Cold Regions Science and Technology 120 (2015) 76–88

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Canadian icing envelopes near the surface and its impact on wind energy assessment

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ARTICLE INFO

Article history:
Received 2 February 2015
Received in revised form 22 August 2015
Accepted 4 September 2015
Available online 16 September 2015

Keywords:
Cloud microphysics
Reanalysis
Cloud icing
Design envelopes

ABSTRACT

The present study aims at producing localized near-surface icing envelopes that contribute to optimal designs of near-surface structures under icing conditions. For this purpose, the 99th percentiles of liquid water content and wind speed that correspond to low-level supercooled clouds are used. Near-surface icing events and cloud microphysics are explored using North American Regional Reanalysis during winter months (D–J–F), over 32 years. The investigation of the regional climatology of icing events involves 74 regional zones that cover Canada. For each zone, regional power loss of wind turbines under icing condition is estimated. The East and West coastal regions of the Hudson Bay demonstrate higher liquid cloud water of 0.4 g m^{-3}. The highest potential of wind is located in the West coast. The climatology of liquid water content around the Rocky Mountains manifests orographic condensation of the Pacific moisture transported toward the mountains. Within the range of temperatures [−15 °C to 0 °C], the near-surface results over Canada show that the monthly mean of wind speeds varies mostly between 4 m s^{-1} and 10 m s^{-1}, and the mean supercooled cloud water content decreases linearly from 0.3 g m^{-3} to 0.2 g m^{-3}, with decreasing temperature. The quantification of ice accumulation and the duration of icing events reveal that the West and the South of the Hudson Bay as well as the North of Manitoba and Ontario are exposed to extreme icing conditions, with a monthly accumulation that varies from 150 mm to 225 mm, and a monthly duration of icing events near 375 h. Over the region encompassing the Gaspe Peninsula, St. Lawrence River and New Brunswick the higher limit of wind speed varies around 15 m s^{-1}. The cloud water upper limit of 0.45 g m^{-3} occurs in December and January, and 0.3 g m^{-3} in February. With decreasing temperature these upper limits reach 0.1 g m^{-3} at −15 °C. The highest wind energy is located in the Canadian East Coast regions. The Canadian arctic is characterized mostly by lower wind energy and larger power degradation under icing conditions. The average of wind turbine power loss during winter months (D–J–F) under icing conditions varies throughout Canada and reaches its maximum of about 15% over North-East of Manitoba, South of the Hudson Bay and the North coast of Ontario.

1. Introduction

Design engineering aims at attaining the maximum extraction of energy from the wind turbines, which is 59.3% (Ganander and Ronsten, 2003; Maissan, 2001) and the minimum energy for the aircraft consumption (Fortin and Perron, 2009). In addition to icing risk exposure for wind turbines (Cattin et al., 2007), an aircraft is prevented from taking off in the presence of ice accumulation based on “clean wing concept”. Despite the de-icing procedure performed before the flight, over 25% of icing aircraft accidents are caused by ice accretion during the takeoff (Cole and Sand, 1991). Therefore, to ensure aviation safety, it is recommended to avoid all types of ice that occur near-surface level (Van Hengst and Boer, 1991).

Customizing the optimal geometry for icing conditions is more beneficial than the procedures of anti-icing and de-icing which consume more energy (Virk et al., 2012). Thereafter, under icing conditions, it is cost-effective for designers of wind turbines, aircraft and power transmission lines to take into account the governing meteorological variables and their climatological tendency. The Aircraft industry has benefited the most from the theoretical and experimental studies to regulate the design of structures in icing conditions. These studies have focused on the challenges posed by icing conditions, to establish operational limits (Lewis,1951). Later, motivated by environmental awareness and the economic demand, which is affected by a constant increase of the cost of earth's fossil fuel, wind turbines have increasingly emerged as a cost-effective alternative that operates on a harmless extraction of energy from nature. Comparably to the aircraft, wind

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http://dx.doi.org/10.1016/j.coldregions.2015.09.007
0165-232X/

turbines have not been spared the problems of icing. Cold regions represent a profitable environment for wind energy. Consequently, it is expected for wind turbines to operate under icing conditions. In addition to production loss, iced blades require costly maintenance. The operating efficiency of wind turbines under icing conditions is controlled by various meteorological and geometrical factors (e.g. Lamraoui et al., 2013; Lamraoui et al., 2015).

For ice rate meter, power transmission lines, aircraft and wind turbines, the amount of accreted ice is controlled by the relative wind speed, the supercooled liquid water content and the collection efficiency which is implicitly affected by surface geometry and droplet sizes. Under favorable icing conditions, sharper edges collect more ice (e.g. Lamraoui et al., 2014). Therefore, it is necessary to examine the geometries of key components and evaluate the power loss for different droplets/ice particle sizes. Concise determination of the critical droplet size enables the precise identification of the hazardous regions within the cloud. In addition, wind turbines experience power loss caused by the processes of wet and dry riming (e.g. Messinger,1953; Lamraoui et al., 2014) and an aerodynamic degradation which is subject to the type of accreted ice, freezing fraction and object geometry (Lamraoui et al., 2014).

