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Regional climate model simulations of North Atlantic cyclones: frequency and intensity changes

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ABSTRACT: Frequency and intensity of cyclones over the North Atlantic are investigated using 2 data sets from simulations with the Rossby Centre regional climate model RCA3. The model domain comprises large parts of the North Atlantic and the adjacent continents. RCA3 is driven by ECHAM5-OM1 general circulation model data for May to December from 1985 to 2000 and May to December from 2085 to 2100 assuming the SRES-A2 emission scenario. We apply an objective algorithm to identify and track tropical and extratropical cyclones, as well as extratropical transition. The simulation indicates increase in the count of strong hurricanes and extratropical cyclones. Contrasting, and generally weaker, changes are seen for the less extreme events. Decreases of 18% in the count of extratropical cyclones and 13% in the count of tropical cyclones with wind speeds of ≥18 m s^{-1} can be found. Furthermore, there is a pronounced shift in the tracks of hurricanes and their extratropical transition in November and December—more hurricanes are seen over the Gulf of Mexico, the Caribbean Sea and the western Sargasso Sea and less over the southern North Atlantic.

KEY WORDS: Climate change · Tropical cyclone · Extratropical cyclone · Regional climate model · North Atlantic · Sea surface temperature · Static stability

1. INTRODUCTION

Tropical and extratropical cyclones have profound effects on human activities. Associated strong winds, storm surges and heavy precipitation can have hazardous impacts. Therefore, it is of great importance to examine frequency and intensity of cyclones in future climates. Can we expect a higher frequency of strong tropical and extratropical cyclones over the North Atlantic in a warming climate?

1.1. Tropical cyclones

Observations show that the frequency of North Atlantic hurricanes has increased in recent decades (e.g. Bell & Chelliah 2006). However, due to the large decadal variability and due to the lack of high-quality, long-term observations, it is difficult to attribute any of the observed changes to global warming (Landsea et al. 1996, 2006). There is a lot of uncertainty in future climate predictions, as can be seen from the results of a selection of previous studies (Table 1), which are not always consistent (see also Meehl et al. 2007: Chapter 10.3.6.3). According to Oouchi et al. (2006), a 34% increase in cyclone frequencies is expected over the North Atlantic, while a global 6% decrease with even stronger decreases over the North Atlantic is predicted by Bengtsson et al. (2006). This is despite a tendency towards higher maximum wind speeds and the associated extreme precipitation in cyclones, which is common among high-resolution studies (e.g. Knutson & Tuleya 2004). It should be noted that the relationship between maximum wind speed and maximum rainfall in tropical cyclones is not yet well established from observations (Groisman et al. 2004), although indications for such a relationship exist (Shepherd et al. 2007). Because of the large uncertainty, a start has to be made to investigate

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Table 1. Results of future changes in extratropical and tropical cyclone frequencies and intensities of a selection of studies. GFDL: Geophysical Fluid Dynamics Laboratory; GCM: general circulation model; RCM: regional circulation model; SST: sea-surface temperature

Study and method	Extratropical cyclones	Tropical cyclones
Knutson & Tuleya (2004): large number of idealized experiments with GFDL hurricane prediction system (horizontal resolution: 9 km)		6% increase in maximum wind speed, 18% increase in average precipitation rate within 100 km of the storm centre
Oouchi et al. (2006): 10 yr time slice experiments with GCM (horizontal resolution: 20 km)		30% decrease in frequency of tropical cyclones globally, but 34% increase in frequency of tropical cyclones over the North Atlantic, 16% increase in the average of the annual maximum wind speed over the North Atlantic
Yoshimura et al. (2006): 10 yr time slice experiments with GCM (horizontal resolution: 120 km)		9 to 18% decrease in frequency of tropical cyclones, frequency changes of intense storms uncertain
Geng & Sugi (2003): 20 yr time slice experiments with GCM (horizontal resolution: 120 km)	In the midlatitudes of the Northern Hemisphere 3 to 7% decrease in the total number of cyclones, 26% increase in the number of intense cyclones in summer and 8% decrease in winter	
Leckebusch et al. (2006): evaluation of 30 yr time slices of an ensemble of GCM and RCM simulations (horizontal resolution: ~200 km for GCMs and ~50 km for RCMs)	Decrease in the total number of cyclones over Central Europe, increase in the number of intense cyclones with more extreme wind events for western parts of Central Europe	
Bengtsson et al. (2006): evaluation of 30 yr time slices of GCM experiments (horizontal resolution: ~200 km)	No change in storm intensity, 4% decrease in total number of Northern Hemisphere cyclones in winter, poleward shift of storm tracks	No change in storm intensity, 6% decrease in total number of cyclones, stronger decrease over the North Atlantic
Semmler et al. (2008): 16 yr time slices of idealized RCM experiments considering an increased SST and homogeneous atmospheric warming (horizontal resolution: 28 km)	9% increase in North Atlantic cyclone counts, 4-fold increase in North Atlantic intense cyclone counts (maximum 10 m wind speed ≥34 m s^{-1})	39% increase in North Atlantic cyclone counts, nearly 3-fold increase in North Atlantic Category 2 hurricane counts
Present study: 16 yr time slices of RCM experiments driven by a GCM scenario (horizontal resolution of RCM: 28 km)	18% decrease in North Atlantic cyclone counts, 2-fold increase in North Atlantic intense cyclone counts (maximum 10 m wind speed ≥34 m s^{-1}), increase in maximum 10 m wind speed by 7%	13% decrease in North Atlantic cyclone counts, 10% increase in North Atlantic Category 2 hurricane counts, increase in maximum 10 m wind speed by 4%

different factors influencing the development of tropical cyclones, their movement and their transition into extratropical cyclones. Semmler et al. (2008) (hereafter referred to as S08) performed an idealized sensitivity experiment investigating the influence of an increased sea surface temperature (SST), which is known to be a major influencing factor for tropical cyclones (e.g. Chan et al. 2001, Davis & Bosart 2002) along with other factors such as ambient relative humidity, static stability (SS) (Emanuel 1987), convective available potential energy (Holland 1997) and vertical wind shear (Michaels et al. 2005). The main finding in S08 is that a homogeneous 1 K increase in SST and atmospheric temperature, along with unchanged relative humidity, leads to an increased frequency and intensity of tropical cyclones over the North Atlantic. An increase of 39% in the count of tropical cyclones with wind speeds of ≥18 m s^{-1} (the threshold used by the National Hurricane Centre [NHC] in Miami, Florida) was found in the sensitivity experiment compared to the reference. Furthermore, a nearly 3-fold increase in the count of Category 2 hurricanes (on the Saffir-Simpson hurricane scale, i.e. a wind speed of at least 42 m s^{-1}; NHC 2008a) was simulated in that idealized experiment.

1.2. Extratropical transition

Another important question to be addressed in this study is: Could more hurricanes make a transition into extratropical cyclones and reach western Europe or the north-east coast of North America? This is very important because of the highly destructive potential of such cyclones (Hart & Evans 2001). Many studies were restricted to selected or idealized cases (Ritchie & Elsberry 2001, Klein et al. 2002). They investigated the sensitivity of extratropical transition (ET), and re-intensification to SST, SST gradient and vertical wind shear. Thorncroft & Jones (2000) investigated 2 ET cases in 1995. The interaction of ET cyclones with baroclinic waves and the underlying SST were found to play an important role in the possible re-intensification of ET cyclones. Often subjective ET classification methods were used. Hart & Evans (2001) based their ET climatology on the subjective classification method used by the NHC. Underlying SST, storm structure and asymmetry were taken into account.

However, attempts were made to objectively characterize ET. Evans & Hart (2003) defined ET onset as the point where storm asymmetry increases above an empirically determined threshold. Completion of ET was determined on the basis of the thermal wind. They applied their method to 61 Atlantic storms undergoing ET during 1979 to 1993 and found reasonable agreement with the subjective declaration of the NHC. They found that important influencing factors on the speed of ET are the zonality of the large-scale circulation, the SST and its gradient, and the intensity of the original tropical cyclone.

Another method to objectively classify cyclones into tropical, extratropical and ET has been developed for regional climate model (RCM) simulations and applied to the idealized sensitivity experiment by S08. This method has been shown to be capable of reliably classifying cyclones and will be applied in this study. In the idealized experiment of S08, a slight increase in the ratio of tropical cyclones undergoing ET from 44 % in the standard to 48 % in the sensitivity experiment has been found along with a strong increase in cyclones re-intensifying after ET (12 % in the standard and 24 % in the sensitivity experiment).

1.3. Extratropical cyclones

There are many different factors influencing the development of intense extratropical cyclones. Static instability, i.e. a combination of warm SST anomalies and cold air masses, can lead to explosive cyclogenesis (e.g. Chen et al. 1992, Gyakum & Danielson 2000). Baroclinicity and temperature gradients have also been found to influence the development of cyclones (e.g. Sanders & Gyakum 1980, Pavan et al. 1999, Paciorek et al. 2002). The Eady growth rate — a common measure of baroclinic instability and SS — (e.g. Lindzen & Farrell 1980, Hoskins & Valdes 1990), was used by Hall et al. (1994) to diagnose changes in the storm tracks in a double CO_2 general circulation model (GCM) experiment. They found an increase in the kinetic energy downstream the storm tracks by 10 %, particularly over the north-east North Atlantic. Different indices important for cyclone development, frequency and intensity (meridional temperature gradient, Eady growth rate, 500 hPa temperature variance, cyclone count, count of intense cyclones, extreme wind) were used by Paciorek et al. (2002) to investigate changes in extratropical cyclone activity over 1949 to 1999. Their results suggest a slight increase in the total number of cyclones and Eady growth rate over the North Atlantic until 1970 and a slight decrease thereafter. A pronounced increase in the number of intense cyclones and extreme wind speeds over the North Atlantic was reported until 1970; afterwards a stabilisation of these indices was found.

