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# Tropical Cyclone Behavior in a Warmer World

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**Abstract**

The surfaces of most tropical oceans have warmed by 0.25 - 0.5 degrees Celsius during the past several decades. The Intergovernmental Panel on Climate Change (IPCC) considers that the likely primary cause of the rise in global mean surface temperature in the past 50 years is the increase in greenhouse gas concentrations. The global community of tropical cyclone researchers and forecasters as represented at the 6th International Workshop on Tropical Cyclones of the World Meteorological Organization recently released a statement on the links between climate change and tropical cyclones. During the past decade, there have been a number of high-impact tropical cyclone events around the globe. These include 10 landfalling tropical cyclones in Japan in 2004, five tropical cyclones affecting the Cook Islands in a five-week period in 2005, Cyclone Gafilo in Madagascar in 2004, Cyclone Larry in Australia in 2006, the first-ever documented hurricane in the South Atlantic Ocean in 2004, and the extremely active 2004 and 2005 North Atlantic tropical cyclone seasons - including the catastrophic socio-economic impact of Hurricane Katrina. The participants of the IWTC 6 worked out a comprehensive statement providing the latest guidance and consensus views of the tropical cyclone community on the effects of climate change on the behavior of tropical cyclones. Common questions asked by the media and the public (and addressed in the statement) include:

Will the basin and global numbers of tropical cyclones go up in a warmer world?

Will the intensity of tropical cyclones increase in a warmer world?

Will the formation regions of tropical cyclones expand in a warmer world?

Will tropical cyclones retain their destructive potential further into the midlatitudes in a warmer world? And,

Are we already seeing the effects of climate change in the behavior of tropical cyclones?

This talk will provide a detailed description of the observed behavior of tropical cyclones over the past 30 or 40 years, and will address the possible changes to tropical cyclone behavior that may occur in a warmer world. The consensus statements concerning tropical cyclones and climate change made by participants of the 6th International Workshop on Tropical Cyclones (IWTC-VI) are presented and critically analyzed in this talk from the perspective of an active participant in the drafting of those statements.
Keywords: climate change, cyclone behavior, global warming, IPCC,

**要　旨**

ここ数十年の間に，熱帯の多くの海の表面温度が0.25～0.5℃上昇した.「気候変動に関する政府間パネル（IPCC)」によると，過去50年間における地球表面の平均気温の上昇は，温室効果ガスの増加が最大の原因であるという．世界気象機関（WMO）が主催した第 6 回熱帯サイクロンワークショップ（IWTC 6 ）では，気候の変化と熱帯サイクロンの関係に関する声明が発表されている．ここ10年間に多数の大型熱帯サイクロンが出現した．2004年，日本に10個の台風が上陸し，2005年，クック諸島は， 5 週間に 5 個の熱帯サイクロンに襲われた．その他，2004年にマダガスカルを襲ったサイクロン「ガフィーロ」や2006年にオーストラリアを襲った「ラリー」があり,2004年には南大西洋で初めてハリケーンが発生している.また,2004年と2005年は北大西洋で多くの熱帯ハリケーンが発生した年であり，ハリケーン「カトリーナ」が引き起こした人的経済的被害は甚大なものとなった．前述したIWTC 6 で発表された声明は，気候の変化が熱帯サイクロンに及ぼす影響に関する，最新の指標や考え方を含めた総合的なものである．声明では，その中で，新聞などのメディアや一般の人々からよく質問される以下の問題についても言及している．すなわち，

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温暖化すると，熱帯サイクロンに影響される地域や熱帯サイクロンの発生数は増加するのか？
温暖化すると，熱帯サイクロンの勢力は強くなるのか？
温暖化すると，熱帯サイクロンが発生する海域は増加するのか？
温暖化すると，熱帯サイクロンはその勢力をさらに高緯度の地域まで維持し続けるのか？
すでに気候の変化の影響は熱帯サイクロンの動きに現れているのか？

