TROPICAL CYCLONE MODELLING

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INTRODUCTION

Tropical cyclones (TCs) are "low-pressure weather system over tropical or sub-tropical waters with organized convections (i.e., thunderstorm activity) and definite cyclonic surface wind circulation" (HRD 2016). In the North Atlantic Basin and the Central and Eastern Pacific Ocean, strong tropical cyclones are called hurricanes, and in the Western Pacific ocean they are called typhoons. Between 1980 and 2015, tropical cyclones produced five of the ten costliest natural hazard events in the world in terms of insured losses (Munich Re 2016).

Tropical cyclone catastrophe models (TCCMs) have been in widespread use for over two decades, gaining increasing acceptance in the insurance industry in the years following the landfall of Hurricane Andrew near Miami, Florida in 1992. In 1995, the Florida Commission on Hurricane Loss Projection Methodology (FCHLPM) was created to evaluate computer models used for projecting hurricane losses. There are currently five models accepted for use by the FCHLPM (2015).

The primary sub-perils associated with TCs are: wind pressures, windborne missiles, falling trees, wind-driven rain, coastal storm surge (i.e., rising water and waves due to the effects of winds, reduced atmospheric pressures, and astronomical tides), and inland flooding due to the run-off and accumulation of rainfall. Historically, catastrophe models have modelled inland flooding as a separate peril because it can also be caused by several other types of weather systems in addition to TCs. Coastal storm surge has historically been an optional sub-peril in TCCMs that can be turned on or off by the user. Wind pressures, windborne debris, falling trees, and wind-driven rain are commonly modelled together, either implicitly or explicitly. In addition to direct wind and flood damage to buildings and their contents, other frequently insured causes of loss include damage to attached or detached appurtenant structures and loss of use, either due to direct physical damage or indirect causes such as loss of power, water, communications, or access to the building site. Losses associated with loss of use are often referred to as time element losses.

The principal components of a TCCM are the hazard model, the damage model, and the financial model. The hazard model typically includes a TC event set generation model, a wind field model, and a coastal storm surge model. The damage model combines measures of hazard intensity (typically wind speed and depth of flooding) with property exposure data to produce probabilistic estimates of building, contents and time element loss. These losses are often referred to as "ground-up" losses, or the losses before the application of any insurance limits or deductibles. Finally, the financial model estimates the allocation of losses between the property owner, the insurer(s), and any reinsurer(s), if applicable. Typically, the financial model is designed to accommodate all types of insured perils. Therefore, the remainder of this section focuses on the fundamental aspects of the hazard and damage components of TCCMs.

EVENT SETS

While it is possible to use site-specific wind and storm surge hazard curves to assess individual risks, all of today's commercially-available TCCMs use event sets to capture the spatial extent and correlation of wind and storm surge hazards to model losses for geographically- and temporally-distributed portfolios with multiple risk locations. At a minimum, event set generation modules must simulate the frequency, location, intensity, size (i.e., radius of maximum winds, R_{max}), forward translation speed, heading, and inland decay of TCs from the time of landfall until the peak surface level winds fall below damaging levels. Some TCCMs use basin-wide event generation modules that simulate the entire life of each hurricane event, from the time of genesis to final dissipation, allowing for multiple landfall events and/or by-passing events.

In most models, TC frequency and intensity are parameterized by the central pressure of the storm, or more precisely, the central pressure difference, Δp, which is defined as the difference between the atmospheric pressure at the periphery of the storm and the pressure at the centre of the storm. Other models use a closely related, but physically-bounded, parameter called relative intensity (Emanuel 1988; Darling 1991). Another equally important parameter used in some models characterizes the rate at which the atmospheric pressure increases from the centre of the storm outward. This pressure field shape parameter, called the Holland *B* parameter (Holland 1980), generally ranges from about 0.75 to 1.75, and it is only slightly correlated with Δp. It can be shown, to first order, that the maximum wind velocity in a TC is directly proportional to $\sqrt{B\Delta p}$ (Holland 1980). Thus, it is possible for storms with the same or similar central pressures to have maximum wind speeds that can differ by up to about 50%.

All TCCMs rely on historical data sets, such as HURDAT2 (Landsea et al. 2015), to fit probability distributions to the track parameters discussed above. It is important to note that the quality of these historical data sets varies significantly with era (e.g., pre- or post-satellite era), and the data are subject to change as events are re-analysed. Further, the maximum surface level winds provided in these data sets are never directly measured. Rather, the wind intensities for events prior to the 1940's have been inferred from sparsely scattered and inconsistently measured surface level wind observations, atmospheric pressure observations, and damage reports. Today, maximum surface level winds are typically estimated through adjustments to upper level winds measured by hurricane reconnaissance airplanes and dropsondes or by correlating airborne (SFMR) or satellite-based (QuikSCAT) microwave sensor readings over oceans to surface level winds.

