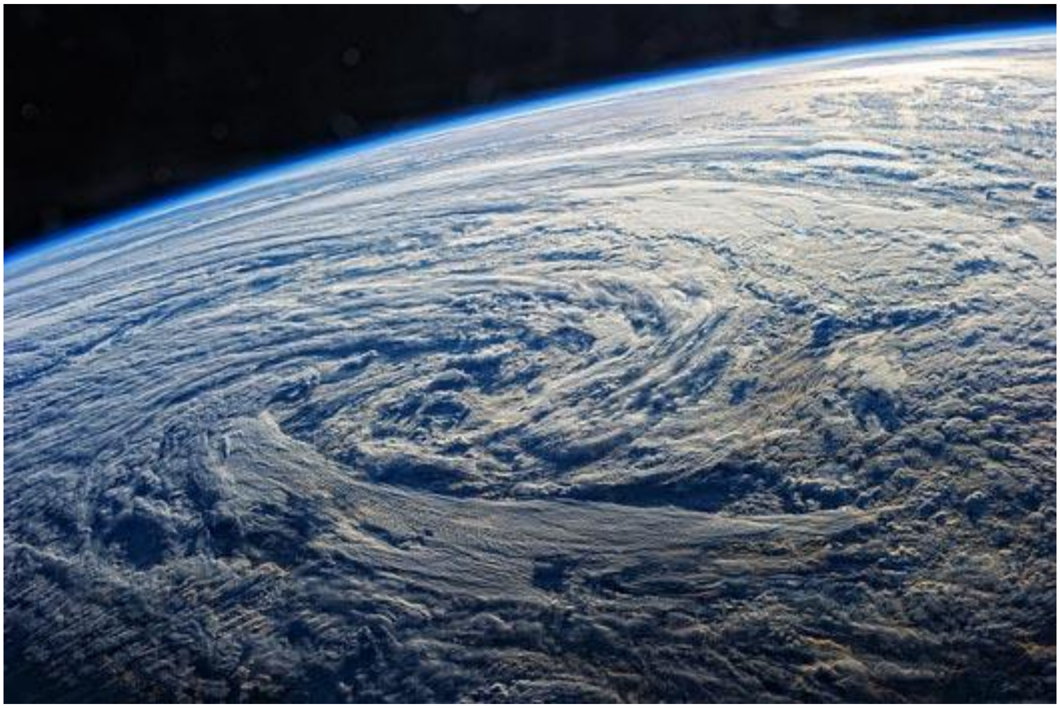
# Future Changes of the North West Pacific Typhoons: using the high resolution GCM EC-Earth



Yang Shu

2015 March

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# Future Changes of the North West Pacific Typhoons: using the high resolution GCM EC-Earth

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# Abstract

Tropical cyclones are common weather phenomena occurring over warm sea and they may cause great damage to human society. The North West Pacific Ocean has the largest number of tropical cyclone each year, and this number may change in the future due to climate change. This study used a high resolution (25 km) climate model (EC-Earth), to simulate the present, near future and future weather conditions to explore the change of tropical cyclones over the North West Pacific Ocean. According to our results, the number of typhoons (strong tropical cyclones) will slightly decrease in the near future and increase at the end of 21st century. The change will mainly happen in northern regions, like the East China Sea and around Japan. Furthermore, it appears that a shift of the typhoon peak season, which means we can expect more typhoons earlier in the year.

**Key words**
Tropical cyclones, North West Pacific, Climate change, Typhoons, EC-Earth

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I should thank Michiel Baatsen from Utrecht University as well. He started his work about extra tropical cyclones in the North Atlantic area last year and I followed his path to some extent. He helped me solve several practical issues and he is always willing to offer his help and advice.

I would like to thank my colleagues and fellow interns in KNMI. They helped me get familiar with the environment, Dutch culture, also some feedback on my work. The kindness I received from them made my life in KNMI unforgettable.

Last but not least, I want to thank my family. They support me to study abroad, to see the bigger world and explore the secret of science. And thanks to my girlfriend, she was the person saving me from the KNMI's canteen (the only thing I don't like there) during the lunch time.

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# 1 Introduction

## 1.1 Background

Tropical cyclones (TC) are important weather phenomena with great influence on human society, especially in coastal regions. They may bring water vapor to the continent, but they can also be a hazard bringing heavy rain, high waves, storm surges and tornadoes. In 2013, super typhoon Haiyan/Yolanda, the strongest landfall tropical cyclone on record, made landfall in Asia. More than 6000 people died (NDRRMC, 2013), in total1785 people went missing and the economic damage in the Philippines was estimated at around USD 815,000,000 (ESCAP/WMO Typhoon Committee., 2013). Furthermore, tropical cyclones were responsible for 1.9 million deaths in the past two centuries worldwide. Thus, understanding the formation and development of tropical cyclones is an important task for scientists.

Tropical cyclones can be scaled by their sustained winds. In the western hemisphere, people use the word hurricane to refer to tropical cyclones whose sustained wind speed exceeds 33 m/s. In East Asia, known as North-West Pacific area, people call these intense tropical cyclones typhoons, and in the Indian Ocean, they are called cyclonic storms. Tropical cyclones with lower wind speed are defined as tropical depressions (≤ 17m/s) and tropical storms (18~32 m/s). The threshold may differ for different regions. Researchers use the Saffir–Simpson hurricane wind scale (SSHWS) to classify tropical cyclones (Tropical Cyclone Weather Services Program, 2006) into 5 categories based on their sustained wind speed. In other regions, different ways of classification have been used by different organizations.

The energy source of tropical cyclones is the release of latent heat. Several environmental conditions should be met before a tropical cyclone can be formed (Landsea, 2000). First, warm ocean waters (at least 26.5 ºC) throughout a sufficient depth. Second, a potentially unstable atmosphere. Third, relatively moist mid-tropospheric conditions. Fourth, the location of at least 50 km away from equator. Fifth the existence of a near surface disturbance is needed. The last prerequisite for tropical cyclone formation is a low magnitude of vertical wind shear. These six conditions are necessary but not sufficient for the forming of a tropical cyclone. (Dare & McBride, 2011)

Each year, there are 80-90 tropical disturbances reaching storm intensity (18 m/s), most of which (32 %) occur over the North-West Pacific Ocean (Landsea, 2000), whose coastal area is also one with a large population density. As mentioned above, tropical cyclones are formed over warm sea waters, with a sea surface temperature (SST) threshold of 26.5 ºC (Dare, R. A.& McBride, J. L., 2011). Due to a close relation to SSTs, which may change due to continued greenhouse gases emissions and induced global warming, the formation of tropical cyclones may change in the future as well. This change depends on space and time. Also the distribution of storm intensity might change. Understanding this will be useful to prevent weather disasters and to obtain a better understanding of the impact of climate change.

Several studies on (future) tropical cyclones have been conducted. Some researchers found that the frequency of tropical cyclones making landfall in China has become lower in the past 50 years while the number of intense tropical cyclones has increased (Lei, Xu & Ren, 2009). However, the relationship between tropical cyclones and global warming is questioned by some scientists. They indicate that the number of tropical cyclones may be related to some natural cycles such as ENSO, PDO, NAO and AMO (Lei et al., 2009). The natural variability is hard to identify, thus using a numerical model to carry out a simulation may be a better option. However, many global climate models can hardly simulate tropical cyclones due to their low spatial resolution. For this reason, high resolution climate models are used to simulate tropical cyclones. In this study, we will use the EC-Earth model (Haarsma et al., 2013) at a high resolution (25 km) to estimate future changes in the intensity and frequency of tropical cyclones. We will focus here on the North West Pacific Ocean.

## 1.2 Research questions

Two key words to study tropical cyclones are path and intensity. Tropical cyclones usually cause more damage and loss over land compared with those over sea, and stronger storms pose a greater threat. Thus, we are interested in the change of intensity and path of tropical cyclones in the future. For our area of interest, the North-West Pacific Ocean, researchers focus more on the tropical cyclones because the Asian continent is located to the west of the ocean and the storms usually move westwards.

As we have known that the tropical cyclones can only be formed over the warm ocean with SST higher than 26.5 ºC. We can expect that the increasing air temperature due to greenhouse gases (GHG) emission may have an impact on SST pattern, and furthermore, influence the tropical cyclones in the future. Thus we would like to explore how the frequency, intensity and spatial/temporal distribution of tropical cyclones in the future.

In this study, we are trying to give a projection of future tropical cyclones in the North-West Pacific Ocean. We will focus on the cyclones with sustained wind speed exceeding 33 m/s or 12 Beaufort wind scale, which can be defined as typhoons. We will analyze their intensity and frequency and also the distribution of typhoons' landfall changes in the future. The thesis will start with the background information about tropical cyclones, followed by the methodology, including the dataset, simulation set-up, cyclones tracking algorithm, statistical method, etc. Then the results will be presented, and the conclusions will be compared with some other studies.

# 2 Methodology

## 2.1 Model set up and experiments

We are using EC-Earth in this study. EC-Earth is a global climate model derived from ECMWF's numerical weather prediction (NWP) model. In this case, only the atmospheric component of EC-Earth is used with prescribed sea surface temperature (SST) at a high resolution, T799 L91, which is 25 km for the horizontal resolution and 91 vertical levels. This is sufficient for studying tropical cyclones. The time resolution of the data set is three hours. Three sets of simulations will be used in this study, each of which consists of 5 years and 6 members' ensemble simulations. The first set we use is 2002-2006, which represents the present climate as a baseline. The other two sets are near future (2030-2034) and future (2094-2098) climate, both of which are derived from the IPCC RCP A1B emission scenario, which is comparable to RCP 4.5. For the present climate, daily SST observation data from NASA were applied and for other the two periods, SST simply adds the predicted change from baseline to the observation. See Haarsma (2013) for more information about the experiments

To analyze the change of landfall typhoons, we divided the east coast of the Asian continent into five regions: South China Sea (105-125E, 10-25N), East China Sea (120-135E, 25-35N), Japan (125-150E, 35-45N), Sea of Okhotsk (140-155E, 45-60N) and Bering Sea (155E-175W, 45-60N). These regions cover the most affected areas in the North-West Pacific Ocean.

