The Rise of Extreme Typhoon Power and Duration over South East Asia Seas

Grzegorz Rozynski

ABSTRACT

The study features an analysis of 40 years of records of longitude, latitude and power (wind speed) of tropical storms and typhoons over South East Asia seas. The results demonstrate the growing intensity of the most severe events. The singular spectrum analysis of wind speed series from 1960 till 2000 identified two sub-periods of roughly similar behavior. Then, the recorded events were classified statistically and the escalating power and duration of the most extreme ones were examined with extreme probability distributions to quantify the resulting climate change consequences in the studied region. Finally, conclusions and suggestions for a potential follow-up research were provided.

1. INTRODUCTION

The role of extreme events was highlighted in the 4th IPCC Assessment Report (e.g. Schneider et al. 2007). The current model simulations estimate that increasing extreme events will generate impacts by mid-century (Meehl et al. 2007). However, some data re-analyses imply that, since the 1970s, tropical cyclone intensities have increased far more rapidly in all major ocean basins, where tropical cyclones occur (Trenberth et al. 2007), and that this is connected with increasing sea surface temperatures. Some authors have been questioning the reliability of these data on the grounds that climate models do not predict such large increases. On the other hand the climate models could be underestimating the changes due to inadequate spatial resolution (Schneider et al. 2007). Hence, this issue remains unresolved; some modeling experiments even suggest that the total number of tropical cyclones is expected to decrease slightly (Meehl et al. 2007). However, recent studies have shown that the frequency and intensity of tropical cyclones originating in the Pacific have increased over the last decades (Cruz et al. 2007).

The latest research illustrates difficulties related to the interpretation of North Western Pacific climatic data. Emanuel (2005) introduced the concept of power dissipation index (PDI) as cubed maximum wind speed, recorded at standard 10 m altitude throughout the event, and then integrated over its lifetime. Since PDI is expressed in energy units it is a good measure of the intensity of extreme events. He then found that annually accumulated PDI and average sea surface temperature (SST) show similar growing trends since 1970. Webster et al. (2005) arrived at similar results when they confronted the SST data from 1970-2005 with the number of the most severe hurricanes (category 4 and 5), split into two sub-periods 1975-1989 and 1990-2005. Consequently, they found that for the West Pacific the number of such events grew from 85 (25%) to 116 (41%), again indicating the climate change impact as the positive
relationship between the SST and the number of the most extreme events. This claim was countered by Chan (2006), who argued that the period 1960-2000 was featured by large inter-decadal variations and any inferring about the trends of extreme events remains vague.

The damage caused by intense cyclones has risen significantly in the affected countries, PAGASA, 2001; Cruz et al. 2007. In general, South East Asia is deemed highly vulnerable to the changing climate in sectors such as food production, biodiversity, coastal ecosystems, human health and land degradation with high confidence level. Particularly dramatic consequences can be expected for densely populated, low-lying areas, such as the deltas of large rivers in Vietnam. It is estimated that 17 million people will be affected in Vietnam by climate change aftermaths, of which 14 million live in the Mekong Delta provinces (Zeidler 1997), if no measures are taken. Agricultural activities in that delta will also be at high risk; detailed modeling implies significant changes in the number of rice crops in the Mekong Delta under 20-40 cm of relative sea-level rise (Wassmann et al. 2004).

The above facts demonstrate the timeliness of climate change related research in South East Asia. The research should properly treat uncertainties in studies on extremes, knowing that they hamper accurate predictions and limit the effectiveness of flood risk management. This can be achieved by methods that have lately been developed to better deal with uncertainties in extremes. For example extreme value theory, including sea level and storm surges, has been presented recently (Haan and Ronde, 1998; Todd and Walton, 2000; Coles, 2001). However, it is recognized that uncertainty in the estimation procedure of tropical cyclone intensity makes it difficult to clarify the relationship between cyclone activity and global warming. This problem was highlighted by Kossin et al., 2007, who found that the existing global hurricane records were too inconsistent to extract their trends. For this reason the current study included the Singular Spectrum Analysis (SSA), because this technique is a very powerful and reliable tool for the extraction of trends, non-stationarity and oscillatory components from short and noisy datasets (Vautard et al. 1992). The SSA results, obtained from the available dataset of 40 years of observations of extreme wind speed gave grounds for the division of the whole dataset into two roughly equal sub-periods for which pre-defined classes of wind speed were adopted and the corresponding frequency tables calculated. The frequency tables were then used for the construction of extreme value probability distribution functions of peak wind speed and its duration. We believe that very high increase in the duration of extreme events in the 2nd SSA-defined sub-period cannot be trivial and can illustrate the climate change effect.

