DOI: http://dx.doi.org/10.12989/was.2000.3.2.133

A review of tropical cyclone wind field models

J.A.B. Wills† and B.E. Lee‡

Department of Civil Engineering, University of Portsmouth, Portsmouth PO1 3QL, U.K.

T.A. Wyatt†‡

Department of Civil Engineering, Imperial College of Science and Technology, U.K.

Abstract. Engineered structures such as buildings and bridges in certain regions of the world need to be designed to withstand tropical cyclone winds, otherwise known as typhoons or hurricanes. In order to carry out this design, it is necessary to be able to estimate the maximum wind speeds likely to be encountered by the structure over its expected lifetime, say 100 years. Estimation of the maximum wind involves not only the overall strength of the tropical cyclone, but the variation of wind speed with radius from the centre, circumferential position, and with height above the ground surface. In addition, not only the mean wind speed, but also the gust factor must usually be estimated as well. This paper investigates a number of recent mathematical models of tropical cyclone structure and comments on their suitability for these purposes in a variety of scenarios.

Key words: tropical cyclone; wind structure; mathematical model.

1. Introduction

Typhoons, hurricanes and tropical cyclones are the names given in different parts of the world to the same phenomenon, an enormous wind vortex powered by the heat of the sun, and of potentially great destructive force over a large area. Although superficially similar to the Atlantic depressions that form a large part of European winter weather, tropical cyclones have an additional driving element that gives them their great destructive power in the regions where they form. They share with the temperate cyclone the effect of the earth's rotation, the so-called Coriolis force, that provides the vertically orientated vorticity of the large vortex. The additional element in the case of the tropical cyclone comes from the release of the latent heat of the moist air picked up at the tropical sea surface, and it is this that can result in a minor tropical storm developing into a full-scale tropical cyclone with a diameter of 1000 km, maximum wind speeds that can reach 60 m/s or more, and accompanied by torrential rain.

Fig. 1 shows a schematic vertical section through such a tropical cyclone, exaggerated in vertical scale by a factor of 10 for clarity. As in the familiar bathtub vortex, winds near the sea surface

