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Exploring hurricane wind speed along US Atlantic coast in warming climate and effects on predictions of structural damage and intervention costs

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ABSTRACT

This paper proposes a methodology for the rational assessment of lifetime costs on tall buildings due to hurricane-induced damage along the US Atlantic coastline accounting for plausible future warming climate scenarios. The hurricane simulation is based on Vickery's empirical model. Initially, regression errors in Vickery's model are discussed; some adjustments are proposed to enable hurricane simulation in future climates. After verification of the hurricane model's ability to simulate the results of the United States historical hurricane database, simulation of hurricane activity in future climates is examined. The warming climate scenarios are reproduced from the results of the community earth system model, maintained by the National Center for Atmospheric Research (NCAR). Three different future climate scenarios, RCP2.6, RCP4.5 and RCP8.5, are considered. The influence of warming climate on two quantities, relevant to wind engineering, is examined: hurricane frequency and hurricane intensity. It is found that, in a warming climate environment, the hurricane frequency and hurricane intensity may vary depending on the RCP scenario. Therefore, the probability distribution of the wind speed in hurricane-prone areas of the United States, both coastal and interior areas, will also be influenced by the RCPs.

The numerical methodology for computing wind speed probability distribution in a future warming climate, influenced by the various RCP scenarios, is subsequently coupled with an existing approach for structural performance analysis against wind hazards to predict the indirect effect of future warming climate on the structural intervention costs (i.e. repair costs), induced by the damaging winds. A 180-m tall benchmark building, located in Miami (Florida, USA), is used as one example of application in conjunction with a series of structural fragility curves, derived from a recent study for the same structure. The evaluation of lifetime intervention costs is later expanded to demonstrate the ability of the proposed methodology to predict hurricane wind damage, if the location of the structure is moved to several other cities along the Atlantic coast of the United States.

1. Introduction

Hurricanes are among the most destructive weather phenomena, which can cause severe damage to structures and loss of human lives due to strong winds and surge effects. In 2005, Hurricane Katrina caused 1833 fatalities and $108 billion property damage in several coastal regions along the Gulf of Mexico. In 2012, Hurricane Sandy led to about $65 billion damage in the northeastern coastal region of the USA and in the Ontario Province of Canada. The severity of the consequences, associates with hurricane activity, has motivated several investigations, attempting to forecast hurricane activity in both near and distant future. A short review of the most important models, currently employed for hurricane simulation in wind engineering, is provided in the following section. For example, *Georgiou* derived a pioneering method to numerically model the hurricane wind field and to predict wind speed in a hurricane along the US Atlantic coast [1]. *Simiu* proposed a "single-site" probabilistic model, which employs Monte Carlo simulation to compute hurricane reference wind speeds as a function of five random quantities or parameters [2]. Subsequently, *Vickery* proposed an empirical track model [3,4], derived from statistical linear regression of a large hurricane database. This model has been comprehensively validated and widely used for long-term hurricane wind field predictions. The initial model by *Vickery* has been upgraded a number of times to advance the prediction of

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hurricane wind speeds [5–8] and it is currently employed in its latest form to generate the wind speed maps in the ASCE-7 civil engineering design standard [9].

In recent years various physical observations have been attributed to the effect of "climate change" by the research community, governments and society. These include, for example, melting of glaciers, an increasing hurricane activity and longer periods of drought. Since the publication of the First Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) in 1990 [10], scientists indicate that it is extremely likely (at least 95% probability) that humans are contributing to these effects because of a larger concentration of greenhouse gases in the atmosphere [11]. The current theories [11] tend to suggest that the surface temperature may continue to increase in the 21st century and other climate indicators may also progressively change.

One of the consequences, attributed to climate change by researchers [12,13], is the potential change in hurricane number, duration and intensity. Analysis of the hurricane history in the North Atlantic Ocean indicates that the annual number of hurricanes, especially intense hurricanes, has been increasing in the last century [13]. The relationship between sea temperature and hurricane frequency may lead to the following conclusion: the sea surface temperature (SST), i.e. the power source of hurricanes, may influence hurricane genesis frequency, hurricane genesis spatial location, intensity and trajectory path. Thus, it has been suggested that the increasing SST may likely be correlated with the recent unusual hurricane activity in the North Atlantic Ocean [12].