ここでは，過去30～40年に渡る熱帯サイクロンの動きについて詳述するとともに，温暖化した地球での熱帯サイクロンの動きについて論議する．また，気候の変化と熱帯サイクロンの動きとの関連についてのIWTC 6 の声明の中身について述べるとともに，声明で述べられている今後の見通しについても十分に検討したい．

## Introduction

During the past several decades, the average temperature of the earth's atmosphere and oceans has warmed. The warming has not been steady, but has had some periods of rapid warming, with some periods of steady or cooling temperatures (Fig. 1). During the 1970's (one of the periods during which the global temperatures seemed to be falling), it was thought that the next ice age was imminent. Since then, however, the global temperatures have steadily warmed, and during the past several years many locations have set all-time highs for many temperature statistics. For example, December 2006 was the warmest December of record for most of the continental United States.

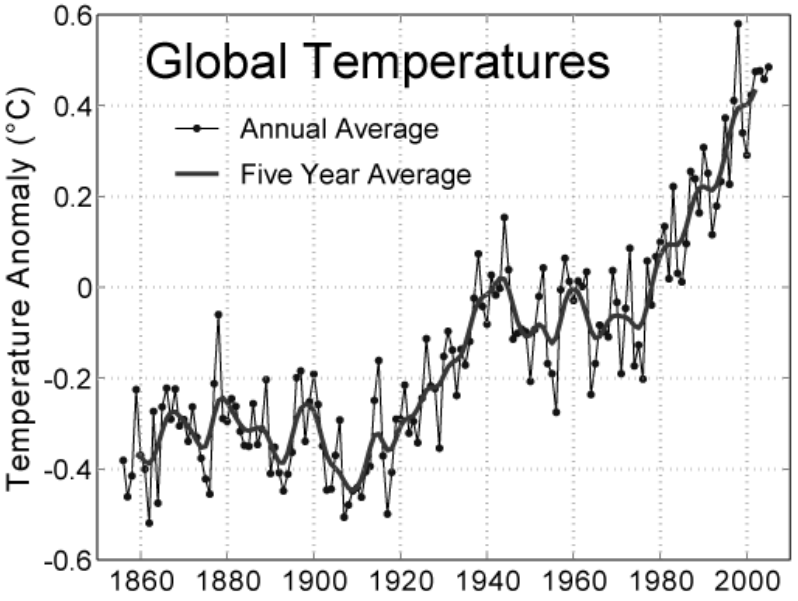


Fig. 1. Global average surface temperature for the past 150 years

The consensus concerning global warming has three tenets that are not widely disputed: 1. Global warming is happening; 2. It is (at least in part), caused by human use of fossil fuels; and, 3. It will continue for many decades. Three other tenets are less certain, but are widely accepted: 1. It poses grave dangers to humanity; 2. Reduction of human output of Carbon Dioxide will slow or even reverse the warming, and 2. The benefits from taking action to reduce $CO_2$ emissions will far exceed the costs. We do not know how much we must change our economic activity to produce a particular reduction of warming. And we do not know whether warming is necessarily dangerous.

Two of the most imminent plausible dangers of the climate in a warmer world are sea level rise and changes to the climate of tropical cyclones. These dangers are obviously more worrisome for low-lying tropical Pacific islands and atolls than in other areas of the world.

At the recent Sixth International Workshop on Tropical Cyclones (IWTC-6) held in San Jose, Costa Rica for two weeks in November 2006, a special group session was convened to generate a statement from the tropical cyclone community on the possible changes to tropical cyclone climate in a warmer world. Over the span of two full days, and many hours of behind-the-scenes work, the IWTC-6 participants produced a draft of its Statement on Tropical Cyclones and Climate Change. The summary statement (http://www.wmo.ch/web/arep/press_releases/2006/iwtc_summary.pdf) is one page and reflects a consensus among *all particpants* (125 people from 34 countries) at the IWTC-6.