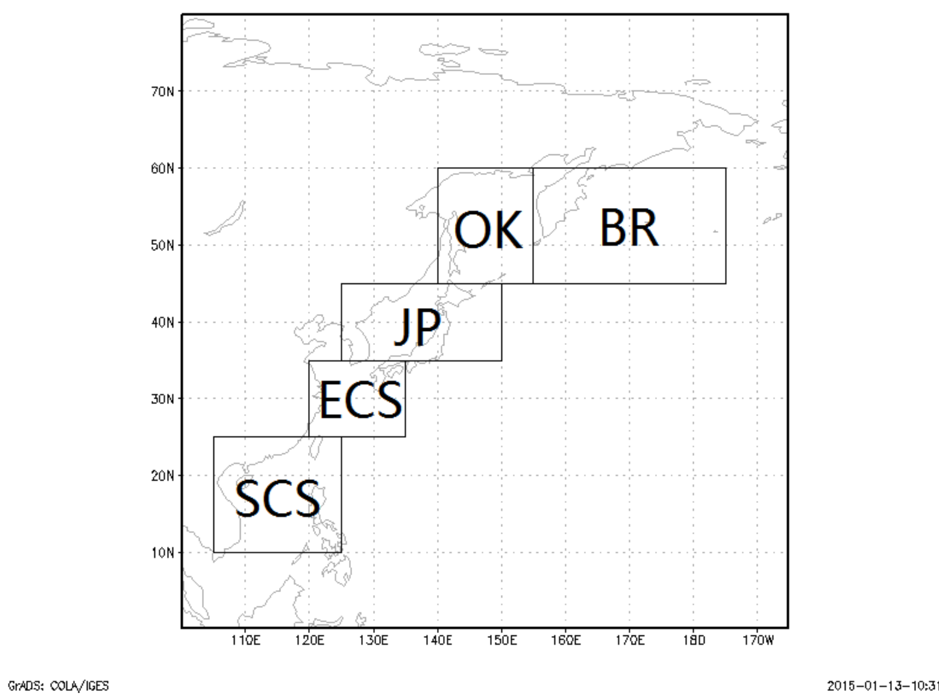



*Fig 2.1. Five regions we selected in this study*

## 2.2 Typhoons selection and tracking method

In this study, we use the method of Baatsen (2014) to identify and track tropical cyclones. Considering the large amount of tropical cyclones in this area, we will only focus on the most severe storms in this study. We chose the cyclones with maximum wind speed exceeding 33 m/s, which are called typhoons in Asia. The data set is not too large for the analysis and is still large enough to give reliable statistical results. Consequently, we searched the events with 3 hourly wind speed exceeding Beaufort 12 (33m/s), which are also referred to as typhoons in Asia. This work was carried out in five regions as mentioned above: South China Sea (SCS), East China Sea (ECS), Japan (JP), Sea of Okhotsk (OK) and Bering Sea (BR). Tracking started at the point where the above criterion is met, after which we tracked one day forwards and ten days (in maximum) backwards. Both minimum mean sea level pressure (MSLP) and relative vorticity (RV,ζ) were used to check the path of typhoons. Three hourly MSLP can be derived easily from the data we used, and relative vorticity is determined by 10 meter wind speed ($\zeta_{10} = \frac{\partial v_{10}}{\partial x} - \frac{\partial u_{10}}{\partial y}$) which is also available at a 3 hour interval. Some events were abandoned due to their weak intensity and assumed to be only noise instead of typhoons.

The tracking process was divided into three steps. First, we have a new initial guess from the extrapolation of the 2 previous locations. The extrapolation is considered with a maximum shift of 20 grid boxes (5 degrees). Secondly, the position around this initial guess with maximum RV was determined within a radius of 20 grid boxes. The position was only accepted when the minimum SLP was lower than the initial guess. Finally, the centre of the cyclone was determined by locating the minimum MSLP within a 10 grid box radius of the current guess. The tracking would continue for 10 days backwards as long as the 3 hourly wind speeds exceed serve tropical storm (90 km/h).

## 2.3 Observation data

We also utilized observation data that can be compared with the present period to evaluate the model performance. We used the International Best Track Archive for Climate Stewardship (IBTrACS) from NOAA's National Climatic Data Center. IBTrACS is a project to collect the historical tropical cyclone best track data from all available Regional Specialized Meteorological Centers (RSMCs) (Knapp et al., 2010). Besides some basic parameters of tropical cyclones, such as minimum center sea level pressure (SLP), maximum sustained wind speed, location of cyclones' center; this data set also provides information such as the origin region of cyclones. It contains the most complete global set of historical tropical cyclones available, but we will only use the West Pacific (WP) region. We will select the same time period for the present period, which is 2002-2006. Considering there are six ensembles, or 30 years of simulation for one period, we will multiply the number of cyclones in IBTrACS (2002-2006) by 5 to make it comparable with our experimental results.

## 2.4 Statistical behavior

The typhoon occurrence follows a Poisson distribution (Tippett et al., 2011) because the events occur independently of the time since the last event. According to Poisson distribution's properties, we know that the expected value and variance are equal. Therefore, in this study, when we discuss the standard deviation of our results, we will use the following equation: $\text{Stdev(X)} = \sqrt{Var(X)} = \sqrt{E(X)}$ .

# 3 Results

## 3.1 Sea surface temperature

The change of typhoons is directly related to the change of sea surface temperature (SST). Warmer water can provide more energy to developing cyclones. The SST will change due to global warming caused by the increase in emission of GHG.

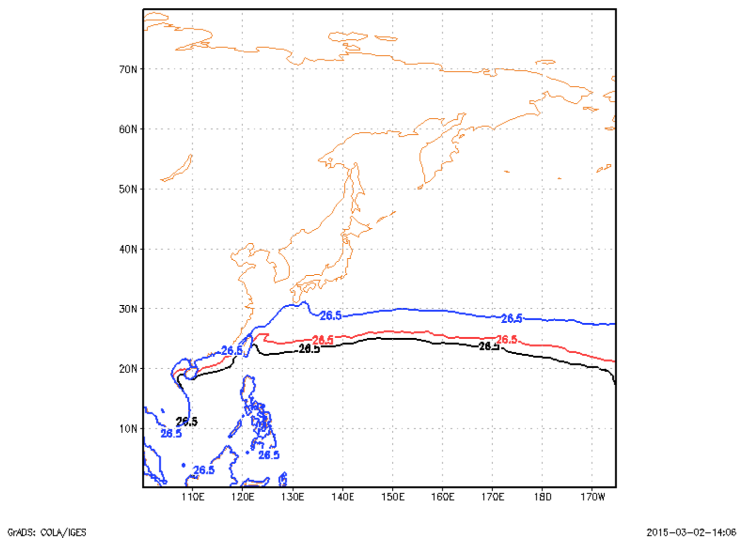



*Fig 3.1. SST pattern with 26.5 ºC isotherm in three periods: present (black), near future (red) and future (blue)*

As mentioned before, this study is based on a SST forced experiment, thus SST in the near future and future were obtained by simply adding the change of air temperature to the observation data of the present period. Figure 3.1 shows the 26.5 ºC isotherms, which is also the threshold temperature for cyclone genesis for the three periods. The 26.5 ºC isotherm moves northward, which is also what we expected. This result suggests that tropical cyclones can be formed further north in the future.

## 3.2 Frequency and intensity

We expect there will be more tropical cyclones in the future as the sea surface temperature increases. At the same time, there are also many studies finding opposite results: fewer storms in the future.  Fig 4.2 shows the number of strong wind events (maximum sustained winds exceeding 12 Beaufort) in the three periods. Darker color indicates that more events occurred. Just as we expected, the frequency of strong wind events will increase in the future according to our results. In the SCS region, the number seems to be smaller in the near future period. And the densest area may expand northward. As a result, the next step is to determine the manner of these changes.

