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Transmission Line Ice Accretion Modelling for New Zealand

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ABSTRACT

It is imperative to model the ice loads on transmission lines to understand when failures are likely to occur to avoid large economic losses and electricity supply instabilities. The combination of ice and wind loads can lead to large failures and there is a lack of both data and good quantitative estimates of these risks in New Zealand. Numerical modelling of the icing loads supplemented with meteorological data is the preferred approach due to the rarity of large icing events and increase in spatial resolution. The time-dependent Makkonen model is implemented to simulate the ice accretion on New Zealand's transmission lines for a storm on 19 June 2013, that resulted in damage in the upper South Island. Ice accumulation predictions were compared to modelling carried out by NIWA, which used a combination of the Sakamoto and Makkonen models. Similar values were obtained for the loads, but a direct comparison could not be made due to the difference in the modelling methodology.

1. Introduction

The modelling of atmospheric ice accretion on cables is essential in designing, planning, and constructing transmission line networks in ice prone regions. If networks are under-designed, the structural damage due to the combined ice and wind loads leads to considerable economic losses and electricity supply instability which at best could be inconvenient and worst lead to loss of life. On the other hand, if the structures were designed for unrealistically high ice loads, the construction cost will quickly increase. Therefore, it is vital to accurately estimate ice accretion and the maximum ice loads in different conditions to optimise the design of transmission line networks.

Two methods exist to obtain the expected ice loads on transmission line structures: statistical and numerical methods. Statistical modelling requires comprehensive databases of measured data, where significant icing events, used to define extreme loads, are rare. Additionally, icing events are complexly related to atmospheric and environmental parameters, leading to large amounts of spatial inconsistencies. These inconsistencies may distort probability distributions derived from measured values leading to low prediction accuracy. These disadvantages demonstrate the importance of the numerical modelling of ice accretion.

On top of that, there are two significant advantages of relying on numerical rather than statistical modelling. Firstly, meteorological data, which has a significantly broader spatial and temporal coverage than icing data, can be used as model inputs to improve the modelling resolution. Extreme value analysis (EVA) can also be applied to verified and validated models to obtain loads for higher return periods using numerical modelling.

A large amount of work has been carried out in the theoretical modelling of the ice accretion on structures from authors such as Imai, (1953) Goodwin *et al.* (1983), Chaine and Castonguay (1974), Sakamoto (2000), Makkonen (2000) and others, all with varying levels of accuracy. Through sensitivity analysis from Mitten *et al.* (1988), the Makkonen, (2000) model was found to be the most comprehensive for modelling ice accretion on transmission lines using atmospheric properties in moderate and extreme conditions.

This paper outlines the implementation of the Makkonen model, using atmospheric modelling data provided by National Institute of Water and Atmospheric Research (NIWA) from their numerical weather prediction (NWP) modelling software New Zealand Convective Scale Model (NZCSM). NZCSM is a 1.5 km grid spaced model which has its own microphysics schemes for forecasting rime and glaze icing which, distinct to the Makkonen model. The detailed formulation of the Makkonen ice accretion model, is omitted here but can be found in Makkonen, (2000). The assumptions used in adopting this model and preliminary results are outlined, pending validation.

2. Theory

Two different icing regimes affect the density and mass of growing ice: dry and wet. The sole driver between the two regimes is the thermodynamic conditions resulting in the system's heat transfer. For scenarios where there is a net heat gain into the system, a layer of liquid forms from the droplets on melted ice surfaces. Wet growth is when the liquid layer freezes, resulting in ice development. Examples of wet growth are glaze ice and wet snow. This occurs close to the melting temperature of the water, resulting in a very sensitive thermodynamic balance. However, for dry growth, the heat transfer can be neglected as the latent heat released during freezing of the droplets dissipates without altering the ice state (Makkonen, 2000). An example of dry growth is rime ice. The ice types typically modelled on transmission lines include rime, wet snow, and glaze ice. Although hoarfrost also forms on the lines, Makkonen, (2000) shows that the additional load is negligible due to the low density compared to other ice types.

The conditions under which the different accretion types will occur has been defined by Sundin and Makkonen, (1998) depending on the wet-bulb temperature.

- Glaze ice occurs when the wet-bulb temperature is less than 0 ℃, and it is raining.
- Rime occurs when the air temperature is less than 0 ℃, and there is fog surrounding the transmission lines, or the transmission lines are above the cloud base.
- Wet snow growth occurs when the wet-bulb temperature is above 0 ℃ and when heavy snowfall is present.

