LETTER

Promising prediction of the monsoon trough and its implication for tropical cyclone activity over the western North Pacific

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Abstract

The monsoon trough (MT) is generally recognized as a feeding ground for tropical cyclones (TCs) over the western North Pacific (WNP). In view of the many challenges that remain in current seasonal TC forecasting, it would be a profound benefit to understand the predictability of variations in the MT and the implications of this for the seasonal prediction of TC activity. This study reveals that high predictability of the MT is shown by the current atmosphere–ocean coupled forecasting system, with the correlation coefficient being 0.84 for the model-ensemble prediction with observations from 1960 to 2005. This high predictability arises mainly from the tropical dipole sea surface temperature over the Maritime Continent and tropical Pacific Ocean, which favors convection around the warm pool and further excites the vorticity anomalies over the WNP. It is further found that good knowledge of the MT could provide promising prediction of TC activity over the WNP, including the occurrence and energy of TCs. The findings of this study suggest that coupling between the WNP circulation and tropical ocean acts as an important source of seasonal predictability in the WNP, and highlight the importance of the MT for seasonal prediction of TCs over the WNP.

1. Introduction

Tropical cyclones (TCs) occur more frequently over the western North Pacific (WNP) than any other basin of the tropical oceans. About 30 TCs form over the WNP every year and their frequency is high between July and November (Chan 2005). Frequent TCs over the WNP have a great impact on people’s livelihoods and cause huge economic loss over East Asia. Many attempts have been made to seasonally predict TC activity using different methods for different regions, but this remains a challenge for modern science and technology (e.g. Camargo et al 2007, Zhan et al 2012, Camp et al 2015). In view of the high frequency of and great damage caused by TC activity over the WNP, better means of forecasting occurrence and associated predictability would carry huge benefits for society and the economy in the region.

Variation of the monsoon trough (MT) exerts a significant influence on the interannual variability of TC activity over the WNP (Chen et al 2004, Wu et al 2012, Molinari and Vollaro 2013). Due to the intertropical convergence zone between the lower-tropospheric off-equatorial westerlies and the northern trade easterlies, more than 70% of WNP TCs form within the MT (Molinari and Vollaro 2013). This is often accompanied by a warm sea surface temperature (SST), low-level relative vorticity, water vapor and advection (Chen et al 2004), providing a favorable environment for the enhancement of low-level synoptic-scale wave disturbances that are key to the occurrence of TCs (Chen and Huang 2009). Regarding interannual variation, the longitudinal shift of the MT has a significant effect on the mean location of TC genesis (Wu et al 2012). In addition, the MT often varies in association with the WNP subtropical high and further modulates the track of TGs (Song et al 2013). Thus, profound impacts of the MT on TC activity suggest that an insightful understanding of seasonal predictability of the MT
Many forecasting approaches and methods, including statistical, dynamical and hybrid dynamical–statistical models, have been applied in recent decades for forecasting seasonal TC activity over the WNP (e.g. Vitart 2006, Li et al 2013, Camp et al 2015, Manganello et al 2016, Zhan and Wang 2016). Advances in prediction of seasonal TC activity largely rely on better understanding and capturing slowly evolving climate signals, such as vertical wind shear, changes in the El Niño–Southern Oscillation (ENSO) and other variations in tropical SST. ENSO and its associated tropical air–sea interaction are currently the main sources for coupled prediction over the WNP (Wang et al 2008, Li et al 2012, Kosaka et al 2013, Li et al 2014). In view of the teleconnections between tropical SST and large-scale circulation in the WNP, Wang et al (2013) showed high predictability of the WNP subtropical high by using an empirical model based on central Pacific SST anomalies and their feedback with the Indo-Pacific warm pool, further indicating that high predictability of the WNP subtropical high would favor the prediction of summer tropical storm activity over the WNP. Their work prospectively implies the feasibility and importance of applying the predictability of large-scale circulation in the WNP to the prediction of TC activity over the WNP (Zhan et al 2012).

Although it is one of the most direct and important factors modulating TC activity over the WNP, predictability of the MT and its sources have not been well understood so far. The correlation between the MT and WNP subtropical high is modest, around 0.5, suggesting relatively independent variation of the MT and subtropical high. In view of its intimate and direct contributions to the frequency and energy of TCs (Chen et al 2004, Wu et al 2012, Molinari and Voller 2013), the implication that the MT has an effect on the predictability of TC activity over the WNP, which also remains elusive, needs further validation.

In this study we make a comprehensive assessment of the how changes in the MT can be used to predict TC activity during the TC season over the WNP. We use five coupled prediction models from the ENSEMBLE-based prediction of climate changes and their impacts (ENSEMBLES) retrospective forecasting system (van der Linden and Mitchell 2009) to investigate the predictability of the MT and explore its profound impact on the prediction of TC activity over the WNP.