For the future climate, some features are common among different studies. The most consistent feature in future predictions is a poleward shift of the storm tracks (Meehl et al. 2007: Chapter 10.3.6.4). Many studies predicted a decrease in the total number of cyclones in the future (e.g. Geng & Sugi 2003, Leckebusch et al. 2006, Bengtsson et al. 2006; see Table 1), while the results of Fischer-Bruns et al. (2005) suggest increasing storm activity over the North Atlantic. Regarding the intensity of cyclones, there still is uncertainty. While many studies predicted more intense cyclones (e.g. Geng & Sugi 2003, Leckebusch et al. 2006), Bengtsson et al. (2006) suggested no change in the intensity of cyclones. The idealized sensitivity experiment by S08 assuming a homogeneous 1 K increase in SST and atmospheric temperature, along with unchanged relative humidity, suggested a 9 % increase in the count of extratropical cyclones with maximum wind speeds of ≥18 m s^{-1} and a 4-fold increase in the count of very intense extratropical cyclones with maximum wind speeds of ≥34 m s^{-1}.

1.4. Aim of this study

In this study, the combined influence of an SST increase and an increased dry static stability (DSS) of the atmosphere on tropical, extratropical and ET cyclones and their associated parameters such as sea level pressure, wind speed and precipitation is investigated for the North Atlantic using high resolution RCM simulations and compared to previous studies. Increased DSS is common to many greenhouse gas warming GCM projections except for the Arctic region (Meehl et al. 2007, their Fig. 10.7). The results can be compared to S08 in detail as the same RCM domain in the same horizontal/vertical resolution and evaluation methods are used.

This article is organized as follows: in Section 2, the design of the RCM experiments is described. Section 3 gives a comparison of simulated cyclone statistics with observations. In Section 4 changes in frequency, intensity and location of cyclones, as simulated in the climate change scenario experiment, are described. Changes in wind speed and precipitation, which are directly related to cyclone frequencies and intensities, are discussed in Section 5. Section 6 gives a summary and discussion of the results achieved in this study.

2. MODEL SETUP AND METHODS OF EVALUATION

In the present study the regional climate model RCA3 (Rossby Centre regional atmospheric climate model, Version 3) (Jones et al. 2004, Kjellström et al. 2005) is applied on a model domain comprising large parts of the North Atlantic Ocean and adjoining land areas (Fig. 1). The model domain of S08 is used here to allow a good comparison with the idealized sensitivity experiment in their study. Moreover, the same lateral boundary relaxation scheme (Davies 1976) and the same convective parameterization (Kain & Fritsch 1990) are used.

RCA3 is driven by data of the coupled ocean–atmosphere GCM ECHAM5-OM1 (Roeckner et al. 2003). For the control simulation, the model is initialized each year from 1985 to 2000 on 1 May and continuously run until the end of December to ensure that we simulate the strongest tropical storms including their transition into extratropical storms. The scenario simulation is run for the same months from 2085 to 2100. The model is used in a horizontal resolution of 0.25° or around 28 km with 31 non-equally spaced vertical levels on a rotated latitude/longitude grid as in S08.

To identify and categorize cyclones into different intensity classes and to track them over their lifetime, an objective method has been developed, which is described in detail in S08. Here a short summary of this method is given. Sea level pressure minima of <1000 hPa within a radius of 4° latitude are found and tracked in comparing 2 adjacent output intervals, respectively. As a measure of cyclone intensity, the maximum 10 m wind speed (W_{max}) rather than the sea level pressure minimum is used, because this parameter is of interest for storm damage. To distinguish between tropical and extratropical cyclones and to determine the time of extratropical transition, maxi-

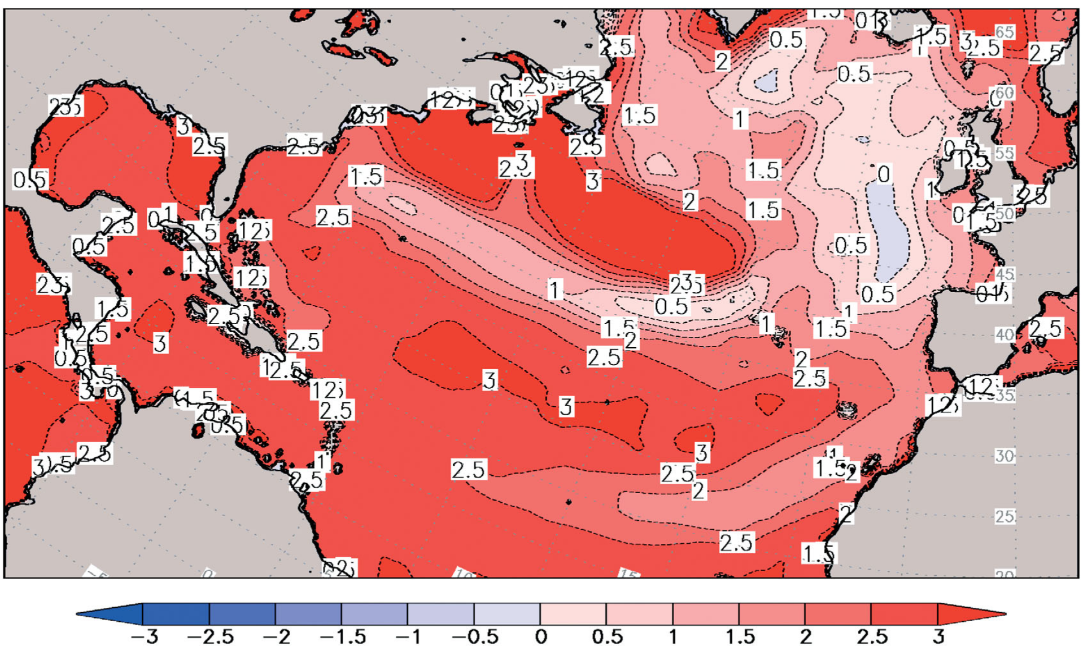

Fig. 1. Difference in the underlying sea surface temperature (SST, °C): scenario experiment (ECHAM5-A2 driven, May to December from 2085 to 2100) minus control experiment (ECHAM5 driven, May to December from 1985 to 2000)

mum wind speeds within the cyclone at 850 and 250 hPa are taken into consideration, similar to procedures described by Walsh (2004). A cyclone is classified as tropical if the maximum wind speed at 850 hPa is >1.2 times larger than the one at 250 hPa, and as extratropical if the maximum wind speed at 850 hPa is <0.8 times the one at 250 hPa. For the remaining unclassified cyclones, a warm core criterion similar to Vitart et al. (1997) is applied. A cyclone is classified as tropical if there is a pronounced and symmetric warm core in 500 hPa. This method is similar to previous algorithms developed for coarse resolution GCM simulations, but had to be adapted to the finer resolution of the RCM.

3. EVALUATION

To gain confidence in the results accomplished with the RCM configuration that was used, our simulation results are compared to observation data for the present-day simulation time period of May to December from 1985 to 2000.

3.1. Tropical cyclones

For tropical cyclones, the 'hurricane best track' observation data from the NHC (2008b) are used for evaluation. In S08, an RCA3 experiment driven by ERA-40 reanalysis data (from the European Centre for Medium-Range Weather Forecasts, ECMWF; referred to as the RCA3 standard experiment) (Uppala et al. 2005) is compared to the NHC (2008b) observation data. The main findings are summarized as follows. On average, 14.1 tropical storms ($W_{max} \geq 18$ m s^{-1}, lifetime ≥12 h) and 6.8 hurricanes ($W_{max} \geq 33$ m s^{-1}, lifetime ≥12 h) were simulated per year, while 10.8 tropical storms and 6.2 hurricanes were observed (Table 2). W_{max} refers to the maximum 1 min average, 10 m height wind speed within the cyclone during its lifetime. Gusts are not included in the observation or simulation data. The agreement for the frequency of hurricanes was excellent, while the frequency of the weaker systems appeared to be overpredicted. Both in the observed and in the simulated data the year with the lowest number of tropical storms was 1986 (6 observed and 4 simulated) and the year with the highest number was 1995 (19 observed and 27 simulated). There were 3 hurricanes observed and 1 simulated for 1997, and 11 observed and 13 simulated for 1995. The interannual variability expressed as the standard deviation was overpredicted (Table 2), but years with little (much) simulated tropical storm activity matched years with little (much) observed activity. Therefore, the correlations between observed and simulated yearly tropical storm and hurricane numbers were high: 0.85 and 0.82, both significant at the 99.99% level. However, no major hurricanes (Category 3 or more on the Saffir-Simpson hurricane scale [NHC 2008a]; $W_{max} \geq 50$ m s^{-1}) were simulated, indicating that an even higher resolution would be desirable.

Table 2. Observed and simulated yearly average (±SD) tropical cyclone (TC) and hurricane (H) counts as from NHC (2008b) best track data, ERA-40 driven RCA3 simulation (RCA3 standard, results from Semmler et al. 2008) and ECHAM5 driven RCA3 control and scenario simulations. NHC: National Hurricane Centre; RCA3: Rossby Centre regional atmospheric climate model, Version 3

	NHC	RCA3 standard	RCA3 control	RCA3 scenario
TC	10.8 ± 3.6	14.1 ± 6.0	8.1 ± 2.6	7.0 ± 2.9
H	6.2 ± 2.6	6.8 ± 4.0	4.4 ± 1.5	4.1 ± 2.0

RCA3-simulated cyclone counts of different intensity classes grouped by W_{max} have been compared to ERA-40 data in S08. It turned out that RCA3 clearly simulated stronger cyclones than given by the coarse-resolution (~125 km) ERA-40 data. In the ERA-40 data, no hurricanes and no tropical cyclones with $W_{max} \geq 26$ m s^{-1} occurred, whereas RCA3 driven by ERA-40 simulated hurricanes with $W_{max} \geq 46$ m s^{-1}. The observations show hurricanes with $W_{max} \geq 78$ m s^{-1}. This indicates once more that a high horizontal resolution is important to capture strong wind speeds associated with cyclones. In addition, it should be noted that different convection and boundary layer processes in RCA3 and ERA-40 may be responsible for different cyclone intensities.

