5.1 A statistical-dynamical model for quantifying regional storm climates

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1. INTRODUCTION

While earthquakes and tropical hurricanes often receive considerably more media attention, mid-latitude winter storms are the cause of a considerable amount of damage. Indeed, some of the costliest events in modern history (in terms of insured losses) have been associated with frontal-wave cyclones over northwestern Europe. Costly winter storms have also occurred in North America, the infamous “Storm of the Century” (March 1993) being just one example.

The winds associated with winter storms over Europe can be particularly severe. The intensity of these storms and the destruction they bring make them particularly important to those insurers and re-insurers whose portfolios include those regions affected. Over just the last 15 years, the nine most damaging storms have resulted in over $28 billion (USD) of insured losses. Two storms that occurred in late December 1999 (Lothar and Martin) caused insured losses of nearly $8 billion. Concern for the potential economic cost from these storms to the European Community has provided justification for increasing research and field studies in hopes of improving the ability to forecast these extreme events (e.g., Joly, et. al, 1997; Goyette, et. al, 2000).

The insurance industry is not only interested in the intensity of such storms, but also in the frequency with which they occur. Since robust and dependable observations extend back just over 50 years, it can be a challenge to estimate with what frequency damaging winds will occur for longer “return periods” of 100 or 500 years. The risk of enormous insured losses provides the motivation to characterize the regional extreme wind climate over Europe as realistically as possible.

Traditional actuarial methods usually require large, accurate historical data sets that are non-existent for weather-related catastrophes. In response, computer-based natural catastrophe (CAT) models began to be developed in the late 1980s. The first CAT model using a natural hazard basis estimated insured losses resulting from hurricanes making landfall on the US coast. It was not until after Hurricane Andrew in 1992 that they began to become widely used.

A regional "storm-climate" model has been developed as an integration of the NCAR-NCEP Global Reanalysis Model (GRM) data set and the 5th generation NCAR - Penn State University mesoscale model (MM5). In its statistical-dynamical (or Monte Carlo based ensemble) implementation, this model produces realistic return-period profiles when compared with other extreme event metrics.

Once we understand the nature of extreme wind events, we can apply structural engineering models to estimate monetary losses associated with such events for all regions affected. This process can be applied to historical storms for verification purposes, for real-time losses, and to profile the financial vulnerability to potential future extreme windstorms. These economic vulnerability profiles provide another constraint

2. MODEL SYSTEM DESIGN

As of the time that this paper was written, the model was still being implemented for North America, thus specifics in the following discussion will relate to the extreme wind climate over northwestern Europe. The basic approach we have used is to create a regional windstorm climate model for mid-latitude winter storms through the application of numerical weather prediction (NWP) modeling technology. First, using a sophisticated mesoscale NWP model we obtain high-resolution information about storm structure and evolution. Second, we apply a stochastic Monte-Carlo ensemble technique (e.g., Berliner, 2001) to extend the reanalysis wind climate to 10,000 virtual years. This allows us to include extreme events that occur with return periods of 10, 50, 100 years and more.

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2.1 *Event Generation Model*

Using Numerical Weather Prediction (NWP) technology, we can more accurately depict the time-dependent three-dimensional structure extratropical cyclones and the damaging winds and precipitation associated with these storms. NWP technology represents a major advance over the conventional approach many catastrophe modelers have taken in the past and still use today. Traditionally, simple highly parameterized “engineering models” have attempted to model the wind footprints left by such storms using simple relationships between central pressure, storm track, and the wind field. Engineering models can be a practical tool for symmetric storms (e.g., tropical cyclones), but are inadequate for more spatially complex mid-latitude frontal cyclone systems (Figure. 1).

Given the initial three-dimensional state of the atmosphere, NWP models are designed to predict its evolution in time. Since we are concerned with how it varies in both space and time, these are often referred to as “state-of-the-atmosphere variables” (SAVs). In practice, SAVs are environmental data that may include air pressure, air and sea surface temperature, moisture and wind. The process begins with an initial three-dimensional field of these SAVs, that is, an initial “snapshot” of the three-dimensional atmospheric structure. This three-dimensional atmospheric structure of field, defined by these SAVs, is moved forward in time through the application of the set of partial differential equations governing fluid flow. These equations are referred to as the Navier-Stokes, or “primitive” equations, and have as their basis the law of conservation of momentum, mass and energy.

