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Tropical cyclones in ERA-40: A detection and tracking method

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[1] A tracking method for tropical cyclones (TCs) is presented and their characteristics for data sets with a lower horizontal resolution, e.g., the ERA-40 Reanalysis data set from 1958 to 2001 are explored. The tracking method uses sea level pressure, relative vorticity and wind speed at 850 hPa, and vertical wind shear. The method, assessed in the Atlantic basin, identifies a realistic number of TCs. However, the ERA-40 TCs compared with best track data from the U.S. National Hurricane Center are too weak to reach hurricane character, i.e., the tracked TCs do not show hurricanes of category three to five. Another caveat is that the life cycle of central pressure values is often not realistically reproduced by ERA-40 TCs. To correct the life cycle of the central pressure, a two-step statistical downscaling approach is applied to the ERA-40 TCs which strongly improves the finding of major hurricanes. **Citation:** Kleppek, S., V. Muccione, C. C. Raible, D. N. Bresch, P. Koellner-Heck, and T. F. Stocker (2008), Tropical cyclones in ERA-40: A detection and tracking method, *Geophys. Res. Lett.*, *35*, L10705, doi:10.1029/2008GL033880.

1. Introduction

[2] During the last years the understanding and diagnosis of tropical cyclones (TCs) and their characteristics has strongly increased. The year 2005 was the most intense season in the Atlantic with 28 tropical storms of which 15 reached hurricane character [*Trenberth and Shea*, 2006]. This year is considered to be an extreme, but a substantial increase of the activity of TCs in the tropical Atlantic over the last decades is documented [*Webster et al.*, 2005; *Emanuel*, 2005; *Hoyos et al.*, 2006; *Sriver and Huber*, 2006]. The role of the sea surface temperatures (SST) in the tropical Atlantic, and their connection with the tropical storm activity was discussed in detail [*Emanuel*, 2005; *Hoyos et al.*, 2006].

[3] The TCs and their characteristics such as intensity, frequency and track are hypothesized to be modulated by natural phenomena, like the Atlantic Multidecadal Oscillation or the Atlantic Meridional Mode [*Vimont and Kossin*, 2007].

[4] To get an impression of how climate change affects the characteristics of TCs, it is important to know how these modes of natural climate variability influence the behavior of the TCs [*Holland and Webster*, 2007]. This is not only relevant from a scientific point of view, it also becomes increasingly important for the society and economy, which are affected by the consequences [*Katz and Brown*, 1992].

[5] First steps to assess the impact of climate change on TCs are provided by *Bengtsson et al.* [2007a, 2007b]. They applied a novel technique to ERA-40 data and model output in order to investigate the model's ability to simulate TCs in a rather coarse resolution of $\sim 1^\circ \times 1^\circ$. Our study presents another TC tracking technique to investigate impacts of natural and anthropogenic induced variability on TCs in comprehensive climate models. Compared to *Bengtsson et al.* [2007a], we use different detection and tracking criteria. The method is based on a technique, developed for midlatitudes [*Blender et al.*, 1997; *Raible et al.*, 2007], but substantially enhanced in its complexity to be appropriate for TC and hurricane detection and tracking. In particular the life cycle of intensity is treated carefully by a two-step statistical downscaling approach. As an example the method is applied to the tropical Atlantic.

2. Data

[6] The Reanalysis data set (ERA-40), covering the period from 1958 to 2001 [*Uppala et al.*, 2005], is used as input data for the proposed tropical cyclone detection and tracking method. The European Centre for Medium-Range Weather Forecasts uses its operational medium-range forecasting system with a horizontal resolution of T159 and 60 vertical levels to generate the ERA-40. For this study data are interpolated to a regular grid of $1.125^\circ \times 1.125^\circ$ in longitude and latitude; the time resolution of the data is 6-hours.

[7] To assess the ERA-40 results obtained by the new method, we use the best track data set for the Atlantic basin from the U.S. National Hurricane Center (NHC) as reference for the overlapping period 1958 to 2001. This data set contains the following parameters: the zonal and meridional position of the cyclone center, the date and time (UTC), the maximum sustained wind speed (kt), and the central pressure (hPa) every 6 h. Note that the accuracy of the data has changed due to better monitoring facilities since the early 70s [*Landsea*, 1993]. For reference, Figure 1a shows all tracks in the period 1958 to 2001 based on best track data.