It is also important to know if RCA3 driven by different boundary data — namely ECHAM5-OM1 data as in this study — captures the observed cyclone climatology for present-day climate. Since in ECHAM5-OM1 no observations are assimilated, it cannot be expected that the observed year-to-year differences are simulated. However, frequency and interannual variability of cyclones of different intensity classes should be comparable. In the RCA3 control experiment, on average 8.1 tropical cyclones and 4.4 hurricanes are simulated per year (Table 2). Compared to the NHC observations, average tropical cyclone and hurricane numbers per year and their standard deviations are underestimated, while they were overestimated in the RCA3 standard experiment using ERA-40 boundary data. This difference might be explained by different vertical wind shear. The wind speed difference between 250 hPa and the surface appears to be stronger over the Gulf of Mexico and parts of the Caribbean and Sargasso Seas in the ECHAM5-driven control experiment compared to the ERA-40-driven standard experiment in August and September, the months with the strongest tropical cyclone activity (not shown). Other possible influencing factors, namely SST and atmospheric temperature up to the 250 hPa level, are very similar in both experiments over the tropical regions (difference below 1 K). As in the RCA3 standard experiment from S08, no Category 3 hurricanes are simulated in our control experiment, but the maximum wind speed of 49.9 m s^{-1} comes very close to 50 m s^{-1}, the threshold for Category 3 hurricanes as defined by the NHC (2008a).

For confidence in the results, it is also crucial that the dependencies of the maximum wind speed during lifetime (W_{maxl}) on oceanic- and atmospheric-influencing factors can be captured in our model simulations. Therefore, dependencies on the SST, temperature differences between the sea surface and different tropospheric levels (250, 500 and 850 hPa) and vertical wind shear between the different levels are examined for NHC observations and for RCA3 control and scenario experiments. For the analysis of the observations, only W_{maxl} and location and time of the ET are available from the NHC database, while the remaining parameters have to be obtained from ERA-40 data. The most significant regressions are found for the SST, the temperature difference between the sea surface and the 850 hPa level and for the vertical wind shear between 850 and 250 hPa. Scatterplots including the derived regressions are shown in Fig. 2.

All regressions are significant at the 99.5% level according to the Student's *t*-test, but R^2 values indicating the explained proportion of variance are low. A slightly higher R^2 value is found for the vertical wind shear in the observations, which is not captured in the simulations. This indicates that model tropical cyclones are not hindered by the vertical wind shear as much as observed ones. For the SST and the temperature difference, R^2 values are slightly higher in the simulations than in the observations. This indicates a tendency towards a too strong dependency on these parameters in our model simulations. For the temperature differences between sea level and 500 hPa, as well as sea level and 250 hPa, less significant regressions with even lower R^2 values are found for both the observations and the simulations. The same is true if using other levels than 850 and 250 hPa for the calculation of vertical wind shear. As in the 2 RCA3 experiments in S08, the regression coefficients indicating the slopes of the regression lines are smaller for the simulations compared to the observations. In fact the regression coefficients for SST_{maxl} of all 4 RCA3 experiments from both S08 and from the present study agree with each other within the uncertainty limits. However, for ΔT_{maxl} this is not the case: the slopes of the regression lines are smaller in the present study than in S08. The smaller regression coefficients in our model simulations compared to the observations are probably related to the underpredicted maximum wind speeds.

Despite the detected biases in tropical cyclone and hurricane numbers, their standard deviation and the sensitivity of cyclone intensity to oceanic and atmospheric parameters, the application of a high-resolution RCM leads to an improvement in simulating tropical storms and hurricanes compared to a coarse-resolution GCM and even compared to the ERA-40 data in which no hurricanes and no tropical cyclones with $W_{max} \geq 26$ m s^{-1} were found. This strengthens the confidence in our climate change results compared to previous coarse-resolution GCM studies. While we can use the same wind speed thresholds for tropical cyclone and hurricane detection as used in the NHC, in coarse-resolution GCM studies, artificially low thresholds are usually used to match frequency climatologies (Walsh 2004).

3.2. ET cyclones

The dependencies of the maximum wind speed of the ET cyclones in the extratropical stage ($W_{maxle} \geq$ 18 m s^{-1}) on the same oceanic and atmospheric parameters as for the tropical cyclones are examined for both the NHC observation and for the RCA3 simulation data. As in the 2 experiments in S08, ET cyclones in their extratropical stage show no significant dependencies, unless only the cyclones travelling across the North Atlantic and moving east of 40° W are considered. Due to the restricted number of cases in each experiment, a regression of DSS (temperature difference between sea surface and 850 hPa) to maximum wind speed is calculated on the combined dataset of both RCA3 experiments (not shown), which agrees with the data by S08 for the idealized pair of experiments within the uncertainty bounds.

As ET cyclones assume extratropical characteristics, it can be expected that their intensity is related to quantities important for extratropical cyclones, such as the Eady growth rate, which is a combined measure of SS and baroclinic instability. Therefore, the dependency of ET cyclones moving east of 40° W on the Eady growth rate is investigated from the combined NHC observation and ERA-40 reanalysis data and our model simulations. The Eady growth rate is determined according to Paciorek et al. (2002) such that:

$$\text{Eady} = 0.31\, f/N \times |\mathrm{d}v/\mathrm{d}z|$$

with f being the Coriolis parameter; N, the Brunt-Väisällä frequency (Lee & Mak 1994); z, the vertical distance; and v, the horizontal wind vector. Different

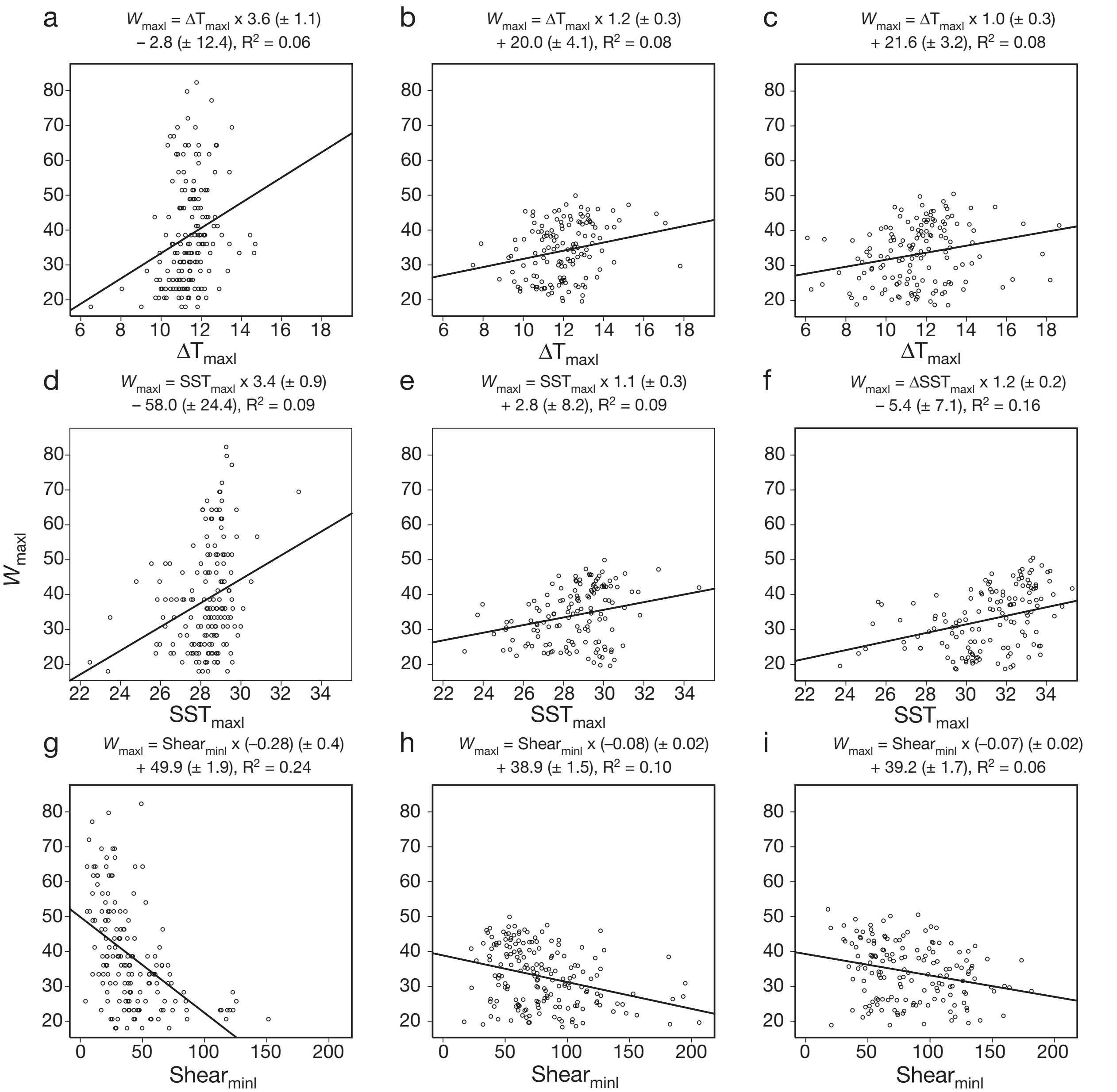

Fig. 2. Scatterplots and regressions of maximum wind speed of tropical cyclones during their lifetime (W_{maxl} [m s^{-1}]): (a–c) versus maximum temperature difference between sea surface and 850 hPa (ΔT_{maxl} [K]); (d–f) versus maximum SST (SST_{maxl}[°C]); (g–i) versus minimum vertical wind shear ($Shear_{minl}$ [d^{-1}]). (a,d,g) From National Hurricane Centre (NHC) observations, (b,e,h) from the control experiment and (c, f, i) from the scenario experiment. Panels (a) and (d) reproduced from Semmler et al. (2008), their Fig. 5 (a,d). In the regression equations, numbers in parentheses are standard errors; R^2 values (indicating the explained proportion of variance) also given. Regressions fitted using the least-squares method

vertical levels have previously been used to determine the Eady growth rate; we use 850 and 925 hPa in our study, since higher levels result in lower R^2 values and significances. Since the maximum 10 m wind speed almost always occurs over sea, the problem of the chosen levels lying below the land surface (Paciorek et al. 2002) is not relevant here. Scatterplots and regressions (significant on the 99.9% level) are shown in Fig. 3.