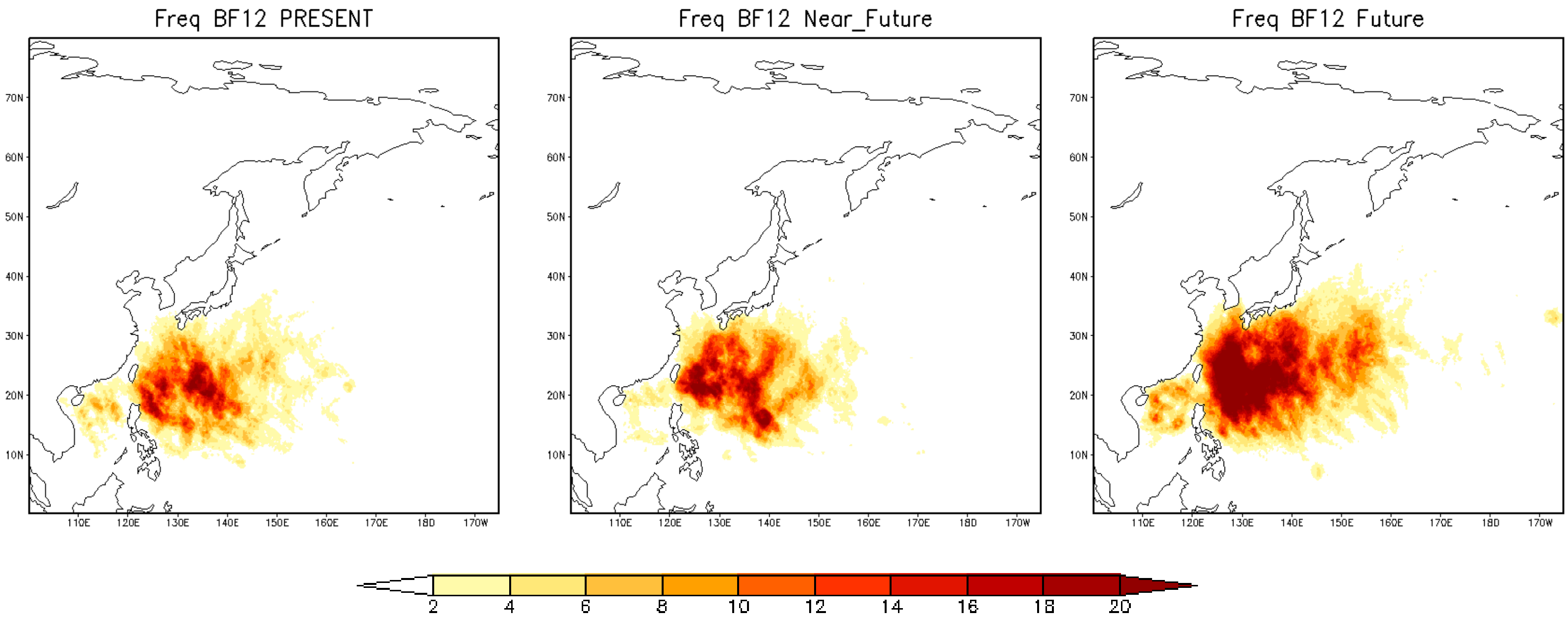



*Fig 3.2. The number of strong wind events in three periods.*

### 3.2.1 Frequency distribution on different intensities

Before we analyze the change of frequency and intensity of typhoons in the NWP region, we will first compare the simulations with observations. We use the IBTrACS best track dataset as observations for 2002-2006 and count the events which can reach typhoon/hurricane intensity. Instead of local tropical cyclones classification, we use the SSHWS wind scale, which is more generally used. There were six members for each year's simulation, so we simply multiplied the number of typhoons in observation data set by six.

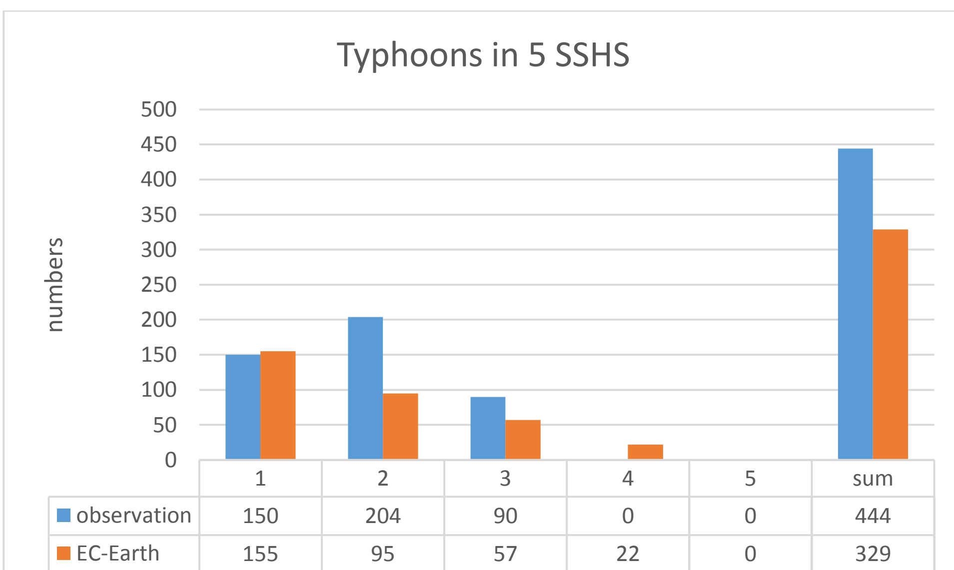



*Fig 3.3. The number of typhoons in present period (2002-2006), over 5 SSHWS categories. The blue columns are*

*observation data multiplied by six, the red columns are EC-Earth simulation.*

Figure 3.3 shows the results for the five SSHWS categories. It reveals that the EC-Earth model underestimates typhoons in categories two (43-49 m/s) and three (50-58 m/s) and overestimates by about 26% in category four (58-70m/s). Due to the simulation got fewer typhoons with high wind speed, the total number of EC-Earth is underestimated.

Next, we examine the change in typhoons frequency. Figure 3.4 shows the amount of typhoons in five coastal regions for the present (2002-2006), near future (2030-2034) and future (2094-2098). Each column represents 30 year typhoons. For the present period, the total number is a little bit larger than that in figure 3.3, which is due to that there are 16 cases were not taken into account in figure 3.3 whose maximum wind speed does not reach category 1. For the five separate regions, typhoon events are counted as they entered that region, so several events are counted repeatedly. However, when considering the total number, these cases have been deleted to ensure that one event is counted only once.

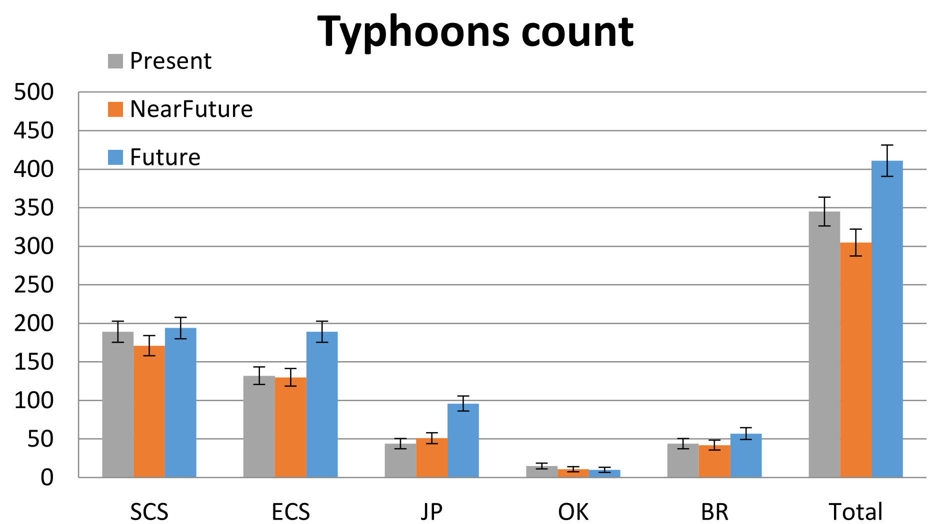



*Fig 3.4. The number of typhoons in different regions and different time periods with standard deviation as error bars.*

For the present the amount of typhoons decreases northwards, except for the Bering Sea region, which has more events than Okhotsk Sea. This result is reasonable since tropical cyclones originate in the tropical ocean and move north, thus southern areas will experience more storms. For the Bering Sea, we infer that the increase is caused by the relatively larger area of this region.

We also find that the change in time varies. In the South China Sea region and Okhotsk Sea region, the differences among the three periods are not significant. In other regions, however, there will be more typhoons in the future compared to the present and near future, which means that the largest increase in typhoons in the future will happen in the East China Sea and Japan regions. For the near future period, there is a slight increase in the JP region, while for all other regions no significant change can be detected. Overall, excluding the events counted in more than one region, we find that the events in the near future will decrease, indicating a lower total number of typhoons in the near future, which may, however, travel longer among different regions.

For now, we know that the amount of typhoons may decrease slightly in the near future and increase in the future period, but will they decrease/increase homogeneously for different intensity? Figure 3.5 may give an answer to this question. In figure 3.5, three columns (gray for present, red for near future and blue for future) represent the number of typhoons in 30 years in 5 categories (based on SSHWS). This shows that there will be fewer weaker typhoons (categories 1 and 2) and more stronger ones (categories 3, 4, 5). In the near future, the change is not as significant as in the future period for categories 1, 3, 4, 5. However, the situation is different for category 2. The decrease in the number of the near future's typhoons is the most significant for this category, leading to fewer typhoons in the near future. In the future period, we find significant change for every category. In category 1 and 2, the number of typhoons decreases by 28.4% and 42.1%, respectively, but for the higher categories, it increases much more: by 89.5% for category 3 and 445.5% for category 4. This is also the only one period when category 5 typhoons are formed. The IPCC AR5 report also mentions that an increase in frequency of the strongest storm is more likely than not (Qin et al., 2014).

