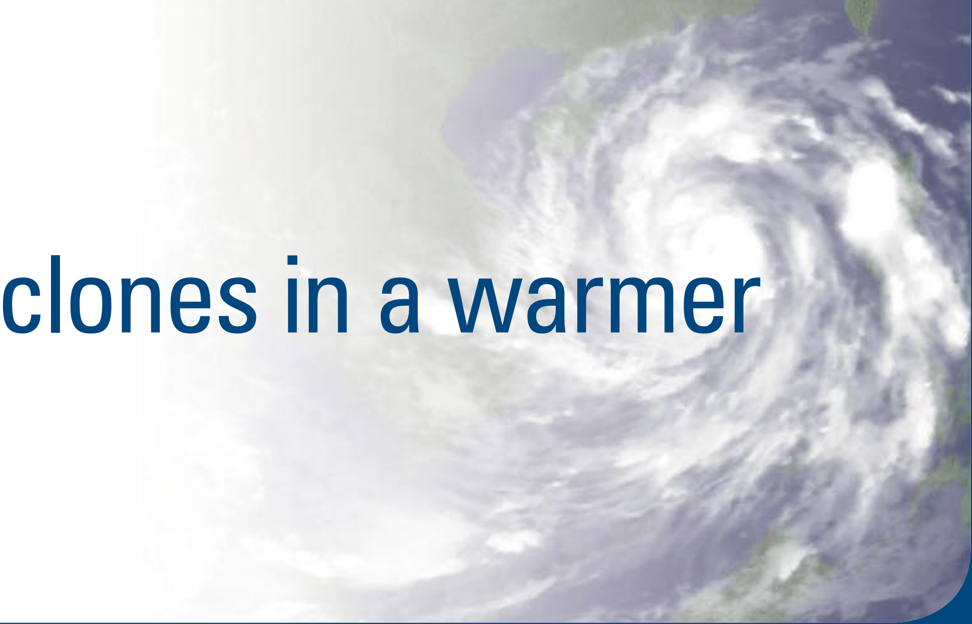

Tropical cyclones in a warmer climate

by Lennart Bengtsson*

Introduction

Tropical cyclones are among the most devastating of natural disasters, frequently causing loss of human life and serious economic damage. This is because of ocean storm surges in coastal regions, destructive winds and flash floods resulting from excessive precipitation. The annual cost for the USA has been estimated at US$ 5-10 billion but, after the extensive damage caused during the active 2005 hurricane season, including hurricane *Katrina*, with damage estimated at some US$85 billion, the figure is likely to increase.

In New Orleans and neighbouring communities, which were partly destroyed by *Katrina*, some 1 800 lives were lost. Presumably, most of these individuals would have been saved if the evacuation of people had been more effective. Conversely, the situation would have been significantly worse without accurate weather predictions and warning systems. During a tropical storm in 1970 in Bangladesh, more than 300 000 people were killed—as many as during the Sumatra earthquake of December 2004. The increasingly accurate prediction for tropical cyclones is one of the great achievements of international meteorology during the last two decades.

Tropical cyclones are low-pressure systems, which originate over tropical and subtropical oceans. They are characterized by organized convection and a well-developed cyclonic circulation at the surface.

A weak cyclonic circulation may intensify into a tropical cyclone. The boundary layer friction in such an onset vortex causes the air to spiral inward towards the storm centre. Clouds near the centre become organized into spiral rain-bands and eventually into an eye wall by the strong rotation of the vortex. As the winds strengthen and surface pressure decreases, increasing amounts of water are extracted from the warm ocean. The air rises and cools and water vapour condenses, releasing latent heat. The heating leads to a further intensification, in turn increasing surface wind and evaporation. The storm will continue to intensify until the energy input by surface evaporation is balanced by frictional dissipation. In this process, a well-developed tropical cyclone converts ocean heat energy into mechanical energy of the winds like a steam engine or Carnot engine (Emanuel, 1988).

Observations indicate (Schade, 2000) that the empirical relations based on the concept of a Carnot engine provide a good measure of the upper boundary on the intensity of a tropical cyclone as can be determined from sea-surface temperatures (SSTs) and the state of the atmosphere. However, the conditions responsible for the development and actual intensity of tropical cyclones are poorly understood, mainly because of a lack of accurate observations in areas where they develop. Empirical data (Goldenberg *et al.*, 2001) and model studies are in broad agreement that the following conditions must be met.

