Tropical Cyclones in the 7-km NASA Global Nature Run for Use in Observing System Simulation Experiments

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ABSTRACT

The National Aeronautics and Space Administration (NASA) nature run (NR), released for use in observing system simulation experiments (OSSEs), is a 2-yr-long global nonhydrostatic free-running simulation at a horizontal resolution of 7 km, forced by observed sea surface temperatures (SSTs) and sea ice, and inclusive of interactive aerosols and trace gases. This article evaluates the NR with respect to tropical cyclone (TC) activity. It is emphasized that to serve as an NR, a long-term simulation must be able to produce realistic TCs, which arise out of realistic large-scale forcings. The presence in the NR of the relevant dynamical features over the African monsoon region and the tropical Atlantic is confirmed, along with realistic African easterly wave activity. The NR Atlantic TC seasons, produced with 2005 and 2006 SSTs, show interannual variability consistent with observations, with much stronger activity in 2005. An investigation of TC activity over all the other basins (eastern and western North Pacific Ocean, north and south Indian Ocean, and Australian region), together with important elements of the atmospheric circulation, such as the Somali jet and westerly bursts, reveals that the model captures the fundamental aspects of TC seasons in every basin, producing a realistic number of TCs with realistic tracks, life spans, and structures. This confirms that the NASA NR is a very suitable tool for OSSEs targeting TCs and represents an improvement with respect to previous long simulations that have served the global atmospheric OSSE community.

1. Introduction

Observing system experiments (OSEs), also known as data impact studies, represent a procedure to explore the impact of an existing instrument on a given forecasting capability. OSEs require a comprehensive set of observations, a data assimilation system (DAS), and a forecast model. At least two sets of parallel analyses are produced by assimilating 1) the comprehensive observational dataset (ideally comprising all of the data operationally used) and 2) the same observational set with or without the data from the specific instrument whose impact is being investigated. Corresponding sets of parallel forecasts are initialized from each set of analyses so that their different skills can be assessed with various metrics against some validating analyses.

In contrast, observing system simulation experiments (OSSEs) are often used by atmospheric scientists and instrument developers to evaluate the potential impact of a future instrument. With respect to OSEs, an OSSE framework requires a nature run (NR) and a methodology for simulating realistic observations, in addition to the DAS and forecast model. An NR is a free-running simulation produced by a state-of-the-art model and is supposed to satisfy many stringent requirements, one being “a realistic climatology consisting of realistic weather patterns” (McCarty et al. 2012, p. 1863; italics added). The NR is needed to extract simulated synthetic observations of a future sensor that are assimilated, together with the simulated observations of the existing sensors, in the DAS, producing sets of analyses from which forecasts can be issued.

One fundamental difference between OSEs and OSSEs is that in OSSEs, the true atmospheric state is precisely known from the NR. Consequently, instrument errors can be explicitly formulated and OSSEs can be used to explore...
analysis error statistics of already existing observing systems (Errico et al. 2007). For a comprehensive review of OSSEs see, among others, Errico et al. (2013), Privé et al. (2013a,b), Atlas et al. (2015), Ma et al. (2015), and Hoffman and Atlas (2016).

The purpose of this article is to evaluate the realism of the new 7-km National Aeronautics and Space Administration (NASA) NR with respect to tropical cyclone (TC) activity. Two caveats are necessary. First of all, it is important to clarify that different instrument science teams may have different requirements for an NR to be considered realistic. This particular assessment aims at demonstrating that this new NR can 1) produce realistic TCs from realistic large-scale forcings and 2) represent features at scales of about 15 km around TCs. Therefore, the science team for the Cyclone Global Navigation Satellite System (CYGNSS), or other teams focused on comparable future instruments, could benefit from this NR to produce realistic OSSEs focused on the prediction of wind features around high-impact weather systems, such as TCs and intense extratropical disturbances. Teams performing OSSEs for measurements at much higher resolution could still benefit from this NR by using it as a forcing for downscaled simulations, a strategy previously documented by Nolan et al. (2013).

Second, the terms “evaluation” and “assessment” are preferred to “validation” in this work. The reason is that an NR cannot strictly be validated as an actual forecast can be. In fact, being a free simulation forced by sea surface temperatures (SSTs) and sea ice, weather events in an NR cannot match corresponding actual weather events, since the memory of initial conditions is lost within a few weeks. Time in the NR does not correspond to factual time, except that we may expect some statistical similarity on an interannual basis due to the real SST and sea ice that are used. The evaluation of the NR therefore comprises two steps: an overall assessment of its statistical properties, as complete as possible (which is not the subject of this article); and a verification that these statistics arise out of instantaneously meaningful states of the atmosphere. A phenomenological approach showcasing comparisons between weather events in the NR and weather events in the real world is one way to investigate instantaneous states of the atmosphere. These comparisons are the focus of this article.

The article is organized as follows: Section 2 discusses TCs as detected in previous NRs; section 3 provides a general description of the new NASA NR and of the extensive team evaluation effort that has already been carried out; section 4 focuses on an examination of NR TC activity compared to observations over the various basins (Atlantic Ocean, eastern and western North Pacific Ocean, north and south Indian Ocean, Australian region). Elements of the circulation that are important in TC formation or in controlling the TC evolution are also discussed. Last, section 5 states the conclusions of this work.
2. Tropical cyclone activity and structure in previous nature runs

Considering the cost of spaceborne instruments, a realistic estimate of their potential benefit is exceptionally important, hence the political and economic implications of OSSEs. However, in order to be realistic and credible, a standardized OSSE framework would be desirable. OSSEs do not provide the desired benefit if different investigators perform them for the same instrument and obtain contrasting results.

An important source of discrepancy in OSSEs can arise out of the use of different NRs. Even if the same NR is used, the credibility of OSSEs could be hindered by the use of 1) NRs whose quality is not sufficiently good or whose resolution is inadequate; 2) NRs whose realism has not been investigated in depth; and 3) NRs that are too close to the forecast model, potentially resulting in the so-called identical twin problem (Atlas 1997).

Ideally, the NR should be as far from the forecast model as the true atmosphere (Hoffman et al. 1990) is. Aside from the difficulty of attaining this goal, the creation of an NR for widespread use is a nontrivial matter. The NR should be among the best possible simulations available at a given time. It should also be evaluated by, distributed to, and shared with a large OSSE community. To produce a global nature run with these requirements is a demanding and extraordinarily computationally expensive
task that only few centers in the world can afford. For this, among other reasons, multiagency collaborations to standardize OSSEs were attempted as early as the mid-1980s (e.g., Atlas et al. 1985; Arnold and Dey 1986). With this frame of mind, a renewed international informal collaboration, often referred to as Joint OSSE project, between scientists in different agencies and centers including, but not limited to, the European Centre for Medium-Range Weather Forecasts (ECMWF), the National Oceanic and Atmospheric Administration (NOAA), and NASA, was initiated in the mid-2000s (Masutani et al. 2007; Kleist and Ide 2015). As part of this collaborative effort, the ECMWF produced and released in 2006 a 1-yr-long NR to serve the OSSE community.