† Research Fellow
‡ Head of Department and Balfour Beatty Professor
†‡ Professor

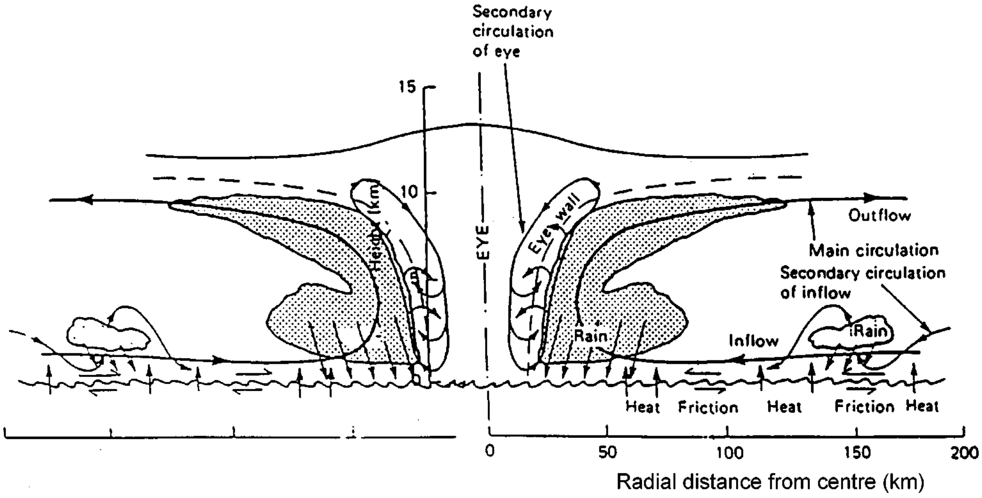

Fig. 1 Section through a typhoon

spiral in towards the centre, picking up moisture from the warm surface. The warm saturated air rises as it nears the eye-wall, the region of maximum wind speeds, cooling as it expands in the lower hydrostatic pressure. Water begins to condense out at the lower temperature, releasing its latent heat to the air and thus raising its temperature above the adiabatic value for that height, and this release of latent heat continues until a height is reached where all the water has condensed, typically 10-15 km. The whole inner region becomes a hot chimney driven by the release of latent heat, drawing in warm saturated air at the surface and rejecting dry air at altitude. Emanuel, among others (Emanuel 1991, Lighthill 1996), has likened the process to the Carnot cycle, the heat engine of the tropical cyclone being powered by the gain of entropy at sea surface temperature, and rejection at upper air temperature before the cycle recommences. The condensed water falls as heavy rain in concentrated areas, and flooding due to a combination of rain and storm surge caused by the very low atmospheric pressure in the centre of the tropical cyclone often causes more damage than the wind itself.

Many workers have developed mathematical models of tropical cyclone wind structure in the last thirty years. Some were developed in order to model the atmospheric physics of the phenomenon, others with the more engineering interest of predicting actual wind speeds near ground level. Of the latter, there are normally three types of application. The first type is used after a tropical cyclone has passed over an area. It provides a framework to incorporate data obtained at different locations and at different levels, such as wind-speed data from airports, offshore buoys and reconnaissance aircraft, into a model that can be used to estimate conditions at sites where no actual measurements have been made. The second type of application is used to provide short-term forecasts of wind conditions when a tropical cyclone is approaching a coast. When reconnaissance aircraft data are available, the model is established in a similar way to the first method, except that very little, if any, surface data may be available. When no aircraft data are available, the intensity and radius of maximum winds must be estimated from satellite images, a rather dubious process, but the model may be able to give a reasonable distribution of wind conditions, bearing in mind the limitations of the basic input data. The third type of application is used to simulate a wind climate from the statistics of tracks, forward speeds and intensities (usually expressed in terms of central pressure).

Our aim was not to try to develop a more accurate or reliable model, rather to study existing models in order to assess which were the most appropriate to use for the purpose of wind-sensitive design of engineering structures, primarily in the developing nations of the Pacific Rim. From a study of the available literature, it is obvious that the wind speed at any fixed point within the wind field depends on many factors. The two most important are the overall strength of the tropical cyclone and the distance of the point in question from the centre of rotation. The overall strength is usually represented by the reduction in ground-level atmospheric pressure measured at the centre compared with the pressure far away from the tropical cyclone's effects; this is called the central depression ΔP. Many other factors affect the wind speed at a point; height of the point above the surface is one that is obviously important where effects on buildings is concerned. Another is the overall translation speed of the tropical cyclone relative to the surface and, related to this, the azimuthal position of the point relative to the overall direction of motion. So the wind speed at a point may depend on all three length dimensions relative to the centre of rotation, as well as on the strength of the tropical cyclone and its translation speed, neglecting less easily parampterized factors that contribute to the wind field such as the environmental shear and convection. With five main factors to consider, it is important to be able to decide which are the most significant, in order to have a model available that can easily predict the expected wind speeds to sufficient accuracy without requiring an excessive amount of calculation time and effort, especially if estimates are required to assess the likely effects of an approaching tropical cyclone in real time.

A further complication arises when the cyclone that has developed over the warm ocean makes landfall and travels inland. Two major further factors then come into account, firstly the increase in surface roughness has an effect on the vertical profile of wind and hence on surface winds, secondly the loss of the power source of the cyclone, the warm ocean. The overall strength starts to decline and the storm eventually decays. It is in these areas that significant differences in the models exist, with consequent errors. For example, the typical inland gust factor of 1.6 is often applied at the coastline, whilst the tropical cyclone model takes many kilometers to adjust the mean wind speed to a typical inland site value, leading to unreasonably high gust-speeds near the coast.

