

Cyclone Database Manager

A tool for converting point data from cyclone observations into tracks and wind speed profiles in a GIS



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Abstract

A comprehensive investigation was carried out to identify the regions affected by different cyclone events. The observations of historical cyclone events are sparse globally, which forced this investigation to estimate the radial wind speed profile by using a parametric model. The selected model was created by G.J. Holland 1980 (Bureau of Meteorology, Australia) and is considered to be generally superior to other similar models by a wide range of tropical cyclone specialists. This model was programmed for calculating winds speed regions around cyclone tracks for different wind speed strengths. Another essential part of the program is to structure the wide range of gathered data sets from different sources. This program can be an important tool for building a unified global cyclone database, including first level basic meteorological information (the geographical position and date of the cyclone observation, the measured wind speed and the central pressure) and geospatial data (the cyclone tracks, and their radial wind speed profiles). This global cyclone database renders possible post-analysis of historical cyclone events.

Keywords: cyclone, geospatial data, parametric model, wind speed, wind speed profile, wind speed buffer.

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Introduction

Background

This work started as a study of the possibilities to identify the regions affected by different cyclone events, "windspeed buffers". This investigation was carried out, by GRID-Geneva, in order to extract the number of persons affected by unique cyclone events globally. Since this post-cyclone analysis by GRID-Geneva was carried out on a global scale the wind speed buffer estimations had to be adequate to the severe cyclone events worldwide.

Aim

The aim of this study is to build a tool for unifying the severe historic global cyclone data and to identify the regions affected by the different cyclone events.

The main purpose of this tool is to facilitate the composition of a global cyclone data base, including first level basic meteorological information (the geographical position and date of the cyclone observation, the measured wind speed and the central pressure) and geospatial data (the cyclone tracks, and their wind buffers).

Method

In order to fulfil the main aim of this research it was important to identify and verify existing projects. This research didn't allow us to identify any relevant study for our purposes, that is to say any earlier work that is possible to apply on a global scale at a low cost. Another important detail was that our research comprised historical cyclone events, as the purpose of our work was to establish a tool for facilitating the creation of a cyclone database for post-cyclone analysis. This implies limited data accessibility, since the observations already are carried out and the quantity and quality of the data variables are therefore difficult to ameliorate. The sparse observations of historic cyclone events forced us therefore to estimate the radial wind speed profile, wind speed buffer, by using a parametric model.

By a fruitful collaboration with Nanette Lomarda, Scientific Officer at World Meteorological Organisation (WMO) we were able to get in contact with a wide range of tropical cyclone specialists, who all referred to the same parametric model. A model created by Greg Holland at Bureau of Meteorology Australia (Holland, 1980), for calculating the wind and pressure profiles of a cyclone, in order to define its wind speed buffer. For a more detailed description of the data process see appendix A.

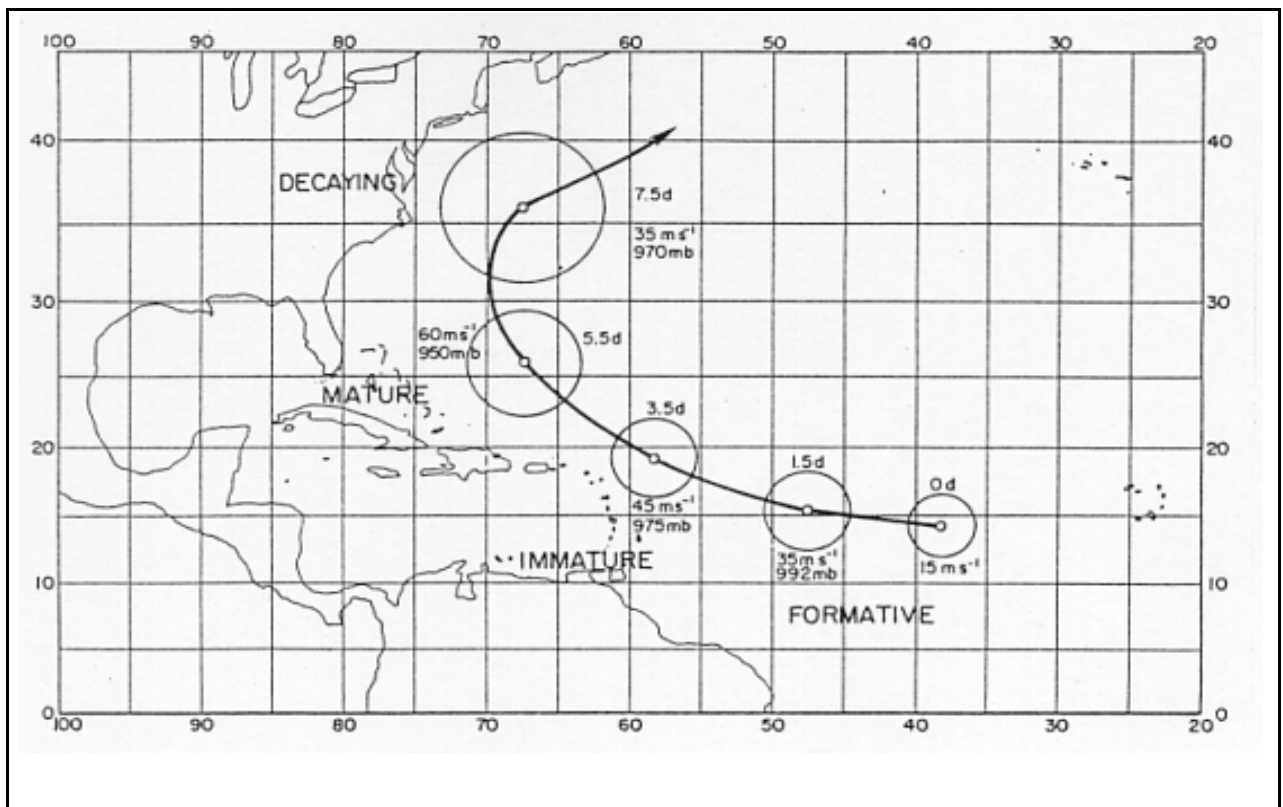
Examples of existing wind speed buffers

A precise wind analyse of the outer circulation of tropical cyclones is difficult to construct and interpret. The ultimate solution would be frequently observations from different sources as islands, ships, coastal regions, aircraft, etc. but the observations of the outer circulation of tropical cyclones are generally quite sparse, and from different sources and are subject to substantial errors. These two reasons make it difficult to find accurate examples of cyclones horizontal wind structure on a global scale (Holland, G. J., 1997)

The outer closed isobar as a wind speed buffer limit

The Radius of Outer Closed Isobar (ROCI) is one way of analysing and forecasting the outer circulation of tropical cyclones and it can be seen as an approach to identify a wind speed buffer. Identification of the outer closed isobar is only possible with the information of the cyclone structure and the structure change over time. Since the outer circulation probably is the easiest element to observe directly and the most difficult to infer remotely from satellite imagery, a homogeneous interpretation on a global level is hard to achieve. An extensive study of the outer circulation of tropical cyclones by the ROCI method would therefore be complicated and time consuming (Merrill, 2000).

Figure 1: The circle is the radius of the average outer closed isobar (Merrill, 2000)



A solution to this could be to identify an average radius of the outer closed isobar for different tropical cyclones within the different regions. This was done in Merrill (1984), where he identified the average size of twelve Atlantic cyclones by calculating the average radius of the outer closed isobar. He used also the average in intensity of the cyclones for identifying a cyclone's change in shape over time. He divided thereafter the cyclone's lifetime into four different phases: formative, immature, mature and decaying and determined the four phases with surrounding circles (see Figure 1, (Merrill 2000)).

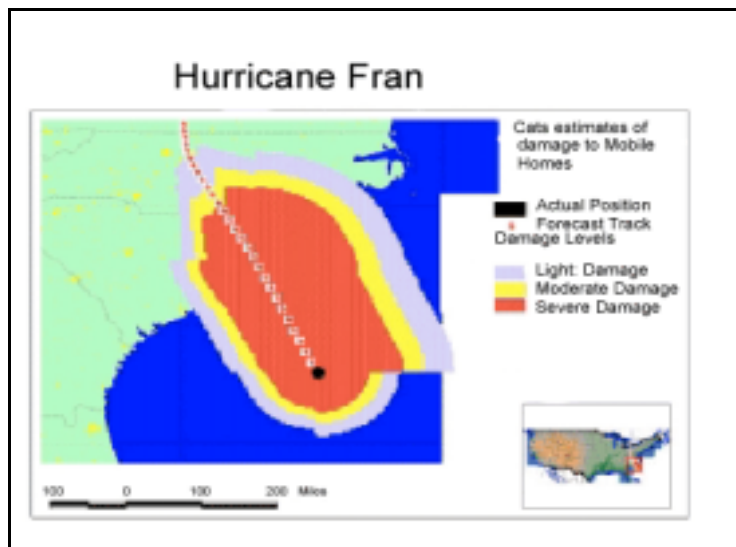
These four circles can be seen as wind speed buffers since the average wind speed and pressure are given inside the circles. The work by Merrill is not possible to find for other cyclone basins and the circle size of the four lifetime phases for the twelve cyclones are not adequate for a study on global scale with different years represented.

The Cats (the Consequence Assessment Tool Set)

Another example of wind speed buffers is The Cats (the Consequence Assessment Tool Set) model, which is a GIS-based model, made for estimating losses after a cyclone or tropical storm. The CATS system estimates in real-time the population and civil resources at risk from threatening hurricanes and associated storm surge; its primary application is to assist preparation and recovery efforts in emergency planning, readiness actions, and the prepositioning of relief supplies and personnel.

The module automatically parses advisory messages to extract current and forecast hurricane characteristics. Messages are usually disseminated every six hours, and contain observation and forecast data provided by the National Hurricane Center (NHC) in Miami, FL, the Central Pacific Hurricane Center (CPHC) in Honolulu, HI, or the Joint Typhoon Warning Center (JTWC) in Guam. The National Weather Service's Family of Services, the NOAA Weather Wire, University Internet servers, or commercial vendors of meteorological data provide access to these messages. Hurricane data collected from the messages includes the current and forecast positions of the storm, its maximum wind speed, and the spatial distribution of winds around the storm centre. At each quadrant of the storm, and for its current and forecast positions, radial profiles of dynamic pressure and wind speed are analysed. Colour-coded damage bands are then generated which display results of structural response modelling, which correlates hurricane wind gust velocity and dynamic pressure to damage to various structure types. Figure 2 presents estimates of wind damage to mobile homes calculated by CATS for Hurricane Fran (September 1996). The light purple area represents light damage, yellow moderate damage, and red severe damage (<http://www.saic.com>, 1999)

Figure 2: Damage estimation of Fran (1996) with CATS (www.saic.com, 1999)



Since this application is made for estimations in real-time and the aim is uniquely predictive, the wind speed around the cyclone track is not identified. For a spatial analysis (the movement of cyclones, best cyclone tracks, and their radial wind speed profiles) and global post-analysis of storms, an estimation of the wind speed is important due to regions varying sensitivity (see figure below and Appendix C for Saffir-Simpson). A more precise description of the CATS is difficult to obtain since it is a commercial product (<http://www.saic.com>, 1999).

CATS is today used by some important institutions, one example is FEMA's (Federal Emergency Management Agency) Mapping and Analysis Center, who use this model for estimating the losses after a hurricane or tropical storm (Personal contact with Leslie Weiner-Leandro at FEMA, July 2001). For more precise data FEMA has developed and are about to develop a program with different wind data to enable a more precise spatial analysis (the movement of cyclones, best

cyclone tracks, and their radial wind speed profiles). This program is called U.S. HAZUS model and is expected to be available in 2003, according to Mark Powell at NOAA, the National Oceanic and Atmospheric Administration (Personal contact, July 2001).

Figure 3: Saffir Simpson Scale

Saffir-Simpson Scale				
The Saffir-Simpson Scale is used to classify the intensity of tropical storms and hurricanes.				
Category	Pressure (millibars)	Winds (knots)	Winds (mpd)	Surge (feet)
Tropical Depression	--	less than 34	less than 39	--
Tropical Storm	--	34-63	39-73	--
Category 1 Hurricane	more than 980	64-82	74-95	4-5
Category 2 Hurricane	965-980	83-95	96-110	6-8
Category 3 Hurricane	945-965	96-113	111-130	9-12
Category 4 Hurricane	920-945	114-135	131-155	13-18
Category 5 Hurricane	less than 920	more than 135	more than 155	more than 18

Point estimation of transversal buffers

In order to estimate wind speed buffers along the whole track, the first step is to estimate the wind speed profile at a certain time (corresponding to a certain position of the cyclone's eye). As well as deduce the transversal buffers, i.e. right and left intervals on the line perpendicular to the track (and going through the cyclone's eye) where the wind intensity is (or have been or will be) greater than a chosen wind speed threshold V_{crit} . For this purpose we built a wind speed profile model based on the known observed parameters.