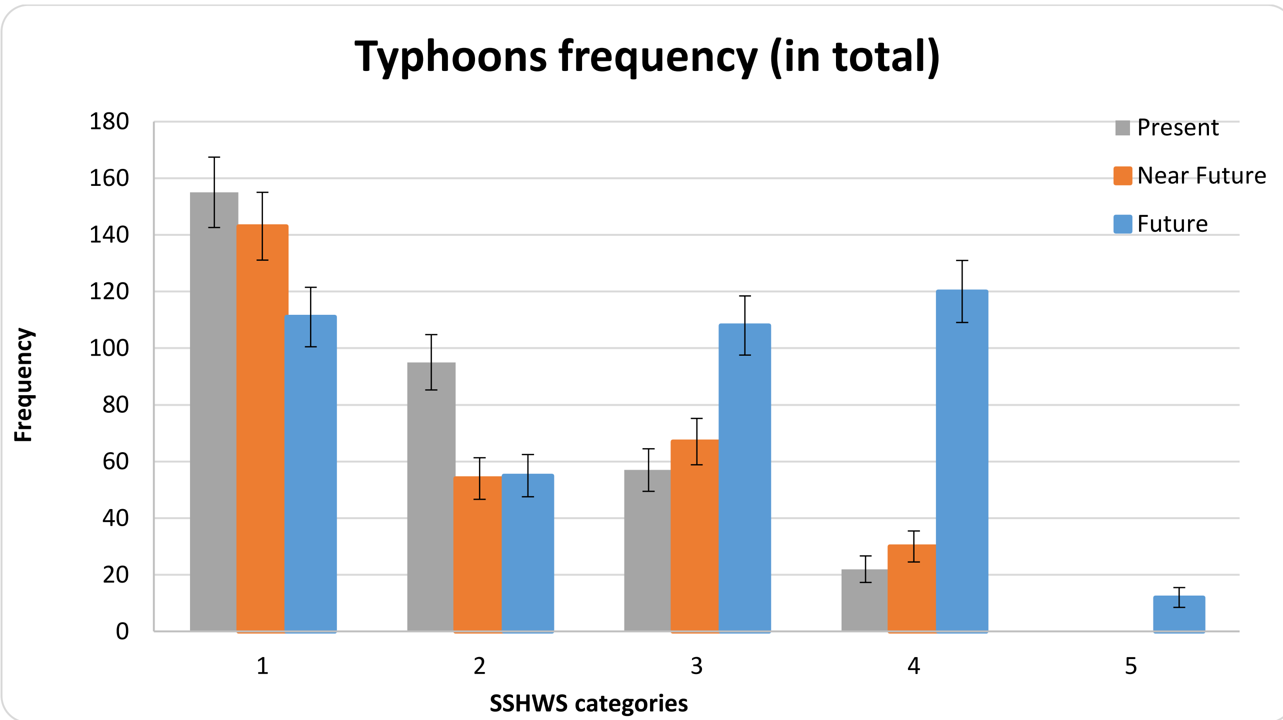
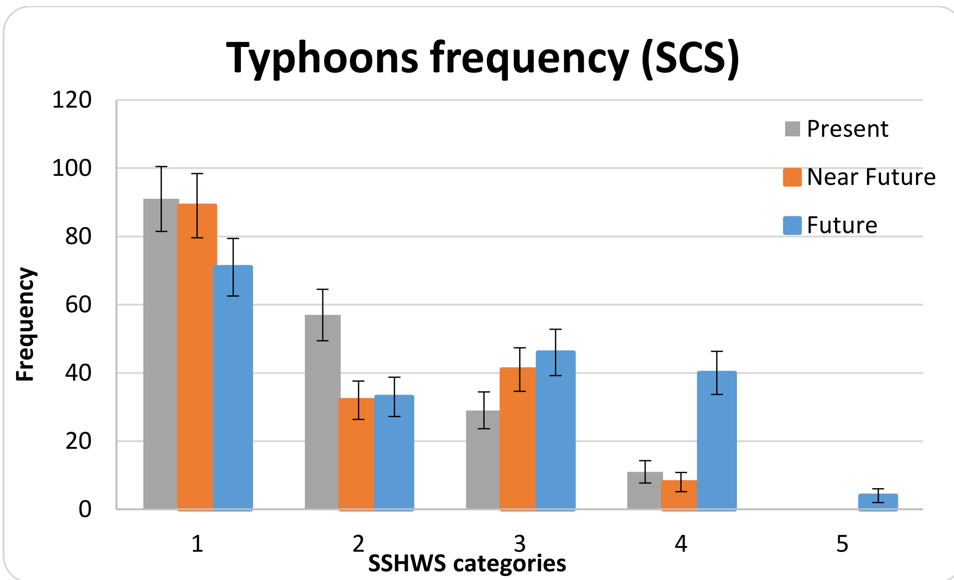
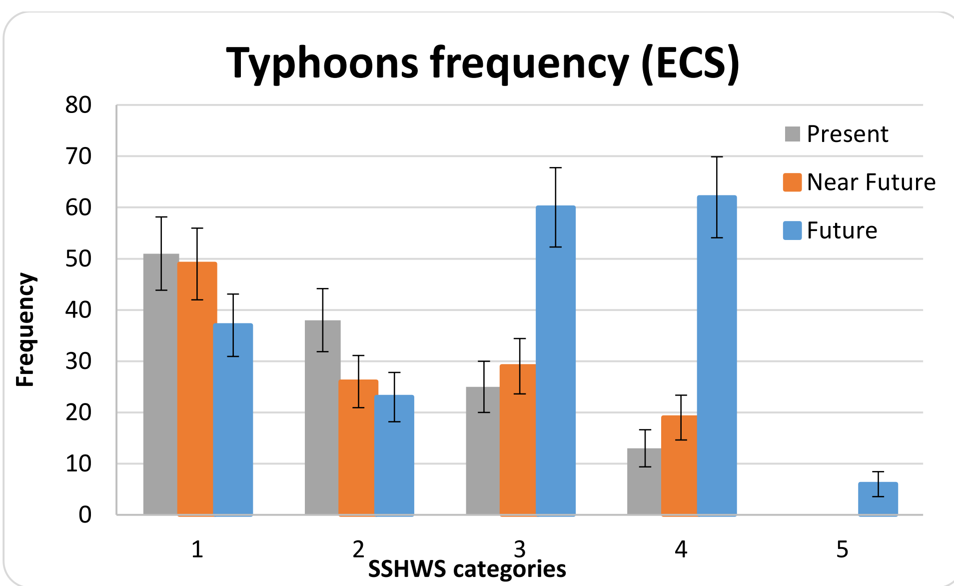


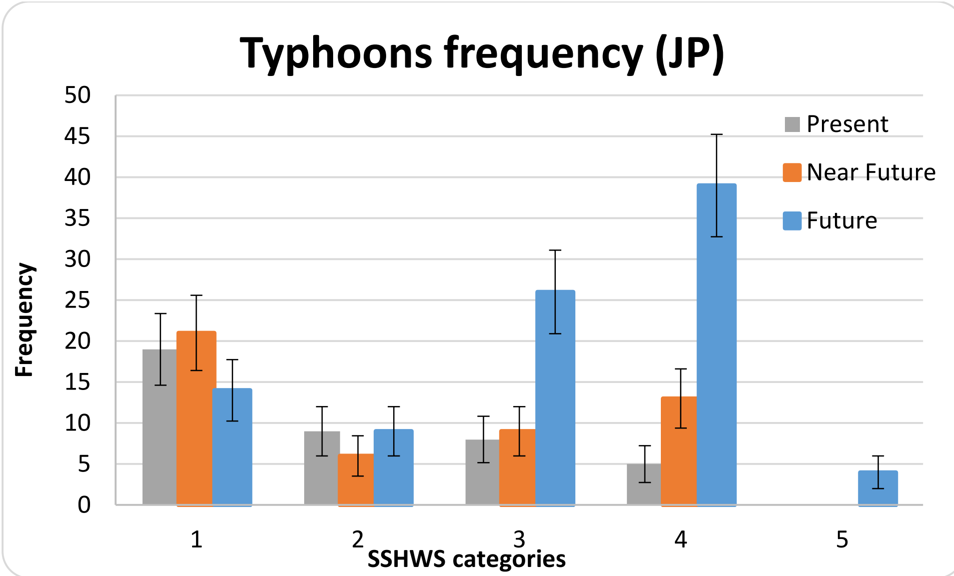

*Fig 3.5. Typhoons frequency distribution in different categories based on SSHWS in three periods with standard deviation as error bars.*

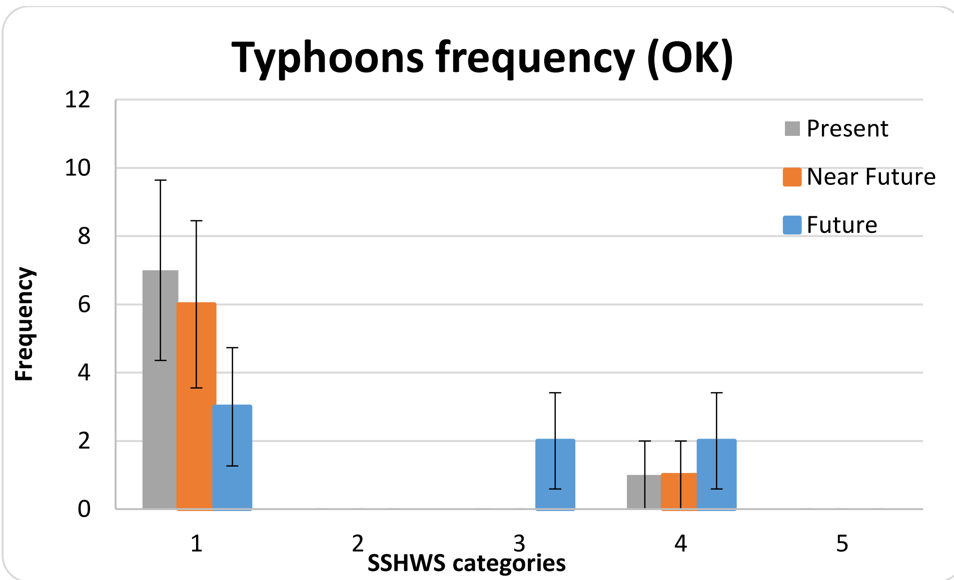
We conclude that there may be a slight decrease in the total number of typhoons in the near future, but a marked rise in the future. The common trend is that there will be fewer weaker typhoons (maximum wind speed < 50 m/s) and more stronger typhoons (>50 m/s). It is interesting to examine whether the same trend exists for specific regions, and if there is any spatial difference. Figure 3.6 shows the situation in different regions, from south to north. The South China Sea (SCS) is the most southern region, which means more proximity to the tropical cyclones' origin area, where most typhoons are found. Thus, the distribution in this region is more similar to the total trend, except in category 3, where the future increase is less dramatic, while the near future also experiences a significant increase. Although SCS will face more typhoons, most of them are weaker ones, most of the stronger typhoons (>50 m/s) occurring in the East China Sea (ESC) region in the future period. To be specific, half of categories 4 and 5, even more (55.6%) of category 3 typhoons will hit this region in the future, and 63.3% of category 4 typhoons in the near future.