2. Description of basic models

The mathematical models we have studied have been selected from a considerable body of work carried out over many years by many workers. Our main criteria for consideration have been that the work be recent (within roughly the last 30 years), and that they allow the estimation of at least the mean wind speed near ground level anywhere within the circle of influence of the tropical cyclone. These models generally follow a consistent pattern. They mostly contain the following elements:

1. An expression for the radial distribution of circumferential velocity as a function of the central depression, usually at the gradient height, i.e., at the height above which the velocity is assumed to be invariant with height. The velocity is usually taken to be the mean velocity over 10 minutes or 1 hour.
2. An expression for the vertical profile of the circumferential velocity, usually as a function of surface roughness, and sometimes also of radial position.
3. An expression for the gust factor or turbulence intensity as a function of radius and/or height, allowing peak velocities to be estimated.
4. An allowance for circumferential variation of velocity, based on the fact that tropical cyclones move as a whole relative to the earth's surface, by a complex interaction of winds at different

levels and influence distances. Some models also allow for the fact that surface drag varies circumferentially because of the combined effects of rotation and translation, and this is included in the circumferential force balance used to calculate the velocity field.

The starting point for all models is the radial force balance equation equating the radial pressure gradient to the centripetal and Coriolis forces. This can be written:

$$\partial P_r / \partial dr = \rho \, (V^2 / r + 2V\Omega \sin \psi) \tag{1}$$

where P_r = pressure in the fluid
r = radius from the centre of the tropical cyclone
ρ = density of the fluid
V = circumferential speed of fluid at radius r
Ω = rotation speed of the earth (rad/sec)
ψ = latitude

This equation allows the circumferential speed V to be calculated at any radius if we know the radial pressure distribution $P_r(r)$. The next step is usually to assume an empirical form for $P_r(r)$ based on observations made in actual tropical cyclones. Assuming $P_r(r)$ to be differentiable, we can then calculate V directly for any radius at any given latitude. Perhaps the simplest form used for P_r is that of Gomes and Vickery (1976),

$$(P_r - P_0)/(P_n - P_0) = \exp\,(-R_m / r) \tag{2}$$

where P_0 = pressure at centre of tropical cyclone
P_n = asymptotic pressure at large r
R_m = radius at which maximum wind speed occurs

A subsidiary expression is needed to determine R_m. It is often assumed that R_m is related to $(P_n - P_0)$, although observation shows that there is a considerable degree of variability in any such relation.

The second feature of the basic model is the assumptions made to relate these wind speeds calculated at gradient height to that at lower levels, where the definition of gradient height is given within the model description. Eq. (1) contains no term representing surface friction, and so applies only in the region where there is no vertical shear, i.e., above gradient height. Surface friction must reduce wind speeds at lower levels to some degree, and a model suited to wind engineering purposes must address the question of vertical shear at the lower levels. In the Gomes and Vickery model, this is done in two stages. The first assumes a fixed factor c_0 that converts the gradient wind V_{gx} to that at 10m height, V_{10}. A second factor, c_1, then converts the 10 m wind to that at any desired height using a factor that may depend on the surface terrain roughness. Other models may allow for additional variation, say with distance from the tropical cyclone centre, but all use a model based on observation of actual tropical cyclone records.

The third feature is an assumption about the gust factor, a means of converting the mean velocity to a short-period peak value that represents the true destructive power of the wind. Again, this may be a function only of surface roughness, or it may also take account of additional gustiness of the tropical cyclone flow structure associated with thermal instability and other effects. As with the radius of maximum wind speed, the gust factor is variable, and the model may allow for a random variation with some probability distribution, such as normal or Fisher-Tippett type 1 in calculating a population of tropical cyclones.