3. Tracking Method

[8] Sea level pressure (SLP), horizontal wind components (850 hPa), vertical wind shear, and relative vorticity (850 hPa) are used as input variables for the TC tracking and detection method. The standard method for midlatitudes [*Blender et al.*, 1997] identifies low pressure systems as minima of SLP and connects these to cyclone trajectories by a next-neighbor search within 1000 km in 24 hours. The

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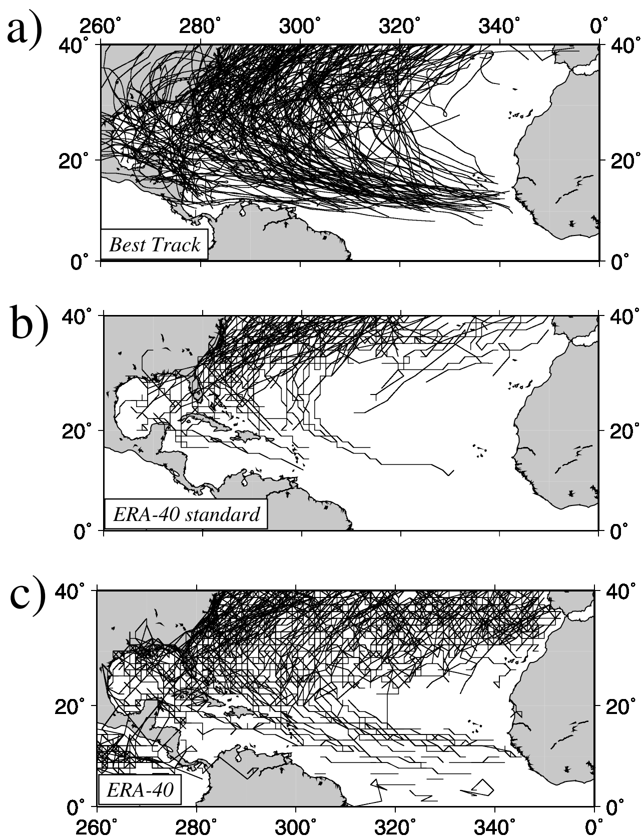

Figure 1. Tracks of all hurricane seasons (June–November) from 1958 through 2001 with (a) the best tracks of NHC, (b) the standard tracking technique of midlatitudes, and (c) the adapted tracking technique with different land-sea tracking.

intensity of a cyclone is characterized by the mean gradient of SLP. Applying this standard method to the tropical Atlantic, enables us to identify pathways during the strongest phase of the hurricanes (Figure 1b). However, comparing the best track data (Figure 1a) with the ERA-40 tracks using the standard method (Figure 1b) the genesis of TCs as well as the decay of TCs and their landfall are not detectable. Another caveat is that during a possible weakening phase of a TC the standard method loses the tracks. Thus, there is the necessity to find specific hurricane criteria for lower resolution data like ERA-40 to detect the entire observed track of the hurricanes.

[9] We address this difficulty by combining SLP and relative vorticity at 850 hPa to identify the pressure lows in the tropics at each time step. For the development of hurricanes the strength of the vertical wind shear is an important factor, therefore the vertical wind shear is also taken into account. If TCs make landfall they weaken which complicates their tracking. Therefore, the wind speed at 850 hPa is used as third parameter. The detection criteria for searching tropical cyclones are:
(1) a local minimum of SLP is observed within a neighborhood of eight grid points, (2) the magnitude of the maximum relative vorticity at 850 hPa exceeds 5.0×10^{-5} s^{-1} and shows a maximum at the TC-center, (3) a vertical wind shear (difference of wind speed between 200 hPa and 850 hPa) threshold of 10 m/s, (4) a TC life time $\geq$ 36 hours, and (5) over land: either the relative vorticity condition is fulfilled or the wind speed at 850 hPa has a maximum in the ambient 24 grid points (~250 km in all directions) of the TC-center.

[10] As in the standard method, the TC centers are connected by a next-neighbor search. Criterion 4 reduces the number of weak and artificial TCs selected by the vorticity criterion. Note, that the warm core of a TC can not be detected in the ERA-40 temperature because of the low resolution.

