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Preliminary evaluation of the European Centre for Medium-Range Weather Forecasts' (ECMWF) Nature Run over the tropical Atlantic and African monsoon region

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[1] Meteorological observing systems are continuously being developed to improve our knowledge of the atmosphere and our forecasting capabilities. Observing System Simulation Experiments (OSSEs) are a general technique to assess a priori the potential impact of future instruments, which is particularly important in the case of spaceborne systems. One crucial component of OSSEs is the Nature Run (NR), representing a virtual atmosphere from which observations can be simulated so that the impact of future instruments can be assessed. A community-based, 13-month T511 NR was designed in an international collaborative effort and was produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) to build a next-generation OSSE capability. This new Joint OSSE NR is being analyzed with emphasis on tropical development over the western African monsoon region and the tropical Atlantic. The NR representation of the African Easterly Jet and the characteristics of African Easterly Waves including their propagation and development in tropical-cyclone like vortices are investigated. This is the first NR that encompasses one entire Atlantic tropical cyclone season producing realistic tropical cyclone activity. As such it is a valuable tool to perform OSSEs to assess the possible impact of future instruments targeting hurricanes.
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1. Introduction

[2] Impact studies of existing instruments over an assimilation and forecasting system are called Observing System Experiments (OSEs). The constituents are a comprehensive data set of observations, a data assimilation system (DAS), a forecasting model, and the observations from the instrument to be evaluated. The typical setting of an OSE is represented by a Control run in which the DAS assimilates all the observations of the comprehensive data set, producing a set of analyses, which are a representation of the state of the atmosphere. Then another assimilation run is performed by adding (or withdrawing) the data obtained from the investigated instrument and thus producing a new set of analyses: the 'Experiment' analyses. Two sets of forecasts are produced with the same forecast model, each initialized by the set of Control and Experiment analyses. Anomaly correlation (or other metrics) is computed to assess the forecast quality of the two sets, thus evaluating the impact of the observing system under scrutiny.

[3] However, when dealing with future or planned instruments, the capability of assessing their impact a priori relies on simulation: a virtual representation of the atmosphere called the Nature Run (NR) and considered as truth. From the NR a set of simulated observations (conventional and space based) is extracted. Observational characteristics, errors, spatial distribution and coverage are designed to be similar to the real world. Then one additional data set is extracted to reproduce the data that would be provided by the future instrument. Again, two data assimilation cycles are produced, generating a control set of analyses and an experiment set. From these, forecasts are run, and anomaly correlations and other metrics are compared, using the NR as validating truth. The forecast model should be different from the model used for the NR to avoid the identical twin problem, preferably at higher resolution and from a model that differs from the forecast model to an extent the true atmosphere differs from the forecast [*Hoffman et al.*, 1990; *Atlas*, 1997]. To produce and validate a high-quality NR is always very expensive and it is in general desirable to have a common high resolution NR to be used by various investigating centers.

[4] The European Centre for Medium-Range Weather Forecasts (ECMWF) has agreed to perform a 13-month long NR with its state-of-the-art forecasting model at a resolution of T511 (approximately 40 km horizontal resolution). This NR is being called the Joint OSSE NR, is the longest global NR ever produced at this resolution and replaces a previous, T213 NR which served the OSSE community for several years [*Masutani et al.*, 2006]. It