Regressions from observed and simulated data agree within the uncertainty limits. In contrast to the tropical cyclones, the range of observed and simulated maximum wind speeds is comparable. R^2 values are smaller in the simulations than in the observations. Further-

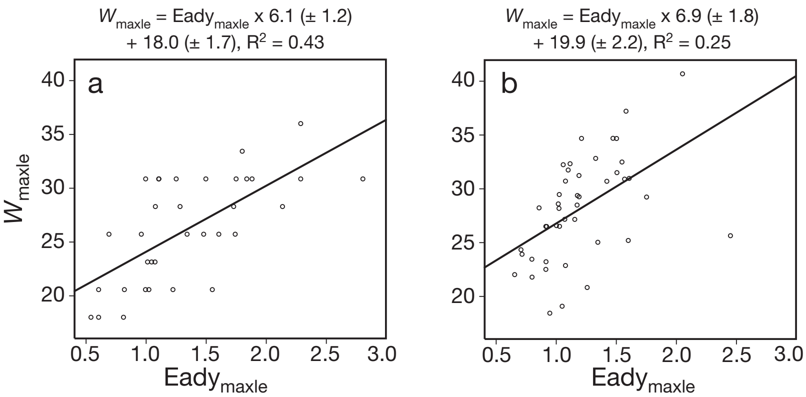

Fig. 3. Scatterplots and regressions of maximum wind speed during the lifetimes of extratropical transition cyclones east of 40° W (W_{maxle} [m s^{-1}]) versus maximum Eady growth rate ($Eady_{maxle}$ [d^{-1}]) (a) from NHC observations and (b) from pooled data of control and scenario experiments

more, the average yearly number of ET cyclones moving east of 40° W ($W_{maxle} \geq 18$ m s^{-1}) is similar between the NHC observations (2.1) and the RCA3 control simulation (1.8). Therefore, it can be concluded that our model setup is able to simulate the characteristics of ET cyclones.

3.3. Extratropical cyclones

Cyclone counts of different intensity classes grouped by W_{max} have been compared to ERA-40 data in S08. It turned out that RCA3 simulated stronger cyclones than given by the coarse-resolution (~125 km) ERA-40 data. In the ERA-40 data no extratropical cyclones with $W_{max} \geq 30$ m s^{-1} occurred, whereas RCA3 driven by ERA-40 simulated extratropical cyclones with $W_{max} \geq 38$ m s^{-1}. The difference between RCA3 and ERA-40 is clearly more pronounced for tropical cyclones, indicating that the horizontal resolution is less important for the simulation of intense extratropical cyclones.

The sensitivity of the intensity of extratropical cyclones to the Eady growth rate is calculated in the same way as for the subset of ET cyclones in their extratropical stage. Fig. 4 shows scatterplots and regressions (significant on the 99.99% level) for ERA-40 data and RCA3 control and scenario experiments. Certainly the ERA-40 data cannot be seen as a replacement for observation data because of the underestimation of the maximum wind speeds; nevertheless, a qualitative comparison can be made. RCA3 control and scenario experiments agree with each other within the uncertainty limits, while the ERA-40 data show a smaller slope of the regression line, probably related to the underestimation of the maximum 10 m wind speed in this dataset.

Together with the good agreement with NHC observations for the ET cyclones in their extratropical stage — which are basically a subset of all extratropical cyclones and which show extratropical characteristics by definition — it can be stated that there is less of a resolution dependency for the simulation of the most intense extratropical cyclones compared to tropical cyclones.

4. CYCLONE STATISTICS IN THE SCENARIO EXPERIMENT

4.1. Tropical cyclones

In contrast to the idealized study (S08), the count of all tropical cyclones ($W_{max} \geq 18$ m s^{-1}) decreases by 13% in the scenario experiment compared to the con-

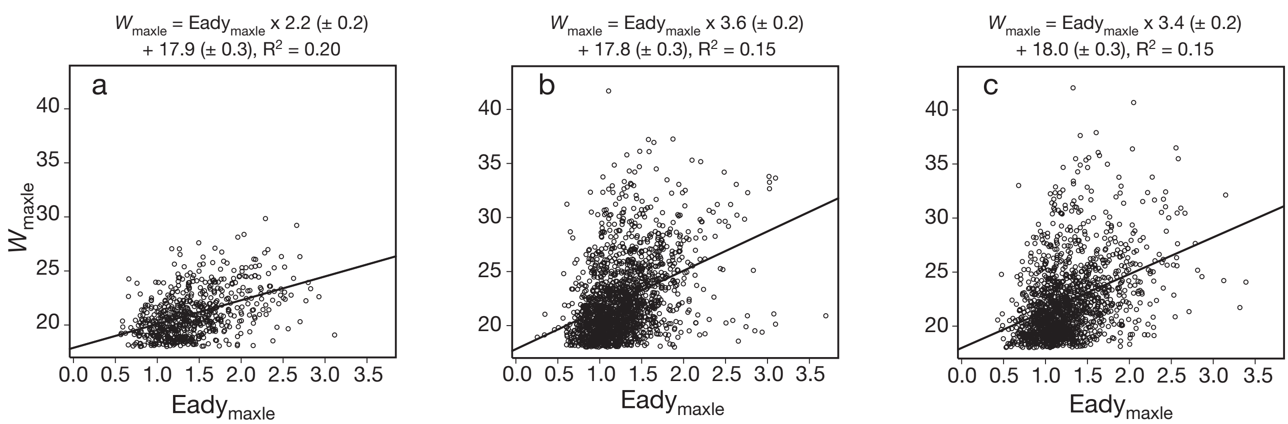

Fig. 4. Scatterplots and regressions of maximum wind speed of extratropical cyclones during their lifetime (W_{maxle} [m s^{-1}]) versus maximum Eady growth rate ($Eady_{maxle}$ [d^{-1}]): (a) from ERA-40 data, (b) from the control experiment and (c) from the scenario experiment

trol experiment (Fig. 5). Also for Category 1 hurricanes (33 m s^{-1} ≤ W_{max} < 42 m s^{-1}) there is a slight decrease in the count. In addition, the 10 % increase in the count of Category 2 hurricanes (W_{max} ≥ 42 m s^{-1}) is smaller than in the idealized study. A total of 207 and 227 Category 2 hurricane counts are simulated in the control and scenario experiment, respectively. The maximum wind speed increases slightly (by 4 %), consistent with previous findings (Knutson & Tuleya 2004, Oouchi et al. 2006). However, despite some improvements in the simulation of the most intense hurricanes compared to previous coarse-resolution GCM studies (Section 3.1), RCA3 still underestimates the maximum wind speeds and shows biases in the dependencies on SST, SS and vertical wind shear. Therefore, simulated changes in hurricane counts and intensities have to be interpreted with some caution. The length of the tropical cyclone season remains similar.

The decrease in the tropical cyclone counts and the smaller increase in the counts of strong hurricanes happens despite a stronger warming in the present study compared to in the idealized study. The SST is increased by >2 K in the scenario experiment in large regions of the tropics (Fig. 1), while a homogeneous 1 K increase was applied in the idealized study. Whereas in the idealized study the DSS has been left unchanged, in the present study the vertical temperature profile change in the future according to ECHAM5-OM1 is reflected. A comparison between ECHAM5-OM1 and RCA3 data on selected pressure levels shows that RCA3 strongly follows ECHAM5-OM1 long-term averages. Maximum differences in average temperature for the simulation time period at 850 hPa are generally below or close to 1 K, except for the hurricane-prone regions of the Gulf of Mexico, the Caribbean Sea and the Sargasso Sea. From statistical analysis, the 850 hPa level seems to be more important for the development of cyclones than the higher 500 and 250 hPa levels (Section 3.1). The RCM to GCM differences are similar for the scenario and the control experiments. This indicates that the GCM-simulated changes in the vertical structure of the atmosphere are also valid for the RCA3 simulations.

Fig. 6 shows ECHAM5-OM1 vertical profiles of temperature, dew point temperature and wind vectors for a representative location in the tropics (the Caribbean Sea) for the control and the scenario time periods. Here, the surface to 850 hPa temperature difference

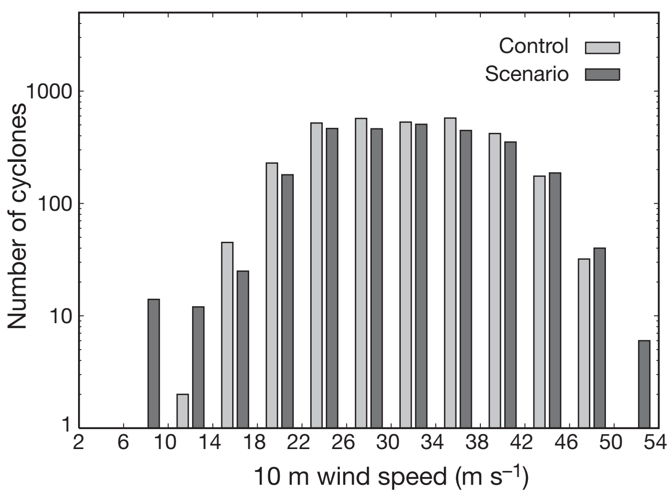

Fig. 5. Tropical cyclone counts as in the control experiment for May to December from 1985 to 2000 and in the scenario experiment for May to December from 2085 to 2100. In each 3 h time interval, all cyclones are categorized in intensity classes with a width of 4 m s^{-1} maximum wind speed (2 to 6, 6 to 10,..., 50 to 54 m s^{-1}) and counted. Thus, the statistics are weighted by the lifetime of the cyclones, in order to consider the higher potential impact of cyclones with a long lifetime. Note the logarithmic scale