The ECMWF NR (ECMWF T511 NR) was produced at a T511 wave truncation, corresponding to an actual resolution of about 40 km at the equator and was documented, among several others, by Reale et al. (2007), Masutani et al. (2010), Andersson and Masutani (2010), and McCarty et al. (2012). Amidst many outstanding and unprecedented qualities, the ECMWF T511 NR was arguably considered the first free-running long simulation, forced by prescribed 2005 SSTs and sea ice, which produced a realistic depiction of TC activity. The TC activity was considered realistic because 1) the average climatological factors that are conducive to cyclogenesis were present and 2) the frequency, distribution, life cycle, and track of TCs were within observed climatological values. The team evaluation of the ECMWF T511 NR

![Fig. 3. As in Fig. 2, but for 2006.](image)
demonstrated not only that TCs were present, but that they originated out of realistic and very specific weather patterns associated with TC genesis in reality. The evaluation also showed that TCs produced by the ECMWF T511 NR underwent realistic evolution and decay, including dissipation, landfall, extratropical transitions, and binary vortex interaction. Moreover, individual TCs displayed an overall realistic structure in terms of vertical alignment, presence of a warm core, low-level winds in excess of 50 m s⁻¹, and an eyelike feature (i.e., a virtually windless column), as shown by Reale et al. (2007). While the eyelike feature was broader and more diluted than a real TC eye, due to limited T511 horizontal resolution, the ECMWF T511 NR nevertheless represented a remarkable modeling achievement and has been serving as an invaluable tool for several years. Among others, the NOAA Earth System Research Laboratory OSSE capability (Privé et al. 2013c) and the NASA Global Modeling and Assimilation Office (GMAO) OSSE baseline (Errico et al. 2013) and evaluation (Privé et al. 2013b) were built on the ECMWF T511 NR.

However, since 2006, with the exponential growth in high-end computing resources, the associated increase in global models’ resolution, and the steady augmentation of new sensors’ capabilities, there are multiple reasons to create a new nature run. NASA has a special interest in OSSEs, because they enable instrument developers to conceive, justify, and develop new sensors. Aside from assisting the design of a future sensor, OSSEs are also an essential tool for science teams of instruments that are already scheduled to launch but are not in space yet, because OSSEs can be used to design, develop, and test the new data assimilation procedures needed to maximize the lifetime utility of the new sensor. An example, documented by Annane et al. (2015), is focused on the mission CYGNSS, which has an expected launch in December 2016.

Pressed by these needs, a number of long simulations at increasing resolutions have been produced over the years by the GMAO with a similar configuration to the ECMWF T511 NR: initialization in May 2005, prescribed SSTs and sea ice, but with the integration extending more than 2 years in order to have a measure of some interannual variability. Comprehensive assessments were performed by this and other teams.

From the point of view of TCs, which are the focus of this article, particularly noteworthy was the 2-yr cubed-sphere c720 simulation at 14-km horizontal resolution (Putman and Suarez 2011). It represented an important advance in that it produced not only a reasonable number of TCs but also a very good representation of the interannual variability in TC activity observed between 2005 and 2006. Additional GMAO 2-yr simulations with the same settings, but at 10-km resolution, were also produced and provided further improvement (not shown). These long simulations and others were all evaluated as potential next-generation NRs but ended up representing only intermediate steps toward the NR that eventually was publicly released in 2015 by the GMAO, and which is the subject of this investigation.

3. The 7-km NASA nature run

a. General description and comprehensive team evaluation

The new NASA NR, produced with a cubed-sphere nonhydrostatic mesoscale version of the Global Earth Observing System Model, version 5 (GEOS-5), is described in great detail in the comprehensive NASA technical memorandum by Gelaro et al. (2015), which is a public document available online. The GEOS-5 NR (G5NR) was run with a cubed-sphere geometry of 1440 x 1440 grid cells (c1440) within each of the six faces.
of the gnomonic cube-sphere grid (Putman and Lin 2007) nearly uniformly distributed around the globe. This corresponds to a horizontal resolution of about 7 km around the equator \[40000 \text{ km} / (1440 \times 34 \text{ grid cells}) \approx 7 \text{ km}\]. The G5NR is thus capable of partially resolving features as small as mesoscale complexes and TCs.

A major collaborative effort, involving several months of work by a multidisciplinary team of about 25 scientists, was necessary to evaluate the G5NR. As part of this effort, Putman (2015) provides a general overview of the model aspects and an overall description of the type of phenomena that can be represented in the simulation. Privé et al. (2015) give a general statistical evaluation of wind and temperature, inclusive of spectral analysis, comparing it with reanalysis data and confirming the overall realism of the NR. Molod et al. (2015) investigate in depth humidity and precipitation fields, comparing the G5NR with both reanalyses and observational datasets. Draper et al. (2015) investigates the surface characteristics from land, ocean, and ice perspectives. Norris et al. (2015) performs an evaluation of clouds and radiation in the NR against the Clouds and the Earth’s Radiant Energy System (CERES) and Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP) data. Ott et al. (2015) produces an assessment of the representation and realism of aerosol and trace gases in the NR. It should be emphasized that the treatment of radiatively active aerosols and trace gases is a novel feature for the OSSE community, made possible by the inclusion of the Goddard Chemistry Aerosol Radiation and Transport model (GOCART; Chin et al. 2002), which is coupled with the GEOS-5 radiation code (Colarco et al. 2010). From the perspective of TCs, which are the subject of this article, previous work had demonstrated that the impact of interactive treatment of Saharan dust improves the representation of the African easterly jet in the GEOS-5 (Reale et al. 2011) and affects tropical cyclogenetic processes (Reale et al. 2014).

Aside from the evaluation of an NR’s comprehensive statistical properties, which may differ up to a certain acceptable threshold (within observed natural variability) from the corresponding properties of the real atmosphere, it is important to evaluate any NR from a phenomenological perspective, that is, focusing on snapshots of specific weather events. While these events cannot correspond to actual events that occurred in the real world, they nevertheless must constitute an acceptable representation of something possible, falling within the range of observed phenomena.

In fact, OSSEs are often carried out by targeting one specific weather event simulated in the NR. Analyses are created by assimilating synthetic observations extracted

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**Table 1. Simulated (NR) and observed (BT) TCs, 2005 Atlantic season.**

<table>
<thead>
<tr>
<th>Nature run</th>
<th>Start–end date</th>
<th>Min SLP (hPa)</th>
<th>Best track</th>
<th>Start–end date</th>
<th>Min SLP (hPa)</th>
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</thead>
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<td></td>
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<td>TC No.</td>
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<td>931</td>
<td>1800 UTC 28 Jun–0000 UTC 30 Jun</td>
<td>1002</td>
<td></td>
</tr>
<tr>
<td>3</td>
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<td>972</td>
<td>1800 UTC 3 Jul–0600 UTC 11 Jul</td>
<td>991</td>
<td></td>
</tr>
<tr>
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<td>1800 UTC 4 Jul–0600 UTC 18 Jul</td>
<td>930</td>
<td></td>
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<tr>
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<tr>
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<tr>
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<td>—</td>
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<td>0600 UTC 8 Oct–1200 UTC 11 Oct</td>
<td>988</td>
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<tr>
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<td>1800 UTC 15 Oct–1800 UTC 26 Oct</td>
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<td>22</td>
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<td>—</td>
<td>1200 UTC 22 Oct–1800 UTC 24 Oct</td>
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<td>1800 UTC 26 Oct–0000 UTC 31 Oct</td>
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<td>—</td>
<td>—</td>
<td>0000 UTC 14 Nov–0000 UTC 22 Nov</td>
<td>1002</td>
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<tr>
<td>25</td>
<td>—</td>
<td>—</td>
<td>1200 UTC 19 Nov–1800 UTC 29 Nov</td>
<td>980</td>
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<tr>
<td>26</td>
<td>—</td>
<td>—</td>
<td>0600 UTC 29 Nov–1800 UTC 9 Dec</td>
<td>981</td>
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<td>27</td>
<td>—</td>
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<td>0000 UTC 30 Dec–1800 UTC 7 Jan</td>
<td>994</td>
<td></td>
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</tbody>
</table>
from NR states preceding that specific event, and forecasts can be initialized from those analyses. Therefore, an OSSE can give information on whether the addition of a new sensor can enhance the ability to predict that event, using the NR as a validating truth.

b. Weather phenomena and possible use of the G5NR

Aside from TCs, which are the subject of this article, it is important to mention that the G5NR has been investigated also from the point of view of other weather phenomena that may be of interest to scientists developing OSSEs.

