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Vertical variation of ice loads from freezing rain

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ABSTRACT

Ice that accumulates on structures during a freezing rain storm can impose significant loads. The design of open structures, including power transmission lines and communication towers, takes into account the vertical load imposed on the structure by the weight of the ice and the horizontal load imposed from the wind drag on the ice-covered structural components. The increase in wind speed with height above ground in the boundary layer increases the horizontal flux of drops of water to the structure, resulting in an increase in ice load with height above ground. This paper evaluates the additional effect of the evaporation of precipitation in the cold air layer at the surface on the vertical variation in the accreted ice load on tall communication towers and masts. The results show that ice thickness increases over the height of the tallest towers, enhancing the thickness increase from the wind speed gradient in the boundary layer. The magnitude of the effect depends on the assumed rain drop distribution. The evaporation-enhanced ice thickness profiles based on data from freezing rain storms at nine weather stations in the United States can be approximated by a power law.

1. Introduction

Ice that accumulates on structures during a freezing rain storm can impose significant loads. The design of open structures, including power transmission lines and communication towers, takes into account the vertical load imposed on the structure by the weight of the ice and the horizontal load imposed from the wind drag on the ice-covered structural components (e.g. ASCE, 2010a,b; TIA, 2014). The increase in wind speed with height above ground in the boundary layer increases the horizontal flux of drops of freezing rain to the structure, resulting in an increase in ice thickness with height above ground. In the United States, the magnitude of that effect is provided as a height factor on ice thickness from freezing rain in the Ice Loads chapter of ASCE Standard 7 (ASCE, 2010a). Note that there are many other national standards, as well as international standards, and they may have different provisions for the vertical variation in the thickness of ice from freezing rain. The ISO Standards (ISO, 2017) 12494 and 2394 (ISO, 2015) apply to the atmospheric icing of a variety of structure types. This paper evaluates the additional effect of the evaporation of precipitation in the cold air layer at the surface on the vertical variation in the accreted ice load on tall communication towers and masts.

2. Background

Freezing rain occurs when there is a layer of subfreezing air at the earth's surface with an overriding layer of warm, moist air. Any precipitation that is liquid at the bottom of the warm air supercools and remains liquid as it falls through the subfreezing air below. When the drops collide with an object such as a tree branch or a power line or a component of a lattice tower, they freeze if the latent heat of fusion is removed, typically by convective and evaporative cooling, before the accumulated water drips off the object.

A simple model for the accretion of ice from freezing rain on a horizontal cylinder with axis perpendicular to the wind direction is provided in Jones (1998). That model is conservative, that is, it assumes that all the impinging precipitation freezes. It also assumes that the water freezes in a uniform layer of thickness t around the cylinder so that the cross section remains round. The accreted ice thickness is

$$t\,[\mathrm{cm}] = \frac{1}{\rho_i \pi} \sum_{j=1}^{N} [(0.1 P_j \rho_w)^2 + (0.36 V_j W_j)^2]^{1/2} \tag{1}$$

where $P[\mathrm{mm\,h^{-1}}]$ is the precipitation rate, $W[\mathrm{g\,m^{-3}}]$ is the water content of the rain-filled air, and $V[\mathrm{m\,s^{-1}}]$ is the wind speed in each hour j of the freezing rain storm lasting N hours. The densities $[\mathrm{g\,cm^{-3}}]$ of water and ice are ρ_w and ρ_i, respectively. The first term in Eq. (1) is the vertical flux of water from the falling rain and the second term is the horizontal flux from the wind-blown rain. The factor $1/\pi$ spreads the water intercepted by the diameter of the cylinder over its circumference. The water expands as it freezes, given by the ratio ρ_w/ρ_i. This basic model, in which all the precipitation intercepted by the diameter of a cylinder is frozen as a uniform layer around the

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circumference, has a long history. Fowle (1910) presented it using only the falling rain term. Goodwin et al. (1983) added a wind-blown rain term, which required the user to specify the fall speed of the rain drops. In the same conference proceedings Stallabrass (1983) related W to P using Best (1950) to come up with test conditions appropriate for freezing rain. The Jones (1998) formulation expresses wind-blown rain in terms of the water content of the rain-filled air, using the Best (1950) relationship between water content and precipitation rate.

Commonly used expressions for the volume of water in the air $W_{\mathrm{vol}}[\mathrm{mm}^3\ \mathrm{m}^{-3}]$ as a function of the precipitation rate are given by Best (1950) and Marshall and Palmer (1948)

$$\text{Best:} W_{vol} = 67P^{0.846}$$
$$\text{Marshall-Palmer: } W_{vol} = 72P^{0.88}, \quad (2)$$

with $W = 10^{-3}W_{vol}$. Best's formulation includes the measurements underlying the Marshall-Palmer distribution along with those from many other researchers.

The ice mass m_i per unit length of the cylinder can be calculated from the cylinder diameter D_c, ice thickness, and ice density:

$$m_i = \rho_i \pi (D_c t + t^2) \quad (3)$$

Thus for large ice-thickness-to-diameter ratios the ice load is proportional to the square of the ice thickness and for small ratios the relationship is linear. For a given ice thickness the ice load increases with cylinder diameter. The calculation of ice loads on structural shapes with cross sections that are not round is specified in ASCE Standard 7 (ASCE, 2010a) based Jones and Peabody (2006).