Greg Holland's parametric model

The parametric model described in this chapter is defined by Greg Holland at the Bureau of Meteorology in Melbourne, Australia (Holland G.J., 1980) based on an original approach by Schloemer (ref, 1954). The model includes a formula for the wind speed at a given radius, i.e. the distance from a current point to the eye of the cyclone. For this model it is supposed that the cyclone is over the ocean, that the eye of the cyclone is stationary and that the surrounding winds follow a three-dimensional symmetry around a vertical axis (axisymmetric winds). It assumes that the tropical cyclone surface wind field follows:

Equation 1: Wind calculation (Holland G.J., 1980)

$$V_h(R) = \sqrt{\frac{b}{\rho} \cdot \left(\frac{R_{\max}}{R}\right)^b \cdot (P_{\text{env}} - P_{\text{centre}}) \cdot e^{-\left(\frac{R_{\max}}{R}\right)^b} + \frac{R^2 f^2}{4} - \frac{Rf}{2}}$$

Where:

$V_h(R)$: Gradient wind speed at distance R from the eye (in m/s)

b : Parameter that changes the shape of the radial profile

P_{centre} : Central pressure (in Pa)

P_{env} : The asymptotic environmental pressure (in Pa)

R_{\max} : The radius of maximum winds (in meters) as can be seen on the curve below

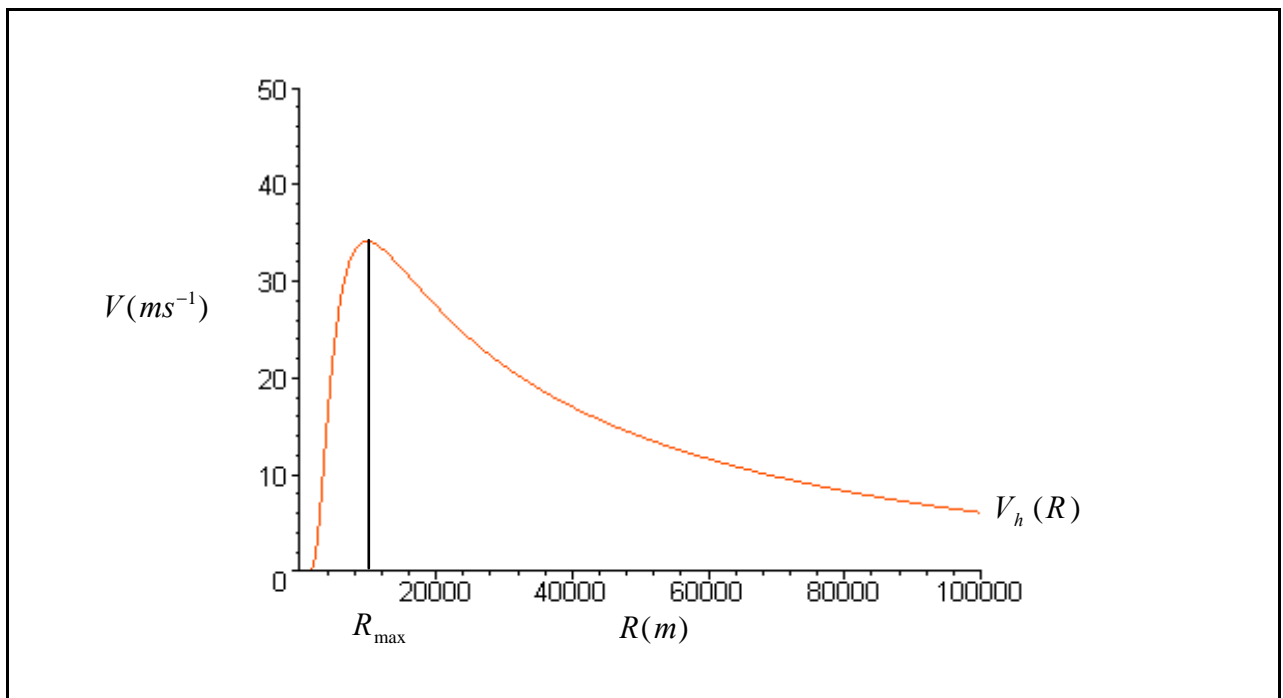
R : The radius where wind speed is $V_h(R)$ (in meters)

ρ : The air density, assumed constant = 1.15 kg m^{-3}

f : The Coriolis parameter = $2 \cdot (\text{Earth's angular velocity}) \cdot \sin(\text{latitude})$ where the Earth angular velocity equals $0.0000729 \text{ radians/s}$.

This formula gives a wind speed profile whose shape can be seen on Figure 4 (for parameters: $b=1.5$, $P_{\text{env}}=1015 \text{ hPa}$, $P_{\text{centre}}=990 \text{ hPa}$, $R_{\max}=10000 \text{ m}$, $\text{latitude}=45^\circ$):

Figure 4: Wind speed profile for Greg Holland's stationary model



Application of Greg Holland's model

The parameters mentioned in the introduction and in the formula above are necessary for a functioning model. An important part of the work was therefore to find the cyclone data for the cyclone basins worldwide. With the following data: the successive positions of cyclone's eye, corresponding central pressure and maximum observed wind speed. This new structure of the different important meteorological parameters enabled spatial analyses, as for instance the movement of cyclones (tracks) and their radial wind speed profiles.

The parameters concerning the geographical position and the intensity of the tropical cyclone are not sufficient for applying Greg Holland's model. To allow computation of the wind speed around a cyclone track, i.e. to estimate a zone around the cyclone corresponding to a wind speed above a certain fixed threshold, some variables have to be identified.

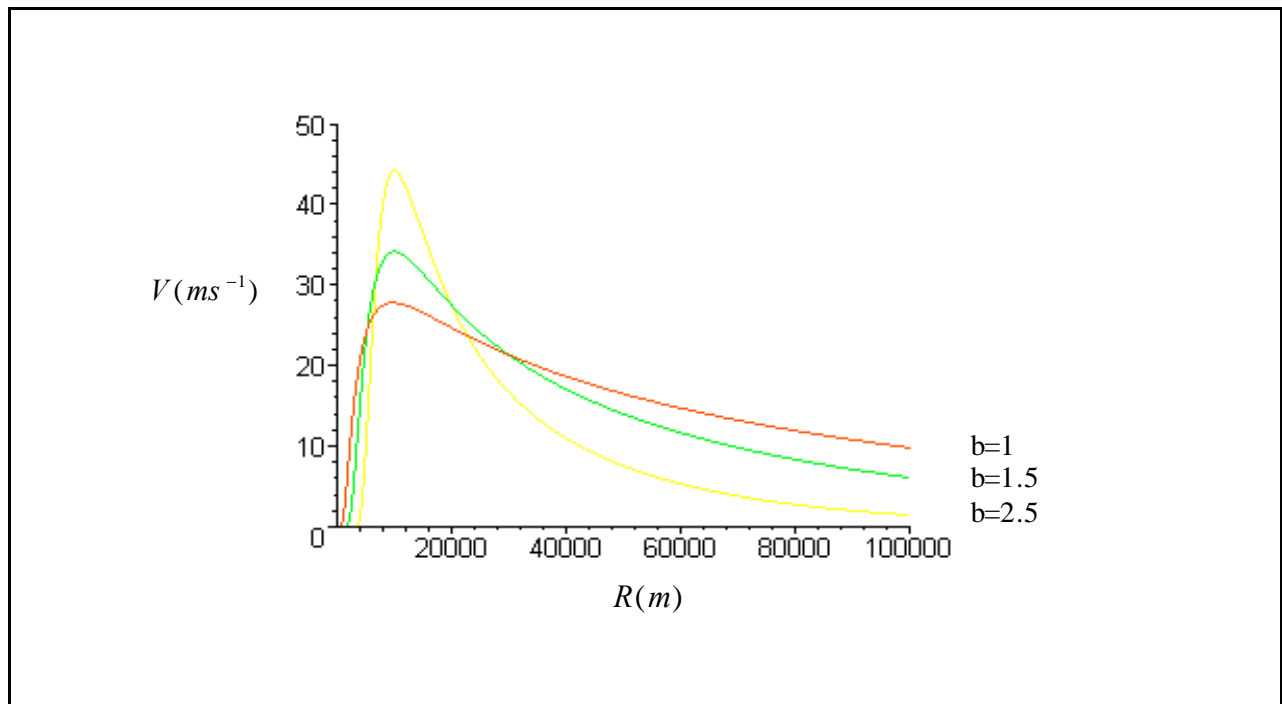
There is a need to:

- Chose a value for parameter b , which dictates the shape of the pressure or wind speed profile.
- Determine the asymptotic environmental pressure P_{env}
- Estimate the radius of maximum wind speed R_{max}
- Take into account the fact that the cyclone is not stationary

The b parameter, the shape of the pressure or wind speed profile

That parameter changes the shape of the profile as can be seen on Figure 5, where, for same other parameters as above ($P_{env}=1015$ hPa, $P_{centre}=990$ hPa, $R_{max}=10000$ m, $latitude=45^\circ$), the three values $b=1$, $b=1.5$ and $b=2.5$ are chosen:

Figure 5: Effect of b parameter on the wind speed profile shape



A first approach consists in choosing a constant value for the b parameter. Physical constraints ensure that $1 < b < 2.5$, supported by a climatological discussion, and for establishing wind speed buffers it is appropriate to use a low value since a high value gives wind speed buffers with too short intervals (Holland G.J., 1980). Following Greg Holland's recommendation a value of 1.5 was used although Bruce Harper was suggesting a value of 1 (Personal contact with Holland G.J. and Harper Bruce, July 2001).

By using $b = 1$ the profile would also be constrained to a single profile, as the profile of Schloemer's relation, which markedly underestimates the maximum winds and overestimates the radial extent of destructive winds (see Figure 5 above).

A second approach for estimating parameter b using Greg Holland's formula and using measurements of maximum wind speed will be described later.

The P_{env} parameter, the asymptotic pressure

The asymptotic pressure varies for the different cyclone events and the observations are primarily focused on the tropical eye's central pressure. It is therefore difficult to obtain data about this parameter for the different cyclone events and an important simplification of this parameter is therefore inevitable. By defining climatic constants for the regions of the different cyclone basins this parameter can be seen as more adequate than by using an overall reference. These constants were defined with the help of Bruce Harper and Greg Holland and according to the authors it is possible to differentiate the regions as follows (Personal contact with Holland G.J. and Harper Bruce, July 2001):

1015 hPa in the North Atlantic, 1005 hPa in the NW Pacific and Australian region, 1008 hPa in the North and South Indian Ocean, 1010 hPa in the NE Pacific. The value of the NE Pacific is based on the proposed overall reference of the two above mentioned authors even though the standard atmospheric pressure is 1013 hPa.

The R_{max} parameter, the radius of maximum winds

The R_{max} parameter is theoretically independent of the relative values of ambient and central pressure and also of the b parameter. It could therefore not be determined by the cyclone intensity data or by the shape of its profile. However, to be able to model the extension of the destructive winds within a cyclone without the information about the cyclone's structure, the available data about the intensity has to be used. In order to estimate the R_{max} of a cyclone, Mark Powell at NOAA (Personal contact, July 2001) suggested to stratify the cyclones into three different classes related to the central pressure: Small, medium and large. Remark that the pressure field can be missing for some observations, and in those cases, Greg Holland's model can not be used. The three classes were defined by aggregating the Saffir-Simpson scale (see appendix C), for the central pressure. By studying earlier cyclone events and their R_{max} , we were able to identify three likely distances for the R_{max} . Details, refinements and comments on that classification will be described later.

The movement of the cyclone's eye

The translation movement of the cyclone is not taken into account in the model. A rough but simple way to include this translation movement is to add the eye's speed value to the speed given by the model (Personal contact with Holland G.J., July 2001), which results in a wind speed profile with a symmetric structure. This structure of a cyclone with double wind maxima, on both sides of the cyclone track, occurs under specific circumstances but it is exceptional. The symmetric way of illustrating a cyclone facilitates the modelling work, but the cyclone's asymmetric characteristic is not to be neglected. The cyclone's asymmetry can be obtained by calculating vectors i.e. by adding the translational vector to the windfield. This gives a net flow behind the cyclone, outflow ahead

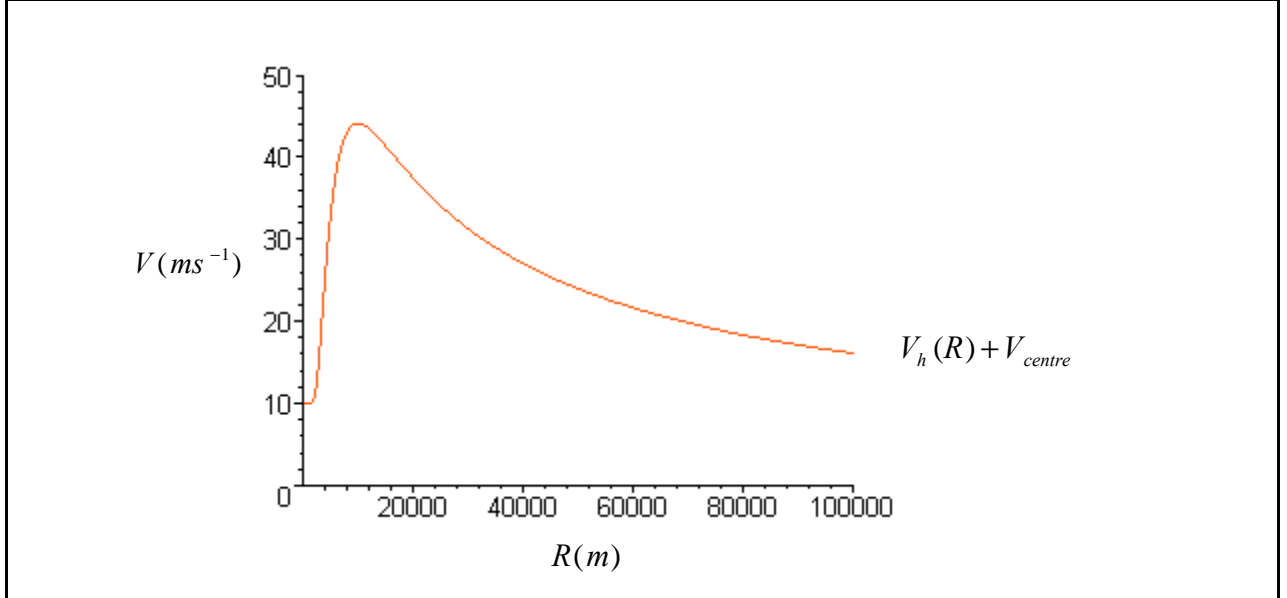
and a maximum wind speed on the cyclone's right hand side in the Northern Hemisphere and on the left side in the Southern Hemisphere.

In practice the eye's speed intensity and direction can be estimated by using the time consecutive positions of the eye.