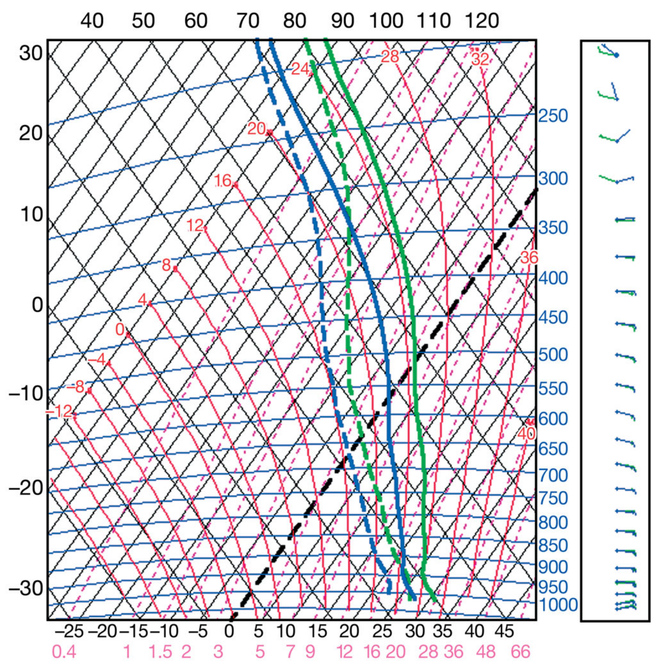

Fig. 6. Tephigram for the Caribbean Sea (15° N, 80° W) from ECHAM5-OM1 averaged over all months of the control experiment (May to December from 1985 to 2000) and over all months of the A2 scenario experiment (May to December from 2085 to 2100). Thin blue lines: isobars (hPa); thin black lines and thick dashed black line from top right to bottom left: isotherms (°C); thin black lines from top left to bottom right: dry adiabats (°C); curved red lines: saturated adiabats (°C); magenta dashed lines: lines of constant mixing ratio (g kg^{-1}); blue and green solid thick lines: temperature profiles of the control and of the scenario experiment, respectively; blue and green dashed lines: profiles of dew point temperature (control and scenario experiment, respectively). The wind vectors (rounded to the nearest 5 knots; short flag: 5 knots; long flag: 10 knots) for the control (blue) and the scenario (green) experiments are shown in the right-hand panel

decreases by 1 K; the potential temperature increases by 5 K from the surface to the 850 hPa level in the control and by 6 K in the scenario experiment. Therefore, the DSS increases. However, it should be noted that the equivalent potential temperature indicates a more conditionally unstable situation in the scenario experiment than in the control experiment: the equivalent potential temperature decreases by 6 K from the surface to 850 hPa in the control and by 10 K in the scenario experiment. There is no difference in the equivalent potential temperature from the surface to 500 hPa in the control, and a decrease of 3 K occurs in the scenario experiment. There are only minor changes in the average vertical wind shear, and, therefore, the increased dry stability could explain the decrease in the total number of tropical cyclones.

While the locations of tropical cyclones remain largely unchanged in May to October, in November and December a pronounced shift is simulated (Fig. 7), which is in contrast to the results by S08 in which cyclone locations remain similar in all months. In the control experiment, tropical cyclones with $W_{max} \geq$ 18 m s^{-1} occur over the southern North Atlantic, while in the scenario experiment, they occur over the Caribbean Sea, the Gulf of Mexico and adjacent areas. This shift in November and December is also seen in the increase in the counts of tropical cyclones over the Caribbean Sea, parts of the Gulf of Mexico and the Sargasso Sea in 10 × 10° boxes when the whole tropical cyclone season is considered (Fig. 8). In most other regions, tropical cyclone counts decrease.

The shift in the location of tropical cyclones in November and December can be explained by changes in the atmospheric moisture. The changes in the temperature profiles are very similar between the Caribbean Sea (Fig. 9a) and the southern North Atlantic (Fig. 9b), with increases of about 3 K close to the surface and of about 8 K at 300 hPa. The relative humidity increases strongly in the middle troposphere over the Caribbean Sea and decreases over the southern North Atlantic. This leads to a strongly decreased moist SS over the Caribbean Sea and an only slightly decreased moist SS over the southern North Atlantic. The equivalent potential temperature over the Caribbean Sea decreases by 2 K from the surface to 850 hPa and increases by 2 K from 850 to 500 hPa in the control experiment, whereas it decreases by 3 K from the surface to 850 hPa and by another 3 K from 850 to 500 hPa in the scenario experiment, leading to a conditionally unstable situation. Over the southern North Atlantic, the equivalent potential temperature increases by 6 K from the surface to 500 hPa in the control experiment and by 3 K in the scenario experiment, indicating that the atmosphere remains stable, on average, in the scenario experiment.

4.2. ET cyclones

A decrease in the count of tropical cyclones undergoing ET by 9% is simulated, which can be explained by the decrease in the total count of tropical cyclones. However, the proportion of cyclones undergoing ET to all tropical cyclones increases: 49% of all tropical cyclones undergo ET in the scenario experiment, while 47%, in the control. Furthermore, in the scenario experiment, 24% of the cyclones re-intensify after their ET, but only 15% re-intensify in the control.

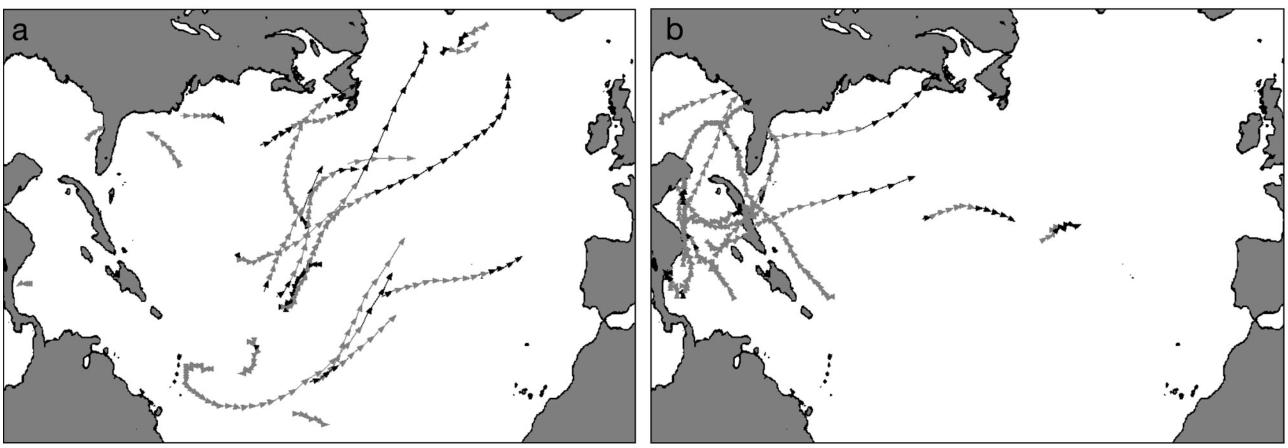

Fig. 7. Cyclone tracks for all November and December storms with a maximum wind speed of 18 m s^{-1} or more from: (a) the control experiment (1985 to 2000) and (b) the scenario experiment (2085 to 2100). Gray arrows: cyclones classified as tropical; black arrows: cyclones classified as extratropical. Only cyclones that sustain a minimum wind speed of 18 m s^{-1} over at least 2 time steps are tracked