2. DATASET

The study was based on data on extreme events in the 1960-2000 period, obtained from the best track data, provided by http://weather.unisys.com/hurricane/index.html. A typical record is presented in Table 1. The first column represents the numbers of consecutive wind speed records in a given event, taken every 6 hours (midnight 6 a.m., noon and 6 p.m.), provided in col.4. Col. 2 represents the latitude and col. 3 the longitude of the center of tropical storm/typhoon. The columns 6 and 7 contain event classification (tropical depressions for the wind speed up to 35 knots, tropical storms with speeds of 35 - 60 knots, 1st class typhoons for 65 - 80 knots, 2nd class for 85 - 95 knots, 3rd class for 100 – 115 knots and 4th class typhoon for speeds above 115 knots. The column 5 contains the wind speed in knots. Below this table duration, year and
event number in that year are given. The columns 2, 3 and 5 of all individual events can be concatenated to obtain the overall spatiotemporal pattern of extreme events between 1960 – 2000 with the same sampling rate of 6 hours. This operation concealed the information on event duration, time between consecutive events, year and event number. In return, identification of crude characteristics of extreme events in the whole analyzed period became possible.

Table 1 Data featuring exemplary extreme event

<table>
<thead>
<tr>
<th>ADV</th>
<th>LAT</th>
<th>LON</th>
<th>TIME</th>
<th>WIND</th>
<th>STAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.5</td>
<td>128.1</td>
<td>07/16/12</td>
<td>30</td>
<td>TROPICAL DEPRESSION</td>
</tr>
<tr>
<td>2</td>
<td>11.4</td>
<td>126.5</td>
<td>07/16/18</td>
<td>35</td>
<td>TROPICAL STORM</td>
</tr>
<tr>
<td>3</td>
<td>12.2</td>
<td>125.2</td>
<td>07/17/00</td>
<td>40</td>
<td>TROPICAL STORM</td>
</tr>
<tr>
<td>4</td>
<td>12.8</td>
<td>124.2</td>
<td>07/17/06</td>
<td>40</td>
<td>TROPICAL STORM</td>
</tr>
<tr>
<td>5</td>
<td>13.4</td>
<td>123.2</td>
<td>07/17/12</td>
<td>40</td>
<td>TROPICAL STORM</td>
</tr>
<tr>
<td>6</td>
<td>14.4</td>
<td>122</td>
<td>07/17/18</td>
<td>40</td>
<td>TROPICAL STORM</td>
</tr>
<tr>
<td>7</td>
<td>15.3</td>
<td>120.8</td>
<td>07/18/00</td>
<td>40</td>
<td>TROPICAL STORM</td>
</tr>
<tr>
<td>8</td>
<td>15.6</td>
<td>119.6</td>
<td>07/18/06</td>
<td>45</td>
<td>TROPICAL STORM</td>
</tr>
<tr>
<td>9</td>
<td>15.9</td>
<td>118.3</td>
<td>07/18/12</td>
<td>50</td>
<td>TROPICAL STORM</td>
</tr>
<tr>
<td>10</td>
<td>16.5</td>
<td>116.9</td>
<td>07/18/18</td>
<td>50</td>
<td>TROPICAL STORM</td>
</tr>
<tr>
<td>11</td>
<td>17.1</td>
<td>115.5</td>
<td>07/19/00</td>
<td>50</td>
<td>TROPICAL STORM</td>
</tr>
<tr>
<td>12</td>
<td>17.2</td>
<td>114.1</td>
<td>07/19/06</td>
<td>55</td>
<td>TROPICAL STORM</td>
</tr>
<tr>
<td>13</td>
<td>17.2</td>
<td>113</td>
<td>07/19/12</td>
<td>60</td>
<td>TROPICAL STORM</td>
</tr>
<tr>
<td>14</td>
<td>17.4</td>
<td>112.4</td>
<td>07/19/18</td>
<td>70</td>
<td>TYPHOON-1</td>
</tr>
<tr>
<td>15</td>
<td>17.7</td>
<td>111.9</td>
<td>07/20/00</td>
<td>75</td>
<td>TYPHOON-1</td>
</tr>
<tr>
<td>16</td>
<td>18.5</td>
<td>111.2</td>
<td>07/20/06</td>
<td>75</td>
<td>TYPHOON-1</td>
</tr>
<tr>
<td>17</td>
<td>19.3</td>
<td>110.5</td>
<td>07/20/12</td>
<td>70</td>
<td>TYPHOON-1</td>
</tr>
<tr>
<td>18</td>
<td>19.7</td>
<td>109.6</td>
<td>07/20/18</td>
<td>70</td>
<td>TYPHOON-1</td>
</tr>
<tr>
<td>19</td>
<td>20.2</td>
<td>108.5</td>
<td>07/21/00</td>
<td>65</td>
<td>TYPHOON-1</td>
</tr>
<tr>
<td>20</td>
<td>20.7</td>
<td>107.2</td>
<td>07/21/06</td>
<td>55</td>
<td>TROPICAL STORM</td>
</tr>
<tr>
<td>21</td>
<td>21.3</td>
<td>105.7</td>
<td>07/21/12</td>
<td>35</td>
<td>TROPICAL STORM</td>
</tr>
</tbody>
</table>