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Firstly, tropical cyclones require that SST reach ~26°C (Palmén, 1948) or more, because a minimum amount

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of ocean heat supply is needed. Indications are (Royer *et al.*, 1998) that this value may have to increase in a warmer climate as the deep convection normally initiated at 26°C also depends on the temperature of the upper troposphere.

Secondly, low vertical wind shear is required, presumably because the convective cloud cells that provide the energy for the cyclones can do so effectively only if their vertical structure is not distorted.

Thirdly, cyclone activity depends also on the large-scale circulation. This can be exemplified by the huge difference in the Atlantic between the overly active 2005 and the less active 2006. The very weak activity in 2006 was not expected: the US National Oceanographic and Atmospheric Administration (NOAA) outlook issued on 22 May 2006 indicated an 80 per cent chance of an above-normal hurricane season and only a 5 per cent chance of a below-normal season. One contributing factor to this—but not the only one—could have been the building-up of an El Niño event in the eastern Pacific during the second half of 2006.

Have tropical cyclones become more intense?

A number of empirical studies have been undertaken recently to see whether tropical cyclones have become more intense following higher SSTs. Some of these studies indicate that an increase is taking place (Webster *et al.*, 2005; Scriver and Huber, 2006). However, results are inconclusive, as other studies claim that no intensification has occurred (Chen, 2006; Klotzbach, 2006; Landsea *et al.*, 2006). There are two main reasons for these different interpretations.

Firstly, tropical cyclones are undergoing interannual variations, including changes on multi-decadal time-scales, thus requiring longer records of reliable observations than currently available. Secondly, observing systems have been undergoing rapid changes that mean that the intensity of tropical cyclones are more accurately observed now than previously. Re-assessment of satellite observations (Kossin *et al.*, 2007) suggests that there is no discernible global trend, although the re-assessed data still support the positive trend in the Atlantic.

What can we learn from climate modelling?

As numerical models have evolved, they have gradually become more reliable in predicting tropical storms several days in advance. Great progress has taken place in predicting the movements of storms, while the intensity and its variations still have deficiencies (DeMaria *et al.*, 2005). However, current supercomputers make it possible to run models at very high resolution, which, in combination with more accurate space-based observations, offers further improvements. The improved computational capabilities also offer new possibilities to study the impact of climate change on tropical cyclones.

There have been several model studies over the last decade that explore possible changes of tropical cyclones in a future climate. The great advantage with comprehensive modelling is that we have potential tools for in-depth understanding. Three different approaches are followed.

In one approach, selected predictors for the development of tropical cyclones have been used. These include SST, vorticity in the lower troposphere, vertical wind shear, static stability and relative humidity. Such assessments are attractive as they can be applied to model integrations at low resolution. These studies generally overestimate the importance of SST and efforts are made to replace the thermodynamical predictors suggested by Gray (1979) with a single measure of moist static stability as calculated by the climate model. Chauvin *et al.* (2006) has recently claimed some success with this approach.

In a second approach, tropical cyclones are identified *per se* in the model, according to specific selection criteria such as a warm core and maximum wind speed in the lower troposphere and central surface pressure (Bengtsson *et al.*, 1995). This is a direct approach but requires sufficient model resolution to simulate realistic looking vortices. It is only recently (Oouchi *et al.*, 2006; Bengtsson *et al.*, 2007(b)) that this has been feasible, as I will demonstrate in this article.

In a third approach, limited-area models at high resolution are used, driven by the atmospheric boundary conditions of the large-scale model (Knutson and Tuleya, 2004)). This is an efficient method as high resolution can be used with limited computer resources. However, the genesis of storms cannot be realistically simulated and the large-scale boundary conditions will therefore have to be prescribed or provided by a global model.

The second approach is most straightforward but previous studies have been hampered by difficulties in running global models at sufficient resolution to be able to resolve the more intense features of tropical cyclones. Previous model results have also been inconclusive; some models have shown an increase in the number of tropical cyclones and others a reduction. It comes as a surprise that a reduction in the number of cyclones in a warmer climate is the most common result (Sugi *et al.*, 2002; Yoshimura *et al.*, 2006), although this does not exclude the occurrence of more intense storms in a warmer climate

(Oouchi *et al*., 2006; Bengtsson *et al*., 2007(b)).