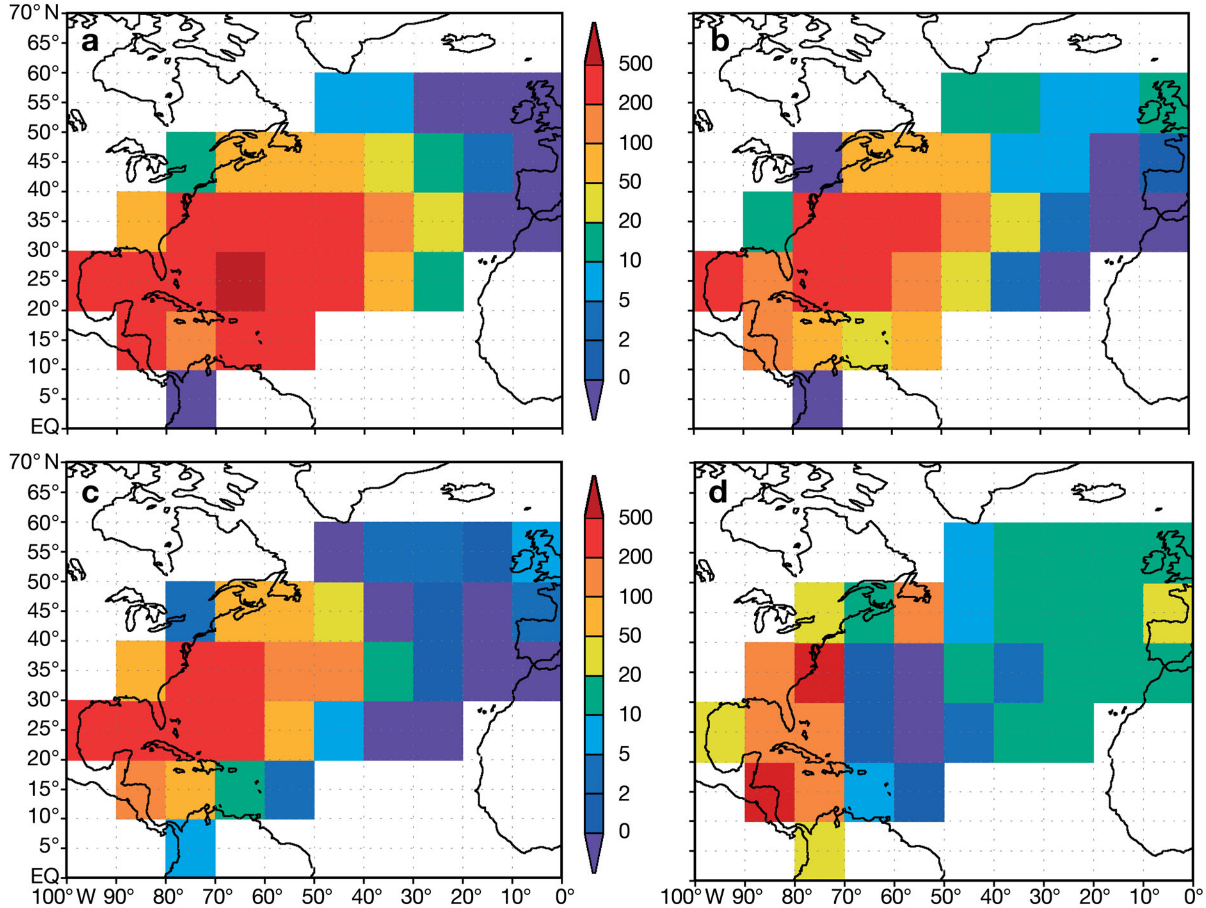

Fig. 8. Counts of tropical cyclones with a maximum wind speed of ≥18 m s^{-1} over all simulated months per 10 × 10° box. (a) NHC observations (May to December from 1985 to 2000), (b) control experiment (May to December from 1985 to 2000), (c) scenario experiment (May to December from 2085 to 2100) and (d) difference scenario minus control. Panel (a) is reproduced from Semmler et al. (2008), their Fig. 7d. All cyclones are counted in each 3 h output interval. Only 10 × 10° boxes completely included in the model domain are plotted

These results are very similar to the idealized sensitivity experiment of S08.

Due to the shift in the location of tropical cyclones in November and December, the areas affected by ET cyclones are also changing in these months. None of them reach the vicinity of western European coastal areas, while more of them affect Central and North American coastal areas (Fig. 7). If considering the whole tropical cyclone season, several ET cyclones hit western European coastal areas in the control experiment, which is not the case for the scenario experiment (not shown). In the control experiment, the re-intensification proportion is 5% for ET cyclones moving to the eastern North Atlantic (east of 40° W) and 21% for all other ET cyclones. These numbers are 13 and 26% for the scenario experiment. Thus, the shift of the ET location enhances the re-intensification of ET cyclones.

4.3. Extratropical cyclones

In the ECHAM5-OM1-A2-driven scenario experiment for 2085 to 2100, extratropical cyclone counts decrease for many intensity classes (Fig. 10). The count of all major extratropical cyclones (W_{max} ≥ 18 m s^{-1}) decreases by 18%. For the stronger intensity classes beyond 34 m s^{-1}, there is an increase in the extratropical cyclone count. However, this 2-fold increase is smaller than in the idealized sensitivity experiment of S08, which showed a 4-fold increase. Because of a weakening of the thermohaline circulation in the ECHAM5-OM1 simulation, the SST does not increase very much over the north-eastern North Atlantic. Indeed, for a small region southwest of Ireland and northwest of Spain, a slight decrease is seen (Fig. 1).

Therefore, the increase in DSS in the extratropics is even stronger than in the tropics. In the extreme case

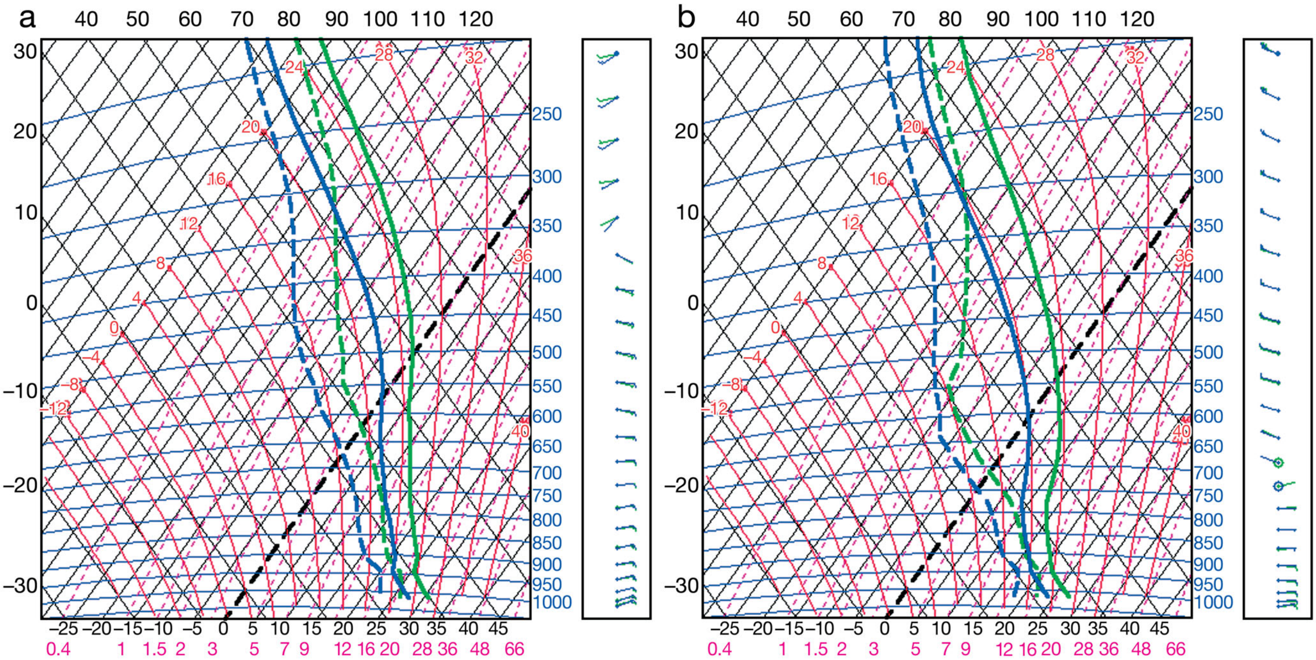

Fig. 9. Tephigrams for (a) the Caribbean Sea (15°N, 80°W) and (b) the southern North Atlantic (25°N, 50°W) from ECHAM5-OM1 averaged over November and December from 1985 to 2000 (control experiment) and over November and December from 2085 to 2100 (scenario experiment). For further explanations, see legend of Fig. 6

southwest of Ireland the surface to 850 hPa temperature difference decreases by 2 K in the scenario experiment (Fig. 11); the potential temperature increases by 7 K from the surface to the 850 hPa level in the control and by 10 K in the scenario experiment. At the same time, the moist SS remains largely unchanged.

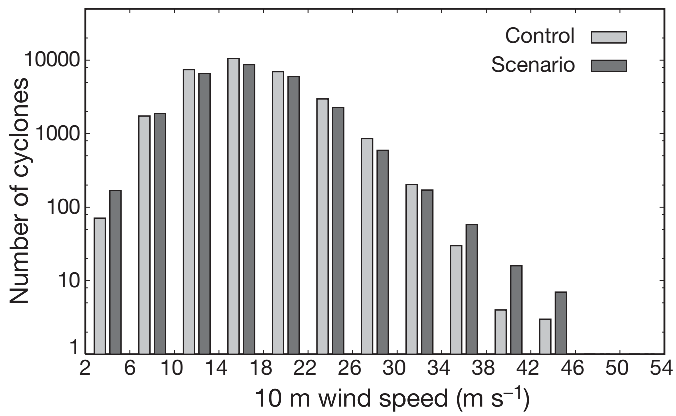

Fig. 10. Extratropical cyclone counts as in the control experiment for May to December from 1985 to 2000 and in the scenario experiment for May to December from 2085 to 2100. In each 3 h time interval, all cyclones are categorized in intensity classes with a width of 4 m s^{-1} maximum wind speed (2–6, 6–10,..., 50–54 m s^{-1}) and counted. This means that the statistics are weighted by the lifetime of the cyclones, in order to consider the higher potential impact of cyclones with a long lifetime. Note the logarithmic scale

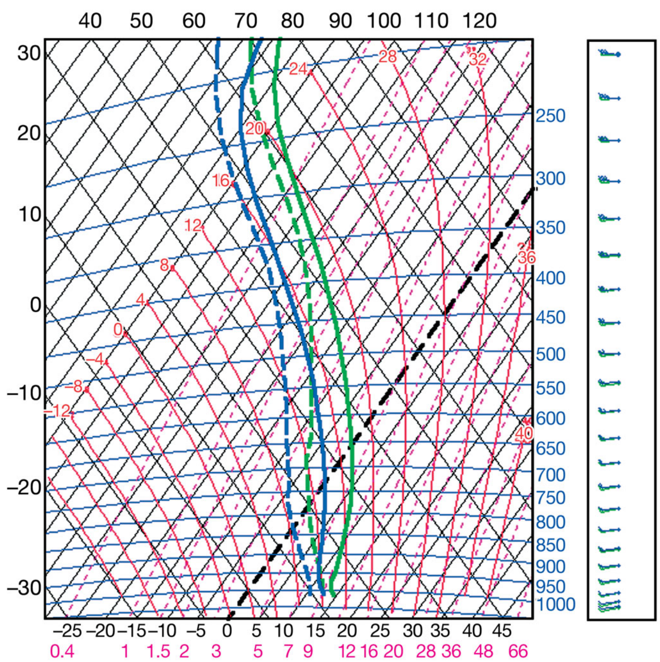

Fig. 11. Tephigram southwest of Ireland (48° N, 15° W) from ECHAM5-OM1 averaged over all months of the control experiment (May to December from 1985 to 2000) and over all months of the A2 scenario experiment (May to December from 2085 to 2100). For further explanations, see legend of Fig. 6

5. WIND SPEED AND PRECIPITATION MEANS AND EXTREMES

The 16 yr datasets for the 2 experiments (control and scenario) are divided into 4 seasonal classes: May/June, July/August, September/October and November/December. Analysis is performed for pressure, average wind, maximum wind and precipitation, but only the results most relevant to this study are presented.

