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# Changes in Activity of the Intense Tropical Cyclones for the Western North Pacific During the Last Decades, Derived From a Regional Climate Model Simulation

Monika Barcikowska, Frauke Feser, and Hans von Storch

*Institute for Coastal Research, Helmholtz-Zentrum Geesthacht, Geesthacht, Germany*
*and*
*Cluster of Excellence 'Integrated Climate System Analysis and Prediction' (CliSAP)*
*of the University of Hamburg, Germany*

## 1. Introduction

The observation-based studies so far haven't reached consensus regarding the trends of tropical cyclones (TCs) in the western North Pacific (WNP) during the last six decades. Such results are related to deficient (Barcikowska 2012; Song *et al.* 2010; Landsea *et al.*) observational data sets (best track data sets, hereafter referred to BTD), containing inhomogeneities introduced by operational practices which are changing over time and measurement techniques. This limits the reliability of derived TC climatologies and also the feasibility to associate the TC activity with environmental factors.

As for an alternative data set, which is long and homogenous enough to derive climate statistics, an atmospheric regional climate model was employed. In this study, we analyze TC activity over the WNP, derived from dynamically downscaled NCEP/NCAR re-analyses for the period 1948-2011.

Section 2 describes the data and methods used for this study. Section 3 examines the spatial and temporal changes in TC activity. Section 4 shows the relation of given changes to large-scale environmental patterns.

## 2. Data and methods

The regional climate model applied to simulate long-term TC climate is COSMO-CLM (CCLM, www.clm-community.eu; Rockel *et al.* 2008; Steppeler *et al.* 2003). The model domain covers the western North Pacific and South-East Asia (Fig. 1) with a horizontal resolution of 0.5° (~ 55 km) and 32 vertical levels. The model runs in non-hydrostatic mode and the Kain-Fritsch scheme (Kain 2004) is used as convective parameterization.

CCLM is driven by large-scale fields provided by global NCEP-NCAR reanalyses I (Kalnay *et al.* 1996; Kistler *et al.* 2001), hereafter called NCEP, at a horizontal resolution of T62 (~ 210 km)) as boundary and initial conditions. Additionally, the spectral nudging technique (von Storch *et al.* 2000) was applied to the whole model domain, and only for the horizontal wind components.

The influence of large-scale circulation patterns on hindcasted TC variability was quantified with a Canonical Correlation Analysis (*e.g.* von Storch and

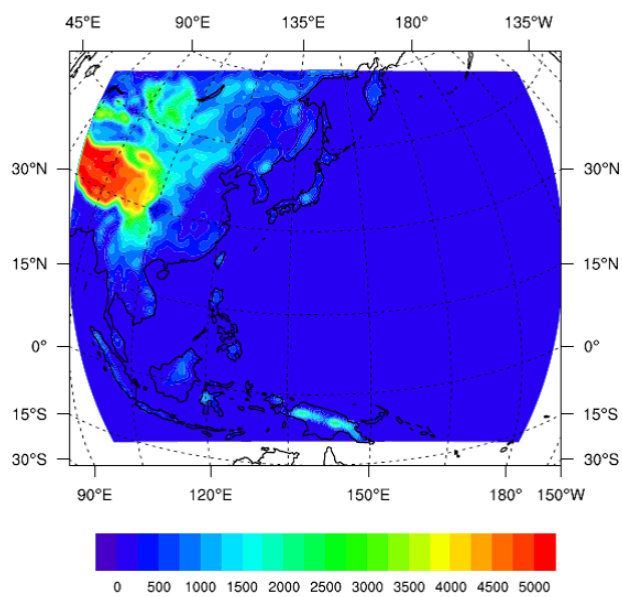


**Fig. 1** CCLM model domain and surface elevation (m) of the CCLM simulation for Southeast Asia and the western North Pacific with a grid distance of 0.5° latitude x 0.5° longitude.

Correspondence to: Monika Barcikowska, Institute for Coastal Research, Helmholtz-Zentrum Geesthacht, Geesthacht, Germany; E-mail: monika.barcikowska@hzg.de.