For example, Putman (2015), discussing resolved features, finds great realism in the overall distribution of extratropical cyclone track and genesis location. Of interest for future OSSEs targeting instruments focused on frozen precipitation is the study of intense baroclinic winter cyclones, such as U.S. mid-Atlantic snowstorms. In this regard, Putman (2015) showcases an example of a simulated major East Coast snowstorm whose track and accumulated precipitation bear a remarkable similarity with observational records (e.g., Kocin and Uccellini 2004).

Other examples of well-reproduced phenomena are several cases of extratropical transitions (ETs). During ET, a warm-cored cyclone evolves into a larger-scale baroclinic system through a number of transformations that include, among others, a change in its primary energy source from latent heat to baroclinic energy conversion processes (e.g., Sinclair 1993; Kyle and Bosart 2014). A very representative case is highlighted in Gelaro et al. (2015, their Fig. 4.31), in which a deep warm-core tropical cyclone undergoing ET is shown.

Several mesoscale structures outside the deep tropics are generally missed or misrepresented in low-resolution global models. For example, high-latitude subsynoptic-scale vortices such as polar lows and Mediterranean tropical cyclone–like storms display similarities with tropical cyclones, including some level of vertical alignment, the presence of an eyelinke feature, the prominent role played by convection, and latent and sensible total heat fluxes, which can reach values comparable to hurricanes, albeit with a larger contribution of sensible heat than latent heat (e.g., Reale and Atlas 2001; Rasmussen and Turner 2003). While the investigation of this type of event is outside the goal of this article and cannot be shown here, polar lows have been noted in the G5NR and they could therefore be targets for OSSEs. In fact, Putman (2015) shows the global distribution of tropical cyclone tracks obtained with a cyclone tracker that detects convective cyclones and requires, among other parameters, the presence of a warm core and vertical

![Fig. 5](image). As in Fig. 4, but for 2006. Corresponding dates in Table 2.

Table 2. Simulated (NR) and observed (BT) TCs, 2006 Atlantic season.

<table>
<thead>
<tr>
<th>TC No.</th>
<th>Start–end date</th>
<th>Min SLP (hPa)</th>
<th>Start–end date</th>
<th>Min SLP (hPa)</th>
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<td>948</td>
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alignment. The tracker, aside from displaying purely tropical cyclones, shows some activity in the high latitudes, for example, between Iceland and Greenland and on the Labrador Sea (Putman 2015, his Figs. 1.13 and 1.14), where polar lows are often observed (e.g., Forsythe and Haynes 2015). These storms’ intensities in the NR range predominantly within the tropical storm level.

Finally, evidence of realistic mesoscale convective complex (MCC) activity in the G5NR is provided by Putman (2015, his Fig. 1.16), showcasing the similarity between one observed MCC over the central United States and one MCC produced by the G5NR, and also documenting a distribution of MCCs during the period May–June of 2005 and 2006 in the NR, which compares well with composite geostationary IR observations (Putman 2015, his Fig. 1.17).

4. Tropical cyclone activity and structure in the G5 nature run

a. Tropical cyclones in the Atlantic

With TCs being the reasonable target of many future instruments, OSSEs have and will often be performed to investigate the potential use of such measurements to improve TC forecasts (e.g., Privé et al. 2014). For this reason, it is of paramount importance that TC activity, life cycle, and structure are realistic in the NR. Following the same strategy that was previously adopted by Reale et al. (2007) to evaluate tropical cyclones in the ECMWF T511 NR, it is important to first verify that TCs occur in the G5NR not as sporadic or localized events, but as a realistic consequence of large-scale forcings in a manner comparable to reality. The preliminary step is to verify that the climatology of the main dynamical factors over the African monsoon region and the tropical Atlantic is well represented. The Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2), described and documented by Bosilovich et al. (2015, 2016) and by Wargan and Coy (2016), is used for comparison. MERRA-2 is the new generation of the well-known MERRA (Rienecker et al. 2011) that has been successfully used, among many others, in studies concerning the meteorology of the African monsoon and tropical Atlantic region (e.g., Wu et al. 2012, 2013).

![Fig. 6. Structure of G5NR-AL022005 (see Fig. 4; Table 1). Zonal vertical cross sections of winds (shaded, m s\(^{-1}\)) and temperature (black contours, °C). Temperature anomalies (°C, red thick contours, contours every 2°C, only values >8°C are plotted for clarity) with respect to a zonal mean within 10° of the TC center. Vertical coordinate in model levels. Levels 72, 50, and 40 correspond to nominal pressures of 985.00, 487.500, and 127.837 hPa, respectively, at the top edge of the layer. Full conversion table in da Silva et al. (2014).](image-url)
Figure 1 shows a meridional vertical cross section of zonal wind at 0°, comparing the NR in the July–September (JAS) months of two different years with the corresponding MERRA-2 years. It is worth stressing that a comparison of monthly means cannot be interpreted as an actual seasonal forecasting validation. Since the NR is a free-running simulation constrained by SSTs and sea ice, and in which the memory of initial conditions is removed by the sufficiently long spinup, a strict correspondence with observed means cannot and should not be expected. It can only be noted that the NR represents the basic features of the African monsoon circulation, namely: 1) the tropical easterly jet (TEJ), an upper-tropospheric jet located close to the equator at about 100–200 hPa; 2) the African easterly jet (AEJ) at about 600 hPa and peaking at about 12°–16°N; 3) the low-level westerly monsoonal flow confined below 800 hPa; and 4) the low-level easterly flow (also known as Harmatthan flow) at about 27°N. The overall depiction of the AEJ in the NR is about 15% weaker than
in MERRA-2, but it should be remembered that the AEJ depiction is affected by very large uncertainties, with differences of 20% in speed even among state-of-the-art reanalyses such as the 40-yr ECMWF Re-Analysis (ERA-40), the National Centers for Environmental Predictions, Reanalysis 2, (NCEP-R2), the Japanese 25-year Reanalysis Project (JRA-25), and MERRA, as discussed in detail in Wu et al. (2009, 2012). On the contrary, the representation of the Harmattan flow is stronger in the NR than in MERRA-2. However, since the Harmattan is a low-level, concentrated, easterly flow partly constrained by the orography of the Atlas Mountains on its northern flank (e.g., Nicholson 1996, 2013), it is possible that the MERRA-2 coarser resolution hinders the Harmattan’s representation in the reanalysis.