Date: 16-21 JUL 1977

3. METHODOLOGY

The concatenation produced three time series describing extreme events over 40 years of observations with N = 2938 triplets. This allowed for application of singular spectrum analysis (SSA). SSA has been widely used in signal processing and diagnostics for over a decade now (Vautard et al. 1992 or Różyński et al. 2001). This method is akin to conventional principal component analysis (PCA) but in contrast to PCA the SSA provides information on the dynamics of the underlying system (von
Storch and Navarra, 1995). Moreover, the complete system dynamics can be reconstructed from the data without any knowledge of the evolution equations (Broomhead and King 1986). The major difference is that in the PCA we analyze eigenvalues of system’s covariance matrix in space, whose elements are realizations of a random field, whereas in the SSA we study eigenvalues of a covariance matrix in time of a 1-D time series. This matrix is symmetric about the main diagonal and elements along each diagonal are the same (Toeplitz structure):

\[
T = \begin{bmatrix}
    c(0) & c(1) & \ldots & c(M-1) \\
    c(1) & c(0) & c(1) & \ldots \\
    \vdots & \vdots & \ddots & \vdots \\
    c(M-1) & \ldots & c(1) & c(0)
\end{bmatrix}
\]

(1)

The user defined embedding dimension \( M \) represents the maximum lag of the covariance matrix and determines its dimensions. Normally, all information about the system’s dynamics above the noise threshold is located in just a few reconstructed components, associated with the greatest eigenvalues of \( T \). All eigenvalues are positive and define the importance of the associated eigenvector and principal component, although they cannot be understood as the contribution to the overall signal variance. Eigenvectors and principal components of the SSA method are rather inconvenient for deducing the behavior of the examined system. Therefore, reconstructed components have been established as the mean values of all the ways every element of \( k \)-th reconstructed component of the analyzed time series can be computed:

\[
x_i^k = \frac{1}{M} \sum_{j=1}^{M} a_{i-j+1}^k E_j^k 
\]

for \( M \leq i \leq N-M+1 \)  

(2a)

\[
x_i^k = \frac{1}{i} \sum_{j=1}^{i} a_{i-j+1}^k E_j^k 
\]

for \( M \leq i \leq M-1 \)  

(2b)

\[
x_i^k = \frac{1}{N-i+1} \sum_{j=i-N+M}^{M} a_{i-j+1}^k E_j^k 
\]

for \( N-M+2 \leq i \leq N \)  

(2c)

The 1st equation is valid for the middle, the 2nd for the beginning and the 3rd for the end of the series and denote i-th element of k-th reconstructed component. The quantity denotes j-th element of k-th eigenvector and represents i-j+1 –th element of k-th principal component. There are always M reconstructed components; they are additive, so the analyzed series is expanded into M sub-series, whose interpretation is relatively straightforward. The reconstructed components are usually cross-correlated, because SSA principal components are cross-correlated as well, despite their orthogonality. Hence, variances of reconstructed components are not cumulative.