Zwiers 1999). The method estimates the maximum correlation between two multidimensional data sets. Here we analyzed the association of TC spatial density with Maximum Potential Intensity (MPI) patterns and Genesis Potential Index (GPI). For this purpose the first ten EOFs were computed using yearly anomalies of atmospheric variables calculated during JASO (July-October, hereafter JASO months) months. It is assumed that the first ten EOFs represent the main patterns of variability and those were used for further analysis (Leoncini *et al.* 2008; von Storch and Zwiers 1999).

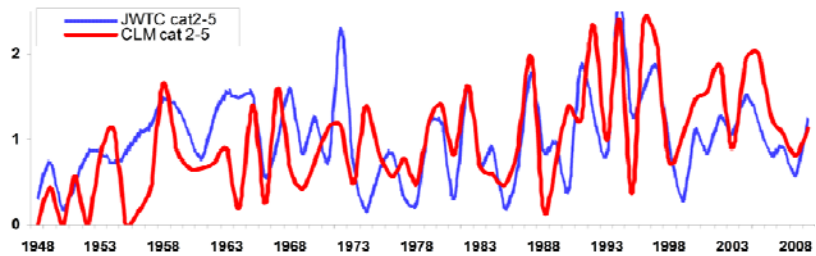


**Fig. 2** Annual numbers for the intense TC days counted for July-October seasons, normalized by their climatological mean values for the period 1948-2011, CCLM (red) and JTWC (blue).

The MPI (Emanuel 1988) is computed with a program provided by K. Emanuel on the website ftp://texmex.mit.edu/pub/emanuel/TCMAX/. The yearly values of MPI for the WNP region were calculated with the sea surface temperature (SST) fields that were used to drive the regional model. The GPI is defined by (Emanuel and Nolan 2004).

Simulated TC activity is compared with the BTD observations, provided by Joint Warning Typhoon Center (http://www.usno.navy.mil/JTWC/).

## 3. Changes of TC activity over the western North Pacific for the years 1948-2011

Impact of TCs on coastal populations depends on their frequency, duration, intensity and location. Therefore we analyse the number of days for intense TCs, which account for the first three given parameters. Figure 2 presents simulated and observed annual numbers for the intense TC days normalized by their mean values for the period 1948-2011.

For the period 1978-2011 yearly TC variability in CCLM (CLM cat2_5) is comparable with the observations, given by BTD set (hereafter referred to JTWC cat2-5,). For the previous period, prior to the satellite-measurement era, observations show higher TC activity numbers. These differences may be related to the limited spatial/temporal coverage of observations and limited accuracy of TC measurement techniques.

Long-term trends in CCLM time series show an increasing trend for the period 1948-2011, with a slope coefficient of 0.02 for the intense TCs. The maximum of the TC activity occurs in the 1990s with a slight shift towards less numbers in the last decade.

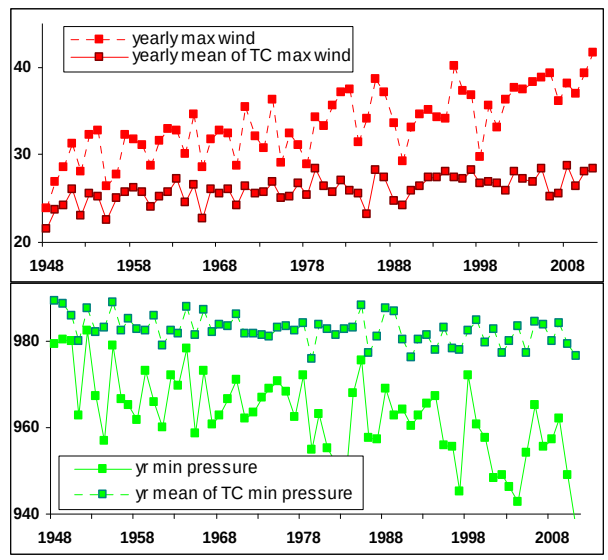


**Fig. 3** Annual maxima of TC intensity (dashed line) and annual mean of TC intensity from all derived TCs (solid line). Intensity is shown in terms of maximum wind speed (top) and minimum pressure (bottom). The x-axis shows years. The y-axis shows (top) wind speed (units: m $s^{-1}$) and (bottom) pressure (units: hPa).