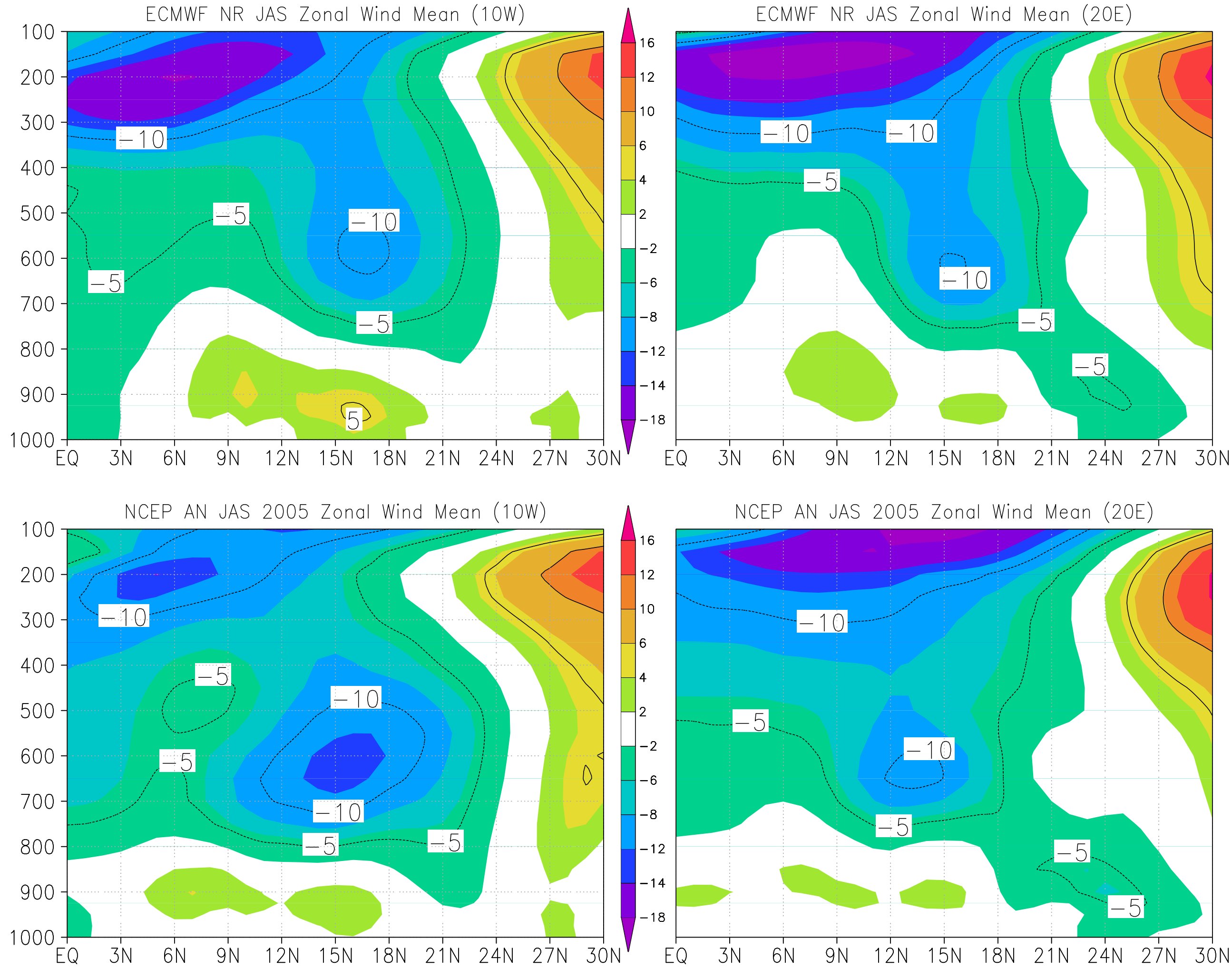

Figure 1. Mean zonal wind (ms^{-1}) vertical meridional cross-sections at 10°W and 20°E to emphasize the African Easterly Jet. Data on pressure levels interpolated on a 1° resolution grid. No significant difference from the original T511 data in sigma levels (not shown).

has been agreed by a large community of OSSE users including, but not limited to the ECMWF, the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), and the National Center for Atmospheric Research (NCAR), to adopt this Joint-OSSE NR as the next-generation NR.

[5] In this work one important aspect of the NR is emphasized, namely its description of the tropical Atlantic and African Monsoon region, and more generally its suitability to OSSEs of future instruments targeting hurricanes.