When we move north to the Japan region, we find some differences. First, there is no significant change in categories 1 and 2, either in the near future or future. On the other hand, the most significant increase can be found in the future for categories 3 and in both future and near future for category 4. Although their absolute number is smaller than for SCS or ECS, it is still a substantial one considering there will be relatively fewer typhoons in this region. The number for the Okhotsk Sea is really small, even for this 30 years data, so on average, there may be fewer than one typhoon event in this region. Bering Sea is located to the east of Okhotsk Sea, so some tropical cyclones can be intensified and enter this region as extra tropical cyclones. In this region, we can only see a significant increase in the near future and future for category 4. To a certain extent, the distribution in the different regions follows the same trend of the total distribution, but they all have their own characteristics. In ECS and JP, the increase of stronger typhoons (>50 m/s) in the future is larger than in other regions.




Typhoons frequency (JP)
Frequency
SSHWS categories
Present
Near Future
Future
0
5
10
15
20
25
30
35
40
45
50
1
2
3
4
5


Typhoons frequency (OK)
Frequency
SSHWS categories
Present
Near Future
Future
0
2
4
6
8
10
12
1
2
3
4
5

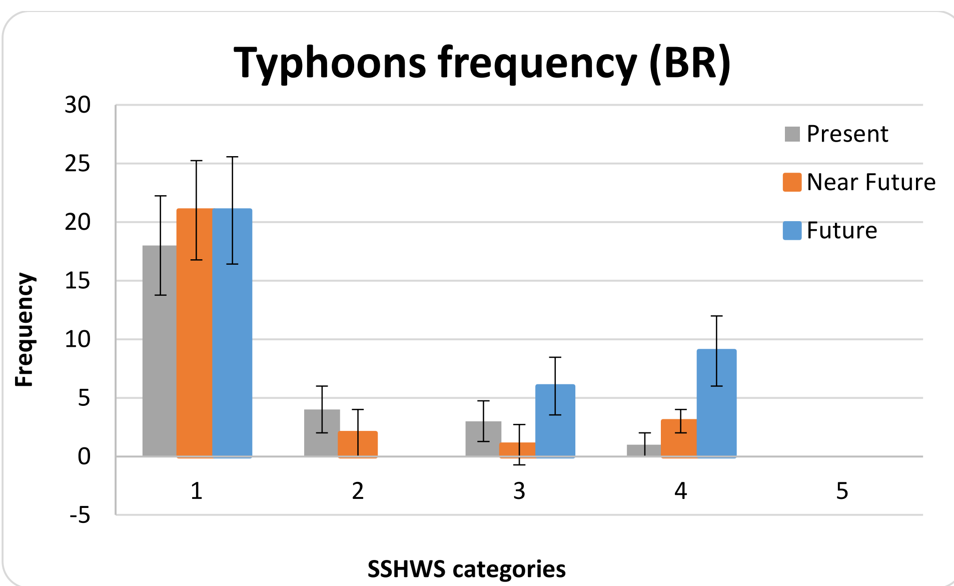

Typhoons frequency (BR)
Frequency
SSHWS categories
Present
Near Future
Future
-5
0
5
10
15
20
25
30
1
2
3
4
5

*Fig 3.6. Same with fig 4.5, but in 5 different regions. Error bars are standard deviation.*

Besides the maximum wind speed, another parameter to measure the intensity of typhoons is the minimum sea level pressure. Figure 3.7 shows the distribution of typhoons according to different minimum sea level pressure in three periods, using the sum of 5 regions, excluding the double counting events (e.g. a typhoon travels through SCS and ECS). Lower MSLP represents more intense cyclones, thus a result similar to the one above can be obtained. In the near future, the total number of typhoons will decrease. This fall will be mainly among weaker storms, that is the events with MSLP between 900 hPa and 920 hPa in this figure. The increase in the near future mainly occurs for 880 to 890 hPa. In the future period, we can observe that there will be more stronger typhoons (MSLP < 930 hPa), and there the peak value shifts from the present 950 hPa to 930 hPa. This means not only that the number of typhoons will change, but also that the majority of typhoons will be stronger in the future period.

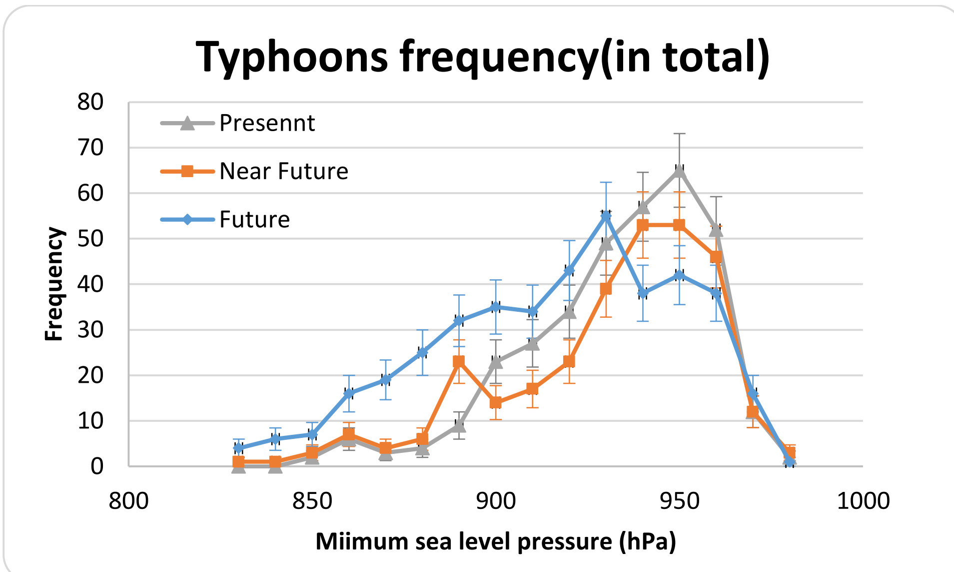
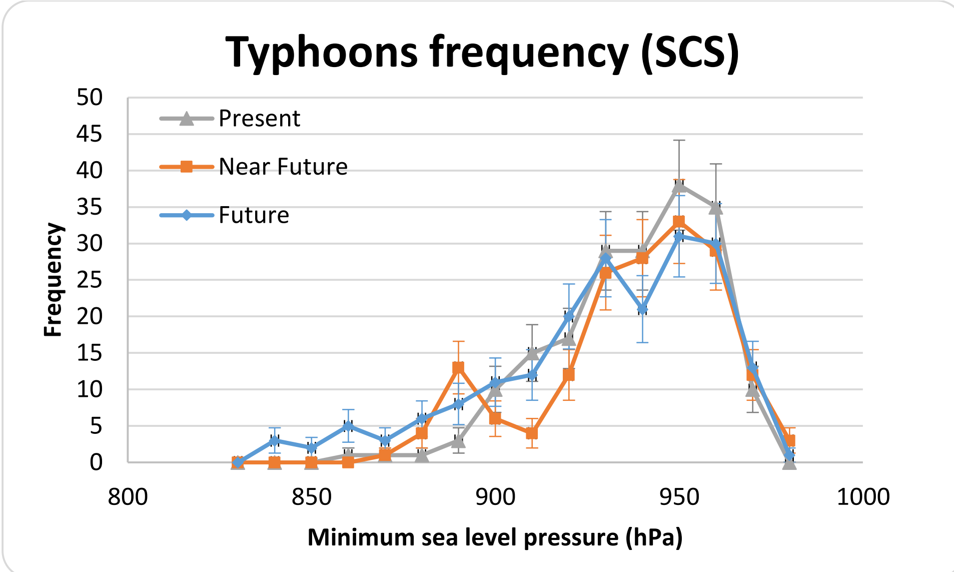
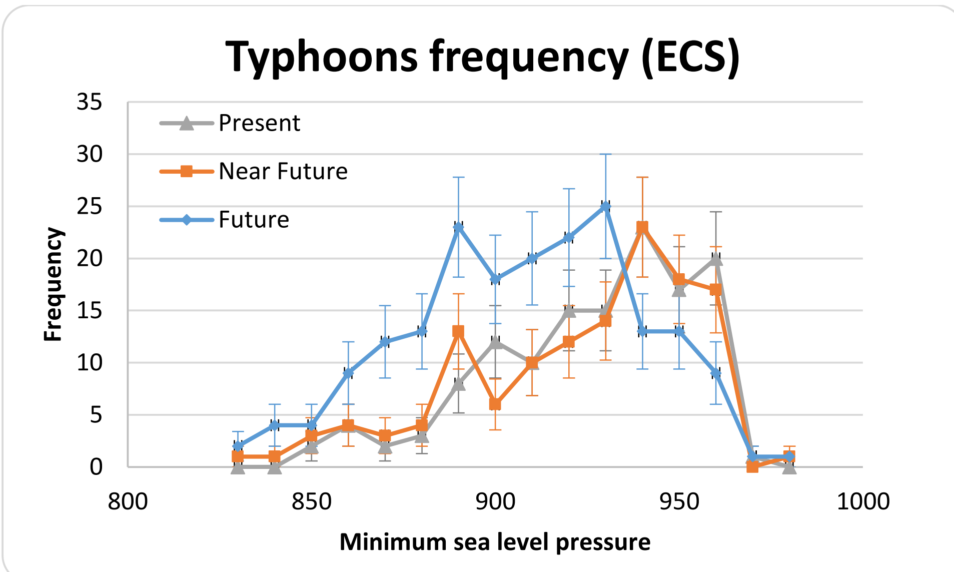
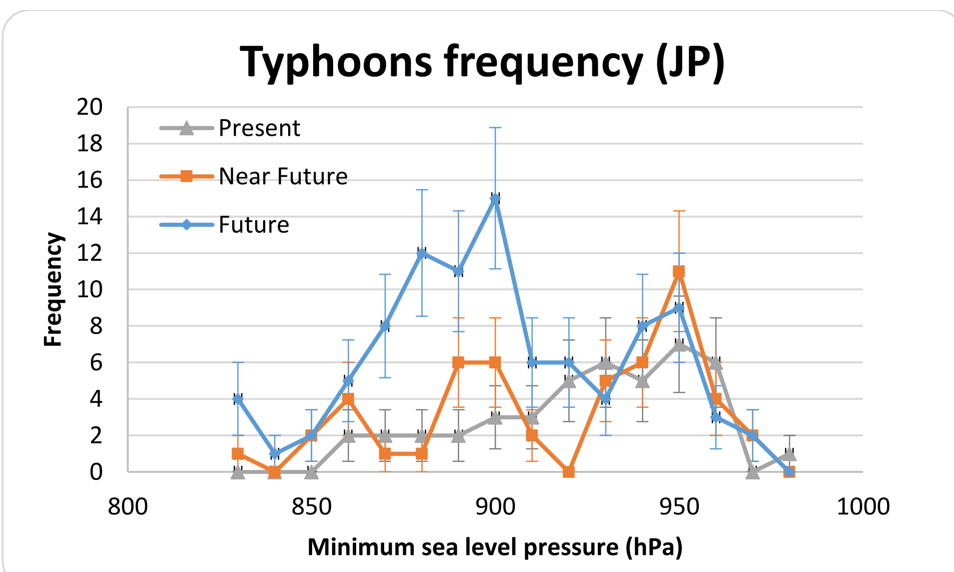


