SEASONAL TROPICAL CYCLONE FORECASTING

PHILIP KLOTZBACH[a], ERIC BLAKE[b], JOANNE CAMP[c], LOUIS-PHILIPPE CARON[d], JOHNNY C. L. CHAN[e], NAM-YOUNG KANG[f], YURI KULESHOV[g], SAI-MING LEE[h], HIROYUKI MURAKAMI[i], MARK SAUNDERS[j], YUHEI TAKAYA[k], FREDERIC VITART[l] AND RUIFEN ZHAN[m]

[a]*Colorado State University, Fort Collins, USA*
[b]*NOAA/National Hurricane Center, Miami, USA*
[c]*Met Office, Exeter, UK*
[d]*Barcelona Supercomputing Centre, Barcelona, Spain*
[e]*Guy Carpenter Asia-Pacific Climate Impact Centre, School of Energy and Environment, City University of Hong Kong, Hong Kong, China*
[f]*National Typhoon Center/Korea Meteorological Administration, Seoul, Republic of Korea*
[g]*Bureau of Meteorology, Melbourne, Australia*
[h]*Hong Kong Observatory, Hong Kong, China*
[i]*Geophysical Fluid Dynamics Laboratory, Princeton University/University Corporation for Atmospheric Research, USA*
[j]*University College London, Surrey, UK*
[k]*Meteorological Research Institute, Japan Meteorological Agency, Tokyo, Japan*
[l]*European Centre for Medium-Range Weather Forecasts, Reading, UK*
[m]*Shanghai Typhoon Institute of China Meteorological Administration, Shanghai, China*

ABSTRACT

This paper summarizes the forecast methods, outputs and skill offered by twelve agencies for seasonal tropical cyclone (TC) activity around the world. These agencies use a variety of techniques ranging from statistical models to dynamical models to predict basinwide activity and regional activity. In addition, several dynamical and hybrid statistical/dynamical models now predict TC track density as well as landfall likelihood. Real-time Atlantic seasonal hurricane forecasts have shown low skill in April, modest skill in June and good skill in August at predicting basinwide TC activity when evaluated over 2003-2018. Real-time western North Pacific seasonal TC forecasts have shown good skill by July for basinwide intense typhoon numbers and the ACE index when evaluated for 2003-2018. Both hindcasts and real-time forecasts have shown skill for other TC basins. A summary of recent research into forecasting TC activity beyond seasonal (e.g., multi-year) timescales is included. Recommendations for future areas of research are also discussed.

Keywords: hurricane, typhoon, tropical cyclone, seasonal forecasting, forecast skill

1. Introduction

Seasonal tropical cyclone (TC) forecasts began with the pioneering work of Neville Nicholls at the Australian Bureau of Meteorology for the Australian region (Nicholls 1979, Nicholls 1984, Nicholls 1985) and William Gray at Colorado State University (CSU) for the Atlantic basin (Gray 1984a, b). These original forecasts were based on statistical relationships between climate phenomena such as El Niño-Southern Oscillation (ENSO) and TCs. Many groups currently issuing seasonal forecasts continue to use statistical relationships between climate indices and TCs as their primary tools for prediction.

Dynamical models are also used as a forecast tool by several groups issuing seasonal TC forecasts. Vitart et al. (1997) showed that TC-like vortices could be tracked in a general circulation model (GCM) and that these vortices showed interannual variability that matched well with observed TC variability when forced with observed sea surface temperatures (SSTs). Vitart and Stockdale (2001) showed that dynamical forecasts could also use forecast SSTs to successfully replicate Atlantic TC activity levels. Additional studies over the next several years documented

---

Corresponding author: Philip Klotzbach, philk@atmos.colostate.edu

DOI: 10.6057/2019TCRR03.03

dynamical model skill at forecasting both basinwide as well as regional TC activity for various portions of the globe (e.g., Vitart 2003, Camargo and Barnston 2009).

Another technique currently in use by many forecasting organizations is a hybrid statistical/dynamical seasonal forecast, whereby large-scale climate factors are forecast by a dynamical model, and then a statistical model is used to relate the predictions of these large-scale climate factors to hurricane activity (Vecchi et al. 2011). The use of hybrid schemes has become more popular in recent years, as evidenced by the number of groups in this manuscript currently using this approach.

The longest continuous operational forecast has been issued for the North Atlantic basin by CSU since 1984 (Gray 1984a, b). Since that time, many other forecast groups have begun issuing forecasts for the North Atlantic basin. In addition, several groups now issue operational forecasts for other TC basins around the globe, including the eastern North Pacific, the western North Pacific (WNP) and the Australian region. Camargo et al. (2007) and Camargo et al. (2010) provided reviews of seasonal forecasting techniques available at that time. This paper summarizes and updates current operational seasonal forecasts available for various TC basins. We do note that many groups other than those discussed here issue forecasts for the Atlantic basin, with several groups not listed here issuing predictions for other TC basins as well. For additional discussion of the mechanisms driving TC variability on seasonal timescales, please refer to Vitart et al. (2014).

Recently, integrated and collaborative efforts for seasonal TC forecasts have been made among research and operational agencies. Currently, 26 different forecast groups including six government agencies, ten private sector weather companies and ten universities are contributing publicly-available seasonal forecasts for the North Atlantic to a collation website http://www.seasonalhurricanepredictions.org. All forecast numbers are available for download. Nearly half of the contributing agencies (12 out of 26) have been issuing publicly-available forecasts since at least 2007. This collation website also provides brief descriptions of each North Atlantic forecast group's methodology and provides links to their websites where more details are included. The forecast technique used by the majority of contributing agencies is a hybrid statistical/dynamical technique, with the UK Met Office being the only publicly-available dynamical model included. The goal is to expand this website in the future to include seasonal TC forecasts for all ocean basins for which multiple agencies are issuing forecasts.

In addition to seasonal forecasts for entire TC basins, some of these forecasts now go beyond predicting basinwide TC activity and highlight areas where TC tracks are more or less likely. The paper also briefly discusses outlooks issued beyond seasonal (e.g., multi-year) timescales and finishes with a summary and some ideas for areas of future research.

2. Seasonal tropical cyclone forecasts

Table 1 summarizes the scope and nature of the forecasts issued by the twelve agencies considered herein. The table lists the agencies in the order that they are discussed. The first seven agencies provide publicly available forecasts while forecasts issued by the latter five agencies are not publicly available.

2.1 Publicly-available forecasts

Colorado State University (CSU)

CSU has been issuing North Atlantic basin seasonal hurricane forecasts since 1984. Forecasts are currently issued in early April, with updates then provided in early June, July and August. These forecasts use a blend of statistical modeling based on historical atmosphere/ocean data such as the Climate Forecast System Reanalysis (CFSR) (Saha et al. 2010), the European Center for Medium Range Weather Forecasts Interim Reanalysis (ERA-Interim) (Dee et al. 2011), and the National Oceanic and Atmospheric Administration (NOAA) optimum interpolation (OI) sea surface temperature (SST) (Banzon et al. 2016). In addition, CSU incorporates an analog year selection process whereby observed and projected climate indices are compared with prior hurricane seasons. Lastly, CSU examines dynamical model predictions of El Niño-Southern Oscillation (ENSO) and North Atlantic SST and sea level pressure (SLP) patterns and qualitatively adjusts its predictions based on these outlooks. CSU is currently developing a statistical/dynamical model based on output from the ECMWF SEAS5 that will be used in real-time in 2019.

Most of CSU's predictors relate closely to ENSO and North Atlantic SSTs, with more active Atlantic hurricane seasons associated with warmer-than-normal waters in the tropical Atlantic and cooler-than-normal waters in the central and eastern tropical Pacific. This combination of SST anomaly patterns also tends to reduce (increase) vertical wind shear in the Atlantic. Too much vertical wind shear is known to be detrimental for hurricane formation and intensification (e.g., Klotzbach et al. 2017 and references therein).

CSU's forecasts have been issued in real-time since 1984 and have shown skill since their inception (Klotzbach and Gray 2009) when compared to climatology or the previous 5-year and 10-year means. CSU's real-time forecasts have also shown competitive skill to those demonstrated by Tropical Storm Risk (TSR) and NOAA in recent years (Figure 1) (Klotzbach et al. 2017). Seasonal forecasts issued in real time by all three agencies from 2003-2018 have shown low levels of skill in early April (r~0-0.2), modest skill in early June (r~0.2-0.4), and moderate to high levels of skill in early August (r~0.5-0.8). Figure 2 displays early August seasonal forecasts for the number of named storms issued in real time by CSU compared with observations.

TABLE 1. Forecast agencies, TC basins predicted, metrics forecast, techniques used, and websites where the forecasts are published.