4. ANALYSIS

From visual inspection (Fig. 1a,b,c) it can be seen that the wind speed exhibits alternating sequences of years with many extreme events followed by years where such events hardly exist. The longitudes exhibit a gentle tendency towards achieving more easterly locations by some events, whereas the latitudes are close to stationarity. The wind speed series was examined for \( M = 20 \). This value of \( M \) covers 120h (5 days), corresponds to lifetimes of shorter events and reflects the fact that patterns shorter than individual events, normally emerging for larger \( M \), would in this case be highly uncertain due to concatenation of single events into one time series. Fig. 2 contains the resulting eigenvalues and indicates that there are 3 significant reconstructed components
above the noise threshold. The most significant one (R1) is the long-term trend in the form of a periodic behavior with the period in the range of 20 years. Fig. 3 shows this component vs. the raw series; R1 incorporates 42.2% of its total variability. Fig. 3 implies that R1 contains one entire cycle (records 1250-2600), one nearly entire cycle (records 1-1250) and the beginning of the 3rd cycle (records 2600-2938). The partitioning of data according to the trajectory of R1 must produce two sub-series with similar behavior; this breakpoint was found for the record 1469, which corresponds to the beginning of 1982, so that one sub-series covered the time between 1960-1982 and the other 1982-2000.

The 2nd reconstructed component R2 incorporates 13% of the variability of the wind speed series. Knowing the sampling interval (6 h), the normalized spectral peak (0.03), see Fig. 4, corresponds to $T = 200$ hours or about 8 days. This coincides with the lifetime of powerful, long events and reflects the fact that the wind speed series was composed of concatenated individual events featuring a cycle from low to high wind speeds and then back from high to low ones. Direct link with the climate change of this component is vague, though. The 3rd reconstructed component R3 encompasses only 3% of wind speed variability. The peak period of R3 can be found for 0.05 of the normalized (cycle/6 hours) frequency, see Fig. 4, which corresponds to 120 hours or 5 days. This peak describes short, much less powerful events like tropical depressions and storms weaker than typhoons that have little relevance for studies on long-term climate change.

After partitioning of wind speed series cross-comparison of the number of occurrences for pre-defined event classes was done. Before that all records below 20 knots were removed, so that 1416 records remained in the 1st sub-series and 1343 in the 2nd one. Table 2 presents the outcome for all wind speed classes. The percentage of the mildest events (20 – 40 knots) grew from 29% to 40% and was compensated by the fall in the (40 – 60 knots) category from nearly 29% to 21%. The percentage in two next classes did not change much and amounted to 24.5% vs. 21 % for the 60 – 80 knots class and to 10% vs. 8.5% for the 80 – 100 knots class. The drop in the next class (100 – 120 knots) is hardly significant as well (5% vs. 4%). In contrast, the percentage of the most extreme occurrences ($v \geq 120$ knots) almost doubled from 2.7% to 5.3%. This illustrates the character of climate change, featured by almost no change in medium events, a slight tendency toward greater number of the mildest events and very significant growth of the number of the most severe typhoons.

More in-depth quantification of climate change consequences was done with extreme value probability distribution functions (PDF). The Gumbel-type PDF needed only 2 model parameters, which sufficed to achieve high skill least square fits between the model and data with the correlation coefficient greater than 0.95. The Gumbel PDF obeys the equation:

$$F(x) = \exp\{-\exp[-\frac{(x-\eta)}{\xi}]\} \quad (3)$$

Fig. 5 presents empirical extreme distributions of wind speed, obtained from annual maxima in both sub-periods, together with the associated least square fitted Gumbel PDF-s. We can see that indeed the maximum wind speed grew between 1982-2000 with respect to 1960-1982 sub-period, although not significantly. For example 90% probability of the maximum wind speed corresponded to almost 150 knots between 1960-1982, whereas between 1982-2000 it grew to a bit more than 160 knots. Therefore, the growth of maximum annual wind speed does not produce dramatic
climate change impacts.