Symmetric buffer

With parameters of the model chosen as above and after adding the eye's speed value (here 10 m/s), the wind speed profile has the following shape:

Figure 6: Wind speed profile after addition of eye's speed



Since the cyclone is not infinite in size, the speed must decrease toward zero as R increases, which is not the case in this example. It was therefore decided to multiply V_{centre} by an absorbing factor for R greater than R_{max} . Among the different absorbing factors that we explored, we have here chosen the following factor for the simplicity of illustration:

$$V(R) = V_h(R) + \left(\frac{R_{max}}{R} \right) \cdot V_{centre}$$

The corresponding wind speed profile can be seen on Figure 7.

By choosing a fixed threshold V_{crit} for the wind speed, one have generically the two cases shown in Figure 8.

In the first case speed values are always below the threshold and the transversal buffers are empty. In the second case, the buffer limit has the unique radius R bigger than R_{max} for which V equals V_{crit} . This value can then be determined by a numerical resolution of the equation $V(R) = V_{crit}$ in the domain $R > R_{max}$. Notice that the wind speed for the area near the eye can be less than V_{crit} but it has been and will be affected by stronger winds due to the cyclone's movement (see example in Figure 10 and case 2 in Figure 13).

Figure 7: Wind speed profile with absorbing term

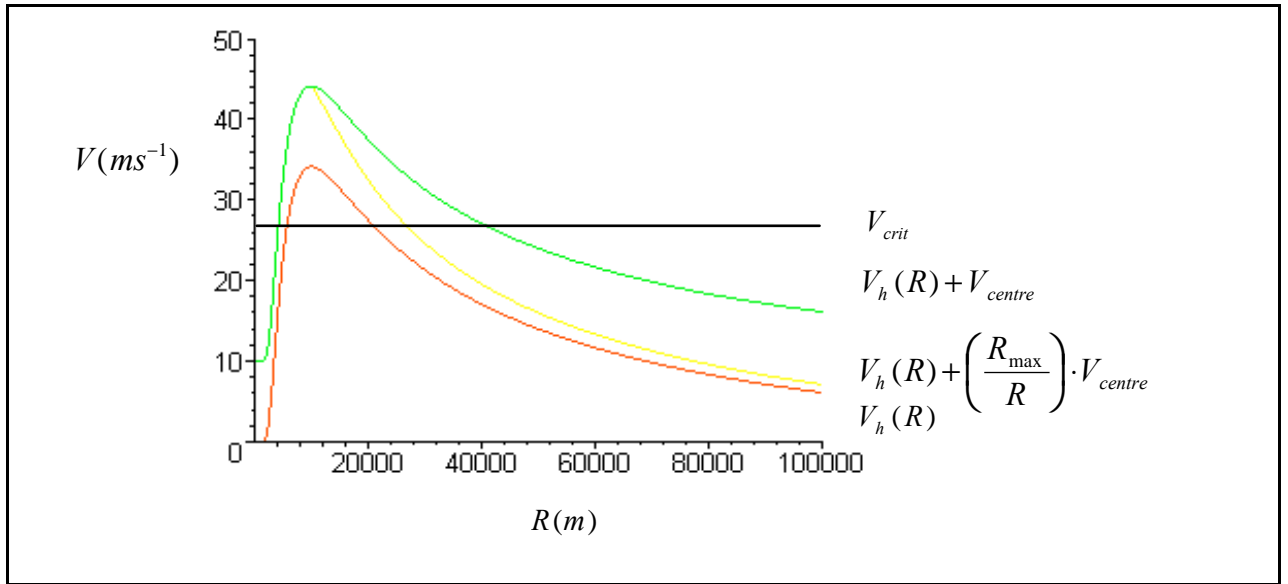
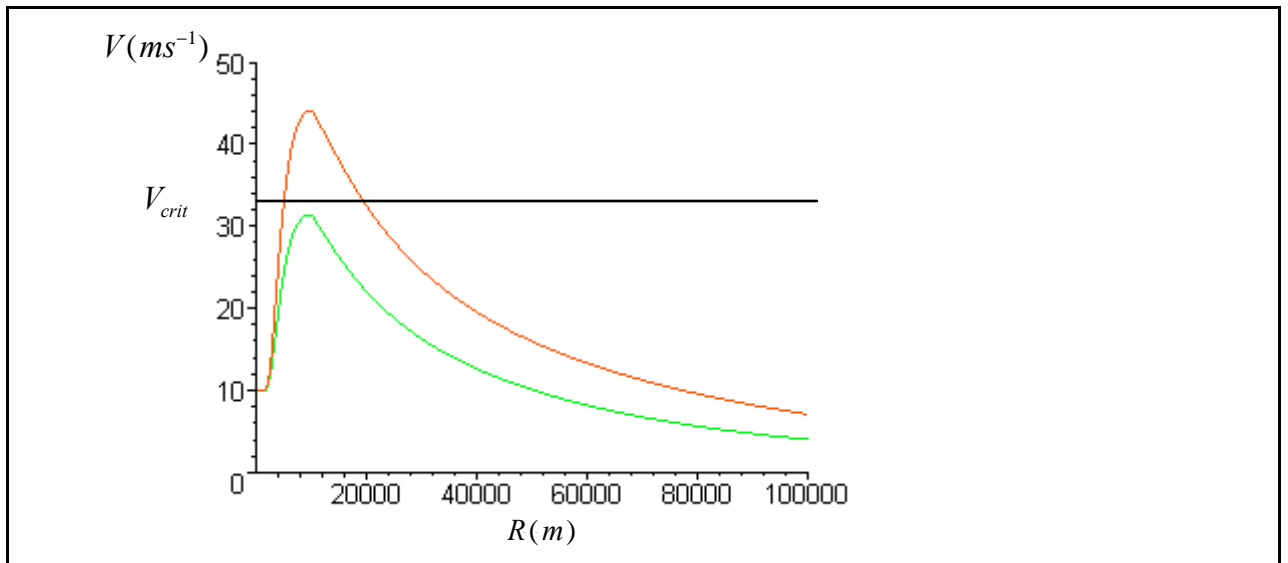


Figure 8: Two cases for threshold

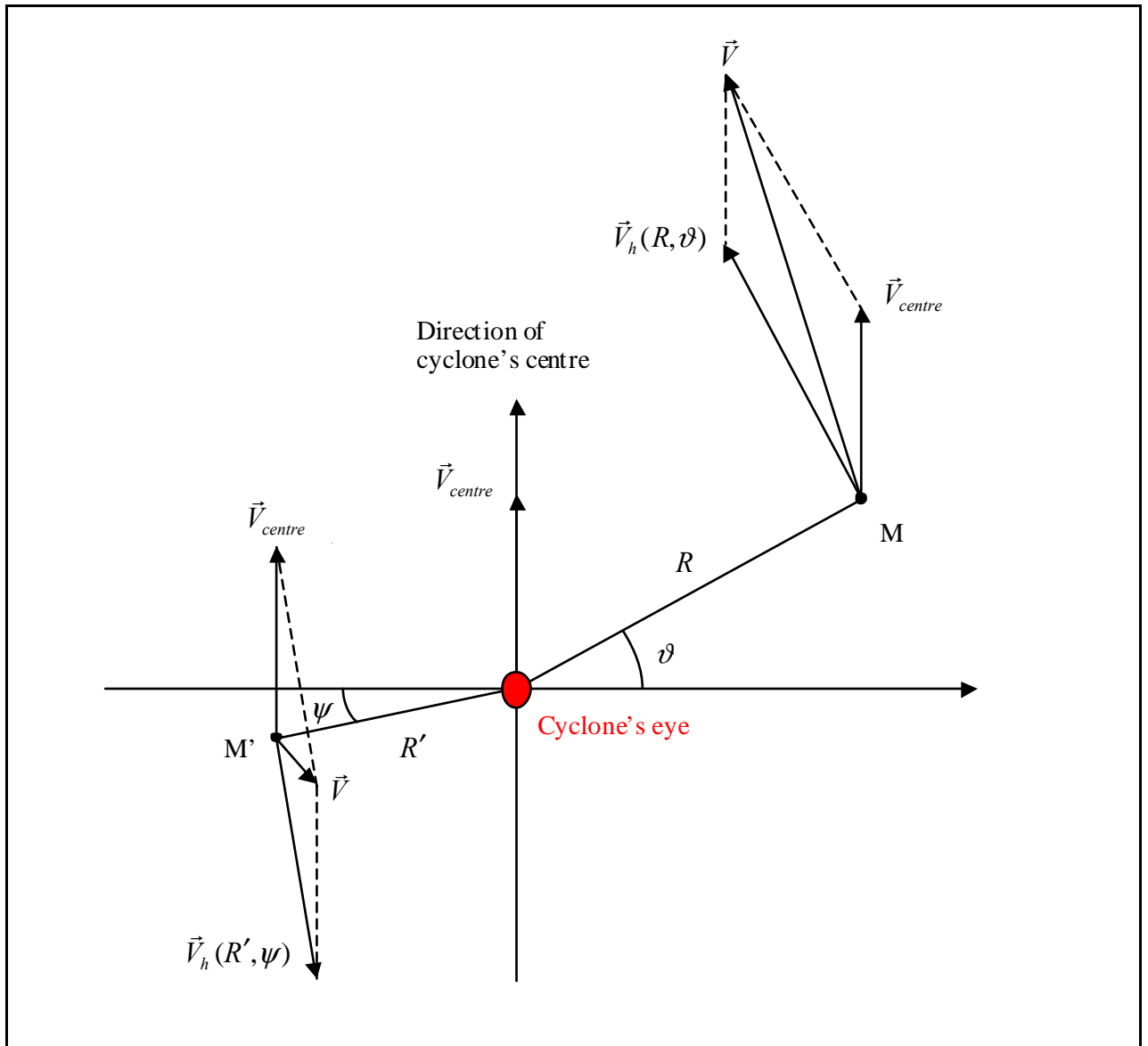


Asymmetric buffer

The wind field in tropical cyclones is rarely, if ever, symmetric. Asymmetries arise from a range of processes, including: cyclone movement; location and structure of the cloudy and clear regions around the cyclone, including the spiral cloud bands; external influences from surrounding weather systems; and occasional high intensity transients, such as meso vortices. Further, transient conditions occur in which two maximum wind belts develop, with the outer contacting inwards and destroying the inner one (Holland G.J., 1997). The only processes routinely included in current parametric wind models are those arising from the cyclone movement.

As mentioned before; the simplest way to include in the model the asymmetry due to the movement, i.e. add the eye's speed vector (translation) to the stationary model's wind vector field (rotation). The cyclones in the Northern Hemisphere rotate anticlockwise (clockwise in the Southern Hemisphere) and the examples treated in this text are in north and the anticlockwise rotation will therefore be described. On the right-hand side of the cyclone's track, the translation vector and the rotation vector are in the same direction, i.e. the two speed values are to be added. On the left-hand side, they move in opposite directions and the two speed values are to be subtracted. More generally, those two vectors make an angle as can be seen on the following figure in polar coordinates, where the wind speed is considered at a point M of radius R and angle θ , respectively at a point M' of radius R' and angle ψ .

Figure 9: Angle between rotation wind speed and eye's translation speed



The stationary model's vector field is $\vec{V}_h(R, \vartheta) = V_h(R) \cdot \vec{u}_\vartheta$

Where \vec{u}_ϑ is the unitary vector perpendicular to the ray OM and pointing like the rotation direction (i.e. anticlockwise). Finally, wind speed is modelled by $\vec{V}(R, \vartheta) = \vec{V}_h(R, \vartheta) + \vec{V}_{centre} = V_h(R) \cdot \vec{u}_\vartheta + \vec{V}_{centre}$

whose norm is

$$V(R, \vartheta) = \|\vec{V}(R, \vartheta)\| = \sqrt{V_h(R)^2 + V_{centre}^2 + 2V_h(R)V_{centre} \cos(\vartheta)}$$

Level curves of $V(R, \theta)$ have thereafter the following shape (Figure 10, with the same parameters as above). A 3-D picture of the graph of $V(R, \theta)$ is presented in Figure 11 and the speed vector field can be seen in Figure 12.

