TROPICAL CYCLONE PREDICTION ON SUBSEASONAL TIME-SCALES

SUZANA J. CAMARGO[a], JOANNE CAMP[b], RUSSELL L. ELSBERRY[c], PAUL A. GREGORY[d],
PHILIP J. KLOTZBACH[e], CARL J. SCHRECK III[f], ADAM H. SOBEL[a,g], MICHAEL J. VENTRICE[h],
FRÉDÉRIC VITART[i], ZHUO WANG[j], MATTHEW C. WHEELER[d],
MUNEHIKO YAMAGUCHI[k], AND RUIFEN ZHAN[l]

[a]*Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, USA;*
[b]*Met Office, Exeter, United Kingdom;*
[c]*Department of Meteorology, Naval Postgraduate School, Monterey, CA and Trauma, Health, and Hazards Center, University of Colorado-Colorado Springs, Colorado Springs, CO, USA;*
[d]*Bureau of Meteorology, Melbourne, Victoria, Australia;*
[e]*Department of Atmospheric Science, Colorado State University, Fort Collins, CO, USA;*
[f]*Cooperative Institute for Climate and Satellites-North Carolina (CICS-NC), North Carolina State University, Asheville, NC, USA;*
[g]*Department of Applied Physics and Applied Mathematics and Department of Earth and Environmental Sciences, Columbia University, New York, NY, USA;*
[h]*Weather Company/IBM, Andover, MA, USA;*
[i]*European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom;*
[j]*Department of Atmospheric Sciences, University of Illinois, Urbana-Champagne, IL, USA;*
[k]*Meteorological Research Institute, Japan Meteorological Agency, Tsukuba, Ibariki, Japan;*
[l]*Shanghai Typhoon Institute of China Meteorological Administration, Shanghai, China*

ABSTRACT

Here we discuss recent progress in understanding tropical cyclone (TC) subseasonal variability and its prediction. There has been a concerted effort to understand the sources of predictability at subseasonal time-scales, and this effort has continued to make progress in recent years. Besides the Madden-Julian Oscillation (MJO), other modes of variability affect TCs at these time-scales, in particular various equatorial waves. Additionally, TC activity is also modulated by extratropical processes via Rossby wave breaking.

There has also been progress in the ability of models to simulate the MJO and its modulation of TC activity. Community efforts have created multi-model ensemble datasets, which have made it possible to evaluate the forecast skill of the MJO and TCs on subseasonal time-scales in multiple forecasting systems. While there is positive skill in some cases, there is strong dependence on the ensemble system considered, the basin examined, and whether the storms have extratropical influences or not. Furthermore, the definition of skill differs among studies. Forecasting centers are currently issuing subseasonal TC forecasts using various techniques (statistical, statistical-dynamical and dynamical). There is also a strong interest in the private sector for forecasts with 3-4 weeks lead time.

Keywords: tropical cyclones, subseasonal, forecasts, hurricanes, MJO

1. Introduction

The modulation of tropical cyclone (TC) activity on subseasonal time-scales by various modes of variability has been well established. Li et al. (2018a) highlighted a manuscript in the Chinese literature (Xie et al. 1963), which first documented a relationship between an oscillatory signal of the 700 hPa zonal winds at stations in Southeast Asia with a 40-50-day period and the occurrence of typhoons. This oscillation was described in detail a few years later in the classic paper by Madden and Julian (1972). Nakazawa

---

Corresponding author: Suzana J. Camargo, suzana@ldeo.columbia.edu

DOI: 10.6057/2019TCRR03.04

(1986) noticed a match between the enhanced convective phase of the Madden-Julian Oscillation (MJO) and an increase in TC activity over the western North Pacific (WNP) during 1979. This result was extended to multiple years and basins by Liebmann et al. (1994). Since these studies, the body of research on the modulation of global TC activity by various intraseasonal modes has steadily grown. For instance, Schreck et al. (2012) examined cases where TC genesis in the deep tropics can be attributed to enhanced convection due to precursor waves, such as convectively-coupled equatorial Rossby waves, mixed Rossby-gravity waves, Kelvin waves and easterly waves (tropical depression-like waves). The MJO also affects TC genesis by modulating these high-frequency equatorial waves, in particular Kelvin waves. The progress in forecasting the MJO and precursor waves using numerical models has opened the possibility of skillful TC forecasts on subseasonal time-scales.

In the last few years, collaborative multi-institutional projects have allowed the scientific community to explore to what extent the current generation of weather forecasting models have skill in forecasting TCs beyond current operational 5-day predictions of individual storms.

At the same time, numerical guidance for the prediction of individual storms has improved in quality, allowing for the lead times at which these predictions are useful to extend into the subseasonal range. Numerical Weather Prediction (NWP) models and ensemble prediction systems can now provide guidance at the 1-2 week range or possibly even longer (Xiang et al. 2015b). A recent review of this topic can be found in Sobel et al. (2018). Historically, and to some extent still, TC forecasting – as practiced by national meteorological services – begins in earnest at the moment when a TC forms. Many forecast agencies predict genesis, typically at lead times up to 5 days or less. They generally do not, however, forecast the subsequent track and intensity at that time, but only do so after genesis has occurred. The typical maximum forecast lead time after genesis has occurred is five days. Ensemble systems, on the other hand, need not draw a sharp distinction between the pre- and post-genesis periods, and several ensemble systems generate forecast products which extend from before the moment of genesis to after the TC has formed. A "strike probability" map is typical (e.g., Vitart et al. 2011). Such products are generally produced by numerical prediction centers, which are often distinct from actual forecast offices. For example, the European Centre for Medium-Range Weather Forecasts (ECMWF) and other centers produce strike probability maps out to 10 or 15 days. Forecast centers such as the US National Hurricane Center (NHC) examine this guidance in producing their forecasts, but NHC forecasts do not extend beyond 5 days, and in general do not begin before genesis. Recently, however, NHC has begun issuing forecasts for "potential tropical cyclones" in instances where genesis is predicted and the system is expected to pose a danger to life and property soon (within two days) afterwards.

Belanger et al. (2010, 2012) quantified skill for TC predictions at lead times beyond 5 days for the North Atlantic and North Indian Ocean basins. Webster (2008, 2012, 2013) argued that ensemble systems should be used to make probabilistic TC forecasts as far in advance as 10-15 days, both in general and in the North Indian Ocean basin in particular. Current practice in most regions, however, is to make forecasts that are largely deterministic and do not extend to such large lead times. The reason for this appears to be that the skill at longer lead times, though arguably usable for some kinds of decision-making, is small, so that forecasters are concerned about false alarms and a resulting loss of public confidence. It appears that research into forecast communication, as well as the optimal use of long-range, low-skill forecasts by key decision makers (e.g., government agencies tasked with disaster preparedness) could be valuable in deriving the maximum societal benefit from existing numerical guidance. As we move towards operational subseasonal TC forecasts, these will be challenges that need to be addressed by the forecasting community.

Here we summarize recent progress in understanding the modulation of TCs by subseasonal modes of variability, the current state-of-the-art in modeling TC variability on subseasonal time-scales, and the currently-existing operational subseasonal TC forecasts.

2. Subseasonal variability of tropical cyclone activity

2.1 *Modulation of TCs by subseasonal modes of variability*

Klotzbach and Oliver (2015a) used a long-period MJO index since 1905 based on sea level pressure data from the 20th Century Reanalysis (Compo et al. 2011) to examine long-term relationships between North Atlantic TCs and the MJO. They showed that when the MJO was enhancing convection over Africa and the western Indian Ocean, North Atlantic TC activity tended to be enhanced due primarily to reduction in vertical wind shear. They also examined the joint relationships between the Atlantic Multidecadal Oscillation (AMO) and the MJO as well as El Niño-Southern Oscillation (ENSO) and the MJO. When El Niño events or a negative AMO were present, favorable phases of the MJO were not enough to enhance TC activity above climatological levels, while La Niña events or a positive AMO could combine with conducive phases of the MJO to lead to hyperactive periods for North Atlantic TCs. Klotzbach and Oliver (2015b) used the same long-period MJO dataset to examine the long-term relationship between the MJO and global TC activity. They documented that the previously-discussed MJO-TC relationships for individual TC basins using the Wheeler-Hendon MJO index (Wheeler et al. 2004) since 1974 showed similar relationships prior to that time. Broadly speaking, TC activity was enhanced in individual ocean basins during and immediately after the convective maximum of the MJO traversed that basin. A similar result was shown in Camargo et al. (2009) using a

TC genesis index. As was found in the North Atlantic basin, the MJO could either constructively or destructively interfere with ENSO's impacts on TC activity on subseasonal timescales.

The MJO has been shown to modulate the occurrence of multiple TC events (MTCEs) over the WNP, which are defined as two or more TCs simultaneously occurring in the WNP (Krouse and Sobel 2010; He et al. 2013; Schenkel 2016; You et al. 2019). When convection associated with the MJO is enhanced east of Indonesia and over the WNP, MTCEs occur more frequently over the WNP than in other regions (He et al. 2013). You et al. (2019) showed that more than 60% of MTCEs occur in the convectively-enhanced phase of the MJO, whereas only ~18% of MTCEs occur in the suppressed phase of the MJO. The Quasi-biweekly Oscillation (QBWO) has also been documented to have an important influence on MTCE occurrence (Jin et al. 2016; You et al. 2019). Generally speaking, the convectively active phase of the QBWO is more favorable for MTCE occurrence than its inactive phase. MTCE occurrence is further modulated by different combinations of the MJO and the QBWO phases. You et al. (2019) found that the most frequent MTCEs occur in the combined enhanced convective phases of the MJO and the QBWO, while the least occur in their combined dry phases.

Chen et al. (2018) evaluated the influence of the MJO, ENSO and equatorial Rossby waves (ERW) on TC genesis, by analyzing the percentage of tropical disturbances that developed into TCs in the WNP. They showed that in the convectively enhanced (suppressed) phase of the MJO, El Niño (La Niña) and positive (negative) vorticity ERWs cause the percentage of developing TCs to significantly increase (decrease) compared with climatology.

