the principal features being that open symbols and lighter-weight lines normally represent non-land exposures. Curves are indicated on the basis of complete analyses or theories, while points represent less comprehensive studies, recommendations or single events. The legends are alphabetical and also indicate either the approximate mean speed range associated with the dataset that formed the theory or the mean speed value used in a speed-dependent theory.

The remaining Figure 4.1 *b* to *d* present data in terms of the nominated exposure classes, as detailed below.

4.1 “Off-Land” Exposure

A brief explanation of each of the datasets follows. AS/NZS 1170.2 is the implicit $G_{3,3600}$ of 1.67 embodied in the Australia/New Zealand design standard (Standards Australia 2002a) for tropical cyclone regions. Ashcroft (1994) is an extract of tabulated gust factors from a reasonably comprehensive study of UK hourly, 1-min and 3-s gust data that considered different methods of analysis, effects of stationarity and roughness, and appears to be the most recent UK study. Cook (1985) is a simplified form based on the Wieringa (1973) approach used as the basis of a structural design procedure in the UK. Durst (1960) was the earliest reasonably complete description of gust factor variation based on UK data and assumed a simple Gaussian gust model, which yields a characteristic "S-shaped" curve in this presentation. It can be seen that Ashcroft, and Durst form a reasonably consistent grouping, while Cook gives higher G values for $\tau > 20$ s. Next is ESDU (2002b), which was initially published in 1983 in its present form, based on the Davenport (1964) statistical approach as discussed in Section 2.4, combined with extensive datasets and boundary layer models from previous UK wind engineering analyses (e.g. Deaves and Harris 1978). The ESDU formulation is only very slightly sensitive to mean speed and latitude ($\lambda = 50°$ here). The shapes of the ESDU and Durst curves are similar although ESDU has higher G for $\tau < 4$ s and much lower G for $30 < \tau < 600$ s, which is the lowest of all the theories shown here.

K&M (Krayer and Marshall 1992) was the first widely adopted USA hurricane-specific investigation and was later adopted by ANSI (1996) for building design in the USA. It follows the Durst approach based on the analysis of 10-min data (strip chart only) from mostly airport AWS sites during four US hurricanes. It has some event sets in common with Powell (1982, 1987) but recommends higher G values. It can also be seen to predict much higher G values than the UK-based formulations. M&T (Mitsuta and Tsukamoto 1989) is based on detailed measurements from the very small Tarama Island near Japan in a typhoon region. However, the dataset is described as based only on overland fetch situations (approx. 4 km sugar cane and coconut palm), which suggests that the boundary layer may have been in transition rather than equilibrium. Powell (1987) analysed surface winds from Hurricane Alicia and found significant variability depending on the location of rainbands. His recommended $G_{3,600}$ values are interpreted here as probably being most representative of the "off land" exposure and are nominally adjusted by 1.05 to represent $G_{3,3600}$ (a reasonable estimate based on ESDU (2002b)).

S&H (Sparks and Huang 2001) was essentially a follow-up analysis to K&M but considered separate digital airport and near-coastal AWS data during recent US hurricanes. The indicated data point here has been taken as representative of their broad conclusions for an "off-land" condition. S&S (Schroeder and Smith 2003) can be seen to provide the highest of all G values (ignoring Cook at high τ) and is based on high frequency data collected during Hurricane *Bonnie* from a WEMITE mobile tower located at an airport site about 10 km from the coast. It can be seen to estimate higher G than K&M for $\tau < 10$s. The Sissenwine et al. (1973) relationship is shown next, which although difficult to classify, has been included here under both the "off-land" and "off-sea" categories mainly because it is implicitly used in that context by virtue of its use in the Atkinson and Holliday (1977) wind-pressure relationship. Some interpretation has been needed to display it in this context as it is referenced to a 5-min wind and is speed dependent. Here the average gust factors for 20 to 40 m s^{-1} are used and a nominal value of 1.09 is assumed for $G_{300,3600}$. The relationship in this case lies below the other candidate forms, consistent with comments by Black (1993). Two separate mean speed results are also shown based on the Wieringa (1973) recommendations that were derived from 12 m s^{-1} mean wind data from a tower on a lake in Holland, with the results compared with other European datasets. While the examples shown here are outside the original data range, it can be seen that the Wieringa analysis suggests a decreasing G for increasing mean speed. Finally, two speed-specific results applicable to the "off-land" case from the recent V&S (Vickery and Skerlj 2005) review are shown. V&S is essentially a further follow-up to the K&M study but includes more (digital) AWS data from a variety of exposures and chooses to reject some data used by K&M as being unsuitable for gust factor analysis. V&S conclude that the ESDU theoretical approach is applicable to hurricane conditions and contradicts the recommendations of K&M and the example from S&S. There is no data shared by V&S and S&H.

In summary, while there is a broad consistency between the analyses based on extra-tropical conditions over land, which mainly derive from UK measurements, there is more inconsistency between studies derived from tropical cyclone conditions, albeit all suggesting increased G values. In regard to the tropical cyclone estimates; Powell (1987) is an averaged value from a number of land stations having varying exposures; S&S is high quality data but only for a single event at a fixed location; M&T is also high quality data but for multiple (unspecified) events at a fixed location, the exposure of which is somewhat unclear.

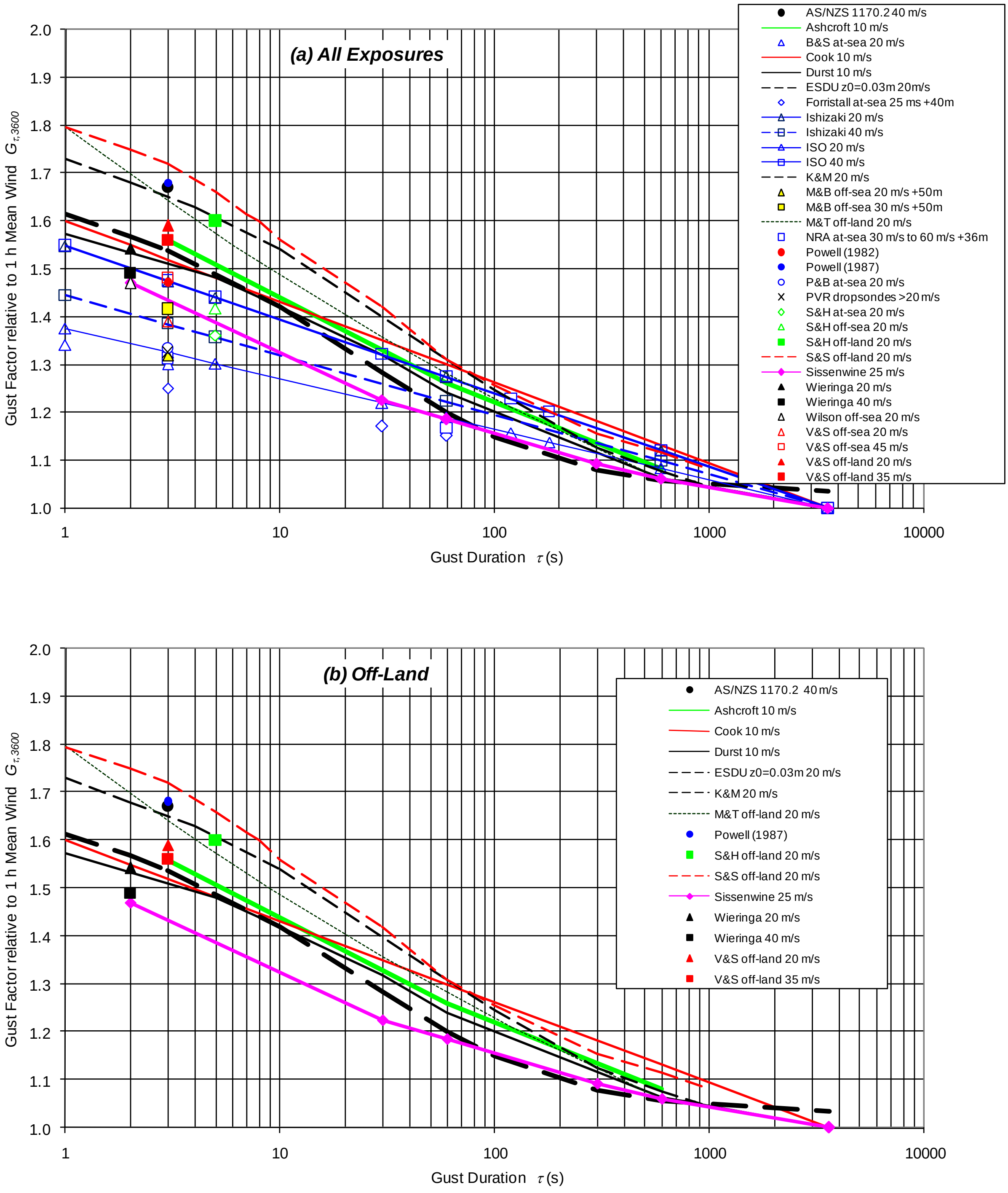


Figure 4.1 Comparison of available gust factors relative to an hourly mean wind.