Global reanalysis models (GRMs) are data-assimilation NWP models that provide an accurate and internally consistent source of data. These data sets have been exploited to address numerous meteorological and hydrological problems. For example, Klawa (2001) was able to demonstrate that extreme windstorms in Europe have extreme baroclinicity and extraordinarily high equivalent potential temperature using GRM data.

While there are several global data-assimilation climate models, perhaps the best known is that of the National Center for Atmospheric Research (NCAR) and NCEP. (Kistler, et al., 2001). One motivation for the global reanalysis project is to use a single data assimilation technique and archived data to produce the most accurate and statistically stationary record of the atmosphere possible. Other GRM projects include those at the European Centre for Medium-Range Weather Forecasts (ECMWF) and NASA Goddard.

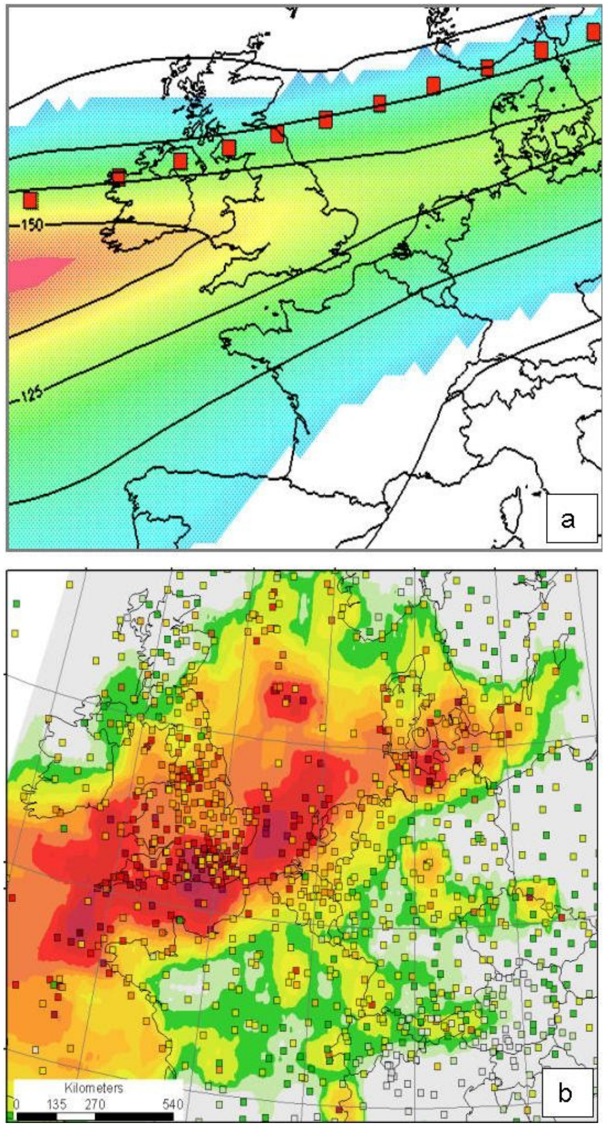

Figure 1. Maximum wind speed footprints for the 1990 windstorm Daria over the 36-hour period from January 25 12Z to 27 00Z using a traditional engineering model (a) and an NWP model b). In panel (a), the wind intensity field is estimated using the storm track (red squares) and the storms central pressure over the lifetime of the storm.

Damaging surface winds and precipitation are associated with coherent mesoscale substructures of vigorous frontal-wave cyclone systems. Our goal in using NWP modeling technology is to “downscale” these systems, as originally resolved in the GRM data set, to a sufficiently high resolution that the features important to the strongest surface winds can be accurately determined. We have selected MM5 as the NWP technology to downscale severe winter storms. MM5 is initialized and bounded by GRM data from 1958 through 1997 for each 36-hour period that includes at least one strong mid-latitude winter-season windstorm passing over Europe. We set the criterion defining such an event as the occurrence of a wind speed of at least 20m/s at the 10-m level as resolved by the GRM data set. The manually intensive process of creating a 40-year "storm catalog" reveals a total of 1037 such storms. In this context, we use the GRM data as a proxy for a coupled global climate model.