The last feature allows for circumferential asymmetry in the flow. The simplest assumption is that the tropical cyclone is simply convected with the local undisturbed wind speed, which adds to the effective wind speed on one flank and decreases it on the other. As there is no fixed relationship between tropical cyclone strength and local wind speed, assumptions must be made based on observations or statistical models. More typically, a tropical cyclone moves as a whole at some velocity not entirely determined by the local surface wind, usually obtained experimentally by satellite observations or from weather radar. The velocity to be added to the stationary tropical cyclone velocity is not always assumed to be just the translation velocity, however. Gomes and Vickery effectively assume 0.5 U_{tr}.

Other tropical cyclone models use more complex methods to calculate the circumferential variations in moving tropical cyclones. This often involves numerical solutions of simplified Navier-Stokes equations on a polar grid. Examples are given in section 3.

3. Variants on basic model

As noted above, the simplest version of the basic engineering model is probably that of Gomes and Vickery (1976). The elements of this are:

1. The simplest exponential expression for radial distribution of pressure,
2. Observationally determined radius of maximum wind speed,
3. Simple log-law representation of boundary layer,
4. Vector addition of a uniform translation velocity.

The sole purpose of such models is the estimation of wind speeds at lower levels for engineering purposes such as wind loading of buildings and other engineering structures. As such, they generally need a number of empirical parameters based on actual observations in order to predict the wind speeds. They do not in any sense attempt to model the complete wind structure of tropical cyclones, a much more complex problem of atmospheric physics.

A second recent model using modern tropical cyclone and hurricane records to set values of its parameters is that of Holland (1980). His basic assumption is that the radial pressure distribution can be expressed as:

$$(P_r - P_0) / (P_n - P_0) = \exp(-A / r^B) \qquad (3)$$

where A and B are empirically determined constants for a given tropical cyclone. With $B = 1$, this model would be identical to Gomes and Vickery, with A equal to their R_m. However, Holland shows that the optimum value of B in the three hurricanes he analysed lay in the range 1.05–1.5, also mentioning the fact that others have placed B in the range 1.5–2.5. Clearly, with B close to 1 the value of A is roughly equal to R_m, but in general $R_m = A^{1/B}$. For Holland's three hurricanes, there is no obvious consistency between the values of B and A or R_m.

Holland appears to consider only the gradient wind in his discussion; some of his wind speed data appear to be surface measurements, others derive from flight measurements at 540 m height. It is difficult to decide if vertical wind profile has been allowed for. In addition, there is no mention of any allowance for translation of the wind field. The estimated wind speeds are a function only of the distance from the centre of the tropical cyclone.

The latest models to be published use numerical methods to calculate wind speeds from the momentum equations using an assumed gradient pressure field. Shapiro (1983) begins by pointing out that observed wind speeds in hurricanes are not circumferentially symmetric even in a frame of reference moving at the hurricane translation speed. He attributes this to the circumferential variation of surface drag associated with the translation of the vortex over the surface, following the method adopted by Chow (1971) in her MS thesis. Shapiro's model assumes a slab boundary layer 1 Km thick with an imposed and circumferentially symmetric pressure field above and a drag force at the lower boundary determined by a drag coefficient given by Deacon's formula

$$C_D = (1.1 + 0.04\,|\boldsymbol{u} + \boldsymbol{U_{tr}}|) \times 10^{-3} \tag{4}$$

where $\boldsymbol{U_{tr}}$ is now the translation velocity vector. Since $\boldsymbol{u}$ varies over the field of the hurricane, while $\boldsymbol{U_{tr}}$ remains constant, the drag force is constant neither radially nor circumferentially. The pressure field is assumed to be such that in gradient balance it would correspond to a solid-body rotation near the centre, merging through a cubic spline to an outer layer where velocity varies as $r^{-0.6}$.