[11] To demonstrate that the vertical wind shear (criterion 3) and the different criterion for land and ocean tracking (criterion 5) are necessary to identify the tracks realistically, in particular the genesis and decay phase, we show sample tracks of the hurricane season 1995. The tracks are detected with the tracking method in ERA-40 with and without different land-ocean tracking and vertical wind shear (Figure 2a). With the new detection criteria in particular criteria 5 the method identifies longer

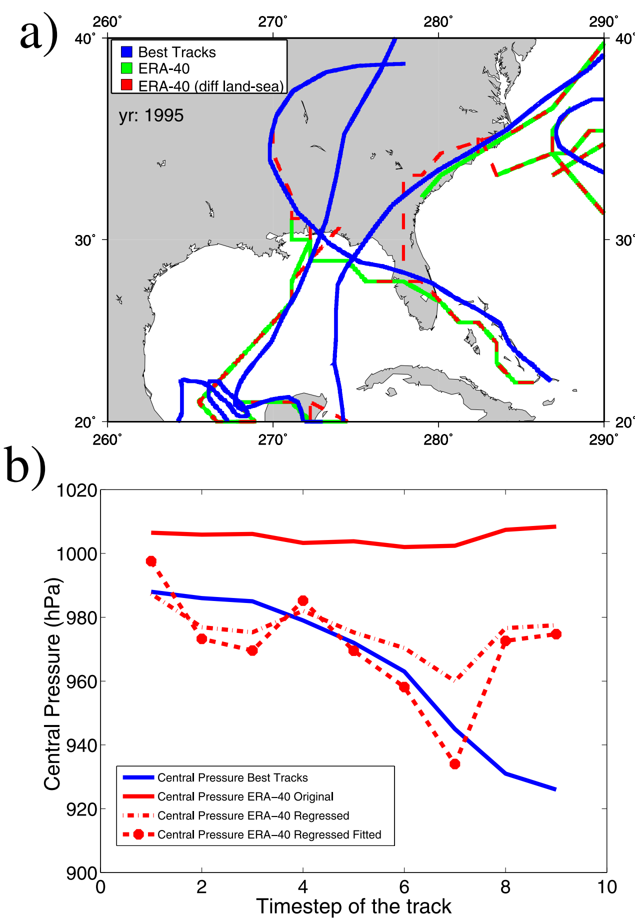

Figure 2. Case studies: (a) Tracks over land of the hurricane season (June–November) 1995 with the best tracks of NHC (blue), the adapted uniform tracking technique in ERA-40 (green) and the adapted tracking technique with different land-sea tracking (red dashed). (b) Central pressures of one exemplary cyclone from 08/31/1977 to 09/02/1977 from best track (blue), calculated with the tracking tool and ERA-40 (red), ERA-40 regressed (red dashed) and ERA-40 regressed and fitted (red dotted and dashed).

Table 1. Number of the TC Time Steps (260°E–0° and 0°–40°N) Using the Standard Method for Midlatitudes, the Adapted Tracking Method and All Best Track Time Steps As Reference[a]

Method	Number of Time Steps 1958–2001/1975–2001	Pairs in % 1958–2001	Pairs in % 1975–2001
Standard	2124/1296	13	16
Adapted	7148/4580	40	57
Best Track	8615/5327	–	–

[a]The correspondence is given by equivalent time steps (=pairs) between the methods using ERA-40 and best track data in % relative to the total number of time steps of the best track data.

tracks. The new tracking method can choose between a maximum of the relative vorticity, or, if this constraint is not fulfilled because the relative vorticity is too low in the Reanalysis, a maximum of the wind speed. That causes a more realistic tracking over land. Tracks over the ocean whose vertical wind shear values are greater than the threshold are no longer tracked (not shown). The case study suggests that the additional use of wind speed over land and vertical wind shear improves the trajectory of TCs in ERA-40 after landfall substantially.

[12] To give a guess of the improvement, Figure 1c shows all TCs tracked with the new method in the Atlantic. In comparison to the reference tracks of best track the pattern of the ERA-40 tracks looks more similar to best track. Some deficiencies, however, remain: over land the method still underestimates the track length, while in the region of 330E to 0 and 25N to 40N our tracking method overestimates the TCs. In comparison with the ERA-40 tracks obtained with the standard tracking technique (Figure 1b), the tracking in the developing region of TCs and over land has considerably improved using the new method (Figure 1c).