Convectively-coupled atmospheric Kelvin waves are emerging as another potential modulator of TCs on subseasonal timescales. These waves have synoptic-scale wavelengths of 3000–7000 km and rapid eastward phase speeds of 10–20 $m\ s^{-1}$. However, their lifespan extends into the subseasonal range. A single wave can circumnavigate the globe over the course of a month. Ventrice et al. (2012a) and Schreck (2015) showed that tropical cyclogenesis is generally inhibited during the 2-3 days before the arrival of the convectively-enhanced phase of a Kelvin wave and then favored 2-3 days after the passage of the convectively-enhanced phase. The schematic below (Fig. 1) illustrates the primary impacts. The Kelvin wave's convection may enhance potential vorticity within the proto-vortices, even if cyclogenesis occurs later (Fang and Zhang 2016). At 850-hPa, equatorial westerlies enhance the cyclonic vorticity for the storm. These persist longer than the period of the Kelvin wave because the strongest Kelvin waves are often embedded within the MJO as the leading edge and with the strongest portion of the convection. In addition, the westward tilt with height of Kelvin waves means that it takes a

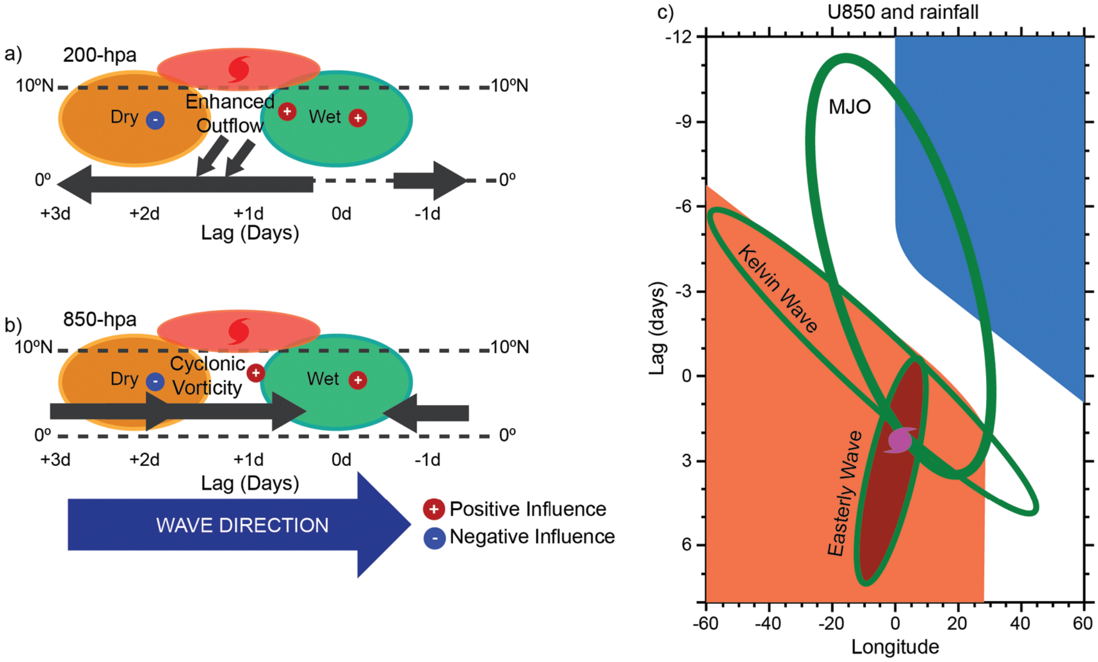


FIG. 1. Schematic of impacts of Kelvin waves on tropical cyclogenesis. Relationships are shown in latitude–time at (a) 200 hPa and (b) 850 hPa, while (c) shows time–longitude interactions between the Kelvin wave, MJO, and the parent easterly wave, with the zonal winds at 850hPa shown in orange and blue shading and the rainfall in green contours. Figure from Schreck et al. (2015), © American Meteorological Society. Used with permission.

few days for these westerlies to build from the surface to the middle-troposphere, which is favorable for TC genesis (Schreck 2016).

Ventrice et al. (2012b) attributes the suppression of TC activity ahead of the active phase of the convectively coupled Kelvin wave to unfavorable large-scale environmental conditions related to the Kelvin wave's leading suppressed phase. Over the Atlantic, the enhanced low-level easterly winds associated the Kelvin wave's suppressed phase can provide the dynamics needed to advect a dry and dusty Saharan air layer off Africa across the tropical Atlantic, further inhibiting the environment from convection. At upper levels, suppressed Kelvin wave phases accelerate westerly flow. This enhanced westerly flow can open a westerly wind duct along the equator, which can then encourage the equatorward propagation of mid-latitude waves into the tropics. As a result, we can see an enhanced frequency of tropical upper tropospheric troughs following the passage of the suppressed Kelvin wave passage, which can act to further suppress the large-scale conditions that are often tied to TC activity. Over Africa, convectively coupled Kelvin waves have been found to enhance the West African Monsoon during boreal summer. This monsoonal enhancement is related to the Kelvin wave's dynamical and convective properties. As a result, convectively coupled Kelvin waves can enhance the frequency easterly waves emerging off Africa up to a week after the passage of the Kelvin wave. These easterly waves act as seedlings for tropical cyclones, potentially extending the impacts of Kelvin waves on TC activity over the Atlantic basin.

2.2 *Impacts of extratropical Rossby wave breaking on North Atlantic tropical cyclones*

Studies on the extratropical impacts on TC formation date back to the 1970s. Sadler (1976, 1978) showed that the tropical upper-level trough, which often has an extratropical origin (Palmén and Newton 1969), can lead to TC formation over the WNP. Similar mechanisms also exist over the North Atlantic, where upper-level troughs or potential vorticity streamers may induce tropical cyclogenesis (Galarneau et al. 2015; Bentley et al. 2017). In particular, the transition of a subtropical cyclone to a TC was termed as tropical transition by Davis and Bosart (2003, 2004), who noticed that the upper-level troughs involved in the tropical transition processes resemble anticyclonic Rossby wave breaking (RWB). Although RWB can occasionally induce TC formation, Zhang et al. (2016, 2017) showed that the overall impacts of RWB on seasonal North Atlantic TC activity are negative. This is because active RWB can induce frequent equatorward intrusions of dry and cold air and enhance vertical wind shear and mid- to upper-tropospheric dryness over the tropical and subtropical Atlantic. The correlations between a RWB index and North Atlantic TC indices (hurricane counts or Accumulated Cyclone Energy (ACE)) are negative (~ -0.7 during 1979-2013) and exceed those for ENSO. In a follow up paper, Zhang and Wang (2019) showed that RWB also influences TC genesis in the western North Atlantic. This finding is closely related to the weather regimes over the North Pacific-North America sector, and suggestes that both tropical and extratropical processes have important implications for understanding the variability of RWB and its impacts on Atlantic TC activity. Chang and Wang (2018) showed that the extratropical impacts on Atlantic tropical cyclones may exceed the direct impacts of local tropical SST in some years. These findings have important implications for the predictability of Atlantic TC activity.

Similar impacts were found on subseasonal time scales. Active anticyclonic RWB episodes over the western Atlantic are associated with a wave train spanning from the North Pacific to the North Atlantic and significant anomalies in sea level pressure, vertical wind shear, tropospheric humidity, and precipitation over the North Atlantic (Li et al. 2018b; Zhang et al. 2017). Consistent with the large-scale circulation anomalies, TC activity is reduced significantly during active episodes of RWB (Fig. 2). Li et al. (2018b) examined the impacts of RWB on the predictability of tropical cyclogenesis using the Global Ensemble Forecast System (GEFS) Reforecast, version 2. Lower predictability of tropical cyclogenesis was found during active RWB episodes than at other times, and it was linked to the lower predictability of environmental variables, such as vertical wind shear, moisture, and low-level vorticity. These variables show a larger ensemble spread during the episodes of active RWB. Wang et al. (2018) examined the dependence of tropical cyclogenesis predictability on different synoptic flow regimes using the concept of tropical cyclogenesis pathways (McTaggart-Cowan et al. 2013) and found that the strong and weak tropical transition pathways, which are subject to strong extratropical influences, are associated with lower predictability than the other pathways. Although the extratropical atmosphere has lower intrinsic predictability than the tropical atmosphere with a forecast leadtime beyond several days (e.g., Davis et al. 2016; Palmer 1996), a better representation of the tropical-extratropical interaction may help to improve the practical predictability of tropical cyclogenesis in numerical models.

3. Modeling subseasonal TC activity

3.1 *TC activity in the S2S dataset*

To bridge the gap between medium-range weather forecasts and seasonal forecasts, in 2013 the World Weather Research program (WWRP) and the World Climate Research program (WCRP) jointly launched a 5-year research initiative called the Subseasonal to Seasonal prediction project (S2S). Its goal was to improve forecast skill and understanding of the sources of subseasonal to seasonal predictability, and to promote its uptake by operational centers and use by the applications communities (www.s2sprediction.net). To achieve this goal, an extensive da-

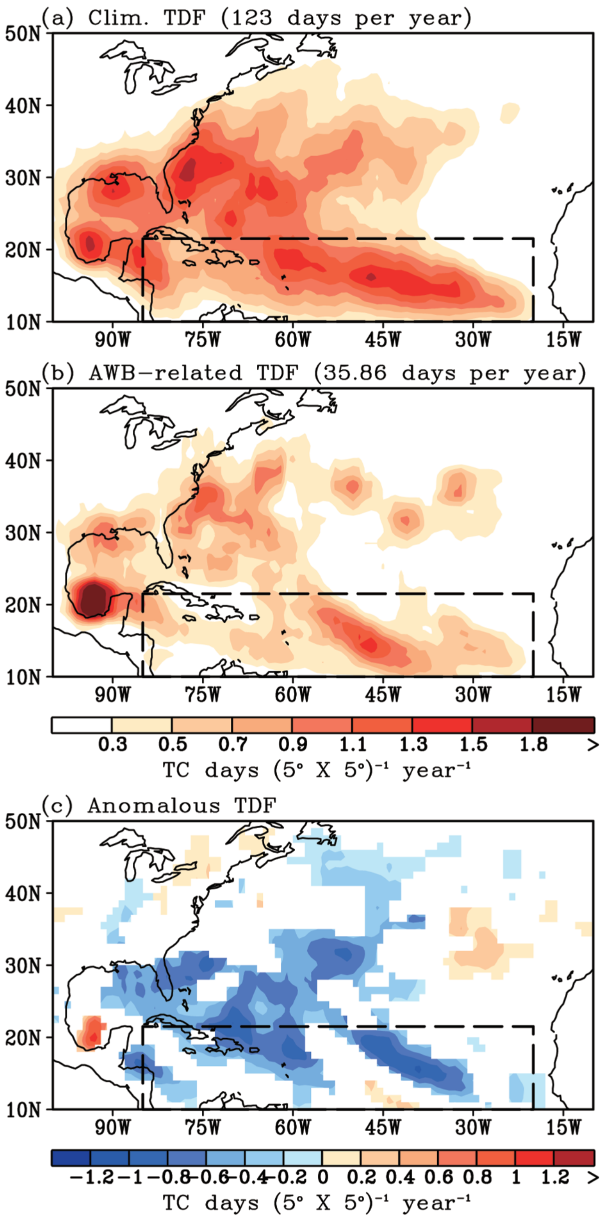


FIG. 2. Mean TC track density function for (a) climatology and (b) during active anticyclonic Rossby wave breaking (AWB) episodes, and (c) TC track density anomalies (only regions above the 95% confidence level shaded). The black dashed box highlights the North Atlantic Main Development Region. Figure originally from Li et al. (2018b), © American Meteorological Society. Used with permission.