The momentum equations for the 1 km slab can be solved numerically over a radial grid of variable spacing for the case of a stationary hurricane, since in that special case the drag force is constant around a circumference. Shapiro computes a time-dependent solution and allows it to evolve to a steady state. In the more general case with translation, the equations must be solved over a two-dimensional grid, and in Chow's original work this was carried out on a Cartesian grid. Shapiro's simplified method uses a radial/circumferential grid, but replaces the full circumferential variation by a Fourier decomposition where only the zero'th, first and second harmonics are retained. Thus instead of solving two momentum equations over a full two-dimensional grid, the problem is reduced to that of solving six modified momentum equations on a one-dimensional, radial grid. The solutions for particular values of $U_{\max}$, R_m and $\boldsymbol{c}$ show circumferential variations in surface velocity that appear to correlate well with observations.

Georgiou (1985) uses Shapiro's model to calculate the wind field at 500 m height, starting with an assumed pressure field at the 700 mb level. He works in fixed co-ordinates, so that his windfield includes the effects of translation and is thus asymmetric azimuthally. He then solves the Shapiro model in this upper slab layer between the 500 m level and the 700 mb level (equivalent to a height of approximately 2.5 km). As he points out, the Shapiro model assumes a slab boundary layer of constant depth, making it difficult to equate real winds to the calculated model values. His solution is to observe that in practice winds at the eyewall are almost constant over the 500 m to 700 mb layer. He then equates the gradient balance wind for a given case to the azimuthally averaged wind at the radius of maximum wind for the Shapiro model result, thus making the necessary connection between the central pressure and the winds anywhere in the Shapiro model wind field, i.e., a wind field independent of height within the 500 m to 700 mb layer, but dependent on radius and azimuth.

This windfield displays inflow velocities typical of observed values at ground level, and Georgiou assumes that the calculated inflow angles apply at ground level, decreasing linearly to 1/3 of that value at 500 m, based on experimental observations.

The calculated winds at 500m from this model are converted to values at 10 m using an empirical factor ϕ_ω which is a function of r/R_m only, varying from 1 at $r/R_m = 0$ to 0.825 over the range $0.5<r/R_m<2.0$, and then 0.75 over the range $r/R_m>5.0$, again based on observational evidence. To then obtain wind speeds at other heights within the 0-500m layer, Georgiou uses an empirical logarithmic expression

$$V(z) = V_{10} + (V_{500} - V_{10}).\ \ln[az^2 + bz + c] \tag{5}$$

where the constants a, b and c are chosen to make $V(z)$ equal to the mean of V_{500} and V_{10} at a height of 150 m, again based on observed values. It has been pointed out to us that the Georgiou model includes some compensating errors that make it unsuitable for the prediction of gradient wind near the eye-wall, but nevertheless gives good results at ground level at all locations.

To use Georgiou's model, it is necessary first to run Shapiro's slab model to obtain the wind field at 500m, and then to calculate the winds at lower heights using Georgiou's additions to that model. Georgiou points out that one of the major uses of such models is as the basis of a Monte Carlo simulation of a large number of tropical cyclones from which population a tropical cyclone climate can be estimated for a given location, and that this may require the calculation of thousands of storms. Since each storm required 280 seconds of CPU time on a supercomputer in 1983, some method to reduce drastically the amount of computation was needed for such a Monte Carlo simulation. Georgiou uses dimensional analysis to show that the wind field of the Shapiro model depends on only four dimensionless groups representing the effects of central depression, translation velocity, turbulent eddy viscosity K and surface drag coefficient C_D. He then points out that the windfield is relatively insensitive to variations of K and C_D, leaving only the variation with central depression and translation velocity. This is tantamount to assuming that both surface roughness and turbulence structure are independent of tropical cyclone intensity.

To overcome the large computational effort involved in a Monte Carlo simulation, Georgiou then calculates a few Shapiro model solutions for different central depression and translation velocity, and interpolates between them for individual storms.

