Atmospheric Research 151 (2015) 2–19

Contents lists available at ScienceDirect

Atmospheric Research

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

A review on ice fog measurements and modeling

I. Gultepe [a,*], B. Zhou [b,c], J. Milbrandt [d], A. Bott [e], Y. Li [f], A.J. Heymsfield [g], B. Ferrier [b,c], R. Ware [h], M. Pavolonis [i], T. Kuhn [j], J. Gurka [k], P. Liu [a], J. Cermak [l]

[a] *Cloud Physics and Severe Weather Research Section, Environment Canada, Toronto, Ontario, Canada*
[b] *I.M. Systems Group, USA*
[c] *NOAA/NWS/NCEP, USA*
[d] *RPN, CMC, Environment Canada, Dorval, Quebec, Canada*
[e] *Meteorolooieches lnstitut, University of Bonn, Auf dem Hügel 20, 53121 Bonn, Germany*
[f] *Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China*
[g] *NCAR, Boulder, CO, USA*
[h] *Radiometrics Corporation, Boulder, CO, USA*
[i] *NOAA/NESDIS, Madison, WI, USA*
[j] *Lulea University of Technology, Division of Space Technology, P.O. Box 812, 981 28 Kiruna, Sweden*
[k] *NOAA/NESDIS, Greenbelt, MD, USA*
[l] *Ruhr-Universität Bochum, Department of Geography, 44780 Bochum, Germany*

ARTICLE INFO

Article history:
Received 18 December 2013
Received in revised form 15 April 2014
Accepted 21 April 2014
Available online 13 May 2014

Keywords:
Ice fog
Arctic weather systems
Aviation
Visibility
Ice fog forecasting

ABSTRACT

The rate of weather-related aviation accident occurrence in the northern latitudes is likely 25 times higher than the national rate of Canada. If only cases where reduced visibility was a factor are considered, the average rate of occurrence in the north is about 31 times higher than the Canadian national rate. Ice fog occurs about 25% of the time in the northern latitudes and is an important contributor to low visibility. This suggests that a better understanding of ice fog prediction and detection is required over the northern latitudes. The objectives of this review are the following: 1) to summarize the current knowledge of ice fog microphysics, as inferred from observations and numerical weather prediction (NWP) models, and 2) to describe the remaining challenges associated with measuring ice fog properties, remote sensing microphysical retrievals, and simulating/predicting ice fog within numerical models. Overall, future challenges related to ice fog microphysics and visibility are summarized and current knowledge is emphasized.

Contents

* Corresponding author at: Environment Canada, Cloud Physics and Severe Weather Research Section, Toronto, Ontario, Canada. Tel.: +1 416 739 4607.
E-mail address: Ismail.gultepe@ec.gc.ca (I. Gultepe).

http://dx.doi.org/10.1016/j.atmosres.2014.04.014
0169-8095/

1. Introduction

Ice fog, which most often occurs in the high latitudes or high elevations at low temperatures, is an important but not well-understood phenomenon. Ice fog, often termed *pogonip* (derived from the Shoshone Native Americans word "payinappih") generally forms at temperatures (T) less than −15 °C and consists solely of ice crystals. The meteorological community, according to the American Meteorology Society (AMS) Glossary of Meteorology (Glickman, 2000), defines ice fog as an event consisting of single ice crystals that occur at T usually less than −30 °C. Ice nucleation activations at temperatures (<−10 °C) by deposition nucleation were stated by Young (1974). Gultepe et al. (2014) suggested that an ice fog particle forms usually due to deposition nucleation process over the saturated environments based on relative humidity with respect to ice (RH_i). Ice fog significantly reduces visibility (Vis) and can cause ice to accumulate on surfaces such as aircraft, power lines, and roads. As such, ice fog is a significant hazard. Unfortunately ice fog forecasting using operational numerical weather prediction (NWP) model is often very difficult (Gultepe et al., 2009, 2014) because of limited surface in-situ, ground based remote sensing, satellite observations, and limitations in understanding of the ice microphysics and nucleation process.

Reduced visibility and other weather events commonly play a major role in aviation related accidents over the Arctic regions. The Transport Canada Civil Aviation Daily Occurrence Reporting System (CADORS) available at www.tc.gc.ca reports that weather-related financial losses and deaths per capita in northern latitudes can be 30 times more than those of mid-latitudes. Considering the fact that Arctic waters will be more accessible in the near future, these numbers may reach much higher values. Records of aircraft accident fatalities in Canada during the period of Jan 1993 to June 2010 from CADORS indicate that

- in cases of aircraft accident fatalities, a weather event was cited as a contributing factor in 27% of accident cases (365/1351), with reduced visibility being cited in 14% of cases (192/1351).
- flying in the Canadian northern latitudes is more hazardous than in the rest of Canada, and weather is a major factor in the increased risk, particularly reduced visibility. The per capita rate of aviation related fatalities in the north is 18 times higher than the national rate.

When only cases where weather was a factor are considered, the aviation accident rate in the northern regions is 25 times higher than the national rate. If only cases, where reduced visibility was a factor, are considered, the average rate of occurrence in the north is about 31 times higher than the national rate. Ice fog occurrence is found about 20–25% of the time during the cold seasons (Gultepe et al., 2007a, 2007b, 2014). The earlier work suggested that cold fog most frequently occurred when the temperature was less than −30 °C. The later one showed that over 67 day ice fog was observed about 25% of time. Gotaas and Benson (1965) also showed that ice fog lasted 6 to 9 consecutive days (~25% of time over two months) during the winter of 1961–1962. Gultepe et al. (2007a) provided a figure showing occurrence of cold fog where cold fog forms at least 20% of times in the northern latitudes. These studies suggest that better understanding of ice fog prediction and detection is required over northern latitudes.

The goals of this review are: 1) to summarize the current knowledge of ice fog microphysics, as inferred from observations and NWP models, and 2) to describe the remaining challenges associated with measuring ice fog properties, remote sensing microphysical retrievals, and simulating/predicting ice fog within numerical models.

2. Earlier studies on ice fog

Earlier studies of ice fog conditions can be found in Thuman and Robinson (1954), Robinson et al. (1957), Benson (1965), Benson and Rogers (1965), and Ohtake (1967). Wendler (1969) described the ice fog as a dense cirrostratus cloud near the surface. Gotaas and Benson (1965) studied two extreme ice fog events and suggested that cooling near the surface is not completely attributed to cold air advection or heat losses from the air and snow surface. In their work, air T was less than −40 °C for two ice fog cases during the winter of 1961–1962. They proposed that heat flow to the ice