Regional model simulation of North Atlantic cyclones: Present climate and idealized response to increased sea surface temperature

Tido Semmler,[1] Saji Varghese,[2] Ray McGrath,[1] Paul Nolan,[3] Shiyu Wang,[1] Peter Lynch,[3] and Colin O'Dowd[2]

Received 31 October 2006; revised 9 August 2007; accepted 31 August 2007; published 22 January 2008.

[1] The influence of an increased sea surface temperature (SST) on the frequency and intensity of cyclones over the North Atlantic is investigated using two 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 reanalysis data for May to December 1985–2000 at the lateral and lower boundaries, using SST and lateral boundary temperatures. A realistic interannual variation in tropical storm and hurricane counts is simulated. In an idealized sensitivity experiment, SSTs and boundary condition temperatures at all levels are increased by 1 K to ensure that we can distinguish the SST from other factors influencing the development of cyclones. An increase in the count of strong hurricanes is simulated. There is not much change in the location of hurricanes. Generally weaker changes are seen in the extratropical region and for the less extreme events. Increases of 9% in the count of extratropical cyclones and 39% in the count of tropical cyclones with wind speeds of at least 18 m/s are found.

Citation: Semmler, T., S. Varghese, R. McGrath, P. Nolan, S. Wang, P. Lynch, and C. O'Dowd (2008), Regional model simulation of North Atlantic cyclones: Present climate and idealized response to increased sea surface temperature, *J. Geophys. Res.*, *113*, D02107, doi:10.1029/2006JD008213.

1. Introduction

[2] The years 1995 to 2005 showed extremely high levels of North Atlantic hurricane frequency. In comparison to the quiet period 1971 to 1994, a more than 2.5-fold increase in the frequency of major hurricanes was observed over the North Atlantic basin, particularly over the Caribbean Sea. Another active period occurred during the 1950s and 1960s, which shows that the decadal variability is large and trends cannot be easily ascribed to global warming [*Landsea et al.*, 1996]. According to *Bell and Chelliah* [2006] the active hurricane period from 1950 to 1969 was related to a very strong West African monsoon circulation and near average SSTs across the central tropical Atlantic. However, the active hurricane period from 1995 to 2004 was related to exceptionally warm Atlantic SSTs and an only modestly enhanced West African monsoon.

1.1. Factors Influencing the Development of Cyclones

[3] The influence of the sea surface temperature (SST) on the development of cyclones is a widely studied topic. *Emanuel* [1987] showed using a Carnot cycle approach that the maximum possible pressure drop toward the eye of a hurricane can be expressed as a function of the SST, the ambient relative humidity and the thermodynamic efficiency which is proportional to the difference between the SST and a weighted mean temperature in the upper atmosphere. Another purely thermodynamic approach to determine the maximum potential intensity was formulated by *Holland* [1997], who employed similar parameters to those used by *Emanuel* [1987], but explicitly incorporated a cloudy eye-wall and a clear eye. *Camp and Montgomery* [2001] compared the two methods and suggested that Holland's method showed a very strong dependence on the convective available potential energy (CAPE). All of those studies as well as many others [e.g., *Chan et al.*, 2001; *Davis and Bosart*, 2002; *De Maria and Kaplan*, 1994] suggested that the SST is one of the key factors influencing the development of tropical cyclones. It is still not clear if the intensity of the strongest hurricanes has changed as a result of the observed increase in SST [*Landsea et al.*, 2006]. This is due to lack of long-term reliable observations and poor knowledge of the different factors that determine the intensity of hurricanes.

[4] The SST also seems to have an important influence on strong extratropical cyclones according to a number of previous studies. *Gyakum and Danielson* [2000] found that the combination of warm SST anomalies with cold air masses over the Western North Pacific leads to enhanced sensible and latent heat fluxes from the ocean into the atmosphere, favoring explosive cyclogenesis. *Chen et al.* [1992], on examining explosive cyclones off the East Asian coast reported rapid cyclogenesis in the Kuroshio Current region due to warm SST anomalies. *Pavan et al.* [1999] stated that baroclinicity and thus temperature gradients are important for the development of cyclones. According to

[1]Met Eireann, Glasnevin Hill, Dublin, Ireland.
[2]National University of Ireland, Galway, Ireland.
[3]University College Dublin, Dublin, Ireland.

0148-0227/08/2006JD008213

Sanders and Gyakum [1980], explosive extratropical cyclogenesis is found mainly over regions with strong SST gradients. Unlike tropical cyclones, there is no minimum SST requirement for explosive extratropical cyclogenesis.

1.2. Extratropical Transition

[5] The extratropical transition (ET) of tropical cyclones has not been widely studied. Many studies are restricted to selected cases. A first climatological study for the North Atlantic was presented by *Hart and Evans* [2001]. In that study, no objective definition of ET was used. ET was subjectively defined by the National Hurricane Center (NHC) in Miami (Florida) based on underlying SST, storm structure and asymmetry. According to *Hart and Evans* [2001], 51% of these cyclones reintensify after ET and have the potential to cause severe damage. Therefore it is of great interest to know if the frequency or intensity of such cyclones is likely to change in the future. In recent years attempts were made to objectively characterize ET. *Evans and Hart* [2003] defined ET onset as when the storm asymmetry increases above an empirically determined threshold. Completion of ET is determined on the basis of the thermal wind. Even though this objective method agrees well with the subjective declaration of the NHC in most cases, there are some considerable differences especially for the completion of ET. The zonality of the large-scale circulation, the SST and its gradient as well as the strength of the tropical cyclone determine the speed of ET. After ET, the tilt and size of the trough and the intensity of the transitioned cyclone determine the further development of the cyclone. The ET process is highly unpredictable because of its strong sensitivity to the influencing factors and interactions between cyclone development and long-wave pattern. The climatology of ET has been investigated for the North Atlantic region, regions of the Pacific and Indian Ocean [e.g., *Jones et al.*, 2003; *Sinclair*, 2002]. Idealized high resolution modeling studies were carried out by *Ritchie and Elsberry* [2001] and *Klein et al.* [2002] to investigate the sensitivity of the development during the transformation and reintensification phases to SST, SST gradient and vertical wind shear. Apart from a study by *Walsh and Katzfey* [2000], no model simulations were performed to investigate changes in ET in a future climate.

1.3. Predicted Future Changes in Cyclone Frequency and Intensity

[6] Possible future changes in the cyclone statistics have been widely studied using general circulation models (GCMs). There is still an uncertainty about the future changes in tropical cyclone frequency and intensity [*Oouchi et al.*, 2006; *Yoshimura et al.*, 2006; *Bengtsson et al.*, 2006]. Coarse resolution GCMs are not able to represent typical inner structures of tropical cyclones which results in underestimation of intensities [e.g., *Krishnamurti et al.*, 1989; *Camargo and Sobel*, 2004]. Thus the predictions of *Oouchi et al.* [2006], which were obtained with a 20 km resolution GCM may be more reliable. However, it is to be noted that the simulation time period was limited to 10 a for both present-day and future conditions. Using estimation strategies to determine the maximum potential intensity of tropical storms based on thermodynamic and dynamic considerations [e.g., *Emanuel*, 1987; *Holland*, 1997] might be an alternative, but it lacks some important processes such as ocean spray feedback or upper ocean layer response. *Knutson and Tuleya* [2004] performed idealized high resolution simulations with the GFDL hurricane prediction system using large-scale thermodynamic boundary conditions from different GCMs. Their results suggest that the risk in the occurrence of highly destructive tropical storms may increase; the maximum wind speed ($W_{\max}$) and the maximum precipitation rate associated with hurricanes might considerably increase in a future warmer world. As in the study of *Emanuel* [1987] and *Holland* [1997] ocean feedbacks are not considered in the work of *Knutson and Tuleya* [2004], but *Knutson et al.* [2001] suggest that simulated changes seem to be similar for a coupled ocean-atmosphere model and a pure atmosphere model. *Michaels et al.* [2005] point out that the idealized hurricane prediction system used by *Knutson and Tuleya* [2004] may not be appropriate for making predictions about greenhouse gas induced changes in hurricane intensity as factors such as the vertical wind shear are neglected.

[7] An alternative is to use regional climate models (RCMs) to study the impact of global warming on the intensity of hurricanes as has been done for example by *Walsh and Ryan* [2000], *Walsh and Katzfey* [2000] and *Nguyen and Walsh* [2001]. A limitation of this method is the restricted horizontal resolution. Even with a high horizontal resolution of 30 km in an RCM, the intensity of strong hurricanes may still be underestimated [*Walsh and Ryan*, 2000; *Walsh et al.*, 2004]. Attempts have begun to run GCMs with finer horizontal resolutions owing to increased computing power. For example, *Oouchi et al.* [2006] have simulated strong pressure gradients and intense warm cores in tropical cyclones. However, as in the previous RCM studies, the intensity of strong hurricanes is underestimated.

[8] The results of previous work using GCMs to study future changes in the frequency and intensity of extratropical cyclones due to increased greenhouse gas concentrations differ with the methodology and the GCM used [*König et al.*, 1993; *Hall et al.*, 1994; *Zhang and Wang*, 1997; *Sinclair and Watterson*, 1999; *Geng and Sugi*, 2003; *Bengtsson et al.*, 2006]. It is very important to reduce the sources of uncertainties to achieve a better understanding of cyclone characteristics. *Jung et al.* [2006] proposed a high horizontal resolution to realistically simulate the frequency of extratropical cyclones. A sophisticated cyclone identification method, a review of the methods and the results in terms of trends in the frequency and intensity of extratropical cyclones of the past are presented by *Benestad and Chen* [2006]. Despite considerable differences in the results of future climate projections, there is agreement that the observed decreasing trend in the total number of extratropical cyclones and an increasing trend in the intensity is to continue in the future. A plausible explanation is that a decreased meridional temperature gradient and the associated reduced baroclinicity in the future climate could be responsible for the decrease of the total number of extratropical cyclones [e.g., *Sinclair and Watterson*, 1999; *Geng and Sugi*, 2003]. The higher moisture supply due to a generally higher SST and the related increase in latent heat