Forecast Agency	TC Basins Predicted	Metrics Forecast	Techniques Used	Forecast Website
Colorado State University	North Atlantic	Basinwide activity; Continental US and Caribbean landfall probability	Statistical, Statistical-Dynamical	http://tropical.colostate.edu
National Oceanic and Atmospheric Administration	North Atlantic, Eastern North Pacific	Basinwide activity	Statistical, Statistical-Dynamical, Dynamical	https://www.cpc.ncep.noaa.gov/products/outlooks/hurricane.shtml
Tropical Storm Risk	North Atlantic, Western North Pacific	Basinwide activity; Continental US landfalling activity; Caribbean Lesser Antilles landfalling activity	Statistical	https://tropicalstormrisk.com
UK Met Office	North Atlantic, Eastern North Pacific, Western North Pacific, South Indian, Australia, South Pacific	Basinwide activity Global map for increased/decreased risk of tropical cyclone tracks	Dynamical	https://www.metoffice.gov.uk/weather/tropicalcyclone/
Australian Bureau of Meteorology/ University of Melbourne	Australia, South Pacific	Australian region and sub-region activity; South Pacific Region and sub-region activity	Statistical	Australia: http://www.bom.gov.au/climate/cyclones/australia/archive.shtml South Pacific: http://www.bom.gov.au/climate/cyclones/south-pacific/archive.shtml
City University of Hong Kong	Western North Pacific	Basinwide activity; Landfall numbers for 3 sections of East Asian coast	Dynamical	http://weather.cityu.edu.hk/tc_forecast/forecast.htm
Hong Kong Observatory	Western North Pacific	Annual number of tropical cyclones within 500 km of Hong Kong	Statistical, Statistical-Dynamical, Dynamical	https://www.hko.gov.hk/wxinfo/season/anlf.htm
European Centre for Medium-Range Weather Forecasts	North Atlantic, Eastern North Pacific, Western North Pacific, South Indian, Australia, South Pacific	Basinwide activity Global map of increased/decreased risk of tropical storm strike probability	Dynamical	https://www.ecmwf.int/en/forecasts/charts Only available to member countries and commercial users.
Geophysical Fluid Dynamics Laboratory	North Atlantic, Eastern North Pacific, Western North Pacific	Basinwide major hurricane activity; Continental US landfalling activity; East Asian landfalling activity	Statistical-Dynamical, Dynamical	Only available internally to forecasters at NOAA
Japan Meteorological Agency	Western North Pacific	Basinwide activity and sub-region activity	Dynamical	Only available internally to forecasters at the Japan Meteorological Agency
Shanghai Typhoon Institute of China Meteorological Administration	Western North Pacific	Basinwide activity; Number of TCs making landfall in China and affecting subregions	Statistical, Statistical-Dynamical, Dynamical	Only available internally to forecasters at the China Meteorological Administration
National Typhoon Center/Korea Meteorological Administration	Western North Pacific	Basinwide activity (number, intensity, track); Annual number of tropical cyclones affecting the Korean peninsula	Statistical, Statistical-Dynamical, Dynamical	Only available to the fourteen member countries under the ESCAP/WMO Typhoon Committee's perennial operating plan. Only available internally to the forecasters at the Korea Meteorological Administration

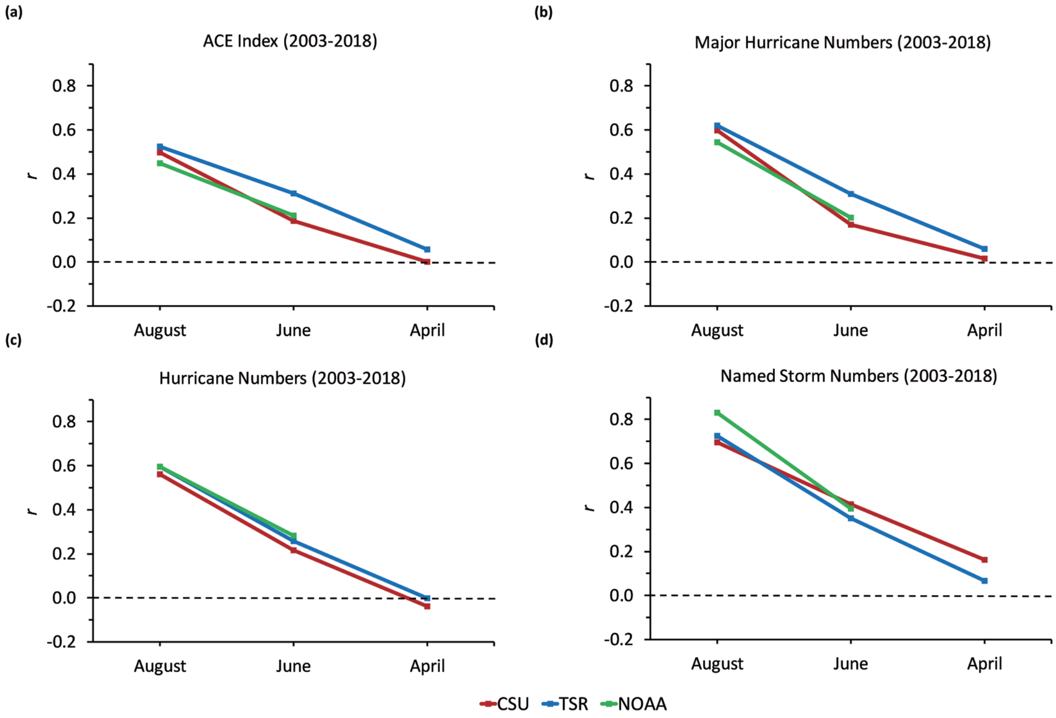

FIG. 1. Real-time skill of North Atlantic seasonal tropical cyclone outlooks assessed for the 16-year period 2003-2018. The skill of the seasonal outlooks issued by CSU (red lines), Tropical Storm Risk (TSR, blue lines) and the National Oceanic and Atmospheric Administration (NOAA, green lines) are compared for (a) ACE, (b) major hurricane numbers, (c) hurricane numbers and (d) named storm numbers. The skill is shown as the Pearson correlation (*r*) between the forecast values (issued separately in early April, early June and early August) and the observed values.

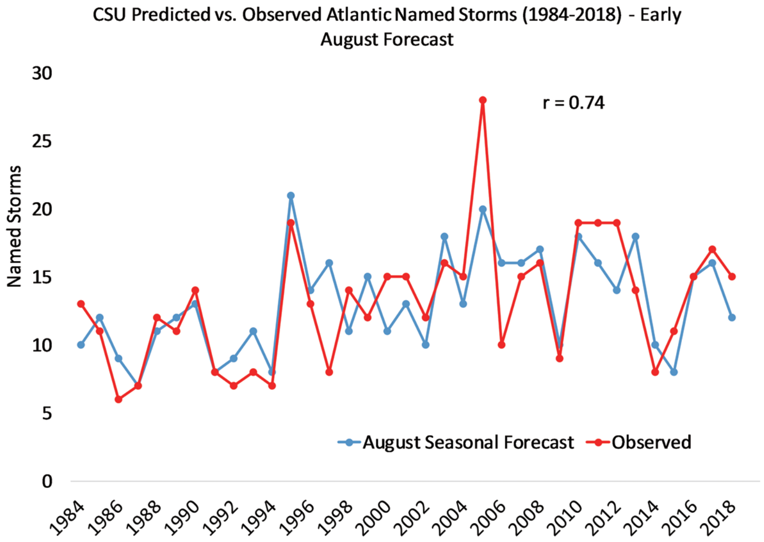

FIG. 2. Real-time named storm forecasts from CSU issued in early August compared with observations from 1984-2018. The correlation between predicted and observed North Atlantic named storms from 1984-2018 is 0.74.

National Oceanic and Atmospheric Administration (NOAA)

The NOAA seasonal hurricane forecasts for the North Atlantic and eastern North Pacific (to 140°W) basins are based on a suite of statistical prediction tools and dynamical model forecasts and have been issued since 1998. The primary statistical aids for the North Atlantic are based, in part, on research detailed in Bell and Chelliah (2006).

One of these aids is the Climate Prediction Center (CPC) statistical analog regression. A range of forecast August–October (ASO) Niño 3.4 temperatures, ASO tropical Atlantic SSTs, and the forecast ASO tropical Atlantic difference from global tropical SSTA (usually a range of 0.5°C is used) are considered. The eastern North Pacific CPC statistical analog regression is based on a range of projected ASO Nino 3.4 and Nino 3 SSTs. These predictors are then regressed upon years with similar climate conditions to provide one statistical forecast, along with a likely range.

NOAA's North Atlantic operational seasonal forecasts have demonstrated skill in real-time over the period from 2003-2018 (Figure 1), with a correlation of 0.39 between the mid-May forecast and observed named storms, increasing to a correlation of 0.83 for named storm outlooks issued in early August. The eastern North Pacific seasonal forecasts for ACE issued in mid-May have correlated with observed ACE at 0.73 from 2005-2018, and forecasts for named storms have correlated at 0.75 from 2005-2018.

One unique aspect of the NOAA forecast is its use of the high-resolution CFS-T382 model. The model is run for 2-3 weeks prior to the May and August forecasts, and these forecasts are collected as an ensemble of large-scale predictions, including shear and SST, along with a count of TCs and overall activity. Finally, the GFDL-FLOR (Vecchi et al. 2014) and HiFLOR (Murakami et al. 2015, 2016a) forecasts, plus the ECMWF, NMME, and UKMET seasonal forecast models are also used for both ASO climate conditions and total storm and activity counts in making the seasonal hurricane forecast. After all of these forecast aids are compiled, subjective adjustments are made, and the forecast is a consensus of 6 forecasters throughout NOAA offices in the Climate Prediction Center, National Hurricane Center and the Hurricane Research Division. The Atlantic seasonal forecasts are issued in mid-May and updated in early August. The eastern North Pacific seasonal forecast is issued in mid-May.

The Climate Prediction Center and the Central Pacific Hurricane Center jointly issue a seasonal hurricane forecast for the central North Pacific basin (defined to extend from 140°W to the International Date Line). The outlooks are based on climate analogs using the Niño 3 and Niño 3.4 region predicted SST anomalies for the July-September and August-October periods. They also reflect the expected seasonal activity in the eastern North Pacific (to 140°W) hurricane region.

Tropical Storm Risk (TSR)

TSR, based at University College London in the UK, has issued public outlooks for seasonal TC activity in the North Atlantic and WNP basins since 2000. TSR forecasts basin-wide TC activity (comprising numbers of storms of different strengths and the Accumulated Cyclone Energy (ACE) index (Bell et al. 2000)) and U.S. landfalling TC activity. The TSR forecast models are statistical in nature and are underpinned by predictors that have sound physical links to contemporaneous TC activity. Outlooks are issued in deterministic and tercile probabilistic form. For the North Atlantic, TSR issues seasonal forecasts in early December, early April, late May, early July and early August. For the WNP, TSR issues seasonal outlooks in early May, early July and early August. All historical TSR seasonal TC forecasts are available online at www.tropicalstormrisk.com/forecasts.html thereby allowing assessments to be made of the TSR real-time forecast skill for the period 2000-2018. TSR's real-time forecast skill was shown to slightly exceed those of CSU and NOAA for ACE based on data from 2003-2014 (Klotzbach et al. 2017).

