Atlantic hurricanes – testing impacts of local SSTs, ENSO, stratospheric QBO – implications for global warming

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Abstract

Processes affecting hurricane development over the North Atlantic like the El Niño Southern Oscillation (ENSO), the stratospheric Quasi-Biennial Oscillation (QBO) and Sea Surface Temperatures (SSTs) are discussed. Global coupled climate model simulations cannot answer directly the question on enhancement of hurricane activities (or its absence) under increased greenhouse gas concentrations because of their too coarse resolution. Therefore large-scale quantities that affect hurricane formation are investigated in a future warmer climate.

More frequent or more intense hurricanes are expected from an increase in the local SST, from more latent heat flux from the ocean to the atmosphere, from more westerly winds in the tropical stratosphere that reduces the occurrence of strong easterly phases of the QBO and from a more moist-unstable stratification of the atmosphere. However, a stronger vertical wind shear similar to the difference between El Niño and La Niña events suggests fewer hurricanes in the northern Atlantic. Also a more dry-stable atmosphere would lead to fewer hurricanes. Of the various forcing factors, the impact of wind shear appears to be more decisive, i.e. with a strong wind shear over the tropical Atlantic like during El Niño events strong hurricanes hardly happen while impacts from SSTs over the tropical Atlantic are less significant. As there are some factors favouring an increase of hurricane activity in a future climate and others favouring a decrease, it remains so far difficult to estimate their joint effect and to suggest any decisive trend. The area of hurricane development is limited among others by an increase of vertical wind shear towards the north and south from a minimum at 5-10˚N. This wind shear pattern does not change in a future climate and has the potential of superseding impacts from ocean warming.
A need for very long time series for obtaining robust results becomes obvious. Here at least 50 years of data were used.

Keywords:
Hurricanes, North Atlantic, ENSO, stratospheric QBO, global warming

1. Introduction

The 2004 Hurricane Katrina over the US Gulf Coast and a further extreme hurricane year 2007 have raised popular and scientific attention to hurricanes. There is growing interest in the scientists' ability to predict such events in the short and medium-range and in regards to anticipated impacts of global warming.

According to the International Council of Sciences or ICSU (ICSU, 2005), the number of recorded natural hazards has increased in the last fifty years with the greatest rise in frequency attributed to hydrometeorological disasters. The number of natural hazards culminating in disasters also has risen considerably (Leroy, 2006). A disaster is the result of both a natural hazard and human impacts. In the case of hurricanes and storms disasters are enhanced because the population density in tropical and subtropical coastal areas grows rapidly often in fragile environments more susceptible to damage. The damage done by hurricanes can be divided in two parts: the first including human injuries, fatalities and economical impacts, the second with longer-term effects owing to population displacement and changes in the social structure. The 1900 Galveston hurricane and the closely following ones were one of the factors that led to the progressive displacement of businesses from Galveston to Houston.

The economic costs of storms and hurricanes are mostly borne by insurance companies, while the costs of other types of natural disaster costs are generally born by the public sector or by individuals (Mills, 2005). Insured property losses have risen dramatically over the last several years. Typically there has been a dramatic underestimation of potential loss resulting from natural hazards on the part of insurance companies, resulting in a sudden rise in claims and subsequent increases in policy costs (Mills, 2005).

These negative impacts on society have resulted in intensive on-going discussions about the changes of hurricane frequency and intensity in a future climate (Landsea et al., 1999; Goldenberg et al., 2001; Knutson et al., 2004; Emanuel, 2005; Trenberth, 2005; Webster et al., 2005, Holland and Webster, 2007; Vecchi and Soden, 2007). A controversy has arisen because hurricane decadal variability is very large and therefore trends in changes cannot be extracted from short observational data sets with confidence. Also global coupled climate model simulations are still too coarse to simulate directly realistic hurricane frequency and intensity; though Bengtsson et al. (2007) use the relatively coarse model results to investigate tropical cyclones with some success. They expanded their investigation by carrying out time-slice experiments with an atmosphere only model which they could run with a much higher horizontal resolution. In both cases a reduction of tropical cyclones for the end of the 21st century was found but less for intense hurricanes. When they increased the resolution of the atmospheric model in their time-slice experiments they even found an increase of intense cyclones. Also Yoshimura et al. (2006) and Oouchi et al. (2006) used this time-slice approach with a very high horizontal resolution atmospheric model and found as well a reduction of tropical cyclones on the whole and increased intense hurricanes under global warming conditions. All these experiments suggest enhanced precipitation in single hurricane events. This modelling approach is obviously the way future research will go but the authors themselves recognize the present limitations of their experiments: the horizontal resolution is still too coarse and with their higher resolution experiments the two-way interaction between ocean and atmosphere is missing. It is important to note that the latter would give a negative feed back caused by the cooling effect of hurricanes on the ocean which would reduce the hurricane activity.