Modelling tropical cyclones in the present climate

The following results have been obtained, using the climate model of the Max Planck Institute for Meteorology in Hamburg. We have divided this study into two parts. In the first part, we compare model results with observations and re-analysis data. The study has been restricted to the northern hemisphere. The model has been run for 30 years, using observed SSTs for the period 1961-1990 in accordance with the Atmospheric Model Intercomparison Project (AMIP) protocol (Working Group on Numerical Experimentation, 1996). Tropical cyclones are identified by their three-dimensional vorticity structure. The initial identification and tracking follow the methodology of Hodges *et al*. (2003) and are also used in Bengtsson *et al*. (2006). This identifies tropical cyclones in the northern hemisphere as maxima in the 850 hPa relative vorticity field with values greater than $0.5 \times 10^{-5}s^{-1}$. The criteria used to identify a tropical cyclone in the northern hemisphere are as follows:

(*a*) Lifetime > two days (eight time steps);

(*b*) Cyclogenesis to occur in (0-20) N over land and (0-30) N over oceans;

(*c*) The maximum intensity of the relative vorticity at 850 hPa must exceed a chosen value, taken to be $6 \times 10^{-5}s^{-1}$;

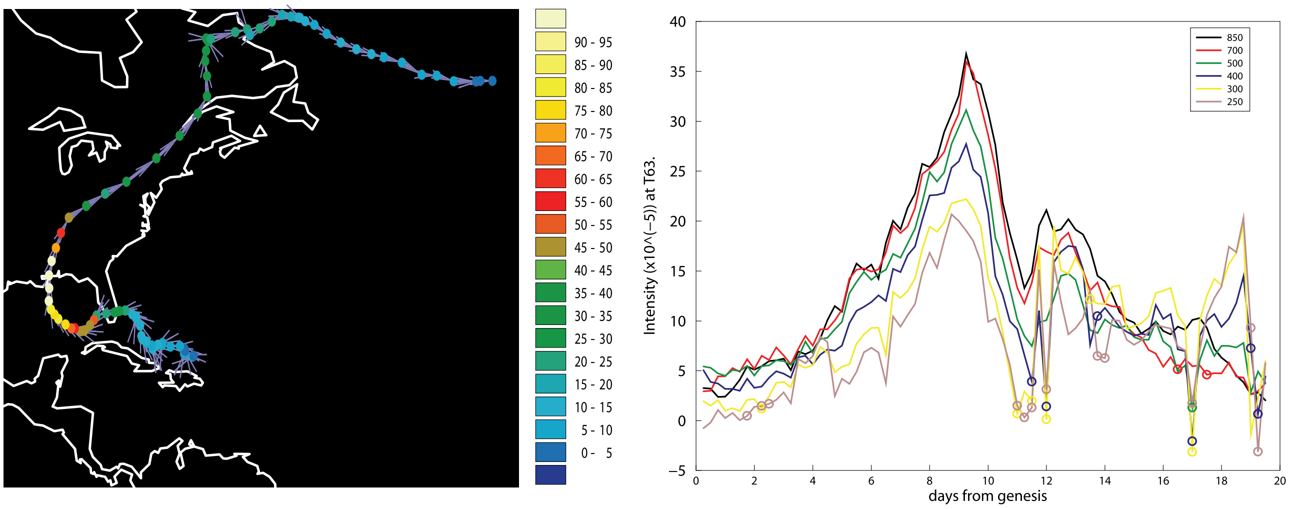
(*d*) The difference in vorticity between 850 hPa and 250 hPa must exceed a chosen value, taken to be $6 \times 10^{-5}s^{-1}$. This implies a warm core;

(*e*) Criteria (*c*) and (*d*) must be valid for at least four consecutive time steps.

These criteria have been compared with the tracks for the years 2003-2005 as obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) operational analyses and was found to be broadly similar to the number of observed tropical cyclones. (Bengtsson *et al*., 2007a, Table 1). Figure 1(a) shows the hurricane track for hurricane *Katrina* as analysed by the operational ECMWF model from the time it was identified until it decayed 20 days later as an extra-tropical storm. The total lifetime is 12 days longer than the best track data. The track finding program found the embryo of *Katrina* two days before it was identified as a tropical depression. Figure 1(b) shows the vertical structure, including the rapid deepening and the reduction of vorticity by height. For the purpose of the track-finding, the vertical structure has been done at a coarse resolution corresponding to T63. At the end of the track, the conversion to an extra-tropical cyclone can be seen as the vorticity increases by height, indicating a cold core system.