Increasing frequency of the intense TCs is consistent with increasing intensity of the intense TCs. Figure 3 shows the annual maxima of TC intensity simulated by CCLM, in terms of maximum wind speed and minimum pressure. The 50th percentile of annual maxima for TC intensities during the analysed period are ~ 34 m $s^{-1}$ and ~ 962 hPa for wind speed and pressure, respectively. Time series clearly show an increasing trend for maximum wind speed and a decreasing trend for minimum pressure. TC cores are deepening from ~ 970 hPa in the early 1960s, to ~ 950 hPa in the 2000s.

Figure 4 shows that TCs that reach an intensity higher than the 50th percentile of TC intensity annual maxima (~ 34 m $s^{-1}$ for wind speed and ~ 962 hPa for pressure) occur mainly in the second part of the analysed period and their frequency increases.

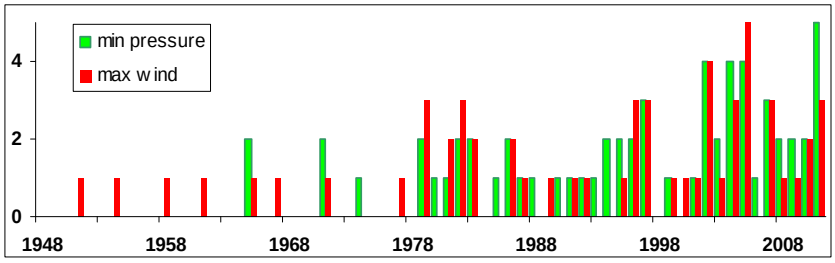


**Fig. 4** Number of TCs reaching the intensity threshold (50th percentile of annual maxima of TC intensity for the period 1948-2011). Intensity is represented as maximum wind speed (red) and minimum pressure (green).

Spatial features of TC activity changes are presented in Fig. 5. The picture presents long-term spatial density trends for intense TCs. Trends were derived with a linear regression using a least squares fit, for every grid box. TC activity shows an increase along the South Asian coast, eastward from the northern part of the Phillipines and extends towards the southern flanks of Japan. The maximum is located in the subtropical latitudes, in the vicinity of Taiwan (Barcikowska *et al.* 2012, submitted). Downward tendencies of TC activity are focused mainly in the south-eastern part (130-150°E, 10-20°N) of the WNP. Overall, the constructed TC climatology shows an increase and a north-westward shift of intense TC tracks for the period 1948-2011.

Several observational studies that analysed the impact of TCs in the WNP for shorter time periods (Ho *et al.* 2004; Wu *et al.* 2005) confirm partly our findings. Tu *et al.* (2009) found strong TC variability after 1982 and an abrupt shift of TC activity in the vicinity of Taiwan in the 2000s. The authors concluded that there is a northward shift of typhoon tracks. Wu *et al.* (2005) identified a westward shift of TC track patterns in the WNP for the last decades and stated that there is a rising influence of TCs on subtropical East Asia.

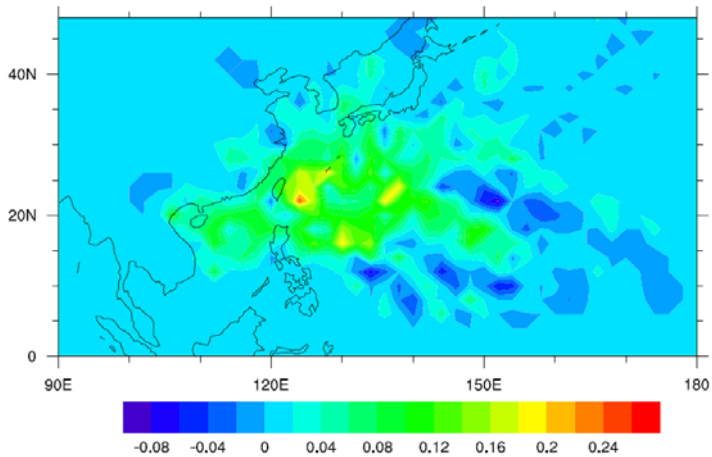


**Fig. 5** Trends for yearly intense TC occurrences, estimated with a linear regression using a least squares fit derived for every 2° latitude x 2° longitude grid box; for the period 1948-2011.