2.2 *Creating the Regional Storm-Climate*

Regional climate models (RCMs) are NWP models that are nested in global-scale models. Since RCMs are run at a higher resolution than global scale models, they can be effective in determining statistics for smaller scale phenomena. This is often referred to as "down scaling". RCM applications have been developed to downscale both prognostic and global data-assimilation climate models. The application discussed here will involve the latter case in order to enhance the hazard component of a stochastic Catastrophe (CAT) model (Figure 2).

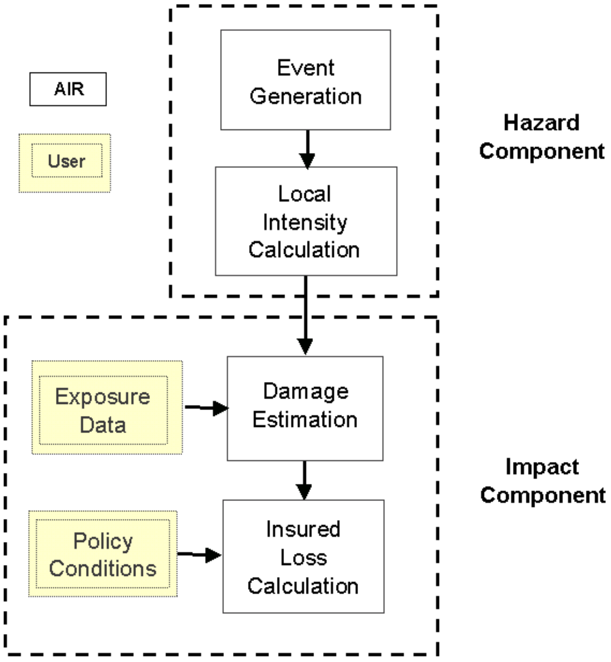

Figure 2. The CAT model loss estimation process.

A surface gust parameterization has been developed based on the isallobaric component of the ageostrophic wind induced by MM5's modeled surface pressure tendency field. This parameterization has also been adapted to include a Monte-Carlo ensemble technique through small random phase and amplitude perturbations of MM5's pressure tendency field. This approach is intended to deal with phase and amplitude errors in both the model and the observations.

Data from the global reanalysis model can then be used to produce "canonical ensembles" of windstorms caused frontal cyclones affecting the European region. Canonical ensembles are families of events spawned from historical storms having similar, specific characteristics. The canonical storm events "captured" in the assimilation model process reflect the storm environment in this region over the past few decades (Figure 3). Slight perturbations in the state-of-the-atmosphere variables at the time of these events can change the trajectory of development significantly.

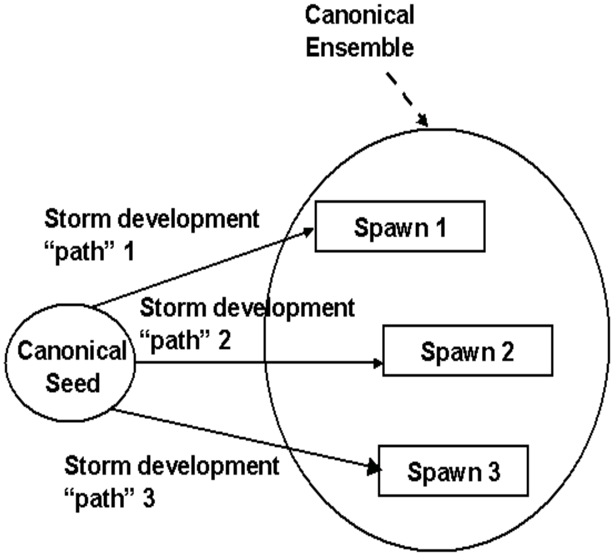

Figure 3. Schematic illustrating the canonical ensemble generation process.

A large ensemble of storm events (many thousands) can be generated, some of which will be stronger and others less strong than the historic seed events originally captured in the global reanalysis model data (Figure 4). Very large ensembles are practical because they need not be created in real time.