The surfaces of most tropical oceans have warmed by 0.25 - 0.5 degree Celsius during the past several decades. The Intergovernmental Panel on Climate Change (IPCC) considers that the likely primary cause of the rise in global mean surface temperature in the past 50 years is the increase in greenhouse gas concentrations. The global community of tropical cyclone researchers and forecasters as represented at the 6th International Workshop on Tropical Cyclones of the World Meteorological Organization has released a statement on the links between anthropogenic (human-induced) climate change and tropical cyclones, including hurricanes and typhoons. This statement is in response to increased attention on tropical cyclones due to the following events:

a) There have been a number of recent high-impact tropical cyclone events around the globe. These include 10 landfalling tropical cyclones in Japan in 2004, five tropical cyclones affecting the Cook Islands in a five-week period in 2005, Cyclone Gafilo in Madagascar in 2004, Cyclone Larry in Australia in 2006, Typhoon Saomai in China in 2006, and the extremely active 2004 and 2005 Atlantic tropical cyclone seasons - including the catastrophic socio-economic impact of Hurricane Katrina.

b) Some recent scientific articles have reported a large increase in tropical cyclone energy, numbers, and wind-speeds in some regions during the last few decades in association with warmer sea surface temperatures. Other studies report that changes in observational techniques and instrumentation are responsible for these increases.

## The Ten Consensus Statements are as Follows:

Consensus Statements by International Workshop on Tropical Cyclones-VI (IWTC-VI) Participants

1. Though there is evidence both for and against the existence of a detectable anthropogenic signal in the tropical cyclone climate record to date, no firm conclusion can be

made on this point.

2. No individual tropical cyclone can be directly attributed to climate change.

3. The recent increase in societal impact from tropical cyclones has largely been caused by rising concentrations of population and infrastructure in coastal regions.

4. Tropical cyclone wind-speed monitoring has changed dramatically over the last few decades, leading to difficulties in determining accurate trends.

5. There is an observed multi-decadal variability of tropical cyclones in some regions whose causes, whether natural, anthropogenic or a combination, are currently being debated. This variability makes detecting any long-term trends in tropical cyclone activity difficult.

6. It is likely that some increase in tropical cyclone peak wind-speed and rainfall will occur if the climate continues to warm. Model studies and theory project a 3-5% increase in wind-speed per degree Celsius increase of tropical sea surface temperatures.

7. There is an inconsistency between the small changes in wind-speed projected by theory and modeling versus large changes reported by some observational studies.

8. Although recent climate model simulations project a decrease or no change in global tropical cyclone numbers in a warmer climate, there is low confidence in this projection. In addition, it is unknown how tropical cyclone tracks or areas of impact will change in the future.

9. Large regional variations exist in methods used to monitor tropical cyclones. Also, most regions have no measurements by instrumented aircraft. These significant limitations will continue to make detection of trends difficult.

10. If the projected rise in sea level due to global warming occurs, then the vulnerability to tropical cyclone storm surge flooding would increase.

For my talk at the Kagoshima Forum, I decided to focus on one particular item mentioned in the IWTC-6 Summary Statement: the 10 landfalling tropical cyclones in Japan during 2004 (Fig. 2) (http://agora.ex.nii.ac.jp/digital-typhoon/year/wnp/1992.html.en). Records dating back to the early 1950's of landfalling typhoons in Japan indicate that 10 in one year was the most (by far) in the record (Fig. 3).

