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**• Review •**

# Understanding of the Effect of Climate Change on Tropical Cyclone Intensity: A Review※

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## ABSTRACT

The effect of climate change on tropical cyclone intensity has been an important scientific issue for a few decades. Although theory and modeling suggest the intensification of tropical cyclones in a warming climate, there are uncertainties in the assessed and projected responses of tropical cyclone intensity to climate change. While a few comprehensive reviews have already provided an assessment of the effect of climate change on tropical cyclone activity including tropical cyclone intensity, this review focuses mainly on the understanding of the effect of climate change on basin-wide tropical cyclone intensity, including indices for basin-wide tropical cyclone intensity, historical datasets used for intensity trend detection, environmental control of tropical cyclone intensity, detection and simulation of tropical cyclone intensity change, and some issues on the assessment of the effect of climate change on tropical cyclone intensity. In addition to the uncertainty in the historical datasets, intertwined natural variabilities, the considerable model bias in the projected large-scale environment, and poorly simulated inner-core structures of tropical cyclones, it is suggested that factors controlling the basin-wide intensity can be different from individual tropical cyclones since the assessment of the effect of climate change treats tropical cyclones in a basin as a whole.

**Key words:** tropical cyclone, climate change, intensity change

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**Article Highlights:**

- Our current understanding of the effect of climate change on tropical cyclone intensity is reviewed.
- Factors controlling the basin-wide intensity can be different from individual tropical cyclones.
- Issues on the effect of climate change on tropical cyclone intensity are discussed.

## 1. Introduction

Tropical cyclones are among the most catastrophic of high-impact weather events, causing substantial mortality and huge economic damage in many tropical and subtropical countries (Pielke and Landsea, 1998; Pielke et al., 2008; Zhang et al., 2009; Peduzzi et al., 2012). Currently, it is a matter of great public and scientific concern whether tropical cyclone activity has changed or will change in a warming climate, and this has been an important topic in the comprehensive scientific reports of the Intergovernmental Panel on Climate Change (IPCC) and a few review papers (IPCC, 2007, 2014; Knutson et al., 2010; Walsh et al., 2015, 2016; Sobel et al., 2016; Knutson et al., 2019, 2020). Although theory and modeling consistently suggest the intensification of tropical cyclones on the basin-wide and global scales in a warming climate, there are uncertainties in the assessed and projected responses of tropical cyclone intensity to climate change (Knutson et al., 2019, 2020). One of the reasons is that the mechanisms controlling the effect of climate change on tropical cyclone intensity have not yet been well understood.

Among the metrics of tropical cyclone activity, the

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effect of climate change on tropical cyclone intensity (mostly maximum sustained wind speed) was the first focus of scientific research, as signified by Emanuel (1987), which assessed the possible change in tropical cyclone intensity in a warming climate. Over the past decade, there have been some comprehensive review papers on the effect of climate change on tropical cyclone activity including tropical cyclone intensity (Knutson et al., 2010; Walsh et al., 2015, 2016; Knutson et al., 2019, 2020). Lee et al. (2012), Ying et al. (2012), and Lee et al. (2020a, b) each provided a literature review on the effect of climate change on tropical cyclone activity in the western North Pacific basin. These reviews focused mainly on the assessment of the response of tropical cyclone activity to climate change. For example, Knutson et al. (2019, 2020) indicated that there is relatively low confidence in detecting the climate change of tropical cyclone activity from historical records, while there is medium-to-high confidence in projections including increased tropical cyclone rainfall, intensity, and proportion of tropical cyclones that reach category 4–5 intensity globally by the end of the century. In the technical summary of the IPCC fifth assessment report (AR5), confidence remains relatively low for long-term (centennial) changes in tropical cyclone activity, with a likely increase in global mean tropical cyclone maximum wind speed (Stocker et al., 2014). On the other hand, there has been relatively less attention paid to the physical mechanisms that control the effect of climate change on tropical cyclone intensity, on both the basin-wide and global scales. Our review focuses on the understanding of the effect of climate change on the basin-wide tropical cyclone intensity.

Our confidence in the assessment of the climate change of tropical cyclone intensity can be augmented only when the associated mechanisms are well understood. Although great progress has been made over the past 100 years to understand tropical cyclone intensity and structure change, as reviewed by Emanuel (2018), most studies on the effect of climate change on tropical cyclone intensity were based on our knowledge derived from individual tropical cyclones, rather than on the basin-wide and global scales. More recently, studies have suggested that factors controlling the basin-wide intensity change can be different from those that affect individual tropical cyclones (e.g., Wu and Wang, 2008; Kossin and Camargo, 2009; Zhao et al., 2011, 2018a, b; Wu et al., 2018; Wang and Wu, 2019; Gao et al., 2020; Kossin et al., 2020). By focusing on the understanding of the effect of climate change on tropical cyclone intensity, this review differs from previous ones in two aspects: 1) We focus on physical factors that control the climate change of tropical cyclone intensity, while previous reviews focused on how tropical cyclone activity has changed and will change; 2) We focus on the changes in basin-wide intensity of tropical cyclones, which can result from changes in formation location and prevailing tracks, even in the absence of changes in the environmental factors that are directly associated with intensity change. The following issues are reviewed: indices for basin-wide tropical cyclone intensity (section 2), historical datasets of tropical cyclone intensity (section 3), environmental parameters for tropical cyclone intensification (section 4), and progress in detecting tropical cyclone intensity change through observational analysis and numerical modeling (sections 5 and 6). In section 7, issues on the effect of climate change on tropical cyclone intensity are discussed, followed by a summary and suggestions for future investigation (section 8).

## 2. Indices for basin-wide tropical cyclone intensity

Nearly all studies that explore the impact of climate change on tropical cyclone intensity focus on the intensity of tropical cyclones on the global or basin-wide scales, rather than an individual tropical cyclone. Thus, it is essential to quantify tropical cyclone intensity on the basin-wide scale. Two types of basin-wide intensity indices have been widely used in the literature. One is based only on the lifetime maximum wind speed. The other is a combination of tropical cyclone duration, frequency, and intensity.

Webster et al. (2005) and Wu (2007) used the annual maximum intensity that is obtained by averaging the lifetime maximum intensity (LMI) of all tropical cyclones each year. The LMI can be in five categories based on the Saffir-Simpson Hurricane Wind Scale in the North Atlantic and eastern Pacific basins. Tropical cyclones reaching category 3 (category 4) and higher are considered major (the most intense) hurricanes or tropical cyclones. Sometimes the most intense hurricanes or tropical cyclones are simply called intense hurricanes or intense tropical cyclones. In China, tropical cyclones are also classified into tropical storms, severe tropical storms, typhoons, strong typhoons, and super typhoons in the order of increasing intensity.