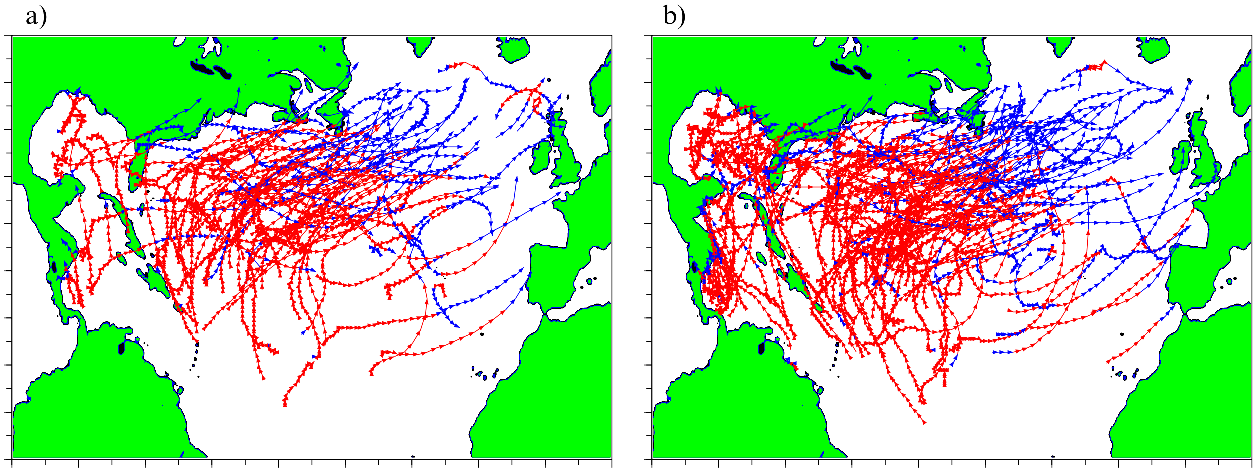

Figure 1. Cyclone tracks for all storms in May to December 1985–2000 undergoing ET during their lifetime with a maximum wind speed of 18 m/s or more from (a) the standard experiment and (b) the sensitivity experiment (red arrows: cyclone classified as tropical; blue arrows: cyclone classified as extratropical). Only cyclones which sustain a minimum wind speed of 18 m/s over at least two time steps are tracked.

fluxes could trigger strong intensity cyclones [*Hall et al.*, 1994].

1.4. Goals of This Study

[9] Because of the uncertainties in the observed and simulated changes in cyclone intensities and frequencies, particular influencing factors must be distinguished and investigated further. There have been only a few case studies on the influence of SST alone on extratropical cyclones [e.g., *Giordani and Caniaux*, 2001] and tropical cyclones [e.g., *Tuleya and Kurihara*, 1982; *Evans et al.*, 1994]. In these limited area model case studies, the atmospheric temperature and specific humidity of the forcing boundary conditions were left unchanged without being adapted to the increased (decreased) SST leading to an artificially strong increase (decrease) of sensible and latent heat fluxes due to a destabilization (stabilization) and drying out (moistening) of the boundary layer.

[10] The main focus of the present study is on the frequency and intensity of tropical and extratropical cyclones. Other associated parameters such as sea level pressure, wind speed and precipitation changes are investigated in terms of mean values and extreme events. Unlike many previous studies, high resolution data of long time periods are evaluated rather than selected cases.

[11] The sections of this article are organized as follows: in section 2, the design of the performed RCM experiments as well as the methods of evaluation of the cyclone counting, classifying and tracking algorithm are described. An example of a simulated cyclone undergoing ET is given to illustrate the method. Section 3 gives a brief description of evaluation results for present-day climate conditions with a focus on the simulated cyclone statistics. Section 4 is the core section dealing with the influence of the SST on the frequency and location of cyclones with different intensities. Changes in wind speed and precipitation, which are directly related to cyclone frequencies and intensities, are discussed in section 5. The last section 6 gives a summary and discussion on the results achieved in this study.

2. Model Setup and Methods of Evaluation

[12] In this study the regional climate model RCA3 (Rossby Centre regional Atmospheric Climate model version 3) [*Kjellström et al.*, 2005; *Jones et al.*, 2004] is applied on a model domain comprising large parts of the North Atlantic Ocean to allow the increased SST to have an impact on the development of cyclones (see Figure 1): Western Europe and North West Africa to the east, Ireland, the UK and the Iberian Peninsula far away from the lateral boundaries to avoid the boundary region inhomogeneities common to limited area models [e.g., *Giorgi*, 1990], the regions south of North America, Central America, the north of South America, the Gulf of Mexico and the Caribbean Sea in the west to allow the simulation of tropical cyclones making landfall or traveling across the North Atlantic toward Western Europe while transforming into extratropical cyclones. The RCA3 lateral boundary relaxation scheme and the convective parameterization are after *Davies* [1976] and *Kain and Fritsch* [1990] respectively.

[13] RCA3 has been driven by the 40-a reanalysis data [ERA-40: *Uppala et al.*, 2005] from the European Centre for Medium-Range Weather Forecasts (ECMWF) at the lateral and lower boundaries. The model has been initialized each year from 1985 to 2000 on the 1st of May and continuously run until end of December to ensure that we simulate the strongest tropical storms including their transition into extratropical storms. The model has been run in a horizontal resolution of 0.25° (around 28 km) with 31 non-equally spaced vertical levels on a rotated latitude/longitude grid. The standard experiment uses the original SST from ERA40 as lower boundary values and the sensitivity experiment an SST increased by 1 K. In the sensitivity experiment the atmospheric temperature is increased by 1 K in the

lateral boundary data at all model levels to maintain the vertical structure of the atmosphere. The relative humidity remains the same as in the standard experiment. According to model projections [*Knutson and Tuleya*, 2004], it is realistic to assume the relative humidity in a warmer climate to be similar to the one observed today while the vertical temperature structure is likely to become more stable.

[14] To identify and categorize cyclones into different intensity classes and to track them over their lifetime, an algorithm has been developed. The center of a cyclone is defined to be at the grid point of a sea level pressure minimum of less than 1000 hPa within a radius of 4° latitude around that point. This reflects an average size of a cyclone. The maximum 10 m wind speed within this radius is a measure of the intensity of a cyclone. W_{max} rather than the sea level pressure minimum has been chosen as a measure of cyclone intensity as this parameter is of particular interest in terms of possible storm damages over land or wind induced flooding in coastal areas. Furthermore, if the sea level pressure minimum is used as a measure of cyclone intensity, the intensity of cyclones in the midlatitudes would be overestimated because of the climatologically lower sea level pressure compared to the subtropics.

[15] To find an objective method to determine if a cyclone shows tropical or extratropical characteristics or if a tropical cyclone undergoes ET is challenging. *Walsh* [2004] classified cyclones with an 850 hPa wind speed greater than or equal to the one at 200 hPa as tropical and the rest as extratropical. The simple wind speed criterion proposed by Walsh works reliably only for pronounced differences between the maximum wind speeds at 850 hPa and 250 hPa when applied to the RCA3 simulation results. For this reason the method is modified in our study. If the maximum wind speed at 850 hPa within the cyclone is larger than 1.2 times the one at 250 hPa, the cyclone is classified as tropical. If this value at 850 hPa is smaller than 0.8 times the one at 250 hPa, the cyclone is classified as extratropical. To determine these wind speed maxima, the size of the cyclone has to be estimated first. The radius of tropical cyclones is generally small (on average 3° latitude over the North Atlantic according to *Liu and Chan* [1999]) while the radius of extratropical cyclones is much larger and often exceeds 5° latitude. There is wide disagreement in the literature on the method of determination of cyclone radius. While many methods use fixed threshold values such as a 10 m wind speed of 15 m/s or a vorticity of 10^{-5} s^{-1} to determine the radial extent of a cyclone [*Liu and Chan*, 1999], we use a relative threshold value based on the maximum 10 m wind speed. This choice (based on several experiments) enables us to determine sizes of even weak cyclones not reaching fixed threshold values proposed by others. In the present study, the cyclone radius is defined as the maximum radius at which the 10 m wind speed falls below 60% of the maximum 10 m wind speed.

[16] Furthermore, to classify the cyclones with a maximum 850 hPa wind speed of 0.8 to 1.2 times the maximum at 250 hPa, a warm core criterion similar to the one proposed by *Vitart et al.* [1997] is used in the present study. To determine the location of the warm core, the 500 hPa temperature is smoothed as following: for cyclones with a radius of 2.8° or more, for each grid point within this radius, a new temperature is obtained by averaging the 500 hPa temperature over all grid points within a radius of 0.7° which we call the smoothing radius. For cyclones with a radius of less than 2.8°, the smoothing radius is restricted to a quarter of the cyclone radius. If the warm core is 1° latitude or more separated from the pressure minimum, the cyclone is classified as extratropical. A cyclone is also classified as extratropical, if there is no pronounced warm core or the warm core is highly asymmetric. This happens when the 500 hPa smoothed temperature falls by less than 0.5 K per degree latitude from the center to the periphery of the cyclone. This is also valid for the case when the minimum gradient of the smoothed 500 hPa temperature from the center to the periphery of the cyclone is less than 40% of its maximum. The periphery of the cyclone is defined as a ring with a width of 0.5° latitude.

[17] In the present study more importance is attached to the symmetry and less to the intensity of the warm core than in the study of *Vitart et al.* [1997]. This is following *Hart* [2003] who suggests giving equal importance to both symmetry and intensity of the warm core in cyclone classification. The maximum displacement of the warm core for classification as a tropical cyclone is reduced from 2° to 1° latitude. Moreover, in the present study the warm core intensity criterion is only applied to the actual cyclone radius rather than to a fixed radius of 8° latitude as in the work of *Vitart et al.* [1997]. It is possible to make these adaptations because cyclones are highly resolved in our RCA3 simulations. In addition, due consideration is given to the symmetry of the temperature gradient in cyclones.

[18] The present combination of criteria is generally robust. However, misjudgments can occur in the following cases: tropical cyclones that do not necessarily show a pronounced warm core in the early stage of their development or if they are asymmetric. In this case cyclones are wrongly classified as extratropical. A few cyclones north of the jet stream are wrongly classified as tropical due to the comparably weak 250 hPa wind speed and a pronounced warm core, a characteristic feature which can be found in observed polar lows [e.g., *Moore and vonder Haar*, 2003]. Additional criteria could be introduced to avoid these discrepancies: the underlying SST or the latitude of the cyclone center could be used. This is not done in the present study to consider the possibility of changed conditions in a warmer climate; tropical cyclones could move to higher latitudes or they could need a higher SST to form in a warmer climate [e.g., *Henderson-Sellers et al.*, 1998, Figure 2].

[19] For tracking cyclones over their lifetime, the centers of low pressure systems of two consecutive output periods are compared. If the resulting moving speed is below 30 m/s, they are identified as the same low pressure system. This empirical threshold value allows fast moving cyclones to be still considered as single systems. Climatological values of cyclone moving speeds are generally below 15 m/s according to *Geng and Sugi* [2001]. According to *Blender and Schubert* [2000], a high temporal resolution is essential for capturing all cyclone tracks. In the present study the tracking algorithm is applied to 3-h RCA3 output.

[20] Some of the tracked cyclones are tropical at first and become extratropical later after ET. ET can be objectively categorized into different types and stages, for example by

determining the wind patterns or the magnitude of asymmetries in the thermal structure. The classification of ET into different types and stages is beyond the scope of our study. The objective is not to investigate thoroughly the processes involved in ET but only to determine if ET takes place during the lifetime of a cyclone.