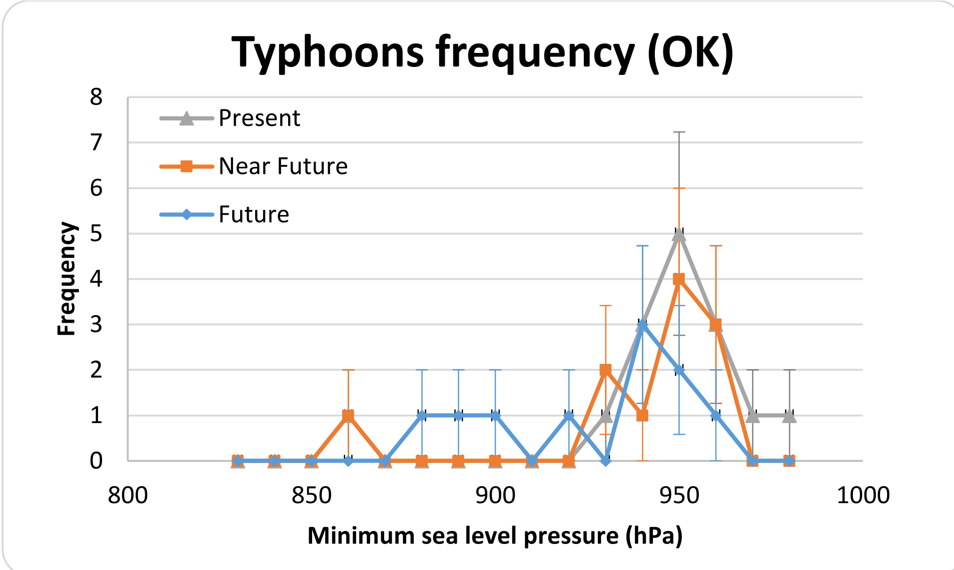

*Fig 3.7. Typhoons frequency distribution with different intensity based on minimum sea level pressure in three periods. Error bars are standard deviation.*

Figure 3.8 shows the distribution of typhoons in different regions. In the South China Sea, where we find most events, a trend similar to the total one can be noticed. However, the shift of the peak value is not observed. In the near future, the frequency will decrease for 910 hPa and increase for 890 hPa. In the future period, the increase of stronger events (840 hPa ~ 890 hPa) is still significant. In the East China Sea and Japan, the shift of the peak value in the future period is much more significant, and the change in peak value in JP region is even stronger. Although the amount of typhoons in these two regions is smaller than that in SCS, the number of stronger events is still considerable. And in Japan, both in the near future and future period, the weaker typhoons, with MSLP 950 hPa which is also the majority of the present ones, will also increase with time. The total amount in Okhotsk Sea is too small to be discussed. In Bering Sea, where we assume that most events are extra tropical cyclones, no obvious shift of peak value in either period is seen; and consequently, the change among three periods is not significant. Compared with figure 3.6, the number for category 4 in BR region has a significant increase in the future, we can conclude that the cyclones in this region may cause stronger wind but not 'deeper' system. In ECS and JP, the results are similar with that from figure 3.6: more stronger cases in the future.


Typhoons frequency (SCS)
Present
Near Future
Future
Frequency
50
45
40
35
30
25
20
15
10
5
0
800
850
900
950
1000
Minimum sea level pressure (hPa)


Typhoons frequency (ECS)
Present
Near Future
Future
Frequency
35
30
25
20
15
10
5
0
800
850
900
950
1000
Minimum sea level pressure


Typhoons frequency (JP)
Present
Near Future
Future
Frequency
20
18
16
14
12
10
8
6
4
2
0
800
850
900
950
1000
Minimum sea level pressure (hPa)



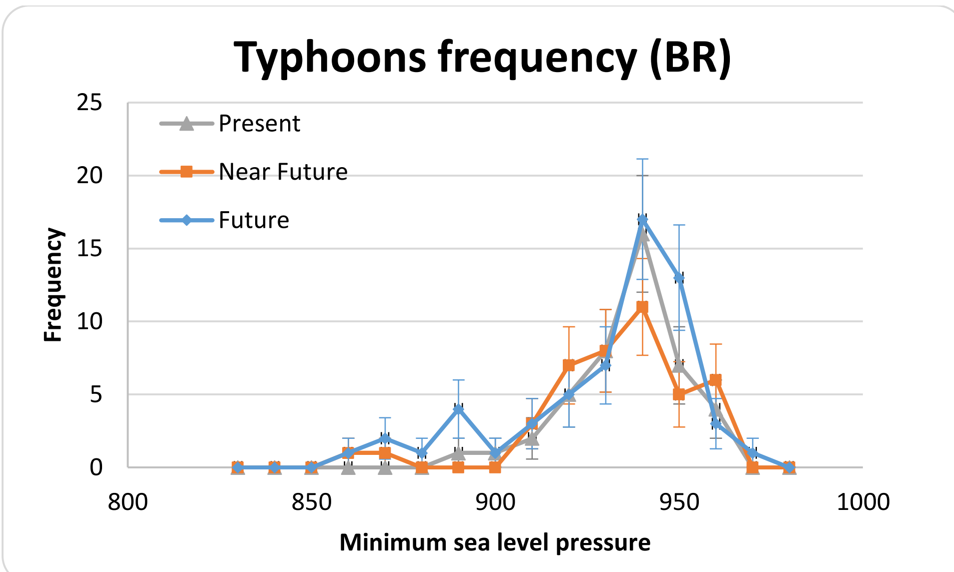




*Fig 3.8. Same with figure 3.7, but in 5 different regions.*

### 3.2.2 Seasonal (monthly) frequency distribution

Not only the total number and intensity of typhoons will change but also the seasonal occurrence. Typhoons can be formed all year long in the North West Pacific Ocean, but most of them occur in the summer and autumn. However, it is important to examine if typhoons start to occur earlier or later in the year.