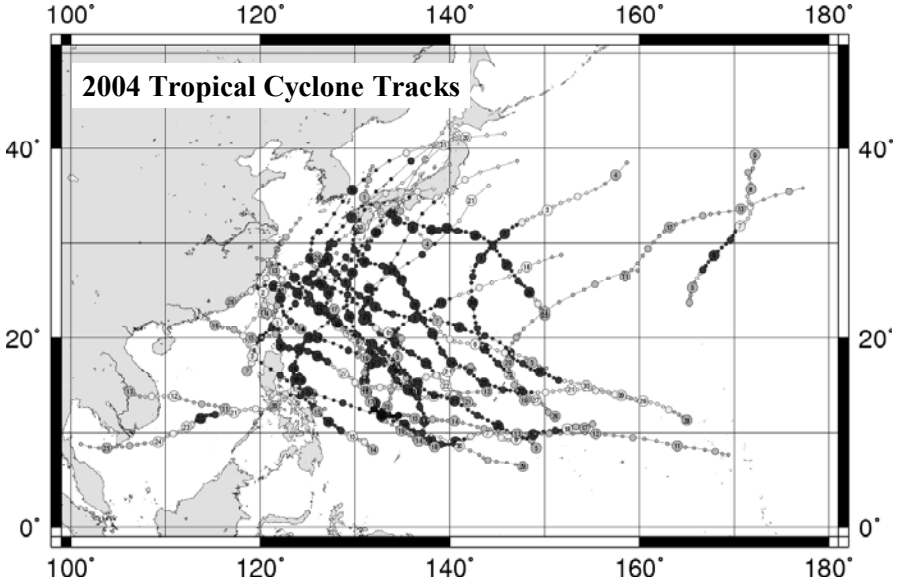


Fig. 2. Typhoon tracks of 2004 indicate a large number affecting Japan.

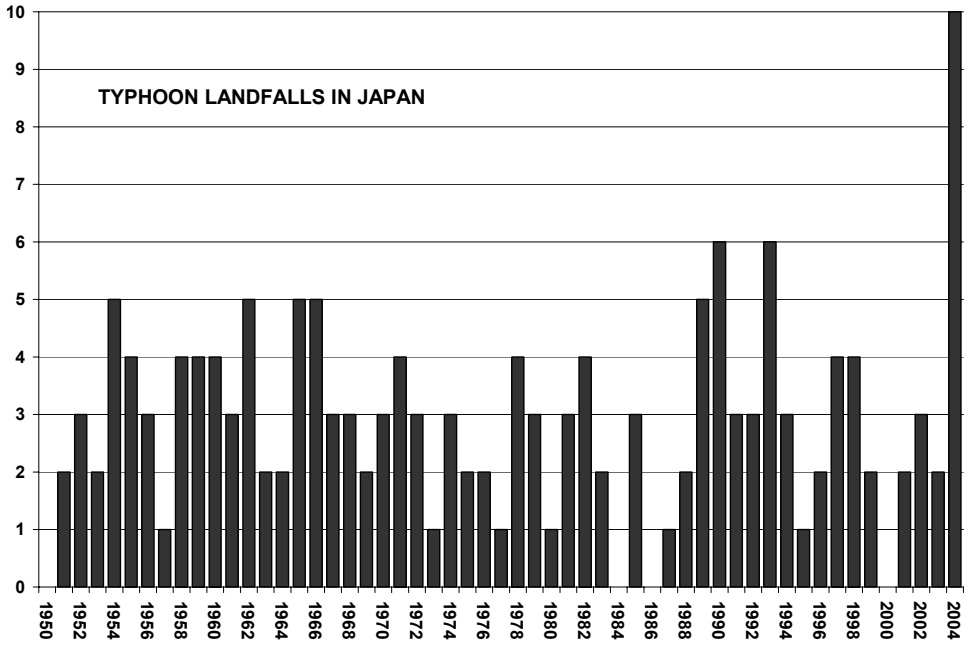


Fig. 3. The historical record of the annual number of landfalling typhoons in Japan.