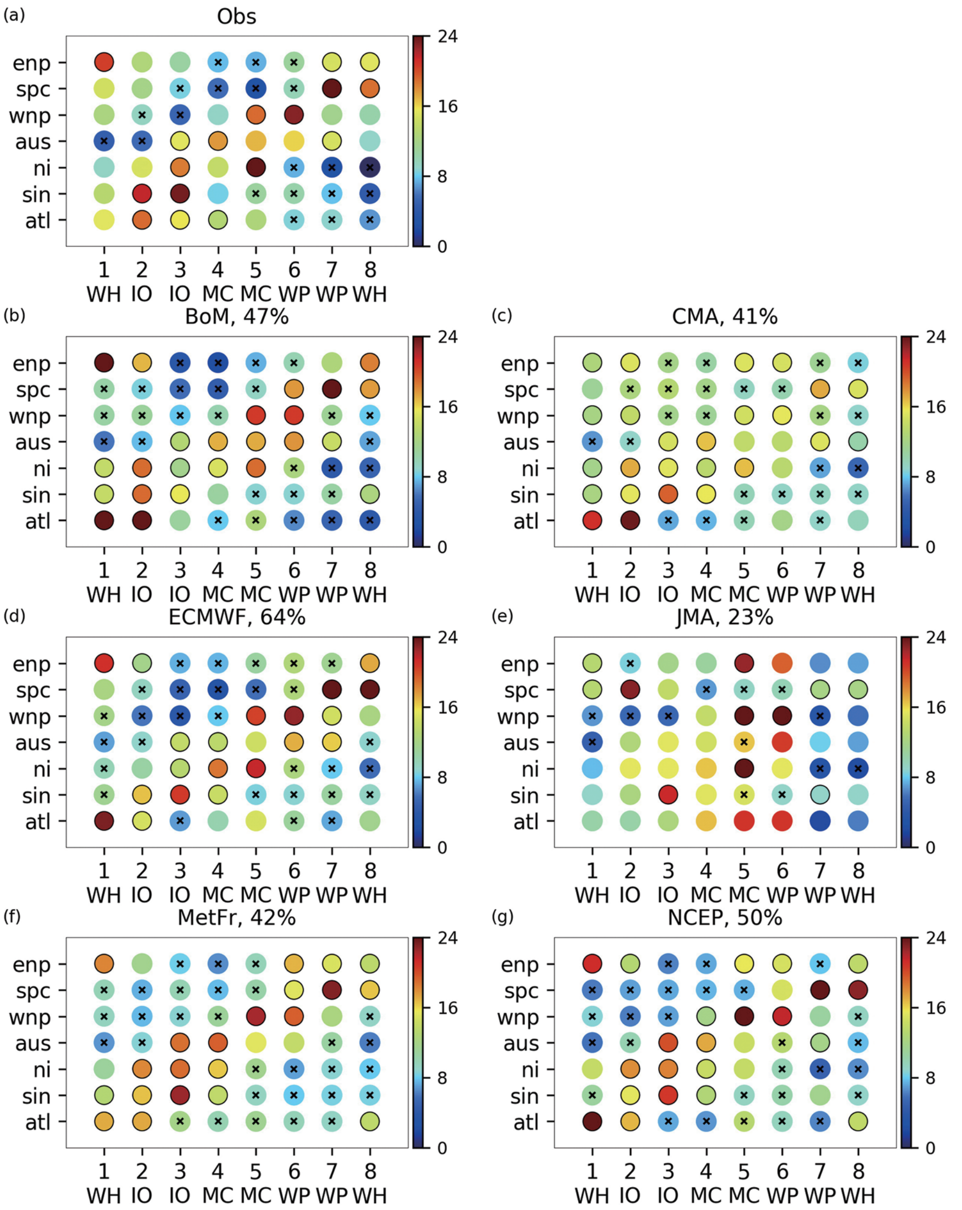
tabase has been established, containing subseasonal (up to 60 days) near real-time forecasts (3 weeks behind real-time) and re-forecasts from 11 centers (Vitart et al., 2017). The re-forecasts use the same models as the near real-time forecasts and are run for long-periods, in order to allow for the evaluation of possible model biases. The S2S database, available to the research community since May 2015, contains daily data for ~80 variables. A TC tracker (see Vitart and Robertson 2018 for details) has been applied to all S2S real-time forecasts and re-forecasts. The TC tracks, as well as MJO indices, are publicly available from s2sidx@acquisition.ecmwf.int. Using these MJO indices and TC tracks, Vitart and Robertson (2018) showed that eight S2S models display more (less) TC activity over the South Indian Ocean and less (more) TC activity over the South Pacific and near the Maritime Continent when the convectively active (suppressed) phase of the MJO propagates across the Indian Ocean in the model (their Figure 2) during the boreal winter, which is consistent with observational studies and with previous modelling studies. This result suggests that the S2S models are capable of reproducing the modulation of TCs in the Southern Hemisphere by the MJO, even if the model resolution is very coarse. The Predictive Ocean Atmosphere Model for Australia (POAMA) from the Australian Bureau of Meteorology (BoM), for example, has a resolution of only ~200 km.

Yamaguchi et al. (2016) investigated the performance of operational global ensembles in predicting the number of TCs generated for a month in the WNP basin using the S2S database. The model climatology of the number of TC genesis events over 4 weeks from initial times of the predictions was assessed with the re-forecast dataset from the global BoM, ECMWF, JMA, and NCEP ensembles and then compared to the best track data. The ECMWF model simulates well the seasonal variability of TC genesis. JMA underestimates the number of TC genesis events even with a lower wind threshold applied. The BoM tends to overestimate (underestimate) the number of TCs during the early and late (peak) TC season. NCEP simulates the seasonal variability realistically but over- and under-estimates TC frequency if a constant threshold value is used throughout the year.

Lee et al. (2018) evaluated subseasonal probabilistic prediction of TC genesis using the S2S dataset. Forecasts for basin-wide TC occurrence and weekly time-scales were considered, and the forecast skill was evaluated using the Brier skill score relative to a seasonal monthly varying climatology. Most models have favorable skill relative to climatology for week 1, when the model initialization is important. Among the models evaluated, the ECMWF has the best performance, followed by the BoM. Both systems have skill for several TC basins at week 2. There is a relationship between the models' skill scores and their ability in accurately representing the MJO, as well as the modulation of TC activity by the MJO (shown in Fig. 3) and the models' TC climatology. All of these factors are basin dependent.

3.2 Re-forecasts of TC activity in the TIGGE dataset

Yamaguchi et al. (2015) evaluated the skill of TC activity (genesis and subsequent track) forecasts from operational global medium-range ensembles as well as the relative benefits of a Multicenter Grand Ensemble (MCGE) with respect to a single model ensemble using the International


(a) Obs

(b) BoM, 47%

(c) CMA, 41%

(d) ECMWF, 64%

(e) JMA, 23%

(f) MetFr, 42%

(g) NCEP, 50%

FIG. 3. Plots of the MJO–TC relationship in the observations and from the S2S models from week 2 forecasts. The color of each circle indicates the PDF (%) in the corresponding MJO phase in the basin. The sum of the circles across the MJO phases in each basin is 100%. The black circle outline indicates that the value is above the 90th percentile while the cross symbol (x) at the center means the value is below the 10th percentile. The percentage on the title corresponds to the spatial correlation of that model plot with observations (top panel). Figure from Lee et al. (2018), © American Meteorological Society. Used with permission.

Grand Global Ensemble (TIGGE, Swinbank et al. 2016) dataset. The global ECMWF, JMA, NCEP, and UKMO ensembles were analyzed in seven TC basins. The Brier skill score (BSS) was calculated within a 3-day time window over a forecast length of 2 weeks to examine the skill from short- to medium-range time scales (0–14 days). In most of the TC basins evaluated, these operational global medium-range ensembles were capable of providing skillful guidance of TC activity forecasts with a forecast lead time extending to week 2. The MCGE has more skill (larger BSS) than the best single-model ensemble (ECMWF). The reliability of these forecasts is improved in the MCGEs compared to the individual ensembles. Both the BSS and the reliability are sensitive to the choice of threshold wind values that are used to define model TCs.

3.3 *TC activity in individual models*

In a sequence of papers, the skill and predictability for the MJO and tropical cyclogenesis by the Geophysical Fluid Dynamics Laboratory (GFDL) coupled system at 50-km resolution was examined. Xiang et al. (2015a) showed that the MJO prediction skill in this system can reach out to 27 days, with a potential predictability of 42 days. The MJO forecast skill is dependent on the amplitude and phase of the MJO. The predictability of this system in forecasting two case studies (Hurricane Sandy and Super Typhoon Haiyan) was examined in Xiang et al. (2015b), showing that the genesis of these events had a maximum prediction lead time of 11 days, while the landfall location was predicted one week ahead for Sandy and two weeks ahead for Haiyan. Jiang et al. (2018) found limited skill in predicting subseasonal cyclogenesis with more than 1-week lead time as well as a high false alarm rate. Higher skill was found for TCs forming during active MJO periods. In the case of the North Atlantic, higher predictability is evident along a tropical belt from the West African coast to the Caribbean Sea, while in the extratropical North Atlantic, the predictive skill is poor.

Kim et al. (2014) analyzed the modulation of WNP TCs by the MJO in the NASA Goddard Earth Observation System version 5 (GEOS-5) model. While the MJO in the model is weaker and propagates faster than observations, the system reproduces the modulation of TCs in the basin, with higher TC activity occurring in the active phase of the MJO. North Atlantic TC modulation by the MJO in the NOAA Climate Forecast System (CFS) version 2 was analyzed in Barnston et al. (2015). The CFS showed useful skill in predicting the MJO phase and amplitude out to 3 weeks. In spite of the too slow MJO propagation, the CFS still showed usable skill in predicting weekly variations of TC activity out to 10-14 days.