[13] Each track of a TC has a defined number of time steps (one time step = 6 h), the so-called life cycle. The sum of these time steps is used to quantify the improvement (Table 1). Therefore we count the pairs of time steps, i.e., data points of the track, which are found at the same place and time in the best track data and ERA-40 (same place means around one grid point in ERA-40 with regard to the best track position). Additionally, two periods, 1958–2001, and 1975–2001 are investigated to illustrate the impact of satellite data since the 1970s. The standard tracking method strongly underestimates the real number of time steps; only 13% (1975–2001: 16%) of the best track time steps are found. The number of time steps tracked with the new method agrees better with the best tracks showing a match of 40% (1958–2001) and 57% (1975–2001) with the time steps of best track. Note, that this is a rigorous and strict criterion because some real tracks might be ignored in our method due to the minimal life-time criterion 4. The tracking for the satellite period works considerably better than for the whole/pre-satellite period. This reveals also a data improvement with the beginning of the satellite period in ERA-40. It should be noted that the accuracy of the best track data also changed due to the availability of satellite data in the beginning of the 70s. Although the tracks are well represented in ERA-40 with the new tracking method, we still need to represent other important TC characteristics such as the intensity, often characterized by the TC central pressure.

4. Statistical Downscaling of the TC Intensity

[14] Due to the coarse resolution of ERA-40, central pressures of the tracked TCs often show unrealistic high values, which lead to a strong underestimation of intense hurricanes. Thus the TCs in the ERA-40 Reanalysis do not show any hurricanes of category three to five which is consistent with the findings of *Bengtsson et al.* [2007a] and *Maue and Hart* [2007]. Most of the cyclones are only tropical storms (not shown). Moreover, the central pressure often shows no realistic time evolution along the life cycle of a TC, whereas the relative vorticity (850 hPa), the horizontal gradient of SLP 1000 km around the center and the wind speed represent the intensity life cycle of the TC more realistically. For this reason these three parameters of ERA-40 and the central pressure of the best track data are used to estimate the central pressure values by applying a linear regression.

[15] To get significant deeper central pressure values in ERA-40, the linear regression is based on the four most

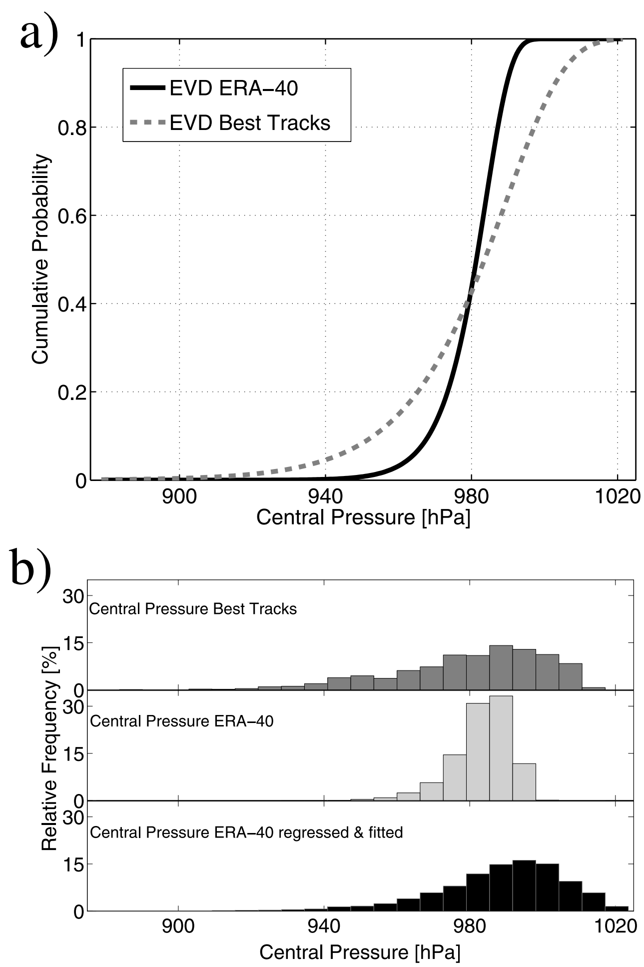

Figure 3. (a) EVDs of all best track central pressures (gray dashed) and all ERA-40 regressed central pressures (black line). (b) Central pressures of all tracks of best track (gray), ERA-40 (light gray) and fitted and regressed ERA-40 (black).