Consequently, it is relevant for the structural engineer to examine the influence of climate change on structural integrity and to possibly consider the concept of "adaption" in the design process. The significance of climate change and adaptation in structural engineering is for example demonstrated by several recent studies on the deterioration of civil structures [14–16]. In the field of wind engineering attention has been paid to the advancement of structural design standards for wind loads, predominantly considering a traditional prescriptive approach [17]. The concept of performance-based approach for structural design has been investigated in wind engineering both for low-rise buildings (e.g., [18–20]), tall buildings (e.g., [21–26]) and long-span bridges (e.g., [27,28]). In recent years several studies have analyzed the effects generated by SST variations, for example promoted by climate change, on the extreme value distribution of the hurricane wind speed [17,29–31]. Research activities have considered the fundamental research question about the correlation between plausible climate change scenarios, SST variations and hurricane extreme wind speed distributions [17,29,30,32,31]. Nevertheless, very few results are available on the indirect effects of such climatic variations on the built environment (e.g., [30,32]).

This research is a continuation of a research activity on the evaluation of lifetime monetary losses due to hurricane-induced damage on tall buildings [24]. This study proposes, for the first time, a numerical methodology for assessing monetary losses, incurred by the owner of a tall building, due to the rising hurricane threat accounting for a progressively warming climate. The aim of this research is not the examination of the connection between the current IPCC model predictions and the role of SST variations on the increased hurricane intensity. On the contrary, this study proposes to "bridge the gap" between the current research activities in climatology, weather extremes and climate change in wind engineering [17,29,30,32] and the crucial issue of the potential indirect consequences on the built environment and, in particular, the damage on the facade of a tall building in structural engineering. This research attempts to evaluate the relative variation of intervention costs due to hurricane-induced damage on a benchmark structure with and without the indirect effect of a future warming climate, given the "best estimate" of the SST variations indicated by current theories and models on climate change [11].

2. Background

2.1. Review of IPCC's forecast of increasing SST in the 21st century

In the fifth assessment report by IPCC, the global mean surface temperature has progressively increased since the late 19th century [11], according to recent climate observations. In the future, warmer temperature extremes will likely be present in many areas of the Earth as global mean temperature tends to increase.

In order to establish a common baseline measure for the comparison among various climate model results, Representative Concentration Pathways (RCPs) have been used by IPCC to provide a more quantitative information on the possible "trajectories" of the main forcing agents responsible for climate change [33]. Currently, four RCP values are used by the climate models: RCP8.5, RCP6, RCP4.5 and RCP2.6. Generally, the four RCP values represent four plausible future climate scenarios, which are illustrated in Fig. 1. The scenarios are defined in accordance with a possible range of radiative forcing values in the year 2100 relative to pre-industrial values: +2.6, +4.5, +6.0 and +8.5 W/m^2 [33].

From around the mid-21st century, the rate of global warming appears to be more strongly dependent on the RCP scenarios. The projections of global mean temperature are illustrated in Fig. 1. Solid lines indicate the mean temperatures predicted by various models and the colored areas are the 90% confidence intervals. Since the number of models used in the various reference time

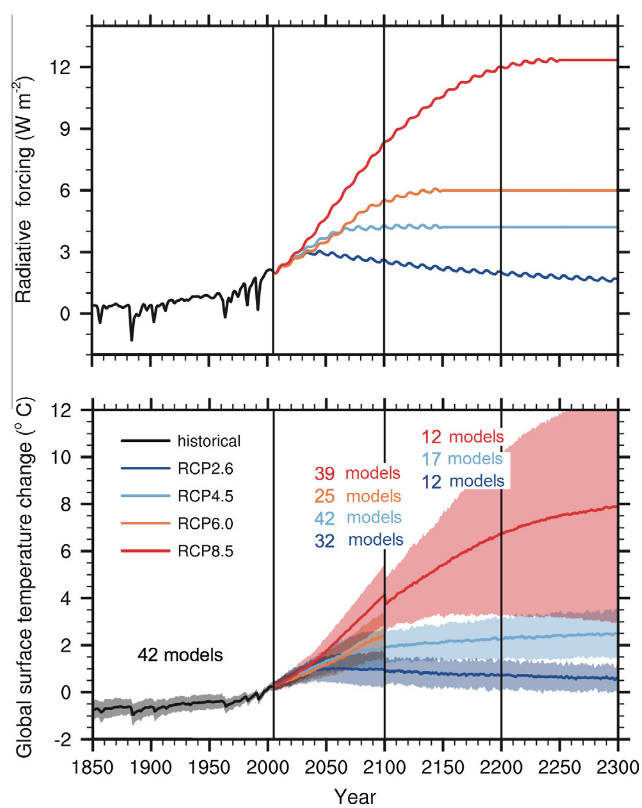

Fig. 1. Projections of total global mean radiative forcing (top) and global annual mean surface air temperature anomalies (bottom) in the 21st century and later, with reference to the average temperature in the period 1986–2005. Curves are reproduced from IPCC report [11]. (The integer numbers on the figure panel indicate the number of models used to generate the results for each RCP scenario in various time periods.)