Recently, Zhao et al. (2019) analyzed the skill of two systems (Met Office Hadley Centre and Beijing Climate Center) in predicting TCs in the western North Pacific on subseasonal time-scales using genesis index anomalies in different MJO phases. Although both systems could reproduce the observed relationship between the MJO and TCs via the genesis index (Camargo et al. 2009), the intensity of the MJO effect on the genesis index is underestimated due to model biases.

3.4 *MJO/Boreal Summer Intra-Seasonal Oscillation in models*

Ensemble prediction systems (EPS) have shown remarkable improvements in MJO forecast skill in recent years (e.g. Vitart, 2014; Wang et al. 2014; MacLachlan 2015; Marshall et al. 2017). Neena et al. (2014) assessed the skill of several dynamical model re-forecasts from the Intra-Seasonal Variability Hindcast Experiment (ISVHE). They found skill for 1 to 4 weeks in the boreal winter, with the majority of the models having skill for 2-3 weeks. More recently, Vitart (2017) found that the S2S Project hindcasts (Malguzzi et al. 2017) have significant RMM (Real-time Multivariate MJO index) prediction skill scores varying widely between 10 to 32 days, which represents an overall improvement over the ISVHE models. In addition, studies have shown MJO prediction skill for various models. About 4-weeks of RMM skill have been demonstrated in the GFDL (Xiang et al. 2015a) and NICAM models (Miyakawa et al. 2014) in boreal winter, with about 3-weeks skill for the UKMO GloSea5 (MacLachlan et al. 2015), BCC (Liu et al. 2017), and FIM-iHYCOM (Green et al. 2017) models in all seasons. Atmosphere-only models, such as GEFS (Hamill and Kiladis 2014) and BCC (Wu et al. 2016) have about two weeks of skill (see Kim et al. 2018 for a more extensive review on the prediction of the MJO). The Boreal Summer intra-seasonal Oscillation (BSISO), which is characterized by a northward propagation in addition to the eastward propagation typically associated with MJO, is also an important source of predictability for Northern Hemisphere TC activity. Jie et al (2017) assessed the skill of the re-forecasts from 10 models of the S2S database to predict the BSISO, using a BSISO index developed by Lee et al. (2013). They found that the operational models from the S2S database can predict the BSISO1 (eastward propagation) and BSISO2 (northward propagation) events up to 24.5 and 14 days in advance respectively, although the models tend to underestimate the amplitude of the BSISO as the lead time increases.

Many of these models also have shown improving skill relative to older models in the prediction ofin other subseasonal modes like equatorial waves that affect TCs. Janiga et al. (2018) compared boreal summer hindcasts from three S2S Project models using a novel Fourier filtering technique with these hindcasts to identify the MJO and equatorial waves. In general, these models derived most of their subseasonal skill for forecasting tropical convection from low-frequency persistent signals like ENSO. However, the MJO contributed significantly in weeks 1–3, especially over the Indian Ocean and Maritime Continent. Equatorial Rossby waves only improved the skill in week 1. Meanwhile, Kelvin waves made no meaningful improvement to skill, even in models that produced them. These results point to some of the primary areas where model skill may be improved to develop better subseasonal forecasts of TC activity.

4. Subseasonal forecasts of tropical cyclones: description, skill and verification

We now describe the existing operational subseasonal forecasts of tropical cyclones. A summary of these forecasts and their main characteristics is presented in Table 1.

4.1 *CSU forecasts*

Colorado State University (CSU) has issued two-week forecasts of North Atlantic hurricane activity during the

TABLE 1 Operational TC subseasonal forecasts

Institution	Type	Lead time	Length	Region	Period	Variables	Availability
CSU	Statistical-Dynamical	2 weeks	2 weeks	Atlantic	August – October	ACE	Public
ECMWF	Dynamical	1 – 4 weeks	Weekly	All TC basins	Year round	NTC NHUR ACE Strike probability	Not public
BoM	Dynamical	1 – 4 weeks	Weekly	Southern hemisphere	November – April	Strike probability	Not public
CMA	Statistical-dynamical	1 month	Monthly	Western North Pacific	June – October	NTC ACE Landfalls China	Not public
CMA	Statistical-Dynamical	1-4 week	30-days	Western North Pacific	June – October	Multiple TC events	Not public

peak months of the season (August-October) since 2009. These statistical forecasts predict ACE in the upper, middle, or lower tercile for the next two-week period using a combination of: 1) current storm activity, 2) NHC Tropical Weather Outlooks, 3) forecast output from global numerical weather prediction models, 4) the current and projected state of the MJO and 5) the current seasonal Atlantic hurricane forecast. Six two-week forecasts are issued for each hurricane season, and these predictions have generally shown skill above a persistence forecast from the prior two weeks. For example, five of the six two-week forecasts in 2017 and in 2018 verified in the correct tercile.

4.2 *ECMWF forecasts*

4.2.1 *ECMWF Forecast products*

The European Centre for Medium-Range Weather Forecasts (ECMWF) has issued week 1-4 forecasts of TC activity for each TC region since 2010. The TC forecast products include: (i) predicted number of tropical storms/hurricanes or ACE over a TC basin for a weekly period (calendar week 1 to 4). (ii) TC strike probability map: the probability of a tropical depression/storm/intense storm (hurricane intensity) passing within 300 km. TC strike probability anomaly maps are also available (anomalies relative to model climatology). The forecasts are issued twice a week but are not available publicly. The skill of the weekly TC probabilities has been assessed in Vitart et al. (2010) over the Southern Hemisphere, and when the model ensemble probabilities are suitably calibrated, the forecasts are shown to be superior to an MJO-based statistical technique (Leroy and Wheeler 2008). A more recent assessment confirms that these forecasts are more skillful than weekly observed climatology and persistence for week 1 and 2 over all TC basins and beyond week 3 for some TC basins.

4.2.2 *Evaluation of ECMWF forecast skill*

Elsberry et al. (2010) combined the ECMWF 32-day forecast ensemble member vortices with similar tracks into "ensemble storm" tracks with a weighted-mean vector motion technique in which the weighting factor was inversely proportional to the distance from the endpoint of the previous 12-h motion vector. A sample of 30 weekly forecasts for 2008 were compared with the Joint Typhoon Warning Center (JTWC) tracks and demonstrated that the formations and tracks of five typhoons and four strong tropical storms were consistently predicted during weeks 1 through 4. Elsberry et al. (2011) made a similar evaluation during the 2009 WNP season and found that 12 typhoons were successfully predicted. Many of the deficient track predictions involved unusual and rapidly changing tracks that are likely not predictable on extended-range (5-30 days) time-scales.

Tsai et al. (2013) developed an objective track analog verification technique in which ensemble storms within specified time and space differences of the JTWC tracks are first extracted as potential analogs, and four metrics of shortest distance, average distance, distance at formation time, and distance at ending time are calculated. An objective quality measure called Likelihood Values (LHV) that assesses the overall track similarity between the potential analogs and the JTWC storm is calculated in terms of membership functions for the four track metrics. The performance in the North Atlantic in terms of the LHV for ensemble storm tracks that matched an observed storm was done in Elsberry et al. (2014). Four hurricanes and one tropical storm were successfully forecast in three of the four weeks. Two hurricanes and three tropical storms were not predicted by the ECMWF 32-day ensemble, even in week-1. Four of these storms began in the central North Atlantic with strong mid-latitude influences. Because the dynamics of those tropical events are strongly affected by baroclinic processes during the interaction of the eastward-moving midlatitude troughs with the westward-moving pre-TC seedlings, and such interactions are inherently difficult to predict, predictability of a considerable fraction of North

Atlantic TC events (formation plus track) is quite limited compared to WNP events.

Similar evaluations were carried out for the seasonal (seven-month) ECMWF ensemble forecasts. Although some useful predictions were made for African easterly wave-type storms, limited or no skill was found for baroclinic-affected TC formations (Elsberry and Tsai 2016). The performance for the WNP was far superior in that nearly all of the JTWC storms could be matched with an ECMWF ensemble storm track. Only two of the 17 storms evaluated were predicted for all four weeks, but eight of the other storms were predicted in three of the four weeks. However, one early season tropical storm, one baroclinically influenced tropical storm, and one late season tropical depression were not forecast in any of the four weeks. Thus, Elsberry and Tsai (2016) concluded that the performance of the ECMWF ensemble performance in the WNP was very encouraging, and proposed that even the distribution of numbers among the three basic track types (westward, northwestward, and recurving) of TC events may be predictable with an appropriate calibration procedure.

4.3 Australian Bureau of Meteorology forecasts

The Australian BoM produced trial subseasonal TC products during the 2017-18 and 2018-19 Southern Hemisphere cyclone seasons, which were made available to internal forecasters. These products aimed to match those provided twice weekly by ECMWF using output from the new BoM seasonal forecasting system ACCESS-S1 (Hudson et al. 2017), which became fully operational in early 2018. The ACCESS-S1 system is based on the UK Met Office Global Seasonal forecast system GloSea5 (MacLachlan et al. 2015) and showed significant skill for predictions of the MJO out to 30 days and changes in the spatial distribution of TC tracks with the phase of the MJO out to 5 weeks ahead (Camp et al. 2018). The trial forecasts showed performance similar to that of the ECMWF forecasts and provided useful guidance out to three weeks ahead for major cyclone events, including Cyclone Gita in the South Pacific and Cyclone Hilda in the South Indian Ocean, which later made landfall in northwest Australia (Gregory et al. 2019). Figure 4 shows forecasts of the probability of TC occurrence for weeks 2 and 3 from ACCESS-S1 and ECMWF for the period 26 December 2017–1 January 2018, alongside corresponding observations of TC Hilda. At week 3 both systems showed a 20-30% probability of TC development, which then increased to 40-50% in ACCESS-S1 during week 2. Overall both systems predicted well the location and shape of the TC track, particularly the landfall over northwest Australia. The BoM is now working towards operational subseasonal forecast for the 2019/20 Southern Hemisphere season. These forecasts have been developed in collaboration with the UK Met Office.

As an example, we show in Table 2 the skill scores of the BoM TC Southern Hemisphere forecasts and re-forecasts for November to April, based on the method from Vitart et al. (2010) and Camp et al. (2018). The re-forecasts had 11 ensembles and 4 forecasts per month and were initialized using ERA-Interim, while the real-time forecasts (issued daily) had 33 ensembles initialized by the BoM global atmospheric model. We can see the real-time performance was better than the re-forecasts, probably due to the differences mentioned. Furthermore, the 2017-18 season was more predictable than 2018-19. Interestingly, while the calibration method improved the forecast skill scores for long-leads for 2017-18, it degraded the skill for 2018-19. Currently, the BoM is examining the causes for this difference.