[21] The proposed criteria are different from the ones which were mainly developed for coarse resolution GCM simulations. There is no agreement on an objective classification of ET in the literature. The only way to prove that the proposed criteria lead to a reasonable distinction between tropical and extratropical cyclones is to subjectively investigate the storm structure and asymmetry as is done by NHC to classify cyclones from observation analyses. An example for a tropical cyclone transitioning into an extratropical cyclone as characterized by the proposed classification method is given in Figure 2. The precipitation and the wind patterns on 27 October 1991, 9 to 12 UTC, both (Figures 2a and 2b) show a symmetric shape. Very strong precipitation of more than 500 mm/day as well as vigorous wind speeds of up to 37 m/s at 10 m above the sea surface are simulated. In addition, a very pronounced warm core is present, with temperatures of more than $-37°C$ in the cyclone center compared to around $-43°C$ only 150 km away from the center at 250 hPa (not shown). After 12 h (Figures 2c and 2d), the precipitation pattern starts to get asymmetric with weaker precipitation in the west of the cyclone whereas the wind pattern still looks rather symmetric and the warm core starts to weaken. After 24 h, on 28 October, 9 to 12 UTC, the maximum precipitation starts to weaken to less than 500 mm/day and an extensive rain belt related to a convergence zone northeast of the cyclone develops (Figures 2e and 2f). At the same time a precipitation belt southwest of the cyclone begins to intensify. The warm core becomes clearly less intense at this stage with a maximum temperature of $-40°C$ and a weaker temperature gradient. According to our classification method this cyclone is still classified as tropical. After a further 12 h, it is classified as extratropical (Figures 2g and 2h), when the warm core gets highly asymmetric and diffused. Both precipitation zones northeast and southwest of the cyclone further intensify, the cyclone adopts extratropical characteristics including two fronts. In particular, the convergence northeast of the cyclone increases. Not only in this example, but in most cases our method starts to classify a cyclone in ET as an extratropical cyclone when it has nearly completed ET; a characteristic behavior which is acceptable for the purpose of this study to find if ET takes place during the lifetime of a cyclone.

3. Evaluation

[22] For confidence in the model results it has to be shown that the basic features of the observed climate regarding the frequency of cyclones of different intensity classes, their interannual variability and their dependency on different oceanic and atmospheric parameters are captured.

[23] More cyclone counts are simulated in the RCA3 standard experiment compared to the ERA-40 data (Figure 3). Maximum intensities are stronger in this experiment especially for the tropical cyclones. Because of the coarse resolution (1.125° or ~125 km), the maximum cyclone intensity cannot be captured in the ERA-40 data. This shows that this data set is not appropriate to validate the RCM simulation with respect to strong tropical cyclones due to their smaller spatial extent compared to extratropical cyclones. It shows again that a high horizontal resolution is crucial for studying strong cyclones.

[24] A comparison of the average cumulative number of tropical storms over the North Atlantic in the RCA3 standard experiment to observations from *NHC* [2007a] shows that the total number of named systems ($W_{\max} \geq$ 18 m/s, lifetime $\geq$12 h) and hurricanes ($W_{\max} \geq$ 33 m/s, lifetime $\geq$12 h) per year are overestimated (Figure 4): 14.1 named systems and 6.8 hurricanes are simulated over the year while 10.8 named systems and 6.2 hurricanes are observed. The onset of the higher frequencies as indicated by strong slopes in the graphs occurs in later months in the simulation compared to the observations. Therefore up to the 1st of September only 4.2 named systems and 1.9 hurricanes occur on average in each hurricane season according to the simulation, whereas 4.9 named systems and 2.4 hurricanes are observed up to this date. Overprediction occurs for September and October. No major hurricanes (category 3 or more on the Saffir-Simpson Hurricane Scale [*NHC*, 2007b], $W_{\max} \geq$ 50 m/s) are simulated in RCA3. This shows that higher horizontal resolution than the present one of 28 km is desirable. Nevertheless, the usage of an RCM leads to an improvement in simulating the frequency and intensity of tropical storms over a GCM, in which artificially low threshold values have to be used for named system and hurricane detection. Frequency and timing of hurricanes are well reproduced in the RCA3 simulation.

[25] It is also important to know if our standard simulation captures observed interannual variability and spatial distribution of tropical cyclone frequency. Table 1 gives the numbers of named systems and hurricanes from the NHC observations and from the standard experiment for each year. Correlations are highly significant. To illustrate this impressive agreement Figure 5 shows time series of the number of named systems and hurricanes. This shows that our RCM is an ideal tool for simulating the frequency of tropical storms if driven by realistic SSTs and lateral boundary values. The spatial distribution of tropical cyclone counts in 10° × 10° boxes is captured fairly well as can be seen from Figures 6d, 6e, and 6f.

[26] To gain further confidence in the model results it is investigated how well the model reproduces observed relationships between different oceanic and atmospheric parameters and the intensity of cyclones. Only if these observed relationships are reproduced, the results of the experiment with an increased SST can be trusted. Therefore the dependencies of the maximum wind speed during cyclone lifetime (W_{maxl}) on the SST, the SST gradient and temperature differences between the sea surface and different tropospheric levels (250 hPa, 500 hPa, and 850 hPa) are examined for both the NHC observations and the two experiments. For the analysis of the observations, only W_{maxl} and the location and time of ET can be used from NHC database while the remaining parameters have to be obtained from ERA-40 data.

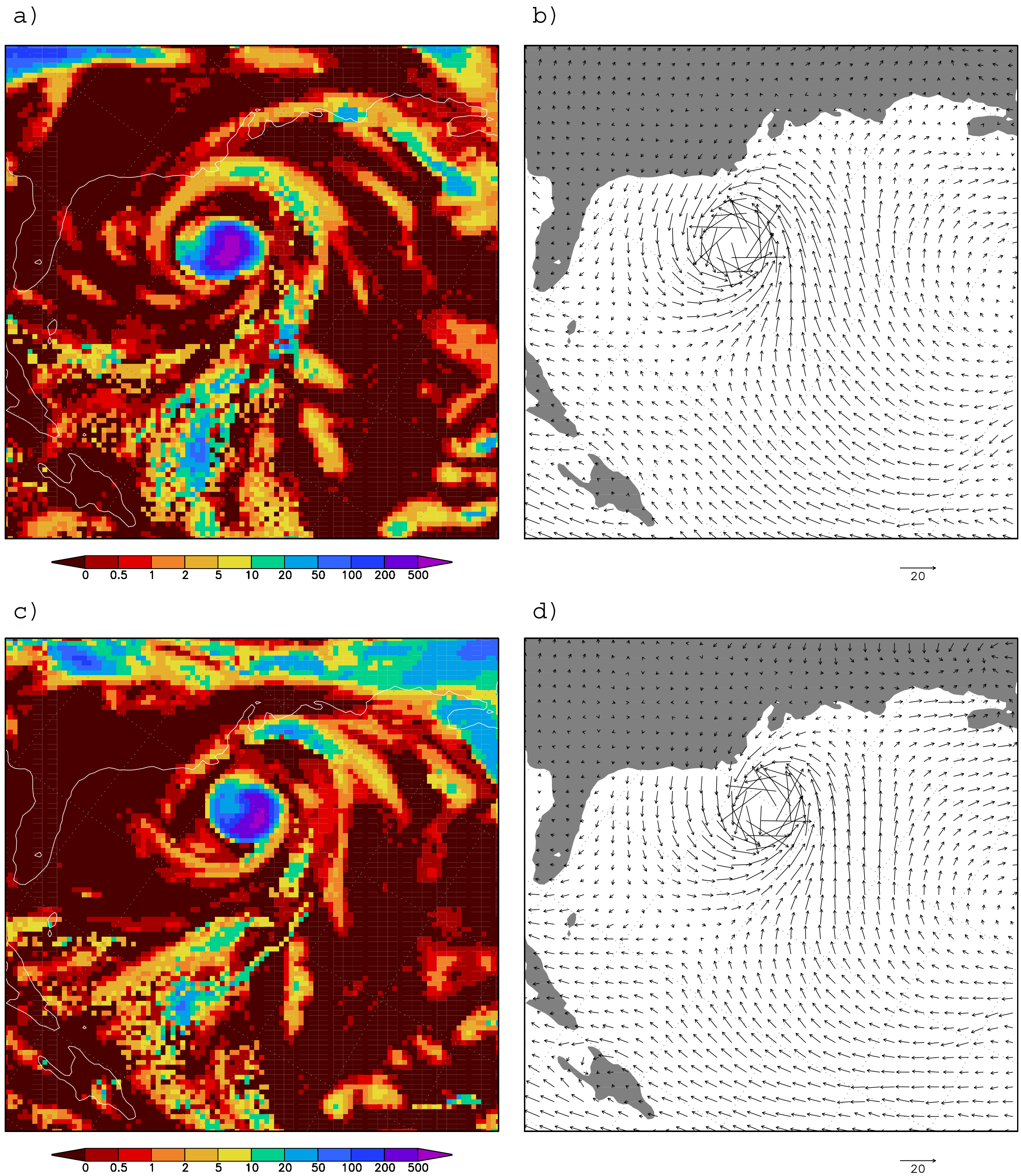

Figure 2. Representative example for a tropical cyclone undergoing ET in the standard experiment. Total precipitation [mm/day] for (a) 27 October 1991, 9 UTC to 12 UTC; (c) 27 October 1991, 21 UTC to 28 October 1991, 0 UTC; (e) 28 October 1991, 9 UTC to 12 UTC; (g) 28 October 1991, 21 UTC to 29 October 1991, 0 UTC. Wind vectors [m/s] for (b) 27 October 1991, 12 UTC; (d) 28 October, 0 UTC; (f) 28 October, 12 UTC; (h) 29 October, 0 UTC. According to our algorithm the cyclone is categorized as tropical up to 28 October 1991, 12 UTC (panels (e) and (f)) and as extratropical thereafter.