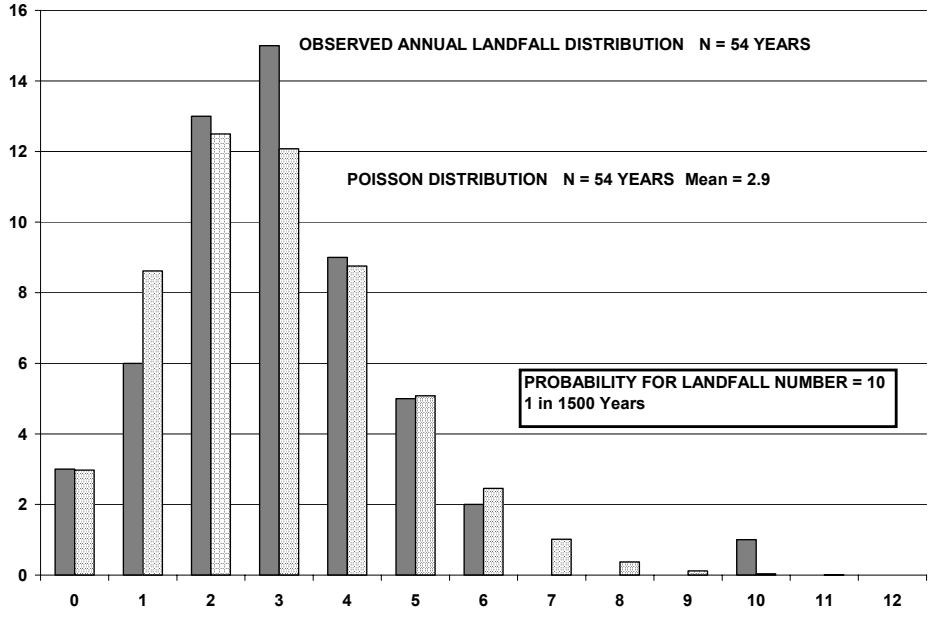


Fig. 4. The distribution of the annual number of landfalling typhoons in Japan during the period 1951 - 2004 (54 years). For example, in this time period there were 13 occurrences of two landfalling typhoons and 15 occurrences of three. Half-tone columns indicate the annual numbers given by a Poisson distribution with the same mean and same number of years as the actual data.

As one can readily see from Fig. 3, the ten Japan landfalling typhoons of 2004 was a remarkable event! There was concern by residents of Japan that this event was a product of climate change, and that it could portend an increase in the frequency of such occurrences in the future. Just how remarkable was this event? Can it be linked to climate change?

The occurrence of an extreme event naturally evokes the question of whether it is just a normal (but infrequent) part of the natural variability of a stable climate system, or whether it represents a jump from one state of the climate system into a different state with wholly new statistical parameters such as the mean of the time series and the year-to-year variability of the occurrences. In order to investigate this, the first thing one might wish to evaluate is the odds of the occurrence of the extreme event, given that the historical record is a snapshot of a stable climate system in which there are no systematic changes or trends underway. If one examines the Japan typhoon landfall record, it is quite clear that it is well represented by a statistical distribution know as the Poisson Distribution (Fig. 4).

The Poisson distribution arises in connection with Poisson processes. It applies to various phenomena of discrete nature (that is, those that may happen 0, 1, 2, 3, ... times during a given period of time or in a given area) whenever the probability of the phenomenon happening is constant in time or space. Examples of events that can be modeled as Poisson distributions include:

(1) The number of cars that pass through a certain point on a road
(2) The number of spelling mistakes one makes while typing a single page.
(3) The number of pine trees per unit area of mixed forest.
(4) The number of stars in a given volume of space.
(5) The number of light bulbs that burn out in a certain amount of time.

And, most certainly:
The annual number of landfalling typhoons in Japan.

In Fig. 4, a Poisson distribution with a mean occurrence rate of 2.9 per year (the same mean as the actual data) and for a sample size of 54 (the number of years of historical data) closely fits the actual data, with some departures that might be expected in a limited sample size. The Poisson model of the Japan typhoon landfalling data can be used to estimate the rarity of the occurrence of a high value, say ten, of the statistic (i.e., the annual number of landfalling typhoons in Japan). In a sample size of only 54 years one would expect 10 landfalling typhoons to occur only .034 times (i.e., far less than once). In order to raise this rate of occurrence to a numerical value of *one*, the sample size would have to be increased to approximately 1500 years. The 10 typhoons affecting Japan in 2004 was thus a rare event indeed, and would be expected to occur (on average) only once in 1500 years! This, of course, assumes that the background typhoon climate is stable.