4.4 China Meteorological Administration forecasts

Since the mid-1990s, the China Meteorological Administration (CMA) has been issuing monthly TC forecasts for the number of tropical storm formations over the WNP and the number of TCs making landfall in China. The forecasts are issued monthly from June to August each year based on projection-pursuit diagnostic analyses and statistical approaches. The diagnostic analyses use the relationship of TC activity with ENSO, the MJO, and local thermodynamic and dynamic conditions. In 2017, a hybrid statistical-dynamical approach was developed based on the relationships between the observed monthly TC activity and the large-scale environmental variables from the NCEP CFSv2 forecast system. In addition to number of tropical storm formations over the WNP and landfalling TCs in China, the forecasts also include basin-wide ACE. The statistical-dynamical forecasts are provided probabilistically with three terciles and also deterministically with a median. The forecasts provide skillful forecasts for monthly TC number and ACE, with probabilities of detection of 65% and 78%, respectively. Since 2013, CMA has also been issuing subseasonal forecasts for active, normal and inactive periods of multiple TC events over the WNP (Gao et al. 2011). The forecasts are produced by analyzing the relationship of multiple TC events with the MJO, as well as with subseasonal variability of the monsoon trough and subtropical high over the WNP based on the CFSv2 45-day forecasts. The forecasts are produced once a week and cover the next 30 days from July through September each year. Preliminary verification shows that the 30-day forecasts have good skill for TCs with a long lifetime but have no skill for TCs with a short duration. An ongoing effort at the National Climate Center of China is to develop an experimental prediction for TC activity for week 1 to week 4 using the subseasonal forecast model developed by the National Climate Center of China (DERF2.0). Weekly TC activity in DERF2.0 forecasts use the TC detection and tracking method of Camargo and Zebiak (2002). These forecasts are likely to be released operationally in about two years.

4.5 Subseasonal prediction of tropical cyclones in the private sector

There is growing interest in the subseasonal prediction of

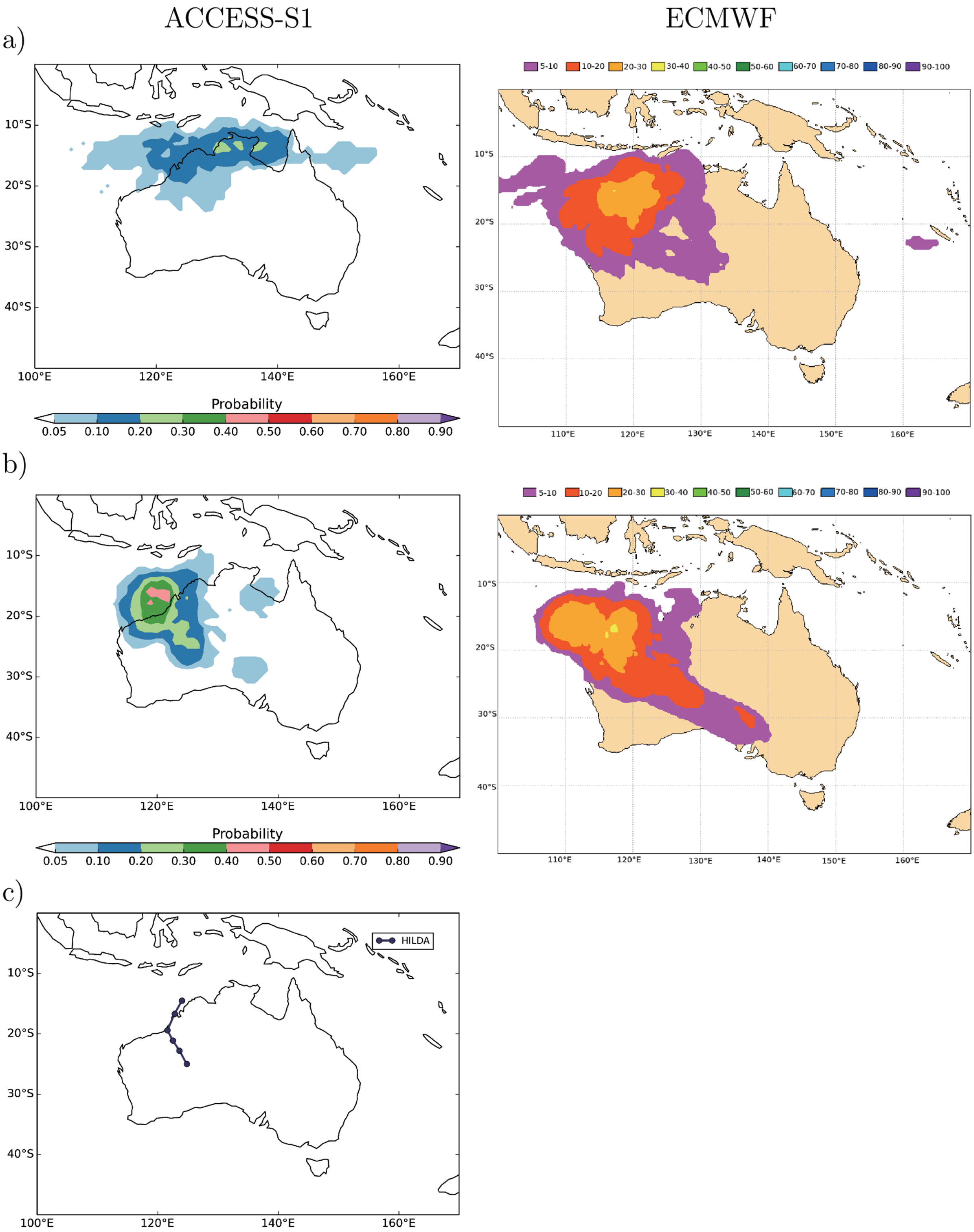


Fig. 4. Probability of a TC passing within a 300km radius for forecasts valid in a) week 3 (initialised 11 December 2017) and b) week 2 (initialised 18 December 2017) for (left) ACCESS-S1 and (right) ECMWF for the period 26 December 2017–1 January 2018. c) Corresponding observed track of TC Hilda during this period. Observed TC tracks are from the US Navy's Joint Typhoon Warning Center (JTWC; Chu et al 2002).

TABLE 2 Brier skill score for the BoM southern hemisphere TC subseasonal forecasts (2017-18, 2018-19) and reforecasts (1990-2012) for the period of November to April using the method of Vitart et al ((2010) and Camp et al. (2018). Reforecasts had 4 forecasts per month with 11 ensemble members and with the ERA-Interim used as initialization. Real-time forecasts were daily, with 33 ensemble members and initialization by using the BoM global atmospheric model.

	Raw			Calibrated		
Lead time	*Reforecast*	*2017-18*	*2018-19*	*Reforecast*	*2017-18*	*2018-19*
Days 8-14	0.128	0.209	0.181	0.155	0.182	0.161
Days 15-21	0.044	0.125	0.068	0.096	0.140	0.066
Days 22-28	0.023	0.108	0.045	0.073	0.121	0.049

TC activity in all facets of business. A threatening TC can alter the decision tree making process of a business, which can then play a direct outcome on the economic performance of that company for a given year. Some companies need 3-4 weeks warning in order for decisions to be made with regards to preparation and or mitigation of a TC. For instance: (i) reinsurers that may need to purchase additional coverage for an oncoming storm; (ii) offshore drilling platforms and freight shipping which both take time to move/ evacuate out of the path of a storm; (iii) retailers that need to pre-position supplies to meet demand in a recovery. Thus, there is a need for skillful predictions of TC activity across all basins for which a company has assets. There is currently a lack of model guidance data that quantifies the TC activity of a particular basin at subseasonal lead-times. Many forecasters in the private sector use concepts discovered in research/academia when drawing their week 3-4 forecasts of TC activity. The MJO (Maloney and Hartmann 2000; Mo 2000; Roundy and Paul 2006; Maloney and Shaman 2008; Klotzbach 2010; Ventrice et. al 2011) and or convectively coupled atmospheric Kelvin waves (CCKWs; Ventrice et al. 2012a,b; Schreck 2015) are often tracked through the use of observational reanalysis and weather model prediction ensemble systems to derive a week 3-4 outlook of whether TC activity across a particular basin will be active versus inactive (e.g., Fig. 5). In addition to these advanced forecasting techniques, the ECMWF monthly model is also utilized for the prediction of TC activity across a basin of interest. Some companies will go a step further and provide above or below TC activity predictions at the week 3-4 lead using the ECMWF monthly reforecast, in which the frequency of TCs in the live run relative to the model climate is computed.

5. Conclusions and future work

Considerable progress has been made by the scientific community during the last four years in understanding the sources of predictability and the modulation of TC activity at subseasonal time-scales. There has also been significant progress in the ability of models in simulating subseasonal modes of variability and their modulation of TC activity. Community efforts have created multi-model ensemble datasets, such as the S2S (Subseasonal to Seasonal) dataset, TIGGE (The International Grand Global Ensemble) and SubX (The Subseasonal Experiment), which have made it possible to evaluate the forecast skill of TCs on subseasonal time-scales in multiple forecasting systems. While there is positive skill in some cases, there is strong dependence on the ensemble system considered, the basin examined, and whether the TC activity has been influenced by the extratropical circulation or not. Furthermore, the definition of skill differs among different authors, as some studies consider a model skillful for forecasting the probability of TCs in a basin, while others require skill of the subseasonal anomaly deviations from the basin seasonal climatology. Therefore, in the first case the model would be considered skillful by forecasting the seasonality of the basin correctly, while in the second only deviations from the basin seasonality count towards the model skill. Furthermore, outputs of the subseasonal TC forecasts are in some cases expressed as local probabilities for specific areas which makes comparison among groups using different verification measures a challenge.

In addition, different centers use different lead-times, periods, and variables. For instance, while some groups forecast the probability of TC occurrence weekly in a basin, others forecast the number of TCs during in the next month. It is virtually impossible to compare the skill of the existing forecasts. This lack of uniformity makes it impossible for stakeholders to understand the current state of the knowledge and to make best use of these forecasts. Therefore, it is important to agree on common standards and verification metrics for subseasonal TC forecasts.

While the main efforts so far have been in the modulation of TCs by subseasonal tropical modes, the extratropical-tropical interaction is another source of predictability. This topic is still in its infancy, and there is a clear need for much more research that could potentially lead to improved forecasts. Efforts in understanding the predictability and model skill on downstream forecasts should also be a focus of the research community.