![Figure 9](image_url)

**FIG. 9.** Hourly accumulated precipitation (mm h\(^{-1}\)) for GSNR-AL042006 (see Fig. 5; Table 2) compared with NEXRAD level 3 accumulated hourly precipitation for Katrina at 1230 UTC 29 Aug 2005.
Aside from the intensity, the position of the AEJ, TEJ, and low-level monsoonal flow is very important because the cyclonically sheared southward side of the AEJ (in which horizontal shear dominates) is conducive to barotropic instability at about the jet level, while the lower levels just below the AEJ (in which vertical shear dominates) are conducive to baroclinic instability. African easterly waves (AEWs) arise out of a combination of mechanisms: the presence of localized triggers, which can be convective in nature and may alter the vorticity and thermal profile of the atmosphere, and the favorable large-scale environment in which barotropic–baroclinic instability of the Charney–Stern type can occur (e.g., Kiladis et al. 2006; Hall et al. 2006; Thorncroft et al. 2008; Wu et al. 2012). Moreover, the presence of the TEJ, which is responsible for strong easterly shear and is generally unfavorable for development of vertically aligned structures, is an important forcing that confines the potential development of TCs to a narrow latitude range (just a few degrees south of the AEJ and north of the TEJ). The presence of all the fundamental elements of the African monsoon region atmospheric circulation is a good preliminary assurance that the model may be capable of producing realistic weather patterns.

The next logical step is to verify whether the NR is able to produce realistic AEW activity. This is a complex issue because at least three types of AEWs are currently known: the 2.5–6-day waves developing to the south of the AEJ at about the jet level, the low-level baroclinic waves developing below the AEJ, and the less-known 6–9-day waves developing at the AEJ level, to the north of it. For a comprehensive discussion of various types of AEWs, see Wu et al. (2013). The AEWs that are more relevant to TC development are the 2.5–6-day waves developing to the south of the AEJ at about the jet level. In addition, the tracking or definition of AEWs may involve sophisticated objective methodologies (i.e., Berry et al. 2005) or the use of spectral techniques, such as the Hilbert–Huang transform (Wu et al. 2013). However, a very simple and immediate way of detecting AEW activity is to plot a latitude–time Hovmöller diagram of the meridional component of the wind at, or

![Fig. 10. Simulated and observed 2005 eastern North Pacific TCs from (a) G5NR and (b) NHC best tracks. Colors as in Fig. 4. Corresponding dates in Table 3.](image)

| Table 3. Simulated (NR) and observed (BT) TCs, 2005 east Pacific season. |
|----------------------------------|-----------------|-----------------|-----------------|
| TC No. | Nature run | Start–end date | Min SLP (hPa) | Start–end date | Min SLP (hPa) |
| 1 | 1730 UTC 29 Jul–0500 UTC 4 Aug | 975 | 1800 UTC 17 May–0000 UTC 21 May | 982 |
| 2 | 2030 UTC 2 Aug–0330 UTC 8 Aug | 968 | 1800 UTC 21 Jun–0600 UTC 26 Jun | 1000 |
| 3 | 1000 UTC 11 Aug–2230 UTC 13 Aug | 967 | 0600 UTC 26 Jun–1200 UTC 3 Jul | 1000 |
| 4 | 0800 UTC 9 Sep–0700 UTC 12 Sep | 967 | 0000 UTC 4 Jul–1800 UTC 6 Jul | 1002 |
| 5 | 0300 UTC 16 Sep–2200 UTC 23 Sep | 962 | 0600 UTC 18 Jul–1800 UTC 21 Jul | 989 |
| 6 | 0700 UTC 20 Sep–1300 UTC 22 Sep | 968 | 1200 UTC 9 Aug–1200 UTC 17 Aug | 978 |
| 7 | 2130 UTC 7 Oct–2230 UTC 10 Oct | 968 | 0600 UTC 11 Aug–1800 UTC 15 Aug | 1000 |
| 9 | — | — | 1200 UTC 25 Aug–1800 UTC 2 Sep | 1000 |
| 10 | — | — | 0000 UTC 12 Sep–0000 UTC 25 Sep | 951 |
| 11 | — | — | 1800 UTC 14 Sep–1800 UTC 30 Sep | 947 |
| 12 | — | — | 1200 UTC 17 Sep–0000 UTC 19 Sep | 1005 |
| 13 | — | — | 1200 UTC 17 Sep–1200 UTC 22 Sep | 987 |
| 14 | — | — | 0000 UTC 23 Sep–0000 UTC 1 Oct | 997 |
| 15 | — | — | 0000 UTC 28 Sep–1200 UTC 5 Oct | 970 |
slightly below, the jet level and at a latitude south of the jet.

In Fig. 2 the 700-hPa Hovmöller of the meridional wind, obtained from the NR for August 2005, is plotted for the latitude of 15°N and for a longitude range spanning from 40°W to 40°E, to be compared with the same quantity computed from MERRA-2 data. In Fig. 3 the same plot is produced for August 2006. The comparison between the NR and reanalyses in both years reveals that the amplitude, frequency, and propagation speed of the AEWs is very similar. In particular, waves occur at a given longitude approximately every 3–6 days and propagate westward at a speed of about 5–8 day⁻¹. Other features of the AEWs present in both the NR and MERRA-2 include 1) a discontinuity at about 15°W, where disturbances transition from land to ocean, and 2) a pronounced diurnal cycle over the continent (evident by the horizontal lines on the easternmost side of the panels). Other realistic features are 1) occasional higher wind speeds, indicating the tendency of some AEWs to develop as TCs; 2) upward curvatures (indicating acceleration); and 3) disappearance (indicating either dissipation or disturbances that move to the north of the Hovmöller latitude). In general, higher detail and slightly more intense waves are present in the NR due to the higher resolution. The overall similarity between the AEW activity in the NR and in the reanalyses can be found in other months as well (e.g., July and September, not shown).

The next step is to investigate TC number, tracks, distribution, and life cycles. Figure 4 shows the tracks and center pressure of TCs in the NR and in the observations for 2005. The corresponding Table 1 shows the storm number, beginning and end dates for each storm, and the minimum center pressure. An important caveat is valid for this and all following figures containing TC tracks and corresponding TC tables for other basins. The storm detection algorithm applied to the NR

![Image of Hovmöller diagram](image)

**Table 4.** Simulated (NR) and observed (BT) TCs, 2006 east Pacific season.

<table>
<thead>
<tr>
<th>TC No.</th>
<th>Start–end date</th>
<th>Min SLP (hPa)</th>
<th>Start–end date</th>
<th>Min SLP (hPa)</th>
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<td>956</td>
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</tr>
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<td>955</td>
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<td>1000</td>
</tr>
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</tr>
<tr>
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</tr>
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</tbody>
</table>
involves thresholding parameters, such as central pressure and the presence of a warm core. The results are sensitive to the values of the thresholds. In particular, it was found that less stringent thresholds in terms of warm-core intensity allow many more (weaker) depressions to be detected as TCS, especially over the Indian Ocean. For clarity, it was decided to use higher thresholds in the tracker, to concentrate on stronger storms, and to use the same more stringent criteria throughout all basins. This led to a slightly lower total number of TCs. Individual researchers can alter these criteria according to their needs, and they may be able to detect a slightly higher number of TCs than the 17 TCs shown in Fig. 4, by including some weak systems at a tropical depression intensity level. The choice of thresholds in the detecting algorithm also affects a TC's life span: a system undergoing transition can be categorized as extratropical (or still tropical) with a more (or less) stringent threshold. Since we have consistently used a stringent definition of TC, it should be noted that some TC tracks shown here could be prolonged if less restrictive tracking choices were to be adopted.