In the most recent model, Vickery and Twisdale (1995) use the Shapiro truncated spectral model to represent the azimuthal variation in wind field, rather than the full non-linear version used by Georgiou, in order to reduce the computational burden. Only slight variations distinguish the Vickery and Twisdale method from the Shapiro model; one of the main differences lies in a modification to the values of C_D used. Shapiro based his drag force values on V_{500}, whereas in the original studies C_D was based on V_{10}. Vickery and Twisdale allow for this apparent discrepancy in Shapiro's calculations by reducing Deacon's values of C_D by 50% to reflect the ratio of V_{10} to V_{500}. A second difference from Shapiro is to use the Georgiou ϕ_ω factor, a function of r/R_m, to convert from V_{500} to V_{10}. An implicit assumption is then that a conventional neutral boundary layer logarithmic profile can be used to calculate wind speed at any other height within the boundary layer. One further small difference is in the value of exponent used in the representation of the gradient wind field in the outer region. Shapiro used a value of 0.6, i.e., $V/V_{\max} = (r/R_m)^{-0.6}$ (although Vickery and Twisdale quote Shapiro as using 0.62); Vickery and Twisdale, however, used several different values and compared results with 25 records from a number of Atlantic hurricanes. A value of the exponent of 0.5 was found to give the most consistent result overall.

By using the Shapiro truncated spectral representation, Vickery and Twisdale were able to obtain solutions for nearly 1000 storms without excessive computation time for use in Monte Carlo simulations. In addition, they were able to produce predicted surface wind speed and direction data for six well-documented storms that fitted well to the recorded time histories.

4. Choice of model

In choosing a tropical cyclone model, the main consideration is that the predictions it makes should be of sufficiently high accuracy for the purpose required**.** At the same time the complexity of the model should be no greater than necessary for that purpose, in order to avoid unnecessary computing effort or choice of arbitrary parameters, for example. Our requirements in this project are for a model that allows the estimation of mean and gust wind speed over heights within the atmospheric layer between ground level and perhaps 300m, the height of the tallest structures we are likely to encounter. The accuracy required is no more than perhaps ±10% on wind speed, since we may expect that many other quantities in the problem will not be known to better accuracy than this. Although we need to know the maximum wind speed that may be reached, we may not actually need to know the detailed time history leading up to, or following, that maximum.

The first feature to be decided is the radial distribution of circumferential velocity at gradient height. The most recent (and probably most accurate) studies of Vickery and Twisdale suggest that V varies as $r^{-0.5}$ in the region outside R_m in a wide range of hurricanes measured near the U.S. coast. Although such a simple relationship is unlikely to be either exact or universal in all situations, it is sufficiently accurate in the energetic region where velocities are high enough to cause damage. In the region inside R_m, Vickery and Twisdale suggest a linear radial profile of velocity and a cubic spline transition between inner and outer regions over the range $R_m \pm 15$ km. The gradient circumferential velocity V is related to the central pressure P_0 through the gradient-level balance Eq. (1) $\partial P_r / \partial dr = \rho (V^2 / r + 2V\Omega \sin \psi)$, which can in principle be integrated numerically for any given latitude and $V_{\max}$ to yield the corresponding value of $(P_n - P_0)$. Because of the non-linearity of Eq. (1), $(P_n - P_0)$ must be calculated for each $V_{\max}$ and latitude, which may perhaps be put into nomograph form to allow $(P_n - P_0)$ to be read off.

The situation is somewhat complicated by the fact that the radius of maximum wind, R_m, appears not to correlate strongly with $V_{\max}$ or any other parameter of the problem, and indeed R_m is often observed to vary widely during the development and decay of a particular tropical cyclone. Luckily, values of R_m can usually be accurately estimated from satellite images, but if the inner and outer regions are separated by a transition region which is a fixed 30km wide rather than one proportional to R_m, then the nomogram to estimate $(P_n - P_0)$ becomes even more complicated.