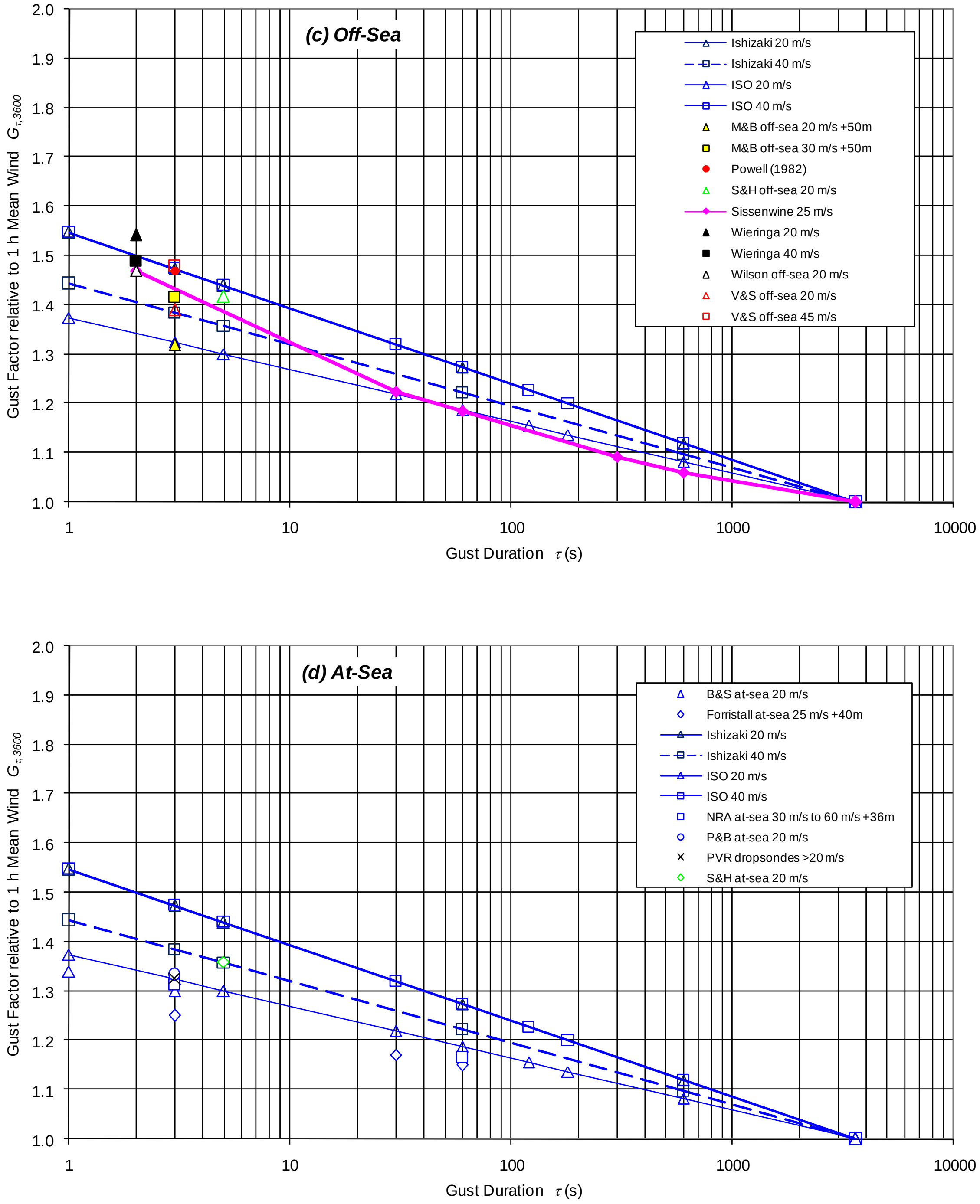


Figure 4.1 Comparison of available gust factors relative to an hourly mean wind. (contd.)

S&H’s single point shown here is not a clear recommendation from that study but has been based on their discussion and seems contrary to their thesis that hurricane winds are similar to extra-tropical; V&S have attempted arguably the most consistent analysis of AWS data from a variety of sites and storms. Conclusions based on this information are that tropical cyclone gust factors “off-land” are probably higher than extra-tropical gust factors and that gust factors in general appear to decrease with increasing mean speed.

4.2 “Off-Sea” Exposure

Immediately the available dataset is diminished as the majority of European land-based studies are removed, although Wieringa (1973) is retained from the “off-land” classification as the theory was largely based on data from a lake and may be more applicable to this exposure category.

Working through the available relationships once more, the first considered is Ishizaki (1983), where two speed-specific ranges are shown, illustrating the theory that G decreases with increasing mean speed. The Ishizaki proposal is largely empirically-based and derives from consideration of nine typhoon datasets in and around Japan and, while not exclusively considering “off-sea” conditions, would appear to mainly consider that case (e.g. includes Tarama Island data). The context of the Ishizaki recommendations was to provide structural design gust factors for typhoon conditions and it has been widely used in Australia within that context with reasonable success (e.g. Holmes 2001; Harper 1989, 1993, 1999, 2001). The Ishizaki curves shown here use that author’s recommended mean non-dimensional turbulence parameter of 0.4. As noted previously the Ishizaki curves tend to follow the envelope of the peak gust and hence may simply be reflecting the effect of improved sample averaging at higher wind speeds, rather than a real reduction in gust factor. Also worth noting is the straightline character of the relationship, similar to the time averaging approximation of Cook (1985).

The next proposal considered is from the draft ISO (2003) standard for offshore structural design, based on the analysis of extensive marine-aspect data from the Island of Frøya on the Norwegian coast by Anderson et al. (1991) and Andersen and Løvseth (1992, 1993). This study was commissioned as a Joint Industry Project for the offshore oil and gas industry in the North Sea and remained under technical embargo for some years. However, the same recommendations, including spectral descriptions, have now been adopted by API (2002), which provides design standards for offshore structures in the Gulf of Mexico, thus apparently endorsing this approach for hurricane conditions. There is a strong wind speed dependency in the ISO proposals that can be seen to be contrary to Ishizaki; for example the ISO 20 m s^{-1} starts from a low base and the ISO 40 m s^{-1} curve overlies the Ishizaki 20 m s^{-1} curve. Notwithstanding that the instrumented towers were located close to the sea, some of the Frøya data may have been affected by an internal boundary layer and this might be reflected in the increased low frequency energy seen in spectra. The ISO lines are also straightline, unlike the “S-shaped” Durst and ESDU formulations, and inspection of the detailed supporting reports shows little evidence for curvature in this context.

Data analysed by Melbourne and Blackman (1982) from Waglan Island near Hong Kong is presented here (M&B) as two speed ranges, showing an increase in G with mean wind (s.d. 0.13 in each case). The M&B analyses are based on Dines data from 39 typhoon episodes over the period 1953 to 1980 but suffer from a number of measurement and siting issues on this rugged and steep site. Firstly the data was strip-chart based and had to be corrected for the (significant) local topographic effects. The +75 m anemometer data was adjusted to a free-stream +50 m over the sea by the application of wind tunnel modelling and a peak factor g of 3.7 was assumed to provide representative mean winds, based on the Deaves and Harris (1978) recommendation for Dines gust response. M&B were amongst the first to suggest that the near-shore sea surface roughness was higher than previously expected in strong wind conditions and this thinking underpinned recommendations in Standards Australia (1989, 2002a) that a z_0 of 0.02 m was representative of tropical cyclone “off-sea” conditions. Notwithstanding this, Sharma and Richards (1999) have pointed to apparent inconsistencies in the AS/NZS 1170.2 turbulence intensities and gust factor approach, claiming higher values should be used.

