13A.5 AN UPDATED PARAMETRIC MODEL OF THE TROPICAL CYCLONE

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Bruce A. Harper[1*] and Greg J. Holland[2]

[1]Systems Engineering Australia Pty Ltd, Brisbane, Australia.
[2]BMRC, Melbourne, Australia.

1. INTRODUCTION

Parametric descriptions of the boundary layer winds in tropical cyclones have proven extremely valuable since they were initially proposed some 50 years ago. The relative simplicity of parametric methods enables a range of engineering and climatological studies that cannot be accomplished using the more sophisticated numerical models that have now evolved (e.g. Wang and Holland 1996; Kurihara et al. 1995). Typical of the applications for the simplified parametric models have been idealisation of structure and behaviour for forecasting, hindcasting, initialisation of numerical models, statistical modelling and public education. Parametric models also provide the spatial and temporal surface forcing for incorporation into a variety of "downstream" engineering design, numerical modelling and risk assessment studies such as: offshore facilities design; wind, wave, continental shelf current and storm surge design criteria; onshore infrastructure design (e.g. ports, public housing, wind sensitive structures); public evacuation and disaster planning (wind and storm surge) and insurance risk assessment.

2. THE NEED FOR AN UPDATED MODEL

While a range of parametric model developments have occurred, there remains no consensus as to the best representations which should be used. This has been complicated by the many features which it might be expected that a comprehensive parametric model should address and some concentration on specific rather than general requirements. The need for an updated parametric model to support these studies was emphasised by the WMO/CAS Fourth International Workshop on Tropical Cyclones (IWTC-IV) in April 1998 (WMO 1998). It was recommended that there would be considerable benefit from the development of a single, comprehensive, benchmark parametric wind and pressure field model of tropical cyclones. This model would provide: a common reference point for other methods; well-documented error and parameter sensitivity ranges; a framework for adding additional features; a systematic facility for storm parameter identification and classification; and a means of reducing potential confusion between various alternative modelling approaches. This paper reports on early progress towards such an outcome.

3. BASIC MODEL CHARACTERISTICS

The common approach in representing the fully-developed features of tropical cyclones over the open ocean is to start with the surface wind field derived from a steady axisymmetric vortex which is stationery in a fluid at rest. The analysis begins with a consideration of the force balance at the geostrophic, or gradient, wind level above the influence of the planetary boundary layer. The gradient wind speed is then reduced to the standard surface reference level over the ocean of +10m MSL (mean sea level) by consideration of boundary layer effects, including wind inflow towards the vortex centre, and asymmetric effects due to storm forward motion or surrounding synoptic pressure gradients. This permits description of the near-surface wind and pressure fields as a function of radial and azimuthal offsets from the centre of the storm. This basic approach provides an analytical representation of a fully-developed storm based solely on four essential time-varying parameters:

1. Storm central pressure; $p_0(t)$
2. Ambient or environmental pressure; $p_n(t)$
3. Radius to maximum winds; $R(t)$
4. Track or forward motion vector; $V_{fm}(t)$; $\theta_{fm}(t)$

Figure 1 illustrates the typical radial wind and pressure profile which results from such an analysis. While many "real" storms may not always exhibit such symmetry and form throughout their full life cycle, this basic model does appear to well represent the essential force balance and spatial

*Corresponding author address: Bruce A. Harper, Systems Engineering Australia Pty Ltd, 7 Mercury Court, Bridgeman Downs, QLD 4035, Australia; e-mail: seng@uq.net.au.

variability of the mature tropical cyclone over the open ocean.

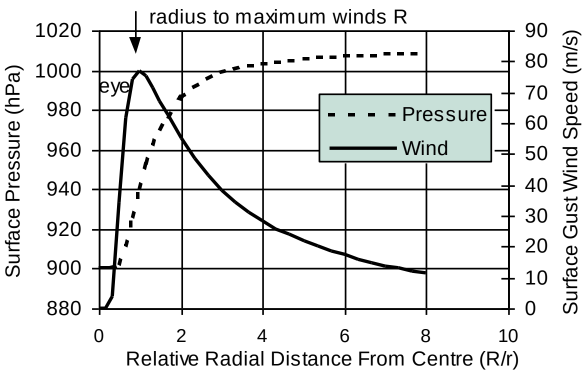

Fig 1 - A Typical Parametric Wind and Pressure Profile

Takahashi (1939) proposed some early empirical methods while perhaps the earliest attempt at describing the full wind field in a parametric manner dates to Depperman (1947) in a study of Philippine typhoons. This was the so-called Rankine-combined or modified potential vortex but practitioners have found it often produces a profile which generally under or over shoots measured winds. A number of specific studies were then undertaken by the US Weather Bureau on behalf of the US Army Corps of Engineers over the period 1954 through to the early 1960s which were aimed at producing objective techniques for estimating hurricane intensities. The pioneering study was by Schloemer (1954), who proposed an exponential pressure profile based on the general principle that:

$$(p-p_0) / (p_n-p_0) = f(r) \qquad (1)$$

His work was significant in being the first to specify a continuous radial wind profile in pressure balance and to recognise the significance of the environmental pressure, an R scale and the surface boundary layer effects. Many other researchers extended and developed Schloemer's work from that time (e.g. Graham and Nunn 1959; Jelesnianski 1965). During the 1970s a large number of model variants also appeared in response to the growing application of these models for engineering design needs.

Holland (1980) addressed the ability to fit wind profiles to a number of specific storms of record in the Australian region (*Tracy* and *Kerry*), especially in regard to matching the peak wind region critical for assessing impacts. To overcome deficiencies in the Schloemer profile he formalised the use of a "peakedness" parameter B, to provide increased dynamic range.

Such has been the variation in model types over the years that Lovell (1990) was able to identify 24 separate parametric wind field model descriptions which had been published up until the late 1980s. His conclusion was that almost all popular formulations were essentially minor variations on those first developed by the US Weather Bureau and the US Army Corps of Engineers in the 1950s, especially when the additional peakedness parameter of Holland (1980) is incorporated.

4. ESSENTIAL PARAMETERISATION

For the purpose of illustration the Holland (1980) model development is followed; the pressure p at any radius (r) from the centre being:

$$p(r) = p_0 + (p_n - p_0)\ exp\ (-R/r)^B \qquad (2)$$

where an additional fifth parameter B has been introduced - the so-called profile "peakedness" parameter, limited by physical arguments to within $1 < B < 2.5$. When B is set to the lower limit of 1, it becomes equivalent to the original Schloemer profile.

The gradient wind balance equation becomes:

$$V_g^2(r)/r + f\ V_g = 1/\rho_a\ dp(r)/dr \qquad (3)$$

where V_g = gradient wind
ρ_a = air density
f = Coriolis parameter ($2\omega \sin \phi$)

and the pressure gradient from differentiation of (2) substitutes into (3) to yield the gradient wind at any radius as:

$$V_g(r) = \sqrt{(p_n - p_0)\ B/\rho_a\ (R/r)^B\ exp\ (-R/r)^B + r^2 f^2/4} - rf/2 \qquad (4)$$

At r = R the maximum gradient wind speed, neglecting Coriolis terms, is given by:

$$V_{gmax} = \sqrt{(p_n - p_0)\ B\ e\ /\rho_a} \qquad (5)$$

where it can be seen that for the Holland model, the pressure differential is further modulated by $\sqrt{B}$ over the original Schloemer estimate for V_{gmax}, thus providing a further dynamic range up to a factor of 1.6. Holland also suggested "standard" B values might be inferred of the form:

$$B(t) = 2 - (p_0(t) - 900)/160 \quad (6)$$

making B a direct function of storm intensity.

A significant component missing from both the Holland and other wind profile formulations, is the variation of air density with pressure towards the cyclone centre. Introducing this variation changes the wind peakedness significantly and may lead to more easily defined values of B.

4.1. Boundary Layer Representations

Equation (4) provides a radially symmetric profile of estimated gradient level winds which must be transferred to the +10 m reference surface. The usual method for achieving this is based on similarity theory and the logarithmic deficit law resulting in the mean near-surface wind V_m, under assumed neutral stability conditions, being estimated by an equation of the form:

$$V_m = Km\, V_g \quad (7)$$

where $Km = ln(10/z_0)/ln(z_g/z_0)$ (8)

with z_g = gradient wind height V_g ($z=z_g$)