### 3. Predictability of the monsoon trough

Variation of the MT can be well represented by low-level cyclonic relative vorticity (Lau and Lau 1992, Wu et al 2012). Thus, we first examine the predictive skill of 850 hPa relative vorticity as shown by the grid-point temporal correlation between the MME prediction and observation for July–November for 1960–2005 (figure 1(a)). This suggests that the interannual variation of low-level relative vorticity is skillfully
predicted by current coupled models. The skill over most of the MT region, in which there is large positive relative vorticity and interannual variability, exceeds the 95% confidence level according to Student’s t-test.

Figure 1(b) shows the interannual variation of the MT index between the model prediction and observation, defined as the 850 hPa relative vorticity averaged over the region (5°–20°N, 130°–180°E) following Wu et al (2012) but excluding the Philippines. The models exhibit a remarkable ability to predict MT seasonal activity. The MT index is reasonably reproduced in most of the hindcast years, and the correlation between the ensemble mean and observation is 0.84 over the whole 46 years. This skillful prediction can also be found in all five models in ENSEMBLES, with the prediction correlation ranging from 0.63 (MF) to 0.84 (ECMWF) (table 1). In addition, the MT is sustainably predictable during the typhoon season from July to November, despite the increase in prediction lead months. The correlation between the MME prediction and observation is 0.79 for July and 0.55 for November, which still exceeds the 99% confidence level. This sustainability in the MT prediction suggests a high predictability associated with various types of slowly varying prediction sources (e.g. tropical SSTs). The signal-to-noise ratio of the MT index, which is defined as the standard deviation of the ensemble mean divided by the averaged ensemble member standard deviation (Kumar 2009, Scaife et al 2014), is 0.91, further supporting the high predictability of the MT.
Furthermore, sources of the predictability of the MT are identified via linear regression of various fields onto the normalized MT index, as shown in figure 2. The MT is characterized by strong low-level cyclonic circulation over the tropical WNP, together with the east–west-oriented dipole of SST and precipitation anomalies between the Maritime Continent and the tropical Pacific Ocean. The correlation coefficient between the MT index and tropical dipole SST, defined as the difference in SST between (5°S–5°N, 170°W–120°W) and (10°S–10°N, 110°–150°E) (figure 2(e)), is 0.88 for observations during 1960–2005. The close teleconnection patterns imply a positive feedback between the MT and dipole SST over the Maritime Continent and tropical Pacific Ocean. The anomalous warm SST over the central eastern Pacific could excite a westward-propagated Rossby wave, enhancing convection around the Philippine Sea and thus positive vorticity over the tropical WNP with a low-level circulation over the tropical WNP, together with the MT region. The anomalous warm SST in the surface sea to the east.

The above teleconnections associated with the MT can be well captured by the models, including the low-level anomalous cyclone over the MT region (figures 2(b)), the dipole precipitation (figures 2(d)) and the SST pattern (figures 2(f)) around the Maritime Continent and tropical Pacific Ocean. This implies that the positive feedback between the MT and SST dipole over the Maritime Continent and tropical Pacific Ocean acts as the primary source of the predictability of the MT. The dipole-like SST anomalies over the Maritime Continent and central eastern Pacific Ocean, which could favor convection around the warm pool and excite vorticity anomalies over the WNP, make a significant contribution to the skillful prediction of the MT. The corresponding correlation coefficient is 0.81 between the predicted dipole SST and MT index. Furthermore, in view of the slowly varying SST, positive feedback can persist for months during the typhoon season, corresponding well to sustainable predictive skill from July to November (table 1).

The dipole SST exhibits a certain relationship with the ENSO in view of the significant anomalously warm SST found in the tropical eastern Pacific (figures 2(c) and (f)). The correlation coefficient between the dipole SST pattern and the Niño 3 index (5°S–5°N, 150°W–90°W) is 0.88 for observations. Nevertheless, compared with the traditional ENSO, the dipole SST demonstrates a relatively larger teleconnection with MT variation. The correlation coefficient between the MT and Niño 3 index is 0.78 (0.71) for observations (MME prediction), lower than for the correlation with the dipole SST. This further suggests that the dipole SST between the Maritime Continent and tropical Pacific Ocean comprises a more predictable signal for seasonal predictability of the MT. In addition, a relatively closer relationship of the MT index is shown with the tropical eastern Pacific part of the dipole SST.
than the Maritime Continent part, with a correlation coefficient 0.85 (–0.59) for the tropical eastern Pacific (Maritime Continent) for observations during the whole hindcast period from 1960 to 2005, suggesting a more stable contribution of the tropical eastern Pacific part to variation of the MT.