Various modeling centers are issuing subseasonal TC forecasts using statistical, statistical-dynamical, or dynamical techniques. Certainly, machine learning and other artificial intelligence techniques will be soon be applied in the development of subseasonal TC forecasts. One way for the

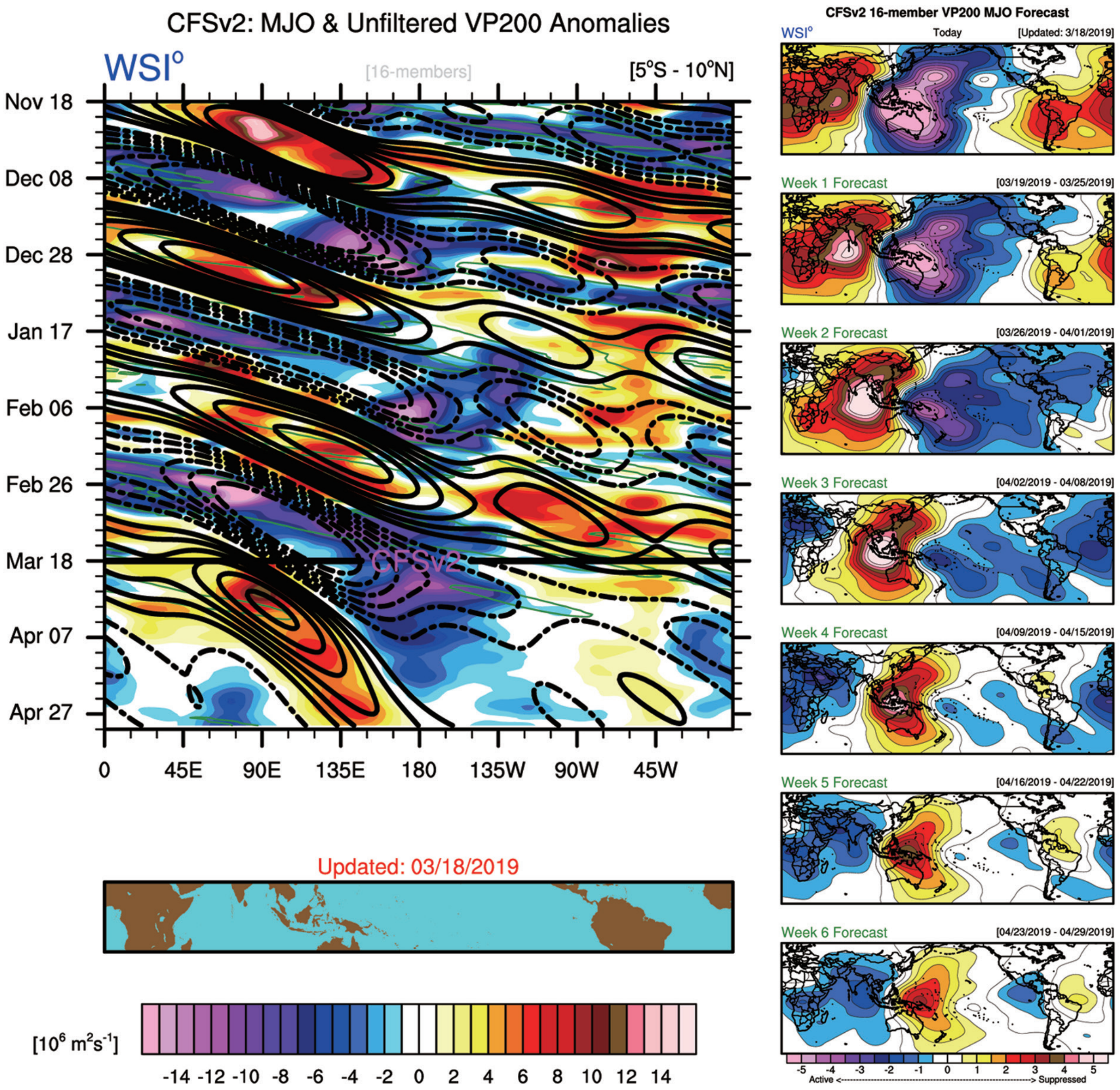


Fig. 5. The Weather Company, an IBM Business, derived MJO products. (Left) A time-longitude plot of unfiltered 200 hPa-velocity potential (VP200) anomalies (shaded) using the GFS-near real-time analysis as observations with a 6-week appended CFSv2 forecast. Contours represent MJO-filtered VP200 anomalies (black) and Kelvin-filtered VP200 anomalies (green), following the methodology of Wheeler and Kiladis (1999). (Right) MJO filtered VP200 anomalies aggregated over weekly time scales using the 6-week CFSv2 forecast model.

scientific community to advance this topic and encourage the comparison of these various techniques across different modeling groups would be by launching an international project on this topic. Funding from international agencies for this project would help advance the progress of TC subseasonal forecasts and their use by stake-holders.

6. Recommendations:

1. The WMO should encourage and facilitate investments in modeling and observational studies that could potentially further improve subseasonal TC forecasts, both for forecasts of basin-wide activity and for regional TC predictions.

2. More verification studies should be done of single and multi-model predictions of TC activity during weeks 3-4, and whether calibration techniques are needed. Common metrics need to be adopted for better assessment and comparison of skill.

3. The researcher community should actively explore improved understanding and prediction of tropical-extratropical interactions to contribute to improved subseasonal TC predictions as well as their downstream impacts on high-impact weather events.

4. The WMO should encourage and facilitate a "Severe Weather Forecasting Demonstration Project" focused on subseasonal TC forecasting, especially in the WNP which is basin, with the highest TC frequency.

5. The WMO should also collaborate with both the meteorological and hydrological services to advance the interpretation and appropriate usage of such subseasonal predictions.

Appendix A - Acronyms:

ACE: Accumulated Cyclone Energy
ACCESS-S: Australian Community Climate and Earth System Simulator – Seasonal
AMO: Atlantic Multidecadal Oscillation
BCC: Beijing Climate Center
BoM: Australian Bureau of Meteorology
BSISO: Boreal Summer Intra-Seasonal Oscillation
BSS: Brier Skill Score
CCKWs: Convectively Coupled Kelvin Waves
CFS: Climate Forecast System
CFSv2: Climate Forecast System version 2
CMA: China Meteorological Administration
CSU: Colorado State University
DERF2.0: Dynamic Extended-Range Forecast Operational System Version 2
ECMWF: European Centre for Medium-Range Weather Forecasts
ENSO: El Niño-Southern Oscillation
EPS: Ensemble Prediction Systems
ERW: Equatorial Rossby Waves
FIM-IHYCOM: Flow-Flowing Icosahedral Model – Icosahedral Hybrid Coordinate Ocean Model
GEFS: Global Ensemble Forecast System
GEOS-5: NASA Goddard Earth Observatory System version 5
GFDL: Geophysical Fluid Dynamics Laboratory
GloSea5: Global seasonal forecasting system version 5
ISVHE: Intral-Seasonal Variability Hindcast Experiment
JMA: Japan Meteorological Agency
JTWC: Joint Typhoon Warning Center
LHV: Likelihood Values
MCGE: Multicenter Grand Ensemble
MJO: Madden-Julian Oscillation
MTCE: Multiple tropical cyclone events
NASA: National Aeronautics and Space Administration
NICAM: Nonhydrostatic Icosahedral Atmospheric Model
NCEP: National Centers for Environmental Prediction
NHC: National Hurricane Center
NOAA: National Oceanic and Atmospheric Administration
QBWO: Quasi-biweekly Oscillation
RMM: Real-time Multivariate MJO index
RWB: Rossby Wave breaking
S2S: Subseasonal to seasonal
TC: tropical cyclone
TIGGE: The International Grand Global Ensemble
UKMO: United Kingdom Meteorological Office
US: United States of America
WMO: World Meteorological Organization
WNP: western North Pacific
WCRP: World Climate Research Program
WWRP: World Weather Research Program

Acknowledgements

SJC and AHS acknowledge support from NOAA grant NA16OAR4310079. We thank Zongjian Ke and Jianyun Gao for their contributions to the China Meteorological Administration forecast summary.

References

Barnston, A.G., N. Vigaud, L.N. Long, M.K. Tippett, and J.-K. E. Schemm, 2015: Atlantic tropical cyclone activity in response to the MJO in NOAA's CFS model. *Mon. Wea. Rev.*, **143**, 4905–4927, doi: 10.1175/MWR-D-15-0127.1

Belanger, J., J.A. Curry, and P.J. Webster, 2010: Predictability of North Atlantic Tropical Cyclones on Intraseasonal time scales. *Mon. Wea. Rev.*, **138**, 4362–437

Belanger, J.I., P.J. Webster, J.A. Curry, and M.T. Jelinek, 2012: Extended prediction of North Indian Ocean tropical cyclones. *Wea. Forecasting*, **27**, 757–769.

Camargo, S.J., M.C. Wheeler, and A.H. Sobel, 2009: Diagnosis of the MJO modulation of tropical cyclogenesis using an empirical index. *J. Atmos. Sci.*, **66**, 3061–3074, doi: 10.1175/2009JAS3101.1.

Camp, J., M.C. Wheeler, H.H. Hendon, P.A. Gregory, A.G. Marshall, K.J. Tory, A.B. Watkins, C. MacLachlan, and Y. Kuleshov, 2018: Skillful multi-week tropical cyclone prediction in ACCESS-S1 and the role of the MJO. *Q. J. R. Meteorol. Soc.,* **144**, 1337–1351, doi: 10.1002/qj.3260.

Chang, C.-C., and Z. Wang, 2018. Relative impacts of local and remote forcing on tropical cyclone frequency in numerical model simulations. *Geophys. Res. Lett*., **45**, 7843 – 7850, doi: 10.1029/2018GL078606.

Chen, J.-M., C.-H. Wu, P.-H. Chung, C.-H. Sui, 2018: Influence of intraseasonal-interannual oscillations on tropical cyclone genesis in the western North Pacific. *J. Climate*, **31**, 4949–4961, doi: 10.1175/JCLI-D-17-0601.1.

Chu J. H., C. R. Sampson, A. S. Levine, E. Fukada, 2002. "The Joint Typhoon Warning Center tropical cyclone best-tracks, 1945–2000", Technical report NRL/MR/7540-02-16. Naval Research Laboratory: Washington, DC.

Compo, G. P., and Co-Authors, 2011: The Twentieth Century Reanalysis Project. *Q. J. R. Meteorol. Soc.,* **137,** 1-28.