It turns out that the annual number of typhoons that make landfall in Japan is strongly linked to the annual total number of tropical cyclones in the whole western North Pacific (Fig. 5a, and Fig. 5b). This is not trivial, since hurricane occurrences in other regions (e.g., the New England States of the U.S. Mainland) are not so strongly linked to basin-wide activity - other regional climate patterns such as the North Atlantic Oscillation (NAO) play a big role there by modulating the tracks of the Atlantic hurricanes independently of the basin activity (for example, Elsner, J.B. http://ams.confex.com/ams/pdfpapers/32845.pdf).

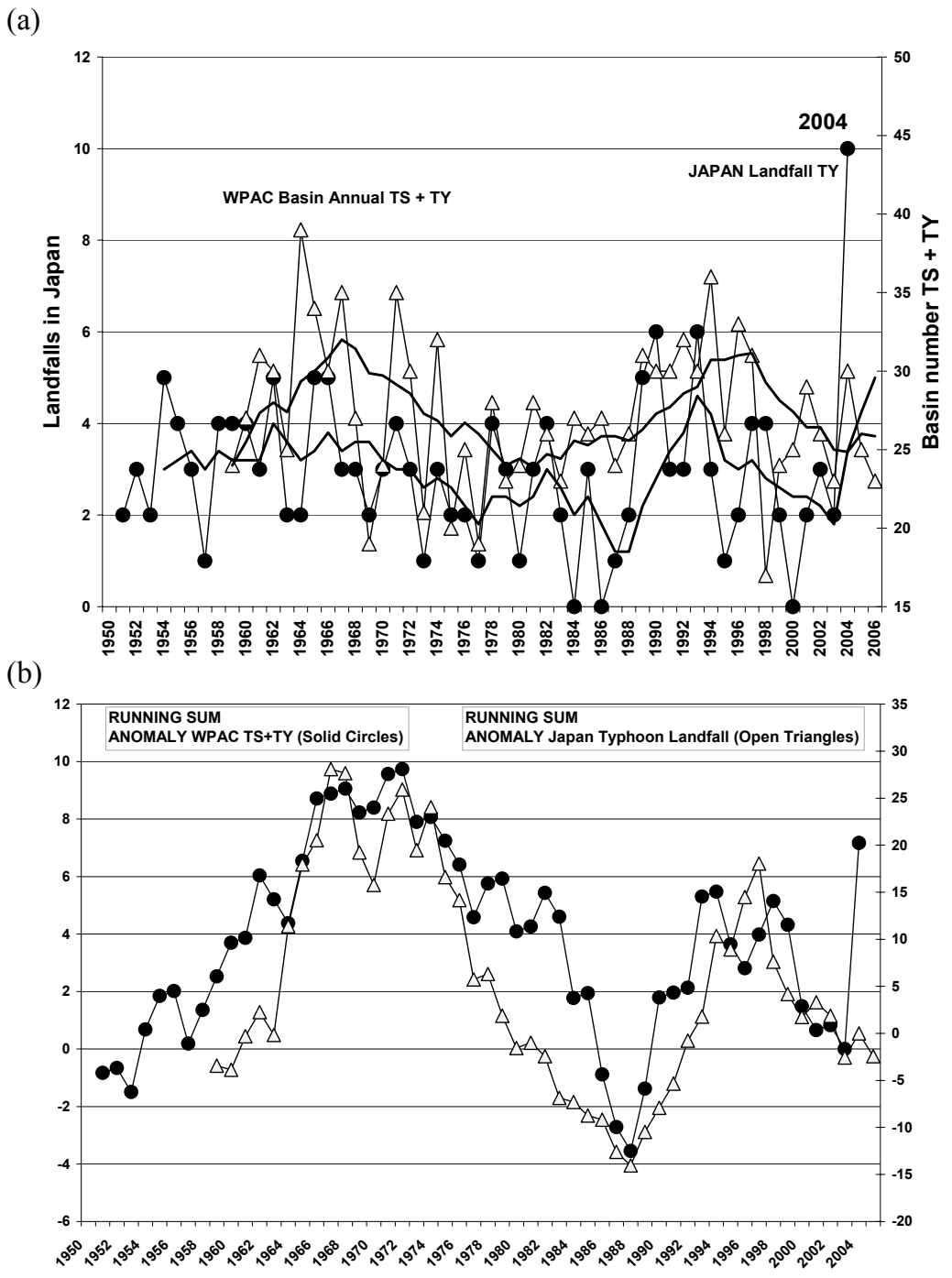


Fig. 5. (a) Time series of annual number of tropical storms and typhoons in the entire western North Pacific (solid circles) and the annual number of Japan landfalling typhoons. (b) Running sum of the anomalies of annual WNP TS + TY (solid circles) and the running sum of the anomalies of the annual number of Japan landfalling typhoons.

