Tropical Cyclone Design Wave Assessment

Brunella GUIDA & Emanuele TERRILE
Outline

• Introduction

• Outline of the Model System
  • Synthetic Tropical Cyclone Database
  • Wind and Wave Modeling

• Conclusions & Ongoing Activities
Introduction to TC Generation and Dynamics

A tropical cyclone is a rapidly rotating storm system characterized by a low-pressure center, strong winds, and a spiral arrangement of thunderstorms that produce heavy rain.

Tropical storms almost always develop over sea surface temperatures (SST) > 26 °C.

The rotation of the earth causes the storm to rotate in a cyclonic pattern (CCW in the northern hemisphere, CW in the southern hemisphere).

As the air heats, it rises rapidly, drawing incoming air to replace the rising air and creating strong wind conditions. The rapidly rising humid air then cools and condenses, resulting in heavy rains and a downdraft of cooler air.
Introduction to TC Generation and Dynamics
Introduction to TC: Worldwide Distribution

Tropical cyclones typically form between 5 and 30 degrees latitude and move toward the west. Sometimes they are steered toward the north and northwest (northern hemisphere) or south and southwest (southern hemisphere). When reach latitudes near 30 degrees they often move northeast (northern hemisphere) or southeast (southern hemisphere).
Introduction to TC: Worldwide Distribution

Tropical cyclones with max sustained surface wind speeds less than 17 m/s are usually called *tropical depressions*.

If winds reach 33 m/s they are called:
- *Hurricane*
- *Typhoon*
- *Severe tropical cyclone*
- *Very severe cyclonic storm*
- *Tropical cyclone*

depending on the geographic area.
## Introduction to TC: Saffir-Simpson Scale

<table>
<thead>
<tr>
<th>SAFFIR-SIMPSON SCALE</th>
<th>MAXIMUM WIND SPEED [Knots]</th>
<th>STORM SURGE [Metres]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TROPICAL DEPRESSION</td>
<td>&lt; 34</td>
<td>NOT APPLICABLE</td>
</tr>
<tr>
<td>TROPICAL STORM</td>
<td>34-63</td>
<td>NOT APPLICABLE</td>
</tr>
<tr>
<td>CATEGORY 1: CYCLONE</td>
<td>64-82</td>
<td>1.0 - 1.7</td>
</tr>
<tr>
<td>CATEGORY 2: CYCLONE</td>
<td>83-95</td>
<td>1.8 - 2.6</td>
</tr>
<tr>
<td>CATEGORY 3: MAJOR CYCLONE</td>
<td>96-113</td>
<td>2.7 - 3.8</td>
</tr>
<tr>
<td>CATEGORY 4: MAJOR CYCLONE</td>
<td>114-135</td>
<td>3.9 - 5.6</td>
</tr>
<tr>
<td>CATEGORY 5: MAJOR /SUPER CYCLONE</td>
<td>&gt; 135</td>
<td>&gt; 5.6</td>
</tr>
</tbody>
</table>
Design Parameters under Cyclonic conditions

Assessment of metocean parameters (extreme values) to define design criteria is commonly done by separating NON-CYCLONIC and CYCLONIC conditions.

NON-CYCLONIC conditions:
• use of short historical database
• POT methods and extreme values extrapolation (up to 100 year return period);

CYCLONIC conditions:
• extension of NON CYCLONIC methods at very low probabilities (up to $10^{-4}$ as required by international rules) bring to highly uncertain estimates.

To overcome the problem of extrapolation a SYNTHETIC TC DATABASE is required → representative of 500-1,000-10,000-10,000 years

This allow examination of storm and wave characteristics at different return period up to 10,000 years and moreover time histories allow response-based criteria.
Synthetic Tropical Cyclone Database

**Synthetic tropical cyclone database** is needed in order to enlarge the number of events to be analysed (James and Mason 2005, Emanuel et al., 2006; McInnes et al., 2014). Constructed starting from historical database.