2. Model and Simulation Settings

[6] The model used is the ECMWF global operational spectral model, version cy31r1 T511L91, which corresponds to a global horizontal resolution of about 40 km and 91 vertical levels. The model is initialized at 12z 1 May 2005, is forced with daily SSTs and sea ice provided by the National Centers for Environmental Predictions (NCEP), and the run length is 13 months. The output has been saved three-hourly on the model's 91 sigma levels at full resolution, and on 31 pressure levels at 1 degree resolution. The surface fields have been archived at the resolution of the model's Gaussian grid.

[7] It is important to stress that the experimental set-up is such that the NR is neither a climate run nor a hindcasting run. It is not a climate run because it is not forced by climatological SSTs and marine ice, but with the observed values of 2005. It is not a hindcast run for 2005 since no atmospheric data of 2005 are assimilated after initialization. As such, it cannot and should not be expected that the NR produces either the climatology or the particular realization of 2005. However, it has to produce a reasonably realistic representation of the atmosphere. The NR realism can be investigated through statistical techniques by determining how the means and variability in the NR compare with reanalyses or operational analyses. The problem of a rigorous statistical validation is quite complex, is the target of an ongoing work involving a major multi-agency and international collaborative effort and will not be discussed in this paper. In this work we focus instead on a phenomenological approach targeting one specific region and one specific category of events, namely Atlantic hurricanes, which were

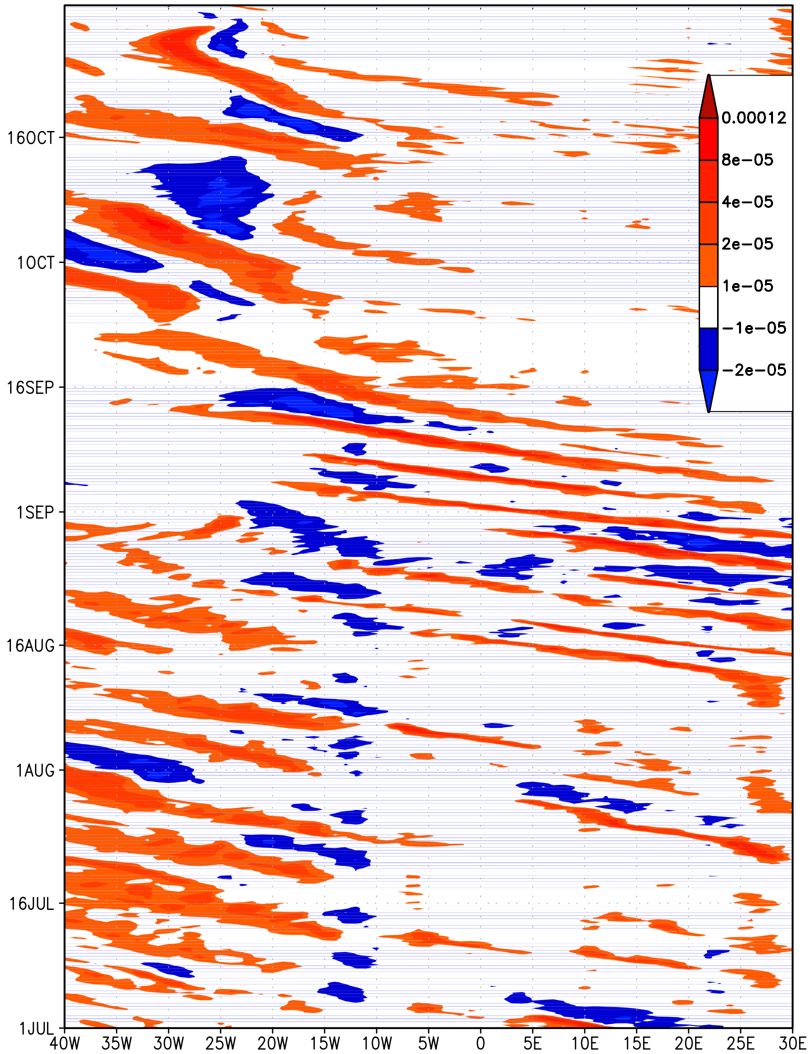

Figure 2. Latitudinally averaged (10°–18°N) 850 hPa relative vorticity (s^{-1}) to emphasize African Easterly Wave activity. From 1° interpolated fields.

not represented in any of the previous ECMWF Nature Runs.