The comparison between NR and BT TCs shows that the TCs produced by the NR are less than the observed (17 vs 27, the latter number being an all-time record), but it also indicates that the track distribution in the NR is very realistic (Fig. 4). The majority of the TCs are of the Cape Verde type, moving across the Atlantic and recurving north. Two TCs originate in the Gulf of Mexico, leading to an overall realistic partition between Gulf and Atlantic systems (e.g., Asnani 2005). One system (G5NR 2005 TC 17) originates in the westerlies, which is typical for late-season hurricanes. It is particularly noteworthy that five G5NR TCs reach center pressures of less than 945 hPa, in good agreement with the observations for that year.

FIG. 12. Hovmöller of equatorial low-level zonal wind in JJA 2006 across the central Pacific from (left) G5NR (at level 70) and (right) MERRA-2 (at 950 hPa).

1 http://www.nhc.noaa.gov/data/#hurdat.
In contrast, the NR produces only 10 TCs in the 2006 season, which agrees closely with the 9 TCs observed in the much less active observed 2006 year (Fig. 5; also see Table 2). It should not be expected that a free-running model forced by SST and sea ice produces the same number of cyclones as in observations, since there are many factors controlling TC frequency other than SST. Moreover, as previously stated, the choice of the detection algorithm affects the TC number. However, it is important that model-generated natural variability does not contradict the observed variability. For reference, it should be noted that the ECMWF NR produced 12 TCs with 2005 SSTs (Reale et al. 2007).

The fact that the interannual variability in the NR has the same sign as the observed one suggests that SST alone, as reasonable to expect, exerts some control on TC number. As noted for 2005, the distribution of tracks in 2006 is realistic in the NR, with a majority of Cape Verde systems and four storms forming in the Caribbean or in the Gulf.

In both years the TCs produced by the NR display a life time of a few days or less to almost two weeks. Individual tracks reveal singularities (i.e., discontinuous curvature changes) as well as binary interaction (i.e., two cyclones rotating around a common center with the stronger one moving slower, not shown), all features that are well known to forecasters and that frequently occur in the real atmosphere.

The final step in the investigation consists of examining the individual structure of the most intense storms taken at representative times. Figure 6 shows a zonal vertical cross section of wind and temperature across G5NR 2005 Atlantic TC 2 (see Fig. 4, G5NR-AL022005), taken at 1200 UTC 16 August 2005. The expected features of a mature hurricane can be noted: a vertically aligned structure, with wind speeds in excess of 65 m s$^{-1}$, a well-defined warm core (temperature anomaly greater than 12°C), a scale on the order of a few hundred kilometers, a radius of maximum wind on the order of about 40–50 km, and a distinct eyewall feature with a relatively calm column. The overall structure is very realistic and represents an improvement with respect to the hurricanes seen in the previous ECMWF T511 NR (Reale et al. 2007, their Fig. 4).

The realistic representation of G5NR-AL022005 is not an isolated occurrence in the NR. The subsequent Fig. 7 displays a snapshot of another 2005 hurricane in the NR: TC 12 (G5NR-AL122005) at a mature development stage. The vertical cross section again displays realistic features: a relatively calm central column, a vertical alignment, a scale on the order of hundreds of kilometers, a radius of maximum wind on the order of tens of kilometers, and a pronounced warm core. Interestingly, the snapshot depicting the strongest and most mature hurricane (Fig. 7), whose warm-core temperature anomaly exceeds 14°C, is also the one characterized by the tightest and most narrow eyewall feature. The same plot also shows the wind speed at the level of maximum wind, with the isochrons of 17, 25, and 32 m s$^{-1}$ superimposed. To further appreciate the horizontal scales, a transect of sea level pressure and 10-m wind for the same storm is shown in Fig. 8. The objective determination of TC scales from observations is a very complex problem that has been discussed, among others, by Chavas and Emanuel (2010), Knaff et al. (2014), Chan and Chan (2015), and Chavas et al. (2016). While the objective computation of scales for all TCs in the NR exceeds the purpose of this work, it can be stated that for the storm noted in Figs. 7 and 8, the size appears within the observed range. Moreover, NR TC structures have been investigated at the early stage of development in the Atlantic and in other basins as well (not shown), finding an overall reduction of scale with intensification; a generally larger size for TCs in the western Pacific, in agreement with observations (e.g., Chavas et al. 2016); and also an increase in size with baroclinic transition (Gelaro et al. 2015, their Fig. 4.31), also in agreement with observations (e.g., Hart and Evans 2001).
Another meaningful feature from an OSSE perspective is represented by precipitation structure. Teams designing future sensors to measure precipitation from space may be interested in performing OSSEs on TC-produced precipitation fields. TCs close to landfall in the NR can be qualitatively compared with radar imagery of observed storms whose tracks and intensity are similar.

Figure 9 shows hourly accumulated precipitation produced by G5NR 2006 TC 4 (G5NR-AL042006) and the corresponding precipitation field from Katrina (2005), obtained NEXRAD data level 3 (1-h precipitation totals). G5NR-AL042006 is chosen because its track is comparable to Katrina’s and because of its landfall just to the east of New Orleans. The NR produces a reasonably realistic banded structure and an eye size comparable to Katrina’s eye at landfall.

b. Tropical cyclones in the eastern North Pacific

The seasonal TC activity and the presence of interannual variability have been verified for all the other basins, paying special attention to the problems typically noted in global models. Especially for the Pacific, the impossibility of surface fluxes determined by prescribed SST to respond and adapt to the atmospheric forcings of the simulated TCs present some difficulties. In general, it is observed that a slow-moving TC partially consumes the available heat energy in the underlying ocean, whereas in the G5NR a slow-moving TC over a particularly warm ocean feature will have a constant energy source. Moreover, in the Pacific, mesoscale coupled ocean–atmosphere fluctuations associated with tropical instability waves add an additional level of complexity to the SST structure that cannot be captured without a coupled system (e.g., Zhang and Busalacchi 2009; Zhang 2014).

Figure 10 and Table 3 compare the eastern Pacific TC activity for 2005 in the NR and in observations, while Fig. 11 and Table 4 depict the corresponding 2006 activity. As for the Atlantic, some weak or after-analysis storms in the BT database are not included (EP162005 and EP022006, EP182006 and EP202006). Given the same caveats about the TC detecting and tracking algorithm previously noted, and the fact that by choosing a less restrictive definition of TC, a larger number of weak TCs and longer tracks could be detected, the figures and tables show that some level of interannual variability is reproduced by the NR, with more TCs in 2006. In fact, for 2005 and 2006 observed TCs were 15 and 18, respectively, versus 8 and 19 in the NR. As for TC genesis, the most active region is between 90°–120°W and between 10°–15°N in both the NR and observations, with a predominant TC motion toward the west-northwest. However, the presence of outliers and of TCs displaying erratic

<table>
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<th>Start–end date</th>
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<td>—</td>
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<td>991</td>
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</table>
and/or retrograde motion with respect to the easterly flow, an aspect well known to forecasters and particularly frequent in 2006 (e.g., Pasch et al. 2009), is not captured very well by the NR, with NR TCs displaying less track variability than observed.