Research by Powell et al. (2009) suggests that there is a high bias of 4.6 m/s (~10 mph) in official landfall wind speeds for the recent historical record. To avoid this bias, some TCCMs do not attempt to match the wind intensities at landfall that have been estimated for historical events; instead, they seek to reproduce the central pressures at landfall (which are more robust than wind speed estimates) and surface level observations at multiple locations, such as data buoys, airports, and mobile research towers, where direct surface level observations of wind speeds, wind directions, and atmospheric pressures vs. time have been recorded.

WINDFIELD MODELLING

Given a specific historical or simulated TC storm track, wind field models are needed to compute the wind speeds and wind directions at anemometer locations for model validation and at property locations for loss modelling. Wind fields are also a primary input to coastal storm surge and wave models. Typically, TC wind fields are modelled in three steps: (1) mean gradient level wind field, (2) mean surface level wind field, and (3) gust factors.

Gradient level winds are the mean winds in the "free atmosphere" above the frictional effects of the earth's boundary layer (Holmes 2001). For TCs, the primary drivers of gradient level winds are the closed pressure field contours and the rotation of the earth. The resulting winds rotate counter clockwise about the centre of the storm in the northern hemisphere and clockwise in the southern hemisphere. Some TCCMs model the maximum gradient level wind for a stationary TC as:

$$V_{G\max} \approx K\sqrt{\Delta p} \quad (1)$$

where K is an empirical constant and Δp is the central pressure difference described in the previous section. The maximum gradient level wind, R_{max}, and latitude can then be combined with an empirical radial profile model (e.g., Willoughby et al. 2006) and the forward velocity vector of the storm to complete the gradient level wind field model. Some TCCMs employ more complex 2-D slab models that consider surface friction in their initial mean wind field calculations, producing a vertically averaged mean wind field rather than a gradient wind field. These models account for the effects of surface friction on wind field asymmetries and enhanced inflow and enable the prediction of super gradient winds (e.g., Vickery et al. 2000 and 2009b).

Next, the gradient level winds (or the vertically averaged winds) are adjusted to mean surface level winds through the use of an atmospheric boundary layer model or a wind speed reduction factor. A number of different approaches are in use, producing reductions over water ranging from 5 to 35% (Vickery et al. 2009a).

Finally, the mean surface level winds are adjusted for terrain and averaging time using gust factors. Terrain or surface roughness is a parameter used to model the frictional effects of trees, buildings, and other objects on the winds near the surface of the earth. Averaging time is the time period over which the peak winds occur. Commercially available TCCMs typically use averaging times of either 3 seconds or 1 minute. When comparing wind speeds from TCCMs or weather observations, it is very important to know the terrain, averaging time, and height of the winds and, of course, the units (e.g., m/s, mph, or knots). In mountainous or hilly areas, it may also be necessary to consider orographic effects that can either speed up or slow down the winds for specific wind directions.

The accuracy of a wind field model must be verified by directly comparing modelled winds to wind speeds and wind directions measured in actual TC events. Such comparisons should be evaluated over water, near the coast, and inland to ensure that the model is performing well in all three zones. The sea-to-land transition zone and the treatment of surface roughness, both at the coast and inland, are areas where significant differences remain between TCCMs. It is important to understand that any biases in modelled winds for historical event can lead to the development of biased vulnerability curves, and that small errors in wind speeds can result in much larger errors in modelled losses.

STORM SURGE MODELLING

Storm surge is the "abnormal rise of water generated by a storm, over and above the predicted astronomical tide," and storm tide is "the water level rise during a storm due to the combination of storm surge and the astronomical tide" (HRD 2016). Storm surge is primarily produced by the wind pushing the water on shore and into bays and estuaries. The slope of the ocean floor near the coast, the shape of the coastline, the angle at which the storm approaches the coast, and the size (R_{max}) and forward translation speed of the storm can each have a significant influence on the magnitude of the storm surge. A secondary contributor is the reduced atmospheric pressure in a TC, which allows the water to expand upward slightly. In addition to storm surge and tide, there may be waves on top of the surge in unprotected coastal areas.

The key inputs needed to model storm surge are the wind field, digital elevation data (i.e., topographic data for the land and bathymetric data offshore), the locations and sizes of channels that will permit the flow of water, and the locations and heights of barriers (e.g., levees) that will inhibit the flow of water. Collecting and validating information on channels and barriers can be very time consuming. As a result, TCCMs typically rely on third-party hydrodynamic models (e.g., SLOSH, ADCIRC, or MIKE) for their storm surge hazard modelling.

Astronomical tide can be directly incorporated as a time-varying input to some hydrodynamic models, or it can be treated approximately as a fixed shift in the still water elevation, either as an initial condition or as an adjustment to the computed still water elevation. Likewise, wave computations can be dynamically coupled with the storm tide calculations, or they can be modelled approximately as depth-limited waves with further attenuation for protected locations where wave action will be reduced. For wood frame construction, wave heights as small at 1.5 feet can significantly increase the level of damage beyond that which would occur with the same total depth of still water flooding.