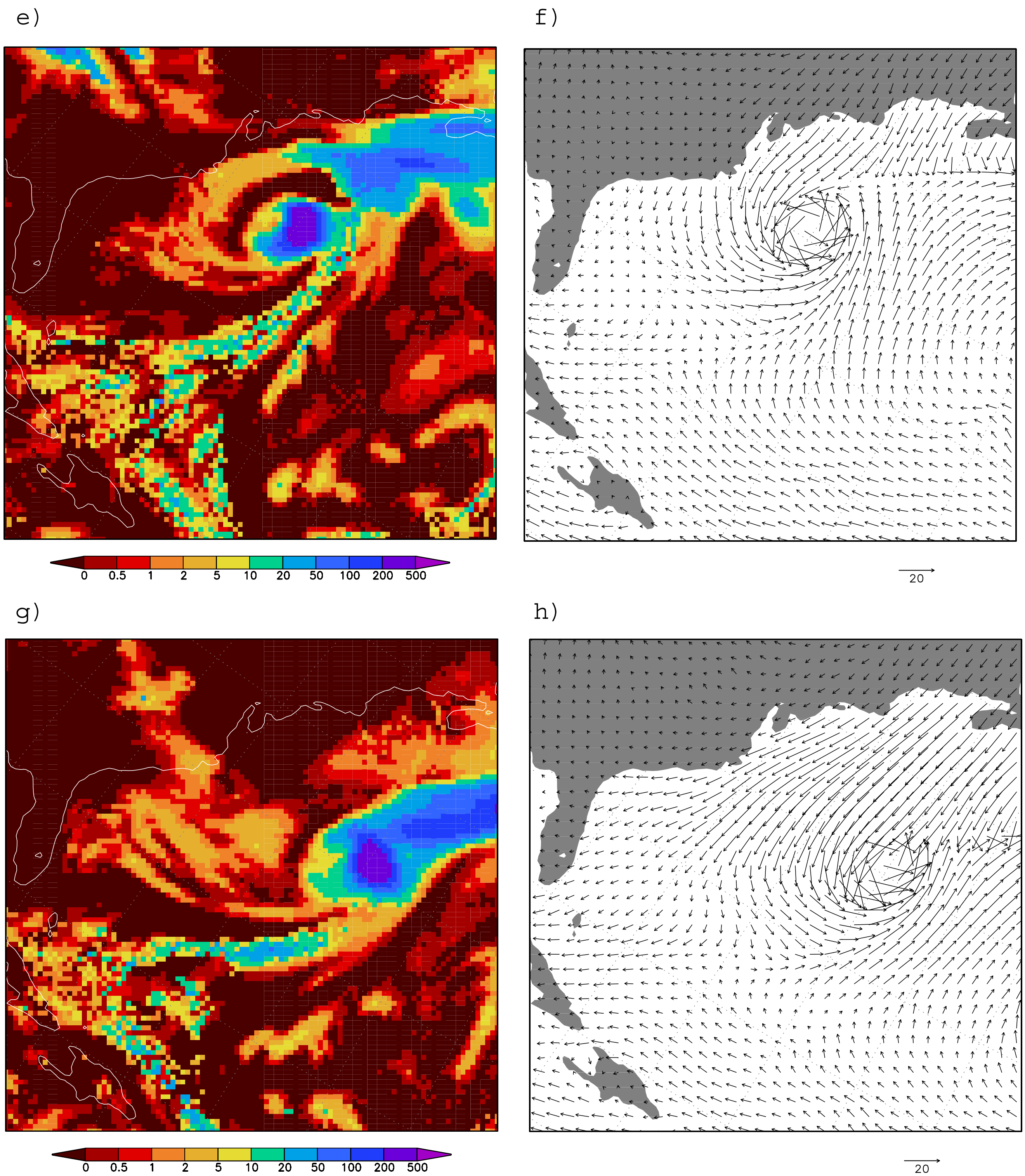

Figure 2. (continued)

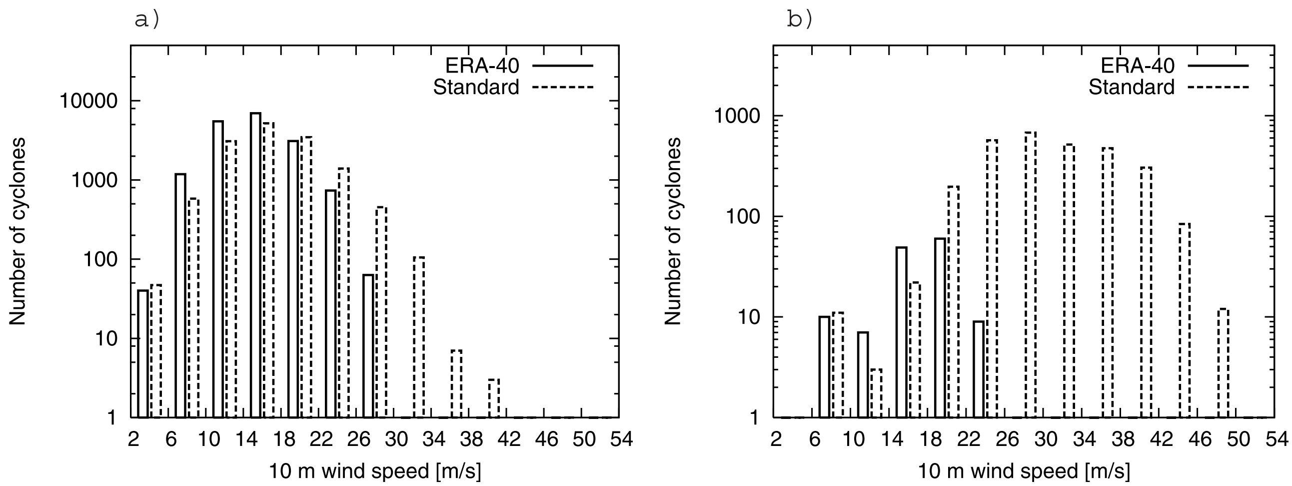

Figure 3. (a) Extratropical and (b) tropical cyclone counts in the ERA-40 data and in our standard experiment for May to December 1985–2000. In each 6-h time interval, all cyclones are categorized in intensity classes with a width of 4 m/s maximum wind speed (2–6 m/s, 6–10 m/s, . . ., 50–54 m/s) and 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.

[27] For named systems the following regressions are found:

$$
\begin{aligned}
W_{maxl} &= \Delta T_{maxl} \times 3.6(\pm 1.1) - 2.8(\pm 12.4), \quad R^2 = 0.06 \quad \textit{NHC observations}\\
&= \Delta T_{maxl} \times 2.1(\pm 0.3) + 9.2(\pm 3.3), \quad R^2 = 0.21 \quad \textit{RCA3 standard}\\
&= \Delta T_{maxl} \times 1.8(\pm 0.3) + 13.3(\pm 3.1), \quad R^2 = 0.12 \quad \textit{RCA3 sensitivity}
\end{aligned}
$$

where W_{maxl} is the maximum wind speed in the cyclone during its lifetime in m/s and ΔT_{maxl} is the maximum temperature difference between the sea surface and the 850 hPa level in K. The numbers in parenthesis are the standard errors; R^2 values are given in addition. The regressions are fitted using the method of least squares.

$$
\begin{aligned}
W_{maxl} &= SST_{maxl} \times 3.4(\pm 0.9) - 58.0(\pm 24.4), \quad R^2 = 0.09 \quad \textit{NHC observations}\\
&= SST_{maxl} \times 1.4(\pm 0.2) - 3.9(\pm 6.7), \quad R^2 = 0.14 \quad \textit{RCA3 standard}\\
&= SST_{maxl} \times 1.1(\pm 0.2) + 2.8(\pm 6.3), \quad R^2 = 0.07 \quad \textit{RCA3 sensitivity}
\end{aligned}
$$

where SST_{maxl} is the maximum sea surface temperature in °C. All regressions are significant at the 99.5% level according to the Student's t-test, although the percent variance explained is rather small in both the observations and in the model. To illustrate these relationships, scatterplots including the found regression lines are shown in Figures 7a–7f. The other oceanic and atmospheric variables result in less significant or insignificant regressions. Some of the individual regression coefficients of multiple regressions using both predictors ΔT_{maxl} and SST_{maxl} are insignificant. The regression coefficients are larger for the observations compared to the simulations. This suggests that we underestimate the sensitivity of W_{maxl} to ΔT_{maxl} and SST_{maxl}. This is because the model is unable to capture W_{maxl} of the most intense hurricanes.

[28] The results of ET from the standard experiment are compared to that of *Hart and Evans* [2001], which were obtained by analyzing the climatology of Atlantic tropical cyclones from NHC in combination with ERA-40 reanalysis data. In the standard experiment, 44% of all tropical cyclones undergo ET during their lifetime whereas according to *Hart and Evans* [2001] it is 46%. This is a very good agreement and confirms that our classification method works well. However, there is no good agreement on the number of these cyclones reintensifying after ET. 12% of the tropical cyclones reintensify after ET according to the standard experiment while this is 51% according to *Hart and Evans* [2001]. The difference is partly due to the different methods used. *Hart and Evans* [2001] use the core pressure as a measure for intensity whereas 10 m wind speed is used here. If the core pressure is used in the standard experiment, 24% of the tropical cyclones reintensify after ET. This is because of the generally lower ambient pressure in the extratropical environment compared to the tropical environment. In addition, *Hart and Evans* [2001] use the relatively coarse resolution ERA-40 data set to determine if a cyclone reintensifies. In this data set, extratropical cyclones (due to the large spatial extent) are better represented than tropical cyclones in terms of their intensity. An artificial strengthening might take place during ET as the system increases in its size and then gets covered by more grid points.

[29] The dependencies of the maximum wind speed of the ET cyclones in the extratropical stage (W_{maxle}) on the same oceanic and atmospheric parameters as for the tropical cyclones are examined for both the NHC observation and

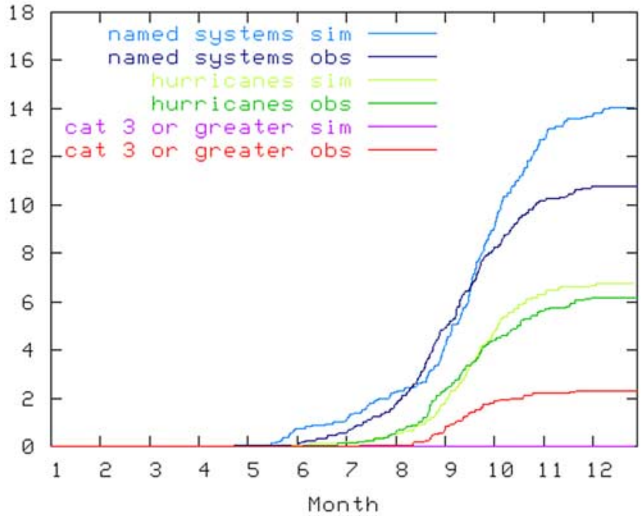

Figure 4. Accumulated number of tropical cyclones per year averaged over 1985–2000 as simulated (sim) in our standard experiment and as from observations from *NHC* [2007a] (obs). Named systems include all tropical cyclones with maximum wind speeds of 18 m/s or more, hurricanes are storms with maximum wind speeds of 33 m/s or more and category 3 or greater hurricanes are storms with maximum wind speeds of 50 m/s or more. All tropical cyclones exceeding the threshold wind speed at least four 3-h output intervals for RCA3 and at least two 6-h observation times for the observations are counted.

