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Communication

Trends in Intense Typhoon Minimum Sea Level Pressure

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Abstract: A number of recent publications have examined trends in the maximum wind speed of tropical cyclones in various basins. In this communication, the author focuses on typhoons in the western North Pacific. Rather than maximum wind speed, the intensity of the storms is measured by their lifetime minimum sea level pressure (MSLP). Quantile regression is used to test for trends in storms of extreme intensity. The results indicate that there is a trend of decreasing intensity in the most intense storms as measured by MSLP over the period 1951–2010. However, when the data are broken into intervals 1951–1987 and 1987–2010, neither interval has a significant trend, but the intensity quantiles for the two periods differ. Reasons for this are discussed, including the cessation of aircraft reconnaissance in 1987. The author also finds that the average typhoon intensity is greater in El Nino years, while the intensity of the strongest typhoons shows no significant relation to El Nino Southern Oscillation.

Keywords: typhoon; tropical cyclone; intensity; climate change

1. Introduction

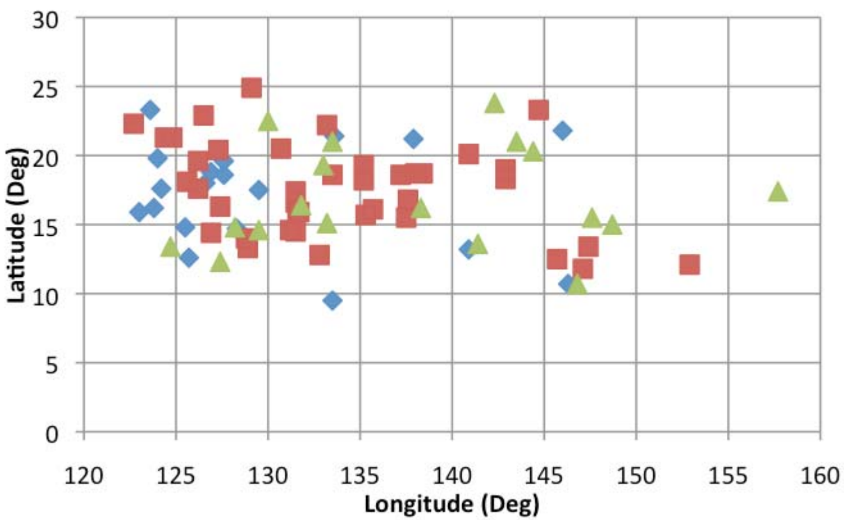
There has been considerable discussion in the past few years regarding the impact of climate change on tropical cyclone intensity, with some evidence indicating a significant increase in the number of intense storms [1], and other evidence suggesting no trend or even a downward trend [2,3]. At least part of the reason for the discrepancies are likely due to data quality issues [4,5], which also are manifested when comparing different best track datasets [6]. Most of these studies of tropical cyclone intensity trends have focused on wind speed or related parameters such as Power Dissipation Index (PDI) and Accumulated Cyclone Energy (ACE). However, as pointed out by Knaff and Sampson [7], the minimum sea level pressure (MSLP) may be a more accurate quantity in the western North Pacific.

Here we examine western North Pacific MSLP data over the period 1951 to 2010, looking for trends in the most intense typhoons.

2. Data and Analysis Methods

The primary source of data in this study is the World Meteorological Organization (WMO) best track in International Best Track Archive for Climate Stewardship (IBTrACS) [8]. The simplest approach for looking at very intense typhoons is to apply a threshold, as done in [9]; we can, for example, look only at those storms with MSLP near and below 900 hPa. Figure 1 shows the location at which the lifetime minimum MSLP was reached for all storms with minimum MSLP below 905 hPa in the period 1951 to 2010, the years covered by WMO IBTrACS. The color coding shows storms that occurred during El Nino, La Nina, or neutral conditions, based on the Southern Oscillation Index (SOI) during September of the year of occurrence; here, El Nino is SOI less than −1 and La Nina is SOI greater than +1. There appears to be a slight preference for reaching minimum MSLP farther east during El Nino years. This is consistent with previous findings indicating a relationship between El Nino Southern Oscillation (ENSO) and typhoon location and intensity [10–13]. These publications found that during El Nino events, locations of high sea surface temperature (SST) and tropical cyclone genesis are shifted farther east and that higher intensity is reached.

Figure 1. Locations (north latitude and east longitude) at which minimum sea level pressure (MSLP) was reached for typhoons with minimum MSLP <905 hPa. Green triangles are for El Nino years, blue diamonds are for La Nina years, and red squares are for neutral years.