Considering uncertainty in the historical records of tropical cyclone intensity (Landsea et al., 2006; Knutson et al., 2010; Kossin et al., 2013), the basin-wide intensity is also measured by the annual count of the major (the most intense) tropical cyclones. Since the annual counts of major and intense tropical cyclones depend on the annual tropical cyclogenesis frequency, the proportion of tropical cyclones with LMI reaching a certain category is used in many studies. For example, Webster et al. (2005) used the annual count and proportion of category 4–5 tropical cyclones to detect the trends in tropical cyclone intensity. The advantage of the proportion index is that the influence of the change in the annual tropical cyclone frequency is removed. For this reason, the proportion of the most intense tropical cyclones has been an important index in the study of climate change (Knutson et al., 2010, 2019).

The other type of indices for basin-wide tropical cyclone (TC), intensity is a combination of tropical cyclone duration, frequency, and intensity. Wu et al. (2008) summarized it as a storm activity index (SAI), SAI = $\sum_0^N \sum_0^\tau V_{\max}^n$, where $V_{\max}$ is the maximum sustained wind speed and $n$ is an integer. The two Σ signs denote the summations over the lifetime ($\tau$) of each storm at certain (usually 6-h) increments and for all the tropical cyclones ($N$) that occur each year in a specific basin. When $n = 2$ and 3, SAI becomes the annual accumulated cyclone energy (ACE) (Bell et al., 1999; Camargo and Sobel, 2005; Bell and Chelliah, 2006) and accumulated power dissipation index (PDI) (Emanuel, 2005), respectively. When $n = 1$, SAI becomes the sum of all intensities.

## 3. Datasets for tropical cyclone intensity

Observational analysis is fundamental to the understanding of climate change of tropical cyclone intensity, which is defined by the maximum sustained surface wind in the eyewall or the minimum sea-level pressure in the eye. Recently Klotzbach et al. (2020) indicated that the minimum sea-level pressure is much more easily identified than the maximum sustained surface wind. In fact, the two intensity measures can be converted in the historical datasets (Emanuel, 2005). According to the World Meteorological Organization (WMO) standard, the maximum sustained wind is a 10-min average wind speed at a 10-m height above the surface. However, the averaging period for the maximum sustained wind varies among different agencies. Harper et al. (2010) suggested conversions of the maximum wind speed between different averaging periods. It is suggested that a factor of 0.93 rather than the traditional value of 0.88 should be used to convert the 1-min maximum wind to 10-min maximum wind.

Direct observations of the maximum sustained wind and minimum sea-level pressure are rarely available. Before the availability of aircraft reconnaissance, limited observations were from ships at sea and coastal weather stations (Landsea et al., 2006, 2008). After World War II, aircraft reconnaissance began in the North Atlantic and western North Pacific basins, but it was terminated in the western North Pacific basin in 1987 (Emanuel, 2008). Intensity estimates based on aircraft measurements are also prone to a variety of biases owing to changing instrumentation and means of inferring wind from central pressure and the flight level (Emanuel, 2005, 2008). Even in the basins with aircraft reconnaissance, aircraft can monitor only about half of the basin and are not available continuously (Landsea et al., 2004).

A satellite-based pattern recognition scheme known as the Dvorak Technique is now the main method globally for estimating tropical cyclone intensity (Dvorak, 1975; Landsea et al., 2006; Emanuel, 2008). The Dvorak technique has evolved significantly (Velden et al., 2006). Application of this technique is mostly subjective, and it is common for different forecasters and agencies to estimate significantly different intensities based on identical information (Landsea et al., 2006). Considering the lack of homogeneity in both the data and techniques applied in the post-analyses, Kossin et al. (2007, 2013) constructed a relatively homogeneous data record of tropical cyclone intensity by creating a new consistently analyzed global satellite data archive (ADT-HURSAT) from 1982 to 2009. Recently, the dataset was extended to the 39-year period 1979–2017 (Kossin et al., 2020).

The International Best Track Archive for Climate Stewardship (IBTrACS) provides location and intensity for global tropical cyclones (Knapp et al., 2010). Among the six basins, tropical cyclone records are dated back to 1851 in the North Atlantic and 1945 in the western North Pacific. In the other basins, the tropical cyclone records are relatively short in time. Considerable changes with time are included in the techniques and methods for estimating tropical cyclone intensity, leading to uncertainty and temporal inhomogeneities in the tropical cyclone intensity estimates. It is generally believed that the intensity records are considered relatively reliable after satellites started to routinely monitor tropical cyclones in the 1970s (Emanuel, 2008).

In addition to the best track data from the Joint Typhoon Warning Center (JTWC), there are several datasets available for the western North Pacific basin from the Regional Specialized Meteorological Center (RSMC) of Tokyo, the Shanghai Typhoon Institute (STI) of the China Meteorological Administration, and the Hong Kong Observatory (HKO). It has been found that the intensity trends are different in these datasets (Kamahori et al., 2006; Wu et al., 2006; Yu et al., 2007; Elsner et al., 2008; Song et al., 2010; and Ren et al., 2011). Using an intensity model adopted from Emanuel et al. (2008), Wu and Zhao (2012) simulated the basin-wide tropical cyclone intensity in the western North Pacific basin and compared it when forced with the datasets from JTWC, RSMC, and STI. They found that the evolution of the basin-wide tropical cyclone intensity in the JTWC best-track dataset can be generally reproduced with the observed tracks and large-scale environmental parameters over the period 1975–2007. Figure 1 shows an update of the comparisons of the frequency and proportion of intense tropical cyclones in the JTWC, RSMC, and STI best track datasets in Wu and Zhao (2012). Note that the simulation was conducted with the ocean-coupled intensity model (Wu et al., 2018). The differences among the three datasets are clear, and the intensity evolution after 1970 can be generally simulated in the JTWC dataset, but not in the RMSC or STI datasets.

