Simulating the effect of climate change on tropical cyclones: current issues

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Keywords: *Tropical cyclones; climate change; global warming*

EXTENDED ABSTRACT

The main issues involved in the simulation of the effect of climate change on tropical cyclones are discussed. These include the effect of climate change on the El Niño/Southern Oscillation phenomenon; the development of simple idealized models of tropical cyclone characteristics; the ability of climate simulations to generate tropical cyclones in the correct numbers and to encompass the full range of observed tropical cyclone intensities; and the detection of the effects of global warming in the observed tropical cyclone record, for comparison to model predictions.

An incomplete knowledge of the theoretical foundations of the El Niño/Southern Oscillation (ENSO) phenomenon is greatly hindering our understanding of how it might change in a warmer world. Year-to-year variations in tropical cyclones respond strongly to ENSO variations in many parts of the world, so this affects future estimates of tropical cyclone numbers. Climate simulations of ENSO require further improvement.

A hierarchy of simulation techniques has been used to simulate the physics of tropical cyclones. Simple idealized models are still used and indeed have led to some of the most robust conclusions of the effects of climate change on cyclones. Most successful have been models of the Maximum Potential Intensity of tropical cyclones, which treat tropical cyclones as simple Carnot heat engines. These models have been used to project some increases in tropical cyclone wind speeds in a warmer world. Dynamical simulations have tended to support this conclusion. Less success has been obtained for projections of future cyclone numbers, as operational statistical forecast models of cyclone formation have not been applied to climate change simulations. Evaluation of climate simulations of tropical cyclones is limited by disagreement regarding what actually constitutes a cyclone in a climate simulation, as differing definitions are given. A new technique that is objective and resolution-dependent may resolve this issue.

In general, climate simulations have a poor simulation of the distribution of tropical cyclone intensities, compared with observations. This is certainly due to inadequate horizontal resolution. It will be some time, though, before global climate simulations are performed that have sufficient horizontal resolution to simulate good tropical cyclone intensity distributions. In the meantime, variable-resolution global models, where fine resolution is only applied over a limited region of interest, offer a better option for improving simulations of tropical cyclone intensity.

A related issue is when projected changes in tropical cyclone behaviour will be noticeable. Recent research has claimed that they are already. Nevertheless, there remains considerable scope to improve our understanding of this issue.

1. INTRODUCTION

This paper outlines some of the current issues in the topic of the effect of climate change on tropical cyclones. A recent review is that of Walsh (2004). The purpose of this paper is to further discuss the issues raised in Walsh (2004), as well as suggesting means by which some of the current uncertainties might be resolved.

2. CRUCIAL ISSUES

2.1. The effect of ENSO on climate change

It is probably fair to say that there is no issue that currently concerns climate modellers more than how and if climate change will affect the El Niño/Southern Oscillation phenomenon. Scientific opinion is currently divided on how ENSO might change in a warmer world (Tsonis et al. 2003; Karl and Trenberth, 2003). One of the issues for the general modelling community is that no current climate model gives a genuinely good simulation of ENSO in all of its characteristics, namely the speed of movement of the temperature anomalies associated with ENSO, the period of the ENSO cycle, and the geographical pattern of the warm and cold water anomalies (e.g. Guilyardi et al. 2004). One major issue in the climate modeling community is that almost all climate models currently in use for the prediction of climate change exhibit a "cold tongue" along the equatorial Pacific, a phenomenon that is seen in nature but not as strongly as it is currently simulated in models (e.g. Dai et al. 2005; Luo et al. 2005). Recent simulations that incorporate enhanced subsurface warming due to the absorption of radiation by organisms (Marzeion et al. 2005) suggest that this may be a factor in reducing this cold bias.

The relevance of this for tropical cyclones is that numbers of tropical cyclones in many regions of the world are strongly related to the phase of ENSO, including the Australian region (e.g. Nicholls et al. 1998). Thus any substantial change in ENSO characteristics would affect tropical cyclone numbers in the Australian region.

There are a number of possible avenues that could be explored in the modelling community to improve the simulation of ENSO. Both horizontal and vertical resolution in the ocean appear to be important: vertical resolution in particular better resolves the thermocline, the region of sharp temperature gradient beneath the mixed layer at the top of the ocean. A sharply-resolved gradient is one that permits large-amplitude ENSO oscillations of the kind observed to develop (e.g. Cai et al. 2003; Wang et al. 2005).

One drawback is that at present there are a number of competing paradigms that are used to explain the complex ocean-atmosphere interaction causing ENSO (Wang 2001). Without a clear-cut theoretical understanding of what causes ENSO in the current climate, it is difficult to see how firm conclusions can be drawn regarding its behaviour in a changed climate.

2.2. Simple models of tropical cyclone intensity and formation

Simple models of tropical cyclone intensity have been employed with some success in tropical cyclone forecasting. These are models based upon the concept of a tropical cyclone as a simple Carnot heat engine, where the warm reservoir is the sea surface and the cold reservoir is the upper atmosphere (Emanuel 1988; Holland 1997). This theory is used to calculate a Maximum Potential Intensity (MPI), which is the maximum wind speed of a tropical cyclone that could occur in a particular region. While tropical cyclones rarely attain this maximum value, the most well-known tropical cyclone statistical intensity forecast model (DeMaria and Kaplan 1999; DeMaria et al. 2005) uses the Emanuel MPI as one of the parameters employed to predict tropical cyclone intensity a couple of days in advance.

This is relevant to the issue of climate change because these simple models can also be used to project MPI values into the future, given future atmospheric and oceanic conditions as projected by climate models. These have usually projected a modest to moderate increase in future tropical cyclone intensity (5-10% by the middle of this century). Results from climate simulations have generally supported this (Knutson and Tuleya 1999; Walsh and Ryan 2000; Knutson and Tuleya 2004).

While simple models have had some success in projecting future cyclone intensities, the same cannot be said regarding tropical cyclone numbers. Simple statistical cyclone formation models have been developed (e.g. DeMaria et al. 2001; Hennon and Hobgood 2003; McDonnell and Holbrook 2004) that have shown some success in forecasting tropical cyclone formation a day or so in advance, but versions of these models have yet to be applied to the output of climate models. Thus there is no generally accepted simple model of tropical cyclone formation that can be applied to the output of climate models to determine possible changes in tropical cyclone formation in a warmer world. This is important because the ability of the climate simulations themselves to generate tropical cyclones in the correct numbers is quite variable (Walsh et al. 2005), and a simple model diagnostic may provide a better estimate of changes in numbers given the current state of the art of climate simulation.

2.3. Ability of climate models to generate tropical cyclones

Climate models can and do generate tropical cyclones, but an important issue is whether they are generating the correct number of storms, and for the right reasons. Numerous climate modelling groups have simulated tropical cyclones; for a summary, see Walsh (2004). But there is presently no objective criterion for determining what a tropical cyclone really is in a climate model. There are as many criteria for detecting these lows in models as there are simulations. This is important because for a climate simulation to claim to be able to say something about climate change, it must be producing a reasonable simulation of actual numbers of tropical cyclones compared with observations.

Walsh et al. (2005) have developed an objective, resolution-dependent criterion for the detection of tropical cyclones in climate models. The criterion is resolution-dependent because low-resolution climate models produce lower-intensity cyclones, all other things being equal. Walsh et al. (2005) suggest that this criterion should be applied to all climate model experiments that analyse the formation of tropical cyclones.

2.4. Tropical cyclone intensity in climate models

Climate models generally have inadequate simulations of tropical cyclone intensity distributions. This is hardly surprising, as experiments with short simulations of tropical cyclone models suggest that a horizontal resolution of 5 km or better is needed to capture fully the horizontal gradients of pressure that lead to strong winds in cyclones. The finest resolution global model that has been analysed for tropical cyclones is a run of the Earth Simulator supercomputer, as documented by Oouchi et al. (2005), with a global resolution of 20 km. It will be some time before a global climate change simulation will be performed at 5 km resolution, due to the extreme demands of such a run on even the world's fastest present-day supercomputers. Variable-resolution climate models, such as the Conformal-Cubic Atmospheric Model (CCAM; McGregor and Dix 2001) may offer a better modelling solution in the medium term, as these models give fine resolution over a limited area of interest, while having coarse resolution over other regions of the globe, thus saving considerable CPU time (see Fig. 1).

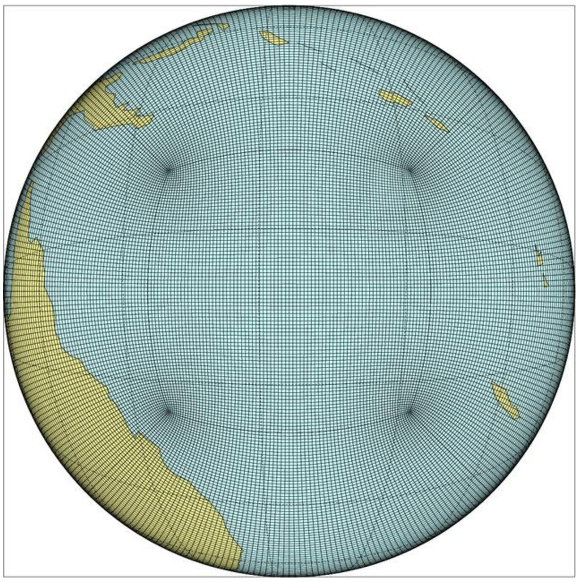

Figure 1. Example of CCAM variable-resolution model grid over eastern Australia.

This model grid has recently been used to perform fine resolution simulations of tropical cyclone formation. Results are preliminary at present but more will be presented at the conference, including a description of the special issues faced when simulating tropical cyclones using a variable-resolution model.

2.5. Detection of global warming effect on tropical cyclones

Prediction of the effects of climate change on tropical cyclones must be accompanied by analysis of observed trends. Walsh (2004) claimed that there were presently no trends in the climate record of tropical cyclones that could be unambiguously ascribed to global warming. The main difficulty in detecting such trends is that the year-to-year variability of tropical cyclone numbers is very large; thus the signal-to-noise ratio of changes is small.

Recently, Emanuel (2005) has published a controversial paper claiming to have detected a global warming signal in a tropical cyclone record of the Atlantic Ocean. Emanuel defines a tropical cyclone power index that is proportional to the area-integrated cube of the wind speed over the region affected by the storm. His results show that there has been a large increase in power over the North Atlantic since the mid-1990s, with a peak in the last few years considerably greater than any seen since 1950.

Causes of this increase are not clear at present. Emanuel (2005) speculates that there have been trends in atmospheric and sea temperatures that have influenced the MPI of tropical cyclones in this region, noting a shift in the difference between atmospheric and sea surface temperatures over this time.

3. CONCLUSION

While the challenges of simulating tropical cyclones in climate models are daunting, results obtained to date are gradually shedding light on this issue. There still remains scope for further development of simple, idealized models of tropical cyclone processes that may capture essential aspects of the physical processes governing tropical cyclones.

4. ACKNOWLEDGMENTS

The author would like to thank the School of Earth Sciences, University of Melbourne, for supporting this work.

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