In recent General Circulation Models of the atmosphere run for a warmer world, the annual numbers of tropical cyclones in the models actually decreases in most basins. This was noted in the IWTC-6 report (summary point 8). Given this, one might then predict that in a warmer world with fewer TCs in the whole basin, Japan might have a slightly reduced, or at least unchanged number of landfalling tropical cyclones. However, even if the whole basin saw a slight reduction in the annual numbers of tropical cyclones, it is not known whether there will be any processes operating to change the regional distribution of the cyclones within the basin or to change the track patterns so as to offset or even negate the consequences of a reduction in number.

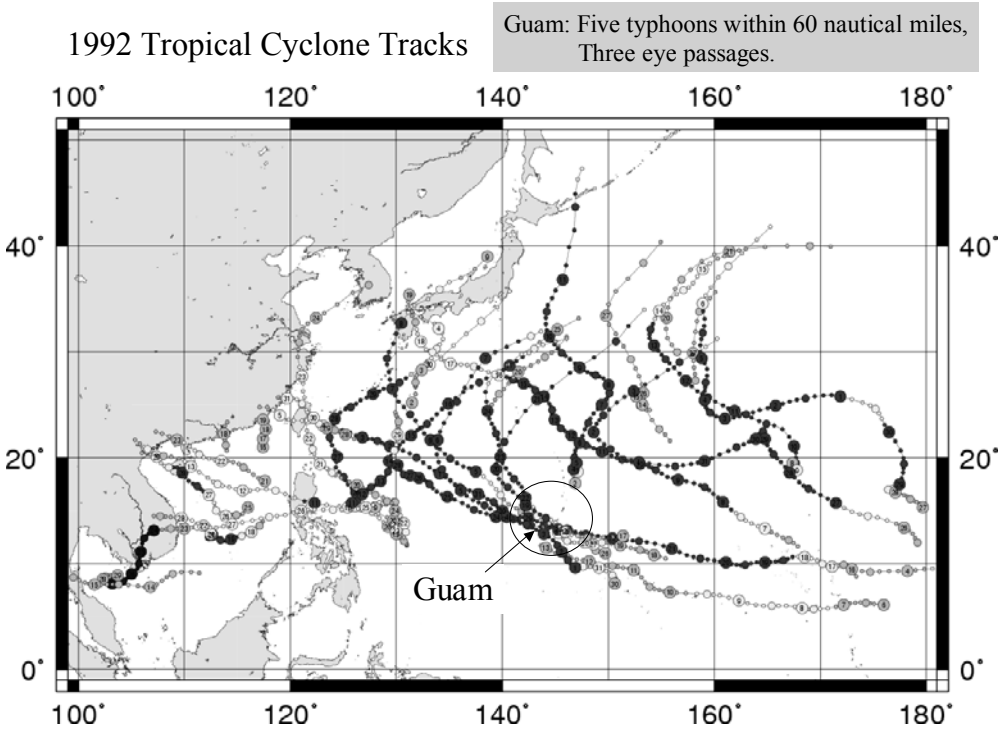


**Fig. 6. The tropical cyclone tracks of 1992 showing a clustering of tracks near Guam. Guam experienced typhoon conditions five times in 1992 including three directs hits (eye passages over the island).**

