Tropical Cyclone Count Forecasting Using a Dynamical Seasonal Prediction System: Sensitivity to Improved Ocean Initialization

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ABSTRACT

This study investigates the predictability of tropical cyclone (TC) seasonal count anomalies using the Centro Euro-Mediterraneo per i Cambiamenti Climatici–Istituto Nazionale di Geofisica e Vulcanologia (CMCC-INGV) Seasonal Prediction System (SPS). To this aim, nine-member ensemble forecasts for the period 1992–2001 for two starting dates per year were performed. The skill in reproducing the observed TC counts has been evaluated after the application of a TC location and tracking detection method to the retrospective forecasts. The SPS displays good skill in predicting the observed TC count anomalies, particularly over the tropical Pacific and Atlantic Oceans. The simulated TC activity exhibits realistic geographical distribution and interannual variability, thus indicating that the model is able to reproduce the major basic mechanisms that link the TCs’ occurrence with the large-scale circulation. TC count anomalies prediction has been found to be sensitive to the subsurface assimilation in the ocean for initialization. Comparing the results with control simulations performed without assimilated initial conditions, the results indicate that the assimilation significantly improves the prediction of the TC count anomalies over the eastern North Pacific Ocean (ENP) and northern Indian Ocean (NI) during boreal summer. During the austral counterpart, significant progresses over the area surrounding Australia (AUS) and in terms of the probabilistic quality of the predictions also over the southern Indian Ocean (SI) were evidenced. The analysis shows that the improvement in the prediction of anomalous TC counts follows the enhancement in forecasting daily anomalies in sea surface temperature due to subsurface ocean initialization. Furthermore, the skill changes appear to be in part related to forecast differences in convective available potential energy (CAPE) over the ENP and the North Atlantic Ocean (ATL), in wind shear over the NI, and in both CAPE and wind shear over the SI.

1. Introduction

Severe tropical cyclones (TCs), also known as hurricanes in the North Atlantic Ocean and northeast Pacific Ocean and as typhoons in the west Pacific Ocean, are one of the most devastating natural phenomena, often causing severe human and economic losses. The reduction of the social and economic impacts of TCs by the
improvement of the accuracy and reliability of the related analysis, forecasts, and warnings is a major aspiration of the international community, coordinated by the World Meteorological Organization. The assessment and the understanding of the degree to which TC frequency is predictable one season in advance are of particular relevance (Connor et al. 2008). To this aim coupled general circulation models (CGCMs) have been shown to be valuable tools for the study and the seasonal prediction of interannual TC frequency anomalies (e.g., Bengtsson et al. 2007a; Vitart et al. 2001; Vitart 2006).

Among the other factors potentially conditioning the genesis of TCs (Gray 1984), ocean surface temperature is believed to have a central role. A necessary condition for genesis is that the ocean surface temperature must be high enough to support sufficiently large amounts of convective available potential energy (CAPE) in the above atmosphere. In this regard, Palmen (1948) established that tropical cyclones form only over ocean water with temperatures higher than about 26°C. Besides the seasonal modulation, the TC activity exhibits a rather strong year-to-year variability. A number of studies have shown that TC activity varies substantially on interannual and decadal time scales. In particular, the sensitivity of the TC activity to the phase of El Niño–Southern Oscillation (ENSO) has been documented in several works (e.g., Gray 1984; Chan 2000; Chia and Ropelewski 2002). The relationship between ENSO and TC activity is different depending on the region considered. Frank and Young (2007) have shown that the number of observed TCs and ENSO appear to be negatively correlated in the North Atlantic, and one hypothesized mechanism is the modulation of the vertical wind shear strength (Goldenberg and Shapiro 1996). In contrast, TC counts and ENSO tend to be positively correlated in the northeast and northwest Pacific Ocean.

The prediction of climate at the seasonal time scale constitutes a boundary value problem for the atmospheric component and relies on the interaction of the atmosphere with slowly varying components of the climate system, such as the ocean (e.g., Navarra 2002). Dynamical models of the coupled ocean–atmosphere demonstrated their ability in predicting ENSO cycles and the associated tropical Pacific SST anomalies seasons in advance (Cane et al. 1986; Zebiak and Cane 1987; Latif et al. 1998; Palmer 2006; Balmaseda et al. 2007). The initialization of subsurface ocean through assimilation of in situ temperature and salinity profiles can contribute to improve the skill of seasonal forecasts by reducing model errors (e.g., Alves et al. 2004; Vidard et al. 2007) and by increasing the skill in the prediction of ENSO (Chen et al. 1995; Ji and Leetmaa 1997; Rosati et al. 1997; Balmaseda et al. 2007) and of the related teleconnections (e.g., Alessandri et al. 2010). Therefore, subsurface data assimilation has been increasingly adopted during the last decade to initialize the ocean component for seasonal forecasting (Rosati et al. 1997; Alves et al. 2004; Ji and Leetmaa 1997; Wang et al. 2002; Balmaseda et al. 2007; Vidard et al. 2007; Alessandri et al. 2010). Using the European Centre for Medium-Range Weather Forecasts (ECMWF) Seasonal Prediction System (SPS), Vitart (2006) suggested that the assimilation of subsurface data could improve the predictability of tropical storms. In fact, over the Atlantic and the northern Indian basins, they reported a considerable increase of the correlation of predicted versus observed tropical storms frequency due to the assimilation of in situ temperature and salinity profiles.

This work investigates the predictability of TC seasonal count anomalies using the Centro Euro-Mediterranee per i Cambiamenti Climatici–Istituto Nazionale di Geofisica e Vulcanologia (CMCC-INGV) Seasonal Prediction System, which includes an assimilation at the global scale of in situ vertical profile observations in the oceanic model to produce initial conditions (ICs). Furthermore, we evaluate the impact of the assimilation of the subsurface information in the performance of the SPS by comparing it with control forecasts (i.e., without ocean assimilation). The paper is organized as follows: Section 2 describes the seasonal prediction system, the experiments performed, and the validation data. After a brief evaluation of the tropical climate simulated by the latest release of the system, in section 3b we analyze the predicted TCs climatology and in section 3c we assess the predictability of interannual TC count anomalies. Section 4 addresses the effects of the subsurface assimilation on the prediction performance by comparing it with control forecasts. Finally, section 5 contains the discussion of the main results and the conclusions obtained from this study.