Over the open ocean the surface roughness is dynamically a function of wave growth with time, while over land it varies spatially according to the natural and built environment. Application of this theoretical approach is strictly limited to stationary wind conditions where the peak gust is related to a mean wind reference by a Gaussian distribution function. In this context V_m is to be considered as a 10 minute averaged wind sample. A basic limitation of this theory is that convective storm elements, especially within rainbands, are thought capable of allowing gradient winds to penetrate to the surface without the assumed vertical mixing processes occurring. Also, microburst and vortex breakdown components can simply add horizontal wind at the surface as localised transient features. These essentially convective elements are becoming recognised as at least partially responsible for relatively high gust factors often being reported in landfalling tropical cyclones (Holland and Black personal communication 1997). A variety of values for Km exist in the literature, the differences are complicated by the often unstated choice of averaging period for the surface wind. As an order of magnitude, Km can be considered as approximately 0.7 over the ocean which, when combined with a peak gust factor of order 1.4, typically delivers 2 to 3 sec gusts basically equivalent to the gradient speed. Microbursts and other transient features might further cause super-gradient winds to develop locally for short periods. The potentially arbitrary choice of Km and associated wind averaging periods is typically a major source of variation between "similar" parametric models and can have significant impact on predicted storm damage.

In addition to the scalar reduction in wind speed, surface friction and continuity demand that the wind must flow inward across the isobars. The angle of inflow is approximately 25° in the outer region, but reduces to zero near the radius of maximum winds.

4.2. Forward Motion Asymmetry

Tropical cyclone motion produces complex changes to the surface wind field, which are intrinsically related to the 3-dimensional structure of the storm, its forward motion speed, the underlying surface conditions, and the atmospheric environment within which the cyclone is embedded. Parametric models to date have sought to reproduce only the first-order effects of the observed forward motion on the surface windfield. This provides a left-right asymmetry, with the maximum winds to the right (left) when looking in the direction of motion of the cyclone in the Northern (Southern) Hemisphere. The actual location of the region of maximum surface winds in individual storms can occur almost anywhere.

This asymmetry is thus achieved by various models such that some proportion of the forward speed δ_{fm} (typically 0.5 or 1) is added along an assumed line of maximum winds θ_{max} (measured relative to the cyclone movement direction) and then azimuthally adjusted about the storm, e.g.

$$V_m(r,\theta) = Km\, V_g(r) + \delta_{fm}\, V_{fm} \cos(\theta_{max} - \theta) \quad (9)$$

This is perhaps the least satisfactory aspect of the current empirical approaches to modelling the cyclone surface wind field.

5. IDENTIFICATION OF DESIRABLE MODEL ELEMENTS

A comprehensive parametric wind field model of tropical cyclones should conceivably address a wide range of application-specific features. These needs vary considerably from the open marine environment to coastal, landfall and post-landfall conditions. The following items, *inter alia*, are planned to be addressed in the formulation of a comprehensive parametric wind field model of tropical cyclones which can be universally applied:

(a) Open Ocean Conditions
* axisymmetric wind and pressure fields
* frictional inflow at the surface
* peak wind versus central pressure
* size versus intensity
* forward speed asymmetry
* boundary layer, mean and gust profiles
* ocean surface responses
* concentric eye formation, outer core structures
* evolution (initiation, maturity, decay)
* synoptic scale interactions
* extra-tropical transformation
* SST and mixed layer influences on MPI

(b) Landfall
* surface roughness changes
* wind field asymmetry changes
* topographic influences, global and local
* thermodynamic changes
* boundary layer, mean and gust profiles
* high-speed transients (e.g. mesoscale vortices, tornadoes)

(c) Post-Landfall
* decay mechanisms
* potential reintensification mechanisms

Efforts also must be directed towards definition of parameter dynamic ranges and statistical measures applicable to specific ocean basins. These will gradually emerge from the systematic application of a standardised parametric model to "best track" estimates by regional forecasting centres, greatly extending the present often minimalist parameter set of track and central pressure alone.

6. CONCLUSIONS

There now exist many opportunities to gather together a more comprehensive parameterised description of tropical cyclones than has been attempted to date. For example, much more data are now available and numerical models have the degree of resolution and sophisticated physics to be used in parametric developments. In addition to improved structure definition, an updated parametric model will need to include capabilities which could represent transient surface wind features and life-cycle storm structural changes. A multi-faceted model which addresses aspects of near-surface wind and pressure profiles both before, during and after landfall is now feasible and could be used to form a new standardised reference. This paper has reported on early progress towards such an outcome.

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