## 4. Relationship of TC activity with large-scale environmental patterns

Variability of TC activity is determined by many environmental factors. High sea surface temperature, high moisture content in the lower troposphere, conditional convective instability, cyclonic vorticity and weak vertical shear of horizontal winds are necessary conditions, although not sufficient for tropical cyclogenesis to occur (Gray 1968).

We utilize two indexes (MPI and GPI), combining given parameters, to estimate and explain derived yearly variability of intense TCs. The MPI (Emanuel 1988) is determined by: sea surface temperature, the outflow temperature and convective available potential energy. It represents thermodynamic conditions which influence TC genesis and intensification. The GPI combines additionally dynamical factors, *e.g.* vertical wind shear, absolute vorticity. Thus GPI indicates how favourable thermodynamical and dynamical conditions are for TC genesis and development.

In order to quantify the relation between yearly variability of intense TCs and large –scale environmental patterns (represented by MPI and GPI), we apply canonical correlation analysis (CCA). CCA results are two pairs of correlating patterns. Figure 6a and 6b show the pattern of anomalies for: 3-yr MPI fields and 3-yr spatial density of the intense TCs. Figure 6c presents the time series of those patterns. The time series of CCA pattern for the intense TCs explains 71 % of total variability. Figure 7 shows in the same manner the relationship between intense TC activity and GPI.

CCA patterns for 3-yr MPI and TCs share a correlation of 68 %. The relationship represented by CCA patterns indicates that anomalously positive MPI along the SE Asian coast is strongly related to an anomalously high activity of the intense TCs in the same region. Time series of given patterns share a correlation of 0.65. Both time series show an increasing activity with the maximum in the early 2000s.

However, anomalously high TC activity in 1982/83 and in the early 1990s cannot be explained with the derived MPI pattern, which in these years is rather inactive (Fig. 6c). In these years, other modes of variability might reduce the strength of the derived MPI pattern, particularly ENSO variability, which was in a strong, positive phase (El Niño) in 1982/83 and the early 1990s. At that time the sea surface temperature (and consequently MPI) shows positive anomalies in the equatorial central and eastern Pacific, but – negative anomalies in the western North Pacific. Consequently the positive anomalies of these factors, which are visible along the SE Asian coast in the first CCA MPI pattern (Fig. 6a), are diminished during the warm ENSO phase.

To find a potential reason for anomalously high TC activity in 1982/83 and the early 1990s we analysed its relation to GPI. Figure 7a, b represents the first canonical correlation patterns derived between anomalies of GPI and TCs (CCA GPI and CCA TC, respectively). The patterns share a correlation of 45 %. The CCA GPI (Fig. 7a) captures the ENSO signal quite clearly, indicating positive anomalies in the eastern part of the western North Pacific and negative anomalies in coastal regions. CCA TC reflects the spatial features of the GPI pattern. The time series of CCA patterns confirm an influence of ENSO on TC activity. The magnitude of GPI values (Fig. 7c) clearly indicates strong ENSO phases in 1982/1983, in the 1990s and 1999/2000. This corresponds to high TC activity in El Nino phases (1982/1983 and 1990s), and low TC activity in La Nina (1999/2000). The time series of the given patterns show a correlation of 60 %.