2. Method and data

The modeling data employed in this work are the seasonal predictions produced with the CMCC-INGV Seasonal Prediction System (Alessandri et al. 2010). The coupled model included in the system is an evolution of the ocean-atmosphere CGCM Scale Interaction Experiment-Frontier (SINTEX-F; Gualdi et al. 2003a,b; Luo et al. 2005). The atmospheric component is ECHAM-4 (Roeckner et al. 1996). Here it is run at T106 spectral resolution, corresponding to a horizontal resolution of about 1.125°, with 19 vertical layers. The ocean component is the OPA8.2 ocean model (Madec et al. 1998) in its ORCA2 global configuration. The horizontal resolution is variable, with a nominal resolution of 1.5° in latitude and 2° in longitude, with an increase to 0.5° near the equator.
There are 31 vertical levels with 10-m resolution in the top 100m. The System does not include an interactive cryosphere and ice cover is relaxed toward climatology. The two components are coupled with the OASIS2.4 (Valcke et al. 2000) coupler every two hours, with no flux corrections.

a. Experiments performed

In this study we use the set of retrospective forecasts described with details in Alessandri et al. (2010). The experiment is composed of 5-month seasonal forecasts for the period 1992–2001. To consider the possible impact of the seasonal cycle on the forecasts, the predictions started from two different dates of the year: 1 May and 1 November. In all simulations, the atmospheric radiative forcing was constant and set equal to the average of the period 1992–2001. Two sets of nine-member ensemble forecasts have been produced, taking the same ICs for all the coupled model components but the ocean. In the first set, the ocean initial states were estimated by using the assimilation of observed profiles of temperature and salinity through the water column [DAS experiment; for a description of the assimilation scheme used, see Di Pietro and Masina (2009); Bellucci et al. (2007)]. In the second set, no observed in situ data were assimilated (NODAS experiment). As described in Alessandri et al. (2010), the temperature and salinity profiles used for this study are taken from the Enhanced Ocean Data Assimilation and Climate Prediction archive version 3 (EN3) package [an assembling of the World Ocean Database 2005 (WOD05), and the Global Temperature and Salinity Profile Program (GTSPP) and Argo databases; http://hadobs.metoffice.com/en3/]. Only the profiles that passed all the quality checks described in Ingleby and Huddleston (2007) have been retained for assimilation.

For both DAS and NODAS, the ocean model was forced starting from 1955 with momentum, heat, and mass flux data from the 40-yr ECMWF Re-Analysis (ERA-40; Uppala et al. 2005). Furthermore, to keep the simulated SST close to observations, the model field was damped with a time scale of 7 days toward the observed Reynolds SST (Reynolds and Smith 1994) from 1982 onward and the ERA-40 SST before. In practice, ICs produced by the NODAS experiment are simply forced from atmospheric fluxes and relaxation to surface SST, whereas the DAS experiment included assimilation of in situ ocean profiles.

Atmosphere ICs were obtained from an Atmospheric Model Intercomparison Project (AMIP)-type run performed with the atmospheric component of the model forced with observed SSTs and sea ice extent [Met Office Hadley Centre Sea Ice and Sea Surface Temperature version 1.1 (HadISST1.1); Rayner et al. 2003] for the period 1985–2001. To represent the uncertainties in the initial state of the system, an ensemble of nine atmospheric ICs has been produced by taking lagged days as initial states; that is, for each starting date, we take not only 1 May (or November) but also the 4 days before and after.

In summary, for both DAS and NODAS (i.e., with and without assimilation of in situ data) and for each starting date, an ensemble of nine atmospheric initial states were created. Starting from these ICs, the coupled model has been integrated for 5 months, producing two sets of nine-member ensemble retrospective forecasts covering the period 1992–2001.

b. Method of detection of simulated TCs

In this study, we use the TC location and tracking method described in Gualdi et al. (2008), which is based on the approach defined in Bengtsson et al. (1995) and Walsh (1997). The location and tracking method is applied over each grid point with a 12-h time step. To make sure that moving TCs are detected, for each time step it is checked whether TCs are moving from a grid point toward the adjacent grid points with a checking area radius of 350 km. In the following, we summarize the criteria for the detection of an active model TC over a certain grid-point A [see Gualdi et al. (2008), for further details]:

(i) The relative vorticity at 850 hPa is greater than $3 \times 10^{-5}$ s$^{-1}$.
(ii) There is a relative minimum of surface pressure, and wind velocity is greater than 14 m s$^{-1}$ in an area of 2.25° around grid point A.
(iii) The wind velocity at 850 hPa is greater than the wind velocity at 300 hPa.
(iv) The sum of temperature anomalies at 700, 500, and 300 hPa is greater than 2 K, where the anomalies are defined as the deviation from a spatial mean computed over an area of 13 grid points in the east–west direction and 2 grid points in the north–south direction.
(v) The temperature anomaly at 300 hPa is greater than the temperature anomaly at 850 hPa.
(vi) The above conditions persist for a period longer than 1.5 days.

In this paper “observed tropical cyclone” refers to the cyclones that have been officially classified as tropical cyclones with an intensity as high as or exceeding the intensity of tropical storms (maximum sustained surface wind speed is greater than 17 m s$^{-1}$) by agencies that are monitoring tropical storm activity, such as the National Hurricane Center (NHC) and the U.S. Joint Typhoon Warning Center (JTWC). As explained in Gualdi et al. (2008), the choice of the parameters in the dynamical and
structural threshold detection criteria is very similar to the values indicated by Bengtsson et al. (1995) and Walsh (1997), and the parameters optimize the detection and the climatological amount of simulated TCs in our model. The sensitivity of the results to small changes in these parameters has been checked. We found that the number of detected TCs is scarcely sensitive to the threshold values, but it exhibits some sensitivity to the size of the areas over which the reference averages are computed (Gualdi et al. 2008).