## 4. Environmental control of tropical cyclone intensity

Observational, theoretical, and modeling studies have established the relationships between environmental parameters and tropical cyclone intensity. However, it should be noted that tropical cyclone intensity is controlled by both environmental parameters and internal dynamics (Wang and Wu, 2004; Montgomery and Smith, 2013; Emanuel, 2018). The environmental influences can be understood by first estimating an upper bound on tropical cyclone intensity, or maximum potential intensity (MPI), for given atmospheric

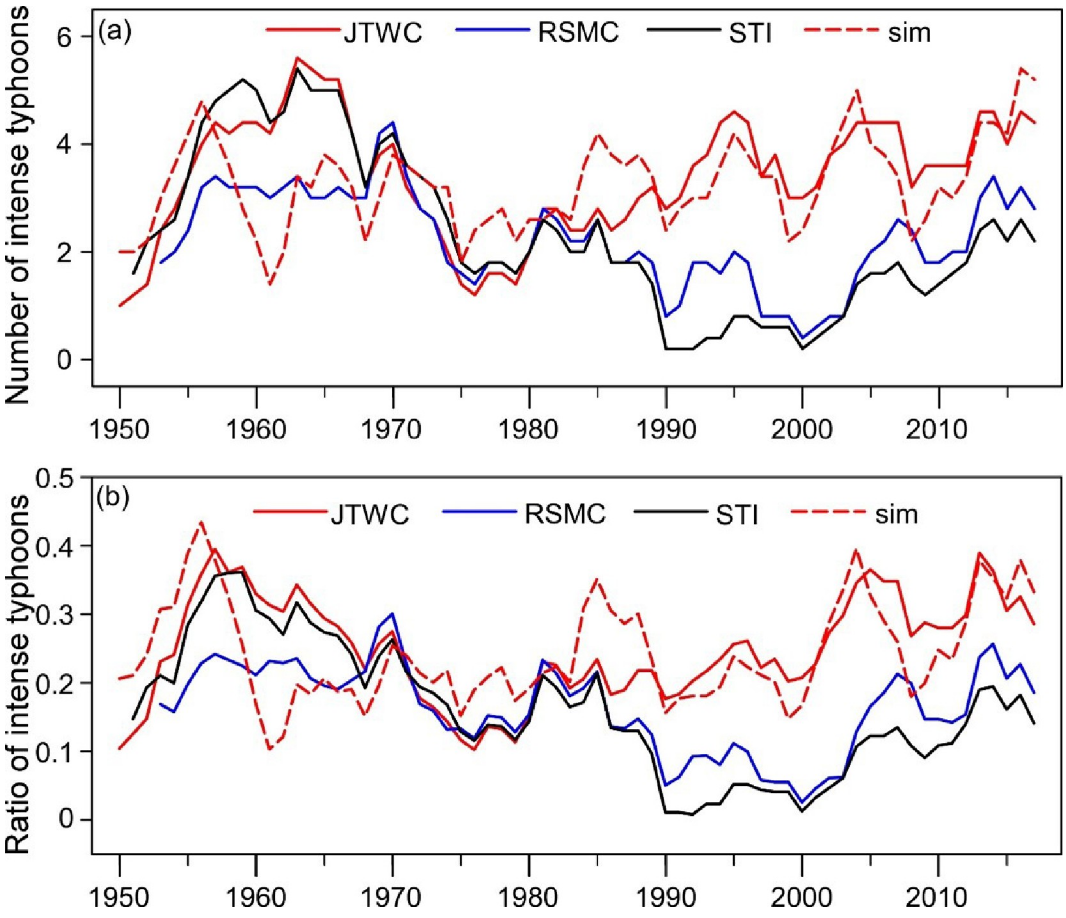

**Fig. 1**. Comparisons of the annual frequency (a) and proportion (b) of category 4 and 5 typhoons among the datasets from JTWC, RSMC, and STI during the period 1951–2019. The dashed lines indicate the simulation, and a 5-year running average is applied to the time series. This is an update of the comparisons of the frequency and proportion of intense tropical cyclones in Wu and Zhao (2012), and the simulation was conducted with the ocean-coupled intensity model (Wu and Wang, 2018).

and oceanic conditions (Miller, 1958; Malkus and Reihl, 1960; Emanuel, 1986; Holland, 1997). Here we focus only on the MPI theory proposed by Emanuel (1986, 1987, 1991), in which a mature tropical cyclone can be treated as a Carnot heat engine in terms of its energy cycle, deriving its primary energy from the underlying ocean. The MPI theory assumes that the mature tropical cyclone has an axisymmetric structure with flows that satisfy both hydrostatic and gradient wind balances and is in a state of slantwise moist neutral condition. The giant heat engine consists of four legs: isothermal expansion along with the low-level inflow, adiabatic expansion within the eyewall, isothermal compression along with the upper-level outflow, and adiabatic compression in the hypothesized environmental subsidence. In the Carnot heat engine, the MPI is achieved when the net energy input for mechanical work is balanced by the mechanical energy loss to the underlying ocean (Fig. 2, Wang, 2012), which can be written as

$$V_{\mathrm{m}} = \sqrt{\frac{C_k}{C_D}\frac{\mathrm{SST}-T_{\mathrm{out}}}{\mathrm{SST}}\left(k_0^*-k_{\mathrm{a}}\right)}\,. \tag{1}$$

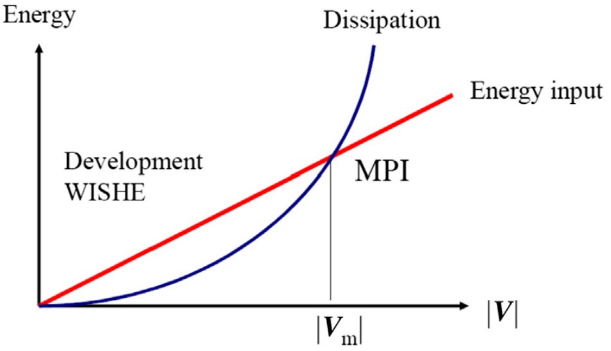

**Fig. 2**. Schematic of changes of dissipation and energy input with wind speed in a typical hurricane. WISHE, wind-induced surface heat exchange; MPI, maximum potential intensity. [Reproduced with permission from Wang (2012).].

It is indicated that MPI ($V_{\mathrm{m}}$) is a function of the thermodynamic efficiency [$\varepsilon = (\mathrm{SST} - T_{\mathrm{out}})/\mathrm{SST}$], the ratio of the surface exchange coefficient for enthalpy to the surface drag coefficient ($C_k/C_{\mathrm{D}}$), and the difference between the saturation enthalpy at the sea surface and the enthalpy of the air in the well-mixed boundary layer ($k_0^* - k_a$). Equation (1) suggests that the underlying sea surface temperature (SST) and the outflow temperature ($T_{out}$) establish theoretically an upper limit for tropical cyclone intensity, or MPI.

