Aircraft icing detection with satellite data in Southwestern Siberia

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Abstract. An approach to the detection of aircraft icing zones based on information from MODIS (Terra, Aqua) and ATOVS (NOAA18, NOAA19, MetOp) radiometers is presented. The prospects of using such an approach are demonstrated for Tomsk airport, which has a 2011-2017 PIREP data bank. The annual icing frequency in the vicinity of Tomsk is rather high and amounts to 14% of days per year, increasing by 30% in October to December according to the PIREPs. The following satellite products are used: 1.375 and 8.50 μm channel information, cloud-top temperature, cloud water path, temperature and specific humidity vertical profiles. The temperature and humidity profiles restored from the satellite data make it possible to identify icing zones on a three-dimensional scale using physical and statistical regularities. An example of a severe icing diagnosis based on the Godske method and a computed intensity of icing in-flight at 250 kph is considered in the paper. A combined analysis of the materials confirms that the identification of icing zones is satisfactory.

1. Introduction

The development of aviation equipment, the expansion of the geography of flights, and the increase in the traffic intensity claim new requirements to the provision of meteorological information to air services. This process is accompanied by the improvement of measuring technology, the introduction of new remote sensing tools, as well as the enhancement of computer technology and numerical modeling, which expands the possibilities of ever more accurate and reliable prediction of meteorological conditions. These trends are reflected in the ICAO strategy. In particular, the Global Air Navigation Plan, formulated prior to 2028 [1], demands in future full automation of the provision of meteorological information at any point, at any altitude, and at any given time. Thus, one of the main trends in the development of meteorological maintenance for aviation is the improvement of short-range forecasting and nowcasting based on numerical prediction and remote measurements (radars and satellites) and data of dense networks of ground (automatic) stations, as well as aircraft measurements and transfer of meteorological information from airplanes [2–4]. The short-range forecast and nowcasting in the meteorological service of aviation involve information on a set of meteorological features and atmospheric phenomena, such as wind, height of the lower cloud boundary, turbulence of the atmosphere, icing of aircraft, etc.

Icing is among aviation's most serious weather hazards, because it renders to loss of lift force, to reduce flight speed and, in some cases, to loss of control in-flight (LOC-I). All this can lead to aviation accidents [5–6], including human casualties. Deterioration of the flight performance of an aircraft during a flight in the icing zone depends on the intensity of icing, the amount of ice bonded to the fuselage of the aircraft, the shape of ice accretion, and the structure of ice. These factors, in turn,
depend on the water content of the cloud, the phase state and size of the cloud particles, the air
temperature and surface of the aircraft, and the aircraft flight speed.

Climatic and weather conditions in the south of Western Siberia (air temperature and humidity
combination, cloudiness and supercooled precipitation) contribute to a high probability of formation of
icing zones within the atmospheric boundary layer. The knowledge of issues related to complex
algorithms and products for the diagnosis and forecast of aircraft icing based on satellite data in the
Russian Federation as a whole and in Western Siberia in particular remains insufficient. Therefore, the
research is relevant for ensuring safety of flights.

2. Brief of icing detection systems and methods
Satellite data have a number of distinct benefits in the analysis of aircraft icing, such as multispectral
capabilities, frequent sampling (geostationary satellites only), and excellent spatial coverage and
resolution. Since the early 1990s geostationary and polar-orbiting meteorological satellites have been
used to help detect in-flight icing [7]. The studies on the diagnosis and forecast of icing in-flight using
satellite data are actively conducted in the US and European countries.

Curry and Liu [8] demonstrated the possibility of icing conditions diagnosis from satellite data with
the determination of the water parameter – supercooled water (SLW). Further Ellrod and Nelson [9]
described a method using Geostationary Operational Environmental Satellite (GOES) to recognize clouds that are likely to consist of SLWs on the upper boundary of a cloud. Later this
method was improved with an estimate of cloud height to indicate the upper boundary of the icing
layer [9]. Bernstein et al. [3] consider methods for the definition and prediction of areas with potential
icing conditions by combining various data from sources such as satellites, weather stations, radars,
lightning detectors, and pilot reports (PIREP) with numerical predictions of temperature, relative
humidity, SLW, and vertical speed. Current and forecasted icing in-flight products (CIP and FIP)
resulting from this integrated approach are available in the USA and southern Canada. Smith et al.
[10] found out a fair good correspondence between the liquid water path (LWP) and effective
droplet radius Re for clouds with SLW according to GOES-8 data and similar parameters retrieved
from ground-based remote sensors and aircraft measurements. Considering the obtained dependence,
Minnis et al. [11] developed an icing algorithm, which is based on satellite-derived cloud parameters.
In [12], an algorithm was developed to determine the flight icing threat to aircraft utilizing quantitative
information on clouds derived from meteorological satellite data as input. The algorithm inputs
include the satellite-derived cloud-top temperature, thermodynamic phase, water path, and effective
droplet size. The satellite-based icing method has been applied to current GOES data.