Table 1. Numbers of Named Systems (Maximum Wind Speed >18 m/s) and Hurricanes (Maximum Wind Speed >33 m/s) From NHC Observations and our Standard Experiment

	# named systems		# hurricanes	
Year	NHC observations	Standard	NHC observations	Standard
1985	11	8	7	3
1986	6	4	4	2
1987	7	9	3	3
1988	12	13	6	6
1989	11	16	7	10
1990	14	16	8	8
1991	8	10	4	5
1992	7	14	4	5
1993	8	14	4	5
1994	7	7	3	3
1995	19	27	11	13
1996	13	16	9	7
1997	8	9	3	1
1998	14	20	10	11
1999	12	22	8	14
2000	15	20	8	12
Correlation	0.85		0.82	
Significance level	>99.99%		>99.99%	

the RCA3 experiment data. ET cyclones in their extratropical stage show no significant dependencies unless only the cyclones traveling across the North Atlantic and moving east of 40° W are considered. Because of the restricted number of cases in each experiment, a regression is calculated on the combined data set of the two RCA3 experiments, which results in a regression significant at the 95% level:

$$W_{maxle} = \Delta T_{maxle} \times 0.50(\pm 0.22) + 23.9(\pm 1.9), R^2 = 0.06$$

where W_{maxle} is the maximum wind speed in the cyclone during its lifetime as an extratropical cyclone in m/s and ΔT_{maxle} the maximum difference between the SST and the temperature at 850 hPa in K. The respective scatterplot and its regression line are shown in Figure 7g. For the NHC observations, the dependency on ΔT_{maxle} (and on the other parameters) is insignificant. This is also true if the analysis period is extended to the entire period of the ERA-40 data (1957–2002). It should be noted that the combined usage of the NHC observation and ERA-40 data is not ideal, because small scale features of the SST and the upper air parameters cannot be captured in the latter.

[30] For all extratropical cyclones with $W_{\max} \geq 18$ m/s the following regressions are calculated:

$$\begin{aligned} W_{maxle} &= SST_{maxle} \times 0.29(\pm 0.02) + SSTG_{maxle} \times 0.16(\pm 0.03) + 18.1(\pm 0.5),\ R^2 = 0.11 \quad \textit{RCA3 standard} \\ &= SST_{maxle} \times 0.28(\pm 0.02) + SSTG_{maxle} \times 0.12(\pm 0.02) + 18.2(\pm 0.5),\ R^2 = 0.10 \quad \textit{RCA3 sensitivity} \end{aligned}$$

where W_{maxle} is the maximum wind speed in the cyclone during its lifetime as an extratropical cyclone in m/s, SST_{maxle} the maximum SST in °C and $SSTG_{maxle}$ the maximum SST gradient in K/degree latitude. These regressions are highly significant (at the 99.999% level) and agree with each other. Scatterplots with regression lines are shown for the dependency of W_{maxle} on SST_{maxle} in Figures 7h and 7i. The dependency of the intensity of extratropical cyclones on the SST and its gradient agrees with findings of previous studies (see section 1.).

[31] Although according to this evaluation a higher model resolution is desirable, the present experiment setup is adequate to study the sensitivity of cyclones to the SST. Tropical cyclone and hurricane numbers, their interannual variability, spatial distribution and ET as well as sensitivities to the examined parameters can be simulated fairly well.

4. Cyclone Statistics

[32] Figure 8 shows extratropical and tropical cyclone counts grouped into intensity classes for the standard and the sensitivity experiment. The counts of less intense extratropical cyclones do not change very much with increasing SST while the more intense extratropical cyclones increase. For the tropical cyclones, an increase can be seen for nearly all intensity classes except for the weak classes. A 9% and 39% increase in counts of major extratropical cyclones and tropical cyclones respectively ($W_{max} \geq 18$ m/s) can be found in the sensitivity experiment compared to the standard experiment. The differences are most evident in the very strong intensity classes. In fact, no extratropical cyclones with maximum wind speeds of more than 42 m/s are simulated in the standard experiment whereas a cyclone maintaining this intensity over 20 time intervals is simulated in the sensitivity experiment. The count of extratropical cyclones attaining maximum wind speeds of more than

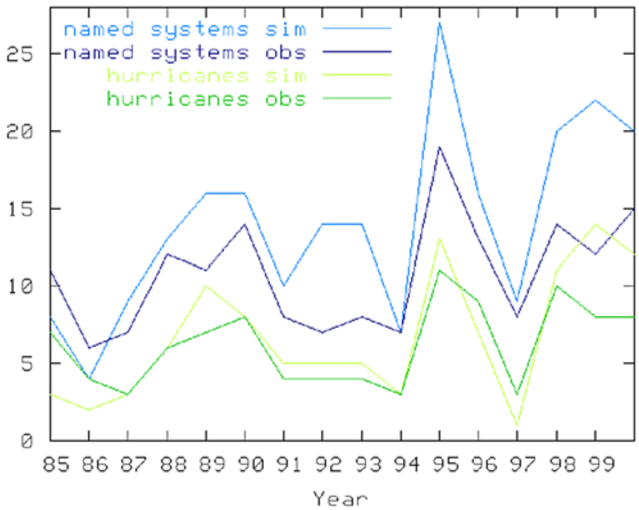

Figure 5. Time series of the number of named systems and hurricanes per year as simulated (sim) in our standard experiment and as from observations from *NHC* [2007a] (obs).

34 m/s in the sensitivity and the standard experiment is 84 and 21 respectively. The count of hurricanes with wind speeds of more than 42 m/s (category 2 on the Saffir-Simpson Hurricane Scale) increases from 196 to 570 which is a factor of nearly 3.

[33] From the spatial distribution of the occurrence of major cyclones (Figure 6), it can be seen that in most regions the count of cyclones increases. The most obvious increase occurs for tropical cyclones over the Gulf of Mexico, the Caribbean Sea and the western Sargasso Sea where the count of major tropical cyclones is more than 500 over the 16 hurricane seasons per 10° × 10° box in the sensitivity experiment. In some cases, the increase is more than a factor of 2. In addition more tropical cyclones undergo ET (48% in the sensitivity experiment and 44% in the standard experiment) and substantially more cyclones reintensify after that (24% and 12% respectively). Therefore more major cyclones with tropical origin reach the vicinity of Western European coastal areas and more major tropical cyclones and extratropical cyclones with tropical origin reach the Eastern US according to the sensitivity experiment (Figure 1).

5. Wind Speed and Precipitation Means and Extremes

[34] The 16-a data sets for the two experiments are divided into four 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.

[35] Figure 9a shows the ratio of average precipitation for the sensitivity and standard experiments. It should be noted that the changes in the boundary relaxation zone, which extends about 2° latitude from all boundaries toward the interior of the model domain are artificial; a common feature in RCMs [e.g., *Giorgi*, 1990]. Strong increase in precipitation is seen in the Gulf of Mexico, the Caribbean Sea and parts of Sargasso Sea with maximum increase of up to 100% in the middle of Gulf of Mexico and some areas between the Caribbean islands. In the southeast of the North Atlantic 50% increase is simulated but absolute values are very small. Very little change is seen in the northeast Atlantic. In September and October the increase over the Gulf of Mexico, the Caribbean Sea and parts of the Sargasso Sea is more pronounced (Figure 9b), whereas it is less in November and December (Figure 9c). In the northeast of the domain, the precipitation in the sensitivity experiment remains close to the standard experiment. The erratic behavior of the precipitation pattern over the Central North Atlantic is most pronounced in September and October. Changes in 99 and 99.9 percentile precipitation ratios are generally consistent with the changes in mean precipitation (not shown). Figure 9d shows the ratio of the maximum wind speed over the entire simulation period. There is an increase in the maximum wind speed over most parts of the domain. The largest changes occur in the tropical region due to a shift in the location of the few strong tropical cyclones.

[36] The strong increase in precipitation over Gulf of Mexico, Caribbean Sea, Sargasso Sea and adjoining areas can be attributed to the more frequent occurrence of strong tropical storms. It is worth noting that the increase in mean and extreme precipitation related to the tropical storms is more pronounced than the increase in the maximum wind speed, which is consistent with previous findings [e.g., *Knutson and Tuleya*, 2004].

6. Summary and Conclusions

[37] In this study two RCA3 experiments have been conducted to investigate the influence of the SST on cyclones. RCA3 has been driven by ERA-40 data with the original SST (standard experiment) and with an SST increased by 1 K with adapted lateral boundary values (sensitivity experiment). Both experiments have been performed for 8 consecutive months for 16 a: May to December 1985–2000.

[38] To distinguish between tropical and extratropical cyclones, a methodology has been developed based on

Figure 6. Counts of extratropical and tropical cyclones with a maximum wind speed of 18 m/s or more over all simulated months (May to December 1985–2000) per 10° × 10° box. (a) Counts of extratropical cyclones in the standard experiment, (b) counts of extratropical cyclones in the sensitivity experiment, (c) difference sensitivity minus standard. (d) Counts of tropical cyclones from NHC observations, (e) counts of tropical cyclones in the standard experiment, (f) difference standard experiment minus NHC observations, (g) counts of tropical cyclones in the sensitivity experiment, (h) difference sensitivity minus standard. All cyclones are counted in each 3-h output interval. For the observations all cyclones are counted in each 6-h observation interval and counts are multiplied by 2 for comparability. Only 10° × 10° boxes completely included in the model domain are plotted.