Regarding aircraft icing probabilities over ocean areas based on the collection of cloud icing data, Perkins et al. (1957) used icing-to-cloud ratio which is a statistical estimation of the conditional probability of icing when clouds are known to be present. This statistical study of Perkins et al. (1957) showed that within subfreezing clouds the ice accretion decreases with decreasing temperature until its minimum of 0% of approximately −40 °C. These results corroborate the fact that toward colder temperatures at higher altitudes, the subfreezing clouds are mainly composed of ice particles rather than supercooled liquid droplets (Feigelson, 1978; Mazin, 1995). Regardless of the type of physical and dynamical processes involved in the formation of clouds, it remains an important contributor to climate change and general atmosphere circulation (Gultepe and Isaac, 1997). Since clouds are crucial for localizing hazardous hydrometeors, their structure is highly dependent on the profiles of ice and liquid water content in the atmosphere. The total cloud water content ($TCWC = LWC + IWC$) is an important cloud microphysical parameter (King et al., 1978; Mazin, 1995) that determines the type of clouds. This parameter is controlled by the cloud droplet number concentration (Gultepe and Isaac, 2004), and the cloud droplet/particle size distribution (Wallace and Hobbs, 2006).

Due to its significance, numerous studies (Feigelson, 1978; Gultepe and Isaac, 1997) have previously addressed the relationship of liquid-water-content/Temperature (LWC–T). Gultepe and Isaac (1997) have utilized a dataset of liquid water content at temperatures between of −30 °C and 25 °C which is subsequently subdivided in bins of 5 °C. Similarly, Mazin (1995) has utilized a subdivision of 5 °C for a colder range of temperatures between −50 °C and 5 °C, in order to represent cumulative frequencies of total cloud water content occurrences.

According to Lewis (1969), the “Probable maximum” represents the 99th percentile values. These values have been recognized as relevant for civil designing (Jeck, 2002). Also, the size of supercooled cloud droplets can significantly affect the collection efficiency, conforming to the streamlines of air flow, and consequently the amount of accumulated ice (Lamraoui et al., 2014). Further, as claimed by Jeck (1983) and Lewis (1951) the comparability between median effective diameter and median volume diameter of droplets makes it easy to use them interchangeably.

For the aircraft industry, the wind speed was excluded from the previous icing envelopes that focused mainly on cloud water, drop sizes and temperature because of the neglected values of wind speed compared to aircraft speed. On the other hand, under icing conditions, the wind speed can significantly contribute to the accumulation of accreted ice, during the aircraft takeoff, on the wind turbines, power transmission cables and on all other low speed and motionless structures, all of which operate in much localized geographical areas and less diverse climate and weather conditions.

Therefore, once near surface icing variables are identified locally, designers and operators face a small number of concerns. The fact that ice water content is predominant at higher altitudes in the troposphere while the focus of this study is exclusively near the surface, only supercooled liquid water content rather than ice water content is addressed. To identify and assess the potential icing conditions, this study aims to determine the behavior of relevant meteorological variables that control the ice accumulation of the entire continent and coastal territory of Canada. Furthermore, due to its high investment in wind energy, atmospheric investigation in this study pays particular attention to the Gaspé region, St. Lawrence River and New Brunswick. The leading idea of this study focuses on developing icing envelopes and regional cloud microphysics characterizations that can provide design guidance for near-surface structures that are sensitive to cloud icing. For this reason, a large dataset (32 years) acquired from North American Regional Reanalysis is used to improve the understanding of the behavior of meteorological key parameters that control ice accretion.

2. Data and method

The North American Regional Reanalysis data known as NARR (Mesinger et al., 2006) of the National Centers for Environmental Prediction (NCEP) originates from data assimilation of observations from NCEP/NCAR Global Reanalysis project and Eta 32 km model output. Despite the existence of some model and assimilation limitations, the use of meteorological data from different reanalysis has increased tremendously to investigate various atmospheric phenomena. NARR data are widely utilized in previous studies. Namely but not limited to the following studies: for the purpose of comparison with other reanalysis (Kennedy et al., 2011), analyzing atmosphere–land surface interactions (Dominguez et al., 2008; Fall et al., 2010; Ruiz-Barradas and Nigam, 2013; Weaver et al., 2009), the climatological trend of wind speed (Holt and Wang, 2012), the evapotranspiration and energy budget feedbacks (Jaksa et al., 2013; Kumar and Merwade., 2011), atmospheric water cycle (Ruane, 2010), precipitation climatology (Becker et al., 2009; Bukovsky and Karoly, 2007; Neiman et al., 2011), validation of solar radiation (Schroeder et al., 2009), investigation of spurious grid-scale precipitation (West et al., 2007) and atmospheric icing (Lamraoui et al., 2013; Lamraoui et al., 2014; Lamraoui et al., 2015).

NARR data which are continuously evolving through new releases (NOAA) are available from 1979 to present and distributed on 29 vertical layers with 32-km horizontal resolution that are generated every 3 h. NARR are the result of the three-dimensional variational data assimilation (3DVAR) that blends output from the operational NCEP Eta Model and observation. Furthermore, the Zhao and Carr microphysics scheme (Zhao and Carr, 1997) used in NARR is incorporated into the NCEP'S Eta Model in order to prognostically determine cloud water. This scheme is based on an earlier version of Sundqvist et al. (1989). The cloud condensate mixing ratio can be either liquid water or ice, depending on local temperature. Zhao's scheme uses a cloud/ice mixing ratio to save computational time. After cloud condensate is calculated, that output field is partitioned into cloud water or ice depending on local temperature and cloud top temperature. In instances when local temperatures or top cloud temperatures (seeding) are colder than −15 °C, the ice cloud is considered. Further to this, for cloud temperature warmer than −15 °C, the cloud condensate is considered as liquid (Zhao and Carr, 1997). Also, Gultepe et al., (2014) reported that stratiform ice clouds and ice fog are common at temperatures colder than −15 °C, due to the water vapor deposition into ice nuclei.

Canada is characterized by a variety of regional climates. Thus, it is convenient to subdivide the study area into sub-areas in order to obtain a concise description of each Canadian regional climate. The total zone