In reality, most tropical cyclones cannot achieve their MPI because of a variety of negative environmental influences, such as vertical wind shear (Gray, 1968; DeMaria and Kaplan, 1994; Frank and Ritchie, 2001; Wu and Braun, 2004; Zeng et al., 2010), entrainment of dry air (Dunion and Velden, 2004; Wu, 2007; Shu and Wu, 2009), and SST cooling from air–sea interaction (Bender and Ginis, 2000; Shay et al., 2000; Wu et al., 2005; Lin et al., 2008, 2009; Pun et al., 2013). It should be mentioned that the mechanisms by which the environmental factors affect tropical cyclone intensity have not been fully understood and are still at the forefront of tropical cyclone research.

Vertical wind shear is generally unfavorable for tropical cyclone intensification. Various mechanisms have been proposed to understand how vertical wind shear affects tropical cyclone intensity, including ventilation effects (Frank and Ritchie, 2001; Wong and Chan, 2004; Tang and Emanuel, 2010), increasing tropospheric stability (DeMaria, 1996), and eddy momentum fluxes (Wu and Braun, 2004; Gu et al., 2015). The effect of vertical wind shear on tropical cyclone intensity also depends on tropical cyclone intensity, translation speed, and the shear depth (Zeng et al., 2007, 2008, 2010; Wang et al., 2015; Fu et al., 2019). The shape of the shear profile also affects tropical cyclone intensity, and the deep-layer shear alone may not be sufficient for understanding the impact of vertical wind shear on tropical cyclones (Onderlinde and Nolan, 2014; Finocchio et al., 2016). On the other hand, recent studies have demonstrated that tropical cyclone rapid intensification (RI) can sometimes occur in an environment with vertical wind shear larger than 10 m s$^{-1}$ (Molinari et al., 2006; Molinari and Vollaro, 2010; Chen et al., 2018; Qiu et al., 2020). Lee et al. (2016) found that the vast majority (79%) of major storms are RI storms, suggesting that RI plays a crucial role in shaping tropical cyclone climatology.

The entrainment of dry air can be induced by vertical wind shear. Such an effect of vertical wind shear is called mid-level ventilation (Simpson and Riehl, 1958; Tang and Emanuel, 2010). When a tropical cyclone moves along the western edge of the subtropical high over the western North Pacific, Shu et al. (2014) found that a strong westerly vertical shear promotes the intrusion of dry environmental air associated with the subtropical high from the north and northwest, inhibiting moisture supply and convection over the western half of the tropical cyclone. The dry air intrusions into the tropical cyclone circulation in the Atlantic basin can be from the Saharan air layer (SAL), which forms as air moves across the Sahara Desert with substantial amounts of mineral dust. Wu (2007) showed that the long-term trend in hurricane peak intensity generally follows the Sahel rainfall and SAL activity. Shu and Wu (2009) suggested that the SAL can affect tropical cyclone intensity when its dry air intrudes within 360 km from the tropical cyclone center.

As a tropical cyclone intensifies, vertical mixing and upwelling of cooler subsurface ocean water reduce the SST. The SST reduction depends on the ocean subsurface thermal structure, as well as the tropical cyclone translation speed, size, and wind speed (Price, 1981; Bender and Ginis, 2000; Wu et al., 2005). Lin et al. (2013) proposed a new MPI index by incorporating ocean coupling, which can more realistically characterize the pre-storm ocean contribution to tropical cyclone intensity. The ocean mixed layer depth (MLD) is important to the sea surface cooling induced by tropical cyclone circulation (Price, 1981). The shallower the MLD, the stronger the resulting sea surface cooling (Bender and Ginis, 2000; Shay et al., 2000; Wu et al., 2005; Lin et al., 2008, 2009; Pun et al., 2013). The influence of the ocean MLD on the climate change of tropical cyclone intensity has been recently confirmed (Emanuel, 2015; Mei et al., 2015). The MLD is closely associated with the ocean heat content, which has been identified as an important factor for tropical cyclone intensity change (Zhang et al., 2016).

## 5. Observed trends in tropical cyclone intensity

In many trend-detecting studies, the MPI theory has become the theoretical underpinning for assessment and understanding of how TC intensity may change with climate (e.g., Emanuel, 1987; Lighthill et al., 1994; Knutson et al., 1998; Webster et al., 2005; Emanuel, 2005). In other words, the detected tropical cyclone intensity trend was implicitly or explicitly linked to the tropical SST warming. Webster et al. (2005) were the first to report the global increasing trends in the number of the most intense tropical cyclones and their proportion during 1970–2004. They argued that the increasing trends were consistent with the SST warming (Webster et al., 2005; Hoyos et al., 2006; Mann and Emanuel, 2006). Emanuel (2005) found that the PDI, which increased markedly in the North Atlantic and western North Pacific basins during the period 1975–2003, was highly correlated with tropical SST.

The relationship with the SST warming suggested by Webster et al. (2005) and Emanuel (2005) was further investigated. Holland and Webster (2007) found three relatively stable regimes in tropical cyclone and hurricane frequency over the past century in the North Atlantic Ocean. Each regime was associated with a distinct range of SSTs in the eastern Atlantic Ocean and experienced 50% more tropical cyclones and hurricanes than the previous one. Elsner et al. (2008) argued that upward trends in the estimated lifetime-maximum wind speeds of the strongest tropical cyclones (99th percentile) over each ocean basin are qualitatively consistent with the hypothesis that as the seas warm, the ocean has more energy to convert to tropical cyclone wind. Mei and Xie (2016) linked the intensified typhoons that strike East and Southeast Asia to locally enhanced ocean surface warming on the rim of East and Southeast Asia.