3. Analysis

3.1. Motivation for This Analysis

[8] The focus of this work is the African Monsoon (AM) region and the tropical Atlantic. The fundamental difference between previous NRs and this one is particularly evident over this region, and the implications of being able to perform OSSEs centered over hurricanes are so relevant that this fact alone deserves a special, separate recognition. Prominent elements of the meteorology of the AM region and tropical Atlantic are the African Easterly Jet (AEJ) and the Tropical Easterly Jet (TEJ), the low-level monsoonal flow and the Harmattan flow. For a general discussion of the meteorology of the AM region see, among others, *Asnani* [2005].

3.2. AEJ, TEJ, and the African Monsoon

[9] The AEJ, a predominantly easterly flow at about 700–600 hPa [e.g., *Cook*, 1999] controls through a combination of barotropic and baroclinic instability the development of weather systems known as AEWs (among others, *Hsieh and Cook* [2005]). The AEJ representation in global models is of paramount importance and continuous efforts to improve it are made.

[10] In Figure 1 the average representation of the AEJ in July, August and September (JAS) in the NR is compared with the one obtained through operational NCEP analyses in JAS 2005, through two meridional cross-sections at 20°E and 10°W. As said before, a direct comparison between the NR and Analyses cannot and should not be done, and the ‘dates’ used in the NR are purely conventional, since the NR is a free running model with prescribed 2005 SSTs and therefore neither the climatological or the actual 2005 representation of the AEJ should be expected. However, the observed AEJ in the NCEP analyses and the virtual AEJ in the NR qualitatively compare very well. The AEJ core is at about 600 hPa, with intensity slightly above 10 ms^{-1}. The depiction of the AEJ in earlier versions of the ECMWF was not as satisfactory, because of the use of prescribed stationary climatological aerosol distributions. This has now been replaced by a more recent climatology with month-to-month variation [*Tompkins et al.*, 2005]. In the NR the