Powell (1982) analysed surface winds from Hurricane Frederic and his recommended $G_{3,600}$ values are interpreted here as probably being representative of the "off sea" exposure and are also nominally adjusted by 1.05 to represent $G_{3,3600}$. Sissenwine (1973) is again shown and in this context appears somewhat closer to the consensus. A single indicative value from Sparks and Huang (2001) is next, based again on their general discussion, although lower values around 1.3 were individually reported, say, for Hurricane *Bonnie* from the Cape Lookout CMAN station. A single mean value from Wilson (1979) is indicated for North West Cape coastal tower data but this has been adjusted here from his original $G_{3,600}$ of 1.40 by the 1.05 factor. Finally two examples from Vickery and Skerlj (2005) for marine and near-shore coastal exposure are indicated (V&S).

In summary, for the "off sea" exposure there appears to be some support for the extra-tropically based ISO proposals amongst the tropical cyclone experience, but with the distinct exception of the Ishizaki approach (which was a mixture of offshore island and coastal data).

4.3 "At-Sea" Exposure

The ISO and Ishizaki 20 and 40 m s^{-1} cases have been carried forward here to provide a background to the remaining very limited data for the "at sea" exposure class. The first new data points (B&S) are from Brown and Swail (1991), showing their $G_{1,3600}$ and $G_{3,3600}$ recommendations based on extra-tropical data from West Sole platform in the North Sea and Bedford Tower near Nova Scotia. Also shown are values interpreted from Forristall (1988) for Hurricane *Eloise* in the Gulf of Mexico. Black (1993) has dismissed the B&S and Forristall data previously as being too low and unsuitable for tropical cyclone conditions because of stability issues arising from relatively cool air being swept into the storms. However, for comparison, some composite estimates for $G_{3,3600}$ and $G_{60,3600}$ based on four tropical cyclones (including *Orson* from Section 3) measured at +36m on North Rankin 'A' platform (NRA) show that the B&S values at least may not be unusually low. The NRA values are all in winds of order 30 m s^{-1} or greater but have been adjusted here by 1.05 from their 600 s T_o base reference period.

Searching for more data in this offshore context, Powell and Black (1990) data from buoys on the US Atlantic coast during hurricanes is shown as P&B, taking their nominal $G_{5,510}$ as approximately equivalent to $G_{3,600}$ and then multiplying also by 1.05. Next is Powell et al. (2003), providing the first indication of gust factors in hurricanes as measured by GPS dropwindsondes (shown as PVR). Their mean nominal +10 m mean gust factor value of 1.25 has been interpreted here as a $G_{3,600}$ and adjusted by 1.05, although it is noted that the authors comment on not being entirely certain at this stage as to the likely applicable τ value because of loss of high frequency components in the analysis. Indeed, because of the quasi-Lagrangian reference of the 10 to 15 m s^{-1} fall rate of GPS dropwindsondes, there remains some doubt at this time as to the applicable T_o reference period. Finally, the Sparks and Huang (2001) broad recommendation for offshore situations is included.

In summary, all available "at sea" gust factors are significantly lower than the "off-sea" case and are closely approximated by the ISO 20 m s^{-1} curve. However, many of the data represent mean winds well in excess of 20 m s^{-1} and are therefore at significant variance with (say) the ISO 40 m s^{-1} curve, even allowing for some elevation differences. Meanwhile, the empirical Ishizaki curve would converge onto the data at about 65 m s^{-1}. It is concluded that the ISO curve may be too sensitive to the mean wind in this situation and that this may relate to its formulation based on the near-shore wave shoaling and breaking environment rather than in the open ocean. It is also worth noting that the NRA data are a particularly valuable reference in these circumstances, especially since the data have been collected from several types of instrumentation in winds up to 30 m s^{-1}.

4.4 A Simplified Gust Model for Tropical Cyclone Forecasting

The accurate measurement of wind speed fluctuations, especially under tropical cyclone conditions, is a difficult and demanding activity that will always result in scatter from even the most careful analyses. There are significant gaps in our understanding of atmospheric turbulence characteristics and with necessarily complex empirical descriptors, many degrees of freedom result.

The forecasting of tropical cyclones is an already difficult task. In consideration of the apparently wide range of observational data presented, and the difficulties in ensuring consistent analysis, a sensible approach in the context of recommending wind averaging formula would therefore seem to be one of applying consistency within a suitable theoretical framework. This section therefore proposes a simplified approach to achieve that goal, which can be readily updated as further information comes to hand. Based on the foregoing review of theoretical studies of the relationship between different wind averaging periods and the assessment of available data, the approach recommended by ESDU (2002b) is deemed the most appropriate basis for conversion and comparison purposes. In this regard the present review supports Vickery and Skerlj (2005), which also proposes the ESDU method. However, not all aspects of this approach are necessarily of interest here with regard to tropical cyclones. In particular, the full method relies on largely UK datasets for estimating turbulence intensities, their variation with height and also changes in terrain roughness and the like.

For the present forecasting purposes the standard (nominal) observational elevation of +10 m only is of interest and it will be assumed that the terrain/sea is of constant form and roughness and that mean winds are in excess of 17 m s^{-1}. Under these limitations, it is considered appropriate to replace the complex ESDU formulations with suitable a priori estimates of the longitudinal turbulence intensity I_u. This specifically permits adjustment of turbulence values to better represent the apparently enhanced conditions observed near and on land during tropical cyclones, and also conveniently avoids any determination of actual z_o values at this time. Appendix D presents a summary of the recommended method, which also requires some extension of the ESDU procedures for the shorter τ values of interest to this study.

The way forward here is therefore to use only the available tropical cyclone specific data, suitably grouped into the previous exposure classes, to calibrate the recommended ESDU method for a range of I_u values. This also permits the use of some data from Appendix C that was not used in Section 4 because of T_o reference periods less than 600 s, and therefore deemed unreliable for converting to an hourly reference. Only 3600 s, 600 s and 60 s reference period data are available for this procedure and the best-fit condition was arrived at objectively based on least squared error.

Figure 4.2 presents the final calibrations in terms of the three previously defined “over water” exposure classes and Table 4.1 summarises the adopted values for longitudinal turbulence intensity and roughness length, which also includes a nominal “in-land” class based on the “roughly open” classification of Table 2.1. By way of explanation, each set of data points in the figure refers to a different wind averaging period of the mean wind, which is overlaid by the proposed equivalent ESDU analytical form. From Appendix C it can be noted that the standard deviation of the gust factors, where available, is of order 0.1 and this is indicated by the nominal error bars.

Table 4.1 Recommended turbulence intensities and associated roughness lengths for tropical cyclone forecasting purposes.

Exposure Class	Turbulence Intensity I_u	Roughness Length z_o (m)
“in-land”	0.250	0.18
“off-land”	0.200	0.07
“off-sea”	0.150	0.013
“at-sea”	0.100	0.0005