4. Implication for prediction of TC activity

While providing favorable dynamic and thermodynamic conditions for TC activity (Chen et al 2004, Wu et al 2012, Molinari and Vollaro 2013), the detailed contributions of the MT over the WNP need to be verified via a statistical correlation between the above-defined MT index and TC activity at each grid point (figure 3). It is found that the MT exerts a large influence on both the frequency of occurrence of TCs and the ACE, with a significant positive correlation around the Philippine Sea. The key regions of TC activity related to the MT correspond well to those regions with a large interannual variability of relative vorticity. When the MT is stronger with a positive relative vorticity anomaly, more TCs and increased TC intensity tend to occur around the Philippine Sea, and vice versa. The correlation coefficients between the MT index and the averaged TC frequency and ACE over the tropical WNP (10°–30°N, 135°–160°E) are 0.61 and 0.62, respectively. In view of the significant teleconnections with the tropical dipole SST over the Maritime Continent and central eastern Pacific Ocean, as shown above (figure 2), this further suggests that the MT acts as a key factor in bridging the tropical air–sea interaction and TC activity over the WNP.

Based on skillful seasonal prediction of the MT, we attempt to predict TC activity directly using the MT index as the only predictor. Statistical transfer of large-scale features of the model into other target predictions, including some regional rainfall and mesoscale systems, has been successful (e.g. Zhu et al 2008, Ndiaye et al 2011, Wang et al 2013). A cross-validated reforecast, built by a linear regression method leaving one target year out for prediction (Michaelsen 1987), was used here to test the predictive capacity of TC activity averaged over (10°–30°N, 135°–160°E). Figure 4 shows the time series of observed and reforecast TC frequency.
and ACE over the tropical WNP. The cross-validation achieves a temporal correlation coefficient of 0.62 for the 46-year prediction for both the number of TCs occurring and the ACE index. Most of the anomalous years of TC activity, such as positive anomalies in 1972 and 1997 and negative anomalies in 1973 and 1999, can be well reproduced. Furthermore, the MT could also be capable of predicting the location of TCs over the WNP, as a similar predictive skill could be achieved for the location of TC formation (the average longitude over the WNP when a TC is generated), with a temporal correlation coefficient of 0.60 shown by the cross-validated reforecast. The high predictability suggests that the MT is a promising means for seasonal prediction of TC activity over the tropical WNP.

A cross-validated reforecast of TC activity was also performed using the tropical dipole SST over the Maritime Continent and tropical Pacific Ocean as a predictor, instead of the MT index. The reforecast skill is 0.54 for both the number of TCs occurring and ACE index. In addition, the correlation coefficients of the number of TCs and the ACE index with the tropical dipole SST are 0.64 and 0.65, respectively, similar to those with the MT index. This implies that the above tropical dipole SST makes a remarkable contribution to the seasonal prediction of TC activity over the WNP. The models are quite capable of reproducing the tropical dipole SST, with a predictive skill 0.85 for the MME result. The contributions of the tropical dipole SST described here are similar to those in Zhan and Wang (2016), which demonstrates the importance of tropical SST for the prediction of ACE over the WNP based on a hybrid dynamical–statistical prediction.

Nevertheless, compared with the TC activity predicted by the tropical dipole SST, a more skillful reforecast is achieved by the MT index. This further suggests that variation of the MT could effectively bridge tropical SST and WNP TC activity, and comprise more predictable signals for the seasonal prediction of TC activity over the WNP.

This study reveals that TC activity predicted by the MT tends to be skillful over a wide region of the tropical WNP, including frequency, energy and formation location. In comparison, the WNP subtropical high is more closely related to variation of the TC track and favors the prediction of tropical storm occurrence over the subtropical WNP around the west front of the subtropical high (Wang et al 2013). In addition, the faithful reforecast demonstrated in this study employed the MT as the only predictor and directly used the output of model hindcasts. Greater prediction skill would be expected if an empirical model related to interannual variation of the MT is applied, in view of the quite high correlation between subtropical WNP tropical storms and the subtropical high in summer established by a physically based empirical model, which included tropical air–sea interactions and the North Atlantic Oscillation as predictors (Wang et al 2013).

5. Summary and discussion

This study assesses the predictive skill of variation in the MT during the TC season, identifies the sources of predictability and investigates the implications for the
seasonal prediction of TC activity over the WNP. It is found that the remarkable predictive skill of the MT is seen in current coupled models, mainly as a result of its significant positive feedback with the dipole SST over the Maritime Continent and tropical Pacific Ocean. Our further findings reveal that this positive interaction between the MT and tropical oceans acts as a primary source for the seasonal prediction of TC activity over the WNP, including the frequency, intensity and formation location of TCs, and implies huge potential for understanding the predictability of TCs.

As an important environmental factor for TC activity over the WNP, the MT could provide a key basis for further improving the seasonal prediction of TC activity. Furthermore, it is anticipated that a comprehensive TC seasonal forecast system could be built by combining the MT with other TC-related factors, such as the WNP sub-tropical high and vertical shear, based on dynamical or statistical downscaling; this deserves further work.

Using a multi-model approach, this study delivers a definitive statement on the current capacity of global coupled climate models to predict the MT and further development for TC activity forecast. A simple statistical cross-validated prediction is used here. While we build a reasonable predictive link between the MT to TC activity, high predictability of the MT and the associated statistical downscaling method further imply a convenient means for climate services to produce a seasonal forecast of TCs.

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