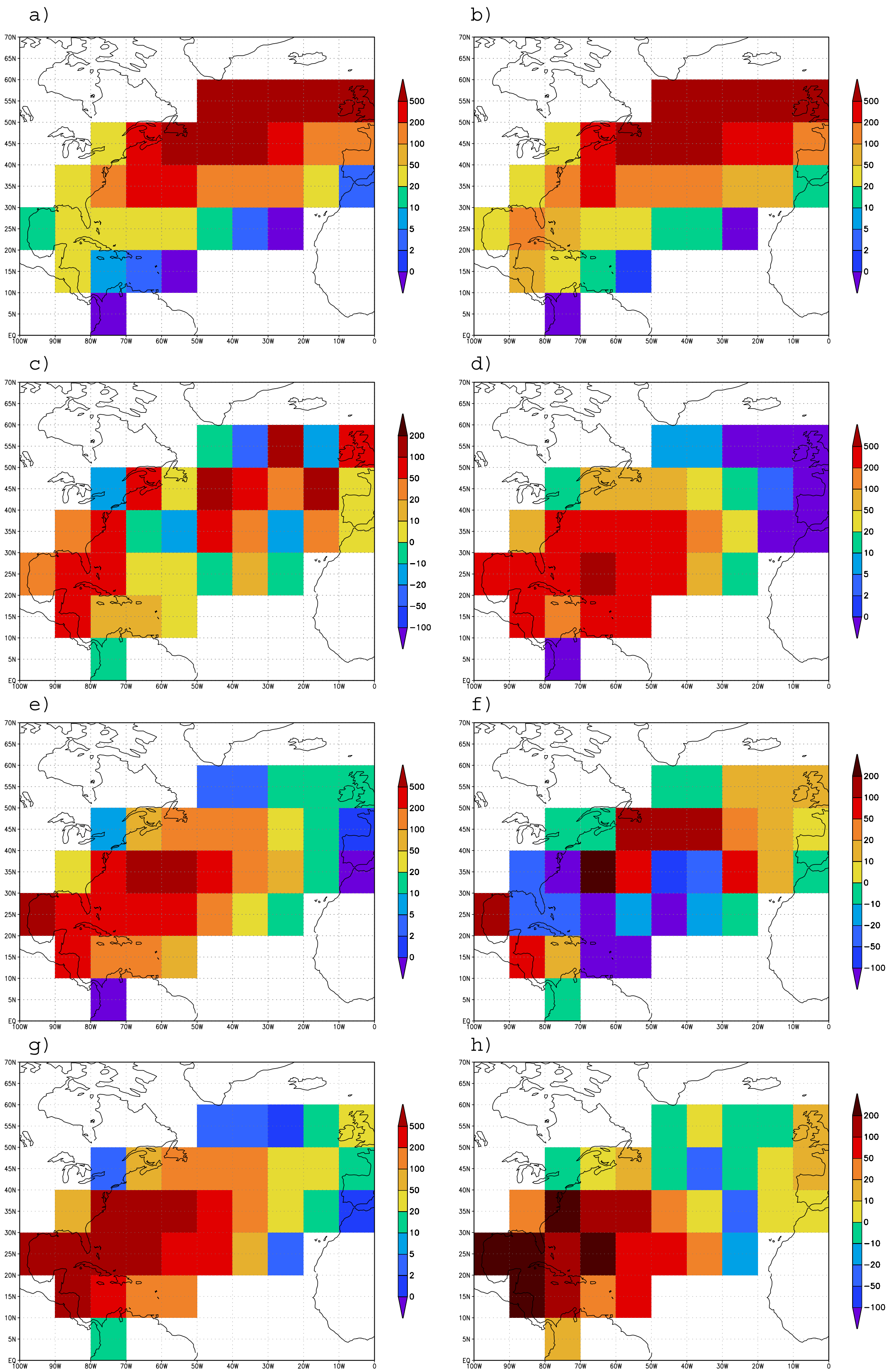

Figure 6

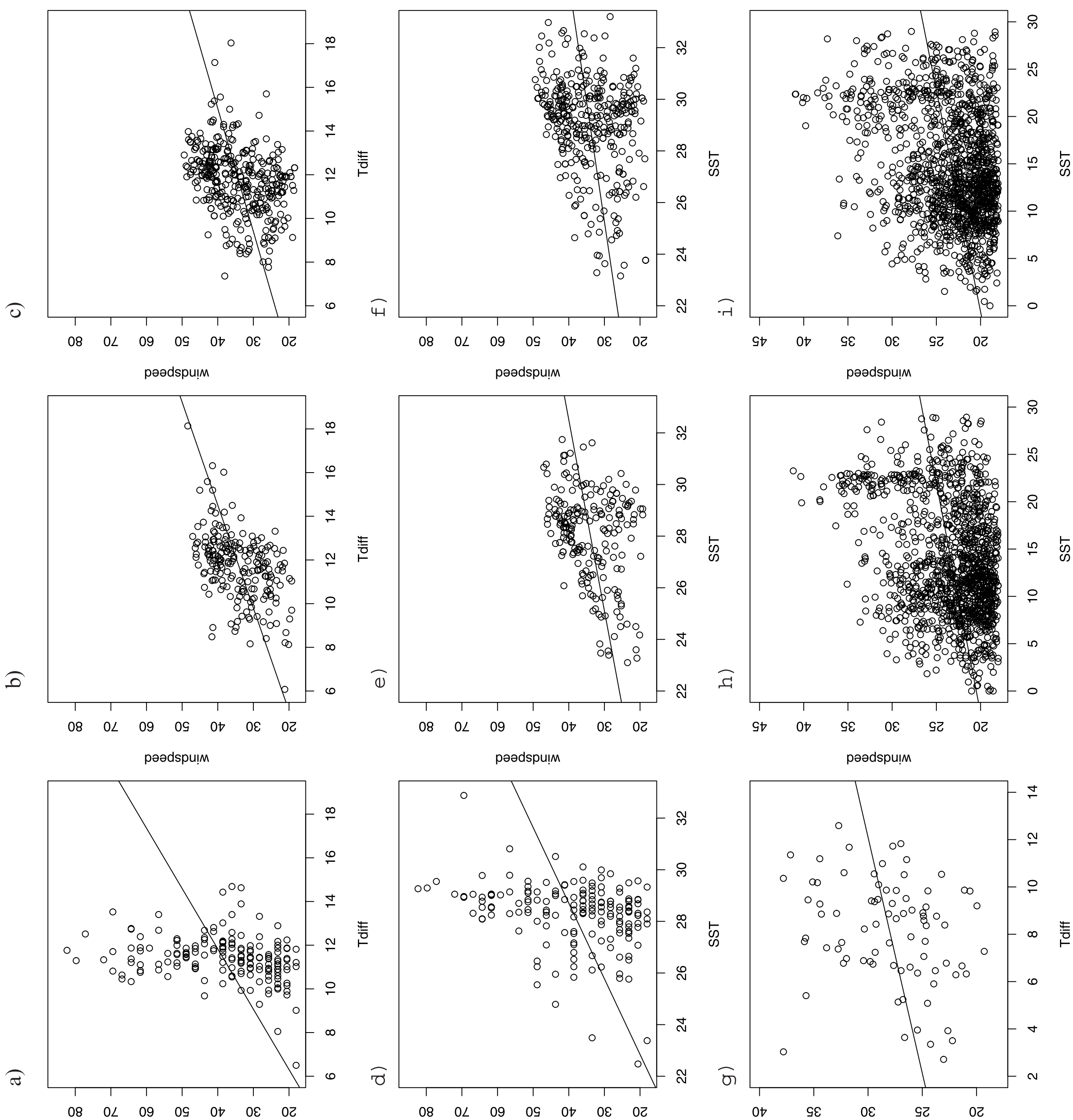

Figure 7

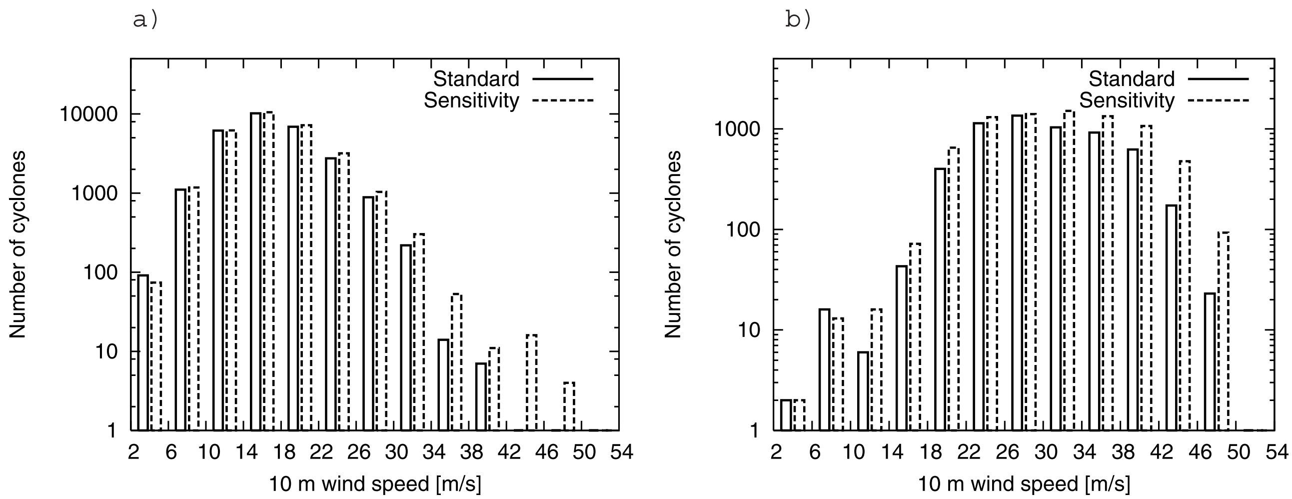

Figure 8. (a) Extratropical and (b) tropical cyclone counts as in the standard and in the sensitivity experiment for May to December 1985–2000. In each 3-h time interval, all cyclones are categorized in intensity classes with a width of 4 m/s maximum wind speed (2–6 m/s, 6–10 m/s, . . ., 50–54 m/s) and 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.

methods used for analyzing GCM output. Criteria used for GCM simulations partly had to be adapted to the higher resolution of RCM output as GCM simulated tropical cyclones are generally too weak and show a large horizontal extent. Our method leads to a reliable classification of cyclones into tropical and extratropical.

[39] In comparison with GCM simulations of tropical cyclones, RCA3 simulated tropical cyclones show better agreement with observations in terms of their intensity. Whereas in GCM experiments usually an artificially low threshold value of 10 m wind speed is used for the detection of hurricanes [e.g., *Walsh*, 2004], it has been proved to be possible to apply the same threshold values as used by the National Hurricane Centre (NHC in Miami, Florida) to detect named systems and hurricanes in the RCA3 experiments. In this study, the count of named systems and hurricanes per hurricane season is oversimulated by 31% and 9% respectively. This over prediction could be due to neglecting the ocean feedback or deficiencies in model parameterizations. A coupled ocean-atmosphere model might improve the results. The failure of simulating the most intense hurricanes with wind speeds of more than 50 m/s (storms of the categories 3, 4 and 5 on the Saffir-Simpson Hurricane Scale) is consistent with the findings of *Walsh and Ryan* [2000] and *Walsh et al.* [2004], who agree that a horizontal resolution considerably better than 30 km is desirable.

[40] The interannual variability of tropical cyclone counts is very well simulated in our RCA3 standard experiment compared to NHC observations. Correlations of yearly counts of named systems and hurricanes between the RCA3 standard experiment and the NHC observations are as high as 85 and 82% and are significant on the 99.99% level. Furthermore, the spatial distribution of tropical cyclones is fairly well represented in our RCA3 standard experiment.

[41] A comparison of the count of extratropical cyclones in the RCA3 standard experiment and the ERA-40 data shows a reasonable agreement for low intensity classes. However, a higher count of strong extratropical cyclones with wind speeds of more than 26 m/s is found compared to the ERA-40 data. Even though extratropical cyclones show a larger horizontal extent than tropical cyclones, the problem of an underestimation of strong wind speeds due to a coarse resolution in the ERA-40 data is not restricted to tropical cyclones.