Particularly useful in areas where the historical cyclone database is characterized by few data.
Outline of the CycloMo Model System

Two main stages can be identified:

- Creation of a “new” tropical cyclone database
- Wave simulations for each selected track

SYNTHETIC TROPICAL CYCLONE DATABASE

- Historical Database
  - Statistical Analysis
- Regression Module
  - Set-up and Calibration
- New Cyclone Generation
  - Generation of new extended synthetic cyclone database
- Selection
  - Selection of cyclone tracks around the study area

WAVE MODELLING

- Cyclone Wind field
  - Modeling of wind field for each selected track
- Wave field
  - Modeling of cyclone-induced wave field for each selected track
- Selection
  - Extraction of wave time series for each simulated cyclone

STATISTICAL WAVE EXTREME ANALYSIS

- Extreme distribution
  - Definition of the extreme distribution to be used
- Cyclonic Extreme Wave
  - Definition wave extreme values at the study area for fixed return period
Historical Database

**South Hemisphere:**

- Joint Typhoon Warning Center Best Track Data (1945-2010)
  
  For each cyclone with 6 hours interval:
  - position in latitude and longitude;
  - maximum sustained winds;
  - central pressure (in the cyclone eye);
  - cyclonic radius;
  - cyclonic forward speed and direction.

- MeteoFrance La Reunion database (2011-2014)
  - distances from the cyclone eye of fixed wind intensities – “TC shape”
Synthetic Tropical Cyclone Database

**Regression Module**
Following James and Mason (2005) regression was investigated involving the available variables and their first differences.

Regression was done on the first differences of the time series of $x$ (longitude), $y$ (latitude) and $w$ (maximum wind). The first differences are direct measures of $V_x$, $V_y$ and maximum wind rate of change.

\[
\Delta x_t = a_1 + a_2 \Delta x_{t-1} + a_3 x_{t-1} + a_4 y_{t-1} \\
\Delta y_t = b_1 + b_2 \Delta y_{t-1} + b_3 y_{t-1} + b_4 x_{t-1} \\
\Delta w_t = c_1 + c_2 \Delta w_{t-1}
\]
Synthetic Tropical Cyclone Database

Regression Module

Pairs of first differences $\{\Delta x_t, \Delta x_{t-1}\}$ were assembled and aggregated over all locations of all historical cyclones over an area of 2000 km of radius centred on the study area.
**New Cyclone Generation**

The first two values of $x$, $y$, and $w$ are required to initiate the process randomness is given from the residual of regression, i.e. $\epsilon_t$ (James and Mason, 2005).

The initial conditions of the historical tracks could be used – **Not enough**

The initial conditions are the initial values of $x$, $y$, $w$, $\Delta x$, $\Delta y$ and $\Delta w$ (6D space in which historical values are distributed).

Method employed by Scheffner et al. (1996) and James & Mason (2005), preserving any dependencies among the parameters.

Historical database: **65 years 209 tracks**  
New database: **500 years 1607 tracks**
Synthetic Tropical Cyclone Database

New Cyclone Generation

Check → Probability Density Function

Hysterical Database - N=209 events

Model Results - N=1607 events
Genoa, October 16th, 2015

**Synthetic Tropical Cyclone Database**

**New Cyclone Generation**

**Results** → **New tracks – 1607 events**

- Historical Cyclone Tracks within 2000 km from Point A - N=209 events
- Model Results: New Cyclone Tracks within 2000 km from Point A - 1607 events
Synthetic Tropical Cyclone Database

New Cyclone Generation

**Comparison with Historical data**

- Hypothesis that the historical and simulated values come from the same statistical population;
- For each parameter, such as forward speed, we tested the goodness of fit between the cumulative distribution function of the historical data and the CDF obtained from the model results.