Fig. 12a shows the ratio of precipitation for the scenario and control experiments averaged over all days of the entire simulation periods. An increase of up to 50 % can be seen in large areas north of 40° N, the Gulf of Mexico and north of it, as well as some areas adjoining the Caribbean Islands. Over the southern North

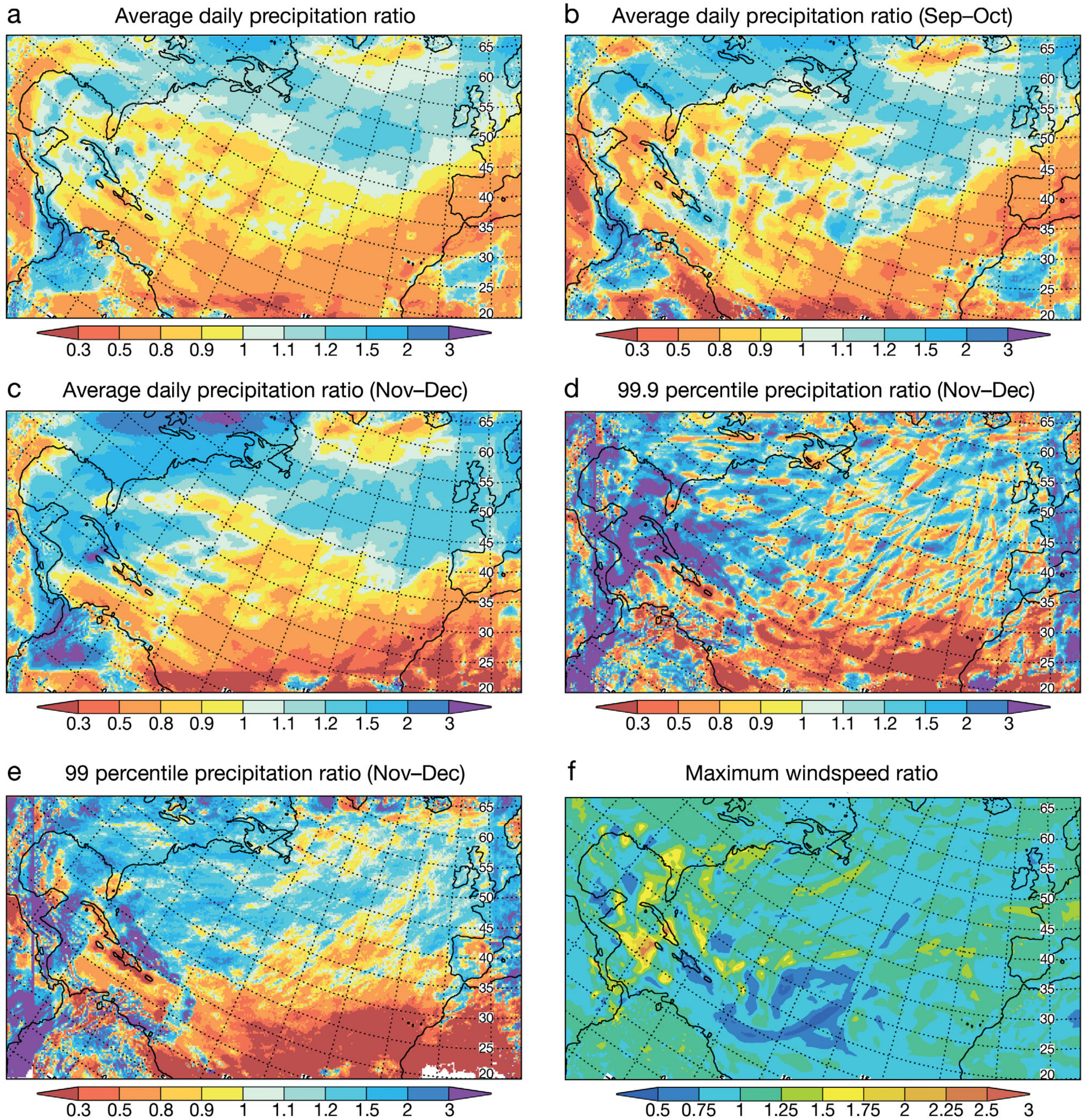

Fig. 12. Ratios for average daily precipitation for (a) the 16 yr period, (b) September/October, (c) November/December, (d) 99.9 percentile precipitation ratio for November/December, (e) 99.0 percentile precipitation ratio for November/December and (f) the maximum wind speed ratio for control and scenario experiment

Atlantic and the southwest of Europe a decrease is found. The September/October period (Fig. 12b) appears to be quite similar to the average one, with larger increases in the north of the Gulf of Mexico and the northeast of North America. In November and December (Fig. 12c) even larger increases can be found over the Gulf of Mexico, the northeast of North America (in a band extending from 40 to 55° N) and the northern Caribbean Sea. A decrease in precipitation is noted in the southern North Atlantic during this period. The extreme precipitation events increase in November and December as seen from Fig. 12d,e, particularly over the Gulf of Mexico, the Caribbean Sea and the Sargasso Sea. In the 99.9 percentile plot, an increase of >200% can be seen over large areas in this region. The maximum wind speed (Fig. 12f) over the entire simulation period substantially decreases in the south-central North Atlantic, while a strong increase is seen in the Caribbean Sea. It is interesting to note that the most dramatic changes are seen in the hurricane-prone regions. Over the northeast of the North Atlantic no major changes can be found in the maximum wind speeds.

Compared to S08, there is a more pronounced change in the extreme wind speeds. This change can be attributed to the change in the location of strong tropical storms in November and December as seen in Fig. 7. The strong increase of mean and extreme precipitation over the Gulf of Mexico, the northern Caribbean Sea and large parts of the northeast of North America can be explained again by the changed location of these storms.

6. SUMMARY AND CONCLUSIONS

In the present study 2 RCA3 experiments have been conducted to investigate possible future changes in the frequency and intensity of tropical and extratropical cyclones. RCA3 experiments with a high horizontal resolution of 28 km have been driven by lateral boundary conditions of the general circulation model ECHAM5-OM1 for May to December from 1985 to 2000 (control simulation) and May to December from 2085 to 2100 (scenario simulation). For the scenario simulation, the SRES-A2 scenario has been assumed. An objective cyclone identification and classification method has been employed to track tropical cyclones and their extratropical transition, as well as extratropical cyclones.

We have performed an evaluation of frequencies and intensities as well as their dependency on different influencing factors such as SST, SS and vertical wind shear for tropical cyclones and Eady growth rate for extratropical cyclones. RCA3 underestimates the intensity of hurricanes, but is able to simulate their intensity better than coarse-resolution GCMs. Because of the underestimation of the wind speeds of the most intense hurricanes, the increase of the maximum wind speed with increasing SST, decreasing SS and decreasing vertical wind shear is smaller in the simulations than in the observations. While the explained proportion of the variance of regressions for SST and decreasing SS is slightly larger in the simulations than in the observations, it is clearly smaller for vertical wind shear. For the ET cyclones, a good agreement in their frequency and in their intensity dependence on the Eady growth rate is achieved, although the explained proportion of the variance is smaller in the simulations than in the observations. For extratropical cyclones, a qualitative agreement in the sensitivity of their intensity to the Eady growth rate can be found between RCA3 and ERA-40 data. However, due to the lower maximum wind speeds in the coarse-resolution ERA-40 data, the maximum wind increases more strongly with Eady growth rate in RCA3 than in ERA-40. On the other hand, the explained variance is smaller in the simulations than in the ERA-40 data.

The counts of all tropical cyclones (maximum 10 m wind speed ≥ 18 m s^{-1}) decrease by 13%, while the counts of Category 2 hurricanes (maximum 10 m wind speed ≥ 42 m s^{-1}) increase by 10%. The maximum wind speed increases slightly from 49.9 to 52.1 m s^{-1}, corresponding to 4%. Despite some improvements in the simulation of intense hurricanes compared to previous coarse-resolution GCM studies, their intensities are still underestimated in our simulations and some caution is necessary when interpreting the results in intensity changes.

A reason for the decrease in the counts of all tropical cyclones could be the enhanced DSS in the scenario experiment compared to the control experiment. Changes in the vertical profile of the atmosphere seem to be responsible for a shift in the location of tropical cyclones in November and December, from the southern North Atlantic to the Gulf of Mexico, the Caribbean Sea and the western Sargasso Sea.

Therefore, a shift in the location of ET cyclones also occurs: none of them reach western European coastal areas, while more of them affect Central and North American coastal areas in the scenario experiment compared to the control. The total number of ET cyclones decreases by 9%, but the proportion of tropical cyclones undergoing ET increases: 49% of all tropical cyclones undergo ET in the scenario experiment, while 47% undergo ET in the control. In addition, re-intensification after ET occurs more often: 24% of all ET cyclones re-intensify after their ET in the scenario experiment and only 15% re-intensify in the control.

The count of all major extratropical cyclones (maximum 10 m wind speed ≥ 18 m s^{-1}) decreases by 18%.

For the stronger intensity classes beyond 34 m s^{-1}, a 2-fold increase in the extratropical cyclone count is simulated. The maximum 10 m wind speed increases by 7%, from 42.8 to 45.9 m s^{-1}.

A particularly strong increase in extreme precipitation over the hurricane-prone region of the Gulf of Mexico, Caribbean Sea, Sargasso Sea and adjoining land areas can be seen. This is associated with hurricanes. Average and extreme precipitation increases north of 40° N and in the hurricane-prone region, with a considerable decrease in the remaining areas. The maximum percentage change in precipitation occurs in the November/December period rather than in September/October, which is due to a change in the location of tropical storms in these 2 mo. Relative changes in the maximum wind speed are generally smaller than changes in extreme precipitation.