However, these trend-detecting studies were questioned due to data quality and changes in observational capabilities over time (Landsea et al., 2006; Hagen and Landsea, 2012; Zhao et al., 2014; Klotzbach and Landsea, 2015). Landsea et al. (2006) argued that subjective measurements and variable procedures made existing tropical cyclone datasets insufficiently reliable to detect trends in the frequency of category 4–5 tropical cyclones. Klotzbach (2006) suggested that most of the increase was likely due to improved observational technology. Klotzbach and Landsea (2015) extended the analysis of Webster et al. (2005) by including 10 additional years of data, indicating that the global frequency of category 4 and 5 hurricanes showed a small, insignificant downward trend. Kossin et al. (2013) found that the LMI trend is –2 m $s^{-1}$ (10 yr) $^{-1}$ in the western North Pacific, +1.7 m $s^{-1}$ (10 $yr)^{-1}$ in the south Indian Ocean, +2.5 m $s^{-1}$ (10 $yr)^{-1}$ in the south Pacific, and +8 m $s^{-1}$ (10 $yr)^{-1}$ in the North Atlantic during the period 1982–2009. The global trend in the LMI of the strongest storms is +1 m $s^{-1}$ (10 $yr)^{-1}$ with a p-value of 0.1. Recently, Kossin et al. (2020) extended their analysis to the 39-year period 1979–2017 and identified a global increasing trend in tropical cyclone intensity.

The trends in tropical cyclone intensity have also been questioned due to the influence of natural variability (Chan, 2006; Sobel et al., 2016). A portion of the detected intensity trend likely results from natural variability due to the limited time range of the historical records (Chan, 2006). Liu and Chan (2008) revealed strong multidecadal (16–32 years) variations in the frequency of intense typhoon occurrence over the western North Pacific. Over the western North Pacific, it has been found that tropical cyclone activity is affected by interdecadal variations such as the Pacific Decadal Oscillation (PDO), Interdecadal Pacific Oscillation (IPO), and Atlantic Multi-decadal Oscillation (AMO) (Chan and Shi, 1996; Yumoto and Matsuura, 2001; Matsuura et al., 2003; Ho et al., 2004; Liu and Chan, 2008; Wu et al., 2015; Hong et al., 2016; Zhao and Wang, 2016, 2019; Takahashi et al., 2017; Zhang et al., 2018; Zhao et al., 2014).

## 6. Projected future intensity change

The response of tropical cyclone intensity to climate change has also been assessed by downscaling with regional models and statistical–dynamical frameworks in which the projected large-scale environment is from global climate models under different climate change scenarios. High-resolution global climate models are also used to project future intensity change (Knutson et al., 2020), and recently, a few coupled global climate models were able to explicitly simulate category 4 and 5 tropical cyclones (Small et al., 2014; Murakami et al., 2015; Scoccimarro et al., 2017). In this section, progress in the projection of tropical cyclone intensity change is reviewed based on these three approaches.

### 6.1. *Downscaling with regional models*

Knutson et al. (1998) were the first to assess the influence of the $CO_2$-induced climate change on tropical cyclone intensity using the Geophysical Fluid Dynamics Laboratory (GFDL) Hurricane Prediction System with a grid size of about 18 km, while the environmental conditions and storm cases were from the GFDL global climate model in the control and high-$CO_2$ climate simulations. They found that $CO_2$-induced warming led to more intense typhoons in the western North Pacific basin. Knutson and Tuleya (1999) further found a 5%–11% increase of intensity under high-$CO_2$ conditions with SSTs warmer by about 2.2°C in the western North Pacific basin.

Downscaling with regional models can be further classified into two categories. The first includes regional models similar to one-way nesting within global climate system models, usually with relatively coarse resolutions (Walsh et al., 2004; Stowasser et al., 2007; Wu et al., 2014; Sun et al., 2017; Zhang and Wang, 2017). Regional models are run for one or more tropical cyclone seasons with the time-slice of the output from the climate change experiment, and the intensity metrics of the simulated tropical cyclone-like vortices are compared between the present-day and future experiments. For example, Walsh et al. (2004) conducted regional climate simulations over the eastern Australian region with a horizontal grid spacing of 30 km. Stowasser et al. (2007) used the International Pacific Research Center (IPRC) regional climate model with ~50-km grid spacing.

The other category of regional models for downscaling tropical cyclone intensity change uses a relatively high resolution, even including cloud-resolving and non-hydrostatic models (Knutson et al., 1998, 2001, 2013; Knutson and Tuleya, 2004; Bender et al., 2010; Hill and Lackmann, 2011; Tsuboki et al., 2015; Kanada and Wada, 2017). The intensity and inner-core structure simulated in these models can be comparable with observations (Bender et al., 2010; Knutson et al., 2015; Tsuboki et al., 2015). Using two different operational versions of the GFDL hurricane model with a grid spacing of 8 km, Bender et al. (2010) found a doubling of the frequency of category 4 and 5 Atlantic storms by the end of the 21st century. Knutson et al. (2015) used a two-stage downscaling procedure to derive global projections of intense tropical cyclones from the GFDL High-Resolution Atmospheric Model (HiRAM; 50-km grid) and the GFDL hurricane model. Tsuboki et al. (2015) performed very high resolution (2-km) downscaling for 30 category 4 and 5 typhoons from the 20-km mesh global simulation of a warmer climate. These studies indicated an increase of intense tropical cyclones.

Recently, regional models have been used to investigate whether present-day climate change has affected specific tropical cyclones (Patricola and Wehner, 2018; Reed et al., 2020; Kawase et al., 2021). Using convection-permitting regional climate model simulations, Patricola and Wehner (2018) found that climate change to date enhanced average and extreme rainfall of Hurricanes Katrina, Irma, and Maria, but did not change tropical cyclone intensity. In addition, future anthropogenic warming robustly increases wind speed and rainfall of intense tropical cyclones among 15 events sampled globally. Kawase et al. (2021) investigated the impacts of historical warming on Typhoon Hagibis (2019) using the Japan Meteorological Agency Nonhydrostatic Model (JMA-NHM), indicating that historical warming intensified the strength of Typhoon Hagibis (2019) and enhanced the extremely heavy precipitation induced by the typhoon.

The advantage of downscaling with regional models is that they are relatively cheap in computation so that it is possible to examine the sensitivity of the results to various model choices such as environmental conditions, model parameterizations, and the use of fixed SST or a coupled ocean model (Knutson et al., 2001). However, regional models for downscaling tropical cyclone activity share common issues with other regional simulations, such as model domain selection, lateral boundary condition technique, choice of physics schemes, and choice of initial conditions (Giorgi, 2019). Also, biases in the driving global climate model may lead to uncertainty in the projection (Camargo and Wing, 2016). Zhang and Wang (2017) used the so-called pseudo-global warming approach (the initial and boundary conditions in the regional model are from the projection in the warming climate) to avoid some climate drift of global climate models.