Figure 10: Level curves of wind speed intensity

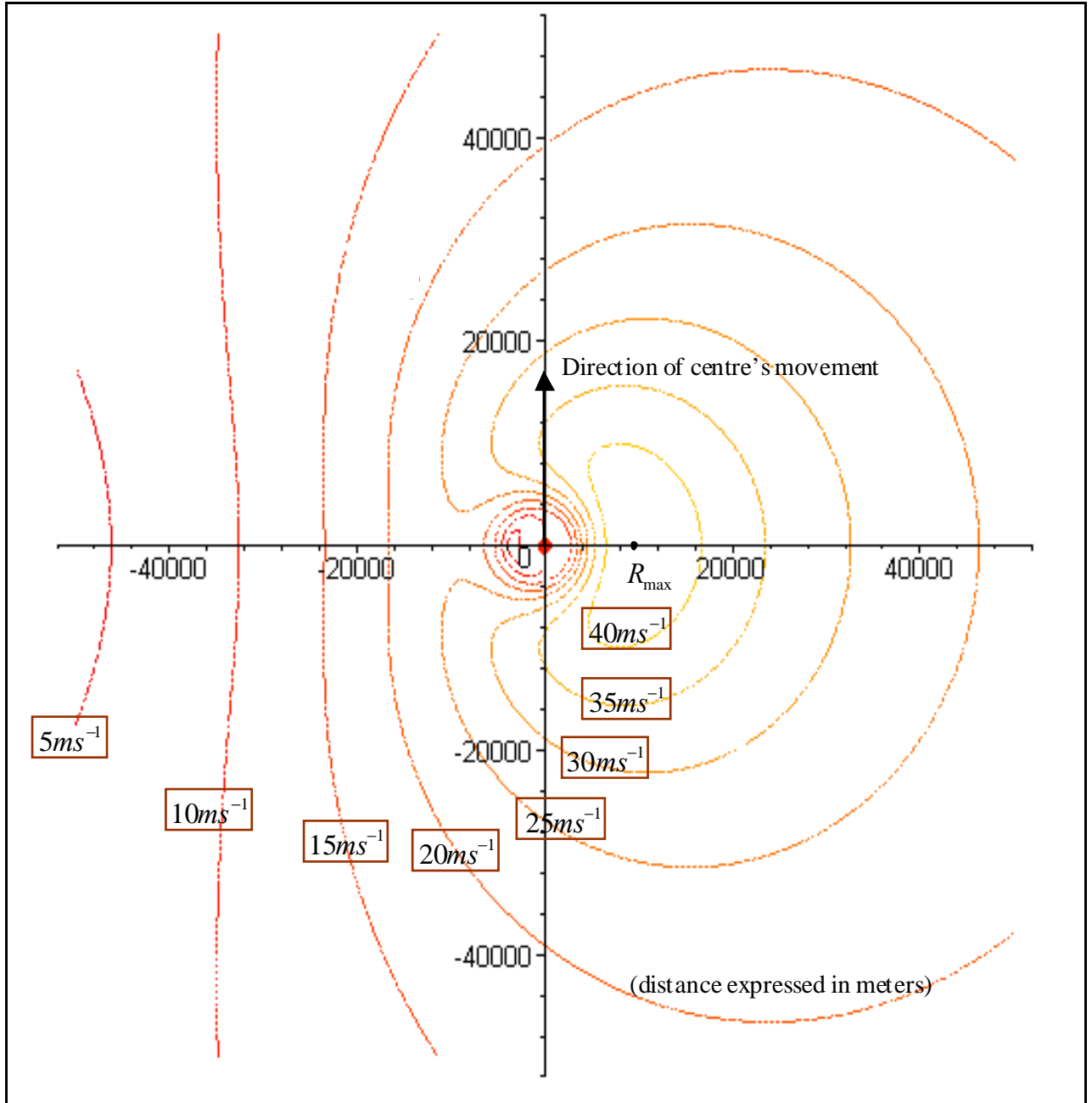


Figure 11: Graph of $V(R,\theta)$

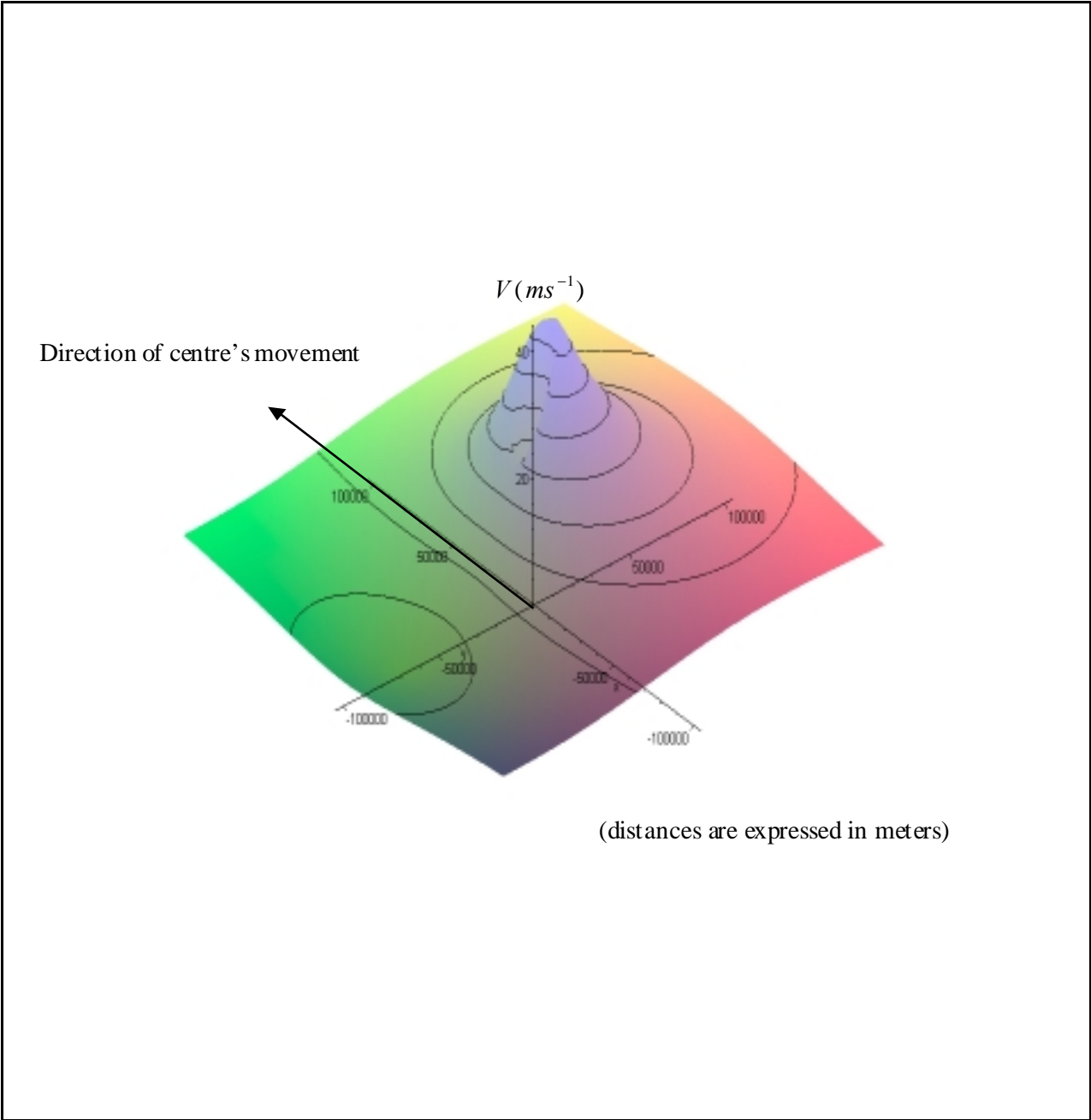
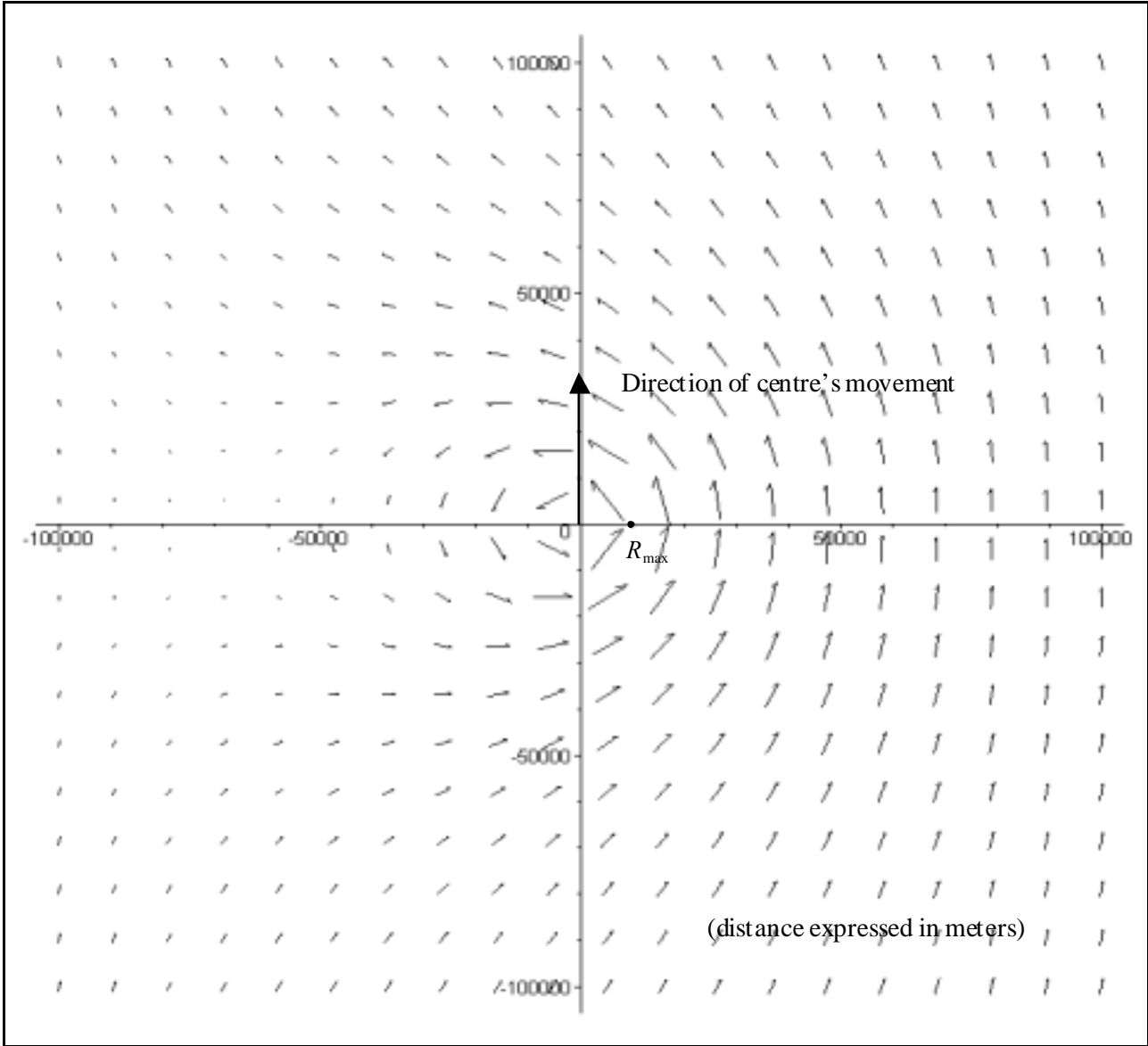
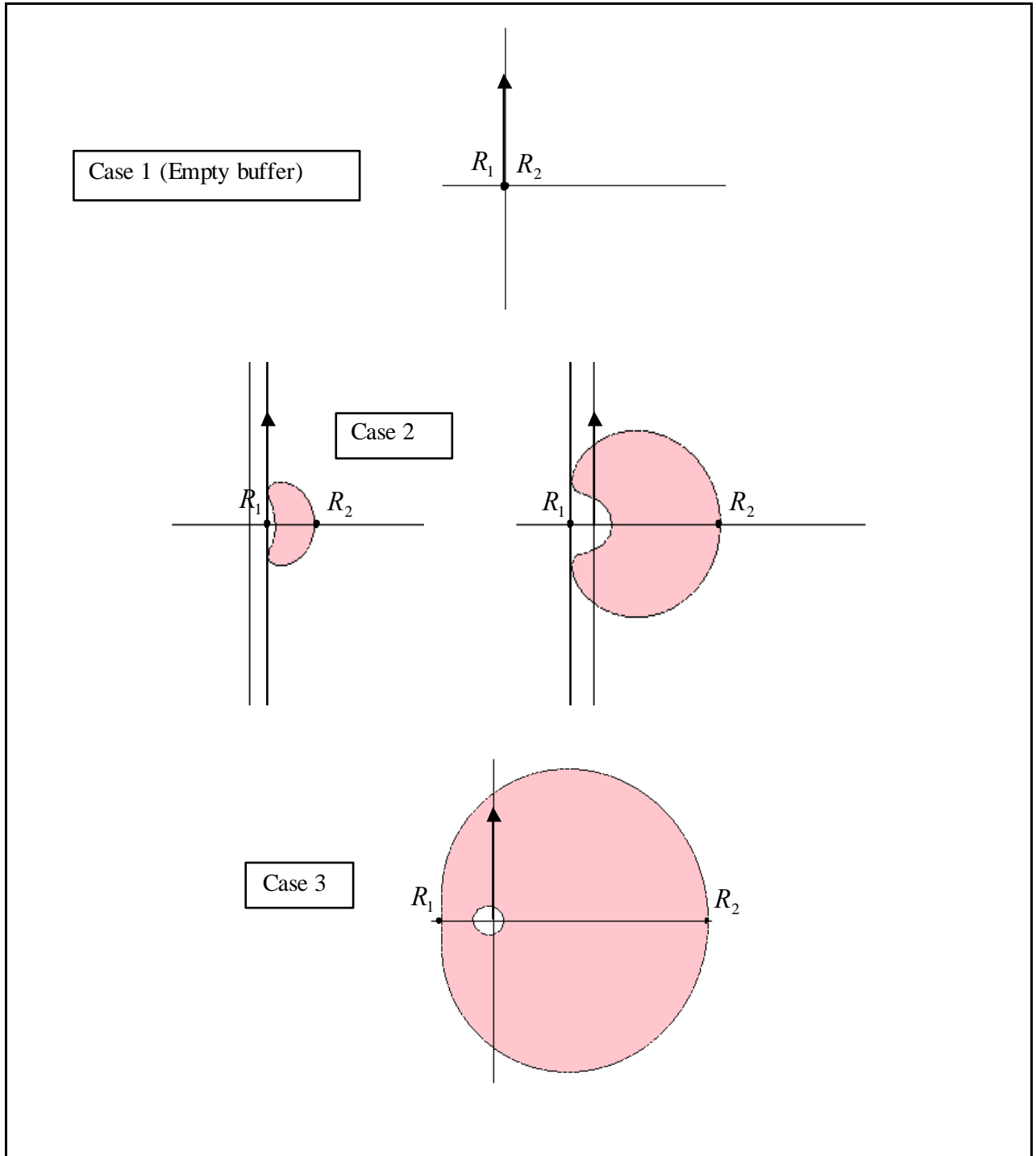


Figure 12: Speed vector field



For a given threshold V_{crit} , the region $V > V_{crit}$ can have the following shapes, which lead to transversal buffer limits R_1 and R_2 as indicated in case 1, 2 and 3 below (Figure 13). Notice that some of the points between R_1 and R_2 are not actually moving with a speed greater than V_{crit} but they have or will do due to the cyclone's movement.

Figure 13: Different cases for critical region



Limit R_2 in the previous section is calculated, as a symmetric buffer but R_1 needs to be computed or at least approximated as an asymmetric buffer.