Table 2 Categorization of occurrences in two sub-periods

<table>
<thead>
<tr>
<th>Wind speed category (knots)</th>
<th>Occurrences' 1st sub-period</th>
<th>Occurrences' 2nd sub-period</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 &lt;= v &lt; 40</td>
<td>416</td>
<td>536</td>
</tr>
<tr>
<td>40 &lt;= v &lt; 60</td>
<td>402</td>
<td>282</td>
</tr>
<tr>
<td>60 &lt;= v &lt; 80</td>
<td>348</td>
<td>287</td>
</tr>
<tr>
<td>80 &lt;= v &lt; 100</td>
<td>141</td>
<td>114</td>
</tr>
<tr>
<td>100 &lt;= v &lt; 120</td>
<td>71</td>
<td>53</td>
</tr>
<tr>
<td>v &gt;= 120</td>
<td>38</td>
<td>71</td>
</tr>
<tr>
<td>Total</td>
<td>1416</td>
<td>1343</td>
</tr>
</tbody>
</table>

occurrence = 6 hours

Maximum empirical annual durations and the associated Gumbel probability distributions of typhoons with v >= 120 knots are presented in Fig. 6. They are expressed by hours and were calculated knowing the sampling interval of 6 hours. Immediately we can see that the duration of the most extreme events is the major manifestation of the changing climate. For example, from the Gumbel functions we can read that between 1960-1982 90% probability denoted the duration of 40 hours of typhoon peak (v >= 120 knots) and in the later period 90% probability was associated with nearly twice as long duration (70 hours). Therefore, Fig. 6 informs that coastal areas will have to absorb much larger amounts of peak storm energy than they used to do in the past.
Fig 1. Raw data; (a) longitudes, top left, (b) latitudes top, right, (c) wind speed, bottom

Fig 2. Eigenvalues of SSA decomposition of wind speed series….
Fig3. Wind speed and SSA 1st reconstructed component - partitioning of data for cross-examination of long-term change

Fig4. Spectral densities: R2 and R3
Fig5. Empirical and extreme value Gumbel PDF-s for maximum annual wind speed in two SSA determined sub-periods.

Fig6. Empirical and extreme value Gumbel PDF-s for maximum duration of annual events for v >=120 knots in two SSA determined sub-periods.
5. DISCUSSION

Chan (2006), using the power dissipation index (PDI) concept, found that 1960 – 2000 period was characterized by large inter-decadal variations that make inferring about climatic changes rather problematic. Thus, the use of SSA is so important, because it allowed for objective identification of two similar ‘epochs’, featuring the trends of extreme weather conditions over South-East Asia seas. The identification of similar epochs then established grounds for tracing the manifestations of non-trivial climate change over the 40 years of observations through the examination of peak wind speed and duration of the most extreme, annual events in both epochs. The resulting Gumbel PDF-s demonstrate that changes in peak power do not differ much and probably are not significant. On the other hand, durations of wind speed above 120 knots nearly doubled, so climatic changes are manifested rather by longer durations of the most extreme events. However, these quantities were derived from very small amounts of extreme records, so they remain uncertain. Since extreme value theories assume the independence of extreme occurrences, we can replicate the series of extreme annual events by re-sampling the annual maxima and returning each drawn element. The re-sampled series can then be used for fitting of an extreme PDF. With a sufficient number of such replications (1,000 or so) we can obtain envelopes of extreme distributions and calculate the expected values and standard deviations for every extreme wind speed and duration. Better modeling accuracy can be achieved in this way, because uncertainties, inherent in fitting a curve to the data, are exposed in this way. This bootstrap re-sampling method was applied by Reeve et al., 2008 for the coastal data. Interesting results of this study prove this method can also be recommended for further research on climate variability.

The 2\textsuperscript{nd} problem is the precision of PDI estimation. The definition of PDI involves:

\[ PDI = \int_0^\tau \left(\frac{V_{\text{max}}}{V_0}\right)^3 dt \quad (4) \]

where \(V_{\text{max}}\) is maximum sustained wind speed at 10m altitude and \(\tau\) is the event lifetime. This formula shows that small errors in the assessment of peak wind speed can produce dramatic errors in the evaluation of PDI, because it involves cubed speeds. Another important aspect is that peak wind speeds are evaluated at rather large intervals, e.g. 6 hours, so random errors due to coarse ‘sampling’ are likely to appear as well. In this regard the evaluation of duration of maximum wind speed above a certain, high threshold appears to be a lot ‘safer’, because errors in its estimation propagate linearly in the PDI integral. Fig. 5 indicates that changes in maximum wind speeds in both sub-periods need not be significant. By contrast, the almost doubled duration of events with speeds greater than 120 knots in the 1982-2000 period vs. the 1960-1982 interval appears to be much more significant and indicates that the coasts of South East Asia countries will have to approximately absorb twice as much quickly released energy of the most powerful typhoons. Thus, the peak forces exerted on coastal systems/defenses are not likely to grow, although they will probably be operating twice or so longer.