In Figure 2(a) we show examples of a tropical cyclone from the model and ECMWF 40-year re-analysis project (ERA-40). For ERA-40 we have selected an intense tropical cyclone for the period 12 September–3 October 1991. The storm track agrees well with super typhoon 21, although there are large differences in intensity. The maximum wind speed in ERA-40 is 45 m/s, while the maximum wind speed for the super typhoon 21 was 66 m/s. Furthermore, the observed maximum wind did not coincide with ERA-40 but occurred a few days earlier.

Although there is a broad agreement in the number and distribution of tropical cyclones between ERA-40 and



(a) (b)

Figure 1 — (a) The track of hurricane Katrina *as obtained from the ECMWF operational analyses, first identified on 8 August 2005 at 20h12; coloured dots indicate the T159 intensities (vorticity x 10^{-5} s^{-1}) at each six-hourly position; (b) T63 vertical structure of hurricane* Katrina*: the open circles indicate values at the T42 centre at the relevant level due to failure to find a maximum.*

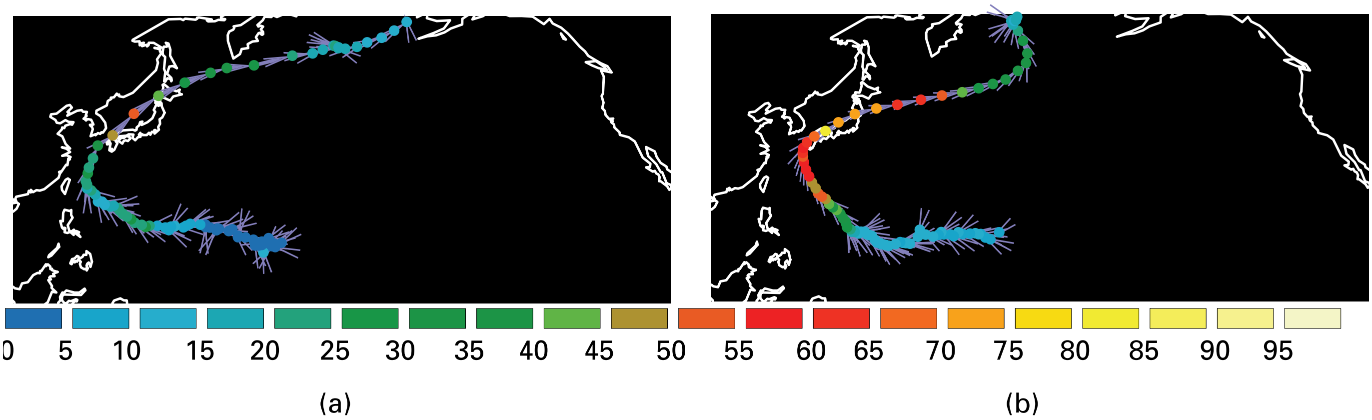


Figure 2 — Examples of similar storms from ERA-40 and The ECHAM5 model: (a) track of Super Typhoon 21 in ERA-40, first identified 1991/09/12:18, intensity is vorticity at T159 x 10^{-5} s^{-1}; (b) track of a similar storm in the ECHAM5 model, first identified 1987/08/24:06, intensity is vorticity at T159 x 10^{-5} s^{-1}.