The rate of ice accretion is computed from Eq. (1)

$$\frac{dM}{dt} = \alpha_1 \alpha_2 \alpha_3 WVA \tag{1}$$

where W is the liquid water content (LWC) in the air, V is the average velocity of the impinging droplets and A is the frontal area of the cable. The three factors α_1, α_2 and α_3 are the collision, collection and accretion efficiencies, respectively, and are dependent on the properties of the flow and surrounding atmospheric conditions. Although it appears that higher impact velocities result in larger accretion, the model demonstrates lower accretion as the wind speed increases due to α_1, α_2 and α_3.

Collision Efficiency

The collision efficiency is related to the droplet trajectory around the transmission line. There are two main characteristics which determine this: the aerodynamic drag and the droplet inertia. When the droplets are small with low inertia, the drag dominates, resulting in their trajectories closely following the airflow streamlines. This reduces the number of impacting water particles on the transmission line, leading to a lower ice accumulation. However, inertia dominates for large droplets, resulting in more droplets colliding with the lines without substantial diversion. Finstad *et al.,* (1988) parameterised the collision efficiency using two dimensionless numbers: the Stokes number and the Langmuir number based on the droplet diameters. This parameterisation is based on potential flow streamlines around cylinders. For large droplets, such as those in snow or rain, the collision efficiency can be approximated as unity, as there is large droplet inertia (Makkonen, 2000).

Collection Efficiency

The collection efficiency is the proportion of the LWC in the air, which sticks to the transmission line surface. This factor is lower than unity when a portion of the droplets rebound off the surface instead of sticking. For the application to transmission lines, particles are considered to stick when they settle on the lines long enough to affect the heat transfer of the system, resulting in ice growth (Makkonen 2000). There is no current theoretical basis for the collection efficiency. However, Admirat and Sakamoto (1988) proposed an empirical formulation based on laboratory experiments and field observations, which is a function of wind speed only. This should only be used as a first approximation until theoretically sound models are available.

Accretion Efficiency

The accretion efficiency is the fraction of the LWC which freezes on the transmission line's surface. It relates the icing rate due to the impact of supercooled water droplets on the overall heat balance in the system (Makkonen, 2000). All the water droplets freeze on the object for dry growth and wet snow accretion (Makkonen, 1989), resulting in an accretion efficiency of unity. However, for freezing rain, the freezing rate is controlled by the rate which the latent heat released in the freezing process can be removed. A heat balance for the icing process is used to model the accretion efficiency, equating the latent heat of freezing to the sum of all other heat transfer mechanisms. A negative temperature gradient exists, leading to supercooling of the impinging droplets (Makkonen, 2000). The heat transfer mechanisms in the heat balance are the latent heat released during freezing, the convective heat loss due to the temperature difference between the cable surface and the air, the heat loss due to convective mass transfer, long-wave radiation and the heat loss in the warming of the supercooled droplets to freezing temperature (Makkonen, 2000).

Icicles

In previous ice accretion models, icicle growth was neglected as it was thought that they only grow from the freezing of the run-off water from the rest of the accretion. This means that the overall heat balance of the object was used to model the accretion (Goodwin et al. 1983). However, recent numerical studies have shown that the total load may be significantly greater when icicles are present than without them (Makkonen, 2000). This means that the growth of icicles must be modelled, although these icing events are rare.

Analogous to accretion efficiency, icicle growth is controlled by the amount of latent heat removed from the surface during freezing. Therefore, a similar heat balance can be conducted on the icicle surface with the dominating mechanisms being convective heat loss and heat loss from the convective mass transfer. The radiation and conduction heat transfer mechanisms are small, with the conduction term being neglected (Makkonen, 2000).

Implementation

The Makkonen model must be solved numerically due to the time-dependent nature of atmospheric properties and ice thickness. At every timestep, the transmission line dimensions change due to mass accumulation, which changes the collision and accretion efficiencies. Therefore, the complete model needs to be recalculated at every timestep with the accumulated mass and equivalent diameter. The different icing regime densities can be calculated from the various expressions proposed by Admirat (2008) and Makkonen and Stallabrass (1984).