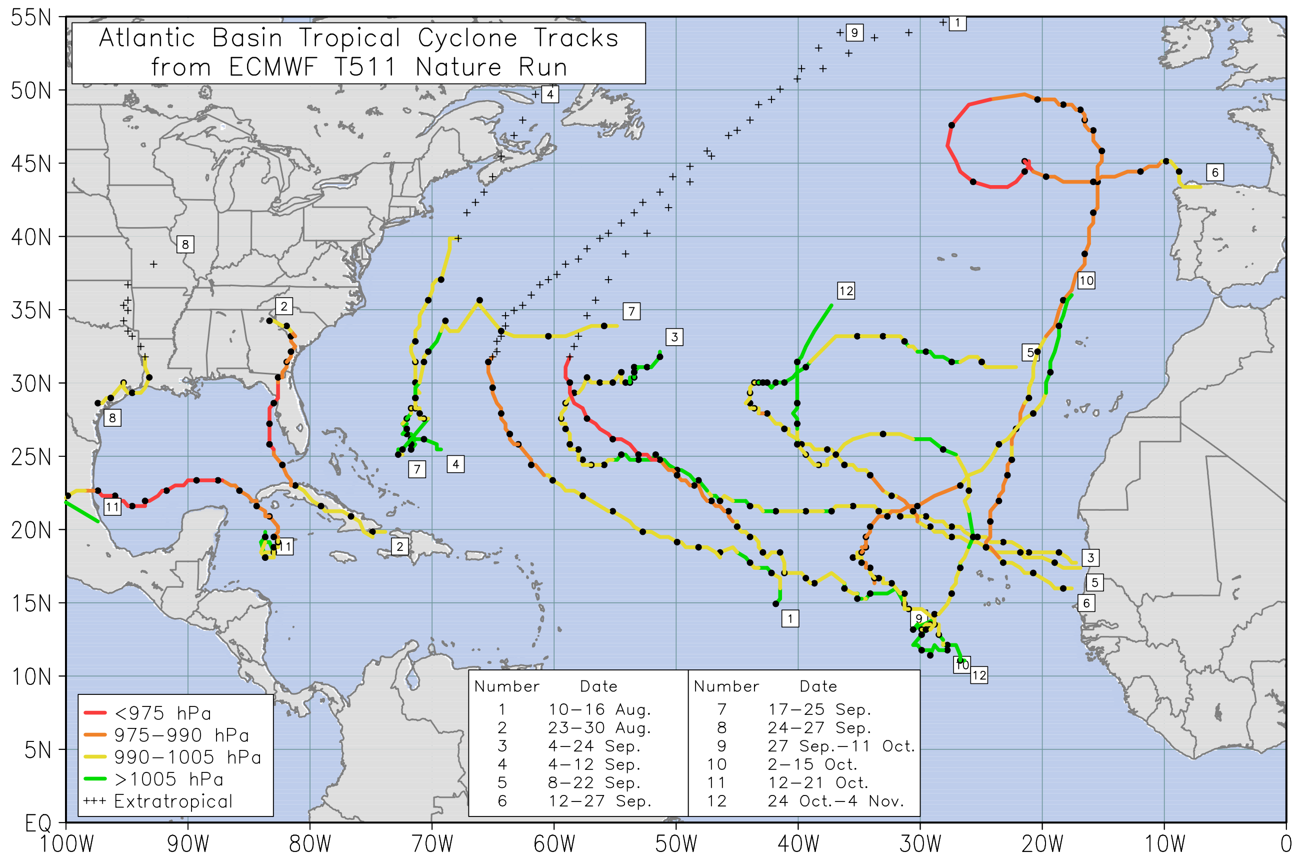

Figure 3. Atlantic TCs in the NR 'hurricane season.' Different colors show center pressure in the full resolution surface fields. Crosses indicate extratropical storms defined when the 200 hPa minus 850 hPa shear exceeds 10 ms^{-1}. Tracks are from original full-resolution T511 surface fields.

depiction of the AEJ is consistent with this newer improved version of the operational model.

[11] Another important player in the tropical genesis process, the TEJ, is stronger in the NR than in the NCEP analyses, particularly in July and August, with a rapid decrease in September (not shown). As a consequence, the environment in the NR is subject to stronger vertical easterly shear at latitudes between 10° and 15°N than the observed 2005, being thus less conducive to tropical development in these months. A stronger TEJ in July and August with weakening in September over the AM region is however much closer to the climatological behavior rather than to the truly exceptional 2005 season, in which there was virtually no shear over the AM and main development region, leading to an unusual situation in which almost every wave leaving the African continent could undergo rapid development. The 2005 NR Atlantic hurricane season, as it is shown later, is instead closer to a more normal season, albeit still more active than climatology.

[12] Other elements in the AM meteorology are the low-level monsoonal westerly flow, predominantly confined below 800 hPa, very clearly seen in both NCEP analyses and in the NR south of 20°N, and the Harmattan low-level easterly flow over northwestern Africa, evident at about 20°–27° N in the vertical sections at 20°E (Figure 1).