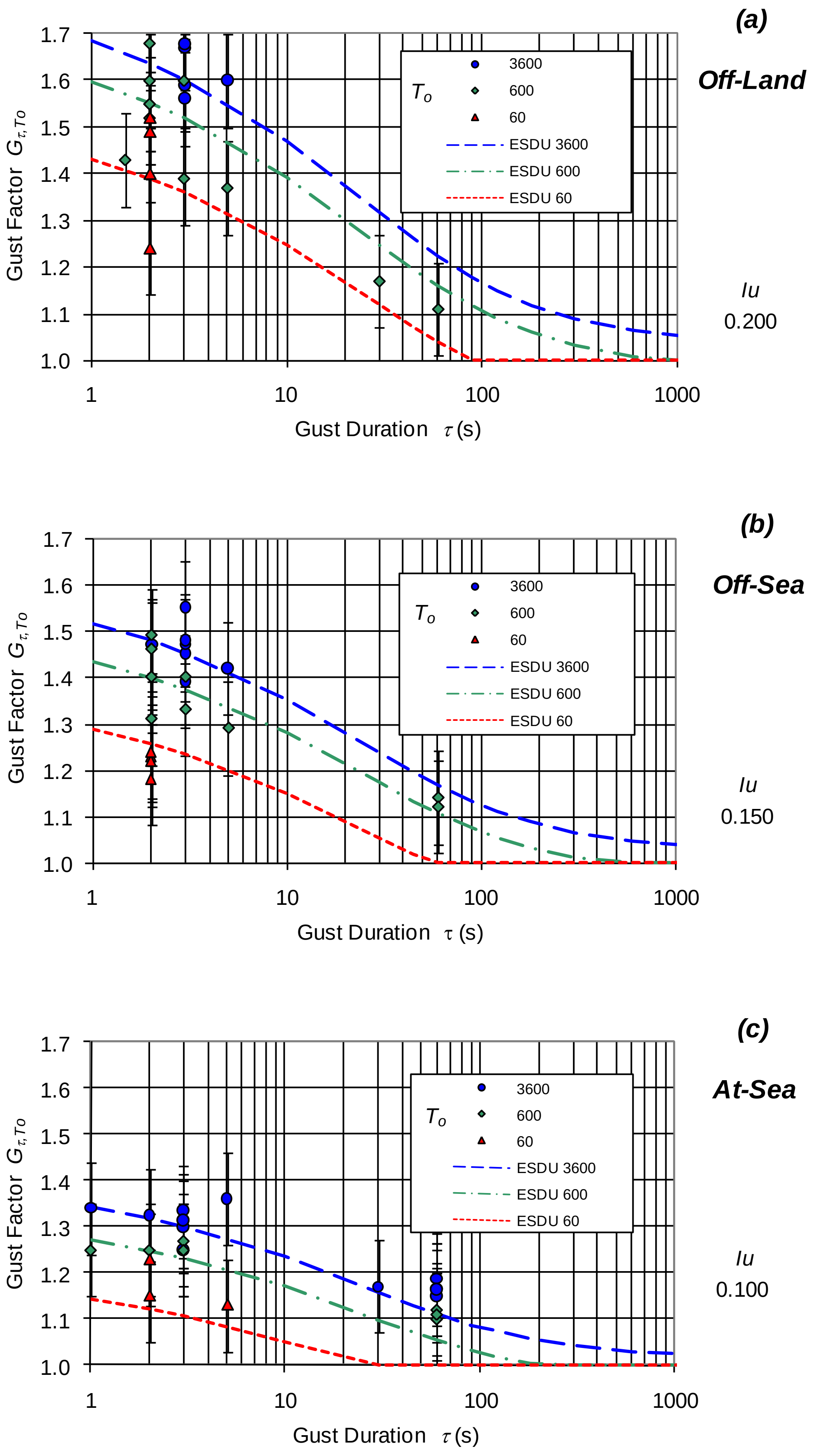


Figure 4.2 Calibration of the modified ESDU method for tropical cyclone forecasting purposes.

5 Conclusions and Recommendations

A review has been undertaken of past and contemporary theory and data relevant to the issue of wind averaging periods and wind speed conversions under tropical cyclone conditions focusing on the open ocean and coastal situations. The recommended conversions are given in Table 1.1.

It is concluded that the accurate measurement of wind speed fluctuations, especially under tropical cyclone conditions, is a difficult and demanding activity that will always result in scatter from even the most careful analyses, and the available data and some theories show many inconsistencies. Clearly there are still significant gaps in our understanding of near-surface atmospheric turbulence characteristics under strong wind conditions. However, because the forecasting of tropical cyclones is an already difficult task, a simplified approach has been recommended that should nevertheless lead to an increase in consistency of quoted and forecast winds. An existing mathematical description of wind over-land in extra-tropical conditions has been adapted for this purpose and nominally calibrated against a wide range of assembled tropical cyclone wind data. The recommended procedure is seen as a practical interim solution until such time as increased data collection and analysis provides a more definitive description of the wind turbulent energy spectrum in various situations under tropical cyclone conditions.

The review has specifically highlighted the need to distinguish clearly between randomly sampled estimates of the mean wind speed based on any chosen averaging period and the peak gust wind speed within a particular observation period. It is particularly noted that mean wind speed estimates should not be converted between different averaging periods – only gust wind speeds.

It is recommended that the WMO regional associations and panels work towards revising and standardising their wind terminology, definitions and associated use of averaging periods in the various operational plans (e.g. as summarised here in Appendix A). This will assist in ensuring that the historical record contains more consistent measurements and/or estimates that can be reliably transformed or converted for assisting in further development of the science.

The review has also identified the need for special considerations in regard to converting between agency estimates of storm-wide maximum wind speed (*Vmax*) that are based on different wind averaging periods (refer Table 1.2). This is because such estimates imply both space and time contexts and the past practice of associating the so-called 1-min “sustained” wind with the Dvorak (1984) intensity estimation method has been done without regard to a stated observation period.

Accordingly, the review recommends an at-sea conversion between the $Vmax_{60}$ estimate of peak storm intensity and the $Vmax_{600}$ estimate of 0.93, rather than the “traditional” value of 0.88, which has been shown here to be associated more with an off-land exposure. This implies that current practice has underestimated the $Vmax_{600}$ by about 5%, relative to an equivalent $Vmax_{60}$ value.

It is also strongly recommended that the WMO work towards a re-calibration of the “Dvorak-related” intensity estimation techniques, based on a more rigorous treatment of wind-averaging issues.

The continued expansion of quality automatic weather station (AWS) networks and research-standard specialist facilities is strongly encouraged in order to gather the necessary information for future reviews and revised recommendations.

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Appendix A A Critique of Existing WMO Practice

The current practices of the five tropical cyclone regional associations, panels and committees in regard to wind averaging periods are contained in WMO (2002abc) and WMO (2003ab). There are three stated wind speed types and associated averaging periods currently in use.

The three declared "surface" wind types found in the WMO regional operational plans are:

- Average (or mean) wind speed
- Wind gust speed
- Maximum sustained wind speed

Table A-1 below summarises the critical points of difference in terms of the stated averaging periods used, while the literal definitions of these wind types are presented overleaf in Table A-2 for reference. It is important to note that these definitions serve two distinct purposes: (i) for the taking of observations (the Average Wind Speed column), and (ii) for describing the intensity of tropical cyclones (the Maximum Sustained Wind Speed column).

It is noted that only RA IV defines "surface" winds as being measured at a height of 10 m and none of the plans specify the actual exposure of the wind measurement or estimate, although "at sea" is implied in the general tropical cyclone context.

Table A-1 Defined surface wind averaging periods in current WMO operational plans.

Association	Region	Average Wind Speed	Gust Wind Speed	Maximum Sustained Wind Speed
RA I	SW Indian Ocean	10-min	Not defined	1-min
ESCAP Tropical Cyclone Panel	N Indian Ocean	10-min (recording) 3-min (non-recording)	Not defined	Maximum value of the average; either 10-min, 3-min or 1-min at the surface.
RA IV	Americas and the Caribbean	1-min (recording and non-recording)[8]	Not defined	*Not defined but average is implied.*
RA V	S Pacific Ocean and SW Indian Ocean	10-min (1min for US territories)	Not defined	Maximum value of the average.
ESCAP Typhoon Committee	NW Pacific, South China Sea	10-min (recording) 3-min (non-recording)	Not defined	Maximum value of the average; either 10-min, 3-min or 1-min.

In addition to the above WMO affiliates, the US Department of Defense Joint Typhoon Warning Center (JTWC) based in Hawaii, which covers certain Western Pacific and Indian Ocean areas, uses nomenclature similar to RA IV. It is also understood that a 2-min average wind may be in use in China, possibly for non-recording situations, but this is not described in the ESCAP Typhoon Committee documentation.

The operational plans define neither the averaging period nor the reference period for a wind gust. Also, while all of the associations recommend archiving the averaging period used for the average wind estimate, only three (IV, V, ESCAP Typhoon) recommend archiving the applicable gust averaging period. RA I provides guidance on converting the average 10-min wind speed to a gust speed (1.41) and to a 1-min sustained speed (1.14) for over-water conditions.

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[8] A 10-min average is reported for international civil aviation compliance and in post-storm country reports.

Table A-2 Literal definitions of the various wind speed types in the glossary of current regional WMO tropical cyclone, typhoon and hurricane operational plans.