The TSR seasonal model for North Atlantic TCs is sophisticated for a statistical model. The model divides the North Atlantic basin into three regions: (1) the tropical North Atlantic; (2) the Caribbean Sea and Gulf of Mexico; and (3) the 'rest' region which comprises the North Atlantic area outside regions (1) and (2). TSR employs separate outlook models for each of the three regions before summing the regional hurricane outlooks to obtain an overall North Atlantic hurricane outlook. The two main predictors used by TSR in making its seasonal outlooks are: (1) The forecast speed of the trade winds for July-August-September for the region 7.5-17.5°N, 100-30°W. The trade winds blow westward across the tropical Atlantic and Caribbean Sea and influence cyclonic vorticity and vertical wind shear over the main hurricane track region; (2) The forecast SST for August-September for the region 10-20°N, 60-20°W between West Africa and the Caribbean where many hurricanes develop during August and September. Waters here provide heat and moisture to help power the development of storms within the hurricane main development region. The nature of the TSR model is shown in Figure 3 and is

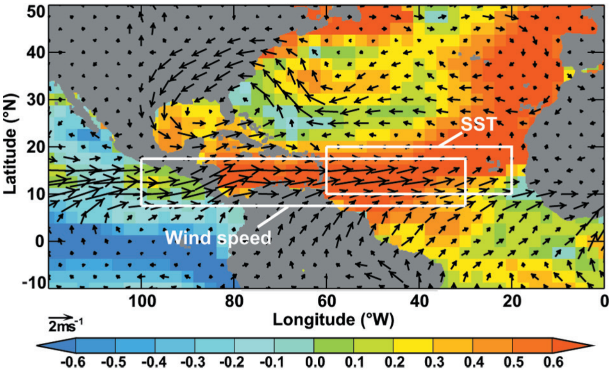

FIG. 3. Nature of the TSR statistical model for replicating North Atlantic seasonal hurricane activity. The figure displays the two August-September environmental field areas that the TSR model employs most often in producing a seasonal hurricane outlook. The figure also displays the anomalies in August-September SST (color coded in °C) and 925 hPa wind (arrowed) linked to active Atlantic hurricane years. Figure taken from Saunders and Lea (2008).

described further in Lea and Saunders (2004, 2006), Saunders (2006) and Saunders and Lea (2008). The basis for the trade wind speed being the environmental field that best replicates long-term hurricane activity is given in Saunders et al. (2017).

The skill of the TSR publicly-released seasonal outlooks for North Atlantic hurricane activity is shown in Figure 1 assessed for the 16-year period 2003-2018. The TSR real-time skill (like that of CSU and NOAA) is low from early April but increases to moderate-to-good skill by early August (prior to the most active part of the hurricane season). Overall TSR has the most skillful prediction of ACE, while NOAA has the best named storm predictions in early August. Assessment of the TSR replicated real-time skill for the 29-year period 1980-2018 shows similar but slightly higher correlation skills compared to Figure 1. The 29-year correlation skills for ACE are 0.36, 0.61 and 0.72 for early April, early June and early August forecasts respectively.

TSR outlooks for US landfalling TC activity issued between December and July employ a historical thinning factor between 'tropical' North Atlantic activity and US landfalling activity. The TSR outlook for US landfalling activity issued in early August employs the persistence of July steering winds (Saunders and Lea, 2005). These winds either favor or hinder evolving hurricanes from reaching US shores during August and September. The replicated real-time correlation skill for predicting the US ACE Index from early August assessed for the 39-year period 1980-2018 is $r = 0.53$.

TSR outlooks for WNP TC activity are made as follows. Predictions of intense typhoon numbers and the ACE index are made using the forecast value for the August-September Niño 3.75 region (5°S-5°N, 140°W-180°W) SST and the current year-to-date ACE index (July and August outlooks). Typhoon numbers and tropical storm numbers are forecasted using the Niño 3 region SST from the prior September and the forecast number of intense typhoons. Above average (below average) Niño 3.75 SSTs are associated with weaker (stronger) trade winds over the region 2.5°-12.5°N, 120°E-180°E. These in turn lead to enhanced (reduced) cyclonic vorticity over the WNP region where intense typhoons form. Figure 4 shows the skill of the TSR publicly-released seasonal outlooks for WNP ACE and intense typhoon numbers assessed for the 16-year period 2003-2018 (the same period as in Figure 1). This shows low prediction skill from early May but good prediction skill ($r = 0.65$ to 0.75) by early July. The correlation skill for typhoon numbers (not shown) is lower, reaching 0.35 by early August.

UK Met Office

The UK Met Office has been issuing seasonal TC forecasts for the North Atlantic annually to the public since 2007 (Camp et al. 2015). These forecasts are made available through the Met Office website https://www.metoffice.gov.uk/weather/tropicalcyclone. The forecasts are produced using output from the Met Office Global Seasonal forecast system GloSea5 (MacLachlan et al 2015, Williams et al 2015), which is a fully coupled ocean-atmosphere-land ensemble prediction system with ~60 km horizontal resolution in the atmosphere and 0.25° in the ocean. Forecast products include numbers of named storms, ACE (since 2009) and numbers of hurricanes (since 2013). Verification of real-time TC frequency forecasts issued by the Met Office between 2007 and 2018 is shown in Figure 5. Over the 12 years of forecasts, 10 have verified well with observed values falling within the range predicted. More recently, GloSea5 provided useful guidance on the extremely active 2017 North Atlantic hurricane season, in particular predicting the enhanced frequency of observed TC tracks across the northeast Caribbean at more than 3 months lead time (Camp et al. 2018).

In 2015, the Met Office expanded its seasonal TC forecasts to include all ocean basins around the world (Camp et al. 2015). These are made available to forecasters internally at the Met Office, as well as to the National Hurricane Center. Forecasts include the number of TCs, the number of hurricanes and ACE, as well as spatial track frequency anomalies, for the forthcoming 6-month period. Figure 5

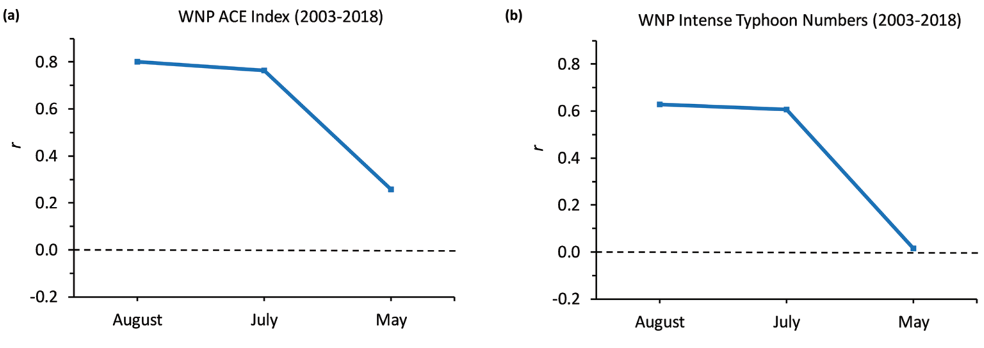

Fig. 4. Real-time skill of the TSR seasonal outlooks for western North Pacific (WNP) (a) ACE and (b) intense typhoon numbers assessed for the 16-year period 2003-2018. Skill is shown as the Pearson correlation (r) between the forecast values (issued separately in early May, early July and early August) and the observed values.