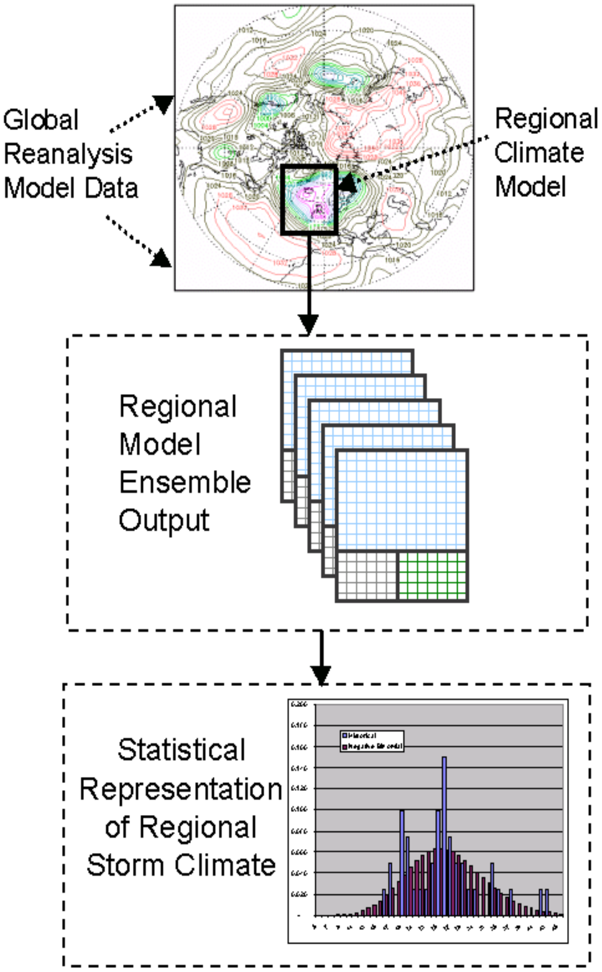

Figure 4. Schematic showing how statistics of the regional storm climate, downscaled by MM5, of the global reanalysis model data set can be extended.

3. MODEL VERIFICATION

As of the time that this paper was written most evaluation and verification has been for extreme wind climate over northwestern Europe. The discussion that follows in the next two sections refers to the verification of the modeling of European regional storm-wind climate.

3.1 *Individual Events*

We have verified our implementation and calibrated the technique of refining the surface wind field for a number of storms over Europe. Here, we provide one example.

Figure 5 shows time series of modeled wind speeds for a large 251-member canonical ensemble for Lothar (one of the catastrophic European windstorms of December 1999) and wind speeds observed at three sites near Paris. Note the differences in these observations despite their close proximity. There is generally good agreement, however, in the timing of the strongest isallobaric "pulse" of ageostrophic wind for all locations that occurred roughly 20 hours into the simulation.

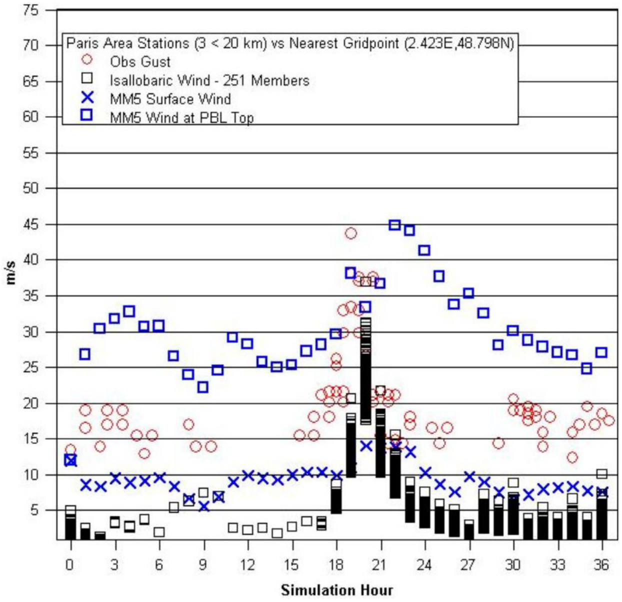

Figure 5. Time series for 251-member ensemble of modeled surface wind speed during Lothar (12Z 25 - 00Z 27 December 1999) and observed for three locations near Paris, France. Observations (METARs) are available every half-hour.