### 6.2. *Downscaling with statistical–dynamical frameworks*

Emanuel (2006) and Emanuel et al. (2008) developed a statistical–dynamical method for downscaling tropical cyclone activity. The synthetic tropical cyclones are generated with the formation, motion, and intensity models, respectively. One of the formation models simply generates track origin points by a random draw from the space–time probability density function of genesis location obtained from observations. An alternative way is to generate track origins by randomly distributing warm-core vortices in space and time, and the survival of the seeds depends on the large-scale environmental conditions when their tracks and intensities are produced in the track and intensity models. Tropical cyclone motion in the track model is determined by large-scale steering and β-drift. The intensity of the synthetic tropical cyclones is obtained by running a coupled intensity model along each tropical cyclone track. In addition to SST and outflow temperature, the influences of changes in the ocean mixed layer and vertical wind shear are included in the intensity model. Using this technique, Emanuel et al. (2008) and Emanuel et al. (2013) assessed the impact of climate change on tropical cyclones by downscaling IPCC AR4 and AR5 simulations, respectively. Based on historical and future climate states simulated by six Coupled Model Intercomparison Project 5 (CMIP5) global climate models, Emanuel et al. (2013) indicated that the frequency of downscaled tropical cyclones increases during the 21st century in most locations, and the tropical cyclone intensity also increases, although most numerical studies have projected a decrease in the frequency.

Lee et al. (2018) developed a statistical–dynamical model for estimating the long-term hazard of rare, high impact tropical cyclone events globally, including an environmental index-based genesis model, a beta-advection track model, and an autoregressive intensity model. The model can simulate the observed number of rapidly intensifying storms. Jing and Lin (2020) developed the Princeton environment-dependent probabilistic tropical cyclone (PepC) model for generating synthetic tropical cyclones to support risk assessment. PepC consists of a hierarchical Poisson genesis model, an analog-wind track model, and a Markov intensity model. The model can simulate the statistics of TC genesis, movement, rapid intensification, and lifetime maximum intensity, as well as local landfall frequency and intensity.

The relative contributions of various factors can be quantified with the statistical–dynamical framework. However, there are two issues regarding downscaling with the statistical–dynamical framework. One is that the tropical cyclone in the intensity model is axisymmetric and the influence of vertical wind shear is parameterized, which is based on the present-day observation. The other is that the initial track points were based on the present-day observation or randomly seeded without considering the possible frequency change of initial tropical disturbances (Vecchi et al., 2019).

### 6.3. *Simulating with global models*

Early studies are based mainly on global atmospheric models with no ocean coupling and other model components. By running 10-year simulations for the present-day and greenhouse-warmed climate with the 20 km-mesh global atmospheric model of the Meteorological Research Institute (MRI)/Japan Meteorological Agency (JMA), Oouchi et al. (2006) found that the maximum surface wind speed for the most intense tropical cyclones (>43 m $s^{-1}$, the threshold used to diagnose category 4 intensity in the relatively coarse global model) increased. Using new versions of the high-resolution 20-, 60-, and 180-km-mesh MRI/JMA GCMs, Murakami and Sugi (2010) found that a significant increase in the frequency of intense tropical cyclones was projected as the 60-km and finer meshes were used. Yamada et al. (2010) and Yamada et al. (2017) investigated the response of tropical cyclone intensity to climate change with the global 14-km cloud-system-resolving model of Nonhydrostatic ICosahedral Atmospheric Model (NICAM). The model in Yamada et al. (2017) projected that the ratio of intense tropical cyclones will increase by 6.6% during the period 2075–2104. Manganello et al. (2014) conducted multidecadal Atmospheric Model Intercomparison Project (AMIP)-style and time-slice simulations with the Medium-Range Weather Forecasts (ECMWF) Integrated Forecast System (IFS) at 16-km and 125-km global resolution. The 16-km IFS projected about a 50% increase in the power dissipation index during 2070–2117, mainly due to significant increases in the frequency of the more intense storms.

With advances in computational resources, coupled global climate models have started to be used to assess the impact of climate change on tropical cyclone intensity. Kim et al. (2014) simulated global tropical cyclone activity using the GFDL Climate Model, version 2.5 (CM2.5), which is a fully coupled global climate model with a horizontal resolution of about 50 km for the atmosphere and 25 km for the ocean. Murakami et al. (2015) used a new GFDL coupled model [the High-Resolution Forecast-Oriented Low Ocean Resolution (FLOR) model (HiFLOR)], which comprises high-resolution (~25-km mesh) atmosphere and land components and a moderate-resolution (~100-km mesh) sea ice and ocean component. Using a suite of high-resolution global coupled model experiments, Murakami et al. (2017) showed that anthropogenic forcing has likely increased the probability of late-season extremely severe cyclonic storms occurring in the Arabian Sea, suggesting that continued anthropogenic forcing will amplify the risk of cyclones. Murakami et al. (2018) found that the increase in Atlantic major hurricanes in 2017 was not primarily caused by La Niña conditions but rather triggered mainly by pronounced locally warm sea surface conditions in the tropical North Atlantic. Bhatia et al. (2018) conducted three 70-yr HiFLOR experiments to identify the effects of climate change on tropical cyclone intensity and intensification and found that the frequency, intensity, and intensification distribution of tropical cyclones all shift to higher values as the 21st century progresses.

Characteristics of tropical cyclones in global climate models are influenced by details of the model configurations, including horizontal resolution and parameterization schemes. Wehner et al. (2014) presented an analysis of version 5.1 of the Community Atmospheric Model (CAM5.1) at a high horizontal resolution. In the absence of extensive model tuning at high resolution, they found that simulation of many of the mean fields was degraded compared to the tuned lower-resolution publicly released version of the model. Robert et al. (2020) suggested that enhanced resolution toward 25 km typically leads to more frequent and stronger tropical cyclones, together with improvements in spatial distribution and storm structure. Moon et al. (2020) performed a process-level examination of tropical cyclone structures in eight GCM simulations that span a range of horizontal resolutions from 1° to 0.25°, indicating that the structures of simulated tropical cyclone circulations become more realistic with smaller horizontal grid spacing, although even at 0.25 degree grid spacing, the radius of maximum winds is too large, especially at higher intensities, and rising motions occurring near the storm centers are inconsistent with observations. Wing et al. (2019) explored tropical cyclone intensification processes in six high-resolution climate models, revealing the contribution of radiative feedback and surface flux feedback. They suggested that the representation of the interaction between spatially varying surface fluxes and the developing tropical cyclone was responsible for at least part of the inter-model spread of moist static energy in tropical cyclone simulations. Recently, the variable resolution approach was used to investigate the impact of climate change on tropical cyclones by embedding high-resolution domains in global models (e.g., Zarzycki and Jablonowski, 2014; Stansfield et al., 2020). Zarzycki and Jablonowski (2014) showed that the variable-resolution simulation produced significantly more TCs than the unrefined simulation, and Stansfield et al. (2020) projected an increase of tropical cyclone strength.