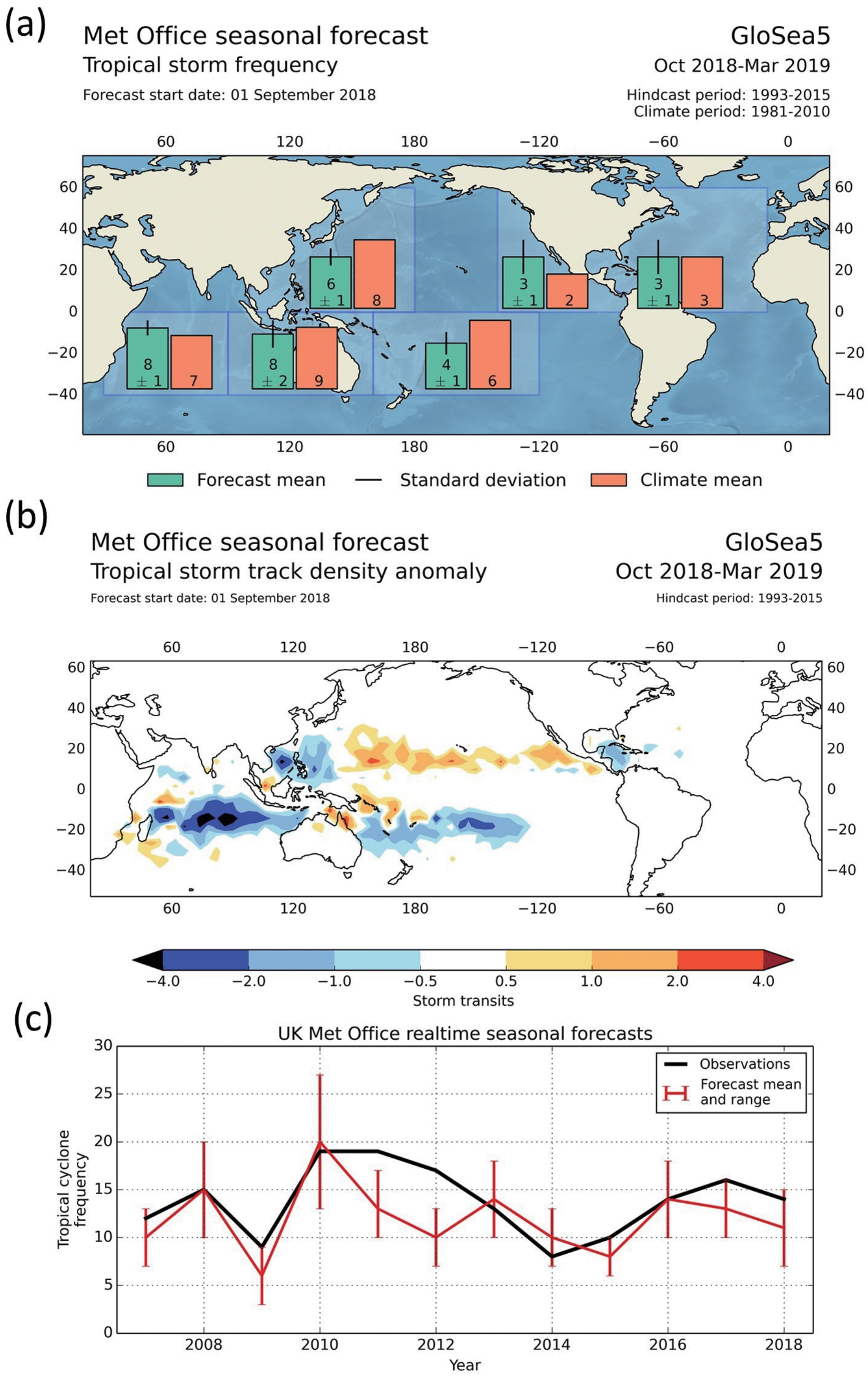

FIG. 5. Example (a) TC frequency forecasts for the North Atlantic, eastern North Pacific, western North Pacific, southwest Indian ocean, Australian region and South Pacific (forecast ensemble mean and 70% range in green; 1981-2010 climatology in orange), and (b) spatial track frequency anomalies relative to model climatology (1993-2015). Forecasts issued on 1 September 2018 for the period October 2018-March 2019. (c) Realtime North Atlantic seasonal TC frequency forecasts (ensemble mean and forecast range in red) and corresponding observations (black line) issued by the UK Met Office for the period July-November 2007 to 2010 and June-November 2011 to 2018.

shows example global forecasts of TC numbers and spatial track frequency anomalies issued in September 2018 for the period October 2018-March 2019. These forecasts are updated on a monthly or weekly basis as required.

Realtime verification is provided alongside each forecast. Overall, GloSea5 shows significant skill for predictions of ACE over the hindcast period June-November 1993-2015, with correlations exceeding 0.8 in the eastern North Pacific and 0.7 in the North Atlantic. Hindcast skill of TC numbers also exceeds 0.6 in the North Atlantic. Recent research has shown that GloSea5 exhibits significant skill for predictions of TC landfall in the Caribbean (Camp and Caron 2017) as well as the WNP for the period June-August when using the WNP subtropical high (WPSH) as a predictor (Camp et al 2019). Following this research, trial seasonal forecasts of TC landfall risk for East Asia are now being developed for the 2019 typhoon season. The Met Office are also expanding its range of seasonal TC forecast products, with major hurricane frequency forecasts and spatial ACE index anomalies being released ahead of the 2019 Atlantic hurricane season.

Australian Bureau of Meteorology/The University of Melbourne

TC season outlooks are issued operationally by the Australian Bureau of Meteorology (BoM) for November to the end of April (Southern Hemisphere TC season) for the Australian Region (AR) since 2009 (http://www.bom.gov.au/climate/cyclones/australia/archive.shtml) and for the South Pacific Ocean (SPO) since 2010 (http://www.bom.gov.au/climate/cyclones/south-pacific/archive.shtml).

The statistical seasonal TC forecast model used by the BoM described in Kuleshov et al. (2009) applies linear discriminant analysis (LDA) to identify the historical relationship between observed numbers of TCs and indices (predictors) describing the state of ENSO. The ENSO predictors employed in the Bureau's statistical prediction model are the Southern Oscillation Index (SOI) and equatorial SST anomalies in the Niño 3.4 region (N34). The LDA technique is applied in the Bureau model to identify the relationship between the JAS mean of an ENSO predictor (either SOI or N34) and the observed number of TCs in a TC season in a region/sub-region over a training period. The resulting statistical relationship is then applied to a predictor value for a JAS period subsequent to the training period to yield predictions for the probability that the number of TCs in the forthcoming season is greater than the median over the training period and for the number of TCs in that season. The skill of the predictions was evaluated over a 30-year hindcast period using a leave-one-out cross validation approach. TC predictions show some skill for the western Australian sub-region (5°-40°S, 90°-125°E) and the Australian region as a whole (5°-40°S, 90°-160°E), however the value over climatology can be small.

The use of support vector regression (SVR) models, exploring new explanatory variables and the non-linear relationships between them, the use of model averaging, and lastly the integration of forecast intervals based on a bias-corrected and accelerated non-parametric bootstrap have been investigated, aiming to improve skills of operational TC seasonal forecasts issued by the BoM for the Australian region and the South Pacific Ocean, as well as sub-regions therein (Wijnands et al 2015). Hindcasting analyses showed that the SVR model outperforms several benchmark methods. Analysis of the generated models shows that the Dipole Mode Index, the 5VAR index (an index that combines the mean sea level pressure from Tahiti and Darwin as well as the Niño 3, Niño 3.4, and Niño 4 indices) and the Southern Oscillation Index are the most frequently selected as explanatory variables for TC seasonal forecasting in all regions. For both the AR and the SPO, normalized root mean squared error (nRMSE) statistics for the hindcast analyses for 2003/2004 to 2013/2014 indicates that SVR has better skill than LDA: in the AR, nRMSE was 0.93 and 1.25 for SVR and LDA, respectively; in the SPO, nRMSE was 0.83 and 0.94 for SVR and LDA, respectively (Wijnands et al 2015). Overall, the new SVR methodology is an improvement over the current linear discriminant analysis models and has the potential to increase the accuracy of seasonal TC forecasts in the AR and the SPO.

City University of Hong Kong

Since 2000, the Guy Carpenter Asia-Pacific Climate Impact Centre (GCACIC) of the City University of Hong Kong has been issuing a seasonal forecast for TC activity for the WNP. For the period 2000-2011, the forecast was for annual WNP TC activity based on a statistical model developed by Chan et al. (1998) and later modified (Chan et al. 2001). However, because of the decreasing trend in WNP TC activity since 1997, the statistical model generally over-predicted such activity. Therefore, the statistical forecast was stopped in 2011.

Huang and Chan (2014) then developed a dynamical seasonal TC activity forecast model based on Regional Climate Model Version 3 (RegCM3). In addition to the TC activity for the entire WNP, the model also produces forecasts of the number of landfalling TCs in East Asia. Three regions are defined: South (southern China, Vietnam and Philippines), Middle (eastern China) and North (Korean Peninsula and Japan). Because the model uses as both initial and lateral boundary conditions the US Climate Forecast System (CFS) global model forecasts, which runs only seven months from the initial time, the forecasts can only be issued for six months (with the initial month used as spin up). This approach was evaluated using CFS hindcasts as boundary conditions for eleven years (2000-2010). The results show that the best forecast performance is for the South region, with a correlation between the forecast and observed of 0.70, which is significant at the 95% confidence level. The total number of landfalling TCs also has a correlation of 0.58 with the observed value, again significant at the 95% confidence level. Furthermore, compared with the hindcast from CFS, the RegCM3 has a higher skill, ranging from 6% to 48%.

Using this setup, the GCACIC has been issuing six-month forecasts for the months of May to October (based on the 1 April run of CFS) for:

· WNP TC activity

· Number of landfalling TCs in each of the three regions

No formal verification of these predictions has been conducted as of yet, but a quantitative evaluation of the forecasts is forthcoming.

Lok and Chan (2017) extended the Huang and Chan (2014) study to predict the annual power dissipation index (APDI) for South China. For every TC that the RegCM3 predicts to make landfall in south China, the position of this TC at three days before landfall was used as the center of the grid of a nested version of the Weather Research and Forecasting (WRF) model. The WRF model uses the forecasts from the RegCM3 as initial and lateral boundary conditions to predict the landfall intensity of the TC, from which the PDI can be calculated. For every season, values of the PDI of all TCs that are predicted to make landfall in south China are then summed to obtain the APDI. This metric gives the expected "damage" to a particular region in a given year. Hindcasts show that this setup is able to predict APDI quite well, especially if there are not too many weak or very intense TCs. No operational forecast of the APDI has been issued yet.

Hong Kong Observatory

The Hong Kong Observatory started issuing experimental seasonal forecasts of TC activity affecting Hong Kong, i.e. TCs necessitating issuance of local signals, in the early 2000s. The annual number of TCs within 500 km of Hong Kong was later adopted as the predictand because it was a more objective criteria and had the same long-term mean as the annual number of TCs affecting Hong Kong. The forecast is given in terms of a range, e.g. 4-7. Among other things, the annual forecast is publicized every March at a press conference and is available on the Observatory's website (https://www.hko.gov.hk/wxinfo/season/anlf.htm).

The initial forecast methodology was primarily based on the statistical analysis of ENSO's impacts on the frequency of TCs tracking within 500 km of Hong Kong. Over the years, the methodology has evolved, and the performance has gradually improved. A statistical-dynamical approach has been developed, using principal components extracted from dynamical climate model output as predictors. Currently, model data from NCEP's Climate Forecast System and the Japan Meteorological Agency's climate model are used. Simple Poisson regression models using predicted SSTs over the Niño 3.4 region and large-scale 500-hPa zonal wind over the South China Sea and the WNP as predictors are also considered. In recent years, tropical storm density anomaly maps published by the ECMWF are used to qualitatively assess anomalous TC activity in the northern part of the South China Sea. All of the aforementioned information are considered when formulating the annual forecast of TC activity. One can see that some expert judgment is required to consolidate the different types of information into an operational forecast which is a range of numbers, e.g. 4-7.

In verification, a forecast is considered correct if the observed number of TCs within 500 km of Hong Kong falls in the forecast range. In the past ten years (2009-2018), 60 percent of the forecasts issued to the public were verified to be correct. It is noted that the statistical-dynamical approach seems promising. The real-time forecasts generated by this approach since 2010 were verified using "mean absolute error" as the metric and taking climatology as the reference forecast. The verification result showed that the statistical-dynamical approach achieved more than 20 percent error reduction against climatology during the past nine years (2010-2018), and the anomaly correlation coefficient was ~0.68, though the sample may be too small to be conclusive. In the next step to improve forecasting skill, machine learning techniques will be explored.