The objective procedure for detecting model tropical storm tracks has been applied to the retrospective seasonal forecasts, and the simulated TC occurrence has been evaluated for the seven specific regions of activity defined following Camargo et al. (2004). Four of these regions are in the Northern Hemisphere: northern Indian Ocean (NI), western North Pacific Ocean (WNP), eastern North Pacific Ocean (ENP) and North Atlantic Ocean (ATL). The other three regions are in the Southern Hemisphere: southern Indian Ocean (SI), the ocean north of Australia (AUS), and the South Pacific Ocean (SP). The ocean basins extending north of equator are characterized by a TC season centered in boreal summer, usually starting in late spring and covering part of autumn. Therefore, for the ATL, ENP, WNP, and NI, we focus on the forecasts starting on 1 May [covering the period June–September (JJAS)]. In contrast, over the SI, AUS, and SP regions, where the tropical cyclone season extends from November to the subsequent austral summer, forecasts starting on 1 November [covering the period December–March (DJFM)] are evaluated.

c. Observed and reanalysis datasets

The simulated TC counts are evaluated by comparing the SPS forecasts with observational datasets. Specifically, as explained before, we use data from the NHC and the JTWC. Furthermore, the capability of the model to reproduce the observed mean climate and its variability is assessed using ERA-40 (Uppala et al. 2005). For the sake of simplicity, in the rest of the paper we will refer to all of these data as observations.

3. Tropical climate simulation and predicted TC climatology

The seasonal mean DAS SST (Figs. 1a,b) and precipitation (Figs. 1c,d) biases computed as the difference between the forecast ensemble means and observed climatologies of the period 1992–2001 are shown. The left panels are for the boreal summer (JJAS), while the right panels for the austral counterpart (DJFM). As discussed in Alessandri et al. (2010), Fig. 1 shows that the systematic error of the model in predicting the SST field is moderate in most of the tropics. The model exhibits an averaged cold bias smaller than 1°C over a large portion of the tropical belt, and the error is remarkably small in the tropical Indian Ocean. Conversely, the equatorial cold tongue is too pronounced and penetrates too far into the west Pacific, producing SST patterns too symmetrical around the equator. The maximum cold bias in the eastern Pacific is higher for the November start date and even exceeds 2°C in a small area around 120°W. Correspondingly, the simulated precipitation tends to be too weak (Figs. 1c,d) over the regions affected by the cold SST bias, resulting in the tendency to produce a double intertropical convergence zone (ITCZ) in the tropical Pacific. As shown in Alessandri et al. (2010), the bias in the cold tongue region is little improved by the subsurface assimilation as a consequence of the model SST drift in this region, which drives the forecasts toward the biased model climatology. This can be further appreciated by noticing that the SST bias in Fig. 1 is very similar to Luo et al. (2010, their Fig. 8), who used the same coupled model but without any subsurface data assimilation. The above-mentioned discussion indicates that the SST bias in this region is mostly related to model internal physics and comes from the growth of errors in the coupled ocean–atmosphere system. In the southeastern tropical Pacific and in the upwelling regions off the North American coast, in the Gulf of Guinea, and in the Arabian Sea (JJAS only), the model is too warm and displays some areas as having an error larger than 1°C. In these regions, over the warm SST the model also tends to overestimate the convection, resulting in an associated too high amount of rainfall (Figs. 1c,d).

The results exhibit some seasonal dependency of the systematic errors on the date of the ICs (Fig. 1). As already discussed in Alessandri et al. (2010), the SST warm bias in the tropical southeastern Pacific, southeastern Atlantic, and Southern Hemisphere midlatitudes appears to be more pronounced for the forecasts started in November (Fig. 1b). Conversely, the warm bias in the tropical northeastern Pacific and Atlantic is found only in the forecasts with start dates in May (Fig. 1a). Considering the equatorial Pacific cold tongue, the error is more evident for the forecasts starting in November. This seasonality also affects the precipitation bias. In particular, the dry bias in the equatorial Pacific is more pronounced west of the date line during JJAS, while it extends to the North American coasts during DJFM.

A first estimate of the SST variability at the daily time scale is reported in Fig. 2. The standard deviation of the daily SST anomalies is reported for both the observations (Figs. 2a,b) and the forecasts (Figs. 2c,d). For the forecasts the ensemble mean of the standard deviations computed for each member is reported. In the observations, the pattern of total variability (Figs. 2a,b) shows maxima over
the equatorial eastern tropical Pacific Ocean and the subtropical basin areas with increasing intensities for the respective summer season hemispheres. Overall, the forecasts (Figs. 2c,d) appear to simulate well the variability both around the equator and over the tropical and subtropical regions. However, during boreal summer, the simulated SST variability appears to be higher than observed in the central equatorial Pacific. Also, the results show some tendency to underestimate the subtropical variability in the respective summer hemispheres. A considerable predictive signal is also found over the equatorial Atlantic and Indian Oceans, whereas relatively lower values are found in the tropics and subtropics of the respective summer hemispheres. Interestingly, the above-mentioned result indicates a seasonal reduction of the signal-to-noise ratio in the subtropical ocean basins experiencing their active TC season.

a. ENSO and tropical Pacific SST prediction skill

The performance of the CMCC-INGV SPS was discussed in detail in Alessandri et al. (2010). The reader is referred to Alessandri et al. (2010) for a detailed assessment of the skill in predicting ENSO and tropical climate anomalies as well as the difference in performance between the NODAS and DAS experiments. In the following, the performance in predicting ENSO and tropical Pacific SST...
anomalies is summarized. Table 1 reports the time correlation for the monthly Niño-3.4 index (SST anomalies averaged over 5°S–5°N, 190°–240°E, top rows) as well as the spatial anomaly correlation coefficients (ACCs) computed over the entire tropical Pacific (25°S–25°N, 140°–280°E, bottom rows) between forecasts and observations. The SPS performs particularly well in predicting the Niño-3.4 index at a 1-month lead time (months from 2 to 5). In fact, the correlations between predicted and observed monthly Niño-3.4 index always exceed 0.9 and with a value of 0.94 while considering the DAS results and both May and November start dates in the computation. The spatial ACCs (Table 1, bottom rows) for the forecast SST also evidence good results of the SPS once considering the whole tropical Pacific basin. DAS, in comparison with NODAS, better represents the observed anomalies in the Niño-3.4 index (correlation coefficient 0.94 vs 0.91; see Table 1), and a similar result is found while considering the ACCs over the tropical Pacific (ACC 0.62 vs 0.59), with the stronger improvements for the November start date (see Table 1, second and third columns). As reported with details in Alessandri et al. (2010), the results show that DAS considerably improves the known problem in NODAS of underpredicting the ENSO anomalies. Of particular relevance, when subsurface data are assimilated, our system appears to represent very well the development of El Niño in 1997/98. Correspondingly, following the improvements for the tropical Pacific, a better prediction of the tropical surface climate anomalies is reported, in particular for the forecasts started in November (Alessandri et al. 2010). Notice that the tropical Atlantic is found to behave differently from the other tropical basins, displaying evidence of a worsening in DAS during boreal summer (Alessandri et al. 2010).
Table 1. Prediction skill over tropical Pacific for 1-month lead time forecasts (months 2–5), taking as reference the ERA-40 data. Results for both DAS and NODAS are reported for comparison. (top row) Time correlations for the monthly Niño-3.4 index (SST anomalies averaged over 5°S–5°N, 190°–240°E). (bottom row) Spatial ACCs computed over the tropical Pacific (25°S–25°N, 140°–280°E) and averaged over the 10 forecast years. Results considering both May and November start dates in the computations, May only, and November only.