Plotting only very intense storms *versus* time would be one way to identify trends and is similar to the approach of examining the number or fraction of Category 4 and 5 storms, as done in some of the works referenced above. However, we prefer to use the technique of quantile regression [14], which defines intensity by a quantile rather than by an absolute threshold. As discussed by Jagger and Elsner [15] and Elsner, *et al*. [16], this is a rigorous way of looking for trends in the extremes of data.

To find the τ^{th} quantile regression line, J in Equation (1) is minimized over all possible values of a and b.

$$J = \sum_{i=1}^{n} f(y_i - (a + bx_i)) \tag{1}$$

where x_i is the year, y_i is an observed MSLP, and $f(z) = \tau z$ for $z \geq 0$ and $f(z) = -(1 - \tau)z$ for $z < 0$. For $\tau = 0.5$, the result is median regression, which minimizes the sum of the absolute error between data and model. For examining very intense typhoons, we need to look at much smaller values of τ; for example, $\tau = 0.05$ gives the regression line for storms with minimum MSLP in the lowest 5%. In applying quantile regression to maximum wind speed, Elsner *et al.* [16] did find some evidence of increasing intensity over the western North Pacific; however, they found more significant increases over the north Atlantic. To apply quantile regression to the western Pacific tropical cyclone data, we use the R statistical language. The R function rq( ) calculates the linear quantile regression line for a given quantile τ. We consider quantiles for storms of at least typhoon intensity, taking the typhoon threshold MSLP to be 976 hPa, based on Dvorak [17].

3. Results

Figure 2 shows the WMO IBTrACS typhoon data, along with the standard least squares regression and 1% quantile regression lines. While the least squares line is nearly flat (trend not statistically significant), there is a decrease in intensity (higher MSLP) of the most intense typhoons with time; that is, the 1% regression line has an upward slope. Table 1 shows the statistics for various quantiles. The last line of the table shows the calculated probability (p-value) of the null hypothesis (that the trend line has zero slope). The results indicate that the positive trend is statistically significant at the 5% level for all quantiles. Stated differently, the probabilities of the actual slope being zero (the null hypothesis) but producing the given data are less than 5% for all the quantiles shown. In contrast, the p-value for the trend of the least squares regression line shown in Figure 2 is 0.19.

The results of Figure 2 and Table 1 indicate that the intensity of the most intense typhoons is decreasing with time (positive trend). Because the MSLP was usually measured by aircraft from 1951 to mid-August 1987 and by satellite only since then, there is a possibility of differing behavior in these two periods just due to MSLP measurement technique. What seem to be missing in the post-aircraft era are typhoons with MSLP well below 900 hPa. The only recent example of such a storm is Typhoon Megi of 2010. Its best track MSLP is 885 hPa; however, it was measured by aircraft as part of a field experiment. One of the aircraft penetrations measured 890 hPa [18], and this was likely factored into the best track data. To investigate whether there are differences between these two time periods, the data for each were analyzed separately; results are shown in Tables 2 and 3. When re-analyzed in this way, neither period has a statistically significant trend for any quantile (at the 5% or even 10% significance level). We also tried different change points to determine the sensitivity of the results in Tables 2 and 3 to the choice of 1987. Using the end of 1980 as a change point also gives no trend for the first part of the data. However, the post-1980 data do have statistically significant trends (decrease in intensity) for the 2.5%, 5%, and 15% quantiles. Going the other direction, using the beginning of 1994 as the change point yields a statistically significant trend in the pre-1994 data toward higher MSLP (lower intensity) for the 10% quantile (p-value 0.01). The trends for the first part of the data (pre-1994) for other quantiles are not significant. There are no statistically significant trends for the second portion of the data (1994–2010). Hence, of the three change points (end 1980, mid 1987, beginning 1994), only mid-1987 has no significant trends for either part of the data for all quantiles.

Figure 2. Scatterplot showing the minimum World Meteorological Organization (WMO) MSLP of western Pacific typhoons 1951–2010. Black dashed line is the usual least-squares regression line. The solid red line toward the bottom of the plot is the 1% quantile regression line.