2.2 Non-publicly available forecasts

European Centre for Medium-Range Weather Forecasts (ECMWF)

ECMWF seasonal forecasts of TCs have been issued monthly since 2001 (Vitart and Stockdale, 2001). At the seasonal range, the TC products include the number of tropical storms (maximum wind speed exceeding 17 m s^{-1}), number of hurricanes, and ACE over several TC basins (the North Atlantic, the eastern North Pacific, the WNP, the South Indian Ocean, the Australian basin and the South Pacific), tropical storm density anomaly and standardized tropical storm density for a six-month period. The TCs are detected using the tracker as described in Vitart et al. (1997), and the statistics of detected TCs are calibrated using the seasonal re-forecasts.

Figure 6 shows the climatology of tropical storm track density over the period 1990-2014 in observations (from the International Best Track Archive for Climate Stewardship (IBTrACS)) System 4 and SEAS5. According to Figure 6, SEAS5 displays a much more realistic tropical storm climatology than System 4. System 4 severely underestimated the number of tropical storms. SEAS5 still underestimates tropical storm activity, but the number of detected tropical storms is significantly higher than in System 4. The higher horizontal resolution of SEAS5 is likely to be a main reason for this improvement in the tropical storm climatology.

The improvement in tropical storm climatology does not necessarily translate into more skillful forecasts of TC inter-annual variability. SEAS5 re-forecasts display significant skill in predicting the interannual variability of TC

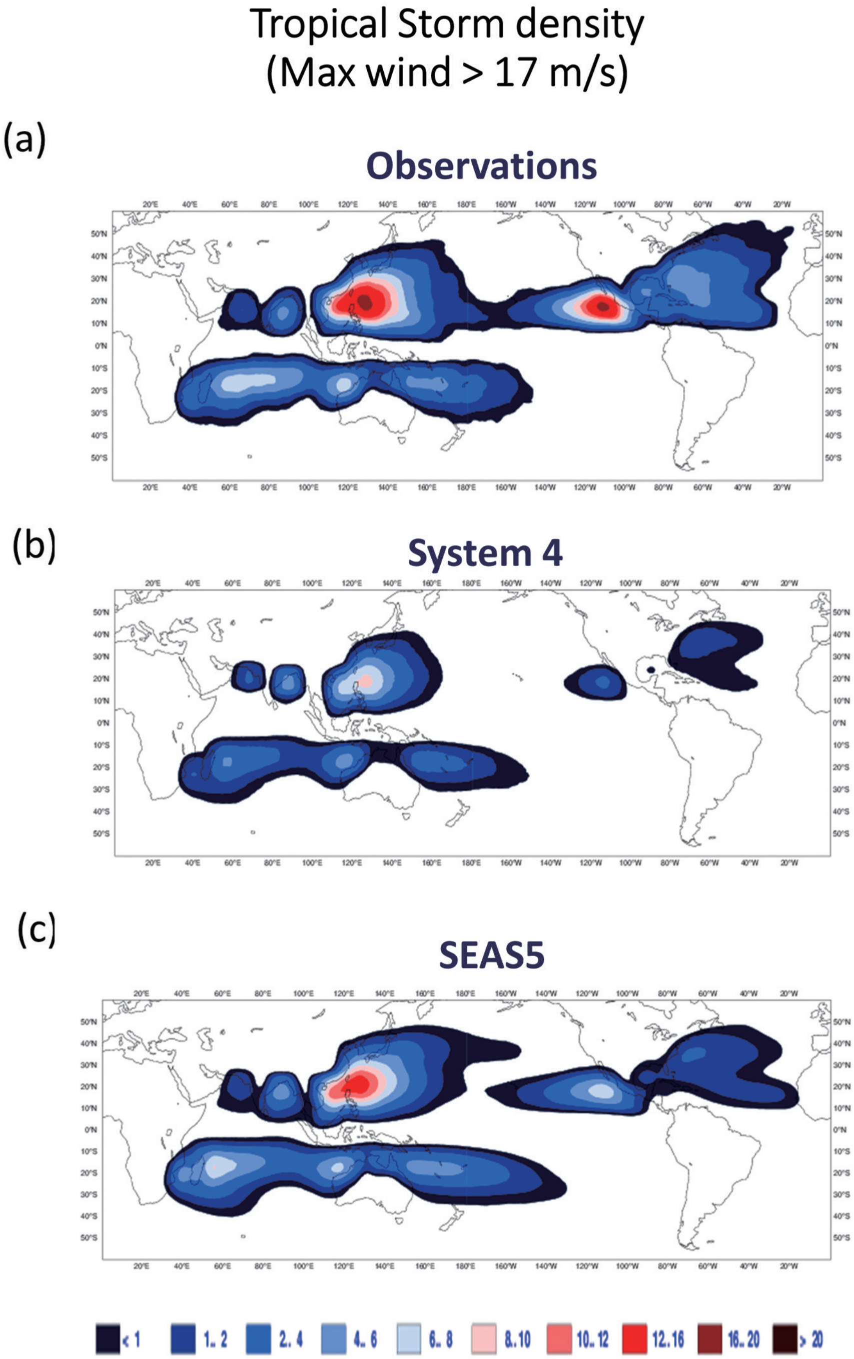

Fig. 6. Tropical storm track density over the period 1990-2014. This figure shows the annual number of TCs passing within 500km in (a) observations, (b) in System 4 and in (c) SEAS5.

ACE over the North Atlantic (r=0.65 from 1990-2014, for July start dates), eastern North Pacific (r=0.42 for May and r=0.51 for June start dates), WNP (r=0.78 for June start dates) and South Pacific (r=0.60 for October start dates and r=0.40 for December start dates) (see Table 2 in Stockdale et al. 2018 for a more detailed assessment of SEAS5 reforecast skill). SEAS5 displays generally lower skill than System 4 over the Atlantic (r = 0.72 from 1990-2014) and eastern North Pacific but higher skill over the WNP (particularly from April to June) and over the South Pacific.

Geophysical Fluid Dynamics Laboratory (GFDL)

GFDL has been conducting retrospective and real-time dynamical seasonal forecasts for every month since 2014 using the Forecast-Oriented Low Ocean Resolution version of CM2.5 (FLOR; ~50 km-mesh horizontal resolution in the atmosphere and 1° in the ocean; Vecchi et al. 2014) and the high-resolution version of FLOR (HiFLOR; ~25 km horizontal resolution in the atmosphere; Murakami et al. 2015) for both research purposes and as a contribution to the North American Multi-Model Ensemble (NMME; Kirtman et al. 2014). HiFLOR shows skillful prediction for frequency of major hurricanes in the North Atlantic a few months in advance (r=0.74; Figure 7a) and landfalling storms in the United States (r=0.53; Figure 7b) in the retrospective seasonal forecast (1980–2016; Murakami et al. 2016a). Real-time predictions by the dynamical models are shared with experts at the National Hurricane Center and the Climate Prediction Center to assist with the NOAA seasonal hurricane outlook.

GFDL has also been developing new statistical-dynamical models to improve prediction skill relative to the dynamical seasonal forecasts by FLOR. Murakami et al. (2016b) and Zhang et al. (2016, 2017) constructed new statistical-dynamical models for landfalling storms over the United States and East Asia, respectively, showing higher skill in predictions of landfalling storms than FLOR does. Specifically, Murakami et al. (2016b) showed that a new statistical-dynamical model retains forecast skill up to lead month 5 with a correlation coefficient of 0.5 and a forecast error of 2.0 for landfalling storms for the United States. Zhang et al. (2017) reported a correlation coefficient between predicted and observed TC landfall over southern East Asia of 0.52 (0.64) for forecasts initialized in January (June).

Japan Meteorological Agency (JMA)

The Japan Meteorological Agency (JMA) started developing seasonal TC prediction products with atmosphere-ocean coupled models more than ten years ago, and prototype products are used for internal demonstration and evaluation. An objective detection and tracking algorithm used for this application is based on a technique described in Takaya et al. (2010). Currently, there are several internal products including TC genesis number, accumulated TC probability, ACE, and mean latitude and longitude of TC genesis in the WNP. There are also map products of TC genesis number, accumulated TC probability and ACE. These predictions have been verified using hindcasts and best track analyses in the WNP as well as other basins such as the North Atlantic and the South Pacific. The predictive skill of the latest system has turned out to be comparable with published results of other seasonal prediction systems. For example, the correlation between predicted and observed ACE in the North Atlantic and WNP based on a 10-member ensemble hindcast run during 1996-2009 were 0.65 and 0.74, respectively. These results are similar to correlations of 0.56 for the North Atlantic and 0.81 for the WNP reported in Camp et al. (2015) based on a 25-30-member ensemble hindcast run of GloSea5 during 1996-2009.

Dynamical probabilistic predictions, which are produced by detecting TCs using objective methods are often overconfident. To calibrate the probabilistic prediction, the JMA also developed a calibration technique based on Bayesian statistics using a set of hindcasts. It was found that the calibrated results give better probabilistic predictive skill for seasonal TC prediction.