c. Tropical cyclones in the western North Pacific Ocean

As noted for the eastern North Pacific, the absence of an atmosphere–ocean interaction in the G5NR is a limiting factor. However, in spite of the absence of air–sea interaction, which could be handled only by a fully coupled global model, it should be noted that some important atmospheric circulation elements, which were missing in previous NRs, are partially represented in the G5NR. Among these, the presence of features resembling westerly bursts is particularly remarkable. Figure 12 compares with matching Hovmöller diagrams the June–August 2006 zonal wind at the equator from the NR (model level 70, nominal pressure of about 955 hPa) and from MERRA-2. Normally, a time–longitude plot of unfiltered equatorial wind across the Pacific should reveal two sets of linear features that represent anomalies propagating in the midst of predominantly easterly flow: peaks of increased easterly speed that travel within the easterly flow, moving from east to west, and regions of decreased easterlies (or westerlies) that travel against the easterly flow, moving from west to east. When the magnitude of the decrease is stronger than the mean easterly flow, these regions of decreased easterlies appear as pulses of eastward-propagating westerly anomalies that are aptly named “westerly bursts.” Westerly bursts are associated with the Madden–Julian oscillation (MJO; Madden and Julian 1971, 1972) but are strongly controlled by other factors, first and foremost the phase of El Niño–Southern Oscillation (ENSO). Transitioning ENSO can affect the “cleanness” of an MJO unfiltered signal. The 2005 and 2006 summers were not very representative in terms of the MJO signal, with the ENSO phase transitioning from positive to negative (2005) and then from negative to positive (2006). However, evidence of westerly bursts (i.e., eastward-moving areas of westerly wind) is nevertheless clear in Fig. 12, particularly to the west of the date line. While the NR underestimated the westerlies’ intensity, it is worth noting that only nonpropagating stationary waves were detected by this team in other previous global noncoupled simulations (not shown). Being cyclonically sheared on their northern flank, westerly bursts propagating along the equator are among the factors that can contribute to increased low-level cyclonic vorticity and therefore to TC genesis over the western North Pacific (e.g., Hogsett and Zhang 2010; Shu and Zhang 2015).

Aside from clear evidence of westerly bursts, the overall complex interaction between the tropical and extratropical atmosphere over the western North Pacific leads to a very large variability of extratropical (ET) transition patterns, well documented in literature (e.g., Harr and Dea 2009). Figure 13 and Table 5 demonstrate that the overall TC activity in the NR is reasonable, with 23 TCs instead of 25 observed. The observed TC tracks and center pressures for the western North Pacific, Indian Ocean, and Australian basins are obtained from the Joint Typhoon Warning Center (JTWC). The majority of the TC genesis points occur between 10°–20°N and 130°–170°E, indicating that there is a general inability of the model to produce TCs close to the equator, possibly because of the weaker-than-observed eastward propagation of westerly bursts (as noted in Fig. 12) and higher-than-observed vertical shear (not shown). A similar situation is noted for 2006 (Fig. 14; Table 6) with 21 simulated TCs against 26 observed. In terms of track distribution, both years show a predominance of west-northwestward tracks with landfall over the Philippines.

Fig. 14. As in Fig. 13, but for 2006. Corresponding dates in Table 6. Observed TC 24 (named Typhoon Dorian) will enter into the north Indian Ocean as TC 7.

and China, and a tendency of northward and northeastward recurvatures north of 25°N. It can be confidently stated that the model reproduces the overall range in track variability. 

As for intensity, several TCs in both NR seasons reach a center pressure well below 950 hPa. Of particular interest is the intensity of one G5NR typhoon in the 2005 season and two in the 2006 season (Tables 5 and 6) whose center pressures go below 920 hPa. However, no TC in the NR reaches the most extreme observed value of 898 hPa recorded in both 2005 and 2006.

G5NR 2006 western North Pacific TC 3 (G5NR-WP032006, following the JTWC naming conventions) is selected for further investigation. Figure 15 shows the meridional and zonal cross sections at peak intensity, when the center pressure reached the remarkable value, for a global model, of 906 hPa. The cross sections indicate a high degree of symmetry with a very well-defined eye, a warm-core temperature anomaly greater than 14°C, winds exceeding 75 m s⁻¹ on all four quadrants, and a radius of maximum wind on the order of about 40 km.

d. Tropical cyclones in the north Indian Ocean

The north Indian Ocean is arguably the most difficult basin for TC forecasting. Aside from well-studied cases in which even the objective analysis of already existing TCs failed to represent TC circulations, as in the infamous 2008 case of Nargis, discussed in Reale et al. (2009), free-running models examined by this team have produced totally inactive north Indian Ocean TC seasons without a single storm, and seasons in which up to 40 TCs were simulated. These unrealistic excesses are probably caused by the extreme sensitivity of any model to small changes in the circulation. In fact, the SSTs over the Indian Ocean are extremely warm (often more than 30°C), but the environment is not generally conducive to TC development because of the very strong shear. In fact, during the summer, the combination of the Somali jet (SJ), southwesterly flow peaking at about 900 hPa, which is particularly important in modulating the Indian monsoon phases (e.g., Krishnamurti et al. 1976; Halpern and Woiceshyn 2001), and the TEJ, easterly flow peaking at about 150 hPa, (e.g., Chen and van Loon 1987; Nicholson et al. 2007), creates zonal shear values of up to ~40 m s⁻¹ or more. In spite of the huge latent and sensible heat fluxes, and the environment being extremely conducive to convection, cyclonic circulations cannot generally overcome the vertical shear except in rare situations when the shear relaxes. Then very sudden development can occur. In other cases TCs can maintain only shallow structures and any upper-level development is eroded above 300 hPa by the upper-level easterly flow. In this

<table>
<thead>
<tr>
<th>Nature run 2006</th>
<th>Best track 2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC No.</td>
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</tr>
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</tr>
<tr>
<td>2</td>
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<td>1230 UTC 28 Jul–1600 UTC 31 Jul</td>
</tr>
<tr>
<td>5</td>
<td>0000 UTC 1 Aug–0200 UTC 2 Aug</td>
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<tr>
<td>6</td>
<td>0330 UTC 9 Aug–1130 UTC 13 Aug</td>
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<tr>
<td>7</td>
<td>0430 UTC 19 Aug–0500 UTC 27 Aug</td>
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<tr>
<td>12</td>
<td>1630 UTC 8 Sep–0500 UTC 16 Sep</td>
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<td>14</td>
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</table>
environment, which essentially has a surplus of energy available but hostile dynamical forcings, small errors in the representation of the shear can lead to large errors in the estimate of TC activity. At the same time, long simulations have suggested that TC activity over this region is very sensitive to the model’s convective parameterizations. It has been customary for this team while analyzing previous long simulations, in addition to finding simulated TC activity over the north Indian Ocean ranging from totally inactive to unrealistically hyperactive, to spot simulated TCs in locations where they have never been detected (not shown).

With this preliminary discussion, it is now easier to place into context the representation of TC activity in the G5NR over the north Indian Ocean. Figures 16 and 17 compare the representation of the Somali jet in 2006 (2005 is not significantly different, not shown). It can be noted that the predominantly easterly flow over the Southern Hemisphere is deflected northward and then northeastward by the combining the effect of the Indian monsoon low and the orography of eastern Africa, in agreement with observations and other modeling studies (e.g., Chakraborty et al. 2009). The higher resolution of the G5NR allows a sharper depiction of the SJ than MERRA-2, including the well-known bifurcation caused by the Horn of Africa. What is most interesting is the SJ vertical structure. From aircraft measurements acquired during campaigns, such as the 1979 Monsoon Experiment (MONEX-79; e.g., Holt and Sethuraman 1985), it is known that the SJ is a very shallow feature, peaking at about 10°–15°N and about 875 hPa, and is disappearing at about 600 hPa. These features are clearly represented in Fig. 17 and are confirmed by the reanalysis. Also noteworthy are the secondary westerly midtropospheric maximum present in the reanalysis at about the equator (which was not detected by this team in any previous long global simulations) and the excellent depiction of the TEJ above 200 hPa.