The system of diagnosis and prediction of icing over the territory of the European Union countries
is based on the same physical patterns. Kalinka et al. [2] showed the Advanced Diagnosis and
Warning System for Aircraft Icing Environments (ADWICE) that has been in development since 1998
in collaboration between the German Aerospace Centre (DLR), Deutscher Wetterdienst (German
Weather Service, DWD), and the Institute of Meteorology and Climatology of the Leibniz Universität
Hannover (IMuK). The warning system consists of two algorithms. Based on output data of the
operational numerical weather prediction model COSMO-EU Europe, the Prognostic Icing Algorithm
(PIA) allows the forecast of areas with an icing hazard. The Diagnostic Icing Algorithm (DIA) realizes
a fusion of forecast, observational and remote sensing data, such as satellite data, to describe the
current icing hazard. Four different satellite based products (Cloud Mask, Cloud Top Temperature,
Cloud-Top Height, and Cloud Phase) derived from METEOSAT 2nd generation, have been implemented.

Meteo-France has developed a system for the identification of icing areas [13], named SIGMA
(System of Icing Geographic identification in Meteorology for Aviation). This system is based on a
combination of three different sources of data: an icing risk index calculated from Météo-France's
numerical weather prediction model, the infra-red data from the geostationary Meteosat spacecraft,
and Météo-France's operational centimetric radar network.
The various icing expert systems, such as ADWICE (DLR, Deutscher Wetterdienst and IMuK), SIGMA (Meteo France), and CIP/FIP (NCAR) are adjusted to the region to which they are applied. Studies on the operation of similar products for the diagnosis and prediction of icing using satellite data are being conducted in Russia [14, 15]. For the European territory of Russia, the authors [15] developed and implemented a specialized complex package (SCP). The SCP automatically pixel-by-pixel classifies the SEVIRI/Meteosat-10 and AVHRR/NOAA data to retrieve cloud, precipitation, and weather hazard properties for day and night all year round conditions above land, water, and snow/ice surface, and automatically validates satellite estimates by ground-based observations at meteorological stations, the meteorological radar, and the same products of independent satellite complexes. The SCP allows one to determine the type of near-surface precipitation (13 classes) and the following dangerous weather phenomena: thunderstorm, hail, and icing with indication of the probability and intensity according to LWC, cloud top temperature, cloud-top height, and instant maximum precipitation intensity, mm/h (I max).

3. Data and results
Unfortunately, currently developed products based on information from geostationary satellites cannot be uniquely used for the territory of Western Siberia due to its geographic location. In our research we utilize retrieved data from polar-orbiting satellites over the territory of study which is currently available.

For the diagnosis and short-term forecast of the temperature and humidity fields in the territory, it is possible to draw information from the spectroradiometer MODIS (Terra, Aqua) and ATOVS (NOAA18, NOAA19, MetOp). At the Department of Meteorology and Climatology of Tomsk State University, the meteorological and synoptic conditions for the formation of icing zones are being studied using satellite monitoring, as well as the results of numerical experiments on mesoscale modeling of icing in the boundary layer jointly with the Mechanics and Mathematics Faculty [16, 17].

The aims of this study are to assess the periodicity of icing events using aircraft pilot reports (PIREPs), to determine the synoptic conditions for the formation of ice on an aircraft, and to explore the possibility of using remote sensing data to detect actual and potential icing zones. The database of icing recorded in the area of Tomsk airport (within a radius of 200–400 km) was formed on the basis of pilot reports (PIREP) and METeorological Aerodrome Reports (METAR) for the period of 2011–2017. In addition to this, for the selected icing events satellite data acquired with the MODIS spectroradiometer (on board NASA’s Terra and Aqua space platforms) and ATOVS radiometer (NOAA 18, NOAA 19, MetOp) were processed.