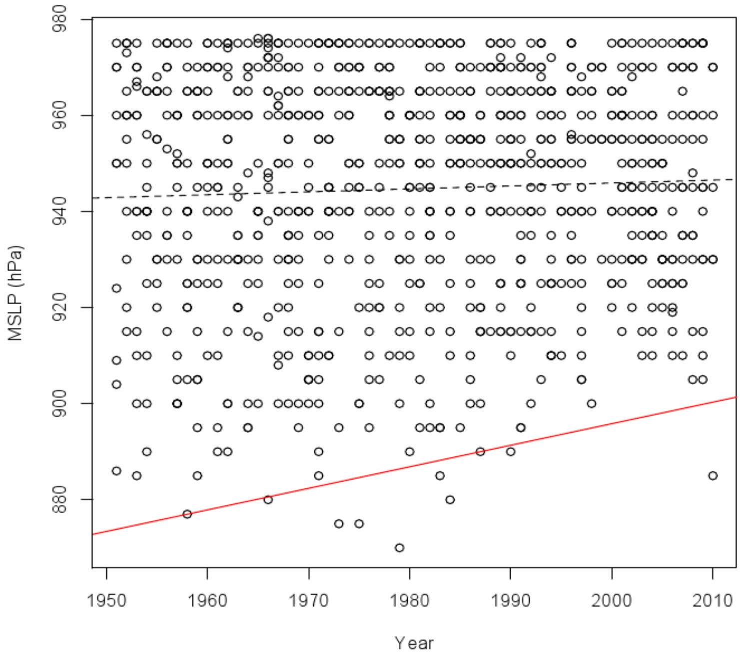


Table 1. Summary statistics for quantile regression 1951–2010.

Statistic	Quantile 0.15	0.10	0.05	0.025	0.01
Trend (hPa/year)	0.30	0.35	0.33	0.36	0.45
Standard Error (hPa/year)	0.09	0.07	0.10	0.10	0.22
Probability of null	0.00	0.00	0.00	0.00	0.03

Table 2. Summary statistics for quantile regression 1951–1987.

Statistic	Quantile 0.15	0.10	0.05	0.025	0.01
Trend (hPa/year)	0.15	0.00	−0.17	0.00	−0.16
Standard Error (hPa/year)	0.20	0.15	0.18	0.32	0.29
Probability of null	0.46	1.00	0.34	1.00	0.57

Table 3. Summary statistics for quantile regression 1987–2010.

Statistic	Quantile 0.15	0.10	0.05	0.025	0.01
Trend (hPa/year)	0.30	0.00	0.00	0.45	0.56
Standard Error (hPa/year)	0.26	0.25	0.40	0.65	0.45
Probability of null	0.26	1.00	1.00	0.46	0.31

Are there other factors that could have contributed to the apparent change in 1987? Several recent papers have investigated the relation of typhoon number and intensity to ENSO (as already noted), the Pacific Decadal Oscillation (PDO), the East Indian Ocean sea surface temperature (SST) anomaly, and the North Atlantic Oscillation [10–13]. Figure 3 shows the same typhoon data as in Figure 2 but plotted *versus* SOI. The least squares regression line shows a statistically significant trend of less intense typhoons with increasing SOI (towards La Nina conditions, p-value of 0.04). This is in accord with previous observations [12,13]. However, the 1% quantile regression shows a decrease in MSLP with SOI (*i.e.*, the strongest typhoons are even stronger with La Nina), although the p-value for this is 0.08, so the result is not statistically significant at the 5% level. This behavior is somewhat analogous to findings for the Atlantic in [15]. Table 4 shows the results of quantile regression for other quantiles, showing no statistically significant trends. These results do not indicate a clear relationship between the intensity of the most intense typhoons and the SOI. Furthermore, the SOI has been both positive and negative since 1987 and doesn't seem able to explain a long term trend. The findings of [19] indicate a change point in typhoon behavior around 1990, with oceanic conditions dominating anomalous typhoon frequency before 1990 and atmospheric conditions dominating afterwards. The authors of [20] found evidence of change points in super-typhoon activity around 1972 and 1989. These are longer term (decadal) shifts with change points near 1987 and could be related to our findings.

Figure 3. Scatterplot showing the minimum WMO MSLP of western Pacific typhoons 1951–2010, as in Figure 2 but plotted *versus* Southern Oscillation Index (SOI). Black dashed line is the usual least-squares regression line. The solid red line toward the bottom of the image is the 1% quantile regression line.