The underlying mechanisms of the seasonal predictabil-

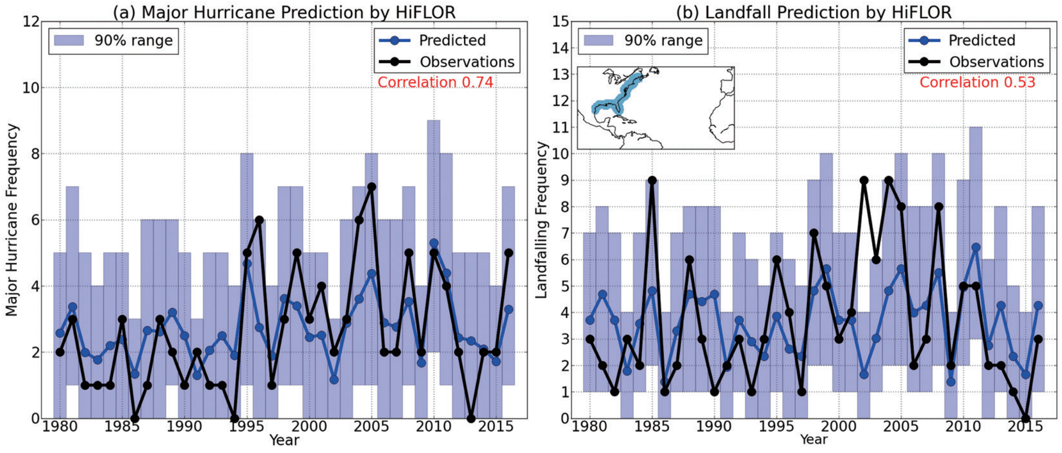

FIG. 7. (a) Frequency of basinwide major hurricanes in the North Atlantic during July–November 1980–2016 for the retrospective forecasts initialized in July using HiFLOR. The black line refers to the observed quantities, the blue line refers to the mean forecast value, and the blue shading indicates the 90% confidence intervals for the 12-member ensemble forecasts. The value of the correlation between the black and blue lines is shown in the red number. (b) As in (a), but for landfalling TC frequency for the United States. Adapted from Murakami et al. (2016a).

ity of TC location and genesis potential in the WNP were discussed by Takaya et al. (2010) and Takaya et al. (2017). Tropical Pacific and Indian Oceans (Indian Ocean Capacitor effect) control seasonal TC activity by modulating the WNP monsoon (monsoon trough), providing seasonal predictability for TC activity.

Shanghai Typhoon Institute (STI) of China Meteorological Administration

STI began making operational forecasts of seasonal TC activity over the WNP in the middle 1990s, based on a statistical technique and an analog-year analysis. These initial forecasts were paused in 2000 and were then restarted in 2005 (Zhan et al. 2012). The current forecasts include the numbers of tropical storms forming in the WNP and making landfall in China, the numbers of TCs (including tropical depressions) affecting the whole of China, East China, South China, and Shanghai City, as well as the number of intense TCs, ACE, and TC track density over the WNP. The forecasts are currently issued in late March of each year, with updates in late June, late July and late August.

At present, operational seasonal TC forecasts issued by STI are mainly based on statistical, dynamical and hybrid statistical-dynamical techniques, as well as climate-based analogs. The final forecast is a combination of these approaches. The statistical schemes were built using mean generation functions (MGF), stepwise regression (SWR), and optimal subset regression (OSR). The predictors in the latest two regression models include sea level pressure (SLP), SST, vertical shear of zonal wind, 500-hPa geopotential height and convective activity, all of which are believed to be closely related to seasonal TC activity over the WNP (Ying and Wan 2011). The STI dynamical forecast is based on a regional atmospheric model (iRAM) developed at the International Pacific Research Center (IPRC) at the University of Hawaii (Zhan et al. 2011a; Wu et al. 2012), in which initial and lateral boundary conditions are obtained from the seasonal prediction of the National Centers for Environmental Prediction (NCEP) Climate Forecast System Version 2 (CFSv2). The hybrid statistical-dynamical forecasts (STI-HSD) of TC activity over the WNP are made in a three-step procedure (Zhan and Wang 2016). First, the predictors are obtained from various ensemble members of the NCEP CFSv2 seasonal forecasts. Second, a statistical regression model is used for predictions. Third, ensemble forecasts are produced. Most of STI-HSD's predictors are closely related to SST anomalies in the Nino3.4 region and the East Indian Ocean (EIO) (Zhan et al. 2011a, b), the SST gradient between the Southwest Pacific (SWP) and the western Pacific warm pool (SSTG) (Zhan et al. 2013), and vertical wind shear over the equatorial western Pacific (Zhan and Wang 2016).

All forecasts issued by STI show positive skill relative to climatological persistence. Using the CFSv2 retrospective forecasts from different initial forecast months for the period 1982–2010, significant skill is found in predicting seasonal TC numbers and ACE starting from January (Figure 8). The correlation coefficients between the STI-HSD predicted TC numbers and the observed with initial months from January to May range from 0.62 to 0.80, and those between the STI-HSD predicted ACE and the observed range from 0.58 to 0.81. The prediction experiments for 2011–2015 using the hybrid dynamical-statistical model showed better skill and longer lead times than those using pure statistical models.

National Typhoon Center/Korea Meteorological Administration

Seasonal WNP TC activity is monitored and forecast by the National Typhoon Center (NTC) at the Korea Meteorological Administration (KMA). The targeted period for the seasonal forecasts is divided into June-July-August

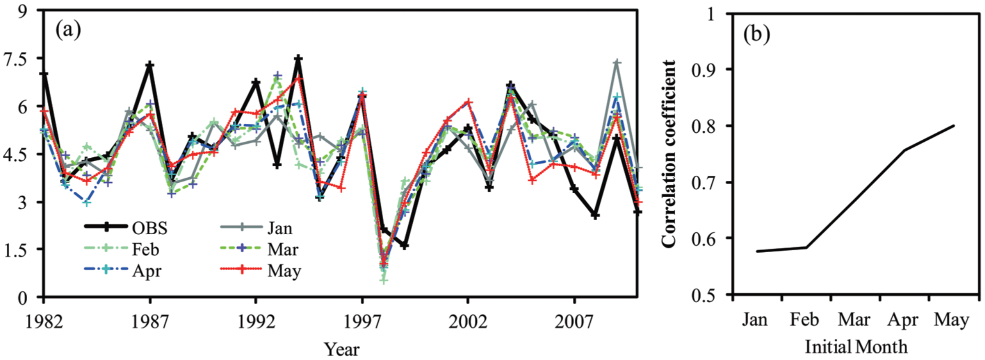

Fig. 8. (a) Time series of the observed and hindcast ACE over the WNP in the typhoon season based on the CFSv2-predicted ENSO and SWP SST predictor model with initial months from January to March, on the CFSv2-predicted Ushear and SSTG predictor model with April initial conditions, and on the CFSv2-predicted Ushear with May initial conditions and observed April SSTG, and (b) correlation coefficients of the corresponding seasonal ACE between observations and CFSv2 forecasts for each initial condition listed in (a). Adapted from Zhan and Wang (2016).

(JJA) and September-October-November (SON). The NTC produces seasonal forecasts of TC frequency in late May for JJA, and in late August for SON. The forecast output is issued to the public, and some of the products are shared with fourteen countries under the ESCAP/WMO Typhoon Committee's perennial operating plan.

The forecast is subjectively arranged based on a combination of statistical and numerical prediction sources. Among other techniques, a statistical-dynamical model has been developed based on previous studies on the environmental connections with WNP TCs (Kang and Elsner 2015, 2016; Yang et al. 2018). Multiple linear regression of the forecast TC frequency using environmental factors as explanatory variables is used to find the range of the forecast uncertainty. Here, the GloSea5 model is utilized for the ensemble predictions of the seasonal environment, and then each set of predicted environments is interpreted into the climatological TC activity. The probability distribution of the forecast includes the uncertainty of the numerical predictions and their statistical TC outputs as well. The seasonal forecast is assigned to a category of either 'Below Normal', 'Normal', or 'Above Normal' which is referenced with probability information.

The statistical-dynamical approach is characterized by a statistical interpretation of the environmental predictions made by GloSea5 into seasonal TC frequency. Then, the operational forecast performance of this model is verified by a correlation analysis between the observed and interpreted TC frequency. The correlation between observed and hindcast TC frequency is (r = +0.69, [0.36, 0.87] with the 95% confidence interval highlighted in brackets for JJA and is (r = +0.71, [0.40, 0.88] with the 95% confidence interval highlighted in brackets for SON over the past 20 years (1991-2010).

3. Beyond seasonal timescales

Recently developed decadal climate prediction systems (Smith et al. 2007) attempt to fill the information gap that exists between seasonal forecasts and climate change projections. As such, decadal predictions (typically covering 2-10 years) can be considered an extension of (dynamical or hybrid) seasonal forecasts wherein climate models are initialized by introducing observation-based data and run for multiple years under the influence of contemporaneous changing external forcings (for instance, with rising greenhouse gas concentrations), as in climate projections. In this case, incorporating changes in external forcings is necessary since at this timescale the evolution of the climate is impacted by both internally generated variability and externally-forced components (Meehl et al. 2009).

At present, the skill level for these forecasts is generally considered to be relatively low, but the North Atlantic stands out as one region where decadal forecasts consistently return significant and positive skill (Meehl et al. 2014). As a consequence, a few recent studies have reported significant skill in forecasting North Atlantic hurricane activity at the multi-annual timescale. Using a direct detection technique, Smith et al. (2010) were the first to show predictability of TC frequency beyond the seasonal timescale. This positive skill was linked by Dunstone et al. (2011) to the ability of their forecast system at predicting a number of atmospheric variables over the main development region. They also identified the North Atlantic sub-polar gyre as a key region driving the skill in their model. Relying on hybrid statistical-dynamical techniques, subsequent studies have confirmed the ability of these forecast systems at predicting not only the number of basinwide hurricanes (Caron et al. 2014, Vecchi et al. 2013), but also some landfalling statistics (Caron et al. 2015, Camp and Caron 2017). In a recent comparative study, Caron et al. (2018) showed that these decadal prediction systems offer an improvement over climatological forecasts and, in some cases, over a 10-year persistence forecast.

While decadal forecasting is still considered experimental, the Grand Challenge on Near-Term Climate Prediction (GC-NTCP) aims to facilitate the development of decadal prediction towards its operational use (Kushnir et al. 2019) through, amongst other things, the production and dissemination of climate outlooks for the forthcoming years based on real-time forecasts produced by a number of institutions (Smith et al. 2013). Because of the encouraging results derived from the initial studies highlighted above and the strong interest for such a product, Atlantic hurricane statistics are a prime candidate to be added to the list of climate variables being forecasted operationally in the near future.