[42] The results suggest that higher SSTs alone lead to a higher count of cyclones over most parts of the North Atlantic at least during the extended hurricane season. In particular, the count of very intense cyclones increases strongly. Extreme precipitation from storms mainly increases in regions where tropical cyclones are frequent, whereas the maximum wind speed increases in most parts of the model domain. The number of tropical cyclones undergoing extratropical transition (ET) increases and reintensification after ET occurs more often. However, our simulations are not intended to serve as projections of TC activity in a greenhouse gas warmed climate, since in such scenarios the atmospheric temperature structure is predicted to stabilize according to many GCM predictions, which counteracts the SST influence.

Figure 7. Scatterplots with regression lines of maximum wind speed of cyclones [m/s] versus different oceanic and atmospheric influencing factors. (a) Maximum wind speed of tropical cyclones [m/s] versus temperature difference between sea surface and 850 hPa [K] from NHC observations, (b) from standard experiment and (c) from sensitivity experiment. Figures 7d to 7f same as Figures 7a to 7c but versus SST [°C]. (g) Maximum wind speed of extratropical cyclones east of 40° W after ET versus temperature difference between sea surface and 850 hPa [K] from pooled data of standard and sensitivity experiments. Maximum wind speed of extratropical cyclones versus SST [°C] (h) from standard experiment and (i) from sensitivity experiment.

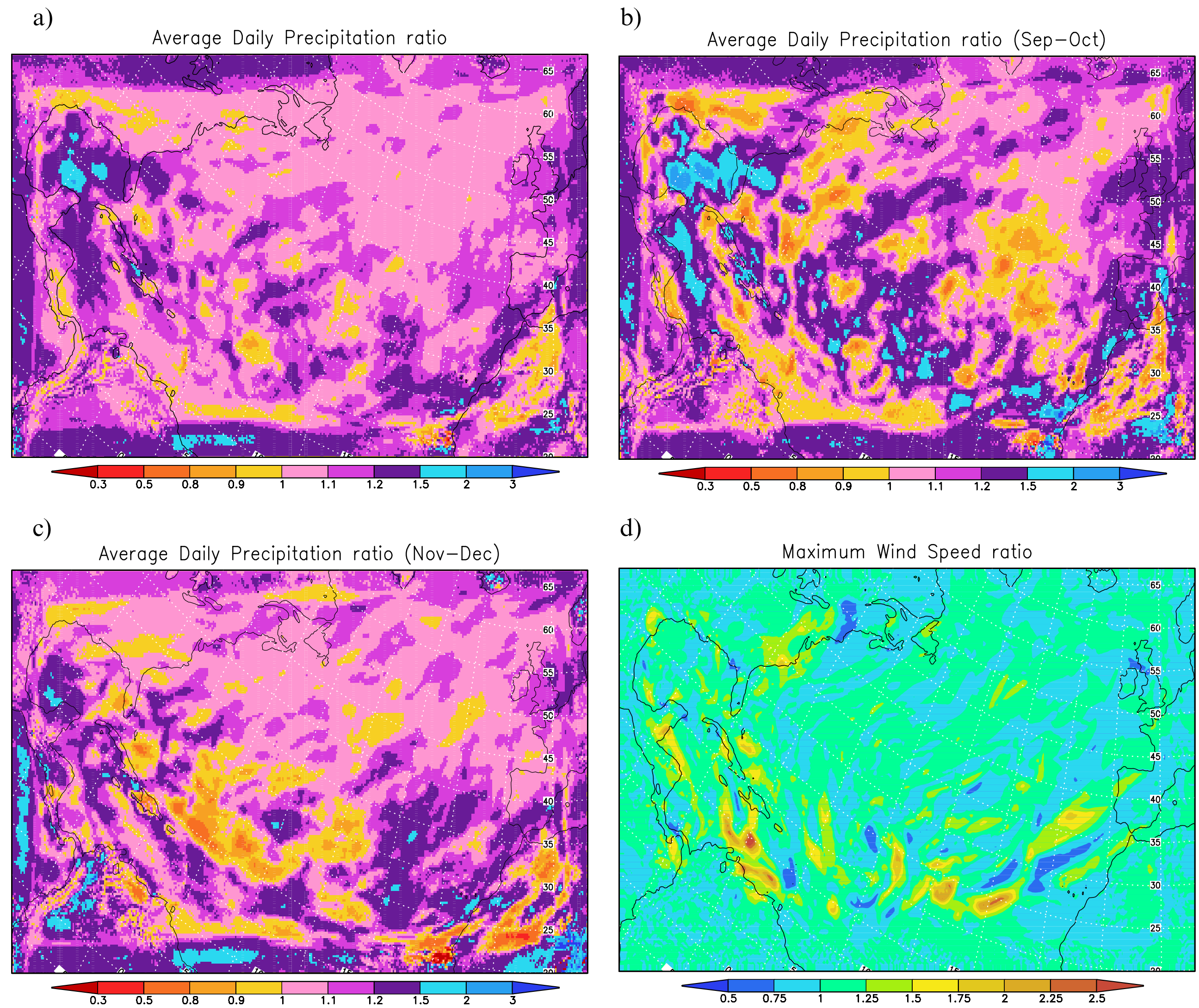

Figure 9. Ratios for average daily precipitation for (a) the 16 year period, (b) September–October period, (c) November-December period and (d) the maximum wind speed ratio for sensitivity and standard experiment.

Table 2. Predicted Changes in Extratropical and Tropical Cyclone Frequencies and Intensities of a Selection of Studies due to Global Warming

Study and method	Extratropical cyclones	Tropical cyclones
Knutson and Tuleya [2004]: large number of idealized experiments with GFDL hurricane prediction system (horizontal resolution: 9 km)		Increase in maximum wind speed, stronger hydrological cycle
Oouchi et al. [2006]: 10-year time slice experiments with GCM (horizontal resolution: 20 km)		Increased frequency of tropical cyclones over the North Atlantic, increase in the maximum wind speed
Yoshimura et al. [2006]: 10-year time slice experiments with GCM (horizontal resolution: 120 km)		Decreased frequency of tropical cyclones, frequency changes of intense storms uncertain
König et al. [1993]: evaluation of 10-year time slices of GCM experiments (horizontal resolution: ~600 km)	No significant changes in the total number of cyclones	
Lambert [1995]: evaluation of 5-year time slices of GCM experiments (horizontal resolution: ~400 km)	Decrease in the total number of cyclones, increase in the number of intense cyclones during winter	
Sinclair and Watterson [1999]: evaluation of 30-year time slices of GCM experiments (horizontal resolution: ~500 km)	Increased winter cyclone activity near downstream ends of principal tracks	
Bengtsson et al. [2006]: evaluation of 30-year time slices of GCM experiments (horizontal resolution: ~200 km)	No change in storm intensity, decrease in total number of cyclones, poleward shift of storm tracks	No change in storm intensity, decrease in total number of cyclones, especially over the North Atlantic
This study: 16-year time slices of idealized RCM experiments considering a homogeneous warming (horizontal resolution: 28 km)	Slight increase in total number of cyclones, strong increase in number of intense cyclones	Slight increase in total number of cyclones, strong increase in number of intense cyclones

[43] Important differences are the drastic change in precipitation and its spatial and temporal distribution which is linked to the cyclone genesis and its path. It is interesting to note that increases in extreme precipitation are particularly strong over the hurricane prone region of Gulf of Mexico, Caribbean Sea, Sargasso Sea and adjoining land areas. There is also a change in the location of occurrence of maximum wind speeds which is again largely associated to the shift in the location and intensity of tropical cyclones. Most of the changes in wind speed, precipitation increase and its distribution can be attributed to the tropical cyclones. Relative changes in the maximum wind speed are generally smaller than changes in extreme precipitation.

[44] The feature of maximum intensity increase in tropical storms with higher SSTs is common to most other studies which include changes in other parameters than the SST [e.g., *Knutson and Tuleya*, 2004; *Oouchi et al.*, 2006] although contrasting results exist [e.g., *Bengtsson et al.*, 2006] (Table 2).

[45] The sensitivity of the intensity of tropical and ET cyclones to the SST and the stability of the lower troposphere appears to be underpredicted in our simulations compared to observations. For example, *IPCC* [2007] reported a stronger increase in very intense storm activity since 1970 compared to model predictions. However, other factors such as circulation changes since 1970 [e.g., *Bell and Chelliah*, 2006] may explain this discrepancy. The rise in hurricane counts from 1985 to 2000 is reasonably well-simulated in our standard experiment driven by reanalyses and observed SSTs.

[46] To conduct a prediction for the future, 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.

[47] **Acknowledgments.** This work was carried out under the Community Climate Change Consortium for Ireland (C4I) Project, funded by the following Irish agencies: Environmental Protection Agency (under the National Development Plan), Met Éireann, Sustainable Energy Ireland, Enterprise Ireland and the Higher Education Authority. The work was also supported by the CosmoGrid project, funded under the Programme for Research in Third Level Institutions (PRTLI) administered by the Irish Higher Education Authority under the National Development Plan and with partial support from the European Regional Development Fund. Additional support came from the EU Network of Excellence ACCENT as well as from the MAP project. We would like to thank the Rossby Centre at the Swedish Meteorological and Hydrological Institute in Norrköping, Sweden, for supplying us with the RCA3 model. We are grateful to the anonymous reviewers, who greatly helped to improve our paper.

References

Bell, G. D., and M. Chelliah (2006), Leading tropical modes associated with interannual and multidecadal fluctuations in North Atlantic hurricane activity, *J. Clim.*, *19*, 590–612.

Benestad, R. E., and D. Chen (2006), The use of a calculus-based cyclone identification method for generating storm statistics, *Tellus*, *58A*, 473–486.

Bengtsson, L., K. I. Hodges, and E. Roeckner (2006), Storm tracks and climate change, *J. Clim.*, *19*, 3518–3543.

Blender, R., and M. Schubert (2000), Cyclone tracking in different spatial and temporal resolutions, *Mon. Weather Rev.*, *128*, 377–384, doi:10.1175/1520-0493 (2000)128<0377:CTIDSA>2.0.CO;2.

Camargo, S. J., and A. H. Sobel (2004), Formation of tropical storms in an atmospheric general circulation model, *Tellus*, *56A*, 56–67.

Camp, J. P., and M. Montgomery (2001), Hurricane maximum intensity: Past and present, *Mon. Weather Rev.*, *129*, 1704–1717.

Chan, J. C. L., Y. Duan, and L. K. Shay (2001), Tropical cyclone intensity change from a simple ocean-atmosphere coupled model, *J. Atmos. Sci.*, *58*, 154–172, doi:10.1175/1520-0469 (2001)058<0154:TCICFA>2.0.CO;2.