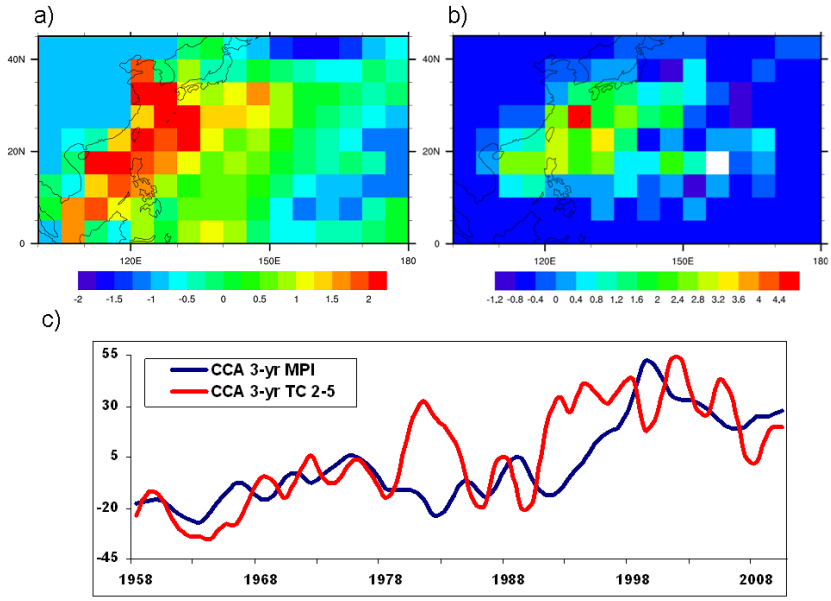


**Fig. 6** The canonical correlation patterns derived between: (a) 3-yr spatial density anomalies of the intense TCs (CCA TC) and (b) 3-yr fields of Maximum Potential Intensity anomalies (CCA MPI). The CCA patterns share a correlation of 68 %. Time series for correlating CCA TC and CCA MPI patterns are shown in c).

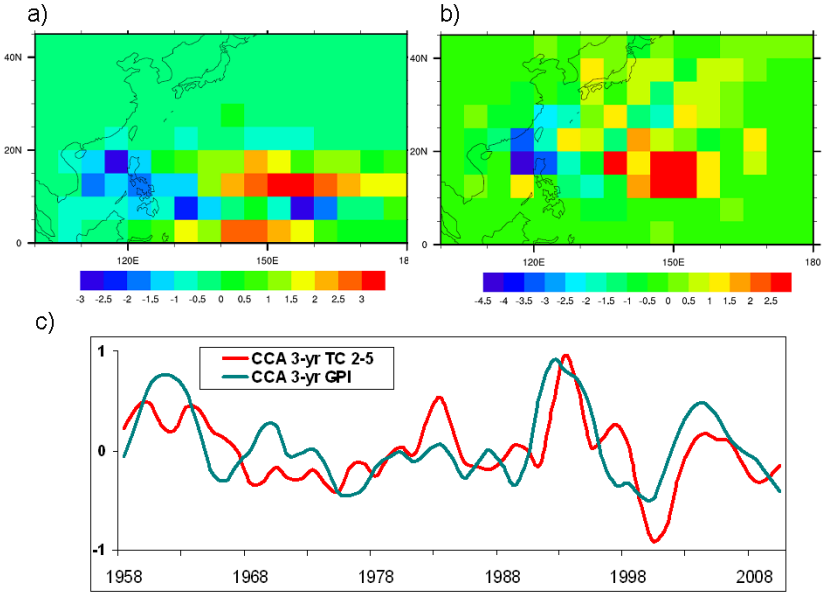


**Fig. 7** The canonical correlation patterns derived between: (a) 3-yr spatial density anomalies of the intense TCs (CCA TC) and (b) 3-yr fields of Genesis Potential Index anomalies (CCA GPI). The CCA patterns share a correlation of 45%. Time series for correlating CCA TC and CCA GPI patterns are shown in c).

## 5. Summary

This paper presents the TC activity over the western North Pacific for the last six decades. In order to construct a TC data set, we employed a regional atmospheric model (CCLM) to dynamically downscale NCEP-NCAR reanalyses.

Comparisons of the resulting data set with more recent observations (1978-2008) show that the simulated TC climatology represents realistic features of TC activity variability on inter-annual to inter-decadal time scales.

The constructed long-term TC climatology shows an increase and a north-westward shift of intense TC tracks for the period 1948-2011. The variability of TC activity shows a relationship with large-scale environmental patterns, represented by MPI and GPI.

Increasing TC activity over the last decades along the SE Asian coast shows a relation with the MPI pattern. The pattern and its time series indicate a change of thermodynamic conditions in the same region towards conditions which are more favourable for TC genesis and intensification. Another mode of TC variability shows a link with ENSO, represented by the GPI pattern. The given relationships explain high TC activity: in the 1990s mainly due to the warm ENSO mode; in the 2000s due to favourable thermodynamic TC genesis and development conditions which occurred over coastal regions of the WNP.

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