The Makkonen model has been implemented in MATLAB with atmospheric variables obtained from NZCSM to allow for direct simulation. The spatial and temporal resolutions for the NZCSM data are 1.5 km x 1.5 km and 15 minutes, respectively. The storm case has been simulated for 36 hours in total, while operational NZCSM simulations are run for 48 hours. It is assumed that the atmospheric properties are held constant for the entire time step. The mass accumulation is calculated at the end of every 15-minute timestep resulting in the model being resolved in the same temporal resolution. There will be slight changes in the mass accumulation if the timestep between re-solving the model was reduced, even with unchanged atmospheric conditions. The model was implemented assuming the wind was always perpendicular to the line, as preliminary runs were applied on a mesoscale where the line orientation is mostly unknown. This will result in slightly larger values. Based on the laboratory observations of Poots (1996), the average droplet size for rime icing was taken as 10 µm, and for glaze icing was taken as 100 µm. However, further refinements can be applied using droplet size distribution models such as the Marshall-Palmer distribution. The median volume diameter (MVD) of the droplets can represent the entire distribution (Finstad *et al.*, 1988).

3. Preliminary Results and Discussion

An illustrative snowstorm case used for the simulation was on 19 June 2013 and was provided by NIWA. The modelled weather system is shown in Figure 1, with the mean wind speed at 10 m above ground level (agl) and sea level pressure contours (hPa) plotted.

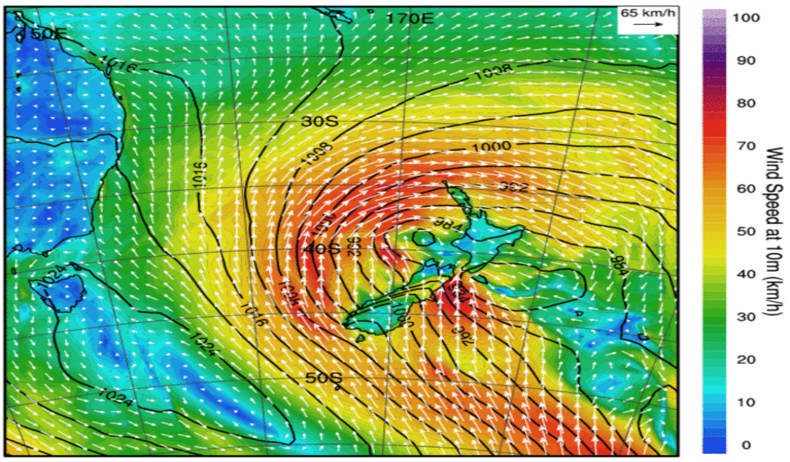

Figure 2. 1.5 km resolution NZCSM output for 19 June 2013 showing mean wind speeds at 10 m agl and sea level pressure contours (hPa)

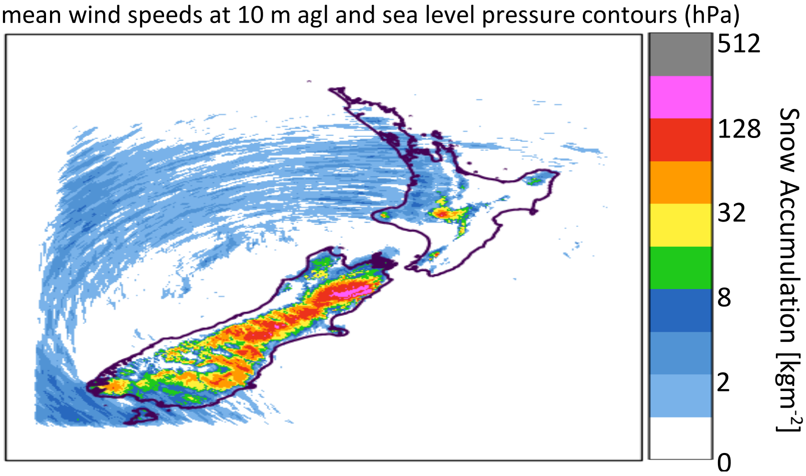

Figure 1: 1.5 km resolution NZCSM output for 19 June 2013 showing total snow accumulation over the 36 hours simulated

The total ground-level snow accumulation is shown in Figure 2. There is a weak correlation between snowfall and ice accretion due to similar atmospheric properties. The initial results from the ice accretion modelling are shown in Figure 3. The New Zealand transmission line network is overlaid in red, and the **location of interest** at the top of the South Island is shown with a yellow dot.