Compared to an idealized sensitivity experiment by Semmler et al. (2008), in which a homogeneous increase in SST and atmospheric temperatures by 1 K along with unchanged relative humidity was considered, there are some differences and some commonalities. Tropical, ET and extratropical cyclone counts generally increased in the idealized experiment, with the strongest increases in the high-intensity classes. Whereas in the idealized experiment the DSS was kept constant by definition, in the present study there is an increase in DSS both in the tropics and in the extratropics. Since the DSS is found to be a factor influencing both tropical and extratropical cyclones (the SS is included in the Eady growth rate), the increase in DSS could be responsible for the decrease in the total cyclone counts and the weaker increase in the counts for the strong intensity classes in the present study. The higher proportions of tropical cyclones undergoing ET, and of re-intensifying ET cyclones, are similar to the idealized study. Furthermore, the strong increase of extreme precipitation in the hurricane-prone regions is common among the idealized experiment and the present study.

It should be noted that this study cannot be seen as a prediction on its own, since the 16 yr time periods are too short to average out multi-decadal variability, and only one realization of future climate is presented rather than an ensemble of simulations with different emission scenarios, driving data from different GCMs and different RCMs. However, this study can be seen as part of an ensemble of studies investigating possible changes in cyclone frequency and intensity. Previous studies, such as the ones listed in Table 1, also lack ensemble simulations and/or a sufficient simulation length to average out multi-decadal variability. Thus, this study contributes another realization of a possible future climate to the pool of available simulations.

Since the results of previous studies for both tropical and extratropical cyclones differ considerably because of the different GCMs and evaluation methods used, it can only be stated that the present results are in the range of previous predictions (Table 1). The feature of maximum intensity increase in tropical storms is common to most other studies (e.g. Knutson & Tuleya 2004, Oouchi et al. 2006) although contrasting results exist (e.g. Bengtsson et al. 2006).

To conduct a prediction using consistent methods, regional ensemble simulations using different GCM projections as driving data could be performed. Before that, an investigation of different GCM projections regarding the factors influencing the development of cyclones could be carried out. The most contrasting GCM projections in terms of these factors could be used for the dynamical downscaling.

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LITERATURE CITED

Bell GD, Chelliah M (2006) Leading tropical modes associated with interannual and multidecadal fluctuations in North Atlantic hurricane activity. J Clim 19:590–612
Bengtsson L, Hodges KI, Roeckner E (2006) Storm tracks and climate change. J Clim 19:3518–3543
Chan JCL, Duan Y, Shay LK (2001) Tropical cyclone intensity change from a simple ocean–atmosphere coupled model. J Atmos Sci 58:154–172
Chen SJ, Kuo YH, Zhang PZ, Bai QF (1992) Climatology of explosive cyclones off the east Asian coast. Mon Weather Rev 120:3029–3035
Davies HC (1976) A lateral boundary formulation for multi-level prediction models. Q J R Meteorol Soc 105:629–655
Davis C, Bosart LF (2002) Numerical simulations of the genesis of hurricane Diana (1984). II. Sensitivity of track and intensity prediction. Mon Weather Rev 130:1100–1124
Emanuel KA (1987) The dependence of hurricane intensity on climate. Nature 326:483–485
Evans JL, Hart RE (2003) Objective indicators of the life cycle evolution of extratropical transition for Atlantic tropical cyclones. Mon Weather Rev 131:909–925
Fischer-Bruns I, von Storch H, Gonzalez-Rouco JF, Zorita E (2005) Modelling the variability of midlatitude storm activity on decadal to century time scales. Clim Dyn 25:461–476
Geng Q, Sugi M (2003) Possible change of extratropical cyclone activity due to enhanced greenhouse gases and sulfate aerosols — study with a high-resolution AGCM. J Clim 16:2262–2274
Groisman PY, Knight RW, Karl TR, Easterling DR, Sun B, Lawrimore JH (2004) Contemporary changes of the hydrologi-

cal cycle over the contiguous United States: trends derived from *in situ* observations. J Hydrometeorol 5:64–85
Gyakum JR, Danielson RE (2000) Analysis of meteorological precursors to ordinary and explosive cyclogenesis in the western North Pacific. Mon Weather Rev 128:851–863
Hall NMJ, Hoskins BJ, Valdes PJ, Senior CA (1994) Storm tracks in a high-resolution GCM with doubled carbon dioxide. Q J R Meteorol Soc 120:1209–1230
Hart RE, Evans JL (2001) A climatology of the extratropical transition of Atlantic tropical cyclones. J Clim 14:546–564
Holland GJ (1997) The maximum potential intensity of tropical cyclones. J Atmos Sci 54:2519–2541
Hoskins BJ, Valdes PJ (1990) On the existence of storm-tracks. J Atmos Sci 47:1854–1864
Jones CG, Willén U, Ullerstig A, Hansson U (2004) The Rossby Centre regional atmospheric climate model. I. Model climatology and performance for the present climate over Europe. Ambio 33:199–210
Kain J, Fritsch M (1990) A one dimensional entraining/detraining plume model and its application in convective parameterisation. J Atmos Sci 47:2784–2802
Kjellström E, Bärring L, Gollvik S, Hansson U and others (2005) A 140-year simulation of European climate with the new version of the Rossby Centre regional atmospheric climate model (RCA3). SMHI Reports Meteorology and Climatology 108, SMHI, Norrköping
Klein PM, Harr PA, Elsberry RL (2002) Extratropical transition of western North Pacific tropical cyclones: midlatitude and tropical cyclone contributions to reintensification. Mon Weather Rev 130:2240–2259
Knutson TR, Tuleya RE (2004) Impact of CO_2-induced warming on simulated hurricane intensity and precipitation: sensitivity to the choice of climate model and convective parameterization. J Clim 17:3477–3495
Landsea CW, Nicholls N, Gray WM, Avila AL (1996) Downward trends in the frequency of intense Atlantic hurricanes during the past five decades. Geophys Res Lett 23: 1697–1700
Landsea CW, Harper BA, Hoarau K, Knaff JA (2006) Can we detect trends in extreme tropical cyclones? Science 313: 452–454
Leckebusch GC, Koffi B, Ulbrich U, Pinto JG, Spangehl T, Zacharias S (2006) Analysis of frequency and intensity of European winter storm events from a multi-model perspective, at synoptic and regional scales. Clim Res 31:59–74
Lee WJ, Mak M (1994) Observed variability in the large-scale SS. J Atmos Sci 51:2137–2144
Lindzen RS, Farrell B (1980) A simple approximate result for the maximum growth rate of baroclinic instabilities. J Atmos Sci 37:1648–1654
Meehl GA, Stocker TF, Collins WD, Friedlingsstein P and others (2007) Global climate projections. In: Solomon S, Qin D, Manning M, Chen Z and others (eds) Climate change 2007: the physical science basis. Contribution of Working Group I to the 4th Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge
Michaels P, Knappenberger PC, Landsea C (2005) Comments on 'Impact of CO_2-induced warming on simulated hurricane intensity and precipitation: sensitivity to the choice of climate model and convective scheme'. J Clim 18: 5179–5182
NHC (National Hurricane Centre) (2008a) The Saffir-Simpson hurricane scale. Available at www.nhc.noaa.gov/aboutsshs.shtml, accessed on 3 January 2008
NHC (National Hurricane Centre) (2008b) Hurricane best track files (HURDAT). Available at www.nhc.noaa.gov/pastall.shtml, section 'Hurricane Best Track Files (HURDAT)', accessed on 3 January 2008
Oouchi K, Yoshimura J, Yoshimura H, Mizuta R, Kusunoki S, Noda A (2006) Tropical cyclone climatology in a global-warming climate as simulated in a 20 km-mesh global atmospheric model: frequency and wind intensity analyses. J Meteorol Soc Jpn 84:259–276
Paciorek CJ, Risbey JS, Ventura V, Rosen RD (2002) Multiple indices of Northern Hemisphere cyclone activity, winters 1949–1999. J Clim 15:1573–1590
Pavan V, Hall N, Valdes P, Blackburn M (1999) The importance of moisture distribution for the growth and energetics of mid-latitude systems. Ann Geophys 17:242–256
Ritchie EA, Elsberry RL (2001) Simulations of the transformation stage of the extratropical transition of tropical cyclones. Mon Weather Rev 129:1462–1480
Roeckner E, Bäuml G, Bonaventura L, Brokopf R and others (2003) The atmospheric general circulation model ECHAM5. I. Model description. Max-Planck-Institute for Meteorology Report 349, Hamburg
Sanders F, Gyakum JR (1980) Synoptic–dynamic climatology of the 'Bomb'. Mon Weather Rev 108:1589–1606
Semmler T, Varghese S, McGrath R, Nolan P, Wang S, Lynch P, O'Dowd C (2008) Regional model simulation of North Atlantic cyclones: present climate and idealized response to increased sea surface temperature. J Geophys Res 113: D02107
Shepherd JM, Grundstein A, Mote TL (2007) Quantifying the contribution of tropical cyclones to extreme rainfall along the coastal southeastern United States. Geophys Res Lett 34:L23810
Thorncroft C, Jones SC (2000) The extratropical transitions of hurricanes Felix and Iris in 1995. Mon Weather Rev 128: 947–972
Uppala SM, Kållberg PW, Simmons AJ, Andrae U and others (2005) The ERA-40 reanalysis. Q J R Meteorol Soc 131: 2961–3012
Vitart F, Anderson JL, Stern WF (1997): Simulation of interannual variability of tropical storm frequency in an ensemble of GCM integrations. J Clim 10:745–760
Walsh K (2004) Tropical cyclones and climate change: unresolved issues. Clim Res 27:77–83
Yoshimura J, Sugi M, Noda A (2006) Influence of greenhouse warming on tropical cyclone frequency. J Meteorol Soc Jpn 84:405–428

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