During 1992, the island of Guam (13.5°N ; 145°E) was impacted by five typhoons. Three of these typhoons were direct eye passages over the island (Fig. 6). There was then concern on Guam that some change in the climate system was acting to produce this unusual event; especially since Guam had experienced the effects of major typhoons in both 1990 and 1991 as well. As with the landfalling typhoons in Japan, the number of typhoons that hit Guam is a good example of an event that can be modeled as a Poisson process. In so doing, one finds that three typhoon eye passages over Guam in one year might happen an average of once every 700 years! This is certainly very rare, but it is actually not quite as rare as 10 landfalling typhoons in Japan, which has a rate of occurrence of about one time in 1500 years. It is always tempting to interpret a very unusual event as something caused by a shift in the climate. To those on Guam

who thought in 1992 that something strange was happening to the climate system, one only needed to point out that the neighboring island of Saipan only 150 km away had not had a direct strike by a major typhoon since 1986! To those in Japan who felt that the record number of typhoon landfalls in 2004 was a sign of a shift in the climate system that would bring such occurrences more frequently, one could point out to them that statistical analysis indicates that an almost impossible increase in the basin-wide number of tropical cyclones would be needed to bring about a large change in the number of them that hit Japan.

## Summary of Important Findings

At the recent Sixth International Workshop on Tropical Cyclones (IWTC-6) held in San Jose, Costa Rica for two weeks in November 2006, a special group session was convened to generate a statement from the tropical cyclone community on the possible changes to tropical cyclone climate in a warmer world. The ten summary points of this statement are included in the text of this manuscript.

During 2004, there were ten landfalling typhoons in Japan. This was a record number, far exceeding anything that had occurred during the previous 53 years. A statistical analysis indicates that this event was indeed rare, with a recurrence interval of approximately 1500 years! The occurrence of such an extreme event is probably not an indication of a shift in the climate system that would result in a noticeable increase in the annual average number of typhoons making landfall in Japan or a more frequent occurrence of an extreme number of them, say 10, in one year. The 100-year extreme event, or the 500-year event, or the 1000-year, or the 1500-year event has to occur sooner or later. That the 1500-year event would occur in any 54-year segment of the time series has a probability of about 3 or 4% - not really all that improbable after all. One has a far smaller chance of winning a major lottery anytime in 54 years!

The annual number of landfalling typhoons in Japan is closely linked to the annual number of tropical cyclones in the whole western North Pacific basin. There are approximately 30 tropical cyclones per year in this basin. There is no evidence that this number will change substantially so as to strongly influence the number of typhoons that hit Japan (or any other location in the western North Pacific).

Point 8 of the summary points of the IWTC-6 statement on tropical cyclones and climate change indicates that there are some indications that the annual totals of tropical cyclones in most basins may decrease slightly in a warmer world. This cannot, however, be interpreted to indicate this decrease tropical cyclone activity would occur in all parts of any particular basin. Other factors governing regional differences and track distribution within each basin would have to be considered. Mostly these are poorly understood.

In typhoon-prone regions of the world, one must always be prepared for a devastating strike. It is tempting to think that one must wait 100 years for an event with a recurrence interval of 100 years to take place. This is not how it works. The 100-year event has a roughly equal (albeit low) chance of occurring in any particular year. Similarly, the idea that one is “due” for an extreme event because of a past lack of it, or that one may “rest easy” for a while after the occurrence of it are equally false notions.

Point 6 of the summary points of the IWTC-6 statement on tropical cyclones and climate change indicates that model studies and theory project a 3-5% increase in tropical cyclone wind-speed per degree Celsius increase of tropical sea surface temperatures. This is cause for concern.

Adequate preparation for today's distribution of tropical cyclones, however, should guarantee resiliency against any changes brought about by global climate change.