<table>
<thead>
<tr>
<th>ENSO and Tropical Pacific Prediction skill</th>
<th>May and November</th>
<th>May only</th>
<th>November only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Niño-3.4</td>
<td>DAS 0.94</td>
<td>0.93</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>NODAS 0.91</td>
<td>0.91</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>DAS 0.62</td>
<td>0.62</td>
<td>0.63</td>
</tr>
<tr>
<td>Tropical Pacific</td>
<td>NODAS 0.59</td>
<td>0.60</td>
<td>0.59</td>
</tr>
</tbody>
</table>

b. Predicted TC climatology

In this section we analyze the ability of DAS to predict TC counts by the use of the location and tracking method discussed in section 2b. As a first step, we compare the climatological total number of TCs per year in the observations with the ensemble mean total TC counts detected in the forecasts over the period 1992–2001 (Table 2). The number of simulated TCs per year is about 30% lower than in the observations. Similarly, the interannual standard deviation is underestimated by about one-third compared to the observed value (Table 2). As a result, if we divide the standard deviations by the mean values, then the resulting weighted variability found in the model is almost equal to the observed one. In Table 2 the results for NODAS are also reported (third column). Notice that NODAS shows results quite similar to DAS in terms of climatological TC activity, with only a slightly reduced total number of TCs and interannual variability. Even if we are using a coupled model with relatively high-resolution atmosphere (T106 spectral resolution, corresponding to about 1.125° × 1.125° in latitude and longitude; see section 2 for details), the underestimation of the amount of detected TCs by the SPS might be in part related to the limited horizontal resolution of the atmospheric model component in use. In fact, the capability of coupled models to represent TC structure and activity becomes increasingly more realistic as the resolution increases (e.g., Bengtsson et al. 2007b). As pointed out by Bengtsson et al. (2007b), the number of identified storms may depend considerably on the atmospheric resolution. For instance, they showed an increase of almost 3 times the number of detected TCs after enhancing their atmospheric model resolution from T63 (about 1.875° × 1.875° in longitude and latitude) to T213 (about 0.5625° × 0.5625° in longitude and latitude).

The geographical distribution of the TC formation positions is shown in Fig. 3. Following Camargo et al. (2004), seven ocean basins are defined to delimit the different observed areas of TC activity (see section 2b). The patterns of observed TC distribution (Fig. 3a) appear to be reproduced well by the forecasts (Fig. 3b), both in the Northern and Southern Hemisphere TC activity domains. Since Fig. 3 reports the track starting points for the considered period, only one forecast member at a time can be compared with observations. The results for the ensemble member 1, which was arbitrarily chosen for comparison in Fig. 3, are well representative of all the other members of the ensemble. A comparison with the climatological distribution obtained from a simulation of the twentieth century (see Gualdi et al. 2008) indicates that the results obtained from the seasonal forecast experiments is more realistic, especially in the tropical South Atlantic. In particular, the coupled model simulation performed with only the prescription of the historical radiative forcing (hereafter free coupled model) generates several TCs over the tropical South Atlantic in the period 1992–2001, though no TCs have been observed in that area during this decade (Fig. 3a). In the forecasts only two TCs are detected in the southern Atlantic, thus resembling much more closely the observations. This improvement in the TCs climatology follows at least in part from the reduction, in the initialized forecasts, of the SST bias that affects the free coupled model (Gualdi et al. 2008). With this respect, the initialization procedure performed in the forecasts appears to effectively reduce the too intense convective activity found in the free coupled model over the warmley biased southern Atlantic SSTs (see Gualdi et al. 2008).

In Fig. 4, we show the box plots representing the mean number of TCs per year for each area, both for the observations (left panel) and DAS (right panel; note that the forecast results have been multiplied by a factor of 1.5). The figure confirms that, overall, in the forecasts there is a lower number of TCs. However, in general the

Table 2. Total number (ToT) and interannual standard deviation (std dev) of the TCs found in the observations (OBS) (first column) and in the DAS ensemble mean forecasts (second column) during the period 1992–2001. The third column reports the results for NODAS.

<table>
<thead>
<tr>
<th>Number of TCs</th>
<th>OBS</th>
<th>DAS</th>
<th>NODAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>ToT</td>
<td>678</td>
<td>438</td>
<td>403</td>
</tr>
<tr>
<td>Mean</td>
<td>67.8</td>
<td>43.8</td>
<td>40.3</td>
</tr>
<tr>
<td>Std dev</td>
<td>7.0</td>
<td>4.9</td>
<td>4.8</td>
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relative TC abundance of the different areas is well represented by a comparison with observations. Furthermore, for each area, the model appears to simulate a fairly realistic year-to-year variability.

c. TC count predictability

Figure 5 shows the predicted interannual variation of the number of TCs in the Northern Hemisphere basins. Dark-shaded circles are the observations, and light-shaded squares are the ensemble mean forecasts. Each single ensemble member is reported with a cross. The time series of the standardized interannual anomalies shown in Fig. 5 indicate that the model simulates a fairly realistic interannual modulation of the number of TCs. The predicted TC count anomalies are significantly correlated to the observed ones in the ENP ($r = 0.78$, 5% significance level), in the ATL ($r = 0.47$, 10% significance level), and in the WNP ($r = 0.44$, 10% significance level). Changes in the SST distribution in the tropical Pacific and the associated changes in the large-scale circulation appear to have a strong impact on the number of TCs that occur in different regions of the globe (Gray 1984; Chan 2000; Chia and Ropelewski 2002; Frank and Young 2007; among others). The relationship between ENSO and TC activity is different depending on the region considered (e.g., Frank and Young 2007). As reported in Table 3 (second column), the number of observed TCs and the Niño-3.4 ENSO index are negatively correlated in the North Atlantic ($r = -0.39$), whereas a positive correlation is observed in the northeast Pacific ($r = 0.40$), the Australian ($r = 0.40$), and the South Pacific ($r = 0.52$) Oceans. Table 3 shows that the interannual variability simulated by DAS (first column) in the ENP and ATL is linked to ENSO, similar to what is found in the observations, though the correlation between ENSO and the forecasted TC counts appears to be overestimated. For ENP the predicted TC counts correlation with ENSO is as high as 0.85, exceeding considerably the observed 0.40 value. Similarly, the negative correlation in the ATL ($r = -0.39$ in the observations) appears to be too large in the predictions ($r = -0.68$).