Probably because of the overall realistic rendering of the mean SJ and TEJ in the NR, the representation of the north Indian Ocean TC activity, while still not optimal, is definitely improved with respect to previous long simulations. Figures 18 and 19, and Table 7, show a total TC number of four simulated versus seven observed in 2005, and six simulated versus seven observed in 2006 (including Typhoon Dorian, which crossed the Malay Peninsula from the Pacific, becoming the seventh north Indian Ocean TC for the season).

However, the distribution of TC locations and their tracks differ significantly between the NR and observations, and the fundamentally erratic nature of TC tracks over that basin does not appear to be fully captured. In
2005, observed TC tracks seem to radiate from the center of the Bay of Bengal in almost all directions, and that variability is not reproduced by the G5NR. A somehow larger track variability, closer to the observed one, is noted in the 2006 G5NR season. As noted previously, very small lapses in the shear can very quickly trigger a TC genesis process, which limits the overall predictability of northern Indian Ocean TC activity.

In terms of vertical structure, the NR displays a significant number of poorly developed systems or systems fighting against shear, in agreement with the climatology (not shown).

e. Tropical cyclones in the south Indian Ocean

The southern Indian Ocean is conventionally treated by the JTWC as one of the two basins of the Southern Hemisphere season with the other being the South
Pacific basin, having the longitude of 135°E as separator between the two (e.g., Lander and Guard 2001). However, the TCs affecting the eastern part of the south Indian Ocean are more often regarded as TCs affecting the Australian region. This article follows the latter convention and plots the TCs over the eastern and western portions of the south Indian Ocean separately.

Figures 20 and 21, and Tables 8 and 9 compare the TCs that formed over the south Indian Ocean (west of 100°E) in the G5NR and in the observations. Specifically, observed TCs 1–9 correspond to TCs numbered in the JTWC BT database as 1, 2, 3, 4, 9, 12, 14, 16, and 22 in 2005–06, and observed TCs 1–10 correspond to TCs 3, 5, 6, 10, 13, 14, 15, 16, 19, and 22 in 2006–07, respectively.

The NR produces a very realistic activity, substantially better than over the north Indian Ocean, not just in terms of overall number but also in terms of track distribution. TCs generally form between 5° and 15°S (except for a few originating west of Madagascar), track...
southward or westward, gradually recurving eastward under the influence of the westerly flow, and display frequent singularities in their tracks, such as loops, sharp recurrences, and binary interactions. The NR exhibits a very convincing spectrum of TC tracks over this basin. A remarkable TC that occurred during the 2006–07 NR south Indian Ocean season is investigated (TC 5 in Fig. 21). Because of its exceptionally symmetry, both meridional and zonal vertical cross sections of wind and temperature across the TC, at a mature stage, are shown in Table 7. Simulated (NR) and observed (BT) TCs, north Indian Ocean seasons: (top) 2005 and (bottom) 2006.

<table>
<thead>
<tr>
<th>Nature run 2005</th>
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<th>Start–end date</th>
<th>Min SLP (hPa)</th>
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<td>1800 UTC 11 Jan–0600 UTC 17 Jan</td>
<td>997</td>
</tr>
<tr>
<td>3</td>
<td>1830 UTC 4 Dec–1830 UTC 7 Dec</td>
<td>982</td>
<td>0600 UTC 1 Oct–0600 UTC 3 Oct</td>
<td>994</td>
</tr>
<tr>
<td>4</td>
<td>1630 UTC 12 Dec–2230 UTC 18 Dec</td>
<td>963</td>
<td>0000 UTC 25 Oct–0000 UTC 29 Oct</td>
<td>997</td>
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<tr>
<td>5</td>
<td>—</td>
<td>—</td>
<td>0600 UTC 26 Nov–0000 UTC 4 Dec</td>
<td>991</td>
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<td>—</td>
<td>—</td>
<td>1800 UTC 14 Dec–0000 UTC 24 Dec</td>
<td>991</td>
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</table>

<table>
<thead>
<tr>
<th>Nature run 2006</th>
<th>Start–end date</th>
<th>Min SLP (hPa)</th>
<th>Start–end date</th>
<th>Min SLP (hPa)</th>
</tr>
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<td>1</td>
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<td>0600 UTC 12 Jan–0600 UTC 19 Jan</td>
<td>991</td>
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<tr>
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<td>0600 UTC 24 Apr–1200 UTC 29 Apr</td>
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</tr>
<tr>
<td>3</td>
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<td>981</td>
<td>1800 UTC 30 Jun–1200 UTC 3 Jul</td>
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</tr>
<tr>
<td>4</td>
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<td>0600 UTC 19 Sep–1200 UTC 26 Sep</td>
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<tr>
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<td>971</td>
<td>0600 UTC 27 Oct–1200 UTC 30 Oct</td>
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<td>7</td>
<td>—</td>
<td>—</td>
<td>1200 UTC 4 Dec–1800 UTC 9 Dec</td>
<td>976</td>
</tr>
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</table>
in Fig. 22, which demonstrates the consistency in TC structures produced by the NR over all basins. This particular system is noteworthy, aside from its symmetry and pronounced warm core, because of its winds, which exceed 70 m s$^{-1}$ on each quadrant. The eye is very well defined and the radius of maximum wind is on the order of 40 km. Its central pressure reaches 919 hPa. However, as noted for the western North Pacific basin, some

Table 8. Simulated (NR) and observed (BT) TCs, 2005–06 south Indian Ocean season.

<table>
<thead>
<tr>
<th>TC No.</th>
<th>Start–end date 2005–06</th>
<th>Nature run</th>
<th>Min SLP (hPa)</th>
<th>Start–end date 2005–06</th>
<th>Best track</th>
<th>Min SLP (hPa)</th>
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<td>944</td>
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<td></td>
</tr>
<tr>
<td>6</td>
<td>1200 UTC 12 Jan 2006–1330 UTC 14 Jan 2006</td>
<td>969</td>
<td>0000 UTC 18 Feb 2006–1800 UTC 23 Feb 2006</td>
<td>991</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>1000 UTC 26 Jan 2006–0230 UTC 3 Feb 2006</td>
<td>944</td>
<td>1200 UTC 3 Apr 2006–1200 UTC 16 Apr 2006</td>
<td>985</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>2200 UTC 5 Feb 2006–0000 UTC 14 Feb 2006</td>
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<td></td>
</tr>
<tr>
<td>11</td>
<td>1800 UTC 12 Feb 2006–1600 UTC 21 Feb 2006</td>
<td>937</td>
<td>—</td>
<td>—</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>2030 UTC 13 Feb 2006–0800 UTC 22 Feb 2006</td>
<td>916</td>
<td>—</td>
<td>—</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>1200 UTC 28 Feb 2006–1430 UTC 4 Mar 2006</td>
<td>930</td>
<td>—</td>
<td>—</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>0330 UTC 4 Mar 2006–1700 UTC 12 Mar 2006</td>
<td>925</td>
<td>—</td>
<td>—</td>
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<td></td>
</tr>
<tr>
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<td>1030 UTC 20 Mar 2006–1900 UTC 22 Mar 2006</td>
<td>972</td>
<td>—</td>
<td>—</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>1630 UTC 24 Mar 2006–1200 UTC 27 Mar 2006</td>
<td>982</td>
<td>—</td>
<td>—</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>0830 UTC 3 Apr 2006–2300 UTC 6 Apr 2006</td>
<td>954</td>
<td>—</td>
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</tr>
</tbody>
</table>
observed cyclones reach even deeper values (observed TC 2 in 2006–07, 904 hPa).