The wind field model and the transfer of wind forces into the water through surface friction stresses are critical components of any storm surge model. For storm surge and wave generation, it is the mean wind speeds (i.e., winds averaged over 10 minutes or more) and wind directions over water that are most important, rather than the 3-second gust or 1-minute sustained winds. This should be reflected in any wind field validations that are presented by the modellers in conjunction with their validation of storm surge and wave results against tide gauge data, buoy data, and inundation maps from historical events.

VULNERABILITY MODELLING

In catastrophe modelling, vulnerability models provide the expected loss and a probability distribution of loss as a function of one or more demand parameters. In most cases, a single demand parameter, such as peak wind speed or peak depth of flooding, is used. The mean loss vs. demand can be referred to as a vulnerability curve, a damage curve, a loss function or any combination of these terms. We will follow the FCHLPM (2015) terminology and use the term vulnerability function.

For the distribution of loss about the mean, some models assume parametric distributions (e.g., Beta distributions with or without discrete probabilities at 0% and 100% loss) while others use non-parametric distributions. If adequately discretized, non-parametric distributions have the ability to capture the probabilities of multiple distinct failure modes at a single hazard intensity level. Parametric distributions have the advantage of convenience and are likely to produce good results for large homogenous portfolios, but they may not be adequate for characterizing high value risks with layered insurance coverages.

The three principal methods that are generally used to develop vulnerability functions and vulnerability distributions for TCCMs are: (1) empirical fits to claims data from past TC events, (2) analytical models, and (3) expert judgment.

Empirical fitting to claims data is a top-down approach that starts with the desired end result (expected losses) and works directly back to a demand parameter. Such models are also referred to statistical or phenomenological models. Typically, empirical fits are developed for broad classes of occupancy, general construction type, and construction era, since segmenting the data into too many dimensions can lead to unreliable or counterintuitive results. Empirical fits can be a highly effective and highly credible approach, provided that the claims data used have been coded correctly, the hazard intensities that produced the claims are well understood and representative of the full range of probable intensities, and the claims data are comprehensive and balanced in terms of the construction types, occupancies, eras, etc. When these conditions are not met, the model developer is faced with the potentially difficult tasks of scrubbing the data, estimating hazard intensity levels that produced the claims data, filling gaps in the data, and, in many cases, extrapolating beyond the range of the available data. Validation can be another challenge. To properly validate an empirical model, a portion of the data must be withheld from the fitting process or, better yet, independent data sets must be acquired after the fitting process is completed for use in validation.

Analytical modelling is a bottom-up approach that starts by predicting the expected physical performance of a system under a range of probable intensity levels and then translating physical damage into economic losses or some other consequence of interest. These models are also referred to as engineering-based, physics-based, or mechanistic models. Analytical models can be used to project damage to new classes of exposure for which claims data are limited or non-existent and can be exercised across a full range hazard intensity levels and uncertainties. Other benefits of analytical models are that they can be: (1) validated in terms of both physical damage and economic loss, (2) used to understand the causes of loss, and (3) used to explicitly model the combined effects of multiple "secondary modifiers" (e.g., shutters, hurricane straps, roof shape, roof deck strength, etc.) that interact in complex, non-linear ways. These complex effects cannot, in most cases, be accurately discerned from noisy claims data or predicted through expert opinion.

Expert judgment is typically used in cases where insufficient empirical data are available for fitting (e.g., at high hazard intensity levels or for less common or newer types of construction/occupancy) and analytical models are either unavailable or incomplete in terms of the loads, resistances, or failure modes that can be modelled. In practice, both empirical and analytical models will have elements of expert judgment embedded in them.

Wind sub-perils (i.e., wind pressures, windborne debris, falling trees, and wind-driven rain) are generally modelled together using a single vulnerability function for each insured risk. In the empirical approach, this combination is typically implicit because claims data sets rarely allocate wind losses to specific wind sub-perils. Analytical vulnerability functions, on the other hand, can be developed by explicitly evaluating each wind sub-peril. However, the final vulnerability functions and distributions must logically combine the wind sub-perils to ensure that losses are not double counted.

Storm surge includes two primary sub-perils: still water flooding and flooding combined with wave action. These two cases are often addressed using separate vulnerability functions that depend on the extent of wave action at the risk location for the event being evaluated. Accurate elevation information is, of course, critical for modelling of storm surge losses. For risks that do not have high-resolution geographic location information, some TCCMs require that the risk be distributed or "disaggregated" in order to compute storm surge losses. This involves distributing portions of the risk to multiple locations within the area of interest (e.g., a postal code) where structures are likely to be found. An alternate approach is to develop a distribution of hazard intensity that is appropriate for the area in which the risk is located.

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