3.3. African Easterly Waves (AEWs)

[13] The Hovmoeller diagram in Figure 2 displays relative vorticity at 850 hPa, averaged on a 10°N–18°N latitude band. The speed of waves is in the range of approximately 5°–8° longitude per day, with a hint of a slight acceleration at transition (about 10°–15°W). About 22 waves occur at a given longitude in four months, with an average frequency of about a wave every 5 days. Truncations at around 30°W are due to northward recurving of the depressions originated from the waves. In the second half of September and October most waves in the NR become tropical cyclones (TCs, not shown). AEWs overall frequency and propagation compare well with observations [e.g., *Burpee*, 1974; *Kiladis et al.*, 2006] and with NCEP analyses (see Figure S1 of the auxiliary material).[1]

3.4. Track and Intensity of Tropical Cyclones

[14] In Figure 3 all the systems with a tropical structure are plotted, with different colors to emphasize their center pressure. The systems are defined tropical when they occur as vertically-aligned closed circulations and are followed also after extratropical transition (ET) by putting as an arbitrary condition for ET that shear at the center between 200 and 850 hPa exceeds 10 ms^{-1}. It is shown that twelve TCs appear during the season, with three of them reaching a center pressure lower than 975 hPa. Since the model is in free running mode and no bogusing of any kind is performed, the center pressures are remarkably low, although still under-representing true TCs. The variability of the

[1]Auxiliary materials are available in the HTML. doi:10.1029/2007GL031640.

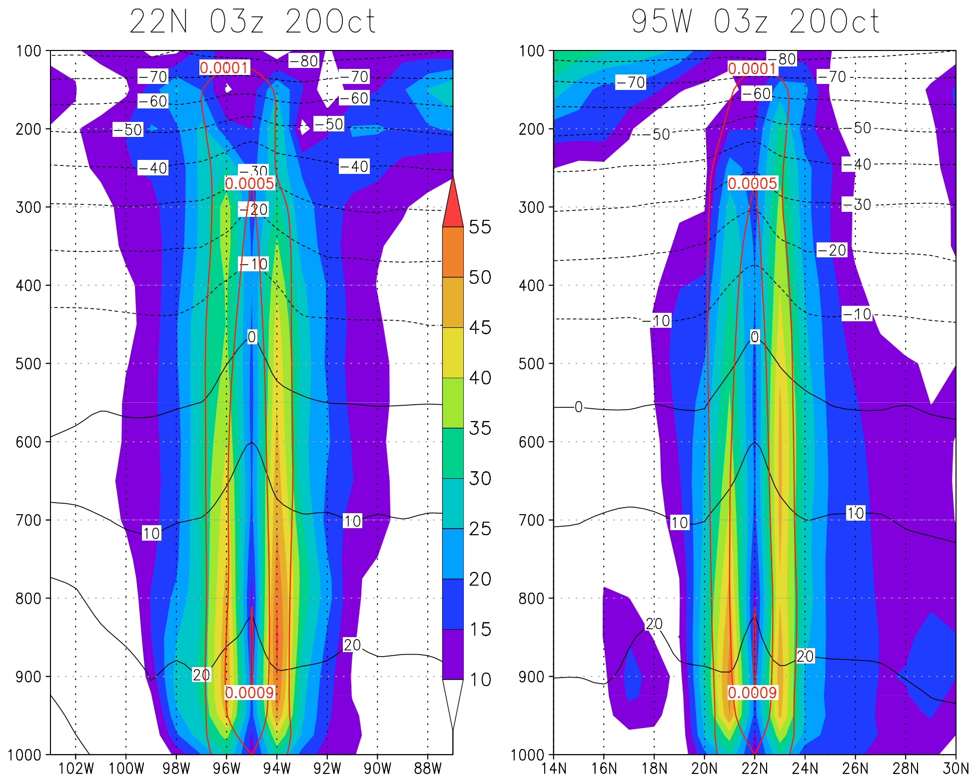

Figure 4. Zonal and meridional vertical cross-sections of wind speed (shaded, ms^{-1}), vorticity (red thick line, s^{-1}), and temperature (solid black line, °C), across TC 11. From 1° interpolated fields.