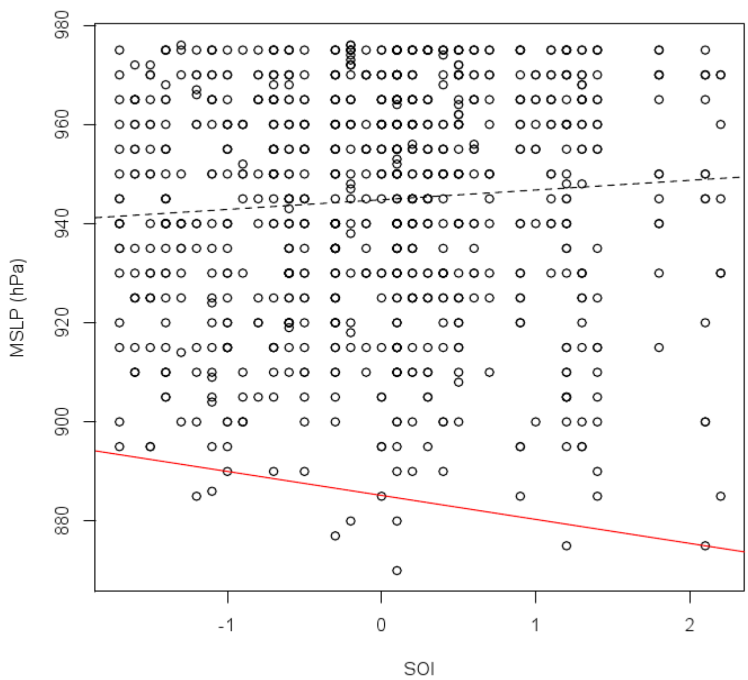


Table 4. Summary statistics for quantile regression, all data *versus* SOI.

Statistic	Quantile				
	0.15	**0.10**	**0.05**	**0.025**	**0.01**
Trend (hPa)	0.00	0.00	0.00	−2.00	−4.84
Standard Error (hPa)	1.90	1.82	1.67	2.29	2.79
Probability of null	1.00	1.00	1.00	0.40	0.08

Is there evidence that the reduction in very intense typhoons in recent years is due to satellite measurement of MSLP? There are least two additional typhoons in the post-aircraft era (Gay 1992 and Angela 1995) that may have had very low MSLP, significantly lower than in the best track data set. Manual Dvorak analyses of these two typhoons by Hoarau *et al*. [21,22] have indicated that their MSLP may have been even lower than Typhoon Tip's 870 hPa record low MSLP. The data for the complete 1951–2010 period was reanalyzed using 870 hPa as the MSLP for these storms, replacing 910 and 900 hPa MSLP values, respectively, in the IBTrACS WMO data. The trend for the 1% quantile *versus* year is no longer statistically significant, although upward trends in MSLP for the other quantiles are still significant. When the data are reanalyzed for their dependence on SOI, the *p*-values corresponding to Table 4 become larger than 0.30 for all quantiles, indicating no dependence of the most intense typhoons on SOI. Finally, we also replaced the WMO MSLP with Joint Typhoon Warning Center (JTWC) MSLP, available for most storms after 2000. With these new values and the modifications for Gay and Angela, none of the regressions (least squares or quantile) show significant trends *versus* year over the period 1951–2010. The least squares regression *versus* SOI still shows a significant trend of increased MSLP in moving towards La Nina conditions. However, the quantile regression trends are again not significant for any quantiles.

4. Conclusions

In this communication, we have investigated possible trends in intense western North Pacific typhoons as measured by the storms' lifetime MSLP during the period 1951 to 2010. We have reached the following conclusions:

- Application of quantile regression to the WMO best track data used here indicates a decrease in the intensity (increase in lifetime MSLP) with time.
- A likely source of the decrease is the change in measurement of MSLP with the cessation of routine aircraft reconnaissance in 1987. There is no significant trend in intense storms either before or after 1987 when the two periods are analyzed separately.
- Lowering the pressures of Typhoons Gay (1992) and Angela (1995) based on [21,22] eliminates the trend in the 1% quantile for the complete 1951–2010 period. Also using JTWC pressures (when available, from 2001 onward) eliminates significant trends in all quantiles.
- While El Nino conditions (negative SOI) are associated with lower average MSLP (greater intensity), in agreement with previous findings, we found no significant dependence of MSLP on SOI for the most intense quantiles considered here, regardless of whether pressures based on [21,22] and JTWC are used.