With the gradient height wind field determined, the more complex models exemplified by Chow, Shapiro and recently Vickery and Twisdale then require numerical solution of their model equations of motion over their horizontal grid to yield the appropriate mean velocity components which represent the values averaged over the lowest layer of the atmosphere, 1 km in the case of all these authors. To use these models to predict the wind field of a developing, translating tropical cyclone, it would be necessary to run the model for the observed values of $(P_n - P_0)$, R_m, translation velocity U_{tr} and latitude every time the parameters changed significantly during the development of the tropical cyclone. Vickery and Twisdale have pre-calculated a large number of storms for a wide range of the parameters, so one technique to avoid tedious continuous computation might be to store the results (910 coefficients from each storm in their case) for a large number of storms beforehand, and select the nearest to the observed parameter values, or interpolate between the nearest parameters.

Although the simpler models that ignore the effects of the variable circumferential surface conditions under a translating tropical cyclone are clearly incomplete and unable, for instance, to calculate inflow angles at the surface, they may be sufficiently accurate for our simple estimates of maximum wind speeds as long as empirical corrections are made for the effects of tropical cyclone translation. Because the tropical cyclone wind velocities at the lowest levels are much lower than those at gradient height, it is likely that the additional velocity due to translation will be lower at the lowest levels. In the simplest model of Gomes and Vickery, an additional velocity at low level equal to 0.5 of the true translation velocity was added vectorially to the tropical cyclone vortex velocity. Although this assumption unrealistically implies maximum wind speeds along a line at right angles to the direction of translation, nevertheless the maximum speeds are unlikely to be seriously in error. It is unusual for the translation velocity to be higher than 10 m/s, so Gomes and Vickery would predict a maximum addition of 5m/s to the stationary tropical cyclone winds. The error on this value is unlikely to exceed ±50%, so the maximum likely error in wind speed is 2.5 m/s, small compared with the likely error in basic wind speed for a tropical cyclone strong enough to cause serious damage. Thus the simple Gomes and Vickery assumption, although incorrect in its placing of the maximum velocities experienced, is unlikely to predict their values inaccurately.

To predict the wind speeds experienced at different heights of a building structure, it is then necessary to estimate the vertical profile of mean wind speed. The main problem is that the models available cannot cope with the complex fluid mechanics of a real tropical cyclone. A common view is that the surface layer of a tropical cyclone is no different from a normal atmospheric boundary layer driven by the flow at gradient level, on the grounds that the tropical cyclone is rather like a thin disc with a predominantly two-dimensional flow below it. In this view, the boundary layer profile can be calculated by the usual log law, either neutral or including the effects of stability via the Monin-Obukhov stability function. Attempts have been made, especially by Georgiou, to compare these predictions with actual measurements made on meteorological towers. The difficulty is that observations can be made over only a very short time, and the variability of flow in a tropical cyclone is certainly even greater than that in normal atmospheric flows. The inevitable result is that comparisons can only be indicative of agreement with the models, rather than convincing proof. However, more convincing evidence that the tropical cyclone boundary layer is similar to that in temperate winds comes from the recent work of Sparks and Huang (1999).

The evidence from tower observations indicates that a log-law profile exists from the surface up to about 1km, and this is the boundary layer thickness assumed by Shapiro and by Vickery and Twisdale. The boundary layer wind speeds calculated by these models are taken to represent the vertically-averaged speed over the layer, which again is generally taken to be close to the actual value existing at 500 m height for a wide range of surface roughness values z_o. On this view, calculation of the wind speed at the lower levels relevant to buildings and other engineering structures can be achieved simply by use of the usual log law, perhaps modified by Monin-Obukhov stability considerations.