Association	Region	Average Wind Speed	Gust Wind Speed	Maximum Sustained Wind Speed
RA I	SW Indian Ocean	Speed of the wind averaged over the previous 10 minutes.	Instantaneous peak value of surface wind speed.	Surface wind speed averaged over the previous 1 minute.
ESCAP Tropical Cyclone Panel	N Indian Ocean	Speed of the wind averaged over the previous 10 minutes (mean surface wind) as read from the anemogram or the 3 minutes mean determined with the non-recording anemometer or estimated wind at sea by the mariners using the Beaufort scale.	Instantaneous peak value of surface wind speed, recorded or expected.	Maximum value of the average wind speed at the surface.
RA IV	Americas and Caribbean	Determined by averaging observed values from a direct-reading instrument or a recorder over a 1 minute period. The standard height of the wind measuring instrument is 10 meters.	Fluctuation in a short time of wind speed with a variation of 10 knots or more between peaks and lowest speeds	(Not defined but average is implied.)
RA V	S Pacific Ocean and SW Indian Ocean	Speed of the wind averaged over the previous 1 or 10 minutes.	Sudden, brief increase of the wind speed over its average value	Same meaning as average.
ESCAP Typhoon Committee	NW Pacific, South China Sea	Speed of the wind averaged over the previous 10 minutes (mean surface wind) as read from the anemogram or the 3 minutes mean determined with the nonrecording anemometer or estimated wind at sea by mariners using the Beaufort scale.	Instantaneous peak value of surface wind speed.	Maximum value of the average wind speed at the surface.

The Global Guide to Tropical Cyclone Forecasting (WMO 1993), which arose as an initiative from the International Workshop on Tropical Cyclones, includes wind gust factors within its wide range of technical recommendations. While none of the WMO operational plans reference the Global Guide it is understood that the guidelines therein are widely used by forecasters.

The Global Guide does not provide background into the various issues that specifically relate to the selection of wind averaging periods, but it does define a gust averaging period as 2-s and also identifies some of the key associated observational issues. The recommendations are summarised within its §Section 9.5.2 and derive from its §Table 4.2, introduced as follows:

Gust factors defined by the ratio of peak 2-s wind to the mean wind at 10 m elevation for various exposures and averaging times and in wind speeds of at least hurricane force. Parenthesis give an indication of the range in gust factors.

Table A-3 Existing Global Guide advice ***(NB: Superceded here)***

	Ocean	Flat Grassland	Woods/City
1-min Mean	1.25 (1.17-1.29)	1.35 (1.29-1.45)	1.65 (1.61-1.77)
10-min Mean	1.41 (1.37-1.51)	1.56 (1.51-1.70)	2.14 (1.89-2.14)
10-min Mean over Ocean	1.41	1.31	1.11

The data used to prepare the above is attributed to studies by Atkinson (1974), Spillane and Dexter (1976) and Padya (1975) and is a simplified form of §Table 7.3 in BoM (1978). The factors provided in the final row of Table A-3 are from Spillane and Dexter (1976) and are relative to the mean over-ocean speed, combining an allowance for an expected reduction in mean winds with increasing surface roughness but offset by an increase in gustiness.

It should be noted that the above table does not explicitly provide a conversion between a 1-min peak gust and a 10-min mean wind, although §Table 7.4 in BoM (1978) recommends 1/0.88 (=1.14), apparently based directly on the recommendation by Atkinson (1974). Meanwhile, §Section 1.3.3 of WMO (1993) does recommend a conversion of 1/0.871 (=1.15), with linkage to Simiu and Scanlon (1978) and Durst (1960) (see also Appendix E). It appears that ratios of the factors in Table A-3 may have also been commonly used to infer that a $G_{2,600}/G_{2,60}$ factor of 1.41/1.25 (= 1.13) is applicable over the ocean for converting from 10-min to 1-min “means”. Use of gust factor ratios in this way, however, is not correct.

Either way, there is confusion or ambiguity in Table A-3 between the wind averaging time and the reference or observing time of the wind speed sample. For example, the labelled “1-min Mean” is not an unbiased estimate of the mean wind in this context and should be referred to as a “gust”, in exactly the same context as the 2-sec gust, which forms the basis of the table recommendations.

It is concluded that the existing WMO regional association definitions of mean winds, “sustained” winds and wind gusts leads to uncertainty and ambiguity with regard to how specific metrics of the wind can be inter-compared. This reflects a lack of rigor generally in describing near-surface winds within the forecasting environment that can lead to misinterpretation and result in unintentional biases (high and low) of forecast winds. In particular, there is a tendency to misuse the term “mean” wind amongst the tropical cyclone community where the maximum 1-min “sustained” wind is involved. Also, it is noted that only RA IV defines the “surface” wind height as being 10 m and no plans explicitly state the wind exposure, although the typical context is “at sea”.

Appendix B History of Scientific Studies of the Wind with Special Reference to Tropical Cyclones

According to Greenway (1979), possibly the earliest scientific consideration of the impact of wind forces was that following the Tay Bridge disaster in 1880 Britain, which resulted in a seven year study of wind pressures on four different sized sensing boards at the location of the Firth of Forth Railway Bridge in Scotland. The resulting differences in maximum wind pressures painstakingly measured over this time not only yielded a level of critical insight into wind turbulence scales that we now appreciate, but also highlights the continuing need for rigour and persistence when attempting to describe local properties of the near-surface wind. The production of the first Dines pressure tube anemometer followed in 1892 and quickly became a worldwide standard for measuring the wind that is still in widespread use today. Its oft-quoted nominal peak response to a “2 to 3 s” gust has underpinned much of the world’s thinking about characterising the force of the wind for structural design purposes (e.g. Sanuki 1952; Whittingham 1964).

Some of the earliest identified comprehensive wind studies in the 20th century appear to be that of Sherlock and Stout (1932) in the USA at Ann Arbor and Giblett (1932) in the UK at Cardington, all understandingly limited to the land environment at that time. However it was not until the mid 1950s that the need for statistical guidance gained prominence and early spectral measurements by Panofsky and McCormick (1954), for example, set the scene for the future study of atmospheric turbulence. Around the same time, tower-based measurements by Deacon (1955) at Sale in Australia were valuable additions to the topic and also addressed the issue of anemometer response and filtering effects in the analysis of peak gusts.

Charnock (1955) used a modest set of measurements made over a UK water supply reservoir to propose a simple yet profound non-dimensional scaling of the surface wind stress over water with wind speed. Perhaps surprisingly, Charnock’s proposal survives to this day as one of the central empirical postulates governing turbulent wind structures over the ocean.

Building on the Panofsky work, Van der Hoven (1957) illustrated the broadband spectral character of the near surface wind and identified the possibility of a near-universal wind energy gap around 1 h, a concept desirable for building a practical statistical description of the wind. Using this concept, a relatively simple analysis by Durst (1960) using Giblett’s UK data (specifically 16 high frequency 10 minute records combined with 44 days of data run) has survived as a useful resource to this day (e.g. Krayer and Marshall 1992; ANSI 1996; Powell et al. 1996) in spite of its simplified statistical approach that assumed Gaussian rather than extreme value gust statistics.

Some of the earliest references to studies of tropical cyclone winds and associated gust factors appear due to Bell (1961), who studied typhoons in the Hong Kong area, and the summary by Tanigutchi (1962), which considers storms near Japan from 1955 to 1962.

In the 1960s, demands for more slender structures and increasingly light-weight construction materials, lead to the structural design specialisation of *wind engineering*. Davenport (1961, 1964) is widely regarded as the father of this science and his development of a spectral form for near-surface winds paved the way for many detailed studies during the 1960s and 1970s. His 1964 treatment of the statistical estimation of short period gusts within a given averaging time is still widely regarded as the method of choice (e.g. ESDU 2002b). Whittingham (1964) provided a solid summary of much work to that time, including an assessment of the peak gust response of the Dines anemometer, and was the first to summarise the significant Australian experience with extreme wind gusts from tropical cyclones. Deacon (1965) presented similar relationships to Durst for the effect of different averaging times on estimating a 2-s gust using data from Sale, Cardington and Shellard’s (1958) UK data. Brook and Spillane (1968) also proposed a variant to the Davenport spectrum, which included a gust profile approach with apparently similar predictive skill.

