Forecast of Extreme Weather Conditions that Promote Aircraft Icing During Take-off or Landing

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ABSTRACT

This work presents the results of forecasting meteorological conditions that promote aircrafts icing in the atmospheric boundary layer; the forecasting results were obtained based on mesoscale meteorological model TSU-NM3. Godske formula which is based on the calculation of saturation temperature above ice, NCEP method, and statistical method of Hydrometeorological Centre of Russia were used as criteria of probability of aircraft icing during take-off or landing. Numeric forecast results were compared with physical observations made in the atmospheric boundary layer in October 2012 at the Tomsk airport. A good agreement obtained provided an opportunity to be certain about the above approach viability.

Keywords: numerical weather prediction, icing, mesoscale model, parameterization of atmospheric processes

1. INTRODUCTION

Icing is the process of covering with ice parts of aircraft, engine units and outside parts of special equipment streamlined by air during the flight. Formation of ice on the front edges of lifting surfaces may cause noticeable changes in aerodynamic performance and deteriorate aircraft flying properties. Mainly nose (face) sections of streamlined profiles of the aircraft are subject to icing. This causes a distortion of the profile shape, surface irregularities that impact the streamlining pattern and cause an increase in the aircraft drag, where among the total drag growth the wings and the tail unit icing is largely (up to 70-80%) accounted for the drag increase. Icing reduces the ascentional force, the aircraft mass increases, engine unit power gets reduced. High energy expenditures of the anti-icing system are determined by high thermal capacity of water and ice, thereby motor power draining takes place. Communication is often interrupted due to icing of external aerials; aircraft flight performance, vertical rate of climb get reduced; ceiling and maximum airspeed of flight grow lower, fuel consumption increase, drag power (draught) for the flight at target speed grows higher [1]. Icing problem has always been given particular attention both in Russia and abroad because a large number of air routes are run in places where meteorological conditions may contribute to icing [2].

It needs to be clarified that "icing" is defined only as the phenomenon occurring when an aircraft is covered with a layer of ice ***during the flight.*** It differs from icing occurring when the aircraft is ***at the parking area*** in that icing during the flight is determined by a high motion speed of the aircraft. Different types of aircrafts have different degrees of sensitivity to icing. Modern air vehicles are less vulnerable to icing, but because they operate flights practically under any conditions and over long distances they are quite frequently subject to harmful icing.

Ice deposit on the outer surface of a flying aircraft may either be caused by sublimation of water vapor on the outer surface or by freezing of super-cooled drops of water running against it. The first icing mechanism is quite rare; it occurs when the aircraft surface temperature turns out to be significantly lower than the surrounding air temperature as it happens in the case of rapid push-down of an aircraft when, in a short period of time, it goes down from cold upper atmospheric layers to warmer lower layers. The second icing mechanism is more significant, i.e., during collision of the aircraft with super-cooled drops of cloud, drizzle or rain. Aircraft icing is largely possible only under negative air temperature. There are recorded cases of icing under the temperature as low as -45 °C, but in most cases icing takes place in the temperature range between 0 and -20 °C, most frequently, in the range between 0 and -10 °C.

21st International Symposium on Atmospheric and Ocean Optics: Atmospheric Physics,
edited by G. G. Matvienko, O. A. Romanovskii, Proc. of SPIE Vol. 9680, 96806T
© 2015 SPIE · CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2205774

Presently a lot of investigations on ice forecasting have been performed using numeric methods. Among the first ones is the work by P. Schultz and M.K. Politovich (1992) [3], who assessed the probability of icing using a combination of model data on temperature and relative humidity as well as inflight weather data. This approach was developed further by G. S. Forbes et al. [4], G. Thompson et al. [5–7], J. Carriere et al. [8] in their works, its microphysical parametrizations was proposed by J. Reisner et al. [9] and A. Tremblay [10] in their works. In his work, C. Gencer [11] proposed a forecast algorithm of icing zones based on the output data of MM5 model on standard isobaric surfaces between 1000 and 100 hPa.

Ice conditions forecasting involves an assessment of temperature and moisture distribution in the flight area, i.e., at what level are 0, -10 and -20 °C isotherms; the presence of clouds; horizontal and vertical distribution of clouds and their microstructural characteristics. It has been known that icing occurs in clouds consisting of drops only or of a mixture of drops and crystals.

For the objective forecasting of icing zones, the most informative predictors are various levels of negative air temperature in combination with specified values of air moisture characteristics (relative, absolute, and dewpoint deficiency) as well as vertical speed values. In Russia, the most frequently used formula was Godske formula (1) (including in the course of rendering meteorological services for the aviation at aviation meteorological station of Tomsk aerodrome) and statistical method (discriminative analysis) of icing forecast, developed in Hydrometeorological Centre of the USSR (2) [12]. They were developed based on the data of upper-air sounding of the atmosphere.

$$T \leq -8 \cdot D \tag{1}$$

For the 850 hPa level the discriminant function looks as follows:

$$L = 1.701 \cdot (T - T_d) - 2.046 \cdot q + 0.239 \cdot T - 1.751 \tag{2}$$

where T is the air temperature at the respective level (°C), T_d is dewpoint temperature (°*C*), q is the specific moisture (g/kg) when $T \leq T_{a.i.}$ ($T_{a.i.} = -8D$, $D = T - T_d$, $T_{a.i.}$ is the saturation temperature above ice), then icing in 0 to 2000 m layer is to be expected; if $L<0$ icing is possible in the 1000 to 2000 m layer.