4. Future developments and recommendations

Seasonal forecasts are now issued for every TC basin around the globe. While these forecasts have documented skill for most basins, the focus has shifted towards applying new techniques to the seasonal prediction problem. Several groups submitting forecasts to http://www.seasonalhurricanepredictions.org are using machine learning techniques to develop seasonal forecasts. Other groups have moved beyond basinwide TC forecasts to issuing regionally-based predictions.

There remains room for improvement in seasonal prediction skill. As new historical datasets come online with longer periods of more reliable upper-level data including ensemble uncertainty back to the 1950s (e.g., ERA5, JRA-55), statistical models for TC activity can likely be improved. In addition, historical reanalysis of North Atlantic hurricane seasons continues, which should help provide an improved calibration target for observed TC activity for seasonal TC forecasts for that basin. Other groups are conducting reanalysis of historical TC activity for other TC basins as well. The combination of improved historical TC records and more reliable reanalysis records should improve statistical forecasts considerably. As dynamical models improve their skill at being able to predict large-scale oscillations such as ENSO, especially during the boreal spring when the springtime predictability barrier is evident, this should also improve skill for hybrid statistical/dynamical seasonal TC forecasts for Northern Hemisphere basins. Global and regional climate models also continue to show steady improvement in skill at being able to predict TC seasons using various dynamical approaches.

Over the next several years, we recommend that new historical reanalysis products be evaluated to improve the skill of statistical models. We also encourage seasonal forecast groups to consider using new techniques for statistical modeling including various machine learning approaches. We suggest that additional efforts be spent on improving seasonal forecast skill for seasons where ENSO-neutral conditions predominate. We also recommend using statistical, statistical-dynamical and dynamical approaches to provide additional value beyond basinwide TC forecasts by considering regionally-based and landfall predictions. Finally, we recommend that additional research be conducted on the potential for multi-annual predictions.

5. Summary and conclusions

This paper has summarized the current status of the different models used to predict seasonal tropical cyclone activity in various basins worldwide, together with the outputs and skill of these models. The number of groups issuing seasonal TC forecasts has continued to grow in recent years with models from twelve agencies based in four continents represented herein. In addition to predicting basin storm numbers several of these agencies now provide landfall and/or region-specific predictions. Some agencies have been issuing public forecasts for many years for the North Atlantic and western North Pacific basins; we have assessed the skill of these real-time seasonal outlooks for the 16-year period 2003-2018 and found good levels of skill before the start of the climatological periods of peak hurricane and typhoon activity. There also has been an expansion in effort to extend predictions beyond the seasonal timescale to the multi-annual timescale in recent years, with skill at these longer-range outlooks so far being mostly restricted to the North Atlantic. We consider that there is scope to further improve seasonal prediction skill and have made a number of suggestions for how these improvements may be realized.

Acknowledgments

An anonymous reviewer provided very thorough comments and helpful suggestions. We would like to thank Gerry Bell for compiling NOAA's eastern North Pacific seasonal hurricane forecast verification statistics. P. Klotzbach was supported by the G. Unger Vetlesen Foundation. L.-P. Caron would like to acknowledge financial support from the European Union's Horizon 2020 Research and Innovation programme (EUCP; grant agreement no. 776613) and from the Ministerio de Economía y Competitividad (MINECO) as part of the CLINSA (CGL2017-85791-R) and HIATUS (CGL2015-70353-R) projects. Y. Takaya would like to acknowledge support of JSPS KAKENHI Grant Numbers JP17K14395 and JP17K01223. N.-Y. Kang would like to acknowledge financial support from the National Typhoon Center at the Korea Meteorological Administration ("Research and Development for Numerical Weather Prediction and Earthquake Services" project). J. Camp would like to acknowledge support from the UK Public Weather Service research programme. The work of J. C. L. Chan was supported by the Research Grants Council of the Hong Kong Special Administrative Region of China Grant E-CityU101/16.

References

Banzon, V., T. M. Smith, T, M. Chin, and W. Hankins, 2016: A long-term record of blended satellite and in situ sea-surface temperature for climate monitoring, modeling and environmental studies. *Earth Syst. Sci. Data*, **8**, 165–176.

Bell, G. D., and M. Chelliah, 2006: Leading tropical modes associated with interannual and multi-decadal fluctuations in North Atlantic hurricane activity. *J. Climate*. **19**, 590-–612.

Bell, G. D., and Co-authors, 2000: Climate Assessment for 1999. *Bull. Amer. Meteor. Soc*., **81**, S1–S50.

Camargo, S.J., and A.G. Barnston, 2009: Experimental seasonal dynamical forecasts of tropical cyclone activity at IRI. *Wea. Forecasting,* **24,** 472 – 491.

Camargo, S.J., A. H. Sobel, A.G. Barnston, and P. J. Klotzbach, 2010. The influence of natural climate variability, and seasonal forecasts of tropical cyclone activity, Chapter 11, pp. 325-360, in Global Perspectives on Tropical Cyclones, from Science to Mitigation, 2nd edition, World Scientific Series on Earth System Science in Asia, vol. 4, J.C.L. Chan and J.D. Kepert, editors, ISBN 978-981-4293-47-1.

Camp, J., M. Roberts., C. MacLachlan, E. Wallace, L. Hermanson, A. Brookshaw, A. Arribas, and A. A. Scaife, 2015: Seasonal forecasting of tropical storms using the Met Office GloSea5 seasonal forecast system. *Quart. Journ. Roy. Meteor. Soc.,* **141**, 2206–2219.

Camp. J., and L.-P. Caron, 2017: Analysis of Atlantic tropical cyclone landfall forecasts in coupled GCMs on seasonal and decadal timescales. In: Collins, J. M., Walsh, K. (Eds.), Hurricanes and Climate Change. Springer International Publishing, 213–241.

Camp J., A. A. Scaife, and J. Heming, 2018. Predictability of the 2017 North Atlantic hurricane season. *Atmos Sci Lett*, **19,** e813.

Camp. J., M. J. Roberts, R. E. Comer, P. Wu, C. MacLachlan, P. E. Bett, N.Golding, R. Toumi, and J. C. L. Chan, 2019: The western Pacific subtropical high and tropical cyclone landfall: seasonal forecasts using the Met Office GloSea5 system. *Quart. Journ. Roy. Meteor. Soc.,* 145: 105–116.

Caron, L.-P., C. G. Jones, and F. J. Doblas-Reyes, 2014: Multiyear prediction skill of Atlantic hurricane activity in CMIP5 decadal hindcasts. *Cli. Dyn.*, **42**, 2675–2690.

Caron, L.-P., L. Hermanson, and F. J. Doblas-Reyes, 2015: Multiannual forecasts of Atlantic US tropical cyclone wind damage potential. *Geophys. Res. Lett.*, **42**, 2417–2425.

Caron, L.-P., L. Hermanson, A. Dobbin, J. Imbers, L. Lledó and G. A. Vecchi, 2018: How skilful are the multi-annual forecasts of Atlantic hurricane activity? *Bull. Amer. Meteor. Soc.,* **99**, 403–413.

Chan, J. C. L., J. E. Shi and C. M. Lam, 1998: Seasonal forecasting of tropical cyclone activity over the Northwest Pacific and the South China Sea. *Wea. Forecasting*, **13,** 997–1004.

Chan, J. C. L., J. E. Shi and K. S. Liu, 2001: Improvements in the seasonal forecasting of tropical cyclone activity over the Northwest Pacific. *Wea. Forecasting*, **16,** 491–498.

Davis, K., X. Zeng, and E.A. Ritchie, 2015: A new statistical model for predicting seasonal North Atlantic hurricane activity. *Wea. Forecasting,* **30**, 730–741.

Dee, D. P., and Co-Authors, 2011: The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Q.J.R. Meteorol. Soc.,* **137,** 553–597.

Gray, W. M., 1984a: Atlantic seasonal hurricane frequency. Part I: El Niño and 30-mb quasi biennial oscillation influences. *Mon. Wea. Rev.,* **112,** 1649–1668.

Gray, W. M., 1984b: Atlantic seasonal hurricane frequency. Part II: Forecasting its variability. *Mon. Wea. Rev.*, **112**, 1669–1683.

Huang, W.-R. and J. C. L. Chan, 2014: Dynamical downscaling forecasts of Northwest Pacific tropical cyclone genesis and landfall. *Clim. Dyn.*, **42,** 2227–2237.

Kang, N.-Y., and J. B. Elsner, 2016: Climate mechanism for stronger typhoons in a warmer world. *J. Climate,* **29,** 1051–1057.

Kang, N.-Y., and J. B. Elsner, 2015: Trade-off between intensity and frequency of global tropical cyclones. *Nature Climate Change*, **5,** 661–664.

Kim, O.-Y. and J. C. L. Chan, 2018: Cyclone-track based seasonal prediction for South Pacific tropical cyclone activity using APCC multi-model ensemble prediction. *Clim. Dyn.,* https://doi.org/10.1007/s00382-018-4075-9.

Kirtman, B. P., and Co-Authors, 2014: The North American Multimodel Ensemble: Phase-1 seasonal-to-interannual prediction; Phase-2 toward developing intraseasonal prediction. *Bull. Amer. Meteor. Soc.,* **95,** 585–601.

Klotzbach, P. J., and W. M. Gray, 2009: 25 years of Atlantic basin seasonal hurricane forecasts. *Geophys. Res. Lett.,* **36,** L09711.

Klotzbach, P. J., W. M. Gray, and C. T. Fogarty, 2015: Active Atlantic hurricane era at its end? *Nature Geoscience,* **8,** 737–738.

Klotzbach, P. J., M. A. Saunders, G. D. Bell, and E. S. Blake, 2017: Statistically-based North Atlantic seasonal hurricane outlooks. Chapter 19 in "Climate Extremes: Patterns and Mechanisms", S. Wang *et al.*, Eds., 30 pp, AGU monograph.