tracks is very convincing, with five systems though being confined to the east of 45°W. The climatological number per year of "early recurvers," i.e., Cape Verde systems that recurve east of or at about 40°–50°W is generally lower, but early recurvers tend to occur in groups and in some years, such as 2004, there can be a large number of systems confined to the eastern Atlantic [*Franklin et al.*, 2006]. Among the early recurvers in the NR, one system, albeit very weak, makes landfall on the Iberian peninsula (system 6), and two skirt the Canary Islands (6 and 10). Tracks like these, although rare, are not unseen and coincidentally it is in the 2005 actual season that one system is reported to have made landfall over the Iberian peninsula (Hurricane Vince [*Franklin*, 2006]) and two are reported to have skirted the Canary islands (Vince and Tropical Storm Delta [*Beven*, 2006]). In the NR three systems develop in the western Atlantic, recurve northward and display convincing ETs (1, 4, 9). Three systems appear over the Caribbean and Gulf (2, 8, 11), with TC11 the strongest system observed (center pressure of 957 hPa, not shown). The overall distribution of tracks reflects scenarios which are all very realistic and none of the systems appear to have a track unseen in the observational records.

[15] From the OSSE perspective, it is particularly desirable that the NR displays 'difficult' tracks, i.e. tracks in which singularities, loops or binary vortex interaction can be seen. This is because it is likely that a well-behaved hurricane may be well predicted by a forecasting system initialized with analyses taken from the NR, leaving thus little room for improvement. On the contrary, systems like 2 (double landfall), 6 (loop), 4 and 7 (singularities), 11 (loop, double recurvature) are likely to present serious challenges for a forecast model, and therefore be susceptible to possible improvements in response to additional or targeted data produced in an OSSE framework.

3.5. Vertical Structure of Tropical Cyclones

[16] For OSSEs it is particularly important that the hurricane-like vortices have a realistic structure, notwithstanding the resolution-induced limitations. It has been generally accepted that General Circulation Models do not have the resolution to accurately resolve the hurricane core structure. However, it has been noted that with the increase of computer power and of global resolution some forecasting models have been successfully reproducing hurricane structures [e.g., *Atlas et al.*, 2005; *Shen et al.*, 2006] with an increasing degree of accuracy. The NCEP and ECMWF operational models, among others, have been also benefiting from the increase in resolution with respect to tropical cyclone representation. A previous one-month long NR produced in 2005 by NASA at a resolution of 0.25° showed clear evidence of hurricanes. However, the ECMWF NR shows this capability throughout an entire season. In Figure 4 the cross section of Hurricane 11 at 03z 20 October shows a vertically aligned structure, prominent warm core, an eye-like feature and wind up to 55 ms^{-1}. This structure is very realistic for a global model and can be seen also in the other TCs. Some caveats are needed: (1) center pressures are still higher and 10 m winds (maximum of 33 ms^{-1} in TC 11) are substantially lower than the observed values of strong hurricanes; (2) eyewall replacement cycles and rapid intensity fluctuations cannot be represented at this resolution; (3) even this NR is not adequate to properly evaluate

the impact of some future instruments operating at a resolution of few kilometers.

4. Concluding Remarks

[17] This work documents the release of a high-resolution, next-generation, community-targeted, Nature Run produced by the European Centre for Medium-Range Weather Forecasts. The 13-month T511 is the longest NR ever produced and is being called Joint OSSE NR. Despite the impossibility of resolving the fine structure of hurricanes, the new Joint OSSE NR produces a virtual atmosphere in the tropical Atlantic with realistic weather features. A rigorous validation of the NR, with mid-latitude cyclone statistics, general circulation properties, cloud properties, is currently in progress and will be the subject of a future article. This work intends to convey to the OSSE community the importance of a new capability being offered by the Joint OSSE Nature Run, namely a realistic representation of an entire Atlantic tropical season, therefore allowing the investigation of future instruments targeting hurricanes.

[18] **Acknowledgments.** NASA authors acknowledge support from Don Anderson through grant MAP/04-0180-0070 and use of NASA HEC systems.

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