Quite a few papers come to the conclusion that a trend due to global warming cannot be detected with confidence but perhaps more are convinced that such a trend exists. The latter group of papers concentrate mostly on data of the last 20 to 30 years because of their higher quality. This shorter period indeed shows a clear upward trend. However, we consider that the inclusion of earlier data is essential for such investigations, even if these data under-estimate the number of events. Several papers insist on a need for separating different time scales but we will discuss below the problems arising from this.

This paper provides a review in connection with an in-depth analysis of the main forcing factors in the development of present-day hurricanes, using reanalysis data from ECMWF (Simmons and Gibson, 2000), and the expected changes of these parameters under global warming, using simulated climate data with the ECHAM5-OM model (Roeckner et al., 2006) which was used as well by Bengtsson et al. (2007). For a clearer understanding of the mechanism at play only original variables are used as far as possible, i.e. temperature and wind and not data modified for example by applying principal component or similar statistics. The aim is also to work on the maximum number of years available, which is more or less 50 years (depending on which dataset) and up to 150 years for hurricanes and Sea Surface Temperatures (SSTs).

Only tropical cyclones over the northern Atlantic are investigated here because long series of observational data are only available for that area. The results shown may not be representative for other areas. In fact Webster et al. (2005) found an opposite trend in the number of tropical cyclones between the Atlantic and other ocean basins during the last decades. They found, however, an increase in the number of hurricanes reaching categories 4 and 5 in each ocean basin.

For estimating the future climate the simulations with the ECHAM5-OM model (Roeckner et al., 2006) were used. Data from other models are available as well but they are not shown here. A discussion of the ensemble of model simulations can be found in Vecchi and Soden (2007).

2. The main processes leading to hurricane development

The main features of tropical cyclone development over the northern Atlantic (hurricane) can be found in numerous publications, e.g. Bengtsson (2001), from which the following has been extracted. A weak cyclonic circulation is needed for initiating hurricane development. This frequently stems from atmospheric disturbances over northern Africa (easterly waves). 85% of the hurricanes which develop into major hurricanes originate from there (Goldberg et al., 2001). Within the disturbance, the air spirals toward the storm centre. Hence, water is extracted from the warm ocean. In the centre of the disturbance, the air rises and by that the air cools adiabatically leading to a condensation of water vapour and a consequent release of latent heat. The heating due to the release of latent heat at the centre of the storm leads to an intensification of the storm, thereby further increasing the surface wind and evaporation. The storm will intensify further until the energy input by surface evaporation is balanced by the frictional dissipation. It has been found that a minimum SST of 26.5˚C is needed for the development of a hurricane. Tropical cyclones thus primarily derive their energy from the evaporation of seawater and the associated condensation in convective clouds. In contrast, extra-tropical cyclones primarily obtain energy from the redistribution of air masses at different potential temperatures.

Additional requirements for a tropical cyclone development are a low vertical wind shear and a moist-unstable stratification through the depth of the atmosphere. If there is a strong vertical wind shear the top of convective clouds may be blown off and the convection will die. Convection can develop only in a moist-unstable stratified atmosphere. Hurricanes hardly occur within a belt of 10˚ north and south of the equator because sufficient Coriolis force is required for the formation of tropical cyclones.

3. The role of hurricanes in the earth energy budget

Tropical cyclones have an important role in the earth energy balance. Solar radiation warms the earth and the oceans. In a nearly balanced budget, this energy has to be radiated back into space. Greenhouse gases, e.g. water vapour and CO_2, hamper the direct radiative transfer from the surface into space. Instead, energy in form of latent heat is transported upward by water vapour from the surface to the upper troposphere. There it is converted into sensible heat by condensation and long-wave radiation into space can take place (e.g. Bengtsson, 1996). The upward transport in the tropics takes place mostly by convection. This transport is most effective if the convection is organized like in cloud clusters and hurricanes. The importance of hurricanes in cooling the ocean was made evident in observations from satellite for the Caribbean during hurricane Katrina. During its passage, the SST of the Caribbean Sea dropped by 1˚C on average and up to 4˚C in smaller areas (Gierach and Subrahmanyam, 2007). Although most of this temperature drop is due to a mixing of the sea, a considerable amount of it can be assigned to evaporation that had been used to feed the hurricane. Price (1981) assigned 85% of the cooling during a hurricane passage to mixing and the remaining to the heat flux. The amount of energy taken from the ocean during a hurricane has been estimated by Gray (1979).

4. Processes leading to a variability of hurricane activity

Fig. 1 shows time-series of hurricane frequencies and hurricane energy since 1850. There has been a clear increase in hurricane activities over the North Atlantic during the last 20 years but if one goes further back in time such an increase is less clear. Hurricane energy is a combination of days with tropical storms, their strength and dimension. From a scientific point of view hurricane energy is a more useful quantity than hurricane frequency. It gives as well a much smoother variability from year to year. For the public, the occurrence of hurricanes and especially of major hurricanes is much more important. In Fig. 1, the data had to be smoothed with a 9-year mean filter; otherwise the extreme year-by-year variability of the occurrence of tropical storms of different strength would hamper the simple trend visualisation. The data before 1944 are, however, less reliable (Landsea et al., 2006). Holland and Webster (2007) suggest that up to three tropical cyclones may not have been detected before 1900 and up to two before 1960. The increase in all variables during the last 20 years is quite obvious. However, the most recent values of all hurricane measures hardly exceed those from the 1950s and 1890s despite the lesser reliability (underestimation). It is clearly dangerous to draw any conclusion concerning trends when looking only at the last 20 to 30 years. From this figure it is indeed hard to suggest that there has been an increase of hurricane activity in the recent decades, especially if one has to assume that in the early years the amounts shown here may be underestimated.

Fig. 2a provides some indication of the impacts of global warming on hurricane energy. A scatter diagram indicates the relationship between hurricane energy and SST over the tropical Atlantic (such as suggested by Emanuel (2005) and shown in *www.zFacts.com/p/120.html*). A tendency for points to gather along the diagonal, suggests that increased tropical Atlantic SSTs tend to be associated with increased hurricane energies. The anomaly correlation (for the 60 years displayed in Fig. 2) between the tropical Atlantic SST and the hurricane energy is 0.49 but it is only 0.34 when emphasising the year by year variability by correlating the year to year changes and increases to 0.79 when applying a 9 year running mean filter before calculating the anomaly correlation. If one compares the time-series of hurricane energy with the time-series of SSTs of the tropical Atlantic (not shown), both curves look indeed very similar. Small but clear long-term trends of the hurricane energy and frequencies, downward in the 1960s and upward in recent years is, however, not followed by the SST. Holland and Webster (2007) compare Named Storms and the SST averaged over an area which was not specified and found a common trend. Increased SSTs can be expected in a future climate, as discussed in section 7 and thus might lead to an increase of hurricane activity. The relation between SSTs and hurricanes breaks down when using frequencies of major hurricanes instead of energies (Fig. 2b), i.e. a suggestive gathering of events along a diagonal, is not found. Therefore drawing a diagonal is hardly justified though the anomaly correlation drops only to 0.40. This will be discussed further below.

5. Other impacts on hurricane development than the in-situ SST

A well-known influence on the hurricane occurrence and its strength is connected with the El Niño Southern Oscillation (ENSO) - e.g. Goldberg et al. (2001) - with fewer and less intensive hurricanes during El Niño events. ENSO is an acronym for an oscillation which is most strongly expressed in the eastern tropical Pacific SST with a frequency of 2 to 5 years. Impacts from ENSO can be found world wide (Ropolewski and Halpert, 1987) in SSTs and atmospheric quantities including precipitation. Its strongest impact can be found during northern winter and spring but is also present in other seasons. It is mostly the warm ENSO events (El Niño) which show stronger signals. Important for the hurricane development over the Atlantic is an increase of westerly winds in the upper troposphere and an increase of easterlies near the surface in the area of hurricane occurrence during El Niño events. In Fig. 3a, vertical profiles of the zonal wind (U) for the season June to November averaged for the area of hurricane development are shown. Means of El Niño event years are compared with overall long-term means. There is a stronger vertical wind shear during El Niño events leading to a suppression of hurricane development.

Fig. 4 demonstrates the importance of vertical wind shear ($\delta u/\delta p$) for the development of hurricanes by comparing time-series of major hurricane frequencies with the difference of zonal winds at 200 hPa minus 850 hPa for the area 5˚-15˚N, 50˚-70˚W, which is a measure for the vertical wind shear. Both curves are strongly anti-correlated. The anomaly correlation is -0.63. It means that there are fewer hurricanes when there is a strong wind shear. The vertical wind shear is large during El Niño events and shows therefore a link between ENSO and the hurricane activity. The El Niño events of 1972, 1982, 1987, 1994 and 1997 are clearly sticking out in both curves. Both curves in Fig. 4 show trends of opposite sign in the 1960s and after 1994. From the many time series we have investigated, it is only the wind shear that follows the trend of the major hurricane frequencies at both these periods.

Swanson (2008) has combined the impacts of the local SST and that from ENSO by investigating the difference between the tropical Atlantic SST and the tropical global SST, though they do not call it like this. The tropical global SST is dominated by the Pacific because of its size. This combination leads to impressively high correlations with the hurricane activity.

Another important factor for the development of hurricanes is the existence of a moist-unstable stratified atmosphere. This is a very sensitive quantity and the analysis data of the atmosphere used here are not stable enough for the 50 years of analysis to show this connection in a straight forward way. This is due to shifts in this quantity with changes in the quality and availability of observational data like the introduction of temperature soundings by satellite. The reanalysis data by ECMWF and that by NCEP (Kalney et al., 1996) do hardly agree in the temperature lapse rate, probably because for this there is not a dynamical constraint as for the vertical gradient of the wind field. The temperature lapse rate in the tropics is strongly influenced by the convection inside the clouds and by subsidence of air around it. The latter is influenced by ENSO with increased downdrafts over the tropical Atlantic (Heckley and Gill, 1984) in the middle troposphere during El Niño events. In fact when correlating the SST in the Nino3.4 area (170˚-120˚W, 5˚S-5˚N - a measure for ENSO) with the temperature of the troposphere, one finds highest positive values over the Atlantic for the 500 and 700 hPa level, i.e. the levels with strongest subsidence during El Niño events, with decreasing values to the upper and lower troposphere. When looking, however, into vertical profiles of temperature anomalies during El Niño or La Niña events, one finds a more uniform vertical distribution throughout the troposphere, i.e. without a change in stability. Investigating the basic data it turns out that this change in the tropospheric temperature can only be found for the 1987 and 1997 El Niño events. Tang and Neelin (2004) indicated that there is a link between the atmospheric stability over the tropical Atlantic and ENSO but without looking into the temperature at different levels and without giving sufficient importance to the original data. For investigating the temperature lapse rate one should not look only into vertical means over the troposphere of the temperature.

Another impact on hurricanes from a global-scale phenomenon is the stratospheric quasi-biennial oscillation (QBO) (e.g. Klotzbach and Gray, 2004). The QBO describes an oscillation of the zonal wind in the equatorial stratosphere with an average frequency of 28 months. There the wind switches from easterlies to westerlies and back. A comprehensive description of the QBO and its impacts is given by Baldwin et al. (2001). The QBO has an impact on the vertical wind shear in the area of hurricane development as shown in Fig. 3a. Probably even more important for the hurricanes is an induced meridional circulation at the equator in the lower stratosphere which results in a change in the vertical temperature lapse rate. During the western phase of the QBO (Fig. 5), the equatorial tropopause is warmed up by 0.8 ˚C in a belt between 5 ˚S and 5 ˚N as described by Baldwin et al. (2001). This stabilizes the stratification of the upper troposphere and results in a damping of convective activity at the equator. The role of the convection to transport latent energy upward to the upper troposphere has already been mentioned above. If this is hampered near the equator, this transport has to be performed further away from the equator and that happens then in the area of hurricane formation. So during the western phase one can expect more hurricane development and during the eastern phase less.

Gray and Klotzbach (2005) describe many of the variables used for predicting the hurricane activities for the next season. There ENSO and QBO are recognised as important factors.

For investigating the impacts of these two parameters, Fig. 2b is repeated in Fig. 6 and 7 but using different markers for years with El Niño events (Niño3.4 area SSTs > 27.5 ˚C during August-September-October: ASO) or La Niña events (Niño3.4 SSTs < 26.0 ˚C during ASO) and the years with the QBO in its west (U 70hPa > 4 m s^{-1}) or east phase (U 70hPa < -5 m s^{-1}) during ASO. During warm ENSO events no more than 2 major hurricanes are observed (Fig. 6d), except for 1951 but then the SST in the Niño3.4

area had values above 27.5 ˚C only in August and September but not before or after; so it is doubtful if one should call 1951 an El Niño year. When the QBO is in an east phase never more than 2 major hurricanes occurred (Fig. 7d). Only when the QBO is in the eastern phase one finds a clear signal. Therefore statistical measures like correlation coefficients would hardly show this connection.

A further impact from the vertical wind shear relates to the meridional distribution of hurricane occurrences. The hurricane development area is bordered in the north by very strong vertical wind shear in connection with the subtropical jet and towards the south by strong vertical wind shear because of strong trade winds. Between these two areas of strong wind shear one finds a relative minimum reaching no shear around 5-10 ˚N when investigating the average of the belt 20-40 ˚W. So it is not only the criterion of 26.5˚C that limits the hurricane developments to a small belt between 5 to 20 ˚N but also the requirement of weak vertical wind shear.

6. Separating variabilities at different time scales

In Fig. 1 and 4 short-term and long-term variabilities are obvious: the longer-term variabilities have a period of perhaps 50 years. Investigating such periods with a data set which covers only 50 or fewer years (e.g. the ECMWF reanalysis and the QBO data) can easily lead to wrong conclusions. In time-series of only 50 years the long-term variability consists mainly out of two events, a number of events which can hardly be used for any statistics.

Some authors, e.g. Holland and Webster (2007), insist that short-term variabilities should not be included in investigating trends due to global warming and therefore they ignore impacts from the stratospheric QBO and the ENSO cycle. However, the QBO has a cycle different to the annual cycle and this will project on a multi-year cycle, if one is interested only in the variability of one season. In fact during the 50 years of available QBO data the years with strong easterlies in the equatorial stratosphere are concentrated on the period 1977 to 1987 (4 out of 7), a period with very low hurricane activity. Also the ENSO events display variabilities with some clustering leading to a long-term variability. We regard therefore a separation into short- and long-term variability as very difficult.

7. Impacts of increased greenhouse gas concentration in model simulations

Coupled climate models cannot directly simulate the impact of greenhouse gas increases on the hurricane activity as their resolution is too low. Therefore in the following, changes of some large-scale parameters, that are important for hurricane development, will be investigated under global warming conditions. Increased SSTs are expected to result from increased greenhouse gas concentrations as shown in Fig. 8 derived from scenario simulations with the ECHAM5-OM model (Roeckner et al., 2006). In Fig. 8 three panels are shown, the top two compare the present climate as observed (Fig. 8a) and simulated (Fig. 8b). One finds a high similarity, demonstrating some ability of the model to reproduce the observed distribution of tropical Atlantic SSTs. Some problems are, however, indicated along the African coast. Comparing Fig. 8b and 8c one can see the expected changes for the next 60 years and it is clear that the maximum SST and the area with SSTs greater than 26.5˚C will increase considerably. Hence more frequent or more intense hurricanes can be expected. It has been argued that the 26.5˚C isotherm represents a threshold temperature only in our current climate. As climate warms, the relevant "threshold temperature" for hurricanes may also change. A plausible reason for having such a threshold is that there needs to be enough energy in the upper oceans to feed the hurricane. This energy can only be taken from the ocean when the water is warm enough. We have not seen so far any argument in the literature why in a warmer climate hurricanes would need more energy from the ocean. However, Shen et al. (2000) show in sensitivity experiments that the increase of SSTs may be compensated by a more dry-stable troposphere.

The increase of area with SSTs > 26.5 ˚C suggests that the area of hurricane development might increase as well. Model simulations, however, do not show such an effect. Knutson et al. (2008) assign this to a change of the SST threshold in a warmer climate. But the unchanged area of hurricane development could also be due to the limits given by the increase of vertical wind shear towards to north and south, as discussed above and which does not change in a warmer climate in the ECHAM5-OM simulations.

Under increased greenhouse gas conditions, the SSTs globally increase fairly uniformly; but there is a stronger increase in the eastern tropical Pacific and it has similar patterns to that during observed El Niño events. Associated with this El Niño type patterns are increased westerlies at 200hPa and increased easterlies in the lower troposphere over the tropical Atlantic (Fig. 3a). Fig. 3b shows vertical profiles of the zonal wind averaged for the area of possible hurricane development as simulated by the model. Under stronger greenhouse gas conditions, the vertical wind shear is similarly increased as during El Niño events at the present in the observations, suggesting that there will be fewer or less strong hurricanes in a future climate. Van Oldenborgh et al. (2005) have shown that two out of the three most realistic scenario simulations with increased greenhouse gas concentrations predict an increase of El Niño type patterns reflected by several quantities in a future atmosphere including an increase of westerlies over the North Atlantic.

Profiles of temperature changes in the area of hurricane development between 1961-1990 and 2071-2099 are investigated as well (not shown). The upper atmosphere warms up faster (6.5˚C at 300 hPa) than the lower atmosphere (3.0˚ C at 925 hPa) under global warming conditions; i.e. the dry atmosphere becomes more stable. Similar profiles of the equivalent temperature experience the opposite change (6 K at 300 and 9 K at 925 hPa). Equivalent temperature includes the energy that would be released when condensing all water vapour. As the humidity increases more in the lower troposphere than in the upper troposphere, the upper atmosphere warms up (in equivalent temperature) slower than the lower atmosphere under global warming conditions; i.e. the moist atmosphere becomes less stable. A future climate has a more dry-stable atmosphere in the area of interest but a less moist-stable atmosphere. This suggests a delayed onset of convection but then a stronger one, supporting increased hurricane activity. Shen et al. (2000) found in their experiments that an increase of the dry-stability by 3-4˚C as found here would compensate an increase of SSTs by 1.5˚C. A less moist-stable atmosphere means a larger convective available potential energy (CAPE) and this is favouring the hurricane activity. CAPE is a measure of how much energy could be released if an air parcel is moving from the lower to the upper troposphere, by that condensing its water vapour, and back to its original level.

A further argument for increased hurricane activities in the future is based on the fact that, in a climate with more greenhouse gases, the direct long-wave radiation from the ocean to space is further hampered. This requires more energy to be transported upward from the ocean to the upper troposphere by convection, perhaps in hurricanes. Model simulations with more greenhouse gases show increased latent heat flux (LHFX) (Fig. 9) but cannot simulate the upward transport in hurricanes because their resolution is too coarse. Bengtsson et al. (2007) found some sort of tropical cyclones in the simulations discussed here with a decrease in the frequency but with increased precipitation and intensities at higher resolutions. Time-series of latent heat flux (Fig. 9) over two oceanic areas in the scenario simulation with ECHAM5-OM show that the fluxes from the ocean to the atmosphere will increase by 7% over the Caribbean and by 2% over the tropical Atlantic in the 21st century. This energy has to be transported upward by increased convection which makes more or more intense hurricanes more likely. The increased upward transport of latent heat is achieved in the model by normal convection but the real atmosphere might choose to do it by the more organized and more efficient convection in hurricanes. Also Shen et al. (2000) show a strong correlation between surface evaporation and hurricane activity.

No investigations are available which give information about the future development of the stratospheric QBO because such experiments need a very high vertical resolution. If assuming that the variability between east and westerly components stays the same, one can look into the background wind in the tropical stratosphere from the available scenario simulation. There one finds that the zonal wind becomes more westerly by 2 m/s. Assuming the same QBO variability, this change means that there will be less easterlies in the lower stratosphere in a future climate. It has been shown above that strong easterlies suppress hurricane. Under global warming conditions there will be weaker easterly phases of the QBO and it is only this phase which suppresses hurricane developments.

Table 1 gives an overview of the impacts of different parameters on hurricane development in a future climate under increased greenhouse gas concentrations. An increase of hurricane development in the future can be expected from the warming of the oceans and would be supported by a less moist-stable atmosphere but at least partly compensated by a more dry-stable atmosphere. Also a shift of the tropical stratospheric wind to more westerlies would support an increase of hurricane activity. The expected increase of wind shear due to ENSO type patterns in the SST and its atmospheric responses would lead to a reduction of hurricane activity. It is difficult to estimate which influence will dominate in the end. Donnelly and Woodruff (2007) found from proxy data that the ENSO type impact on hurricane activities during the last 5000 years seem to dominate over the Atlantic SST impact. Vecchi and Soden (2007) calculated for the ensemble of scenario simulations the genesis potential index suggested by Emanuel and Nolan (2004) and the former scientists showed that this will hardly change in the western tropical Atlantic in a future climate.

8. Conclusions

The impacts from in-situ SSTs, ENSO and QBO on hurricane development have been demonstrated. Warmer SSTs over the northern tropical Atlantic are connected with more frequent or more intense hurricanes while El Niño events and eastern phases of the stratospheric QBO lead to less hurricane activities. It was demonstrated that the latter two affect the hurricane developments through the modification of the wind shear. Claims that ENSO might affect the hurricane activity by modulating the static stability over the Atlantic were not confirmed in the reanalysis data. According to our analysis, the wind shear dominates over direct SST impacts as they are more decisive while SST impacts are less significant.

The inter-decadal variability of hurricane occurrences is so large that up to now a trend of hurricane activity cannot be detected with confidence. Investigating only 20 to 30 years of data, as done in many publications, means looking only at half of a wavelength of the long-term variability and can lead easily to wrong conclusions. Global coupled climate model simulations cannot answer directly the question on enhancement of hurricane activities (or its absence) under increased greenhouse gas concentrations because of their too coarse resolution. Therefore large-scale quantities, to which hurricane developments are sensitive, have been investigated here in scenario simulations.

All climate model simulations with increased greenhouse gas concentrations predict an increase of sea surface temperature which would lead to increased hurricane activity though at least partly compensated by a more dry-stable troposphere. More westerly winds in the tropical stratosphere reduce the occurrence of the easterly phase of the QBO and by that lead to more hurricane activity. Also a more moist-unstable stratification of the atmosphere suggests an increase of hurricane activity. Some climate model simulations predict a larger vertical wind shear in the tropical Atlantic similar to the difference between El Niño and La Niña events which suggests fewer hurricanes in the northern Atlantic. Of the various forcing factors the impact of wind shear appears to be more dominant, i.e. with a strong wind shear over the tropical Atlantic like during El Niño events strong hurricanes hardly happen while impacts from SSTs over the tropical Atlantic are more subtle. As there are some factors favouring an increase of hurricane activity in a future climate and others favouring a decrease it is not possible so far to attribute a precise weighting to each of them. The genesis potential index which was calculated by Vecchi and Soden (2007) for an ensemble of scenario simulations suggests only small changes of hurricane activity over the north Atlantic. The area of hurricane development is limited among others by an increase of vertical wind shear towards the north and south from a minimum at 5-10˚N. This wind shear pattern does not change in a future climate and has the potential of superseding impacts from ocean warming.

Another point re-emphasised by this review is that it is crucial to work on long-time series of instrumental data. Sometimes this may be supplemented by historical documents and proxy data (e.g. from sediment). This is vital to predict future trends in hurricane activities as reliably as possible and to provide the end-users with the best available information to guide their mitigation and preparedness plans.