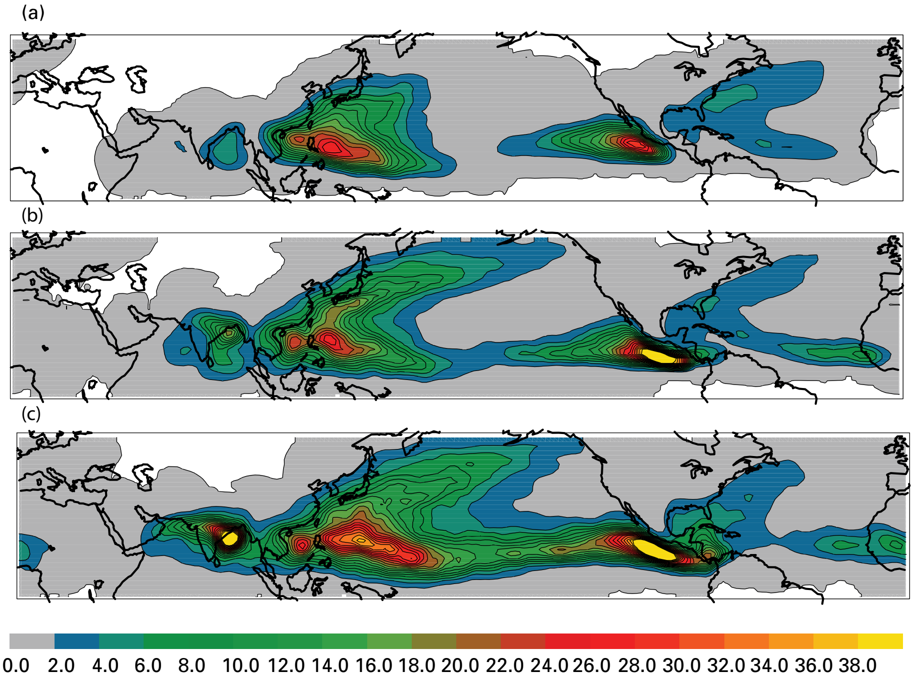


Figure 3 — Track density as number density per year per unit area where the unit area is equivalent to a 5^0 spherical cap (~10^6 km^2): (a) observations; (b) ERA-40; (c) ECHAM5.

the ECHAM5 model, it is, of course, not possible to find any agreement in the evolution of individual tropical cyclone, in spite of the fact that the pattern of SSTs (according to the AMIP protocol) is the same in ERA-40 and in ECHAM5, as the atmospheric circulation is only weakly constrained by the SST.

Instead, we select a typical model-generated tropical cyclone that occurred during the same month but in a different year in the western Pacific. Figure 2(b) shows the track of the model-generated cyclone for the period 24 August–14 September. The intensity is generally higher in the ECHAM5 than in ERA-40. A more detailed study shows that this is a systematic difference. The same is the case with the vertical vorticity gradient, which is larger in the model associated with a more marked warm core. The lifetime of the model-generated storms is also longer.

In Figure 3, we show the geographical distribution of tropical cyclones for the northern hemisphere. We have depicted the track density as the number of density points per year and per unit area (five-degree spherical cap equivalent to about 10^6 km^{-2}). In spite of the fact that there are more tropical cyclones in ECHAM5 and ERA-40 compared to the observed tropical cyclone (by some 15 per cent in ERA-40), there are nevertheless considerable similarities in the patterns of track density. The most direct comparison can be made between ERA-40 and ECHAM5, since the tracks have been obtained in the same way. This shows a remarkably similar distribution between the two, though ECHAM5 has larger values for the track density stretching across the Pacific. Compared to observations, ECHAM5 underestimates the very intense tropical cyclones in all regions but less so than ERA-40. We believe the systematic reduction in intensity is most likely due to insufficient horizontal resolution. Both ECHAM5 and ERA-40 used a spectral transform resolution at T159, corresponding to a grid length of some 80 km.

Of particular interest is to explore what could be the cause of the relatively large interannual variation of tropical cyclones, in particular on a regional basis. This can be considerable as, for example, in the Atlantic between 2005 and 2006, there were only nine in 2006 compared with 31 in 2005. In 2006, four of the five named hurricanes occurred over the central Atlantic far away from the coastal areas. We have investigated how tropical cyclones