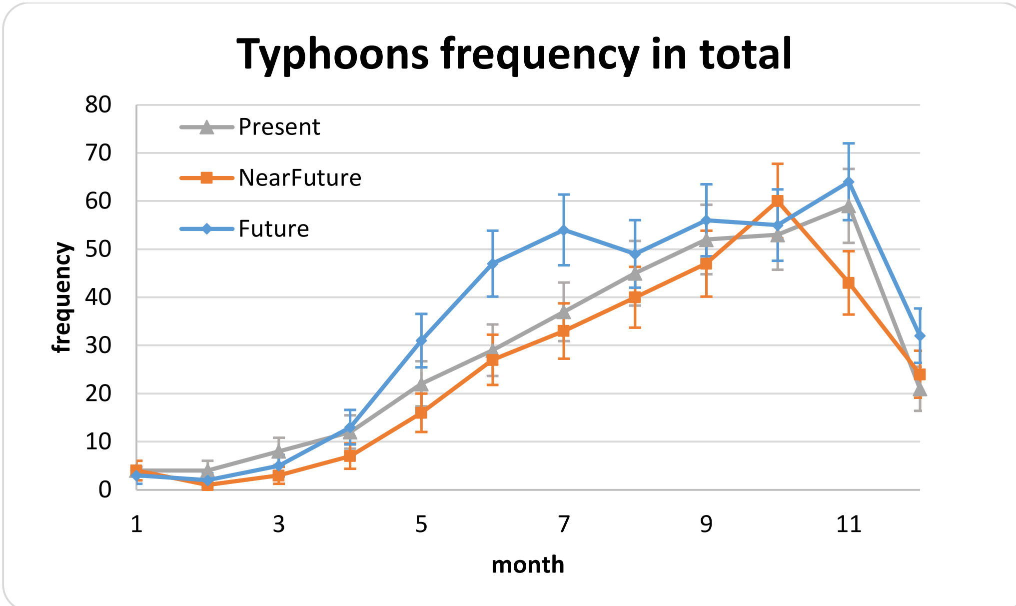
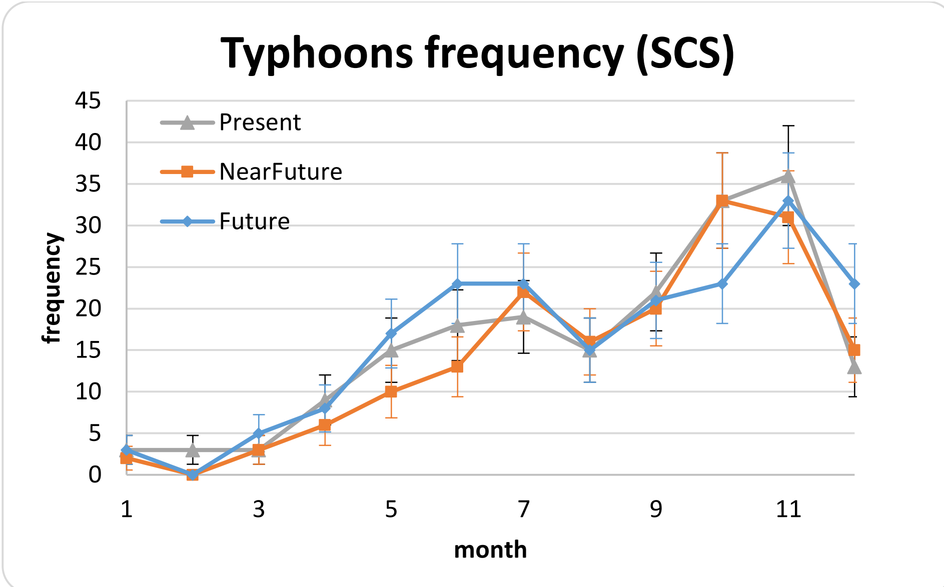
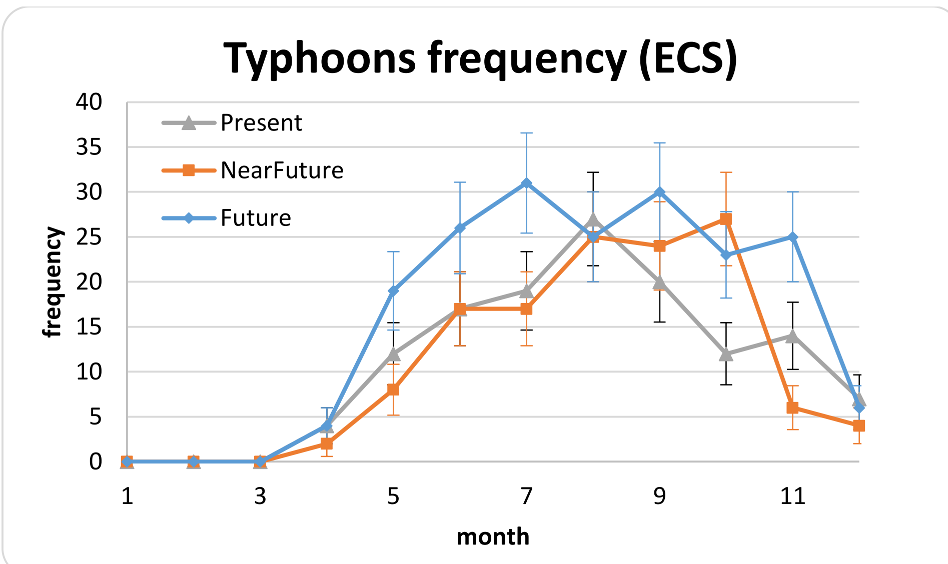


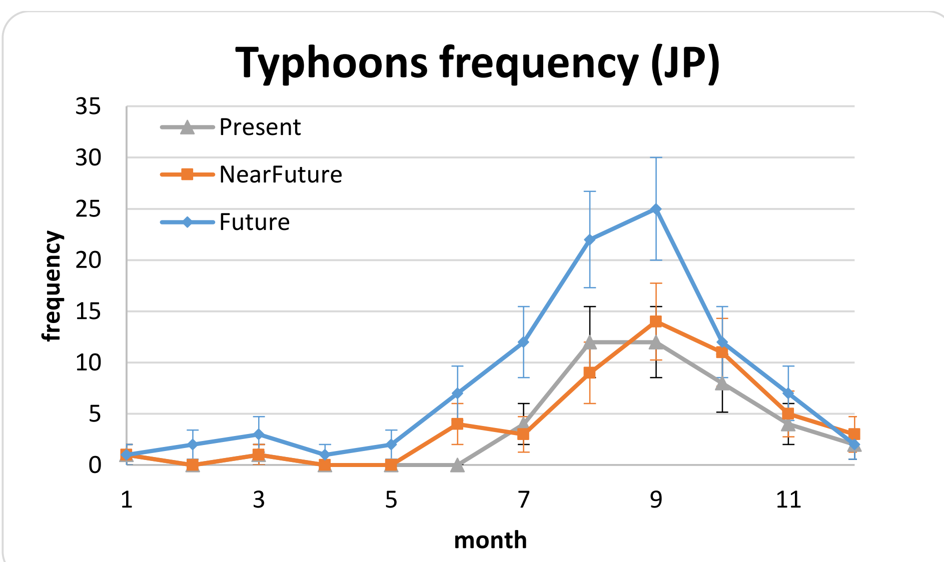

*Fig 3.9. Typhoons time distribution in 12 months for three periods. The gray line represents present, red line is near future and the blue line is future.*

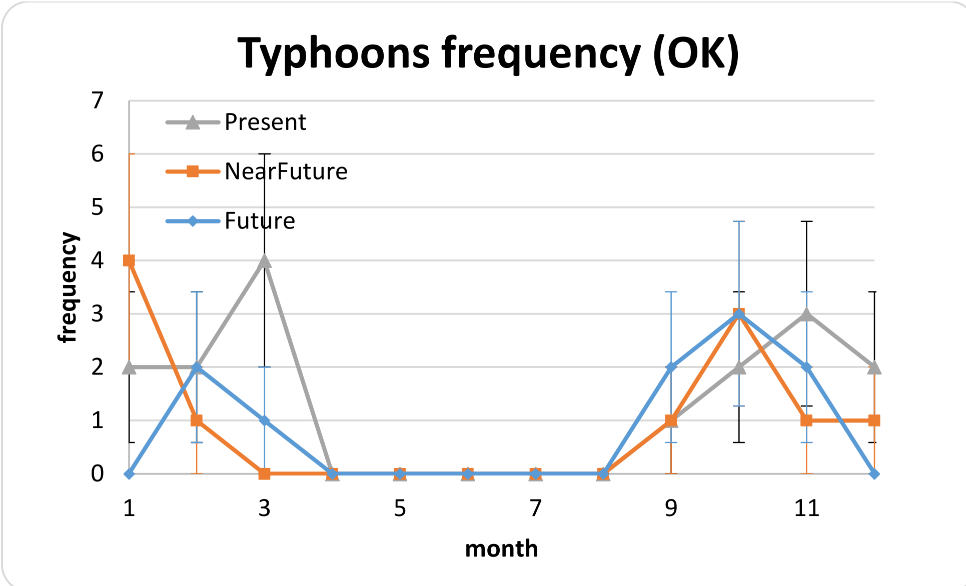
Figure 3.9 is the multiyear averaged monthly typhoon frequency over three 30 year periods. As discussed above, the number of typhoons will decrease slightly in the near future. In figure 3.9 we see a similar trend. The total amount of typhoons in the near future is lower than in the present but not significant. We have already found that this amount will rise significantly in the future, but from this figure we can note that this increase will mainly happen in late spring and early summer (May to July). Normally, most typhoons occur in autumn, and this shift will cause the peak to occur earlier in the year.

Figure 3.10 illustrates the change for different regions. The SCS region has most typhoons, so it has also the most similar trend to the total one. A valley value in August is found in all three periods. Actually, the number of typhoons in August is not small, but it has a similar (in the present and future) or higher value (the near future) to that in May. The change in the near future or future period in this region is not significant, thus we may expect less change in South China Sea. In the East China Sea, the distribution is different. For the present period, maxima occurred in August and this absolute amount does not change much in the near future and future. The number of typhoons will increase substantially in October for the near future, while for the future period it will rise significantly between June and December, except for August, which amounts to almost half a year In the Japan region, the peak value will change from August in the present to September in the future, and the number of typhoons will also increase a lot from June to September in the future. The distribution in Okhotsk Sea and Bering Sea are different: most events occur between autumn and spring, with only a few in the summer. This might be due to the number of events in Okhotsk Sea being too small, and most events in Bering Sea should be counted as extra tropical cyclones.


Typhoons frequency (SCS)
45
40
35
30
25
20
15
10
5
0
frequency
Present
NearFuture
Future
1
3
5
7
9
11
month


Typhoons frequency (ECS)
40
35
30
25
20
15
10
5
0
frequency
Present
NearFuture
Future
1
3
5
7
9
11
month


Typhoons frequency (JP)
35
30
25
20
15
10
5
0
frequency
Present
NearFuture
Future
1
3
5
7
9
11
month



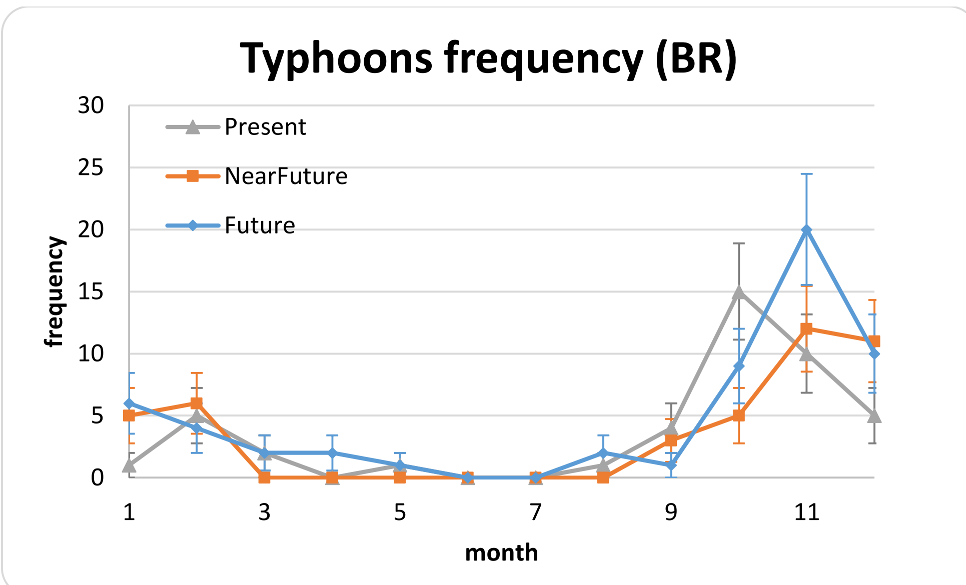




*Fig 3.10. Same with fig 3.9, but in 5 regions*

### 3.2.3 More about East China Sea and Japan

From the above we have learned that the largest increase of typhoon events will occur in the East China Sea and Japan regions. However, we should also notice that those analyses are mainly based on the statistics of all events in that region. In other words, if one typhoon passes through South China Sea and hits East China Sea, it will be counted twice, once in SCS and another in ECS. We have already observed that SCS has the most events in all three periods, thus the significant increase in ECS may simply be due to the fact that more typhoons in SCS can travel longer than before, instead of more typhoons attacking ECS directly. A similar problem can be found for the Japan region. To solve these problems we can check the region through only counting events that directly hit those regions. We have observed that tropical cyclones in this area will move northward, so we count the events number in one box and remove the events that also passed through southern regions. Therefore, in the results below, the events in ESC do not surpass those in SCS. They may hit JP in their later lifetime, but those will not be counted in JP.