Seasonal climate predictability stems from the slowly evolving components of the system, such as the ocean or the land surface (Shukla and Kinter 2006), and much of the skill of present dynamical seasonal climate forecasts comes from their demonstrated ability in predicting ENSO cycles seasons in advance (e.g., Cane et al. 1986; Zebiak and Cane 1987; Latif et al. 1998; Palmer 2006; Balmaseda et al. 2007). The fact that the forecasted TC counts’ sensitivity to ENSO is overrepresented in the boreal summer predictions suggests that other important sources of TC variability might be missing or misrepresented in the predictions. As suggested by some recent studies, the intraseasonal variability, such as the Madden–Julian oscillation (MJO), may play a role in the modulation of TC activity (Hall et al. 2001; Vitart 2009). In fact, the MJO is the dominant mode of variability in the tropics on time scales of 30–90 days (Zhang 2005;...
Vitart et al. (2007). Furthermore, from observational datasets, Vitart (2009) showed that the MJO has a significant impact on the statistics of tropical storms and that the phase of an active MJO leads to significant tropical cyclone density anomalies in the different active basins. However, GCMs tend to suffer from a lack of MJO activity and have difficulties adequately representing the amplitude and propagation of MJO events (Slingo et al. 1996; Sperber et al. 2005; Vitart et al. 2007). In particular, as shown in Sperber et al. (2005), the CGCM included in the CMCC-INGV SPS exhibits deficiencies in representing well-organized MJO convection, thus underestimating MJO activity as well as the possible contribution to TC variability. Conversely, other not well-represented processes or uninitialized phenomena could play a role. For instance, the absence of any proper initialization of the long persisting land variables (e.g., Koster et al. 2004, 2006; Ferranti and Viterbo 2006; Alessandri and Navarra 2008) could be another possible reason for the too weak non-ENSO-related signal in the predictions. This appears to be of particular relevance in the Northern Hemisphere, where the land fraction is large.

In Fig. 6 the predicted interannual DJFM TC count anomalies over the Southern Hemisphere basins are displayed. A good skill in the TC count prediction is observed for the AUS ($r = 0.59$) and SP ($r = 0.67$). Remarkably, for the SP the observed connection with ENSO appears to be fairly well captured by the forecasts ($r = 0.41$ vs the observed $r = 0.52$; see Table 3). In contrast, considering the AUS region, the predicted TC counts are quite neutrally correlated with the ENSO oscillations ($r = 0.15$), while in the observations a stronger relationship is found ($r = 0.40$).

The above-mentioned analysis of the correlations between predicted and observed TC counts suggests competitive results of our SPS compared to the other global-scale dynamical systems described in previous studies and available from the literature (e.g., Vitart
Our system appears to perform particularly well over the ENP, AUS, and SP regions. However, the rigorous and proper comparison of our TC count forecasts with those provided by the other available systems is out of the scope of the present paper and will be explored in future works. Figures 5, 6 show that the model has a poor performance in predicting TC counts in both the northern and southern Indian Ocean. This is consistent with the results obtained in previous studies with other SPSs that have already shown that dynamical models usually perform poorly over the north and south Indian Ocean (e.g., Vitart and Stockdale 2001; Vitart et al. 2007; Camargo et al. 2005, 2007). As pointed out by Camargo et al. (2007), it is not clear to what extent this is caused by model errors or by a lack of predictability. Vitart and Stockdale (2001) attributed the bad performances over the north and south Indian Ocean to the lower impact of ENSO on tropical storm frequency over these basins. Conversely, Vitart et al. (2007) suggested that, over the Indian basins, the intraseasonal variability, such as the MJO, may play a strong role in the modulation of tropical storm activity, and GCMs are generally not very skillful in simulating the MJO (Slingo et al. 1996). The results for our system suggest that the low performance may in part arise from the quite prominent biases in the atmospheric circulation and thermodynamics over these basins. In particular, the climatological circulation shows a considerably underestimated vertical wind shear in the model over the northern Indian Ocean compared to observations (not shown). Similarly, the southern Indian basin displays strong biases with a too strong vertical gradient in the wind north of 10°S and a too low vertical wind shear in the band between 25° and 15°S. Furthermore, over

**Fig. 5. Time series of the JJAS standardized anomaly of TC counts for the ENP, WNP, ATL, and NI. Dark-shaded circles are the observations, and light-shaded squares are the ensemble mean forecasts. Each single ensemble member is reported with a cross. Correlations between ensemble mean forecasts and observations are also reported, with the indication of the associated 5% or 10% level of significance when verified.**

<table>
<thead>
<tr>
<th>TC counts correlation</th>
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</thead>
<tbody>
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<td>Regions</td>
</tr>
<tr>
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<td>ENP</td>
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<tr>
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<tr>
<td>AUS</td>
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<tr>
<td>SI</td>
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<tr>
<td>SP</td>
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</table>
wide areas of both the northern and southern Indian Ocean, the predictions appear to underestimate the CAPE compared to observations (not shown).