In total, 361 days with icing were recorded during this period. The considerable number of days was observed from October to December, an average of 9 days per month, with a maximum in December 2015 (14 days). Most often there was icing of moderate and light intensity (52 and 42%, respectively) (Table 1). Days with severe icing (22 days) were recorded from October to May with a maximum in December (7 days).

| icing intensity | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Severe         | 1.4 | 0.5 | 0.9 | 0.5 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.9 | 2.3 | 3.2 |
| Moderate       | 5.1 | 6.9 | 6.9 | 4.6 | 6.5 | 2.3 | 1.8 | 2.8 | 1.8 | 13.4| 15.7| 18.0|
| Light          | 5.5 | 3.2 | 7.4 | 6.9 | 6.9 | 1.8 | 0.0 | 1.4 | 3.2 | 14.7| 11.1| 7.8 |

More than a third of the icing cases (35%) ensued at altitudes of up to 1000 m, about 32% within a layer of 1000–2000 m, 20% – 2000–3000 m, and 13% at an altitude of 3000 and more. The maximum height where the icing accretion marked was 8 km.
A review of the synoptic processes contributing to the formation of icing zones revealed that about 85% of the cases were under low atmospheric pressure. About 13% of all cases occurred on occluded fronts, 30% during cold fronts passage, in baric trough, centers and rear quadrant of cyclone, more than 30% of icing was recorded on warm fronts and in warm cyclone sectors. Icing in most cases was accompanied by various types of atmospheric phenomena, mainly precipitation (snow, heavy snow, rain, rainstorms, drizzle, supercooled drizzle, snow grains), as well as supercooled fog and haze. The most frequent icing with varying intensity was during heavy snow (~ 40%).

As an example of using the remote sensing data, the event of prolonged severe icing near the Tomsk airport was studied. According to PIREP, on January 4 (23:54 UTC) there was a moderate icing in a 3700/1000 m layer. Since January 5 (00:00 UTC) an increase in the intensity of the process to severe icing was noted, lasting until the next day (00:52 UTC).

The meteorological and synoptic conditions for the icing formation were caused by cyclogenesis and the passage of southern cyclones against the background of the weakening of the Asian anticyclone in the first decade of January 2017. The near-surface temperature in the first ten days exceeded the norm by 2–5 °C; in the first five-day period, the air temperature in the vicinity of Tomsk and the airport varied within -1 ÷ -7 °C. The weather conditions were as follows: heavy snow storms of various intensity, drifting snow low and blizzards with gusts up to 15–17 ms⁻¹ and wind direction of 180–270°, visibility deterioration up to 400 m during a storm. The synoptic conditions on January 5 were determined by the passage of an occluded front concomitant with cumulonimbus, stratuscumulus, altocumulus and nimbostratus in combination with fractonimbus clouds.

To determine the spatial localization of cloudiness fields with actual and potential icing zones, the 1.375 and 8.5 μm channels (Figs. 1a and 1b) were mapped, which allowed assessing the water content in any phase. In the area of the Tomsk airport, cloudiness has volutus (roll) structure, which consists mainly of cumulonimbus and stratocumulus clouds with high water content.

![Figure 1](image1.jpg)

**Figure 1.** MODIS/Terra cloud imagery (bands at 1.375 μm (a) and 8.5 μm (b)), 06:35 UTC on January 5, 2017. The red marker indicates the coordinates of Tomsk.

Figure 2 shows the visualization cloud water path (gm⁻²) of the MODATML2 product of the MODIS / Terra spectroradiometer [18]. There is a specific “spotted” distribution of stratocumulus clouds with cumulonimbus inclusions, which can be detected at cloud water path values above 1500 gm⁻². It is important to note that when using MODIS spectroradiometer data, several points should be taken into account: the most accurate are measurements obtained for the clear sky pixels [19] or with gaps in a dense cloud layer.
Figure 2. Cloud water path (gm$^{-2}$) imagery at 06:35 UTC on January 5, 2017. The black point marks the location of Tomsk airport.