The 1970s represented a rapid period of growth in knowledge. Wieringa (1973) extended the Durst methodology in combination with the Davenport (1961) roughness scaling concepts and produced an analytical approximation to the gust formula, which was compared with a variety of datasets. Counihan (1975) also provides an extensive review of boundary layer studies of special relevance to UK structural design challenges of the time. Sissenwine et al. (1973) undertook a wide-ranging investigation into the characteristics of extreme winds for use worldwide by the US Air Force. Although their available datasets were somewhat disparate and the analyses highly empirical, they proposed a series of nomograms for gustiness as a function of speed and height, and considered averaging intervals appropriate for specific length scales. A contemporary review by Atkinson (1974) for the Joint Typhoon Warning Center (JTWC) appears to offer the earliest review and recommendation of gust factors for tropical cyclone conditions, highlighting the difficulties of such measurements and lamenting the lack of reliable data – a situation that is not much changed 30 years later. The review drew upon a range of discrete observations (many as summarised by Tanigutchi 1962), combined with several years of Navy ship reports and other isolated data. Unfortunately however, both Sissenwine et al. (1973) and Atkinson (1974) began a trend of incorrectly referring to ratios of average wind speeds. The former considers 5 min and 1 min averages, while the latter considers 10 min and 1 min averages, while both additionally accept the concept of a peak gust. Implicit in each development is that the estimated 1-min winds are indeed the highest 1-min winds within either the 5-min or 10-min reference period and hence are not random averages of wind speed but rather gusts.

In the mid-1970s Simpson (1974) and Saffir (1975) were influential in proposing a “hurricane disaster-potential scale” that extended the Beaufort scale ranges, and remains in prominent use today in the USA. In the present context it is worth noting that while Saffir (1975) clearly labelled the proposed index wind speeds as “2 or 3 s gusts”, there is no similar confirmation in Simpson (1974) as to the applicable averaging period. Subsequently, it appears that a popular assumption was made to associate the Saffir-Simpson wind speed ranges with the so-called “1-min sustained” wind. Potential consequences of this sequence of assumptions were recently raised by Sparks (2003).

During the latter part of the 1970s the development of UK wind engineering structural design codes was rapid, moving from earlier power law representations of the boundary layer vertical wind speed profile (e.g. Newbury and Eaton, 1974) to the more theoretically-based logarithmic profile (e.g. Deaves and Harris, 1978). Increasingly, attempts to better describe tropical cyclone conditions were made (Mackey and Ko 1975; Choi 1978; Spillane and Dexter 1976) and some important case studies were presented (Padya 1975; Wilson 1979a,b). Atkinson and Holliday (1977) developed a wind-pressure relationship for typhoons in the Western North Pacific based on adjusting measured peak wind gusts to a 1-min average wind using recommendations from Sissenwine et al. (1973). This relationship is still used extensively worldwide by tropical cyclone forecasters (Velden et al. 2006) as a part of the Dvorak (1984) intensity estimation technique.

In the 1980s the emerging discipline of wind energy fostered further theoretical study (e.g. Fordham 1985; Beljaars 1987; Kristensen et al. 1989) while tropical cyclone related studies increased in the North West Pacific region (Melbourne and Blackman 1982; Choi 1983; Ishizaki 1983; Naito 1988; Ishida 1989; Mitsuta and Tsukamoto 1989). Many of these studies involved nearshore towers or island-based measurements, although the results sometimes showed large variations in the estimated gust factors, likely due to the wide range of exposures. In the Atlantic (Powell 1982, 1987) provided detailed analyses of landfalling Gulf of Mexico Hurricanes *Frederic* and *Alicia*, comparing aircraft observations adjusted using the Powell (1980) boundary layer model with surface measurements and determining representative surface gust factors for forecasting purposes.

In the offshore zone, some of the earliest reliable data on gust factors came from oceanographic studies in the North West Atlantic (e.g. Wu 1982; Tieleman 1985; Smith and Chandler 1987) and Dobson (1981), on behalf of the WMO, comprehensively considered the many issues concerning reliable mean wind measurements at sea. Forristall (1988) was one of the first to propose a specific gust factor model for tropical cyclones, using offshore platform data in the Gulf of Mexico.

In the Australian region, where design codes had traditionally followed UK practice, the devastating impact of *Tracy* at Darwin in 1974 had already prompted a special allowance for tropical cyclone conditions. Standards Australia (1989) further revised these recommendations to recognise an increased turbulence regime during tropical cyclone conditions, this being based largely on subsequently measured data (e.g. Wilson 1979ab; Melbourne and Blackman 1982).

In the 1990s, Brown and Swail (1991) presented a review of available methods for estimating strong wind gusts in general oceanic conditions but were unable to make comprehensive recommendations. Northern European studies (e.g. Kristensen et al. 1991; Mahrt and Gibson 1992; Ashcroft 1994) continued to explore detailed turbulent structures and gust factors, mainly over land. One exception to these was a joint oil industry project (Andersen et al. 1991, 1992, 1993) that specifically addressed marine exposure and has now become a recommended industrial standard for both extra-tropical and tropical conditions (ISO 2003; API 2002).

In Japan, Hayashi (1991, 1992) continued the tradition of high quality spatial analyses and in Europe, Wieringa (1992) provided a revised Davenport surface roughness classification system. In the US, interpretation of the growing database of offshore tropical cyclone winds both at reconnaissance level and the surface became available (Powell and Black 1990) and a number of significant and influential case studies appeared (e.g. Powell et al. 1991; Krayer and Marshall 1992; Powell and Houston 1996; Powell et al. 1996; Schroeder et al. 1998).

Black (1993) provided insight to the historical use of gust factors in the NW Pacific and discounted some of the later gust factor data from extra-tropical systems as being stability-affected. Holmes (1997) proposed revised guidelines for estimating the wind averaging period that would critically affect structures of various scale. Sharma and Richards (1999) provided a review of contemporary practices for specification of turbulence intensities and gust factors in tropical cyclone conditions, suggesting that some present design allowances may be insufficient.

In the current decade, theoretical turbulence studies are still proceeding (e.g. Toriumi et al. 2000; Brasseur 2001; Boettcher *et al*, 2003) but the increasing availability of higher quality *insitu* tropical cyclone data in the US from fixed CMAN and also mobile platforms has caused a sudden burst of analyses (e.g. Sparks and Huang 2001; Schroeder et al. 2002; Paulsen et al. 2003; Paulsen and Schroeder 2005; Vickery and Skerlj 2005, Masters et al. 2005).

Some of the latest insight into open ocean gust factors has now come from analysis of GPS dropwindsondes (Franklin et al. 2003, Powell et al. 2003) and increasing demands are being placed on agencies that provide community wind speed estimates (e.g. Sparks 2003, 2004) for more relevant and accurate advices.

In summary, the science of the natural wind has progressed significantly since its beginnings in the 1930s, with the 1960s and 1970s dominated by applications in wind engineering, and the 1980s onwards benefiting from better and more extensive datasets as a result of advances in computing and storage technology. In the 1990s, knowledge of tropical cyclone conditions in particular has increased markedly. Notwithstanding the increased data however, interpretation still relies on relatively robust concepts founded in the 1950s.