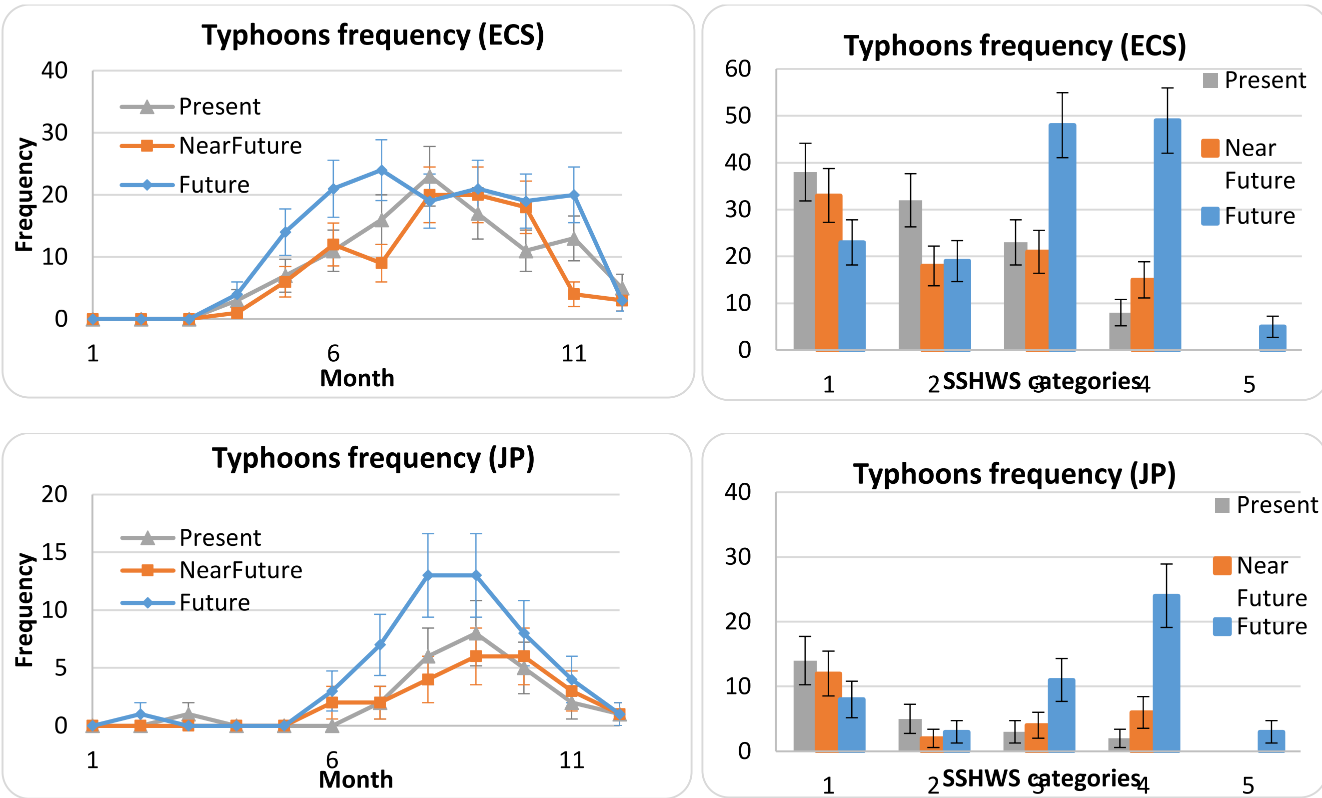



*Fig 3.11. Typhoon frequency distribution on time and 5 SSHWS categories, only in ECS and JP, exclude the events come from southern regions.*

Figure 3.11 shows the distribution of typhoons in ECS and JP regions. Comparing this figure with figures 3.6 and 3.10 ECS and JP part, we can notice that the distribution in these two regions does not change. The numbers decrease uniformly. Therefore, our results in the previous sections are still valid. The changes for different time and wind scale categories do happen.

# 4 Conclusion and discussion

Due to the continuous emission of greenhouse gases in the coming century it is expected that surface temperatures will increase from 1.1 to 2.6 ºC in the late 21 century (Qin et al., 2014). Warmer oceans may have several impacts on the earth system, and the change in tropical cyclones is one of them. In the North West Pacific Ocean, this study considers the tropical cyclones that exceed typhoon intensity that may have a significant impact on coastal regions.

EC-Earth, the earth system model we used in this study, underestimates the forming of typhoons in general, which mainly happened for less intense typhoons. On the other hand, EC-Earth overestimated stronger typhoons (category 4) in the present period.

Using EC-Earth simulations to predict the near future and future typhoon activity, we found different results. In the near future, the number of typhoons in the NWP will be slightly lower than that in the present. The first reason is that the increase for SST in the near future is not very large. However, this is not a convincing explanation of the results. Many other researchers attribute the reduction of tropical cyclones to the decrease of upward mass flux or ascent (upward vertical motion). (Sugi et al., 2012; Bell et al., 2013) In the future period, or the end of $21^{st}$ century, the amount of typhoons will increase significantly due to the expected large increase in SST.

Ying et al. (2012) reviewed recent studies about tropical cyclones activities with projections for the late $21^{st}$ century in the NWP. This study found that more models project a decrease rather than an increase in tropical storm frequency, the frequency change ranges from -70% to +60%. This result disagrees with what we found in the future period. As few studies focus on the near future, but we can still regard the decrease we found agrees with other studies. The reason why we found different results in the near future and future period may be the different dominant mechanism: in the near future, the climate change appears more as the decrease of mass flux, while in the future period, it appears more like increase energy flux.

Furthermore, the increase/decrease in typhoons will not be evenly distributed over different intensities or different regions or different times in the year. Specifically, the main increase of events appears to happen for higher wind scale categories. Thus, we can say there will be a significant increase in stronger events (categories 4 and 5). This kind of change can apply to different regions in the near future and future. Additionally, the typhoon seasonal variation will also change in the near future and future. In general, typhoons in the early months (like May) of the year, the time when there are fewer typhoons at present, will increase in future period. In some regions, like the East China Sea and Japan in this study, the change may be dramatic, therefore we can expect that the peak of the typhoon season will occur earlier in the year. In addition, these two regions also show a higher increase in stronger typhoons compared with other regions.

Ying et al. (2012) also indicated that most studies projected an increase in tropical cyclones' intensity (the change ranges from -3% to +18%). Our results agree with them at this point. Obviously, more stronger typhoons leads to higher average intensities. Manganello et al. (2014) showed that there will be more typhoons in categories 3 to 5 with a reduction in weaker storms. This also partly agrees with our research. Murakami et al. (2011) used a 20-km-mesh model projected the tropical cyclones in this region. They found the seasonal variation showed no significant change but a decrease in autumn and early winter. They also compared the tropical cyclones activities in different regions, and they suggested that most future tropical cyclones will tend to travel along a more eastward course than at present. Ying et al. (2012) also indicated the track/occurrence of tropical cyclones would shift eastwards or northward in general. This may be a possible explanation why we find an increase of typhoons in East China Sea and Japan. The tropical cyclones will consume energy when they move, so the shift of occurrence will lead to more storms can reach more eastern/northern area.

As a major weather disaster in Eastern Asia, the change of typhoon activity presents a new challenge to local people. Changing the distribution and different intensities means that we human beings have to face stronger typhoons in the future, and some northern regions, such as East China Sea and Japan, where weaker storms hit in the present period, may face even more challenges. Furthermore, the shift of typhoons peak time will result in an earlier starting and longer lasting typhoon season in these regions.

# 5 Recommendations

Due to the limited time, some more research about this study will be recommended:

The distinguishing of tropical cyclones and extra-tropical cyclones can be applied to the results. In the northern regions, like OK and BR in this study, most cyclones are extra-tropical cyclones. They may be formed by cyclogenesis or tropical cyclone transition. Using the Hart diagram can analysis the phase of a cyclone. And check if one cyclone has a tropical origin would be easy and helpful.

The reason why we have different results in the near future and future is not clear. As the SST pattern is fixed, the effect of some ocean signal like ENSO can be excluded. I assume the energy flux may play an important role, thus comparing the energy flux in different periods would be recommended. Some other research also indicated the change of mean ascent at 500 hPa may be a key factor influence the tropical cyclones. (Bell et al., 2013) So I will suggest check the circulation change in different periods.

Some other parameters can be involved also. Like air temperature at 2 meters, vertical stability, humidity and precipitation.

And in this study, the typhoons those deplete over ocean are not taken into account, this may result in a bias on the results if the spatial distribution changes in the future (more/less typhoons cause landfall). That could be also worthy to check

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