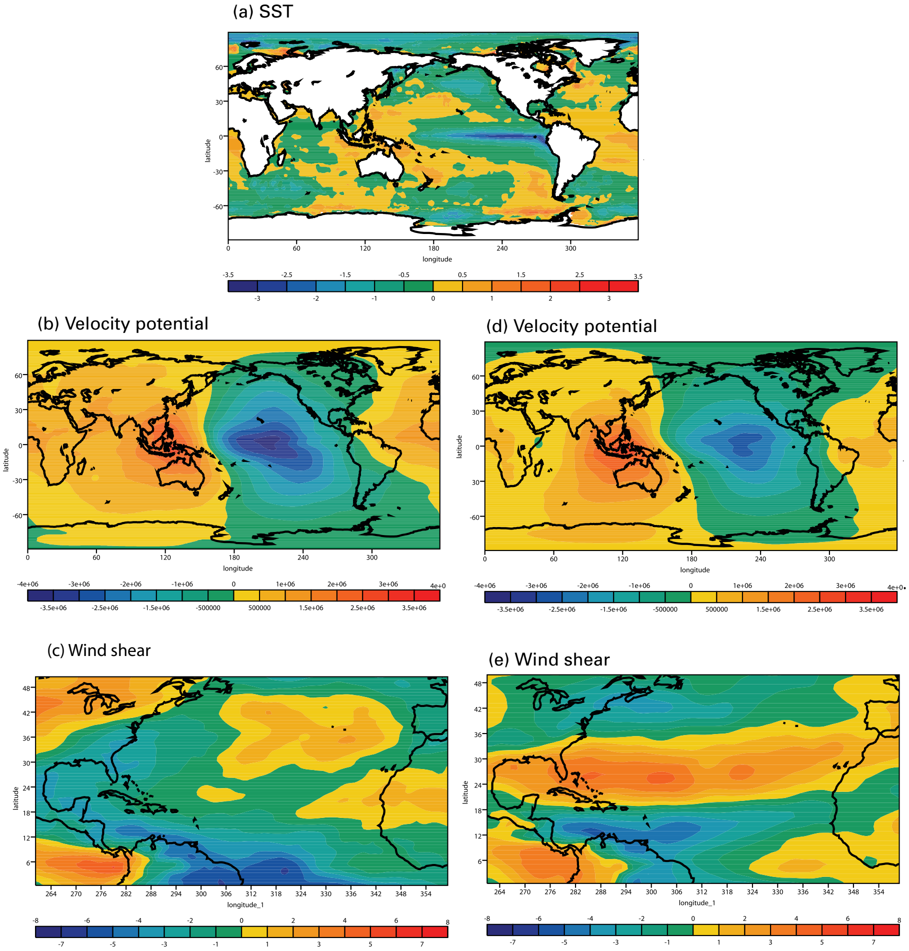


Figure 4 — Difference between high- and low-activity years for the Atlantic of SST (units of °C), 850-hPa velocity potential (units of m²/s) and vertical wind shear between 250 and 850 hPa (units of m/s). High years in the Atlantic are 1988 and 1995 and the low years are 1991 and 1997: (a) SST for the Atlantic, high - low; (b) velocity potential for the Atlantic, high - low; (c) vertical wind shear for the Atlantic, high - low (he same but for ERA-40); (d) velocity potential for the Atlantic, high – low; (e) vertical wind shear for the Atlantic, high - low. The SST is the same in both cases.

in the model and the re-analyses are related to SST anomalies, the large-scale divergent flow and the vertical wind shear. For the Atlantic, we used here the difference between years of high activity in ECHAM5 (1988 and 1996) and years of low activity (1991 and 1997). This was also observed and there were 50 per cent more identified tropical cyclones in the active years compared with the inactive years. Figure 4 shows the difference in SSTs, large-scale divergent flow and vertical wind shear. We also include the analysed velocity potential and wind shear from ERA-40. From the SST, it is clear that high activity in the Atlantic is related to low temperatures in the equatorial Pacific or, alternatively, there are fewer tropical cyclones in the Atlantic when there is an El Niño. The large-scale dynamical circulation has a marked pattern with a net subsidence over the eastern Pacific and ascending motions over the Atlantic, western Pacific and the Indian Ocean. The ERA-40 divergence pattern is virtually identical to ECHAM5, indicating strong coupling to SST anomalies. There is also a general reduction of the vertical wind shear in the tropical Atlantic and the Caribbean, which is favourable for the development of tropical cyclones. Here, the model differs from ERA-40 as the observed band of stronger wind shear between 20 and 35°N is not predicted by the model. This is presumably related to changes in the extra-tropics, where the atmospheric circulation is less well constrained by the SST pattern. Analogue results are obtained for the Pacific and the reader is referred to the paper by Bengtsson *et al.* (2007(a)) for additional information.

Future changes in tropical cyclones

Climate change simulation has been undertaken by the Max Planck Institute for Meteorology atmosphere/ocean coupled climate model ECHAM5/MPI-OM. (Jungclaus *et al.*, 2006). The preliminary calculation was produced by the model at an atmospheric resolution represented by 63 spectral modes with triangular truncation. The model has been driven by observed greenhouse gases and sulphate aerosols from 1860 until the present and thereafter the scenario of the Intergovernmental Panel on Climate Change (IPCC) A1B. This scenario assumes that carbon emissions will increase steadily, reaching a maximum of 16 billion tonnes per year in 2050 (about twice that of 2006), after which they will slowly start to decrease. The aerosol effect will peak in 2020 and diminish thereafter to only 20 per cent of the present concentration at the end of this century. Here, we compare two periods that represent the end of the 20th century (1980-2000) and the end of the 21st century (2080-2100). For a more detailed discussion, see Bengtsson *et al.* (2007(b)).