Given the nature of sensors, it is not straightforward in the case of extreme windstorm events to compare observations with model output. Sensor observations are at specific sites and their measurements reflect sensor type, averaging time, sampling rate, etc. While there are official standards, in practice there can be significant differences from country to country and between different sensor networks within countries. Observations also reflect the sensor's electrical signal model that converts it from a volts to m/s. Furthermore, NWP-modeled wind speeds are representative of a grid cell area of a few tens of km and averaging times related to the fundamental time-step that the model uses, typically several minutes. On the other hand, the upwind footprint for an observed wind could be only a hundred meters. Thus, the value that is reported is more likely to be either significantly too high or too low, and not generally representative over the area of concern. Because of these fundamental differences, it is only possible to say to what degree modeled wind speeds are consistent with observations.

Once a representation of the time dependent behavior for an event is obtained, this information can be used as input to an impact model to estimate damages and losses dependent upon insured exposures. Figure 6 shows for Lothar the modeled maximum wind-speed footprint (a), and the corresponding distribution of insured losses in terms of the industry-wide total (b). The path of strongest winds for this storm passed through northern France and southern Germany. The model shows a region of intense winds over the boundary of France and Switzerland, indicative of the interaction of Lothar with the Alps. Industry wide insured losses provide another form of verification. For Lothar, the modeled losses were approximately $6 B, quite close to those reported.

3.2 ***Regional Storm Climate***

Verifying the regional storm climate is less straightforward: how can one verify average maximum return period wind for periods significantly beyond 10 years? To address this issue it is possible to statistically extrapolate the average maximum return period wind for longer periods by applying extreme value (EV) statistical techniques. A number of these EV statistical techniques have been calibrated and tested using long-term wind observations taken at Ris∅ Laboratory near Copenhagen, Denmark. Using observed maximum winds EV statistical techniques make it possible to estimate average maximum return periods well beyond ten years (annual-occurrence probabilities less than 0.10) and their corresponding uncertainties.

Similar techniques can be applied to NWP model grid point data set for more complete spatial and temporal coverage. To obtain the same for a larger European region, we have applied EV-statistical extrapolation techniques to the reanalysis data set. In this analysis we used the 40-years defining the 1037 seed storms, treating each six-hour sampled wind speed at each grid point as an observation.

Figure 7 shows the 10-year average maximum return-period winds based on the 10k-year European windstorm model stochastic event set (a) and that "expected" as extrapolated from the reanalysis data using EV statistics (b). An adjustment factor of 1.4 was applied to the 10-m, 10-min average surface wind of the reanalysis data to approximate the 3-s engineering-gust values used in the damage calculations.