Case 1 (empty region) is the case where $R_2=0$, and that implies $R_1=0$ so it is very easy to compute. For the other cases an approximation method has been used considering the upper-half circle of radius R_{max} , centred on the eye O:

Figure 14: Distinguishing between case 2 and case 3

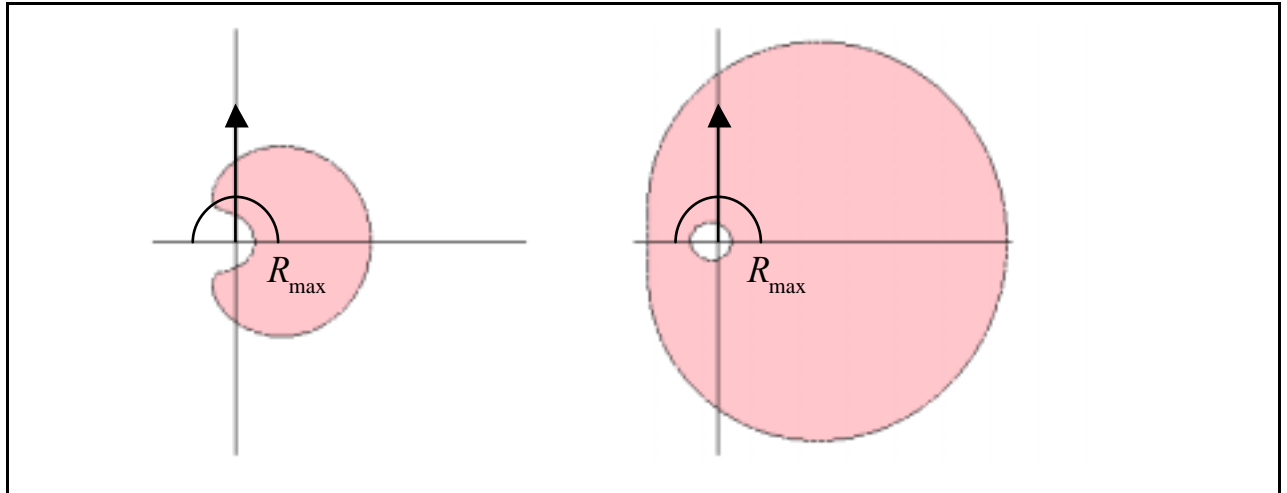
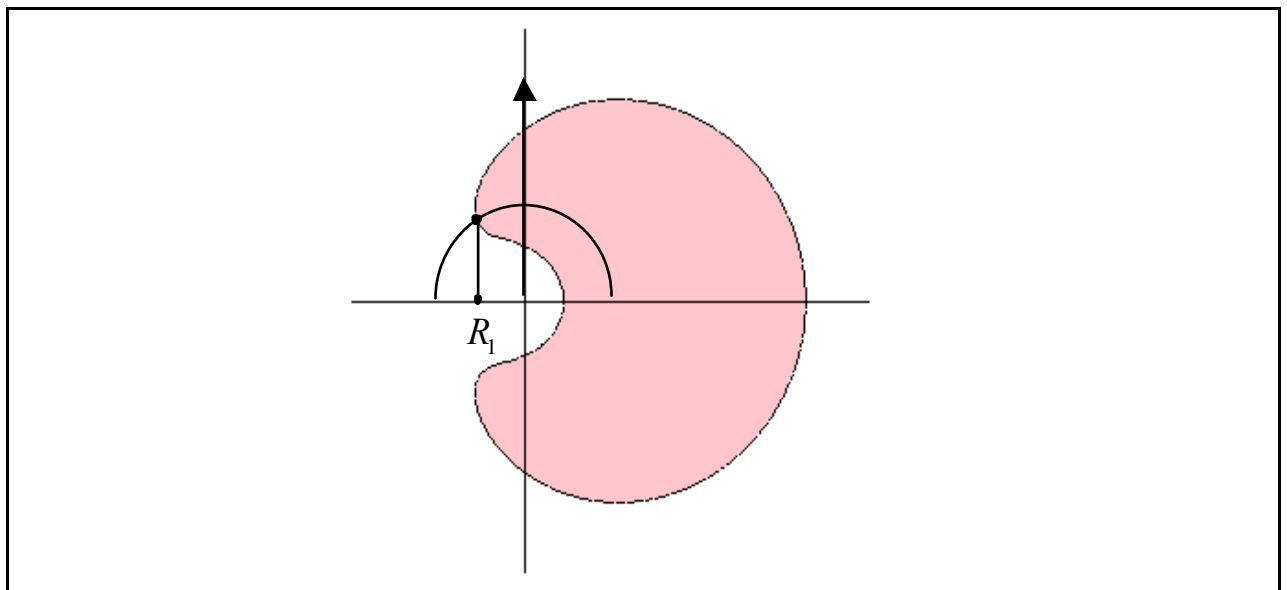


Figure 15: Projection



Note that on the right-hand side, in each direction from O, the maximum wind speed is obtained at distance R_{max} but this is not the case on the left-hand side. Along this half-circle, V is decreasing from right to left. The case where V don't decreases below V_{crit} along the half-circle is defined in case 3 and R_1 is in this case computed by a method analogous to the one for R_2 . In the case where V decreases below V_{crit} , R_1 is approximated by using the projection of the point where $V = V_{crit}$ as in the **Figure 15**.

Notice that the projection point determining R_1 can be either on the right hand side or on the left side with respect to the origin (cyclone's centre). To take into account these two

different cases, the following convention was used: radius R_1 will be positive if the projection is on the left (in the northern hemisphere) and negative if the projection is on the right side, i.e. if the two points for R_1 and R_2 are on the same side. In this case an elementary computation gives then the value of R_1 :

$$R_1 = -R_{\max} \left(\frac{V_{\text{crit}}^2 - V_h(R_{\max})^2 - V_{\text{centre}}^2}{2 \cdot V_h(R_{\max}) \cdot V_{\text{centre}}} \right)$$

This leads to the following algorithm:

```

If Vcrit > (Vh(Rmax) + Vcentre) Then
  'Case 1:
  R1 = R2 = 0
Else
  'Same as symmetric buffer for R2:
  R2 = SOLVE(Vh(R) + (Rmax/R)*Vcentre - Vcrit = 0; R; R>=Rmax)
  'Distinguishing between case 2 and 3 for R1:
  If Vcrit < (Vh(Rmax) - Vcentre) Then
    'Case 3
    R1 = SOLVE(Vh(R) - (Rmax/R)*Vcentre - Vcrit = 0; R; R>=Rmax)
  Else
    'Case 2
    R1 = -Rmax*((Vcrit^2 - Vh(Rmax)^2 - Vcentre^2) / (2Vh(Rmax)Vcentre))
  End If
End If

```

Several numerical resolutions were first proceeded using Microsoft Excel Solver, but were later changed for a simple dichotomy algorithm (see **Visual Basic code** appendix B) implemented in Microsoft Visual Basic. That for several reasons: it allows cross-verifications with earlier results; one has a better control when problems occur in particular cases, and our further objective is a minimum use (none if possible) of Microsoft Excel for best efficiency and transparencies.

Discussion and refinements on the choice of parameters

Estimation of parameter b

The problem with choosing a constant value for the parameter b is the theoretical maximum wind speed intensity that depends almost uniquely upon the pressure value. It results sometimes in a great difference between the theoretical maximum values and the observed maximum speed intensities.

As the maximum theoretical values are obtained at distance R_{\max} , it is a simple computation to chose b such that the maximum theoretical value for stationary model equals the maximum relative (with respect to the centre) speed intensity:

$$b = \frac{\rho \cdot e \cdot (V_{\max\text{obs}} - V_{\text{centre}}) \cdot (V_{\max\text{obs}} - V_{\text{centre}} + R_{\max} \cdot f)}{P_{\text{env}} - P_{\text{centre}}}$$

As the Coriolis term is negligible and also because of the uncertainty in the determination of R_{\max} , an approximation was made:

$$b = \frac{\rho \cdot e \cdot (V_{\max\text{obs}} - V_{\text{centre}})^2}{P_{\text{env}} - P_{\text{centre}}}$$

However, if the b value is not between 1 and 2.5, it's important to consider the problem of physical coherence because b should be in that interval for physical and climatological reasons, as mentioned before e.g. too small values of b results in overestimated buffers. Further, the observed maximum wind speed are less reliable than the pressure observations since the metadata explaining the methodology of measurement and interpolations is insufficient.

For those reasons, we have decided that if the computation gives a b -value less than one, it will be fixed at 1 and the same for values greater than 2.5, which are fixed at 2.5.

Estimation of R_{\max}

The uncertainty is important concerning the estimation of R_{\max} . There's no value for R_{\max} in the observed data and as described before, the only possibility to identify this value is to estimate R_{\max} using the pressure classes. The first approach was to define three pressure classes by aggregating classes in the Saffir-Simpson scale: $p > 980$, $980 > p > 965$, $965 > p$. These classes were thereafter used to define relevant R_{\max} values based on examples of cyclone events with observed R_{\max} .

However, choosing a fixed value of R_{\max} for each of the three pressure classes leads to distinct differences between the classes and a piecewise linear function was therefore used between the determined classes. Further improvement of a R_{\max} estimation could be done by dividing the cyclone's life cycle into three phases: growing, mature and declining. For these different phases the link between central pressure and R_{\max} is different and a great improvement of the buffer estimation could be achieved if reasonable estimations of R_{\max} was furnished by the providers.

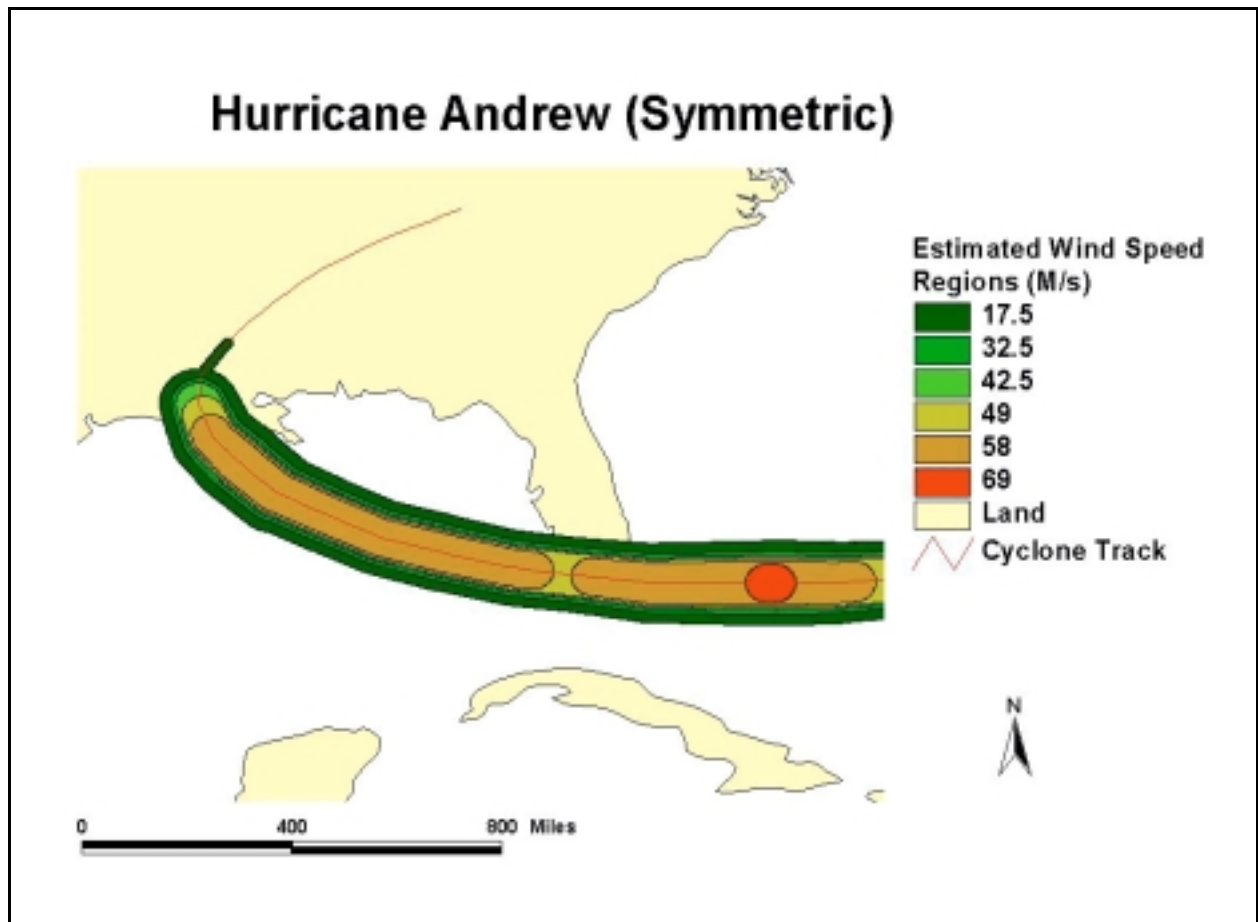
From point estimation to global buffers

Construction of global buffers, wind speed buffer along the cyclone track, from transversal buffer values implies two main problems. Firstly, the width of a buffer along an entire track is not constant and such a buffer is rarely handled by a GIS-software; secondly, in the asymmetric case, left and right widths are not the same. The solution to the first problem may rely on dividing the

track into smaller parts (interpolation) and to adjusting on each part a classical fixed-width buffer, this can easily be handled by a GIS-software. The solution to the second problem is more complicated and a totally different method was selected.