In the northern hemisphere tropics and sub-tropics, SST warming is generally larger than 2°C and in some areas around 3°C. Using the results from climate-change experiments, we undertook a so-called time-slice experiment (IPCC, 2001) using the SST pattern from the coupled model integration. This SST pattern with its variation in time and space was used to drive a high-resolution global version of ECHAM5. The experiment to be reported here used 319 spectral modes equivalent to a horizontal grid of about 40 km. Detailed evaluation shows that the realism of tropical cyclones improved with increasing resolution, with smaller and more intense features. Using the distance between the centre of the tropical cyclone and the area of maximum wind speed showed a reduction with a factor of 2.3 by going from T63 to T319 and an increase in maximum wind speed of the most intense storm from 59 m/s to 81 m/s.

Two key results stand out when we compare the results at 20C (20th century) and 21C (21st century). Firstly, there is a general reduction in the number of tropical cyclones at 21C. This is a somewhat counter-intuitive result, as one would expect a general increase in the number of storms as the areas of high SST increases. However, there is a general weakening of the large-scale atmospheric circulation because of the rapid increase in water vapour as it follows the Clausius Clapeyron relation. The increase amounts to 26 per cent. At the same time, the increase in the global hydrological cycle (evaporation and precipitation) is only 6 per cent. This lengthens the residence time of water vapour in the atmosphere by more than 1.5 days and is related to a slowing-down of the large-scale tropical circulation. Another way to see this is in the fact that the energy transport from low to high latitudes can be somewhat reduced as the energy density is higher because of the huge increase in water vapour. We argue that it is the reduced intensity in the large-scale convergence and divergence which reduces the number of onset vortices.

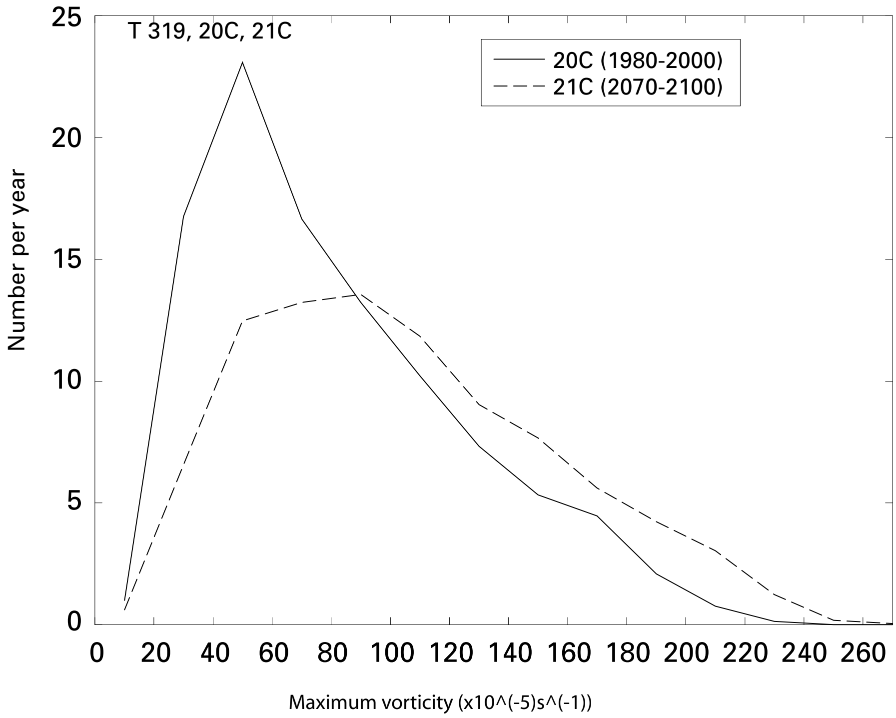


Figure 5 — Maximum attained intensity distributions for northern hemisphere tropical cycloness, based on the 850-hPa relative vorticity for the T319 at 20C and 21C