![Graphs showing comparison between historical and model results for Longitude Velocity, Latitude Velocity, and Maximum Wind.](image)
Cyclone Track selection – track within 600 km from the center of the study area

The distance of 600 km was chosen to ensure that wave and water-level effects at point A from distant storms would be included. Simulated statistics in this area were found to be insensitive to the size and shape of this domain.
Cyclone Wind Field

Wind field for each cyclone - Holland (1980) model:

\[ V_g(r) = \sqrt{\frac{AB(p_n - p_c)\exp\left(-\frac{A}{r^B}\right)}{\rho r^B}} + 0.25 \, r^2 f^2 - 0.5rf \]

*\(V_g\) is the wind intensity at radius \(r\)*
*\(f\) is the Coriolis parameter*
*\(\rho\) the air density (assumed constant at 1.15 km/m\(^3\))*
*\(p_n\) is the ambient pressure (i.e. 1008 hPa in the South Indian Ocean, Mouton and Nordbeck, 2002)*
*\(p_c\) is the pressure in the center of the eye*

Empirical scaling parameters:

- **A** - wind profile location relative to the origin
- **B** – shape parameter
Cyclone Wind Field

Wind field for each cyclone

In the southern hemisphere wind speeds to the left of the storm track are always higher than those on the right.

Jelesnianski (1966) suggests the following simple form for this correction:

\[ V_{sm}(r) = \frac{R r}{R^2 + r^2} V_f \]

where:
- \( V_f \) is the cyclone track velocity
- \( V_{sm} \) is the convective term to be added to the wind field (vector)
Cyclone Wind Field

Wind field for each cyclone - Holland (1980) model:

\[ V_g(r) = \sqrt{\frac{AB(p_n - p_c)\exp\left(-\frac{A}{r^B}\right)}{\rho r^B} + 0.25 r^2 f^2 - 0.5rf} \]

- \( V_g \) is the wind intensity at radius \( r \)
- \( f \) is the Coriolis parameter
- \( \rho \) the air density (assumed constant at 1.15 km/m³)
- \( p_n \) is the ambient pressure (i.e. 1008 hPa in the South Indian Ocean, Mouton and Nordbeck, 2002)
- \( p_c \) is the pressure in the center of the eye

Empirical scaling parameters:
- \( A \) - wind profile location relative to the origin
- \( B \) – shape parameter
Central Pressure

The central pressure $p_c$ is obtained from the JTWC database as function of the maximum wind intensity.

$\text{Central Pressure } p_c (\text{hPa})$

$\text{Maximum Wind Speed } V_m (\text{m/s})$

$\begin{align*}
    p_c &= -0.0078V_m^2 + 0.8181V_m + 1015.7
\end{align*}$
Wind and Wave Modeling

**Location Parameter $A$**

The location parameter $A$ is defined as:

$$R_w = A^{1/B}$$

$R_w$ is the radius of maximum winds.

In order to associate a radius $R_w$ at each time step of the cyclone track evolution, historical database data were analyzed (within 2000 km)

*Maximum Wind Speed vs Corresponding Radius $R_w$*
Shape Parameter $B$

The shape parameter $B$ is defined as function of the maximum wind speed as:

$$B = \frac{1}{\alpha}B^* = \frac{1}{\alpha \left( \rho_n - \rho_c \right)} \rho \exp (1)$$

where $B^*$ is the shape parameter as defined in Holland (1980).

$\alpha$ is a calibrating coefficient included in the definition of $B$ in order to obtain a more reliable wind profile for the South Indian Ocean.
Wind and Wave Modeling

Shape Parameter $B$

MeteoFrance La Reunion database information about the wind profile

Analysis on 515 wind profiles fitting them with the Holland wind model

Higher $\alpha$ induce lower shape parameter $B$ more flat wind profile
Wind and Wave Modeling

Shape Parameter $B$

MeteoFrance La Reunion database information about the wind profile

Analysis on 515 wind profiles fitting them with the Holland wind model

From the historical data analysis the coefficient $\alpha$ varies from 0.25 to 1.0 all over the South Indian Ocean

a mean value for the Mozambique Channel $\alpha = 0.4$
Cyclone Induced Wave Field

Each of the **188 selected synthetic cyclone tracks** was used to model the induced wave field from the generated wind field.