Klotzbach, P. J., C. J. Schreck III, J. M. Collins, M. M. Bell, E. S. Blake, and D. R. Roache, 2018: The extremely active 2017 North Atlantic hurricane season. *Mon. Wea. Rev.,* **146,** 3425–3443.

Kuleshov, Y., L. Qi, R. Fawcett, and D. Jones: Improving preparedness to natural hazards: Tropical cyclone seasonal prediction for the Southern Hemisphere. In "Advances in Geosciences", Volume 12: Ocean Science (OS). Ed. by J. Gan. Vol. 12. Singapore: World Scientific Publishing, 2009, pp. 127–143.

Kushnir, Y., and Co-authors, 2019: Towards operational predictions of the near-term climate. *Nature Climate Change*, **9,** 94-101.

Lea, A. S. and M. A. Saunders, 2004: Seasonal predictability of Accumulated Cyclone Energy in the North Atlantic, Proceedings of the 26th Conference on Hurricanes and Tropical Meteorology, Miami, USA, May 3-7, 2004, pp. 419–420.

Lea, A. S. and M. A. Saunders, 2006: How well forecast were the 2004 and 2005 Atlantic and US hurricane seasons? *Weather*, **61,** 245–249.

Lok, C. C. F. and J. C. L. Chan, 2017: Simulating seasonal tropical cyclone intensities at landfall along South China coast. *Clim. Dyn.,* doi:10.1007/s00382-017-3762-2.

MacLachlan, C., and Co-Authors, 2015: Global seasonal forecast system version 5 (GloSea5): a High-Resolution seasonal forecast system. *Quart. Journ. Roy. Meteor. Soc.,* **141**, 1072–1084, http://dx.doi.org/10.1002/qj.2396.

Meehl, G. A., and Co-Authors, 2009: Decadal prediction: Can it be skillful? *Bull. Amer. Meteor. Soc.,* **90,** 1467–1485.

Meehl, G. A., and Co-Authors, 2014: Decadal climate predictions: An update from the trenches, *Bull. Amer. Meteor. Soc.,* **95,** 243–267, doi:10.1175/BAMS-D-12-00241.1.

Murakami, H., and Co-Authors, 2015: Simulation and prediction of Category 4 and 5 hurricanes in the high-resolution GFDL HiFLOR coupled climate model. *J. Climate*, **28,** 9058–9079.

Murakami, H., G. A. Vecchi, G. Villarini, T. L. Delworth, R. Gudgel, S. Underwood, X. Yang, W. Zhang, and S. Lin, 2016a: Seasonal forecasts of major hurricanes and landfalling tropical cyclones using a high-resolution GFDL coupled climate model. *J. Climate*, **29**, 7977–7989.

Murakami, H., G. Villarini, G. A. Vecchi, W. Zhang, and R. Gudgel, 2016b: Statistical-dynamical seasonal forecast of North Atlantic and U.S. landfalling tropical cyclones using the high-resolution GFDL FLOR coupled model. *Mon. Wea. Rev.*, **144**, 2101–2123.

Saha, S., and Co-Authors, 2010: The NCEP Climate Forecast System Reanalysis. *Bull. Amer. Meteor. Soc.,* **91**, 1015–1058.

Saunders, M. A. and A. S. Lea, 2005: Seasonal prediction of hurricane activity reaching the coast of the United States. *Nature*, **434,** 1005–1008.

Saunders, M. A., 2006: Winds of change. Post Magazine Risk Report, 28-29, 9 November 2006. Located online at http://tropicalstormrisk.com/docs/Hurricanes-Post09112006.pdf

Saunders, M. A., and A. S. Lea, 2008: Large contribution of sea surface warming to recent increase in Atlantic hurricane activity. *Nature,* **451,** 557–560.

Saunders, M. A., P. J. Klotzbach, and A. S. R. Lea, 2017: Replicating annual North Atlantic hurricane activity 1878-2012 from environmental variables. *JGR-Atmospheres*, **122,** 6284–6297.

Smith, D. M., S. Cusack, A. W. Colman, C. K. Folland, G. R. Harris and J. M Murphy, 2007: Improved surface temperature prediction for the coming decade from a global climate model. *Science*, **317**, 796-799.

Smith, D. M., R. Eade, N. J. Dunstone, D. Fereday, J. M. Murphy, H. Pohlmann and A. A. Scaife, 2010: Skilful multi-year predictions of Atlantic hurricane frequency. *Nature Geoscience*, **3**, 846–849.

Smith, D. M., A. A. Scaife, G. J. Boer, M. Caian, F. J. Doblas-Reyes, V. Guemas, and Coauthors, 2013: Real-time multi-model decadal climate predictions. *Climate Dynamics*, **41**, 2875–2888.

Stockdale, T. N., and Co-Authors, 2018: SEAS5 and the future evolution of the long-range forecast system. *ECMWF Technical Memorandum*, 835, 81 pp, https://www.ecmwf.int/sites/default/files/elibrary/2018/18750-seas5-and-future-evolution-long-range-forecast-system.pdf

Takaya, Y., T. Yasuda, T. Ose, and T. Nakaegawa, 2010: Predictability of the mean location of typhoon formation in a seasonal prediction experiment with a coupled general circulation model. *J. Meteor. Soc. Japan,* **88,** 799–812.

Takaya, Y., Y. Kubo, S. Maeda, and S. Hirahara, 2017: Prediction and attribution of quiescent tropical cyclone activity in early summer of 2016: case study of lingering effects by preceding strong El Niño events. *Atmos. Sci. Lett.,* **18,** 330–335.

Vecchi, G. A., R. Msadek, W. Anderson, Y. S. Chang, T. Delworth, K. Dixon and Co-Authors, 2013: Multi-year predictions of North Atlantic hurricane frequency: Promise and limitations. *J. Climate*, **26**, 5337–5357.

Vecchi, G. A., and Co-Authors, 2014: On the seasonal forecasting of regional tropical cyclone activity. *J. Climate*, **27,** 7994–8016.

Vecchi, G.A., M. Zhao, H. Wang, G. Villarini, A. Rosati, A. Kumar, I.M. Held, R. Gudgel, 2011: Statistical-dynamical predictions of seasonal North Atlantic hurricane activity. *Mon. Wea. Rev,* **139,** 1070-1082.

Vitart, F., J. L. Anderson, and W.F. Stern, 1997: Simulation of interannual variability of tropical storm frequency in an ensemble of GCM integrations. *J. Climate,* **10,** 745–760.

Vitart, F., J. L. Anderson, and T. Stockdale, 2003: Seasonal forecasting of tropical cyclone landfall over Mozambique. *J. Climate,* **16,** 3932-3945.

Vitart, F., and T. N. Stockdale, 2001: Seasonal forecasting of tropical storms using coupled GCM integrations. *Mon. Wea. Rev,* **129**, 2521–2527.

Vitart, F., and Co-Authors, 2014: Seasonal forecasts. Topic 5.2 in International Workshop on Tropical Cyclones VIII Report, 29 pp. Available online at http://www.wmo.int/pages/prog/arep/wwrp/new/documents/Topic5.2_SeasonalForecasts.pdf.'

Wijnands, J.S., G. Qian, K. Shelton, R. J. B. Fawcett, J. C. L. Chan, and Y. Kuleshov, 2015: Seasonal forecasting of tropical cyclone activity in the Australian and the South Pacific Ocean Regions, *Mathematics of Climate and Weather Forecasting,* **1,** 21–42.

Williams, K.D., and Co-Authors, 2015: The Met Office Global Coupled model 2.0 (GC2) configuration. *Geoscientific Model Development*, **8,** 1509–1524.

Wu, C.-C., R.-F. Zhan, Y. Lu, and Y. Wang, 2012: Internal variability of the dynamically downscaled tropical cyclone activity over the western North Pacific by the IPRC regional climate model. *J. Climate*, **25**, 2123–2128.

Yang, S.-H., N.-Y. Kang, J. B. Elsner, and Y. Chun, 2018: Influence of global warming on western North Pacific tropical cyclone intensities during 2015. *Journal of Climate*, **31,** 919–925.

Ying, M., and R. J. Wan, 2011: The annual frequency prediction of tropical cyclones affecting China. *J. Appl. Meteor. Sci.*, **22**, 66–76, (in Chinese).

Zhan, R.-F., and Y. Wang, 2016: CFSv2-based statistical prediction for seasonal Accumulated Cyclone Energy (ACE) over the Northwest Pacific. *J. Climate*, **29,** 525–541.

Zhan, R.-F., Y. Wang, and C.-C. Wu, 2011a: Impact of SSTA in East Indian Ocean on the frequency of Northwest Pacific tropical cyclones: A regional atmospheric model study. *J. Climate*, **24**, 6227–6242.

Zhan, R.-F., Y. Wang, and X.-T. Lei, 2011b: Contributions of ENSO and East Indian Ocean SSTA to the interannual variability of Northwest Pacific tropical cyclone frequency. *J. Climate*, **24**, 509–521.

Zhan, R.-F., Y. Wang, and M. Wen, 2013: The SST gradient between the southwestern Pacific and the Western Pacific warm pool: A new factor controlling the northwestern Pacific tropical cyclone genesis frequency. *J. Climate,* **26,** 2408–2415.

Zhan, R.-F., Y. Wang, and M. Ying, 2012: Seasonal forecasts of tropical cyclone activity over the Northwest Pacific: A Review. *Tropical Cyclone Research and Review,* **1,** 307–324.

Zhang, W., G. Villarini, G. A. Vecchi, and H. Murakami, 2016: Statistical-dynamical seasonal forecast of the Northwest Pacific and East Asia landfalling tropical cyclones using the high-resolution GFDL FLOR coupled model. *J. Adv. Model. Earth Syst.*, **8**, 538–565.

Zhang, W., G. A. Vecchi, G. Villarini, H. Murakami, R. Gudgel, and X. Yang, 2017: Statistical-dynamical seasonal forecast of Northwest Pacific and East Asia landfalling tropical cyclones using the GFDL FLOR Coupled Climate Model. *J. Climate*, **30**, 2209–2232.