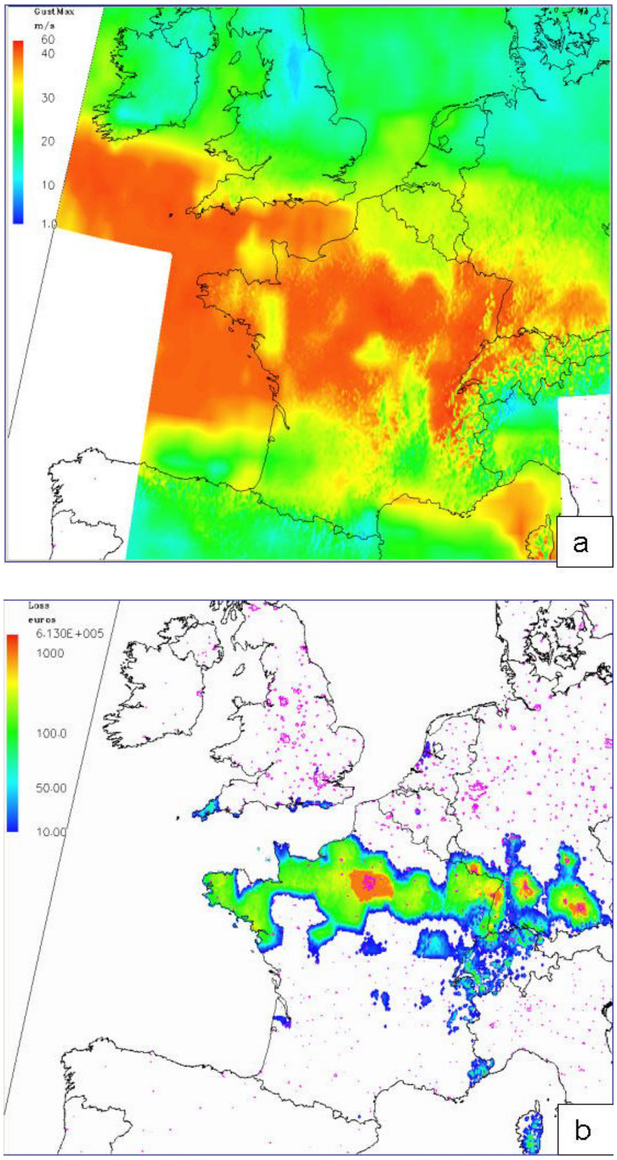

Figure 6. The modeled maximum wind-speed footprint (a), and the corresponding distribution of total industry-wide loss (b), for Lothar 12Z 25 - 00Z 27 December 1999.

Except for artifacts in the field related to the differences between the reanalysis and MM5 land-sea mask, other differences should be expected. Some of the more obvious ones being the six versus one-hour sampling rate and the effect of spatial averaging over a grid scale of more than 200 km for the reanalysis compared to 30 km for the MM5 model output. Consistent with these differences, the discrepancies between the reanalysis and MM5/StormSim results become larger for longer return-periods; that is, more intense events with stronger winds would tend to have smaller footprints with sharper peak amplitudes.

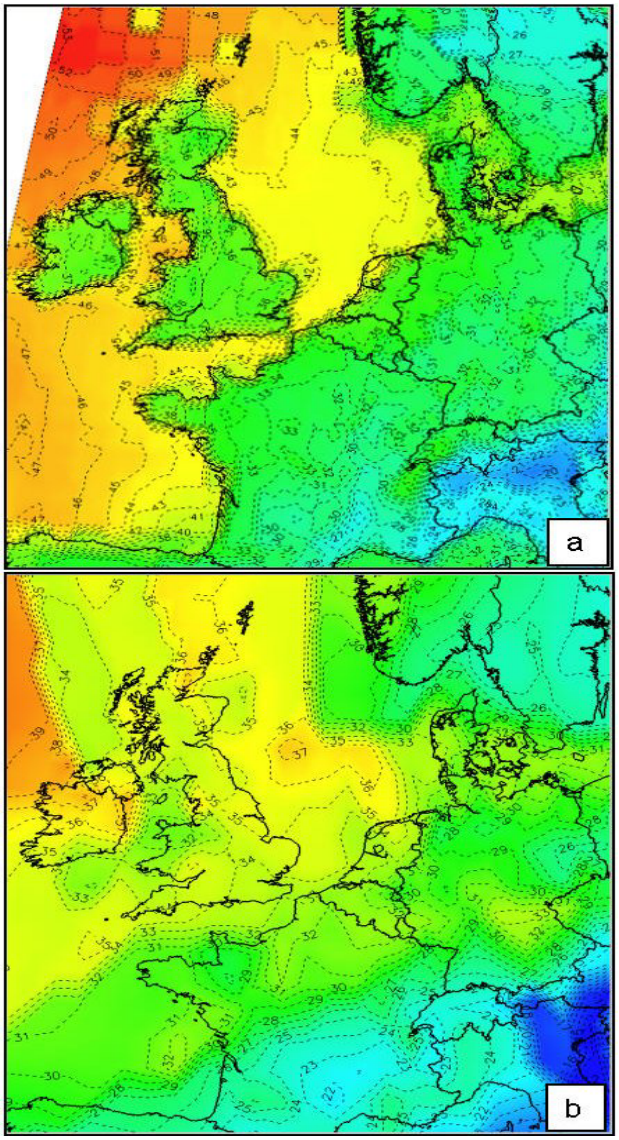

Figure 7. The average maximum 10 year return-period wind field based on the10k-year regional storm-wind climate stochastic event set (a) and that using EV statistical theory applied to the GRM data set.