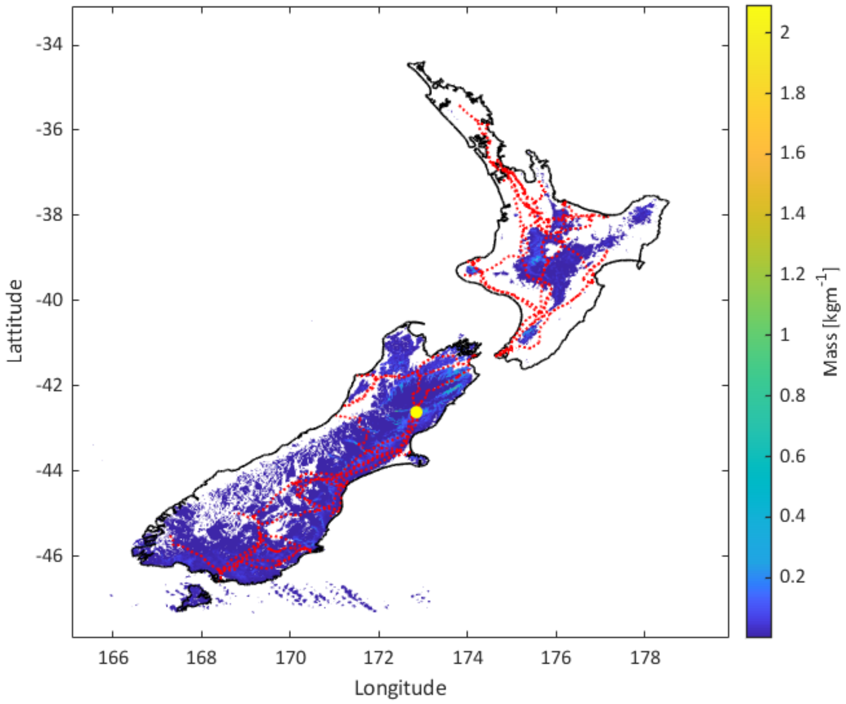

Figure 3. Preliminary ice accretion on the New Zealand transmission line network for the storm of 19 June 2013. The location of interest is shown with a yellow dot

A significant portion of the ice accretion forms in the South Island and consists of both wet and dry accretion. The wet accretion contributes to most of the mass, as a direct result of the snow accumulation. The amount of ice mass in grid points close to transmission lines is all lower than 0.15 kgm^{-1}, where the larger mass is in the Southern Alps and Central Plateau regions where minimal electrical lines exist. Currently, the spatial and temporal resolution of the NZCSM data does not allow for individual transmission lines to be modelled. Therefore, uniform icing profiles are assumed. The modelling provides a mesoscale overview about what ice loads are expected in a 1.5 km x 1.5 km grid which encompasses the lines.

Previous modelling was carried out by NIWA for the location of interest in the upper South Island which showed a combination of wet snow and rime ice accretion on a section of transmission line. The models used were Sakamoto, (2000) for wet snow and Makkonen, (2000) for rime icing. The cumulative ice loads calculated were between 0.133 – 0.296 kgm^{-1}, whereas the Makkonen model predicts between 0.06 – 0.11 kgm^{-1} in the surrounding grid points. Direct comparison between the different methods is not valid due to the uncertainties surrounding the collection efficiency. A sensitivity analysis was conducted by NIWA, while the Makkonen model uses formulations from Finstad *et al.,* (1988). Additionally, the collection efficiency was assumed as unity in NIWA's modelling which is only valid in the Makkonen model if wind speeds were 1 ms^{-1} or lower.

It is important to note that the Makkonen model predicts small amounts of glaze ice which was not observed during the storm. This is due to the atmospheric conditions being suitable for the growth of glaze but realistically the small amount modelled would have been dispersed by the wind. Although the snow accumulation at ground level is quite high, the amount which sticks to the cables is still very low, due to the wet bulb temperature being below 0 °C for a large portion of the storm. The wet-bulb temperature must exceed 0 °C for the LWC in the snow to be high enough to stick to the cables instead of bouncing off.

4. Conclusions

The modelling of ice accretion on transmission lines is critical to ensure that the structural components are strong enough to withstand the additional loading from the added mass of ice and increase wind loads. The Makkonen model has proven to be very comprehensive concerning calculating the expected ice accretion on transmission lines. The fundamental principles behind the Makkonen model have been explained in detail and have been implemented in MATLAB to be used to model ice accretion in New Zealand. NIWA had provided meteorological data from NZCSM for a snowstorm that occurred on 19 June 2013, and the Makkonen-modelled ice accretion has been compared to the earlier NIWA estimates. Due to the uncertainty surrounding the collision efficiency, the exact measurements cannot be compared directly. However, the ice load in the location of interest from the Makkonen model is approximately 0.06 – 0.11 kgm^{-1}, whereas the previously calculated values (from NIWA) were between 0.133 – 0.296 kgm^{-1}. Further investigation is needed to validate the assumptions and modelling inputs .

5. Acknowledgements

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