Symmetric case

Figure 16: An example of symmetric buffer

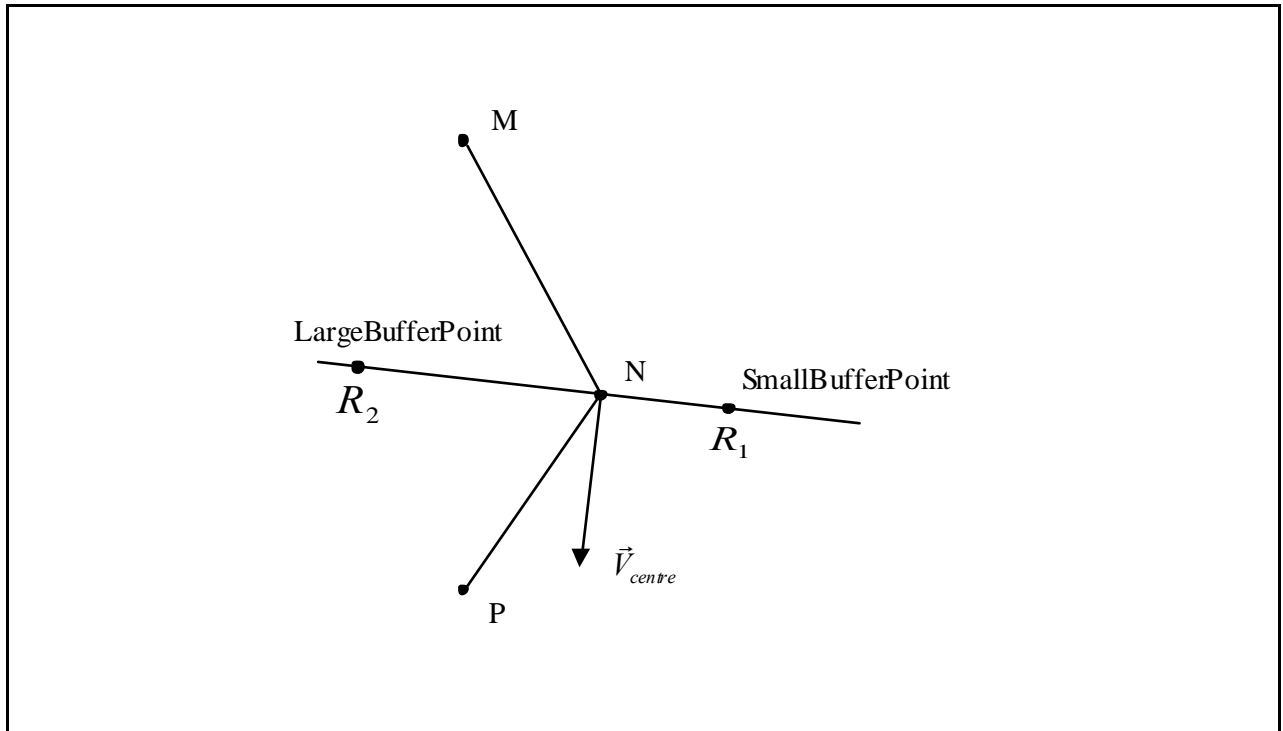


As explained above, a track between two observation points was divided into small parts. For each new point, physical values were interpolated with a linear rule. A computation of buffer radius was thereafter performed according to the symmetric model for each new point and, for each section, a fixed-width buffer based on its radius. The global buffer is simply the union of all those small buffers. This can be done by almost every GIS-software and we used at first ESRI's ArcView. But the second time, the need of automation for treating a great number of cyclones simultaneously lead to program routines in ESRI's ArcInfo. This work was carried out by Christian Herold at UNEP/GRID-Geneva. An example that was constructed in ArcView can be seen on Figure 16.

Asymmetric case

In order to treat the asymmetry (and also varying width) in a simple way, it was decided to construct global buffer as polygons. For that purpose, it has first been computed on each measure point N an estimation of cyclone eye's speed intensity and a perpendicular to cyclone eye's speed direction using the two consecutive last point M and next point P as seen on Figure 17. The perpendicular taken is the bisectrix of angle (MNP).

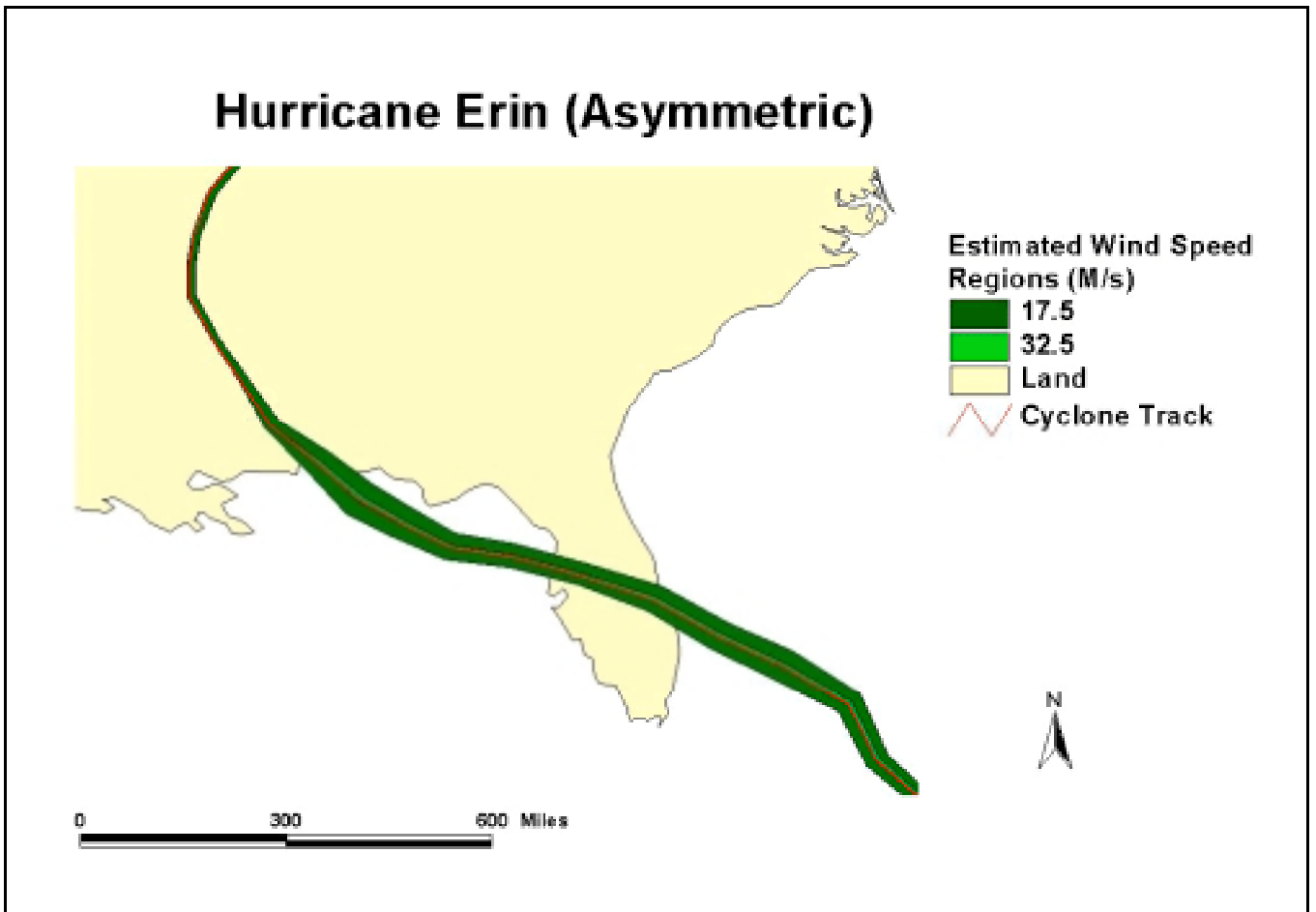
Figure 17: Construction of transversal buffer points



Two points were computed, LargeBufferPoint and SmallBufferPoint on the perpendicular corresponding to the two previously computed radii R_1 and R_2 . All the points were handled by their longitude and latitude coordinates and all computations were made taking into account the sphericity of the earth surface. All corresponding functions are regrouped in a Visual Basic module named SphericGeom (See Appendix B).

Once a LargeBufferPoint and a SmallBufferPoint were computed for each initial track point, it becomes easy in every GIS-software to construct the global buffer as a polygon. However, automation of that process for a large number of cyclones requires routines and has been done by Christian Herold at UNEP/GRID-Geneva using ArcInfo. An example can be seen on Figure 18.

Figure 18: An example of asymmetric buffer



Automation of the model

The observations of tropical cyclones worldwide are carried out by the different Regional Specialised Meteorological Centres (RSMCs) together with six Tropical Cyclone Warning Centres (TCWCs) of World Meteorological Organisation. The different observation centres are well coordinated and they keep the first level basic meteorological information (chronological data about the geographic localisation of the cyclones and their intensity) updated on all the global tropical cyclones events. This collaboration gives a broad range of global cyclone data, but the range of reported data imply problems due to differences in data structure. The following providers were found appropriate for covering the cyclone basins worldwide:

Organisations	URL address
Unisys Weather:	Http://weather.unisys.com/hurricane/
Typhoon 2000:	Http://www.typhoon2000.ph/
Australian Severe Weather:	Http://australiasevereweather.com/cyclone/
Atlantic Hurricane Track Maps & Images:	Http://fermi.jhuapl.edu/hurr/index.html
Hawaii Solar Astronomy:	Http://www.solarifa.hawaii.edu/index.html
Bureau of Meteorology, Australia:	Http://www.bom.gov.au/
Fiji Meteorological Service:	Http://www.met.gov.fj/
Japan Meteorological Agency:	Http://www.kishou.go.jp/english/

Plus printed material from India Meteorological Department (years 1992, 1993, 1994, 1995, 1996, 1997, 1999, 2000 and 2001).

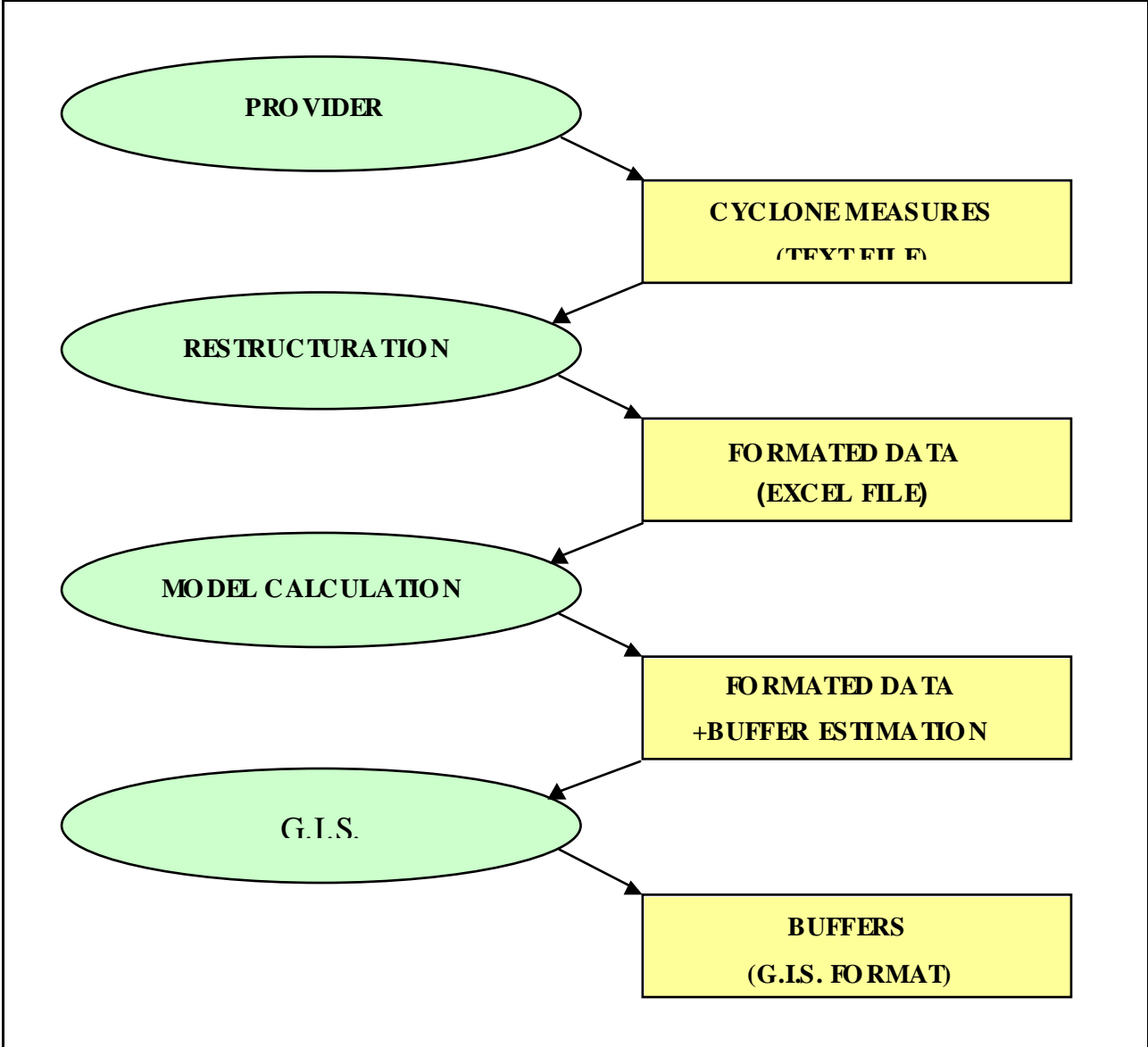
This heterogeneity in the database structure is problematic for a global research over time and it was therefore important to structure the data from the different providers. The main aim with unifying the different data sets to one global database was to establish an easy way of accessing data with identical variables for the use of Greg Holland's parametric wind field model.

This unification of the data was rendered possible by programming a useful tool in Visual Basic for identifying and structuring the different provided data sets (for a detailed manual of this program see appendix B). After that the structure of the cyclone data has been identified, the data is restructured in a unified format. In the symmetric case, this step included interpolation for varying-width buffer construction, but interpolation is no longer necessary in the asymmetric case. The data will thereafter include the following parameters: the longitude and latitude, name, year, month, day, hour, sustained windspeed (in m/s) and the central pressure (in mbar). The observations are carried out with different time intervals for the different cyclone events.

The cyclone track data then allows estimations of the radial wind speed profile for a moving cyclone throughout time, despite that Holland's model is made for a stationary cyclone. The remaining parameters as the constants defined in chapter 2.3, the earlier mentioned meteorological variables identified by observations and interpolations are sufficient for Holland's model. For symmetric case buffer radius are computed and in asymmetric case, buffer limit points are computed.