f. Tropical cyclones in the Australian region

Tropical cyclones over the eastern Indian Ocean and southwestern Pacific are traditionally studied together as TCs of the Australian region. As noted by Hall et al. (2001), the entire northern Australian coastline is affected by landfalls and there are two main cyclogenetic areas: a western one in the Indian Ocean and the Timor Sea, and an eastern one in the Pacific (Coral Sea). Moreover, there are cases of Pacific TCs regenerating in the Indian Ocean after having crossed land (e.g., McBride and Keenan 1982). The comprehensive climatological assessment of TCs in the Australian region by Dare and Davidson (2004), including 500 cases and spanning 40 years, describes, in addition to the eastern and western regions, a third cyclogenetic area to the north of the Australian coastline at about 135°E. Among the prominent factors affecting the Australian region TC season are the proximity between the intertropical convergence zone (ITCZ) and the midlatitude storm
track, the presence of a large landmass, and an overall monsoonal environment (e.g., McBride and Keenan 1982; Holland 1984; Dare and Davidson 2004). Other important forcings are the phase of ENSO (e.g., Nicholls 1979; Solow and Nicholls 1990; Catto et al. 2012) and the MJO activity (e.g., Hall et al. 2001). The overall track variability appears to be larger than the Atlantic or the Pacific, and the proximity of the genesis region in the ITCZ to the coastline can lead to difficult landfall forecasts.

In spite of the complexity, the G5NR performs satisfactorily over the region. In Fig. 23 and Table 10, the comparison between TCs observed in the 2005–06 season and the TCs produced by the G5NR is provided. As noted before, the JTWC BT database is split into two, to treat separately the south Indian Ocean from the Australian region. Therefore the 14 observed TCs listed in Table 10 correspond, in the JTWC BT database, to TCs 5, 6, 7, 8, 10, 11, 13, 15, 17, 18, 19, 20, 21, and 23 for 2005–06, and to TCs 1, 2, 4, 7, 8, 9, 11, 12, 17, 18, 20, 21, 23, and 24 for 2006–07.

Two of the three known cyclogenetic regions appear to be present in the simulations, and the overall track distribution appears to be realistic, including retrograde motion and multiple landfalls with regeneration, which is common for TCs originating close to the coastline. A similar situation can be noted in the 2006–07 season (Fig. 24; Table 11).

The intensity range is quite reasonable with several NR TCs reaching values lower than 950 hPa during both seasons, in agreement with observations. Somewhat perplexing is the persistence of relatively deep storms inland in the NR, possibly because of insufficient surface drag.

5. Conclusions

OSSEs are a labor-consuming and computer-intensive methodology and benefit from large collaborative efforts. An essential element for OSSEs is the NR, which needs to

![Fig. 23. Simulated and observed 2005–06 Australian region TCs from (a) G5NR (a) and (b) BT. Colors as in Fig. 4. Corresponding dates in Table 10.](image)

**TABLE 10. Simulated (NR) and observed (BT) TCs, 2005–06 Australian region season.**

<table>
<thead>
<tr>
<th>TC No.</th>
<th>Nature run Start–end date</th>
<th>Best track Start–end date</th>
<th>Min SLP (hPa)</th>
<th>Min SLP (hPa)</th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
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<td>0000 UTC 19 Mar 2006–0600 UTC 27 Mar 2006</td>
<td>980</td>
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</tr>
<tr>
<td>13</td>
<td>0500 UTC 17 Feb 2006–0130 UTC 23 Feb 2006</td>
<td>0000 UTC 3 Apr 2006–0600 UTC 8 Apr 2006</td>
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</tr>
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<td>961</td>
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</tr>
<tr>
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<td>2200 UTC 19 Apr 2006–1700 UTC 29 Apr 2006</td>
<td>—</td>
<td>905</td>
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satisfy a number of requirements to enable realistic OSSE results.

The previous widely used NR produced by the ECMWF has served the OSSE community for a decade, thanks to its outstanding qualities. However, because of the growth in computer power, modeling developments, and improved observing systems, the need for a new NR has become apparent.

In recent years, in an attempt to provide an NR usable in state-of-the-art OSSEs, the NASA GMAO has produced and evaluated several runs with a configuration similar to the ECMWF T511 NR but at increasingly higher resolution and extending the integration length to 2 years. One example of this type of effort is the 14-km, horizontal-resolution, 2-yr simulation documented by Putman and Suarez (2011), which represented an important milestone, because it generated, in addition to a climatologically realistic total number of TCs, also a very satisfactory interannual variability in TC activity between 2005 and 2006. Multiple evaluation teams have assessed this and other long simulations as candidates for the next-generation of NRs, paying attention, among several other concerns, to the realism of TC activity.

After substantial modeling development, the NASA GMAO has finally released for use in OSSEs a 7-km NR that stems from a large collaborative effort, several years of preparation, and that has been subjected to an extensive evaluation (Gelaro et al. 2015).

The goal of this article is to evaluate the suitability of the G5NR to serve as an NR for OSSEs focused on future instruments targeting TCs. The evaluation is phenomenological and event focused, and includes comparisons with reanalyses and observed tropical cyclone best track information. As is the case for all evaluations focused on an NR, no direct correspondence with observed events can be expected, but the specific events investigated must fall

![Figure 24](image-url) Simulated and observed 2006–07 Australian region TCs from (a) G5NR and (b) BT. Colors as in Fig. 4. Corresponding dates in Table 11.

<table>
<thead>
<tr>
<th>TC No.</th>
<th>Start–end date</th>
<th>Min SLP (hPa)</th>
<th>Nature run</th>
<th>Start–end date</th>
<th>Min SLP (hPa)</th>
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within an acceptable range of observed variability and realism.

This article investigates TC activity in all basins: Atlantic, eastern North Pacific, western North Pacific, north Indian Ocean, south Indian Ocean, and Australian region. The investigation shows that the TC activity lies well within the spectrum of observed activity in all basins and also displays a satisfactory degree and sense of variability between the two years. This article also shows that tropical cyclone structure is well represented, with very clear eye features of reasonable scale. The intensity is also very realistic for the resolution of 7 km, with center pressures reaching values down to 906 hPa and wind speeds often in excess of 75 m s\(^{-1}\). Finally, evidence is provided that the NR TC activity arises out of realistic forcings, and that the major dynamical factors controlling tropical weather are well represented.

The evaluation documented in this article confirms that the 7-km G5NR provides significant advancement with respect to previous long simulations produced for OSSEs, and may represent a valuable tool to perform OSSEs focused particularly on future instruments or missions designed to investigate TCs and other high-impact weather systems, such as, but not limited to, CYGNSS. While the 7-km resolution may still not be sufficient for certain very high-resolution applications investigating future instruments focused on eyelaw replacement cycles, the evidence provided suggests that the 7-km G5NR could be an excellent framework for further downscaling.

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