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 (4^{th} 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.

[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 $G_{\tau,To}$				
			Gust Duration τ *(s)*				
Class	Description		*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 (τ = 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