In earlier versions of the software, the proceeding was divided into different steps, where the steps and the cyclones were treated individually. For the final version these steps are combined and it enables automatically treatment of hundreds of cyclones, once characteristics of the provider have been entered, a file containing hundreds of cyclones (see manual in appendix A for details). The result is a Dbase table that can then be treated with GIS-ArcInfo routines of Christian Herold at UNEP/GRID-Geneva, which construct automatically all the corresponding buffers. The complete process of the cyclone data is visualised in the Figure 19.

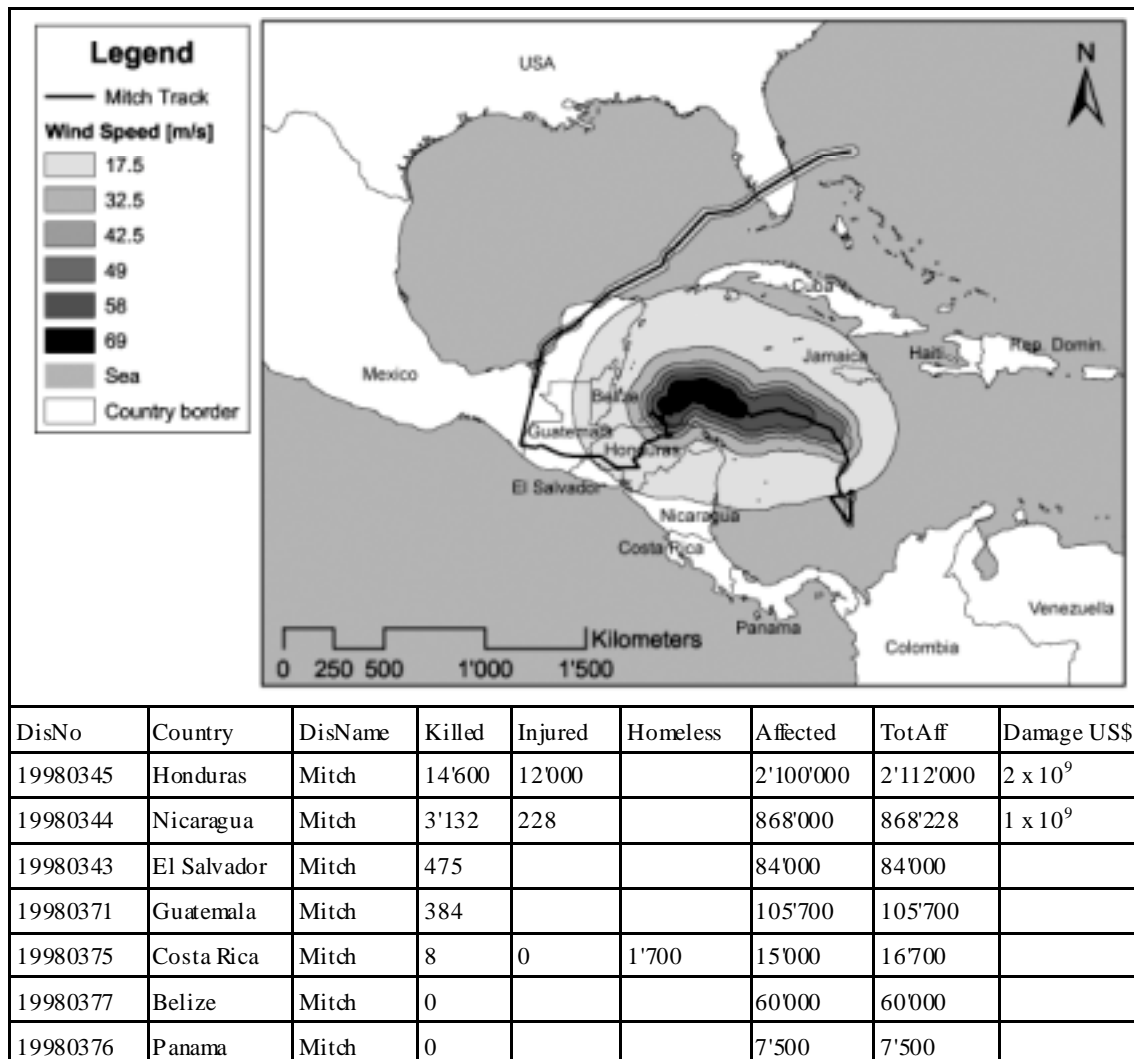
Figure 19: Global processing



Conclusion

Current and future applications

Figure 20: Wind speed buffers around Mitch track linked to information in CRED



This program was made for facilitating the organisation of global cyclone data by unifying the regional cyclone data into one database including the spatial data. This program has been used by UNEP/GRID-Geneva to build a homogeneous structured cyclone database with first level basic meteorological data and spatial data (the best cyclone tracks and their radial wind speed profiles). This database of historical cyclones was built for post-analysis research at UNEP/GRID-Geneva concerning geo-referencing the EM database provided by the Centre for Research on Epidemiology of Disasters (CRED), who is gathering the casualties and other impacts following disastrous events globally. For a global understanding on disasters, geo-referencing the different events is seen as an important approach.

As illustrated in Figure 20, the affected population by the cyclone event Mitch is adequate to the region (including countries) that was befallen by the devastating cyclone. A more precise comparison was also carried out by using existing cyclone buffers in the Southern Hemisphere made by the Bureau of Meteorology in Australia. This comparison (see appendix D) illustrates an important correlation of our global modelling with the more precise regional cyclone observations.

Further importance of a homogenised and combined database can be illustrated by the Atlantic Hurricane Database Re-analysis Project Documentation for 1851-85 Addition to the HURDAT

Database (<http://www.nhc.noaa.gov>, 2002). This work has facilitated the post-analysis research (climatic change studies, seasonal forecasting, risk assessment for country emergency managers, analysis of potential losses, intensity forecasting techniques and verification of official and various model predictions of track and intensity) of all storms occurred in the Atlantic region.

Further developments

As seen above, the aim with this study was obtained and the CycloneDatabaseManager concept has become useful for several purposes. It is nevertheless important to ameliorate this cyclone database procedure and this can be done in numerous ways:

An important improvement for obtaining more precise and adequate results is to improve the cyclone data from the sources, and it's above all a question of clarifying how the data has been retrieved and measured i.e. Metadata.

- According to Holland G.J., 1980 the measured pressures observations are more conservative and error prone than wind observations, but how reliable is this data?
- The sustained maximum wind speed is less reliable than the values of central pressure and this is probably due to the differences in measurement, that is not defined by the provider;
- The most important uncertainty is the value of R_{\max} that we were forced to estimate, since relevant data were not to be found.

In case of a better estimation of the above mentioned points we would be able to take further cyclone variables into account, e.g. landfall (vanishing of cyclone when it reaches the coast), surge (radical elevation of sea level and resulting in an enormous wave and consecutive flood) and rainband (precipitation around cyclone eye). These factors can be studied according to precise coast data.

Another important improvement would be the transmission of the cyclone data between the provider and a centralised global database, where dynamic links could be created in order to establish an automatic data transmission. Buffer estimations could then be performed in real-time and could even help previsions. Such an organisation would need a better reporting network with more convenient data structure but also a common way of observing and reporting the cyclone events.

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<http://www.nhc.noaa.gov/pastall.html> and

<http://www.aoml.noaa.gov/hrd/hurdat/Documentation.html#Introduction>

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APPENDIX A.

CycloneDatabaseManager manual

CycloneDatabaseManager 1. Building a cyclone database for post-analysis research

This appendix describes how to access tropical cyclone data from the different Regional Specialised Meteorological Centres (RSMCs) or from the Tropical Cyclone Warning Centres (TCWCs) of World Meteorological Organisation, and how these data sets can be unified for geospatial research analysis. This geospatial research involves a conversion of the cyclone observations between all three significant symbols for vector data (point, line and polygon). In addition to the feature data conversion another important processes is to structure and homogenise the enclosed data, i.e the information about the intensity of the cyclone.

Data and programs used for managing a cyclone database

To be able to carry out this treatment of cyclone observations the following programs are required:

An Internet browser (e.g. Explorer, Netscape, Opera) for accessing the untreated cyclone data.

Excel and Visual Basic for the database work.

ArcInfo or ArcView for the visualisation of the estimated wind speed profiles (polygondata).

To enable spatial analyses as the movement of cyclones (tracks) and their radial wind profiles the following parameters are obligatory: latitude, longitude, maximum sustained windspeed, central pressure, hour, day, month. This data can be obtained by consulting the following providers:

Unisys Weather, USA:

The website of Unisys (<http://weather.unisys.com/hurricane/>) is the most extensive online cyclone data collection, where the cyclone data is easy to access. The index page of this website gives an overview of the available cyclone data sorted by year and cyclone basin but also an access to a more extensive archive over the last 50 to 150 years for the Northern Hemisphere. The more extensive archive allows the user to download text files including tracking information for all cyclones events in one cyclone basin over a decade. The cyclone events are easy to distinguish from each other since they are defined by name.

The user can also search a unique cyclone event by selecting year and region “Tracking information” the cyclone observations will be displayed.

Japan Meteorological Agency:

The Japan Meteorological Agency’s website (<http://www.kishou.go.jp/english/>) includes a cyclone database with the Best Track data over the period 2000-2002 and the point observations for 1951-2002. The cyclone data is gathered yearly or over periods of a decade and the events are easily separated by the cyclones’ names.

Bureau of Meteorology, Australia:

The website of Bureau of Meteorology (<http://www.bom.gov.au/climate/how/>) comprises an online cyclone data collection of the events in the Australian region from 1906 until 2001. The database structure can be difficult to identify and it is recommended to work per cyclone event.

Fiji Meteorological Service:

On the website of Fiji Meteorological Service (<http://www.met.gov.fj/>) it’s possible to follow an active cyclone event and retrieve its tracking information, but it doesn’t provide any cyclone archives. To obtain this data a demand has to be made.

The mentioned sources are all using various orders and format for their cyclone data, but the data is accessible in text format and it is appropriate for the continuing work in Excel. This is also relevant for the use of other sources. When the text file is to be imported into Excel it’s important to carefully separate the columns in the text file (see detailed procedure for the earlier mentioned sources in the end of this manual). Before activating the Cyclone Database Manager examine the imported data for eventual mistakes during the importing procedure. After that the table columns are well structured the user has to include a empty “titlebar”, in the first table row, before the cyclone data. This “titlebar” will define the different columns in the resulting table.

How to activate the Cyclone Database Manager

In Excel the imported table has to be followed by the cyclonedatabasemanager.xls before the structure work can begin. This file includes the programs (macros) needed and they can be activated by selecting the macro:

CycloneDatabaseManager.xls!Structure.Structure (see figure 1. below for illustration).

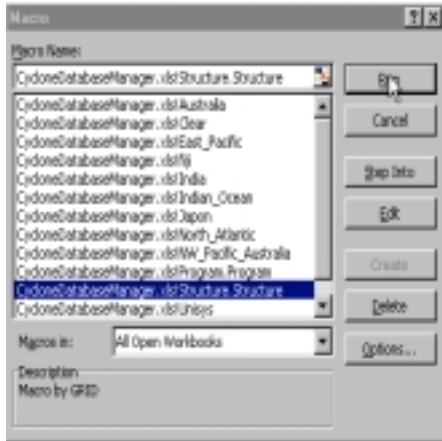


Figure 1. How to activate the macro named “Structure” in the CycloneDatabaseManager.

This procedure for activating the structure macro of Cyclone Database Manager can be facilitated by adding a tool button in the toolbar permanently. This can be carried out by opening the customise menu (under View - toolbars). In this menu, see illustration below, the user can create a proper button by selecting Commands and Macros thereafter modification of the selected button can be made (modify selection). The macro of interest (in this case CycloneDatabaseManager.xls!Structure.Structure) can thereafter be assigned to the button (see illustration in figure 2 below).



Figure 2. How to facilitate the use of the “Structure” macro in the DataBaseManager.

How to identify the cyclone parameters in the Cyclone Database Manager

The CycloneDatabaseManager provide the user with a display, see figure 3 below, where he/she can define the composition of the different variables. The numbers within the figure below illustrate the different steps in the identification procedure of the Cyclone Database Manager.

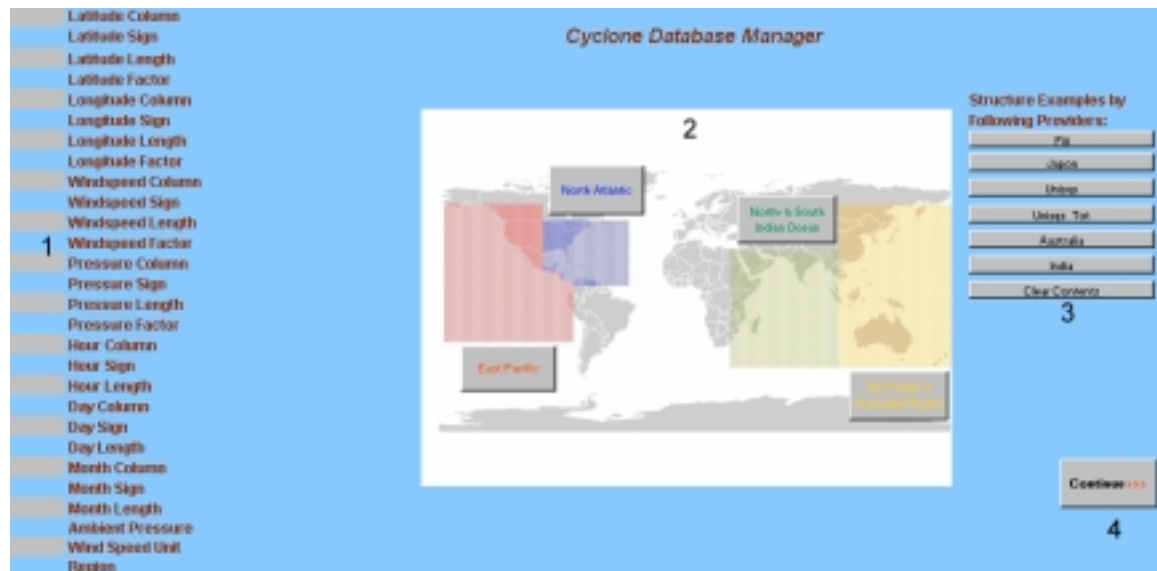


Figure 3. The display of the Cyclone Database Manager (the numbers corresponds to different sections, see clarification below)

1. In the Display the following parameters are to be defined in the left-hand column:

Latitude Column: corresponds to the column where the latitude is to be found.