Earlier, in [20] the possibilities of using radiometers for continuous measurements under different weather conditions were demonstrated. Therefore, the application of ATOVS radiometer data for the calculation of icing parameters is correct. The ATOVS sounding system allows one to restore the temperature and humidity profiles throughout the troposphere, which can be used for the short-term forecast of icing zones using various physical and statistical regularities, for example, the method of K Godske [3] in the formula

$$ T \leq -8 \cdot D . $$

where $T$ is the air temperature at the respective level ($^\circ$C), $D = T - T_d$, $T_d$ is the dew point temperature ($^\circ$C), when $T \leq -8 (T - T_d)$ then icing in the 0 to 2000 m layer is to be expected.

Figure 3 shows that an icing zone occupies the entire computational region along 86 $^\circ$E, extending vertically up to a surface of 750 hPa. At the near surface this zone occupies about 70% of the computational region, overlapping the azimuth of any flight course during takeoff and landing of an aircraft.

Figure 3. Spatial zone of icing (cyan color) according to ATOVS computed with K. Godske’s method. Flight time is 07:34 UTC on January 5, 2017; a – vertical section of icing zone along 86 $^\circ$E; b – horizontal boundaries of icing zone at 850 hPa.
The icing type (light, moderate, and severe) is determined by the intensity of icing encounter, which is computed by formula (2).

\[ I = \frac{1.67 \times 10^{-2}}{\rho_i} \cdot u \omega \bar{E} \beta. \]

Here, \( I \) is the intensity (mm/min), \( \rho_i \) is the density of ice (g cm\(^{-3}\)), \( u \) is the speed of flight (kph), \( \omega \) is the water content of the cloud (g m\(^{-3}\)), \( \bar{E} \) is the total capture coefficient, and \( \beta \) is the icing coefficient.

The formula is simplified for specific types of aircraft, but with any simplification, the cloud water content is major. The other values are determined approximately: \( \rho_i \) varies from 0.8 to 1.0 g cm\(^{-3}\). The coefficient \( \beta \) is close to 1 at an air temperature below -3°C, with an increase in the temperature and water content of the clouds it decreases. The value is maximum at the frontal point of the aircraft and decreases at a distance from it; this parameter also depends on the type of aircraft, its speed, and the size of droplets in the cloud. The \( \bar{E} \) parameter usually varies from 0.25 to 0.50. In this paper, the following values for the intensity calculation are taken: \( \rho_i = 0.9 \text{ g cm}^{-3}; \bar{E} = 0.25; u = 250 \text{ kph}. \) The velocity \( u \) is chosen taking into account that the considered icing processes refer to the layers of the atmosphere that the aircraft crosses when landing at the aerodrome at an actual speed of 250-350 kph.

Hereafter, map schemes of the J distribution on an isobaric surface of 1000 hPa and for a tropospheric lower layer up to 5 km were made (Fig. 4). For the case under study, the intensity varied from moderate to severe, which was reflected in the flight mode by vibrations and speed dropping 20–30 to 60–70 kph [20].

The considered example of the formation of the icing zone refers to the conditions of frontal icing in stratocumulus and cumulonimbus clouds, which has high water content. The aircraft during takeoff or landing at the Tomsk airdrome undergo the icing zone, which was confirmed by PIREPs and satellite data.

**Figure 4.** Distribution of the intensity of icing (I) at specified parameters: (a) on the isobaric surface of 1000 hPa; (b) 3D distribution. Time pass over study area is 07:34 UTC on January 5, 2017.

### 4. Conclusions

A Strategy for the development of air transport in the Siberian region assumes a redistribution of the load on the present airports and the emergence of new air routes. It requires a detailed and high-quality meteorological service with data fusion.

It should be noted that the annual icing frequency in the vicinity of Tomsk is rather high and amounts to 14% days per year, increasing by 30% in October to December according to the PIREPs. A frontal passage with cumulonimbus clouds and showers is a favorable synoptic condition for the formation of potential icing zones.
The approach considered in this paper to use satellite data for the identification of icing zones demonstrated its correspondence to the areas identified by other methods.

The suggested method to detecting icing zones using information from polar-orbiting satellites can be used for the territory of Western Siberia that is not covered by geostationary satellites and has a sparse upper-air sounding network.

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