The wave model SWAN was used to model the non-stationary wave field associated to **each cyclone**.
Cyclone Induced Wave Field

SWAN is a third-generation spectral wave model.

3D Bathymetry from GEBCO database

SWAN reproduce all physical phenomena associated to the wave generation/propagation/dissipation:

• Wave breaking
• Shoaling
• Refraction
• White capping dissipation
• Wave-wave interaction in shallow water
• Correct representation of offshore features (e.g. islands, reefs)

etc.
Wind and Wave Modeling
Trapped-Fetch Waves (TFW)

Occurs when storms move in resonance with the waves they generate and act so that less-intense wind systems can also develop Extreme Storm Seas (Bowyer and MacAfee, 2005).

Waves move with the fetch
Max Wave induced by the single TC track

Island shadow effect on wave propagation

Island shadow effect on wave generation

Shallow water effects
Wind and Wave Modeling

Model Verification

Comparison between wind and wave time series measured at different locations with the corresponding modelled values extracted at the same location.
Wind and Wave Modeling

The obtained time series in order to evaluate the Cyclonic Extreme Values and *response-based* criteria

<table>
<thead>
<tr>
<th>%Point: -11.8 , 40.8</th>
<th>%Track</th>
<th>Hsig</th>
<th>Dir</th>
<th>Tp</th>
<th>W_Hs</th>
<th>DW_Hs</th>
<th>Wmax</th>
<th>DWmax</th>
</tr>
</thead>
<tbody>
<tr>
<td>100002</td>
<td>1.15</td>
<td>325.3</td>
<td>9.1</td>
<td></td>
<td>2.7</td>
<td>70.3</td>
<td>4.5</td>
<td>31.8</td>
</tr>
<tr>
<td>100005</td>
<td>0.57</td>
<td>35.4</td>
<td>7.0</td>
<td></td>
<td>4.2</td>
<td>100.8</td>
<td>5.3</td>
<td>65.4</td>
</tr>
<tr>
<td>100006</td>
<td>2.21</td>
<td>13.6</td>
<td>8.0</td>
<td></td>
<td>9.9</td>
<td>66.8</td>
<td>10.4</td>
<td>62.5</td>
</tr>
<tr>
<td>100010</td>
<td>1.60</td>
<td>331.9</td>
<td>10.2</td>
<td></td>
<td>4.0</td>
<td>109.9</td>
<td>4.6</td>
<td>102.9</td>
</tr>
<tr>
<td>100011</td>
<td>1.41</td>
<td>225.2</td>
<td>9.6</td>
<td></td>
<td>3.2</td>
<td>270.1</td>
<td>3.7</td>
<td>288.0</td>
</tr>
<tr>
<td>100020</td>
<td>3.89</td>
<td>358.7</td>
<td>10.8</td>
<td></td>
<td>11.8</td>
<td>72.3</td>
<td>12.3</td>
<td>76.6</td>
</tr>
<tr>
<td>100027</td>
<td>1.01</td>
<td>216.7</td>
<td>8.4</td>
<td></td>
<td>0.0</td>
<td>0.0</td>
<td>4.0</td>
<td>292.5</td>
</tr>
<tr>
<td>100032</td>
<td>0.14</td>
<td>62.9</td>
<td>1.8</td>
<td></td>
<td>2.7</td>
<td>83.7</td>
<td>2.9</td>
<td>72.6</td>
</tr>
</tbody>
</table>

Max wave recorded at Point A for each TC track
Associated Wind
Max wind recorded at Point A for each TC track
Conclusions and ongoing activities

Present work was aimed at define Extreme wave values in Cyclonic conditions
• Building Synthetic TC database along the Mozambique/Tanzania Coast
• Wind and Wave modeling
• Preliminary analysis

Ongoing activities:
• Expanding the Synthetic TC database up to 10,000 years or more
• Create Extreme values 2D maps
• Coupling Nearshore Hydrodynamic