Appendix C Tropical Cyclone Gust Factor Data Sources

LEGEND *italics indicates adjusted values* **bold indicates data** regular indicates recommendation	***At-Sea*** *To =*									***Off-Sea*** *To =*									***Off-Land*** *To =*									Comment
	3600			600			60			3600			600			60			3600			600			60			
	τ	mean	s.d.	τ	mean	s.d.	τ	mean	s.d.	τ	mean	s.d.	τ	mean	s.d.	τ	mean	s.d.	τ	mean	s.d.	τ	mean	s.d.	τ	mean	s.d.	
AS/NZS 1170.2 (2002)																			3	1.67								Supposedly based on M&B but has higher values.
Brown and Swail (1991)	3	**1.3**		1	**1.25**	**0.100**																						Offshore high latitude non-TC data sets.
	1	**1.34**	**0.134**	60	**1.1**																							Same data from Smith and Chandler (1987)
Black (1993)							2	*1.23*					2	*1.4*		2	*1.23*					2	*1.6*		2	*1.4*		Collation of numerous Asian studies and HRD data.
Black et al (1999)													3	***1.33***	***0.14***													24h of Barrow Island 5 min winds during TC Olivia (1996); marginal sea/land case; assume G3,300=G3,600
Choi (1978)													2	**1.46**														G2,600 assumed; mult=2.71
Forristall (1988)	3	**1.25**																										Hurricane Eloise (inferred) +40m 25 m/s
	30	**1.17**																										
	60	**1.15**																										
Ishizaki (1983)													2	*1.31*		2	*1.18*											Exact exposures for the data sets is unknown but derived from island/coastal towers.
													60	1.14														Recommended gust factors here are based on Iu'=0.4
Krayer and Marshall (1992)																						2	**1.55**					Derived from 4 hurricanes using strip-chart records. Compares with Durst (1960) value of 1.40
																						2	**1.52**					(> 15 m/s)
Melbourne and Blackman (1982)										**3**	**1.45**																	
										3	**1.55**																	
Mitsuta and Tsukamoto (1989)																						1.5	**1.43**	**0.074**				Tamara Island; "off-land"
																						3	**1.39**	**0.069**				
																						30	**1.17**	**0.041**				
																						60	**1.11**	**0.038**				
Paulsen et al (2003)													2	**1.49**	**0.07**							2	**1.68**	**0.11**				WEMITE data from 13 US coastal hurricanes.
Powell (1982)										3	*1.47*		3	**1.4**														Coastal stations during Hurricane Frederic landfall in GoM; assumed G3,600
Powell (1987)																			3	*1.68*		3	**1.6**					Land stations during Hurricane Alicia landfall in GoM; assumed G3,600
Powell and Black (1990)	*3*	*1.33*	*0.28*	3	**1.27**	**0.28**																						CMAN G5,120 and Buoy G5-8,510 Assume G5,510 approx G3,600
Powell, Dodge and Black (1991)							2	*1.15*								2	*1.22*								2	*1.52*	0.33	Recommendations in Table 3. Available measured data in Table 5, mostly from inland stations, averaged V2,60 = 1.52 (0.33).
Powell, Houston and Reinhold (1996)	*60*	*1.19*		60	*1.12*								60	*1.12*														Based on a polynomial fit to K&M, also considering Hurricane Bob and CMAN data etc.
Powell and Houston (1996)							5	*1.13*																				Refers to Hurricane Bob and CMAN analyses.
Powell, Vickery and Reinhold (2003)	3	*1.31*	*0.08*	3	**1.25**	**0.08**																						Dropsonde data; assumed V3,600
Smith and Chandler (1987)	2	*1.33*		2	**1.25**																							
	60	*1.17*		60	**1.1**																							
Schroeder et al (1998)																												Analysis of Hurricane Bob (1991) at Duck S.C.
Schroeder et al (2002)																									2	1.49	0.109	WEMITE data from 6 US coastal hurricanes.
Schroeder and Smith (2003)																						2	1.55					
Sissenwine et al (1973)																2	1.24								2	1.24		Table 13; average of 40 to 60 kts
Sparks and Huang (2001)	5	1.36	0.2							5	1.42	0.2	5	**1.29**	**0.15**				5	1.6	0.25	5	**1.37**	**0.22**				Analysis of 15 US hurricanes 1989-99 using CMAN (coastal), buoy and ASOS (airport) data.
Vickery and Skerlj (2004)										3	**1.39**	**0.08**							3	**1.59**	**0.14**							20 m/s
										3	**1.48**	**0.00**							3	**1.56**	**0.08**							35 to 40 m/s
Wilson (1979a)										2	*1.47*		2	**1.4**	**0.08**													TC Karen at NW Cape 1977
NRA Data	3	*1.31*	*0.09*	3	**1.25**	**0.09**																						NRA: Orson, Olivia, Vance, Frank, Jacob
	60	*1.17*	*0.05*	60	**1.11**	**0.05**																						Consistent with earlier Wanaea analyses

Appendix D The Modified ESDU Gust Factor Method

This method follows the ESDU (2002b) recommended procedure for estimating the appropriate peak factor g, which is here combined with an *a priori* estimate of the longitudinal turbulence intensity I_u in order to estimate the appropriate gust factor G for tropical cyclone conditions. This approach bypasses the normal ESDU *a priori* specification of roughness height z_0 and it should be noted that the I_u-associated z_0 values in Table 4.1 derive from Eqn 11.

Recalling the development of Section 2.4, the gust factor of interest is given by Eqn 14:

$$G_{\tau,T_o} = \frac{V_\tau}{V_{T_o}} = 1 + g_{\tau,T_o} I_u \qquad \text{(D.1)}$$

where:

τ	is the averaging period of the gust wind
T_o	is the averaging period of the reference mean wind
V_τ	is the gust wind speed
V_{T_o}	is the mean wind speed estimate
g_{τ,T_o}	is the peak factor
G_{τ,T_o}	is the gust factor
I_u	is the turbulence intensity

Following Wood (1983) and Greenway (1979), the Davenport (1964) method for obtaining the peak factor g is modified by estimating the spectrally-based zero-crossing rate v, relative to an *hourly* reference period $T_o^{'}$:

$$\upsilon(\tau, T_o^{'}) = \frac{[0.007 + 0.213(T_u/\tau)^{0.654}]}{T_u} \qquad \text{(D.2)}$$

where the integral time scale of the longitudinal turbulence T_u is approximated empirically as a function of the elevation z:

$$T_u = 3.13\, z^{0.2} \qquad \text{(D.3)}$$

In the present case z = 10 m is assumed throughout and the ratio of the standard deviations of the gust and the instantaneous wind are taken as:

$$\frac{\sigma_u(\tau, T_o^{'})}{\sigma_u} = 1 - 0.193\left[\frac{T_u}{\tau} + 0.1\right]^{-0.68} \qquad \text{(D.4)}$$

with $V_{\tau,T_o^{'}}$, the mean of the maximum values of the gust within an hourly reference period, obtained from:

$$\frac{V_{\tau,T_o'}}{\sigma_u(\tau,T_o')} = \sqrt{2\ln[T_o'\upsilon(\tau,T_o')]} + \frac{0.577}{\sqrt{2\ln[T_o'\upsilon(\tau,T_o')]}} \qquad \text{(D.5)}$$

The peak factor *g* is then given by:

$$g_{\tau,T_o'} = \frac{V_{\tau,T_o'}}{\sigma_u(\tau,T_o')} \frac{\sigma_u(\tau,T_o')}{\sigma_u} \qquad \text{(D.6)}$$

such that:

$$G_{\tau,T_o'} = 1 + g_{\tau,T_o'} I_u \qquad \text{(D.7)}$$

This is then adjusted by the ESDU function G_{T_o} to allow for a reference mean period T_o that is other than the *hourly* T_o' so that:

$$G_{T_o} = \frac{G_{\tau,T_o}}{G_{\tau,T_o'}} \qquad \text{(D.8)}$$

To suit the present purposes, the ESDU G_{T_o} function, provided graphically in their §Figure 2b, has been approximated by the following relationship:

$$G_{T_o} = 0.2193\ln[\log_{10}(T_o)] + 0.7242 \qquad \text{(D.9)}$$

which extends the ESDU values for T_o less than 5 min and is consistent with Brown and Swail (1991) data over that range. The final step is therefore:

$$G_{\tau,T_o} = G_{T_o} G_{\tau,T_o'} \qquad \text{(D.10)}$$

It is noted in closing that this formulation does not ensure that $G_{\tau,T_o} \geq 1$ for $\tau = T_o$, but is considered sufficiently close for the present purposes. The mismatch is largely due to the Wood (1983) approximation being a poor fit to ESDU §Figure 2a for $\tau > 300$ s.

Appendix E Converting Between Agency Estimates of Tropical Cyclone Peak Wind Speeds

As detailed in Appendix A, operational centres define the tropical cyclone intensity as the strongest "surface" wind, averaged over some specified period, occurring anywhere within the storm. The exposure for the definition, although not stated, is implicitly taken to be sea before landfall and flat open terrain afterwards, with an observation height of 10 m. Defining intensity as the strongest wind implies that the intensity is dependent on the gustiness, and in turn that the numerical value will depend on the averaging period, since longer averaging periods will filter out more of the turbulence and have a lower maximum wind. The problem is to convert tropical cyclone intensity estimates based on one wind averaging period to those based on another. For convenience, we take the two averaging periods to be the commonly-used 1 and 10 minutes, but the arguments herein are applicable to other periods also.

Consider first an idealised situation with an infinite area exposed to a turbulent wind field in which the true mean wind V is everywhere the same. Suppose that the intensity of this weather system in terms of the maximum 1-min mean wind speed is $Vmax_{60}$ and that we wish to convert this intensity estimate to a different averaging period, that is, estimate the maximum 10-min mean in the storm, $Vmax_{600}$. We estimate the true mean wind V from $Vmax_{60}$ as

$$V = Vmax_{60}/G_{60,infinity} \tag{E-1}$$

where the *infinite* reference time for the gust factor is taken because the domain is assumed infinite.