Latitude Sign: corresponds to the first sign of the “Latitude string” within the Latitude Column.

Latitude Length: corresponds to the number of characters within the “Latitude string”.

Latitude Factor: corresponds to the factor of multiplication; to increase or decrease the Latitude value.

Longitude Column: corresponds to the column where the longitude is to be found.

Longitude Sign: corresponds to the first sign of the “Longitude string” within the Longitude Column.

Longitude Length: corresponds to the number of characters within the “Longitude string”

Longitude Factor: corresponds to the factor of multiplication; to increase or decrease the Longitude value.

Windspeed Column: corresponds to the column where the observed maximum sustained windspeed is to be found.

Windspeed Sign: corresponds to the first sign of the “Windspeed string” within the Windspeed Column.

Windspeed Length: corresponds to the number of characters within the “Windspeed string”.

Windspeed Factor: corresponds to the factor of multiplication; to increase or decrease the windspeed value.

Pressure Column: corresponds to the column where the observed central pressure is to be found.

Pressure Sign: corresponds to the first sign of the “Pressure string” within the Pressure Column.

Pressure Length: corresponds to the number of characters within the “Pressure string”

Pressure Factor: corresponds to the factor of multiplication; to increase or decrease the value of the central pressure.

Hour Column: corresponds to the column where the hour of observation is to be found

Hour Sign: corresponds to the first sign of the “Hour string” within the Hour Column.

Hour Length: corresponds to the number of characters within the “Hour string”.

Day Column: corresponds to the column where the day of observation is to be found

Day Sign: corresponds to the first sign of the “Day string” within the Day Column.

Day Length: corresponds to the number of characters within the “Day string”.

Month Column: corresponds to the column where the month of observation is to be found

Month Sign: corresponds to the first sign of the “Month string” within the Month Column.

Month Length: corresponds to the number of characters within the “Month string”.

Ambient Pressure: A constant defined for each cyclone basin (cyclone region) since the ambient pressure was not to be found for the different cyclone events.

Wind Speed Unit: The unit used by the cyclone data provider to define the sustained wind speed. Given in MPH, Knots, Km/h or M/s.

Region: The region defines the cyclone data provider, if unknown by the display, i.e. not defined as one of the providers in the right hand column, please enter “Unknown”.

2. The world map of the cyclone basins

The world map in the centre of the display illustrates the different cyclone basins globally and these regions are, in this version of the DataBaseManager, identified with different ambient pressures.

3. Examples of cyclone data composition

The buttons in the right hand column of the display are marked with the name of the earlier mentioned providers. These buttons may be used to complete the composition of cyclone data since the structure of the different sources is known. Before continuing it's important to examine if the predefined values in the display corresponds to the structure of the imported text file. It can be difficult to distinguish these values and the tables below might be easier to perceive.

Unisys Cyclone Database of unique cyclone events:

Latitude	Longitude	Month	Day	Hour	WindSpeed(knots)	Pressure(mbar)
----------	-----------	-------	-----	------	------------------	----------------

Unisys Cyclone Database of cyclone events over a 10 year period

Year	Month	Day	Hour	Cyclone nr.	Name	Latitude	Longitude	WindSpeed(Knots)	Pressure(mbar)
------	-------	-----	------	-------------	------	----------	-----------	------------------	----------------

The macro divide the data set with the different cyclones by identifying the name of the cyclone in the sixth column.

Fiji Meteorological Service with cyclone data tables of a 10 year period:

Name	Day	Month	Year	Hour	Latitude	Longitude	WindSpeed(knots)	Pressure(mbar)
------	-----	-------	------	------	----------	-----------	------------------	----------------

The macro divide the data set with the different cyclones by identifying the name of the cyclone in the first column.

Japan Meteorological Agency with cyclone data tables of a year or of 10 year period:

Year	Month	Day	Hour	Latitude	Longitude	Pressure(mbar)	WindSpeed(knots)
------	-------	-----	------	----------	-----------	----------------	------------------

The first line for every cyclone divide the different cyclones, and their names are possible to define in the 10th column.

Bureau of Meteorology, Australia with a cyclone data table of a one hundred year period:

Name	Year	Month	Day	Hour	Latitude	Longitude	Pressure(mbar)	WindSpeed(knots)
------	------	-------	-----	------	----------	-----------	----------------	------------------

4. After identifying all the cyclone parameters within the imported the program can be launched start by using the “Continue” button.

ERIN#	LAT	LONG	WIND	PR	HOUR	DAY	MONTH	YEAR	LBRLA17.5	LBRLO17.5	SBRLA17.5	SBRLO17.5	LBRLA32.5	LBRLO32.5	SBRLA32.5
1	22.3000	-73.2000	23.1480	1004.0000	0	31	7	95	22.8808	-72.6863	15.8890	-78.5442	22.3000	-73.2000	22.3000
2	22.6000	-73.6000	25.7200	1003.0000	6	31	7	95	23.2165	-73.0895	16.0784	-78.7261	22.6000	-73.6000	22.6000
3	22.8000	-73.9000	26.2920	999.0000	12	31	7	95	23.5292	-73.1919	16.6462	-79.5104	22.8000	-73.9000	22.8000
4	23.2000	-74.3000	30.8640	997.0000	18	31	7	95	23.9948	-73.5229	17.0794	-79.9073	23.2000	-74.3000	23.2000
5	23.6000	-74.9000	36.0080	992.0000	0	1	8	95	24.5715	-74.0046	17.2519	-80.3668	24.0149	-74.5198	23.5968
6	24.3000	-75.7000	38.5800	988.0000	6	1	8	95	25.1120	-74.4270	19.4999	-82.7005	24.6778	-75.1119	24.3007
7	25.5000	-76.3000	38.5800	985.0000	12	1	8	95	26.4757	-75.0345	20.1347	-82.7229	25.9720	-75.6922	25.6457
8	26.3000	-77.7000	38.5800	980.0000	18	1	8	95	26.7323	-77.4220	26.5090	-77.5695	26.3000	-77.7000	26.3000
9	26.9000	-79.0000	38.5800	982.0000	0	2	8	95	28.2451	-78.1154	20.0443	-83.1734	27.5648	-78.5960	27.1559

The example above is an excerpt of the cyclone event Erin 1995 after the treatment of the DataBaseManager. The example describes the table structure with the first six columns including the obligatory data as latitude, longitude, maximum sustained windspeed, central pressure, hour, day, month.

These columns, describing the intensity of the cyclone, are followed by a row of columns describing the form of this cyclone event in the North Atlantic cyclone basin. As the cyclone event took place in the Northern Hemisphere the cyclone is characterised as an anticlockwise rotating phenomena. This implies that on the right-hand side of the cyclone’s track the eye speed vector and the translational vector are in the same direction, but on the left-hand side, they are in opposite direction.

This results in asymmetry across the cyclone and the therefore the titles LBRLA17.5 (Large Buffer Latitude for the threshold 17.5 M/s), LBRLO17.5 (Large Buffer Longitude for the threshold 17.5 M/s), SBRLA17.5 (Small Buffer Latitude for the threshold 17.5 M/s) and SBRLO17.5 (Small Buffer Longitude for the threshold 17.5 M/s).The large buffer corresponds to the area on the right hand side of Erin’s cyclone track and small buffer equals the left hand side.

The outer boundary points, on the both sides of the cyclone track for every threshold, can thereafter be visualised in a GIS as one unified polygon. Except the different windspeed polygons (windspeed buffers) it’s also possible to visualise the cyclone track and the points corresponding to the cyclone observations.

The result is shown in figure 16 in the main report: Data Base Manager: A tool for converting point data from cyclone observations into tracks and wind speed profiles in a GIS.

APPENDIX B. Visual Basic code
Not public!

APPENDIX C. Saffir-Simpson scale

The Saffir-Simpson Tropical Cyclone Scale

The Saffir-Simpson Tropical Cyclone Scale is a 1-5 rating based on the tropical cyclone's present intensity. This is used to give an estimation of the potential property damage and flooding expected along the coast from the landfall of a tropical cyclone. Wind speed is the determining factor in the scale, as storm surge values are highly dependent on the slope of the continental shelf in the landfall region. It's important to take into account that there are different variables that can affect both the wind and its effect on trees and structures (<http://www.nhc.noaa.gov/aboutsshs.html>, 2001). Some of these variables include: exposure; the duration of strong winds; the age and weathering of structures; construction techniques; and for trees, the age and flexibility of the vegetation, whether or not the leaves were exposed to high levels of salt water, and whether or not the salt water was flushed from leaves by rain (personal contact with Mr. Charles Guard, July 2001). When applying this scale it's important not to concentrate too much on the individual scale but to study the overall damage in order to come up with a storm wind category. I will here under describe some of the most significant damages of the cyclones, according to NOAA, National Hurricane Center and Charles Guard at the University of Guam.

Tropical depression and tropical storm categories

Tropical Storm Category A: Weak tropical storm

Sustained Wind: <17,5 m/s

Wind Gust: 17.9-28.6 m/s

Storm Surge: Nominally

Potential damage caused by coastal inundation and wave action. The damages are only done to the most fragile structures and to the near-coastal agriculture, primarily caused by salt spray.

Tropical Storm Category B: Severe tropical storm

Sustained Wind: 17,5-32,4

Wind Gust: 28,6-42.0 m/s

Tropical Cyclone Category One: Minimal Cyclone

Sustained Wind: 32,5-42,4 m/s (74-95 mph, 64-82 kt or 119-153 km/hr)

Wind Gust: 42,0-53,6

Pressure: >980 hPa

Storm surge generally 1,2-1,5 m (4-5 ft) above normal

The damages are primarily to unanchored mobile homes, shrubbery, trees and some damage to poorly constructed signs.

The coastal inundation and wave action: Low-lying coastal roads are inundated, minor pier damage occurs and some small exposed craft might break their moorings.

Tropical Cyclone Category Two: Moderate Cyclone

Sustained Wind: 42,5-48,9 m/s (96-110 mph, 83-95 kt or 154-177 km/hr).

Wind Gust: 53,6-62,1 m/s

Pressure: 965-980 hPa

Storm surge generally 1,6-2,5 m (6-8 ft) above normal

Damages to the fragile structures of buildings i.e. roofing material, door, and window damage of buildings. Considerable damages to shrubbery and trees.

Coastal inundation and wave action: Coastal roads and low-lying escape inland are cut by rising water 2 to 4 hours before arrival of center. Considerable pier damage occurs, marinas are flooded. Small craft in unprotected areas can break their moorings. Evacuation of some shoreline residences and low-lying islands areas is required.

Tropical Cyclone Category Three: Strong Cyclone

Sustained Wind: 50-57,9 m/s (111-130 mph, 96-113 kt or 178-209 km/hr)

Wind Gust: 62,1-73,8 m/s

Pressure: 945-965 hPa

Storm surge generally 2,6-4m (9-12 ft) above normal

Some structural damage to small residences and utility buildings with a minor amount of curtain wall failures. Damage to shrubbery and trees with foliage blown off trees and large trees blown down. Mobile homes and poorly constructed signs are destroyed.

Coastal inundation and wave action: Serious flooding occurs at the coast with extensive destruction of smaller structures near the coast. Damages of the larger structures through the battering of floating debris. The low-lying inland escape routes are cut by rising water within three to five hours before arrival of center. The terrain continuously lower than 1.5 m (5 ft) above sea level may be flooded, 12.9 km or more of the inland areas. Evacuation of low-lying residences within several blocks of shoreline may be required.

Tropical Cyclone Category Four: Very Strong Cyclone

Sustained Wind: 58-68,9 m/s (131-155 mph, 114-135 kt or 210-249 km/hr).

Wind Gust: 73,8-88,1 m/s

Pressure: 920-945 hPa

Storm surge: Generally 4,1-5,5 m (13-18 ft) above normal

More extensive curtain wall failures with some complete roof structure failures on small residences. Shrubs, trees, and all signs are blown down. Complete destruction of mobile homes. Extensive damage to doors and windows

Coastal inundation and wave action: Terrain continuously lower than three meters above sea level may be flooded inland as far as 9,7 km. Major damage occurs to lower floors of structures near the shore due to flooding and battering action. Low-lying escape routes inland may be cut by rising water three to five hours before the storm center arrives. Major erosion of beach areas occurs. Massive evacuation of all residences within 457 m of the shoreline may be required and single-story residences on low ground within 3,2 km of the shoreline.

Tropical Cyclone Category Five: Devastating Cyclone

Sustained Wind: >69 m/s (>155 mph, 135 kt or 249 km/hr)

Wind Gust: >88,1 m/s

Pressure: <920 hPa

Storm surge generally greater than >5,5 m (>18 ft) above normal

Complete roof failure on many residences and industrial buildings. Some complete building failures with small utility buildings blown over or away. All shrubs, trees, and signs blown down. Complete destruction of mobile homes. Severe and extensive window and door damage. Low-lying escape routes are cut by rising water 3-5 hours before arrival of the Cyclone center.

Coastal inundation and wave action: Major damage occurs to lower floors of all structures located less than 4,6 m above sea-level and within 457 m of the shoreline. Low-lying inland escape routes are cut by rising water three to five hours before the storm center arrives. Massive evacuations of residential areas situated on low ground within 8 to 16 km of the shoreline may be required.

APPENDIX D. Gwenda 1999

Asymmetric Windspeed Profile