4. Improved ocean IC effect on TC count predictability

This section reports the contribution of oceanic subsurface assimilation to the skill of the prediction of TC count interannual anomalies. The comparison of the predicted interannual TC count anomalies shows a considerably better performance of the forecasts initialized using subsurface assimilation (DAS) than the forecasts performed with no temperature and salinity assimilation (NODAS). As reported in Fig. 7, DAS significantly (5% level; Monte Carlo method) increases the correlation coefficient between predicted and observed TC count anomalies in the ENP ($r = 0.78$ vs $r = 0.53$), NI ($r = 0.22$ vs $r = -0.79$), and AUS ($r = 0.59$ vs $r = 0.21$). Table 3 suggests that the differences between DAS and NODAS in representing the TC counts relationship with ENSO may play a role over the ENP, ATL, and NI. DAS displays increased skill over the ENP while overestimating the positive link between TC counts and ENSO compared to observations. Conversely, NODAS improves over the ATL and at the same time shows a too negative correlation of TC counts with the Niño-3.4 index over this region. The above-mentioned results further suggest that much of the skill of current SPSs comes from their ability in predicting ENSO. On the other hand, the over-sensitivity to ENSO suggests that other sources of TC variability might be not well represented in the models (see discussion in section 3c). Over the NI, NODAS shows an unrealistic positive correlation between TC counts and the Niño-3.4 index (see Table 3). In contrast, the results for DAS display an almost neutral link between ENSO and TC counts over this basin, which is much similar to observations. Interestingly, the NI, which is the region with the larger SST bias reduction (see Table 4) in DAS, is also the region displaying the larger increase in the TC count correlation with observations. This result indicates that the SST bias may strongly affect the prediction of TC counts over the NI in NODAS, which indeed displays a large negative correlation coefficient with observations. This is consistent with several previous works that have shown that the fidelity of the model simulations of the climatology over the tropical Asian–Australian monsoon regions may have a close link to its ability in predicting interannual anomalies in seasonal mean atmospheric circulation, precipitation, and intraseasonal variability (e.g., Sperber and Palmer 1996; Li and Hogan 1999; Innes et al. 2003; Turner et al. 2005; Seo et al. 2007; Lee et al. 2010). In particular, Lee et al. (2010) showed that the ability of dynamical models in simulating the SST mean state closely impacts the prediction skill for the SST anomalies, which in turn are the major predictability
source for Asian monsoon interannual anomalies in circulation and convection activity.

So far we have evaluated the impact of the improvement of the oceanic ICs estimation on the prediction of ensemble mean TC anomalies. However, to be useful at the decision level, we need to exploit the potential of probability seasonal forecasts to provide valuable information. Specifically, it is desirable to evaluate how well a set of probability forecasts is able to discriminate among the occurrence of dichotomous mutually exclusive and collectively exhaustive (MECE) events, where mutually exclusive means that no more than one of the events can occur, while collectively exhaustive ensures that at least one of the events will take place. It follows that for a dichotomous MECE event, there are two possible outcomes: either the event will or will not occur. In particular, in the next subsection we will concentrate on the forecasting of below-normal (i.e., below the lower tercile of the sample distribution) and above-normal (i.e., above the upper tercile of the sample distribution) observed TC count anomalies.

**Probabilistic forecasts of dichotomous predictands**

The joint distribution of forecasts and observed dichotomous predictands can be conveniently analyzed and displayed graphically through the likelihood–base rate factorization (Wilks 2006) as shown:

\[
p(y_i, o_j) = p(y_i | o_j) \cdot p(o_j) \quad i = 1, \ldots, I \quad j = 0, 1, \quad (1)
\]

where the conditional distribution \(p(y_i | o_j)\) expresses the likelihood that each of the allowable forecast values \(y_i\) would have been issued in advance of each of the

**Fig. 7.** Histogram of the correlation coefficients between predicted (ensemble means) vs observed number of TCs, showing sensitivity to the improved ocean IC: NODAS (light gray) and DAS (dark gray). Indication is placed if the DAS–NODAS difference in correlation is significantly different from zero at the 5% level (Monte Carlo method).

<table>
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<tr>
<th>Regions</th>
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<td>DAS</td>
</tr>
<tr>
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<tr>
<td>SP</td>
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</table>

**Table 4.** Comparison between DAS and NODAS of the SST bias (K) averaged over each of the considered TC activity regions. Forecast months from 2 to 5 are considered in the computation, which is performed over each region experiencing an active TC season.
observed dichotomous events \( o_j \) (occurrence \( j = 1 \); no occurrence \( j = 0 \)). Together with the associated sample climatological probabilities, \( p(o_j) \), (1) completely represents the information of the full joint distribution. Specifically, the conditional likelihood distributions, \( p(y_j|o_j) \), are directly indicative of how well a set of forecasts is able to discriminate among the events \( o_j \). Graphically, this can be appreciated through diagrams consisting of superimposed plots of the two likelihood distributions as a function of the forecast probability, \( y_j \) (discrimination diagrams).

The separation of the two likelihood distributions reflects the capability of the probabilistic forecasts to discriminate the observed events. This can be suitably measured with a scalar attribute called discrimination distance \( (d) \), defined as the difference between the means of the two likelihood distributions \( (\mu_{y_j|o_j}) \) following Wilks (2006):

\[
d = |\mu_{y_j|1} - \mu_{y_j|0}|.
\]

Clearly, a necessary condition for TC genesis is that the ocean surface temperature is and maintains sufficiently high (e.g., Palmen 1948; Emanuel 2003). The ability of the forecasts to discriminate below-normal and above-normal daily SST will be evaluated in section 4a(1). Then, in section 4a(2), we will concentrate on the comparison between DAS and NODAS forecasts of the discrimination of interannual TC counts.

1) ABOVE- AND BELOW-NORMAL DAILY SST DISCRIMINATION

The discrimination of the daily SST has been evaluated over all the active TC regions and for both below-normal (cold, \( E_{SST} \)) and above-normal (warm, \( E^{+}_{SST} \)) conditions. All the days in the forecast months from 2 to 5 have been considered in the computations. Figure 8 summarizes the discrimination distances for both \( E_{SST} \) and \( E^{+}_{SST} \) and for all the active basins (see also Table 5). Considering the Northern Hemisphere regions, DAS shows a significant (5% level; Monte Carlo method) enhancement of \( d \) for both cold and warm conditions in the ENP and in the NI \( [d^{+}_{SST}(ENP, NI)] \). In contrast, the subsurface assimilation appears to worsen the discrimination performance in the ATL, where \( d^{+}_{SST}(ATL) \) is significantly higher in NODAS. In the Southern Hemisphere, only the AUS daily SSTA is significantly impacted with higher \( d^{+}_{SST}(AUS) \) in DAS.