For tall structures, the increase in the ice thickness associated with the increase in wind speed with height above ground can be calculated assuming a power law wind profile. In the United States, communication towers and masts can be up to 2000 ft (610 m) tall, as specified in a policy imposed by the FCC and FAA soon after a 2063 ft tall mast was built in North Dakota in 1963 (Wikipedia, 2017). The evaporation of raindrops as they fall through the cold air layer would cause both P and W to decrease with decreasing height z, enhancing the vertical variation in ice load caused by the increase in wind speed with height.

How much the evaporation of the raindrops reduces P and W depends in part on how thick the layer of subfreezing air is in freezing rain storms. In a study of ice storms in the Southeastern United States, Young (1978) obtained soundings data from 43 radiosonde locations between the end of December and the end of February in the years from 1968 through 1977 during times with winter precipitation. While his study focused on the Southeast, 32 of the radiosonde locations are in other regions of the country, so the results are not limited to the southeastern states. For 48 soundings with freezing rain reported in the surface observations and an additional 21 with freezing drizzle reported, Young extracted from the sonde data the height of the top of the cold air layer, defined as the first crossing of the 0 °C isotherm. Sorting these n values in increasing order and assigning the probability of nonexceedance as rank/$(n + 1)$ provides distributions of the depth of the cold air layer (Fig. 1). For both freezing rain and drizzle 25% of the cold air layer depths are less than 520 m and 25% are more than 920 m with a median depth of 690 m.

In Section 3 we use the Pruppacher and Klett (1980) formulation for the evaporation of precipitation drops to determine the variation in drop size with height above ground level (agl) in the cold air layer. The decreasing fall speed of evaporating drops is calculated using Beard (1976). In Section 4 we determine the effect of evaporation on the Best and Marshall-Palmer raindrop distributions. We use data from nine weather stations in the United States to quantify the vertical variation in accreted ice thickness in Section 5 and determine the range of ice thickness profiles. Section 6 is discussion and conclusions.

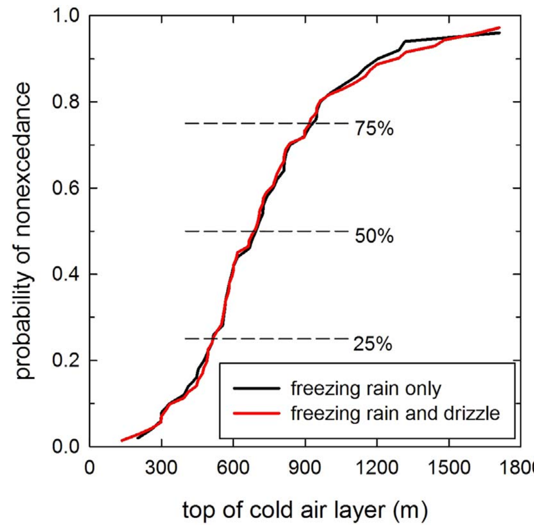

Fig. 1. Depth of cold air layer in freezing rain and freezing drizzle, using data from Young (1978). The median depth is 690 m.

3. Evaporation of raindrops

The equations governing the evaporation of raindrops are presented in chapter 13 of Pruppacher and Klett (1980). Their formulation is repeated here, collecting equations from various portions of that chapter and others that are necessary to compute the decrease in mass of a raindrop as it falls.

The rate of evaporation of a raindrop of radius a in the cold air layer at the surface is given by

$$a\frac{da}{dt} = -\frac{D_v M_w}{\rho_w R} f_v \left(\frac{e_a}{T_a + T_K} - \frac{e_\infty}{T_\infty + T_K} \right) \quad (4)$$

Symbols are defined in List of symbols and acronyms and temperatures are in °C. The saturation vapor pressure $e_{\infty,sat}$ and the vapor pressure at the dew point temperature e_∞ are calculated using

$$e = 6.11x10^{\frac{7.5T}{237.3+T}} \quad (5)$$

(National Weather Service, 2017) with $T = T_\infty$ and $T = T_{\infty,d}$, respectively. At the surface, the air temperature is T_0 and the dew point temperature is $T_{0,d}$. For a lapse rate L the temperature decreases with height agl resulting in an air temperature profile given by

$$T_\infty(z) = T_0 - Lz \quad (6)$$

We assume that the dew point depression $T_{dd} = T_0 - T_{0,d}$ remains constant through the depth of the cold air layer so that

$$T_{\infty,d} = T_\infty - T_{dd} \quad (7)$$

The saturation vapor pressure at the drop radius at temperature T_a taking into account the curvature of the drop is

$$e_a(T_a) = e_{\infty,sat}(T_\infty) \exp\left[\frac{L_e M_w}{R} \frac{T_a - T_\infty}{(T_a + T_K)(T_\infty + T_K)} \right] \exp\left(\frac{2M_w \sigma}{\rho_w R a (T_a + T_K)} \right) \quad (8)$$

The temperature at the drop is

$$T_a = T_\infty - L_e \frac{D_v M_w}{k_a R} \frac{f_v}{f_h} \left(\frac{e_a}{T_a + T_K} - \frac{e_\infty}{T_\infty + T_K} \right). \quad (9)$$

Eqs. (8) and (9) are solved iteratively to determine T_a and e_a., which are then used in Eq. (4) to determine the change in drop radius. The drop ventilation coefficient for vapor f_v is a function of the Schmidt number and Reynolds number: