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Deep uncertainty in long-term hurricane risk: Scenario generation and implications for future climate experiments

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ABSTRACT

Current projections of long-term trends in Atlantic hurricane activity due to climate change are deeply uncertain, both in magnitude and sign. This creates challenges for adaptation planning in exposed coastal communities. We present a framework to support the interpretation of current long-term tropical cyclone projections, which accommodates the nature of the uncertainty and aims to facilitate robust decision making using the information that is available today. The framework is populated with projections taken from the recent literature to develop a set of scenarios of long-term hurricane hazard. Hazard scenarios are then used to generate risk scenarios for Florida using a coupled climate–catastrophe modeling approach. The scenarios represent a broad range of plausible futures; from wind-related hurricane losses in Florida halving by the end of the century to more than a four-fold increase due to climate change alone. We suggest that it is not possible, based on current evidence, to meaningfully quantify the relative confidence of each scenario. The analyses also suggest that natural variability is likely to be the dominant driver of the level and volatility of wind-related risk over the coming decade; however, under the highest scenario, the superposition of this natural variability and anthropogenic climate change could mean notably increased levels of risk within the decade. Finally, we present a series of analyses to better understand the relative adequacy of the different models that underpin the scenarios and draw conclusions for the design of future climate science and modeling experiments to be most informative for adaptation.

1. Introduction

Damages related to tropical cyclones on the US Atlantic and Gulf coasts have spiraled upwards over the past few decades as populations and assets have become increasingly concentrated in exposed coastal regions (e.g. Pielke and Landsea, 1998; IPCC, 2012). There are indications that anthropogenic climate change (hereafter, referred to as climate change) may exacerbate hurricane risk in the future. There is an urgent need to consider future hurricane risk in long-term planning and policy decisions, for example, over how and where new properties and infrastructure are developed, as decisions made today that are appropriate to current climate could lock-in substantial future exposure and vulnerability in a changed climate. The challenge for decision makers is that the future characteristics of tropical cyclone hazards are uncertain, particularly at a regional level.

Knutson et al. (2010) reviewed current evidence and concluded that globally, climate change is likely to lead to either a reduced, or essentially unchanged, tropical cyclone frequency, alongside an increase in average maximum wind speeds. There is lower consensus over projections for individual ocean basins. For the Atlantic Basin, of the twelve studies reviewed by Knutson et al. (2010), around one third predict an increase in frequency and two-thirds a decrease. Studies concerning the intensity of tropical cyclones are more challenged by the resolution of current global climate models, so-called general circulation models (GCMs), which is not yet sufficient to simulate the most intense storms (Emanuel, 2008). The majority of the studies reviewed by Knutson et al. project, on average, an increase in storm intensity in the Atlantic Basin, although a minority of individual GCMs used in these studies do project reductions (where different studies use alternate metrics, including the frequency of the most intense storms, the potential intensity or maximum wind speeds). Many other characteristics relevant to risk estimation are even more uncertain; for example, changes in the distribution of tropical

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storm tracks, genesis locations, speeds, sizes and landfall locations. Knutson et al. reported that few studies have explored the affects of climate change on these characteristics and there is little consensus in projections.

While it is important to continue to refine projections, some types of adaptation decisions cannot be delayed until there is greater certainty in long-term hurricane prediction; for example, greater certainty in projections could take more than a decade to achieve (e.g. Zickfeld et al., 2010) and meanwhile infrastructure and development planning decisions made today will affect risk levels for many decades to come. This paper seeks to provide an informative set of scenarios of wind-driven hurricane risk based on peer-reviewed science and modeling available today. This paper is only a first step toward an informative set of scenarios; firstly, it does not address all uncertainties, only those related to the future frequency and intensity of tropical storms in the Atlantic Basin, and secondly, the scenario set will be refined over time as new information becomes available. The following two sections describe the framework and methodologies used for generating the scenarios. Sections 4 and 5 analyze the hazard and risk scenarios.

Scenarios of future states have long been used in the management of natural hazards, as well as decision-making more broadly. Van der Heijden (2005) suggests that such scenarios can serve as a "*test-bed for policies and plans*" as well as guiding future research to refine projections. Section 6 will briefly discuss the first of these applications, how the scenarios can be used to inform adaptation planning; though most focus in the discussion will be placed on the second application, using the scenarios to consider how future climate science and modeling experiments could be best designed to be most informative for adaptation.

2. The framework

A scenario is a description of a possible future state; in this case, a possible future tropical cyclone climate. Appropriate model selection is crucial in generating a set of scenarios to inform decision making. Groves and Lempert (2006) and Van der Heijden (2005) suggest that a set of scenarios should aim to explore all the most significant driving forces affecting future risks and decisions and be representative of the range of possible future outcomes. Several other authors have also noted the importance of including extreme scenarios in decision analysis (Parson, 2008; Groves et al., 2008a; Hallegatte, 2009; Morgan, 2003) and this was an important lesson learnt from the Thames Estuary 2100 project in the UK, which used a scenario-based approach to design a new tidal flood protection system for London for the twenty-first century (Lowe et al., 2009).

For these reasons, the framework aims to select models to represent the widest possible range of plausible future states for the key determinants of future wind-related risk. A condition imposed on this range, after Lempert et al. (2003), is that the scenarios are scientifically plausible and rigorous; which we define as being based on modeling and approaches that are grounded in scientific theory and published in the peer-reviewed literature.

Van der Heijden (2005) suggests that a framework for developing scenarios can be derived from identifying key events or stages of uncertainty that will drive the scenario progression. Scenarios can then be developed that systematically explore the range of consequences of these events or stages. We suggest there are three major stages of uncertainty in projections of long-term average tropical cyclone activity in the Atlantic Basin (after Jones, 2000). The first (I) is the emissions scenario uncertainty; this is discussed in Section 3. The second (II) is uncertainty in the response of the large-scale (global to ocean basin-scale) climate and ocean environment to manmade emissions. In current projections, this uncertainty stems from missing processes (and structure more broadly) and the parameterization of processes in global climate models; referred to structural and parameter uncertainty, respectively (McAvaney et al., 2001; Randall et al., 2007). The third stage (III) is the uncertainty in the link between the ocean basin-scale environment and basin tropical cyclone activity. This can also be characterized as structural and parameter uncertainty, but we distinguish the second and third stages because these are generally treated by different models. Computational constraints mean that the resolution of global models (even of the highest-resolution models available) is insufficient to simulate all the processes involved in tropical cyclone development and for this reason *downscaling* models are used to project changes in regional tropical cyclone characteristics for a given large-scale environment. These downscaling models add an additional layer of uncertainty (Emanuel, 2008; Maraun et al., 2010).

We note that natural variability is the dominant driver of uncertainty on shorter timescales; the role of this uncertainty in the framework is discussed separately from the long-term drivers.

The scenarios available in the recent scientific literature generally fall into two types that roughly reflect the Van der Heijden (2005) framework. The first type utilizes a range of projections of the large-scale environment sourced from multiple GCMs (i.e. the stage II uncertainty), but only a single representation of the link to basin tropical cyclone activity (stage III), typically using a *dynamical downscaling* model; that is, a higher-resolution regional model that simulates the tropical cyclone climatology conditioned on a particular GCM projection. These scenarios are denoted "Dynamical Model" scenarios. The second type also uses a range of GCM projections, but explores a broader range of the uncertainty in the link to basin tropical cyclone activity (stage III); typically using simpler statistical downscaling approaches. For example, Vecchi et al. (2008) presents a set of simple models which utilize *statistical downscaling* techniques (based on only one or two predictors) coupled with a range of GCM projections. These scenarios are denoted "Statistical Model" scenarios. Few studies explore more than one emissions scenario.

In this study, we utilize both of these types of scenarios (Fig. 1). The Dynamical Model scenarios represent the 'state-of-the-art' in current long-term prediction. These are complemented by the Statistical Model scenarios, which have the advantage of representing a broader range of the uncertainty. Both are driven by a set of large-scale climate projections from multiple GCMs. While the

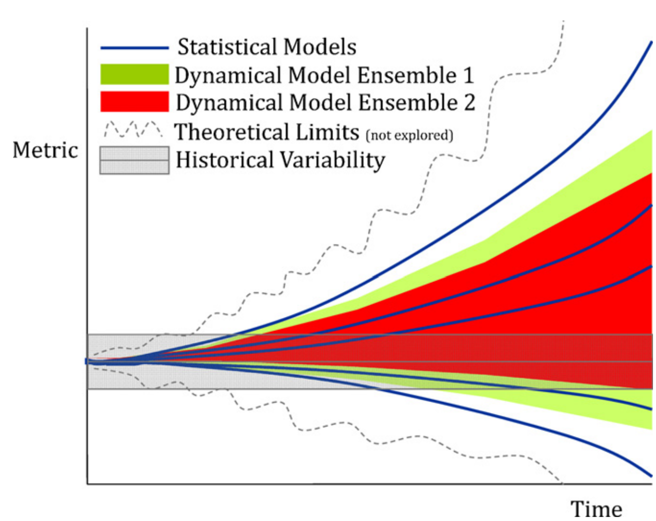

Fig. 1. Schematic diagram illustrating the framework for scenario generation. The grey wavy lines signify that it is not possible to exclude scenarios outside of the ranges indicated by the scenarios. In reality, the evolution of the metric is unlikely to be a smooth progression as suggested by this diagram.