Figure 9 shows the comparison between DAS and NODAS of the discrimination diagrams over the ENP (Figs. 9a,b), the ATL (Figs. 9c,d), and the AUS (Figs. 9e,f). The left panels show the results for the below lower-tercile (cold) daily SST case, while the right panels are for the above upper-tercile (warm) daily SST case. The dashed lines represent the likelihood distribution given the no occurrence of the event \( [p(y_j|o_0)] \), while solid lines are the likelihood distributions verified \( o_1 \) \( [p(y_j|o_1)] \). NODAS (red) and DAS (blue) are displayed in the same diagram. In the ENP basin (Figs. 9a,b), DAS displays larger \( p(y_j|o_1) \) values (dashed lines) for the smaller forecast probabilities for both \( E_{SST} \) and \( E^{+}_{SST} \). Similarly, conditional probabilities given \( o_1 \) (solid lines) are higher in DAS compared to NODAS for the larger probability forecasts. This determines an increase in DAS of the separation between the two respective likelihood distributions, indicating an improved ability of the forecasts to discriminate between warm and cold events. Similarly, the AUS (Figs. 9e,f) and NI (not shown) show a considerable increased discrimination in DAS for both below- and above-normal daily SST conditions. In contrast, DAS tends to reduce the separation between the two likelihood distributions in the ATL (Figs. 9c,d), resulting in the above-mentioned significant (5% level; Monte Carlo method) NODAS increase in the discrimination distance for the cold daily SST case.

2) ABOVE- AND BELOW-NORMAL TC COUNT ANOMALY DISCRIMINATION

The comparison between DAS and NODAS of the discrimination diagrams evaluated over the ENP (Figs. 10a,b), ATL (Figs. 10c,d), and AUS (Figs. 10e,f) is reported in Fig. 10 for the events of both below-normal
The prediction of anomalous TC counts over the ENP region is considerably improved by the subsurface assimilation. Compared to NODAS, the DAS forecasts of below-normal TC counts for the ENP basin [\(E_{TC}(ENP)\); Fig. 10a] display considerably larger values for the larger forecast probability. Besides, for \(E_{TC}(ENP)\) DAS increases substantially, compared to NODAS, the likelihood distribution given the no occurrence of the event \([p(y_i|\theta_0)]\) for the smaller forecast probabilities (Fig. 10b). The AUS (Figs. 10e,f), NI, and SI (see Table 6) confirm a similar impact of the subsurface assimilation on the forecasts. However, in AUS (Figs. 10e,f) DAS appears to improve only for below-normal TC forecasting [\(E_{TC}(AUS)\)]. Conversely, in the SI region, the forecasts improve only for above-normal TC counts.

Figure 11 reports the discrimination distances evaluated over all the regions and for both DAS and NODAS. The comparison between Figs. 11 and 8 confirms that the enhanced discrimination of the interannual TC counts in DAS follows the improvements in the daily SST discrimination. The only exception is the SI, where the improvement of \(d_{TC}^{\text{SI}}\) in DAS does not appear to be associated with a better prediction of anomalous daily SSTs. Notice that in the North Atlantic basin, a significant worsening is shown for the discrimination of above-normal TC counts in DAS. Again, this result is consistent with the better NODAS discrimination of both below-normal (5% significance level) and above-normal (5% significance not verified) daily SST. Conversely, the significant improvement in the discrimination distance of daily SST does not always improve the discrimination distance of TC counts. For instance, the discrimination distance of daily SST enhances in DAS for both cold and warm conditions over the AUS, whereas the discrimination distance for only below-normal TC counts is improved in this region.

In the above-mentioned analysis, it has been shown that the enhancement of the prediction of anomalous TC counts results from the improvement of the oceanic IC, which determines in most regions better discrimination of daily SST anomalies. To further understand the above-mentioned results, we discuss the connection with those characteristics of the tropical atmosphere that are of relevance for the development of TCs. In particular we consider the two major mechanisms, dynamical and thermodynamical, that can influence the occurrence of TCs: the vertical gradient of the wind and the moist atmospheric energy availability. Here we compare the interannual anomalies of the vertical wind
shear and CAPE obtained for the DAS and NODAS cases with the anomalies obtained from the observations. The wind shear is defined as the absolute value of the vector wind difference at 300 and 850 hPa \[ \text{windshear} = \sqrt{(u_{300} - u_{850})^2 + (v_{300} - v_{850})^2} \], and CAPE is defined as follows (Emanuel et al. 1994):

\[
\text{CAPE} = \int_{p_{LFC}}^{p_{LNB}} R_d (T_{vp} - T_{ve}) d\ln p,
\]

where \( p_{LFC} \) and \( p_{LNB} \) are the pressure of the level of free convection (LFC) and the pressure of the level of neutral buoyancy (LNB), respectively; \( R_d \) is the dry-air gas constant; and \( T_{vp} \) and \( T_{ve} \) are the virtual temperature of an air parcel and the environment (sounding), respectively.

Over each TC activity domain, we computed area-averaged correlation coefficients (AACs) between forecasts and observations for both the wind shear and the CAPE. In Table 7 the comparison between DAS and NODAS is reported, showing that the impacts of the ocean initialization are linked to a considerable difference in CAPE. In fact, we found enhanced AACs for CAPE in DAS over the ENP, SI, and SP. However, over the SP a concurrent worsening of the wind shear counteracting the above-mentioned improvement is found. Quite similarly, the WNP also shows mixed results, with a moderate AAC increase for CAPE and a moderate AAC reduction for the wind shear. Conversely, the AAC doubling for CAPE in the SI is also accompanied by the improvement of the wind shear, thus together possibly contributing to the enhanced probabilistic quality of the forecasts over this region (see Fig. 11). In the
ATL, NODAS shows higher correlations with the observed CAPE anomalies, and this is consistent with the reduced probabilistic quality of the TC predictions in DAS (Fig. 11). As discussed in section 3c, the biases in the atmospheric circulation and thermodynamics appear to limit the skill over the NI basin. Consistently, the enhanced TC counts prediction in DAS follows at least in part from the reduction of the bias in the SST (see also the previous discussion earlier in this section) and in the biases in the atmospheric circulation and thermodynamics. In particular, the climatologies of both vertical wind shear and CAPE are closer to observations in DAS compared to NODAS (not shown). Furthermore, Table 7 shows that the enhanced TC counts prediction is also in part related to the improved representation of the interannual anomalies in the wind shear in DAS. This appears to be connected to the improved representation of the relationship between ENSO and TC counts over the NI compared to NODAS (see Table 3). In fact, over the western Indian Ocean, DAS better represents, compared to NODAS, the observed negative correlation between ENSO and wind shear anomalies (not shown). Furthermore, NODAS displays a strong tendency to positive wind shear anomalies over the eastern tropical Indian Ocean during El Niño years, which is not found in the observations. This problem over the eastern tropical Indian Ocean is at least in part due to the known tendency of the coupled model to represent a too shallow thermocline over this region (Fischer et al. 2005). In fact, this systematic bias favors variability by sensitizing the system, and small initial disturbances are allowed to develop into too strong wind thermocline SST feedbacks in this region (Fischer et al. 2005; Cherchi et al. 2007). The above-mentioned shortcoming appears to be strongly reduced in DAS. In this regard, the subsurface initialization procedure appears to effectively decrease reactivity in DAS over the eastern tropical Indian Ocean by deepening and making the thermocline slope more similar to observations.
5. Conclusions