Chen, S.-J., Y.-H. Kuo, P.-Z. Zhang, and Q.-F. Bai (1992), Climatology of explosive cyclones off the east Asian coast, *Mon. Weather Rev.*, *120*, 3029–3035, doi:10.1175/1520-0493 (1992)120<3029:COECOT>2.0. CO;2.

Davies, H. C. (1976), A lateral boundary formulation for multilevel prediction models, *Q. J. R. Meteorol. Soc.*, *105*, 629–655.

Davis, C., and L. F. Bosart (2002), Numerical simulations of the genesis of hurricane Diana (1984). Part II: Sensitivity of track and intensity prediction, *Mon. Weather Rev.*, *130*, 1100–1124, doi:10.1175/1520-0493 (2002)130<1100:NSOTGO>2.0.CO;2.

De Maria, M., and J. Kaplan (1994), Sea surface temperature and the maximum intensity of Atlantic tropical cyclones, *J. Clim.*, *7*, 1324–1334, doi:10.1175/1520-0442 (1994)007<1324:SSTATM>2.0.CO;2.

Emanuel, K. A. (1987), The dependence of hurricane intensity on climate, *Nature*, *326*, 483–485.

Evans, J. L., and R. E. Hart (2003), Objective Indicators of the life cycle evolution of extratropical transition for Atlantic tropical cyclones, *Mon. Weather Rev.*, *131*, 909–925.

Evans, J. L., B. F. Ryan, and J. L. McGregor (1994), A numerical exploration of the sensitivity of tropical cyclone rainfall intensity to sea surface temperature, *J. Clim.*, *7*, 616–623.

Geng, Q., and M. Sugi (2001), Variability of the North Atlantic cyclone activity in winter analyzed from NCEP-NCAR reanalysis data, *J. Clim.*, *14*, 3863–3873.

Geng, Q., and M. Sugi (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.

Giordani, H., and G. Caniaux (2001), Sensitivity to sea surface temperature in the Northwestern Atlantic, *Mon. Weather Rev.*, *129*, 1273–1295.

Giorgi, F. (1990), Simulation of regional climate using a limited area model nested in a general circulation model, *J. Clim.*, *3*, 941–963.

Gyakum, J. R., and R. E. Danielson (2000), Analysis of meteorological precursors to ordinary and explosive Cyclogenesis in the Western North Pacific, *Mon. Weather Rev.*, *128*, 851–863, doi:10.1175/1520-0493 (2000)128<0851:AOMPTO>2.0.CO;2.

Hall, N. M. J., B. J. Hoskins, P. J. Valdes, and C. A. Senior (1994), Storm tracks in a high-resolution GCM with doubled carbon dioxide, *Q. J. R. Meteorol. Soc.*, *120*, 1209–1230, doi:10.1256/smsqj.51904.

Hart, R. E. (2003), A cyclone phase space derived from thermal wind and thermal asymmetry, *Mon. Weather Rev.*, *131*, 585–616.

Hart, R. E., and J. L. Evans (2001), A climatology of the extratropical transition of Atlantic tropical cyclones, *J. Clim.*, *14*, 546–564.

Henderson-Sellers, A., H. Zhang, G. Berz, K. Emanuel, W. Gray, C. Landsea, G. Holland, J. Lighthill, S.-L. Shieh, P. Webster, and K. McGuffie (1998), Tropical cyclones and global climate change: A post-IPCC assessment, *Bull. Am. Meteorol. Soc.*, *79*, 19–38.

Holland, G. J. (1997), The maximum potential intensity of tropical cyclones, *J. Atmos. Sci.*, *54*, 2519–2541.

IPCC (2007), Climate change 2007: the physical science basis. Summary for policymakers. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. IPCC secretariat, Geneve, Switzerland.

Jones, S. C., et al. (2003), The extratropical transition of tropical cyclones: Forecast challenges, current understanding, and future directions, *Weather Forecasting*, *18*, 1052–1092.

Jones, C. G., U. Willén, A. Ullerstig, and U. Hansson (2004), The Rossby Centre regional atmospheric climate model Part I: Model climatology and performance for the present climate over Europe, *Ambio*, *33*, 199–210.

Jung, T., S. K. Gulev, I. Rudeva, and V. Soloviov (2006), Sensitivity of extratropical cyclone characteristics to horizontal resolution in the ECMWF model, *Q. J. R. Meteorol.*, *132*, 1839–1857.

Kain, J., and M. Fritsch (1990), A one dimensional entraining/detraining plume model and its application in convective parameterisation, *J. Atmos. Sci.*, *47*, 2784–2802.

Kjellström, E., L. Bärring, S. Gollvik, U. Hansson, C. Jones, P. Samuelsson, M. Rummukainen, A. Ullerstig, U. Willén, and K. Wyser (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, SE-60176, Norrköping, Sweden, 54 pp.

Klein, P. M., P. A. Harr, and R. L. Elsberry (2002), Extratropical transition of western North Pacific tropical cyclones: Midlatitude and tropical cyclone contributions to reintensification, *Mon. Weather Rev.*, *130*, 2240–2259.

Knutson, T. R., and R. E. Tuleya (2004), Impact of CO2-induced warming on simulated hurricane intensity and precipitation: Sensitivity to the choice of climate model and convective parameterization, *J. Clim.*, *17*, 3477–3495.

Knutson, T. R., R. E. Tuleya, W. Shen, and I. Ginis (2001), Impact of CO2-induced warming on hurricane intensities as simulated in a hurricane model with ocean coupling, *J. Clim.*, *14*, 2458–2468.

König, W., R. Sausen, and F. Sielmann (1993), Objective identification of cyclones in GCM simulations, *J. Clim.*, *6*, 2217–2231, doi:10.1175/1520-0442 (1993)006<2217:OIOCIG>2.0.CO;2.

Krishnamurti, T. N., D. K. Oosterhof, and N. Dignon (1989), Hurricane prediction with a high resolution global model, *Mon. Weather Rev.*, *117*, 631–669.

Lambert, S. J. (1995), The effect of enhanced greenhouse warming on winter cyclone frequencies and strengths, *J. Clim.*, *8*, 1447–1452, doi:10.1175/1520-0442 (1995)008<1447:TEOEGW>2.0.CO;2.

Landsea, C. W., N. Nicholls, W. M. Gray, and L. A. Avila (1996), Downward trends in the frequency of intense Atlantic hurricanes during the past five decades, *Geophys. Res. Lett.*, *23*, 1697–1700.

Landsea, C. W., B. A. Harper, K. Hoarau, and J. A. Knaff (2006), Can we detect trends in extreme tropical cyclones?, *Science*, *313*, 452–454.

Liu, K. S., and J. C. L. Chan (1999), Size of tropical cyclones as inferred from ERS-1 and ERS-2 data, *Mon. Weather Rev.*, *127*, 2992–3001.

Michaels, P., P. C. Knappenberger, and C. Landsea (2005), Comments on "Impact of CO2-induced warming on simulated hurricane intensity and precipitation: Sensitivity to the choice of climate model and convective scheme", *J. Clim.*, *18*, 5179–5182.

Moore, R. W., and T. H. vonder Haar (2003), Diagnosis of a polar low warm core utilizing the Advanced Microwave Sounding Unit, *Weather Forecasting*, *18*, 700–711.

Nguyen, K. C., and K. J. E. Walsh (2001), Interannual, decadal and transient greenhouse simulations of tropical cyclone-like vortices in a regional climate model of the South Pacific, *J. Clim.*, *14*, 3043–3054.

NHC (2007a), [Available online at http://www.nhc.noaa.gov/pastall.shtml, section "Hurricane Best Track Files (HURDAT)"].

NHC (2007b), [Available online at http://www.nhc.noaa.gov/aboutsshs.shtml].

Oouchi, K., J. Yoshimura, H. Yoshimura, R. Mizuta, S. Kusunoki, and A. Noda (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.

Pavan, V., N. Hall, P. Valdes, and M. Blackburn (1999), The importance of moisture distribution for the growth and energetics of mid-latitude systems, *Ann. Geophys.*, *17*, 242–256.

Ritchie, E. A., and R. L. Elsberry (2001), Simulations of the transformation stage of the extratropical transition of tropical cyclones, *Mon. Weather Rev.*, *129*, 1462–1480.

Sanders, F., and J. R. Gyakum (1980), Synoptic-dynamic climatology of the "Bomb", *Mon. Weather Rev.*, *108*, 1589–1606.

Sinclair, M. R. (2002), Extratropical transition of southwest Pacific tropical cyclones. Part I: Climatology and mean structure changes, *Mon. Weather Rev.*, *130*, 590–609.

Sinclair, M. R., and I. G. Watterson (1999), Objective assessment of extratropical weather systems in simulated climates, *J. Clim.*, *12*, 3467–3485, doi:10.1175/1520-0442 (1999)012<3467:OAOEWS>2.0.CO;2.

Tuleya, R. E., and Y. Kurihara (1982), A note on the sea surface temperature sensitivity of a numerical model of tropical storm genesis, *Mon. Weather Rev.*, *110*, 2063–2069.

Uppala, S. M., et al. (2005), The ERA-40 reanalysis, *Q. J. R. Meteorol. Soc.*, *131*, 2961–3012.

Vitart, F., J. L. Anderson, and W. F. Stern (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.

Walsh, K. J. E., and J. J. Katzfey (2000), The impact of climate change on the poleward movement of tropical cyclone-like vortices in a regional climate model, *J. Clim.*, *13*, 1116–1132.

Walsh, K. J. E., and B. F. Ryan (2000), Tropical cyclone intensity increase near Australia as a result of climate change, *J. Clim.*, *13*, 3029–3036.

Walsh, K. J. E., K. C. Nguyen, and J. L. McGregor (2004), Fine-resolution regional climate model simulations of the impact of climate change on tropical cyclones near Australia, *Clim. Dyn.*, *22*, 47–56.

Yoshimura, J., M. Sugi, and A. Noda (2006), Influence of greenhouse warming on tropical cyclone frequency, *J. Meteorol. Soc. Jpn.*, *84*, 405–428.

Zhang, Y., and W.-C. Wang (1997), Model-simulated northern winter cyclone and anticyclone activity under a greenhouse warming scenario, *J. Clim.*, *10*, 1616–1634, doi:10.1175/1520-0442 (1997)010<1616:MSNWCA>2.0. CO;2.

P. Lynch and P. Nolan, University College Dublin, Dublin, Ireland.

R. McGrath, T. Semmler, and S. Wang, Met Eireann, Glasnevin Hill, Dublin 9, Ireland. (tido.semmler@met.ie)

C. O'Dowd and S. Varghese, National University of Ireland, Galway, Ireland.