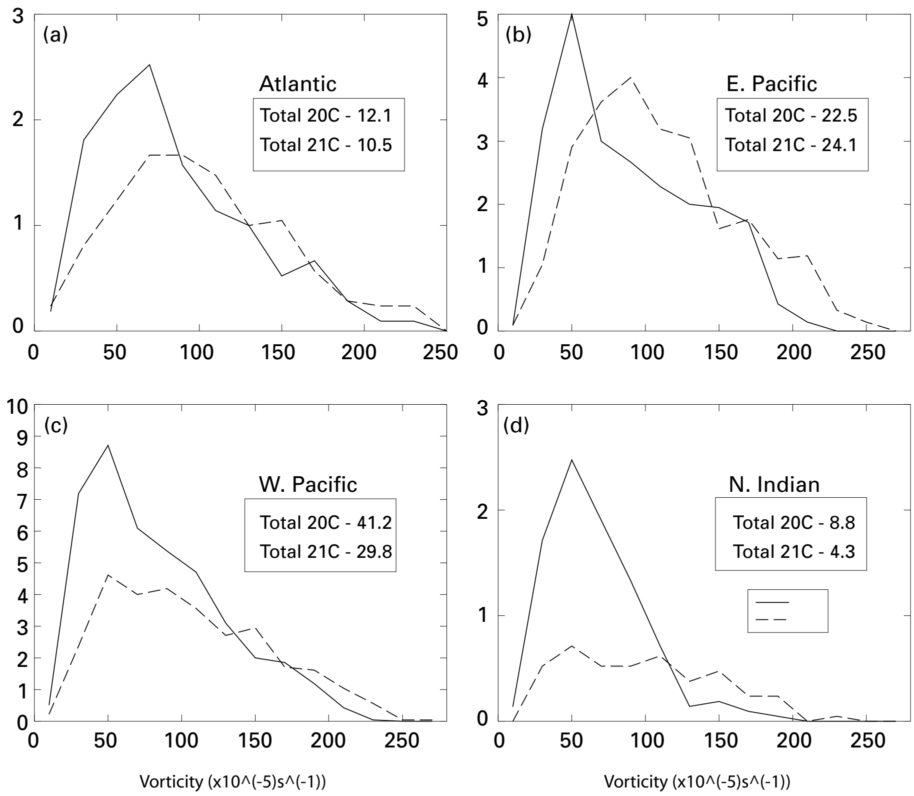


Figure 6 — T319 regional distributions of maximum attained intensity based on 850-hPa relative vorticity for 20C and 21C for (a) Atlantic; (b) eastern Pacific; (c) western Pacific and (d) north Indian ocean. Bin widths are 2 x $10^{-4}s^{-1}$. Inset boxes show the total number per year for each region and for 20C and 21C, respectively.

Secondly there is an intensification of existing storms, in particular of the more powerful tropical cyclones. The explanation here is that when favourable dynamical conditions exist, the larger amount of water vapour is beneficial for an extra intensification. This intensification is not noticeable at the original low resolution but requires the high horizontal resolution to model the organization of convective systems and the convergence of momentum properly. So, here, the low-resolution results are, in fact, misleading. Figure 5 shows the change in the distribution of tropical cyclones at 20C and 21C, respectively. There is an overall reduction of 12 per cent in the total number of detected storms but an annual increase from 12 to 17 tropical cyclones having a maximum wind speed greater than 50 m/s. The overall maximum increases from 81 m/s at 20C to 87 m/s at 21C. The tendency is the same in all regions where tropical cyclones exist, as can be seen from Figure 6. The decrease in the north Indian Ocean is interesting, in spite of the comparatively large SST warming in that region of around 3°C.

Concluding remarks

Comprehensive climate models have now developed to a stage where it is becoming feasible to explore how tropical cyclones may behave in a warmer climate. A necessary condition is to model present climate with a reasonable degree of realism. We have shown that this is possible with respect to the time and space variability of tropical cyclones, their lifetime and characteristic trajectories. The results suggest that the most advanced general circulation models now used in climate change experiments are capable of predicting the typical features of tropical cyclones, as well as the physical processes behind their development. However, much work remains to be done, in particular to model the extreme intensity in the centre of the storm and often explosive development. This is likely to require further major improvement, including further increase in resolution.

The fact that most models now predict an intensification of tropical cyclones in a warmer climate is presumably what may be expected, as the increase in latent heat will provide more energy for the storms. The reduction in the number of storms in a warmer climate, which a majority of models now predict, is less obvious. We have suggested that the main reason for this is the slowing-down of the large-scale tropical circulation. That this is the case can be seen from the increase in the atmospheric residence time of water vapour. The weakening of the large-scale circulation is expected to be the cause of the reduced number of onset vortices which are needed to set off a tropical cyclone. If we see the atmospheric circulation as a tool to distribute heat and energy from areas of surplus to areas of deficit, the speed of transport can be relaxed as the high amount of water vapour in a warmer climate is a more efficient energy carrier.

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