Moreover, there is considerable model bias in the projected large-scale environment (Camargo, 2013; Murakami et al., 2014; Wang and Wu, 2018a, b; Vecchi et al., 2019; Lee et al., 2020a, b). Zhao et al. (2020) evaluated the possible impact of different SST warming patterns on the simulated TC activities. Using output from CMIP5 of 36 climate models in their study, Wang and Wu (2018a) investigated the zonal shift of the tropical upper-tropospheric trough (TUTT), whose strong westerly shear limits the eastward extension of tropical cyclone formation over the western North Pacific. A considerable spread was found in the zonal position, orientation, and intensity of the simulated-climatological TUTT in the historical runs, and the large spread is closely related to the diversity in the simulated SST biases over the North Pacific.

## 7. Issues on climate change of tropical cyclone intensity

While the influences of the environmental factors have been extensively used to understand the effect of climate change on tropical cyclone intensity, relatively few studies have quantified their relative contributions. Moreover, since these climate change studies treat tropical cyclones in a basin as a whole, factors controlling the basin-wide intensity can be different from individual tropical cyclones.

Following Wu and Zhao (2012), Wu et al. (2018) integrated an axisymmetric intensity model coupled with a simple one-dimensional ocean model along the observed tropical cyclone track in the western North Pacific during the period 1980–2015. They demonstrated that the increase in the proportion of intense typhoons was consistent with the corresponding changes in the ocean/atmosphere environment during 1980–2015. The attribution of individual environmental parameters indicated that changes in SST and vertical wind shear have little influence on the increase of the proportion of intense typhoons, while the temporal changes of the ocean mixed layer depth and outflow temperature show a moderate contribution. Although the results of Wu et al. (2018) are not necessarily related to the climate change of tropical cyclone intensity due to the short-period dataset, this study demonstrates the importance of quantifying the individual contributions of environmental factors.

More importantly, Wu et al. (2018) demonstrated that changes in prevailing tropical cyclone tracks can account for more than half of the basin-wide intensity change since the distributions of the environmental parameters are not spatially uniform. The environmental parameters experienced by tropical cyclones can be systematically changed due to prevailing track change. The observed track changes in Wu et al. (2018) have been also shown in previous studies (Wu et al., 2005; Wang et al., 2011, 2015; Zhao and Wu, 2014;

Zhao et al., 2020), and the track change has been projected under future climate change forcing experiments (Wu and Wang, 2004; Wang et al., 2011; Wang and Wu, 2015) (Fig. 3). As shown in Fig. 3, relatively more tropical cyclones take a northward track in the western North Pacific basin in the projected future climate. Besides, the track change may also lead to changes in storm–ocean coupling and the duration in which tropical cyclones reach the lifetime maximum intensity, further changing the basin-wide tropical cyclone intensity.

Recent studies have revealed a few other factors that may affect tropical cyclone intensity. Villarini and Vecchi (2013) used output from 17 state-of-the-art global climate models in three radiative forcing scenarios and found an intensification of North Atlantic tropical cyclones in response to both greenhouse gas (GHG) increases and aerosol changes over the current century. Using the theory of MPI, Sobel et al. (2016) suggested that aerosol cooling largely canceled the effect of greenhouse gas-driven warming over the historical record. Ting et al. (2015) suggested that the decrease in MPI due to aerosols and increase due to GHG largely cancel each other. Other than the local SST, it is suggested that the relative SST change (the SST change in the tropical main development region relative to the tropical mean SST) plays a more important role in causing MPI changes than local SST (Vecchi and Soden, 2007; Vecchi and Knutson, 2008; Murakami et al., 2018). In addition, Kang and Elsner (2015) statistically showed a trade-off between intensity and frequency and argued that an average increase in global tropical cyclone intensity of 1.3 m s$^{-1}$ over the past 30 years of ocean warming occurred at the expense of 6.1 TCs worldwide per year. The mechanisms for the influences of aerosol forcing, relative SST, and the trade-off between intensity and frequency remain inconclusive and need further research.

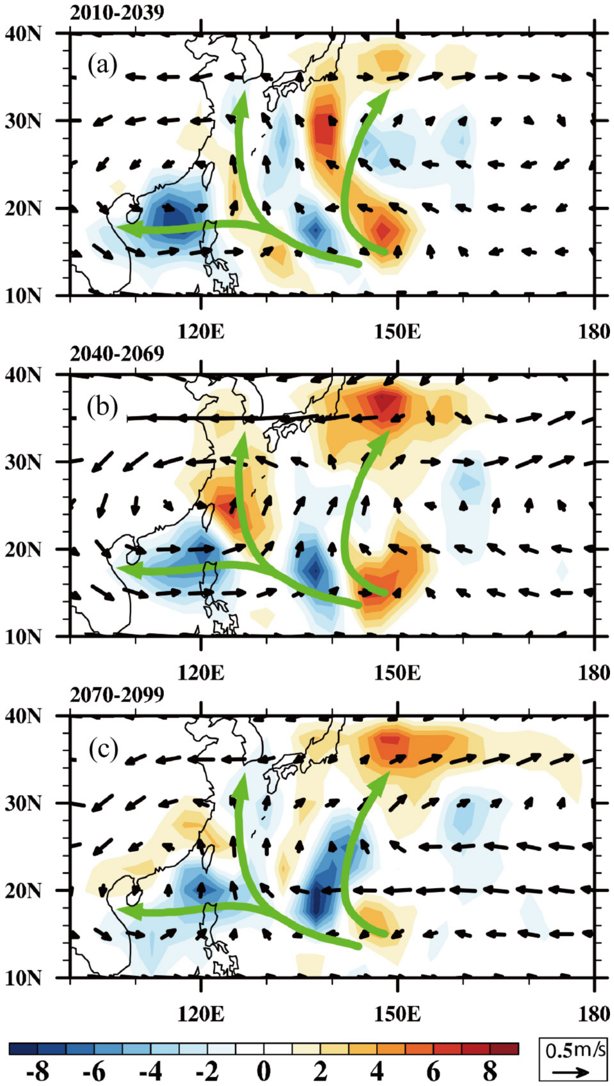

**Fig. 3**. Projected change in steering flow (black vectors) and the associated change in frequency of tropical cyclone occurrence (shading) compared to the historical run for (a) 2010–39, (b) 2040–69, and (c) 2070–99 derived from the selected CMIP5 model ensemble. The thick arrowed lines schematically show the three prevailing tracks. Note the future change of tropical cyclone formation location was not considered in the projection. [Reproduced with permission from Wang and Wu (2015).].