The remaining issue to be decided in calculating the effects of tropical cyclones on structures is that of gust speeds associated with tropical cyclone winds. Despite the fact that experience of tropical cyclone damage patterns indicate that damage is a complex dynamic process with contributions by the structure of the turbulence, wind duration and changes in wind direction of equal importance to that of the peak wind gust, in most wind loading codes buildings and other structures are judged to be damaged by the highest wind speeds averaged over short periods, typically 3 seconds in the case of cladding, rather than by the longer term mean speeds predicted by the tropical cyclone models. The models often ignore altogether the short-term variation of wind speed and concern themselves only with a quasi-steady mean value at each point. Both Gomes and Vickery, and Vickery and Twisdale, do take account of the vulnerability of engineering structures to short-period gusts in their work. Their conclusions are similar, based on the available experimental evidence, namely that gust factors under tropical cyclones are very similar to values found in temperate winds, typically reaching a value of 1.6 for a 3-second gust for a 10-minute mean.

In these last two sections, we have selected five recent tropical cyclone wind speed models and analysed their structure in some detail. Some are simple to apply but may not cover all aspects important to the behaviour of buildings in strong winds; others cover all these aspects but require the use of software that is not freely available to all. It is thus not possible to say which model should be used in a particular case, but the main features are listed below, with an indication of the computational effort required in their application. In this context, a full two-dimensional (2-D) model implies that account is taken of azimuthal variation of wind speed, not just radial variation.

Chow (1971)
· Full 2-D numerical model - heavy computational requirements
· Circumferential wind speed modelled realistically
· No information given on vertical profile of wind or gust behaviour
· Not suited to routine calculation

Gomes and Vickery (1976)
· Simple calculation of mean wind distribution
· Over-simplified assumption for circumferential variation of wind speed
· Over-simplified vertical profile model
· Simple gust behaviour assumed
· Suited to routine calculation

Shapiro (1983)
· Simplified 2-D model, but still significant computational effort required
· Circumferential wind speed modelled realistically
· No information given on vertical profile of wind or gust behaviour
· Not suited to routine calculation

Georgiou (1985)
· Full 2-D numerical model - heavy computational requirements
· Circumferential wind modelled realistically
· Useful findings on vertical profile of wind, but no information on gust behaviour
· Not suited to routine calculation

Vickery and Twisdale (1995)
· Simplified 2-D model, but pre-calculated for several thousand cases
· Circumferential wind modelled realistically
· Realistic vertical profile of wind and gust behaviour
· Routine use possible if access were available to the calculated database

References

Emanuel, K.A. (1991), "The theory of hurricanes", *Ann. Rev. Fluid Mech.*, **23**, 179-196.

Lighthill, M.J. (1996), "Typhoons, hurricanes and fluid mechanics", *IUTAM Conference,* Kyoto, August 1996.

Gomes, L. and Vickery, B.J. (1976) "On the prediction of tropical cyclone gust speeds along the Northern Australian coast", *Inst. Eng. Aust. C.E. Trans*. CE18, **2**, 40-49.

Holland, G.J. (1980), "An analytical model of the wind and pressure profiles in hurricanes", *Mon. Weather Rev.,* **108**, 1212-1218.

Shapiro, L.J. (1983), "The asymmetric boundary layer flow under a translating hurricane", *J. Atmos. Sci*., **40**, 1984-1998.

Chow, S. (1971), "A study of the wind field in the planetary boundary layer of a moving tropical cyclone", MS Thesis, Dept. Meteor. Oceanogr., New York University [NOAA/NHRL Library, 1320 South Dixie Highway, Coral Gables, FL 33146, USA].

Georgiou, P.N. (1985), "Design wind speeds in tropical cyclone-prone regions", Ph.D. Thesis, University of Western Ontario, London, Ontario, *Canada*. BLWT-2-1985.

Vickery, P.J. and Twisdale, L.A. (1995), "Wind-field and filling models for hurricane wind-speed predictions", *ASCE, J. Struct.Engng*, **121**(11), 1700-1709.

Sparks P. and Huang Z. (1999), "Wind speed characteristics in tropical cyclones", *Proc. 10th I.C.W.E., Copenhagen, June.*

(*Communicated by Ahsan Kareem*)