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Table

Impacts of increased greenhouse gas conditions on North Atlantic hurricanes from	increase	decrease
SST of the tropical North Atlantic	x	
QBO	x	
ENSO – wind shear		x
Long-wave radiation – latent heath flux	x	
Dry stability of the atmospheric stratification		x

Moist stability of the atmospheric stratification	x	

Table 1: Summary of the impacts of increased greenhouse gas conditions on North Atlantic hurricanes from different parameters.

Figure captions

Fig. 1: Time-series of hurricane frequency and energy during the last 150 years. The data are, however, less reliable before 1944. Tropical storms, hurricanes, major hurricanes and hurricane energies are shown separately. The hurricane energy values are divided by 10 to get the same scaling as the hurricane frequencies. Data are smoothed using a 9-year running mean. The plot is based on data from http://www.aoml.noaa.gov/hrd/tcfaq/E11.html (prepared by C.W. Landsea).
ener: hurricane energy, MH: major hurricane frequencies, HU: hurricane frequencies, NS: named tropical storm frequencies.

Fig. 2: Scatter diagram of
a) Hurricane energies versa the SST in the tropical North Atlantic (60˚-80˚W, 5˚-15˚N) for the season August-September-October (ASO)
b) Frequencies of major hurricanes versus the same SST.
The hurricane data are taken from http://www.aoml.noaa.gov/hrd/tcfaq/E11.html (prepared by C.W. Landsea) and the SST values are based on data from Rayner et al. (2003).

Fig. 3: Vertical profiles of the zonal wind (U) in the tropical North Atlantic (50˚-80˚W, 5˚-15˚N) for the season June to November.
a) Means of years with the stratospheric QBO in the east phase (QBOe), and means of years with El Niño (nino) are compared with a long-term mean (norm) as observed. The wind profiles are based on the ECMWF reanalysis data (Simmons and Gibson, 2000).
b) Simulations with the ECHAM5-OM model (Roeckner et al., 2006) for the present (now), i.e. 1961-1990 and for the future (+80), i.e. 2070-2099 are compared.

Fig. 4: Time-series of zonal wind shear (δu/δp) expressed as the difference of the zonal wind at 200hPa minus the one at 850 hPa (50˚-70˚W, 5˚-15˚N) for the season June to November and major hurricane frequencies (MH).

Fig. 5: Cross-section of (a) the zonal wind and (b) the temperature for the season June to November averaged between 60˚-80˚W in means of years with the QBO in west phase minus years with east phase. Contours for the zonal wind +/- 0,1,2,3,4,6,8,10,12,14,16,18,20 m/s and for the temperature +/- 0,0.1,0.2,0.3,0.4,0.6,0.8,1.0,1.2 ˚C. Shading in a) for >0.6 and < 0 m/s and in b) for > 0 and < 0.6 ˚C. QBO data are from Labitzke et al. (2002). Other atmospheric data are based on the ECMWF reanalysis (Simmons and Gibson, 2000).

Fig. 6: As Fig. 2b but separating years with El Niño (warm - triangles), La Niña events (cold - crosses) and neither of those (neutral – small squares). Years were sorted according the SSTs during August-September-October (ASO) for the Niño3.4 area (170 – 120 ˚W, 5 ˚N – 5 ˚S) to be > 27.5 ˚C, < 26 ˚C or between.

Fig. 7: As Fig. 2b but separating years with the stratospheric QBO in west (crosses), east (triangles) or neutral (small squares) phase.

Fig. 8: Sea surface temperatures (SSTs) of the tropical North Atlantic for the season August to October as observed (a: observed), simulated for the present (b: mod now) and for the future in 2021-2050 years (c: +60 years). Data are based on a) Rayner et al. (2003) and b) & c) Roeckner et al. (2006).

Fig. 9: Time-series of latent heat flux (LHFX) averaged for the northern tropical Atlantic (a) and the

Caribbean Sea (b) for the season June-November as simulated by the model for the 20th and 21st century. The data are smoothed by a 9-year running mean. Data are based on Roeckner et al. (2006).