Figure 8 shows a comparison of average maximum 3-s engineering-gust return period profiles over central Denmark using two EV statistics methods applied to 70-m tower observations (Abild and Nielson, 1991). A crude adjustment of 0.85 was applied to remove the systematic difference between the 70-m gust observations and the modeled 10-m 3-s engineering-gusts. Also shown is the return period profile for the regional storm-climate model at a grid point in central Denmark.

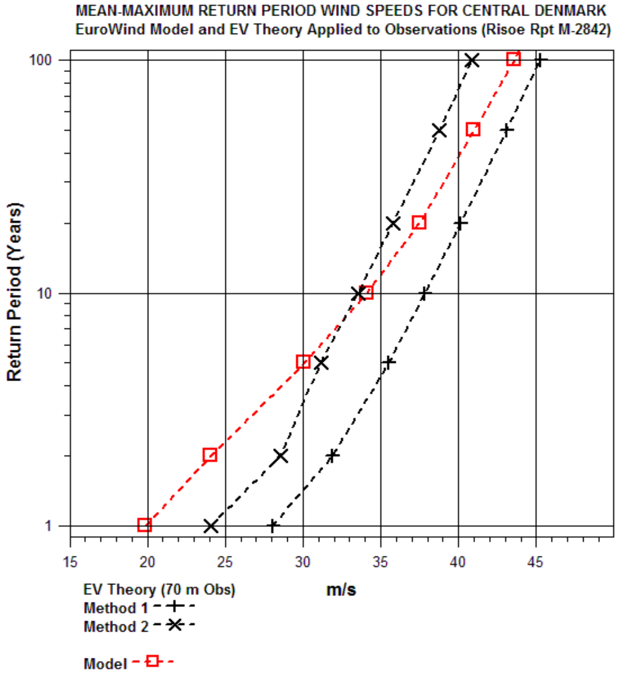

Figure 8. Comparison of average maximum 3-s engineering-gust return period profiles over central Denmark using two EV statistics methods applied to 70-m tower observations.

Differences between the EV methods are a reflection of theoretical uncertainty of the models. There is additional uncertainty in the theoretical profiles resulting from the observation sample size of about 2 to 4 % (1 to 2 m/s). It can be seen that for return periods greater than ten years, the return profile for the modeled surface gusts (10 m) lies within the theoretical profiles of the two EV methods. The low bias for shorter return periods should be expected for two reasons. First because the stronger the wind at the surface (10 m), the more it reflects the 70 m value because of vertical momentum transport resulting from turbulent mixing. The 0.85 correction can only remove the average bias. The second reason is that the smaller the wind speed the shorter the upwind footprint of the observation will be, while the model "footprint" of the grid square remains unchanged.

4. SUMMARY

Applying NWP technology we have developed a regional storm-wind climate model for Northwest Europe that represents a major advance over the parameterized engineering hazard models many catastrophe modelers have used. This heart of the regional climate model-system comprises the integration of the NCAR/NCEP Global Reanalysis Project Model (GRM) data set and the well-established mesoscale model MM5. Using an implementation of a Monte Carlo ensemble NWP technique, called StormSim, we have simulated hundreds of seed storms and produced estimated winds associated with such storms.

We have performed extensive verification of winds observed during the most damaging historical storms. MM5 does an excellent job reproducing pressure tendency "pulses" responsible for the strongest surface winds. These features appear to be associated with fronts and atmospheric gravity waves having wavelengths on the order of 50 - 500 km. Both the overall structure of the simulated footprint and time series for observing stations match well with MM5 predicted winds.

The regional climate model allows us to define the storm-wind climate over northwestern Europe and characterize more realistically the spatial and temporal structures of potential future extreme windstorms. We can extend this extreme wind climate to periods longer than that covered by the NCAR/NCEP GRM data. This provides an alternative to extreme value statistical techniques that use site-specific surface observations, extending this information to areas where sensors have not existed. In the end, it is this information which is key to insurers and re-insurers assessing their portfolios' vulnerability to extreme mid-latitude storms.

5. REFERENCES

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