## 8. Summary and suggestions

The response of tropical cyclone activity to climate change has been an important research topic for more than three decades (Emanuel, 1987; Lighthill et al., 1994). Our understanding of the effect of climate change on tropical cyclone intensity has been remarkably improved. Studies have been conducted through analysis of the observed trends and numerical simulations of possible changes between the present and future climates with various complexities of regional, global, and statistical–dynamical models. Although theory and modeling consistently indicate an increasing trend in tropical cyclone intensity, uncertainty in the historical datasets of tropical cyclones, incomplete understanding of mechanisms for the basin-wide intensity change, intertwined natural variabilities, the considerable model bias in the projected large-scale environment, and poorly-simulated inner-core structures of tropical cyclones lead to relatively low confidence in the assessed and projected responses of tropical cyclone intensity to climate change. A similar situation also occurs for the assessed and projected responses of tropical cyclone formation and tracks. As a result, currently, it is unclear to what degree climate change has affected tropical cyclone intensity or when the impact of climate change on tropical cyclone intensity will be detectable in the future.

Future research may be conducted to address the issues mentioned above, especially on the following topics:

1) **Extending datasets by reconstructing past tropical cyclone activity.** Various types of geological proxies have been tested for reconstructing past tropical cyclone activity (Walsh et al., 2016). The proxy data may be based on hurricane-induced overwash deposits of sediments of coastal

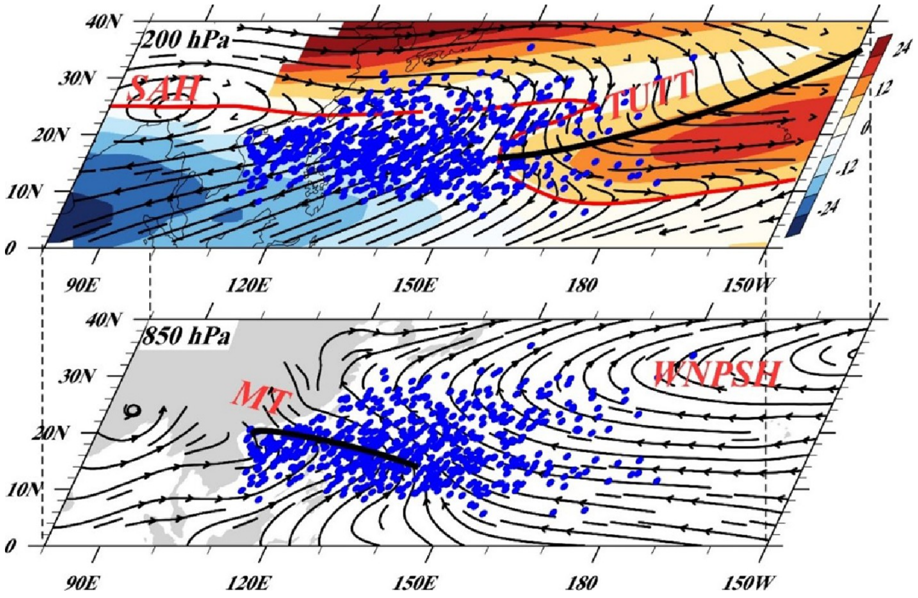

**Fig. 4**. Large-scale atmospheric systems associated with tropical cyclone activity in the western North Pacific basin. The blue dots indicate the formation location of tropical cyclones in the JTWC dataset and the shading shows the vertical shear of zonal wind (units: m s$^{-1}$) between 200 hPa and 850 hPa during 1958–2018. SAH, TUTT, MT, and WNPSH stand for South Asia high, tropical upper tropospheric trough, monsoon trough, and western North Pacific subtropical high.

lakes and marshes (Liu et al., 2001; Brandon et al., 2014; Donnelly et al., 2015), oxygen isotopic ratios of tropical cyclone precipitation in caves (stalagmites), tree rings, and corals (Frappier et al., 2007, 2014; Frappier, 2008). In China, local governments have usually recorded natural disasters, including the passages of tropical cyclones, at least since the Ming Dynasty in the 15th century (Pan et al., 2011; Zhang et al., 2012), and great efforts have been made to compile and analyze the historical records (Chan and Shi, 2000; Pan et al., 2011; Chan et al., 2012; Zhang et al., 2012). These extended records can advance our understanding of natural variations of tropical cyclone activity.

2) **Improving understanding of natural variability of tropical cyclone intensity**. It is crucial to understand the natural variabilities of tropical cyclone intensity since most trend analyses have only focused on the historical records after the 1970s when satellite data began to be available for estimating tropical cyclone intensity. The detected trends involve some degree of natural variability on the interdecadal scale and longer (Chan, 2006; Zhao et al., 2020). For example, Murakami et al. (2017) examined the influence of the strong El Niño event on the extremely active hurricane season of 2015 in the eastern and central Pacific Ocean by running a suite of targeted high-resolution model experiments. They found that the extremely active hurricane season was not primarily induced by the 2015 El Niño tropical Pacific warming, but by warming in the subtropical Pacific Ocean, which is not typical of El Niño, but rather of the Pacific meridional mode (PMM) superimposed on long-term anthropogenic warming.

3) **Examining the simulated influences of climate change on the large-scale environment for tropical cyclone activity and the response of tropical cyclones to the simulated environmental changes.** So far, most studies have focused on changes in environmental parameters. The changes are closely associated with changes in the large-scale circulations. It is clear that bias in projected changes in the large-scale circulations can lead to considerable uncertainty in the projected tropical cyclone activity. For example (Fig. 4), tropical cyclone activity in the western North Pacific basin is largely controlled by the monsoon trough (MT), the western North Pacific subtropical high, the South Asia high (SAH), and the TUTT. It is important to understand how the large-scale circulations respond to climate change as the linkage of tropical cyclone intensity is pursued.

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