Davis, C.A., and L.F. Bosart, 2003: Baroclinically induced tropical cyclogenesis. *Mon. Wea. Rev.*, **131**, 2730–2747.

Davis, C.A., and L.F. Bosart, 2004: The TT problem: Forecasting the tropical transition of cyclones. *Bull. Amer. Meteor. Soc.*, **85**, 1657–1662.

Davis, C.A., D.A. Ahijevych, W. Wang, and W.C. Skamarock, 2016: Evaluating medium-range tropical cyclone forecasts in uniform- and variable-resolution global models. *Mon. Wea.*

Rev., **144**, 4141–4160.

Elsberry, R.L., M.S. Jordan, and F. Vitart, 2010: Predictability of tropical cyclone events on intraseasonal timescales with the ECMWF monthly forecast model. *Asia-Pacific J. Atmos. Sci.*, **46**, 135–153.

Elsberry, R. L., M.S. Jordan, and F. Vitart, 2011: Evaluation of the ECMWF 32-day ensemble predictions during 2009 season of western North Pacific tropical cyclone events on intraseasonal timescales. *Asia-Pacific J. Atmos. Sci.*, **47**, 305–318.

Elsberry R.L., and H.-C. Tsai, 2016: Opportunities and challenges in dynamical and predictability studies of tropical cyclone events. **Chapter 10**, *Dynamics and Predictability of Large-scale High-impact Weather and Climate Events*. Edited by J. P. Li, R. Swinbank, R. Grotjahn, and H. Volkert, Cambridge University Press, 133–140.

Elsberry, R.L., H.-C. Tsai, and M.S. Jordan, 2014: Extended-range forecasts of Atlantic tropical cyclone events during 2012 using the ECMWF 32-day ensemble predictions. *Wea. Forecasting*, **29**, 271–288.

Fang, J., and F. Zhang, 2016: Contribution of tropical waves to the formation of Supertyphoon Megi (2010). *J. Atmos. Sci.*, **73**, 4387–4405, doi: 10.1175/JAS-D-15-0179.1.

Galarneau, T.J., R. McTaggart-Cowan, L.F. Bosart, and C.A. Davis, 2015: Development of North Atlantic tropical disturbances near upper-level potential vorticity streamers. *J. Atmos. Sci.*, **72**, 572–597, doi: 10.1175/JAS-D-14-0106.1.

Gao, J., and T. Li, 2011: Factors controlling multiple tropical cyclone events in the western North Pacific. *Mon. Wea. Rev.*, **139**, 885–894, doi: 10.1175/2010MWR3340.1.

Green, B.W., S. Sun, R. Bleck, S.G. Benjamin, and G.A. Grell, 2017: Evaluation of MJO predictive skill in multiphysics and multimodel global ensembles. *Mon. Wea. Rev.*, **145**, 2555–2574, doi: 10.1175/MWR-D-16-0419.1.

Gregory, P., J. Camp, K. Bigelow, A. Brown, 2019: Sub-seasonal predictability of the 2017–18 Southern Hemisphere tropical cyclone season. *Atmos. Sci. Lett.*, doi: doi.org/10.1002/asl.886.

Hamill, T.M., and G.N. Kiladis, 2014: Skill of the MJO and Northern Hemisphere blocking in GEFS medium-range reforecasts. *Mon. Wea. Rev.*, **142**, 868–885, doi: 10.1175/MWR-D-13-00199.1.

He, J.L., A.M. Duan, and Y.S. Huang, 2013: On the relationship between MJO and clustering of tropical cyclone activities over the western North Pacific, *Adv. Meteor. Sci. Tech.*, **3**, 46–51 (in Chinese with English abstract).

Hudson D., O. Alves, H.H. Hendon, E. Lim, G. Liu, J.J. Luo, C. MacLachlan, A.G. Marshall, L. Shi, G. Wang, R. Wedd, G. Young, M. Zhao, X. Zhou, 2017: ACCESS-S1: The new Bureau of Meteorology multi-week to seasonal prediction system. *J. Southern Hemisphere Earth Syst. Sci.*, **67**, 132–159 doi: 10.22499/3.6703.001.

Janiga, M. A., C. J. Schreck, J. A. Ridout, M. Flatau, N. P. Barton, E. J. Metzger, and C. A. Reynolds, 2018: Subseasonal Forecasts of Convectively Coupled Equatorial Waves and the MJO: Activity and Predictive Skill. *Mon. Wea. Rev.*, **146**, 2337–2360, doi:10.1175/MWR-D-17-0261.1.

Jiang, X., B. Xiang, M. Zhao, T. Li, S.-J. Lin, Z. Wang, and J.-H. Chen, 2018: Intraseasonal tropical cyclone genesis prediction in a global coupled model system. *J. Climate*, **31**, 6209–6227, doi: 10.1175/JCLI-D-17-0454.1.

Jie, W., F. Vitart, T. Wu, and X. Liu, 2017: Simulations of the Asian summer monsoon in the sub-seasonal to seasonal prediction project (S2S) database. *Q. J. R. Meteorol. Soc.*, **143**, 2282–2295. doi: 10.1002/qj.3085.

Jin, X.X., G.R. Han, R.F. Zhan, S.J. Chen, J.H. He, and J. Chen, 2016: Characteristics of the low-frequency oscillation over the South China Sea—western North Pacific and its modulation of the clustering of tropical cyclones. *Trans. Atmos. Sci.,* **39**, 198–208, doi: 10.13878/j.cnki.dqkxxb.20140703002 (in Chinese with English abstract).

Kim, D., M.-I. Lee, and H.-M. Kim, and S.D. Schubert and J.-H. Yoo, 2014: The modulation of tropical storm activity in the western North Pacific by the Madden-Julian Oscillation in GEOS-5 AGCM experiments. *Atmos. Sci. Lett.*, **15**, 335–341.

Kim, H., F. Vitart, and D.E. Waliser, 2018: Prediction of the Madden-Julian Oscillation: A review. *J. Climate,* **31**, 9425-9443**,** doi: 10.1175/JCLI-D-18-0210.

Klotzbach P. J., 2010: On the Madden Julian Oscillation – Atlantic hurricane relationship. *J. Climate*, **23,** 282-293, doi: 10.1175/2009JCLI2978.1.

Klotzbach, P. J**.,** and E. C. J. Oliver, 2015a: Modulation of Atlantic basin tropical cyclone activity by the Madden-Julian Oscillation (MJO) from 1905–2011. *J. Climate,* **28,** 204–217.

Klotzbach, P. J**.,** and E. C. J. Oliver, 2015b: Variations in global tropical cyclone activity and the Madden-Julian Oscillation since the midtwentieth century. *Geophys. Res. Lett,* **42,** 4199–4207, doi: 10.1002/2015GL063966.

Krouse, K. D., and A. H. Sobel, 2010: An observational study of multiple tropical cyclone events in the western north Pacific. *Tellus*, **62A**, 256-265.

Lee, C.-Y., S.J. Camargo, F. Vitart, A.H. Sobel, and M.K. Tippett, 2018. Sub-seasonal tropical cyclone genesis prediction and MJO in the S2S dataset. *Wea. Forecasting*, **33**, 967–988, doi: 10.1175/WAF-D-17-0165.1.

Lee, J.Y., B. Wang, M. Wheeler, X. Fu, D. Waliser, I.-S. Kang, 2013: Realtime multivariate indices for the boreal summer intraseasonal oscillation over the Asian summer monsoon region. *Clim. Dyn.* **40**, 493–509.

Leroy, A., and M.C. Wheeler, 2008: Statistical prediction of weekly tropical cyclone activity in the Southern Hemisphere. *Mon. Wea. Rev.*, **136**, 3637-3654.

Li, T., L. Wang, M. Peng, B. Wang, C. Zhang, W. Lau, and H. Kuo, 2018a: A paper on the tropical intraseasonal oscillation published in 1963 in a Chinese Journal. *Bull. Amer. Meteor. Soc.*, **99**, 1765–1779, doi: 10.1175/BAMS-D-17-0216.1.

Li, W., Z. Wang, G. Zhang, M. Peng, S. Benjamin, and M. Zhao, 2018b: Subseasonal variability of Rossby wave breaking and impacts on tropical cyclones during the North Atlantic warm season, *J. Climate*, **31**, 9679-9695, doi:10.1175/JCLI-D-17-0880.1.

Liebmann, B., H.H. Hendon, and J.D. Glick, 1994: The relationship between tropical cyclones of the western Pacific and Indian oceans and the Madden-Julian Oscillation. *J. Meteor. Soc. Japan*, **72**, 401–411.

Liu, X., T. Wu, S. Yang, T. Li, W. Jie, L. Zhang, Z. Wang, X. Liang, Q. Li, Y. Cheng, H. Ren, Y. Fang, and S. Nie, 2017: MJO prediction using the sub-seasonal to seasonal forecast model of Beijing Climate Center. *Clim. Dyn*., **48**, 3283-3307, doi: 10.1007/s00382-016-3264-7.

MacLachlan, C., A. Arribas, K.A. Peterson, A. Maidens, D. Fereday, A.A. Scaife, M. Gordon, M. Vellinga, A. Williams, R.E. Comer, J. Camp, P. Xavier, G. Madec, 2015. Global seasonal forecast system version 5 (GloSea5): A High-Resolution seasonal forecast system. *Q. J. R. Meteorol. Soc*. **141**, 1072–1084, doi: 10.1002/qj.2396.

Madden, R.A. and P.R. Julian, 1972: Description of global circulation cells in the tropics with a 40-45 day period. *J. Atmos. Sci.*, **29**, 1109–1123.

Malguzzi, I. Mallas, M. Manoussakis, D. Mastrangelo, C. MacLachlan, P. McLean, A. Minami, R. Mladek, T. Nakazawa, S. Najm, Y. Nie, M. Rixen, A.W. Robertson, P. Ruti, C. Sun, Y. Takaya, M. Tolstykh, F. Venuti, D. Waliser, S. Woolnough, T. Wu, D. Won, H. Xiao, R. Zaripov, and L. Zhang, 2017: The

Subseasonal to Seasonal (S2S) Prediction Project Database. *Bull. Amer. Meteor. Soc.*, **98**, 163–173, doi: 10.1175/BAMS-D-16-0017.1

Marshall, A.G., H.H. Hendon, S.-W. Son, and Y. Lim, 2017: Impact of the quasi-biennial oscillation on predictability of the Madden–Julian oscillation. *Clim. Dyn.*, **49**, 1365–1377.