The study results indicate severe future consequences of increasing storminess for the countries located in South East Asia (Vietnam, Philippines…). Low-lying areas, especially river mouths and deltas will thus become increasingly vulnerable to shoreline erosion and/or silting-up of navigational channels, as they will have to absorb much more wave energy. Importantly, the results indicate that extreme forces exerted on coastal defenses are not likely to grow, so also extreme loads, such as peak storm surges,
consisting of low air pressure induced uplift of water table, wind and wave set-up, extreme waves and wave run-up are not supposed to change. The major difference is that coastal defenses will have to withstand even twice longer events. The construction of higher dikes is thus not an obvious option, although new schemes will require safety factors higher than nowadays. This means that emphasis should rather be put on greater resilience of dikes against overtopping and breaching, which means significantly greater expenditures. The combination of natural or nearly natural coastal protection measures with artificial structures should be considered a well; possible solutions may include conservation, maintenance and restoration of mangrove swamps, use of plants resisting relatively long overtopping of landward dike slopes, e.g. vetiver plants, beach fills, combined protection, e.g. dikes protected by fills or mangrove swamps at the dike forefront as first line of defense, etc. These activities should be considered in a wider perspective of ICZM methodology that incorporates the ‘working with nature’ principle.

7. Conclusions

1. The study provided some knowledge on the character of climate change in part of South East Asia using 40 years of observations of extreme storms/typhoons over South China Sea between 1960 and 2000. The results particularly highlight the growing duration of the most extreme winds.

2. The most important weather pattern were alternating sequences of years with many extreme events followed by years where such events did not appear; these sequences produced a long periodicity in the range of 20 years. The first epoch spanned the 1960-1982 period, the 2nd one encompassed the time between 1982-2000. Each epoch consisted of almost the entire, long cycle plus the beginning of the next cycle. The detection of long cycles provided grounds for unbiased and objective comparison of their statistical structures in order to seek climate change effects.

3. The number of the mildest events with wind velocities between 20-40 knots grew from 29% in the 1st epoch to 40% in the 2nd. It was compensated by the fall in the next category (40-60 knots) from almost 29% to just 21%. The number of medium events (60-80 knots) did not change much and amounted to 24.5% vs. 21%, similar situation was also found in the next class (80-100 knots), where the number of events fell from 10% to 8.5%. The same occurred for mighty events (100-120 knots), where 5% in the 1st epoch corresponded to 4% in the 2nd. The most significant difference was found for the strongest winds (120 knots plus), whose number practically doubled from 2.7% to 5.3%.

4. The most important consequence for the coastal zones in the study area is the increasing duration of the most extreme events, so coastal systems will be receiving much more energy than previously. This is well reflected by extreme probability distributions of annual (peak) typhoon duration with speeds greater than/equal to 120 knots.

5. Although a tendency toward the growth of maximum wind speeds was also observed, this growth is far less important than the increase of duration of peak storms. This is visible in extreme probability distributions of maximum annual wind speeds.

6. The PDI series are very prone to nonlinear errors, because the definition of PDI involves the integration of cubed maximum wind speed over event lifetime. Rather coarse sampling of wind speed produces additional errors. Thus, higher precision
of future climatic studies can be expected knowing that errors in PDI calculations due to inaccurate assessment of event lifetimes are linear and that peak wind speeds have not grown significantly.

7. The study results indicate that extreme loads on coastal defenses are not likely to grow, although they will be operating for significantly longer periods. This will have consequences for the construction of more resilient dikes with higher safety factors, designed to resist longer overtopping periods without breaching. Substantially greater expenditures thus become inevitable.

REFERENCES