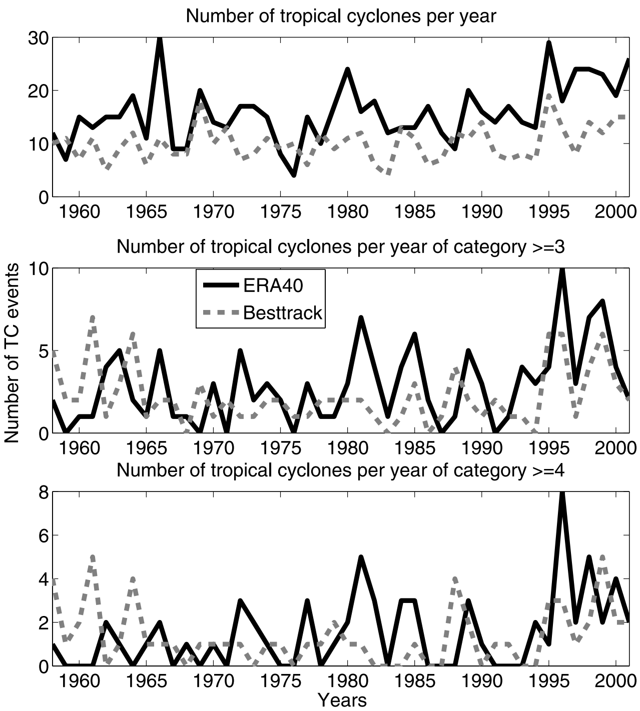

Figure 4. (top) Number of all TCs, (middle) hurricanes of category three and more and (bottom) hurricanes of category four and five per season after the fitting in the Atlantic basin in ERA-40 (black line) and best track (gray dashed).

intense time steps of the best track central pressure of all TCs. In Figure 2b the evolution of the central pressure of a sample track with unrealistic life cycle is shown to demonstrate the effect of downscaling. The ERA-40 pressure is strongly overestimated and does not show the tendency of the best track pressure. After the regression is applied, the central pressures are in better agreement, while the intense phase of the ERA-40 track is still underestimated. Note that tests show that with increasing latitude also the resolution of the data increases which has a minor impact on the regression north of 30°N. To get more realistic central pressure values in ERA-40 tracks, we use a second statistical approach, employing the cumulative extreme value distribution (EVD) Type I, also known as Gumbel distribution. We evaluate the cumulative distribution functions (CDF) respectively for the ERA-40 regressed central pressures and for the corresponding best track central pressures. Both empirical CDFs are fitted with EVDs, which are defined as

$$F(x;\mu,\sigma) = \exp\left(-\exp\left(-\frac{(x-\mu)}{\sigma}\right)\right), \qquad (1)$$

with the location parameter μ and the scale parameter σ. The parameters are fixed with a 95% confidence level (Figure 3a). Based on the ERA-40 EVD the ERA-40 regressed central pressures are interpolated to the EVD from best track to determine the new fitted ERA-40 central pressures.

[16] The distributions of the central pressures show that the fitted and regressed central pressures of ERA-40 agree well with the central pressures of the best track data (Figure 3b). Pressure values less than 980 hPa are again slightly underestimated, but the whole distribution is wider than before, and for the first time there are central pressures between 900 and 950 hPa that become noticeable in the intense phase of the track of Figure 2b.

[17] The improvement of the two-step statistical downscaling approach above is shown in Figure 4. The TCs and hurricanes per season are shown after the fitting from 1958 to 2001 in ERA-40 and, for comparison, in best track classified by their intensity. Based on the central pressure of each TC, a Saffir-Simpson Scale category is assigned. The number of TCs are slightly overestimated (Figure 4 (top)), because in some cases the track is lost and recovered at a later time step, counting them as two TCs. This explains partly the overestimation of all TCs. The comparison of the hurricanes of category three to five (Figure 4 (middle)) shows that the numbers are well represented but the consistency with best track improves in the late 70s. The same applies for the category four and five hurricanes. Summarizing, these results suggests that the numbers of hurricanes are well represented and the tracking method could be used to analyze model simulations with a similar coarse horizontal resolution as ERA-40.

5. Discussion

[18] We developed a new TC and hurricane tracking method which is applied to ERA-40 for the tropical Atlantic. Comparing our method with the existing method of *Bengtsson et al.* [2007a], we found that the length of life cycles are different for the two comparable methods, but both methods underestimate the intensity. Both methods do not determine hurricanes of Saffir-Simpson Scale three to five, due to the coarse resolution and insufficient number of observations in the ERA-40 data set. For the numbers of TCs per season, *Bengtsson et al.* [2007a] find a correlation with best track of 0.23 (1978–1999). With our method the correlation is 0.44 (1975–2001) and 0.40 (1958–2001). For hurricanes of category three to five the correlation is 0.60 (1975–2001) after the fitting, which shows that the statistical downscaling is able to produce the intense hurricanes. Thus, the method is suitable to assess hurricanes in future scenario data sets with rather coarse horizontal resolution and to test statistical forecasting methods in the model environment [*Sievers et al.*, 2000].

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