Miyakawa, T., M. Satoh, H. Miura, H. Tomita, H. Yashiro, A.T. Noda, Y. Yamada, C. Kodama, M. Kimoto, K. Yoneyama, 2014: Madden–Julian oscillation prediction skill of a new-generation global model. *Nat. Commun.*, **5**, 3769, doi:10.1038/ncomms4769.

Nakazawa, T., 1986: Intraseasonal variations of OLR in the tropics during the FGGE year. *J. Meteor. Soc. Japan*, **64**, 17–34.

Neena, J.M., J.Y. Lee, D. Waliser, B. Wang, X. Jiang, 2014: Predictability of the Madden–Julian Oscillation in the Intraseasonal Variability Hindcast Experiment (ISVHE). *J. Climate*, **27**, 4531–4543.

Palmén, E., and C. W. Newton, 1969: *Atmospheric Circulation Systems: Their Structure and Physical Interpretation*. Academic Press, 603 pp.

Palmer, T.N., 1996: Predictability of the atmosphere and oceans: From days to decades. *Decadal Climate Variability: Dynamics and Predictability*, D.L.T. Anderson and J. Willebrand, Eds., NATO ASI Series, **Vol. 44**, Springer, pp. 83–155.

Sadler, J.C., 1976: A role of the tropical upper tropospheric trough in early season typhoon development. *Mon. Wea. Rev.*, **104**, 1266–1278.

Sadler, J.C., 1978: Mid-season typhoon development and intensity changes and the tropical upper tropospheric trough. *Mon. Wea. Rev.*, **106**, 1137–1152.

Schenkel B., 2016: A climatology of multiple tropical cyclone events. *J. Climate*, **29**, 4861–4883, doi: 10.1175/JCLI-D-15-0048.1.

Schreck, C.J., J. Molinari, and A. Aiyyer, 2012: A global view of equatorial waves and tropical cyclogenesis. *Mon. Wea. Rev.*, **140**, 774–788.

Schreck, C.J., 2015: Kelvin waves and tropical cyclogenesis: A global survey. *Mon. Wea. Rev.*, **143,** 3996-4011, doi: 10.1175/MWR-D-15-0111.1.

Schreck, C.J., 2016: Convectively coupled Kelvin waves and tropical cyclogenesis in a semi-Lagrangian framework. *Mon. Wea. Rev.*, **144**, 4131-4139, doi: 10.1175/MWR-D-16-0237.1.

Sobel, A.H., P. Pillai and co-authors, 2018: Improving lead time for tropical cyclone forecasting: Review of operational practices and implications for Bangladesh. World Bank, Washington, DC, 56 pp.

Tsai, H.-C., R.L. Elsberry, and M.S. Jordan, 2013: Objective verifications and false alarm analyses of western North Pacific tropical cyclone event forecasts by the ECMWF 32-day ensemble. *Asia-Pacific J. Atmos. Sci.*, **49**, 409–420, doi: 10.1007/s13143-013-0038-6.

Tsuboi, A., T. Takemi, and K. Yoneyama, 2016: Seasonal environmental characteristics for the tropical cyclone genesis in the Indian Ocean during CINDY2011/DYNAMO field experiment. *Atmosphere*, **7**, 66, doi: 10.3390/atmos7050066.

Ventrice, M.J., C.D. Thorncroft, and P.E. Roundy, 2011: The Madden-Julian Oscillation's influence on African easterly waves and downstream cyclogenesis. *Mon. Wea. Rev.*, **139**, 2704-2722.

Ventrice, M.J., C.D. Thorncroft, and M.A. Janiga, 2012a: Atlantic tropical cyclogenesis: A three-way interaction between an African easterly wave, diurnally varying convection, and a convectively-coupled atmospheric Kelvin wave. *Mon. Wea. Rev.,* **140**, 1108-1124.

Ventrice, M.J., C.D. Thorncroft, and C.J. Schreck, 2012b: Impacts of convectively coupled Kelvin waves on environmental conditions for Atlantic tropical cyclogenesis. *Mon. Wea. Rev.,* **140***,* 2198–2214.

Vitart, F., 2014: Evolution of ECMWF sub-seasonal forecast skill scores. *Q. J. R. Meteor. Soc.*, **140**, 1889–1899.

Vitart, F., 2017: Madden-Julian Oscillation prediction and teleconnections in the S2S database. *Q. J. R. Meteorol. Soc.*, **143**, 2210–2220, doi:10.1002/qj.3079.

Vitart, F., A. Leroy and M.C. Wheeler, 2010: A comparison of dynamical and statistical predictions of weekly tropical cyclone activity in the Southern Hemisphere. *Mon. Wea. Rev,* **138**, 3671–3682.

Vitart, F., F. Prates, A. Bonet, and C. Sahin, 2011: *New Tropical Cyclone Products on the Web*. ECMWF Newsletter 130 (Winter): 17–23.

Vitart, F., C. Ardilouze, A. Bonet, A. Brookshaw, M. Chen, C. Codorean, M. Déqué, L. Ferranti, E. Fucile, M. Fuentes, H. Hendon, J. Hodgson, H. Kang, A. Kumar, H. Lin, G. Liu, X. Liu, P. Malguzzi, I. Mallas, M. Manoussakis, D. Mastrangelo, C. MacLachlan, P. McLean, A. Minami, R. Mladek, T. Nakazawa, S. Najm, Y. Nie, M. Rixen, A.W. Robertson, P. Ruti, C. Sun, Y. Takaya, M. Tolstykh, F. Venuti, D. Waliser, S.Woolnough, T. Wu, D. Won, H. Xiao, R. Zaripov, and L. Zhang, 2017: The Subseasonal to Seasonal (S2S) prediction project database. *Bull. Amer. Meteor. Soc.*, **98**, 163–173, doi: 10.1175/BAMS-D-16-0017.1

Vitart, F., and A. Robertson 2018: The Sub-seasonal to seasonal prediction project (S2S) and the prediction of extreme events. *npj Clim. Atmos. Sci.*, **1**, 3, doi:10.1038/s41612-0013-0.

Wang, W., M.P. Hung, S.J. Weaver, A. Kumar, and X. Fu, 2014: MJO prediction in the NCEP Climate Forecast System version 2. *Clim. Dyn.*, **42,** 2509–2520, doi: 10.1007/s00382-013-1806-9.

Wang, Z., W. Li, M. S. Peng, X, Jiang, R. McTaggart-Cowan, and C. Davis, 2018: Predictive skill and predictability of North Atlantic tropical cyclogenesis in different synoptic flow regimes. *J. Atmos. Sci.*, **75**, 361–378.

Webster, P.J., 2008: Myanmar's deadly daffodil. *Nature Geos.* **1**, 488–90.

Webster, P.J., 2012: Bay of Bengal tropical cyclones and severe convective systems: Predictability, prediction and the Impacts of climate change. Washington, DC: World Bank commissioned background report for the Bangladesh Sundarbans NLTA.

Webster, P.J., 2013: Improve weather forecasts for the developing world. *Nature*, **493**,17–18.

Wheeler, M.C., and H.H. Hendon, 2004: An all-season real-time multivariate MJO Index: Development of an index for monitoring and prediction. *Mon. Wea. Rev.*, **132**, 1917–1932.

Wheeler, M., and G.N. Kiladis, 1999: Convectively coupled equatorial waves: Analysis of clouds and temperature in the wavenumber-frequency domain. *J. Atmos. Sci.*, **56**, 374–399.

Wu, J., H.-L. Ren, J.Q. Zuo, C. Zhao, L. Chen, and L. Qiaoping, 2016: MJO prediction skill, predictability, and teleconnection impacts in the Beijing Climate Center Atmospheric General Circulation Model. *Dyn. Atmos. Oceans*, **75**, 78–90, doi: 10.1016/j.dynatmoce.2016. 06.001.

Xiang, B., M. Zhao, X. Jiang, S. Lin, T. Li, X. Fu, and G. Vecchi, 2015a: The 3–4-Week MJO prediction skill in a GFDL coupled model. *J. Climate*, **28**, 5351–5364.

Xiang, B., S.-J. Lin, M. Zhao, S. Zhang, G. Vecchi, T. Li, X. Jiang, L. Harris, and J.-H. Chen 2015b: Beyond weather time-scale prediction for Hurricane Sandy and Super-Typhoon Haiyan. *Mon. Wea. Rev.*, **143**, 524–535, doi: 10.1175/MWR-D-14-00227.1.

Xie, Y.-B., S.-J. Chen, I-L. Zhang, and Y.-L. Hung, 1963: A preliminarily statistic and synoptic study about the basic currents over southeastern Asia and the initiation of typhoon. *Acta Meteorologica Sinica*, **33**, 206–217 (in Chinese).

Yamaguchi, M., F. Vitart, S.T.K. Lang, L. Magnusson, R.L. Elsberry, G. Elliott, M. Kyouda, and T. Nakazawa, 2015: Global distribution on the skill of tropical cyclone activity forecasts from short- to medium-range time scales. *Wea. Forecasting*. **30**, 1695–1709.

Yamaguchi, M., F. Vitart, S. Maeda, and Y. Takaya, 2016: Were one-month global ensembles capable of predicting inactive TC activity in the western North Pacific basin during early 2016? *Proc. 2016 Fall Meeting of Meteorological Society of Japan*. (In Japanese)

You L., J. Gao, H. Lin, and S. Chen, 2019: Impact of the intraseasonal oscillation on tropical cyclone genesis over the western North Pacific. *Int. J. Climatol.*, **39**, 1969–1984, doi:10.1002/joc.5927.

Zhang, G. and Z. Wang, 2019: North Atlantic Rossby wave breaking during the hurricane season: Association with tropical and extratropical variability. *J. Climate*, **32**, 3777–3801, doi: 10.1175/JCLI-D-18-0299.1

Zhang, G., Z. Wang, T. Dunkerton, M. Peng, and G. Magnusdottir, 2016: Extratropical impacts on Atlantic tropical cyclone activity. *J. Atmos. Sci.*, **73**, 1401–1418.

Zhang, G., Z. Wang, M. Peng, and G. Magnusdottir, 2017: Characteristics and impacts of extratropical Rossby wave breaking during the Atlantic hurricane season. *J. Climate,* **30**, 2363–2379.

Zhao, C., H.-L. Ren, R. Eade, Y. Wu, J. Wu, C. MacLachlan, 2019: MJO modulation and its ability to predict boreal summer tropical cyclone genesis over the northwest Pacific in Met Office Hadley Centre and Beijing Climate Center seasonal prediction systems. *Q. J. Roy. Meteor. Soc.*, **145**, 1089 – 1011, doi: 10.1002/qj.3478.