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References

1. Webster, P.W.; Holland, G.J.; Curry, J.A.; Chang, H.-R. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* **2005**, *309*, 1844–1846.
2. Wu, M.C.; Yeung, K.H.; Chang, W.L. Trends in western North Pacific tropical cyclone intensity. *EOS* **2006**, *87*, doi:10.1029/2006EO480001.
3. Maue, R.N. Recent historically low global tropical cyclone activity. *Geophys. Res. Lett*. **2011**, *38*, doi:10.1029/2011GL047711.
4. Landsea, C.W.; Harper, B.A.; Hoarau, K.; Knaff, J.A. Can we detect trends in extreme tropical cyclones? *Science* **2006**, *313*, 452–454.
5. Kossin, J.P.; Knapp, K.R.; Vimont, D.J.; Murnane, R.J.; Harper, B.A. A globally consistent reanalysis of hurricane variability and trends. *Geophys. Res. Lett*. **2007**, *34*, doi:10.1029/2006GL028836.
6. Song, J.-J.; Wang, Y.; Wu, L. Trend discrepancies among three best track data sets of western North Pacific tropical cyclones. *J. Geophys. Res*. **2010**, *115*, doi:10.1029/2009JD013058.
7. Knaff, J.A.; Sampson, C.R. Reanalysis of West Pacific Tropical Cyclone Maximum Intensity 1966–1987. In *Proceedings of the 27th Conference on Hurricanes Tropical Meteorology*, Monterey, CA, USA, 24–28 April 2006; p. 5B.5.
8. Knapp, K.R.; Kruk, M.C.; Levinson, D.H.; Diamond, H.J.; Neumann, C.J. The international best track archive for climate stewardship (IBTrACS). *Bull. Am. Met. Soc*. **2010**, *91*, 363–376.
9. Bouchard, R.H. *A Climatology of Very Intense Typhoons: Or Where Have All the Super Typhoons Gone?*; Annual Tropical Cyclone Report; Joint Typhoon Warning Center: Pearl Harbor, HI, USA, 1990; pp. 266–269.
10. Elsner, J.B.; Liu, K. Examining the ENSO-typhoon hypothesis. *Clim. Res*. **2003**, *25*, 43–54.
11. Chan, J.C.L. Decadal variations of intense typhoon occurrence in the western North Pacific. *Proc. R. Soc. A* **2008**, *464*, 249–272.
12. Camargo, S.J.; Robertson, A.W.; Gaffney, S.J.; Smyth, P.; Ghil, M. Cluster analysis of typhoon tracks. Part II: Large-scale circulation and ENSO. *J. Clim*. **2007**, *20*, 3654–3676.
13. Zhan, R.; Wang, Y.; Lei, X. Contributions of ENSO and East Indian Ocean SSTA to the interannual variability of Northwest Pacific tropical cyclone frequency. *J. Clim.* **2011**, *24*, 509–521.
14. Koenker, R.; Hallock, K.F. Quantile regression. *J. Econ. Perspect.* **2001**, *15*, 143–156.
15. Jagger, T.H.; Elsner, J.B. Modeling tropical cyclone intensity with quantile regression. *Int. J. Climatol*. **2009**, *29*, 1351–1361.
16. Elsner, J.B.; Kossin, J.P.; Jagger, T.H. The increasing intensity of the strongest tropical cyclones. *Nature* **2008**, *455*, 92–95.
17. Dvorak, V. *Tropical Cyclone Intensity Analysis Using Satellite Data*; NOAA Technical Report No. 11; National Oceanic and Atmospheric Administration: Suitland, MD, USA, 1984.

18. Lin, I.-I.; Black, P.G. Ocean's Impact on the Intensity of Three Recent Typhoons (Fanapi, Malakas, and Megi)—Results from the ITOP Field Experiment. In *Proceedings of* the 65th *Interdepartmental Hurricane Conference*, Miami, FL, USA, 28 February–3 March 2011; p. P08.
19. Yeh, S.-W.; Kang, S.-K.; Kirtman, B.P.; Kim, J.-H.; Kwon, M.-H.; Kim, C.-H. Decadal change in relationship between western North Pacific tropical cyclone frequency and the tropical Pacific SST. *Meteorol. Atmos. Phys.* **2010**, *106*, 179–189.
20. Zhao, X.; Chu, P.-S. Bayesian changepoint analysis for extreme events (typhoons, heavy rainfall, and heat waves): An RJMCMC approach. *J. Clim.* **2010**, *23*, 1034–1046.
21. Hoarau, K.; Padgett, G.; Hoarau, J.-P. Have There been Any Typhoons Stronger than Super Typhoon Tip? In *Proceedings of the 26th Conference on Hurricanes and Tropical Meteorology*, San Diego, CA, USA, 29 April–3 May 2004; p. 16C.1.
22. Hoarau, K.; Chalonge, L.; Hoarau, J.-P. The Reasons for a Reanalysis of the Typhoons Intensity in the Western North Pacific. In *Proceedings of the 27th Conference on Hurricanes and Tropical Meteorology*, Monterey, CA, USA, 24–28 April 2006; p.5B.2.