The forecasts by the CMCC-INGV Seasonal Prediction System are able to reproduce the geographical distribution of observed tropical cyclone (TC) genesis, both in the Northern and Southern Hemispheres. Even if a lower number of TCs is detected in the forecasts compared to observations (an underestimation of about 30% has been evidenced), in general the relative abundance in the different areas is well represented. Compared to a coupled model simulation performed with only the prescription of the historical radiative forcing, the forecasts considerably improve the TC climatological distribution. In particular, in the southern tropical Atlantic, where no TCs have been observed during the period 1992–2001, the forecasts resemble much more closely the observations. This improvement in the TCs climatology follows, at least in part, from the considerable reduction of the SST bias when the coupled model is run in forecasting mode.

The CMCC-INGV SPS displays good skill in predicting the observed TC interannual count anomalies. In particular, the predicted TC count anomalies are significantly correlated to the observed ones in the eastern North Pacific (ENP; $r = 0.78$, 5% significance level), in the South Pacific (SP; $r = 0.67$, 5% significance level), in the oceans surrounding Australia (AUS; $r = 0.59$, 5% significance level), in the North Atlantic (ATL; $r = 0.47$, 10% significance level), and in the western North Pacific (WNP; $r = 0.44$, 10% significance level).

The predicted interannual TC count variability appears to be correlated with ENSO similarly to what is

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<th>Regions</th>
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<td></td>
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<td>ENP</td>
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</tr>
<tr>
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<tr>
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<td>SP</td>
<td>$E_-$</td>
</tr>
<tr>
<td></td>
<td>$E_+$</td>
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Fig. 11. As in Fig. 8, but for TC counts.
found in the observations. However, the connection between ENSO and the forecasted TC counts appears to be overestimated in the Northern Hemisphere basins, indicating that other important sources of TC variability might be missing in the model. A possible missing source for TC count variability could originate from the lack of intraseasonal oscillation activity, such as the MJO (Hall et al. 2001; Vitart 2009), which is known to be underestimated in the CGCM in use (Sperber et al. 2005). Furthermore, other not well-represented processes or uninitialized phenomena could play a nonnegligible role. For instance, the lack of a proper initialization of the long-lasting land variables (e.g., Koster et al. 2004, 2006; Ferranti and Viterbo 2006; Alessandri and Navarra 2008) could be one reason for the too weak non-ENSO-related signal in the predictions over the Northern Hemisphere activity regions.

The prediction of TC count interannual anomalies has been shown to be sensitive to the subsurface assimilation in the ocean for initialization. The comparison of the predicted TC count interannual anomalies shows a better performance of the forecasts initialized using subsurface assimilation (DAS) than the forecasts performed with no temperature and salinity assimilation (NODAS). DAS significantly (5% level; Monte Carlo method) increases the correlation coefficient between predicted and observed TC count anomalies in the ENP \((r = 0.78 \text{ vs } r = 0.53)\), NI \((r = 0.22 \text{ vs } r = -0.79)\), and AUS \((r = 0.59 \text{ vs } r = 0.21)\). Notice that the NI, which is the region with the larger SST bias reduction in DAS, is also the region displaying the larger increase in the TC counts correlation with observations.

The assimilated ocean initial conditions have been shown to improve the probabilistic quality of the predictions. In fact, the capability of the forecasts to discriminate anomalous (i.e., below lower tercile or above upper tercile of the sample distribution) TC counts is enhanced over the ENP, the NI, the AUS, and the SI. For the ENP and NI, the discrimination distance of both below-normal and above-normal TC counts is significantly (5% significance level) improved. In the AUS, DAS appears to improve significantly only for below-normal TC forecasting. Conversely, in the SI region, the forecasts only improve for the prediction of above-normal TC counts. Our results indicate that the enhanced discrimination of the interannual TC counts in DAS follows the improvements in the daily SST discrimination. The only exception is the SI, where a significant improvement is observed in the discrimination distance of above-normal TC counts in DAS, while no substantial effect is observed in the prediction of anomalous daily SSTs. In the North Atlantic basin, a significant worsening is shown for the discrimination of above-normal TC counts in DAS. This result is consistent with the better NODAS discrimination of both below-normal (5% significance level) and above-normal (5% significance not verified) daily SST.

The impacts of subsurface assimilation on the forecast of TC count anomalies appear to be related to the prediction of convective available potential energy (CAPE) and wind shear. Our analysis suggests that over the ENP and ATL, the skill changes are linked to modifications in the ability to represent interannual CAPE variations. Over the SI, both CAPE and wind shear appear to contribute to the enhanced probabilistic quality of the TC counts prediction in DAS (Fig. 11). Considering the NI, the results indicate that the enhanced TC counts prediction in DAS follows mostly from the reduction of the bias in SST, vertical wind shear, and CAPE. Furthermore, the better prediction of TC counts over NI appears to be in part related to the improved forecasts for interannual anomalies in the wind shear over this region. The improvement of the wind shear anomalies, compared to NODAS, appears to be, in turn, connected to the better representation of the relationship with ENSO variability.

Acknowledgments. This work was partially supported by the project Climate Change Assessment in Small Pacific Islands States funded by the Italian Ministry for the Environment, Land and Sea. Many thanks for the generous support from several CMCC staff. We especially thank Annalisa Cherchi, Pierluigi Di Pietro, Fabrizio Massari, Loredana Amato, Alberto Troccoli, Geert Jan van Oldenborgh, and Antje Weisheimer for

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their help and for the inspiring discussions. We are grateful to the anonymous reviewers, whose comments greatly improved the quality of the manuscript.

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