We may then similarly estimate the maximum 10-min gust as

$$Vmax_{600} = V\,G_{600,infinity} = (Vmax_{60}/G_{60,infinity})\,G_{600,infinity} \tag{E-2}$$

So the conversion in this case is to multiply by $G_{600,infinity}/G_{60,infinity}$. In practice, gust factors for infinite reference periods are unavailable, but in expectation that the gust factor will asymptote as the reference period increases, we pragmatically use the longest period considered here, 1 hour, for practical computations.

The top row of Table E-1 shows these values for various exposures, taken from Table 1.1. They should be compared to the ratio of the 10-min mean to the 1-min mean from Appendix A, referred to as the "traditional" approach in Table E-1. For storms with at-sea exposure, the recommended conversion factor is closer to 1 than the traditional value, implying that conversions from 1-min to 10-min standards have in the past tended to underestimate the 10-min intensity of storms by about 5% (assuming that the 1-min estimate is unbiased). Note also that the differences between columns are significant, demonstrating that the conversion factor has a strong dependence on exposure, a variation that does not seem to have been applied in practice.

Table E-1 Comparison of recommended and traditional conversion factor approaches.

	Conversion	At-Sea	Off-Sea	Off-Land	In-Land
Recommended Method	$G_{600,3600}/G_{60,3600}$	1.03/1.11= 0.93	1.05/1.17 =0.90	1.06/1.22 =0.87	1.08/1.28 =0.84
Comparison	$1/G_{60,600}$	0.95	0.90	0.86	0.83
Traditional	See text	0.88			

The origins of the traditional 0.88 (or its reciprocal, 1.13) are not entirely clear. Some users (e.g. Kamahori et al. 2006) cite Simiu and Scanlon (1978), and indeed the ratio $G_{600,3600}/G_{60,3600}$ as calculated from their §Eqn 2.3.30, does equal 0.88 provided that the roughness length z_0 is taken to be 0.02 m. The WMO (1993, §Section 1.3.3) value of 0.871 similarly follows from z_0 = 0.05 m provided that a nonlinear interpolation of the data in Simiu and Scanlon is made (Charles Neumann, personal communication 2008). The ratio 0.88 can also be obtained from Durst (1960, §Table VII with modifications noted by the text), which was subsequently used in Simiu and Scanlon's derivation. However, we note that both z_0 = 0.02 m, z_0 = 0.05 m and Durst's data are all characteristic of open terrain land, and that the roughness length over the ocean is significantly less[9]. Thus the long-standing use of this factor for tropical cyclone intensity conversion over the sea appears incorrect. Indeed, applying Simiu and Scanlon (1978, §Eqn 2.3.30) to a typical high-wind marine z_0 = 0.002 m (e.g. Powell et al. 2003, Donelan et al. 2004, French et al. 2007) yields 0.91, which is closer to the at-sea ratio recommended here. Hence, while we have placed the traditional 0.88 in the at-sea column of Table E-1 to reflect its extensive past usage, properly it belongs in the at-land column.

Some have apparently noted that the factor 0.88 = $G_{2,60}/G_{2,600}$ with these gust factor values taken from the ocean values in WMO (1993, §Table 4.2) or BoM (1978, §Table 7.3). Possibly this association has arisen from the close proximity of the latter table with a statement that the appropriate conversion of intensity for averaging period over the ocean is 0.88, although no clear citation of the source of 0.88 is given there. We regard such a connection as fundamentally incorrect, since it implies a conversion via the maximum 2-s gust, which does not necessarily occur within either the maximum 1-min or 10-min reference periods, and nor is the maximum gust in a 1-min period necessarily equal to the maximum gust in a 10-min period, as can be seen, for instance, in Figure 2.3. Further, this line of argument inherently involves a confusion of reference and averaging periods.

Unlike the idealised situation discussed above, real storms do not have infinite uniform wind fields. One implication of this fact is that the averaging period should not be too long, due to the requirements for stationarity (Section 2.5) and to not smooth out the important strong gradients near the eyewall. A second is that an infinite reference period for the gust factors becomes inappropriate. Searching for the maximum gust in space within a storm is akin to searching in time within an anemometer record, and in principal at least, one could define a reference time equivalent T_{eq} to a given reference area. For instance, we might define T_{eq} so that in each case we are searching over the same number of integral-scale's worth of air for the maximum wind, remembering that one search is linear and the other over an area. Having done so, it is straightforward to extend the above reasoning and conclude that $G_{600,Teq}/G_{60,Teq}$ is the appropriate intensity conversion factor. A complication is that the size and shape of the maximum wind belt varies between tropical cyclones – narrow versus broad, confined to one quadrant versus quasi-axisymmetric, and small RMW vs large. Thus the equivalent reference time T_{eq} is in principal situation-dependent. The maximum wind belt typically scales as 10's of km long and from a few to 10's of km wide. Noting that 10 km along-wind is equivalent to 200 s for a mean wind of 50 m/s, and that the cross-wind turbulence length scale is shorter than the long-wind one, we might reasonably expect that T_{eq} is typically of the order of an hour or more. If, in addition, the storm is in near steady state, then an intensity estimate should be valid for several hours, supporting an even longer T_{eq}. Noting that the gust factor asymptotes as the reference time increases, we therefore take T_{eq} = 3600 s for practical computations.

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[9] We also caution the reader that these authors frequently say "mean" when in fact they mean "gust".

The lower limit for T_{eq} is 600 s, since it is impossible to have a 10-min gust within a shorter reference period. This limit might be approached, but not reached, in a storm with a short and narrow maximum wind belt, and noting that $G_{600,600} = 1$, would justify the intensity conversions contained in the middle row of Table E-1. This case should probably also be restricted to very rapidly intensifying storms, where the intensity estimate is valid for only a short time. Comparing the recommended $G_{600,3600}/G_{60,3600}$ to the limit $1/G_{60,600}$, the differences between these rows of the table are not large, of the order of anemometer instrument error under good conditions, and much less than intensity estimate error from Dvorak (1984) or aircraft-to-surface wind reduction calculations. Hence there is no practical need to make this distinction and we advocate the use of $G_{600,3600}/G_{60,3600}$. The main weakness in this extension of the argument is that the true mean wind speed is not uniform over the maximum wind belt, so the maximum gust might not coincide with the maximum true mean wind. However this weakness is deemed to be immaterial in practice, because the conversion factor is not very sensitive to T_{eq}.

One could note that the marine surface roughness, and hence the gust factor, depends on the wind speed, implying that the intensity conversion factor should likewise vary. However, varying the roughness length from 0.0005 m (fitted here via I_u for “at sea”, and according to Eqn 11) to 0.003 m (the potential upper limit indicated by Powell et al. (2003) and others) changes $\mathrm{G}_{600,3600}/\mathrm{G}_{60,3600}$ from 0.928 to 0.913 according to the ESDU method. Such slight sensitivity of about 1.6% is negligible in the present context.

Thus we recommend that tropical cyclone intensity estimates in terms of the maximum 1-min mean wind are converted to a maximum 10-min mean wind equivalent by multiplying by $G_{600,3600}/G_{60,3600}$ which, over the ocean for the gust parameterisation herein, equals 0.93. We note that this conversion factor makes a smaller adjustment than has traditionally been used in the application of the Dvorak technique. This change is partly due to our use of an updated gust factor parameterisation from that of Simiu and Scanlon (1978), but more that the previous factor seems to have incorrectly applied open terrain, rather than marine, conditions. Our values thus imply a modest numerical increase of about 5% in the 10-min intensity estimate, relative to the equivalent 1-min value. We also emphasise that different conversion factors are necessary for different exposures, a point that seems overdue for reconsideration and implementation. It can be noted that in the extreme wind example of Section 3, that the ratio between the insitu directly measured $Vmax_{600}$ and the $Vmax_{60}$ for severe tropical cyclone *Orson* is 0.938, albeit at a higher elevation than 10 m.

In closing, we note that the above discussion is complex because of the long-standing practice of defining tropical cyclone maximum intensity in terms of a wind gust. A definition of storm intensity in terms of the mean wind speed would avoid such difficulties.