Presently routine icing forecast methods used globally are mainly based on hydrodynamic modelling data; their basic algorithms are presented in [5]. Testing of these algorithms in Hydrometeorological Center of Russia [13, 14] demonstrated that the most successful of the algorithms is the one developed by NCEP researchers within RAP program (Research Application Programme) [5.] The method is based on the analysis of large databases of measurement data using aircraft detectors of icing, temperature, air moisture, and is also used in actual practice for calculation of forecast charts of significant weather for the aviation. According to the method, potential icing zones of aircrafts are identified by forecast fields of temperature and relative humidity on 500, 700, 850 and 925 hPa isobaric surfaces in model grid points. Potential icing zone of an aircraft includes points where the following conditions are met:

$$-16\ °C \leq T \leq 0\ °C \text{ and } f \geq 63\ \%, \tag{3}$$

where T is the air temperature, f is the relative humidity.

The number of cases where aircrafts get iced in the zones of presence of these inequations is a sequence higher than icing outside these zones. It is to be noted that experimental data on icing are of sporadic character and they can very rarely be used in the assessment of numeric modelling algorithms.

2. METHODOLOGY

Tomsk State University has an icing forecast algorithm with 24-hour advance time developed based on hydrodynamic simulation data [15, 16]. The algorithm envisages calculation of data about the availability/absence of icing; the algorithm uses specific humidity q(kg/kg), relative humidity (*f, %*), air temperature (*T, °C*), dew point deficiency (*D, °C*), saturation temperature above ice ($T_{a.i.}$, *°C*). Results of comparison of air temperature and saturation temperature above ice (1), conformity with conditions (3), and value of discriminant function *L850* (2) served as an indicator of presence/absence of icing. The algorithm was realized using modernized mesoscale meteorological model, TSU-NM3, controlling server, network attached data storage and TSU supercomputer SKIF Cyberia.

Apart from the above, inflight weather data base on icing cases in the vicinity of Tomsk aerodrome (within 200 km circle) over a period between October 7, 2011 and December 31, 2013 (816 days) was engaged. During this period 128 days with icing cases occurred, among them weak intensity icing occurred for 64 days, icing was moderately intensive for 56 days and for 8 days icing intensity was strong. The largest number of days with cases of icing was recorded during mid-season with the maximum number of icing cases in October (29 % of the days of the month) (Table 1).

Table 1 Annual frequency of occurrence of days with icing cases (%) graded by intensity

Intensity, mm/min	Months											
	1	2	3	4	5	6	7	8	9	10	11	12
Light (≤0.5)	8,1	1,8	3,2	6,7	17,7	3,3	0,0	3,2	5,0	17,2	13,3	6,5
Moderate (0.6÷1.0)	3,2	3,6	4,8	6,7	8,1	3,3	1,6	3,2	5,0	9,7	13,3	11,8
Heavy (>1.0)					1,6					2,2	1,1	4,3
Total	11,3	5,4	8,1	13,3	27,4	6,7	1,6	6,5	10,0	29,0	27,8	22,6

Most frequently light and moderate icing intensity was observed. Heavy icing was recorded in May and in October-December.

Icing is to a large extent promoted by cloudiness with ≤ 1000 m base of cloud (about 40% of cases); light icing is actually possible in any sort of cloudiness while moderate and heavy icing happens only with ≤ 3000 m base of cloud and at the same time, nearly half of heavy icing cases are observed in clouds with ≤ 500 m bases (Table 2). It is to be noted that in a quarter of all of the cases the base of cloud is not identified and it can be assumed to have been low cloudiness with drizzle precipitation.

Table 2 Recurrence of icing cases (%) depending on the height of the lower limit of icing stratum

Intensity	Height of the lower limit of icing stratum, m								Without specifying the height
	0-500]	500-1000]	1000-1500]	1500-2000]	2000-2500]	2500-3000]	3000-4000]	4000-5000]	
Light	7,0	27,9	12,8	10,5	5,8	4,7	4,7	1,2	25,6
Moderate	23,6	22,2	12,5	5,6	2,8	4,2			29,2
Heavy	44,4	11,1			22,2	22,2			
Total	16,2	24,6	12,0	7,8	5,4	5,4	2,4	0,6	25,7

The shape (combination of shapes) of cloudiness observed during icing is presented in Table 3. From the point of view of icing the most dangerous are combinations of cumulo-nimbus (Cb) cloudiness with scattered rain clouds (Frnb), high cumulus clouds (Ac), stratocumulus clouds (Sc), high stratus clouds (As). In over half of the cases (55,6%) heavy icing was observed with strato-rain cloudiness (Ns) in combination with scattered rain clouds (Frnb). Consequently, it was quite natural that dependence was discovered between a case of icing and simultaneous fallout of precipitation near the ground (62% of icing cases). In ¾ cases of precipitation the fallout was in the form of snow shower or rain showers.

Table 3 Frequency of cases of icing (%) depending on the shape of clouds

Intensity	Shape of clouds												
	Frnb	**Cb**	**Cb**	**Sc**	**Frnb Ns**	**Cb**	**Frnb**		**Frnb**	**Ac**	**St fr**	**Sc**	**St fr**
	Cb	**Ac**	**Sc**	**Ac**		**Ac**	**Cb**	**St**	**Sc**	**Ci**	**Sc**	**As**	**Sc**
	Ac		**Ac**			**Ci**	**As**		**As**		**As**		**Ac**
Light	34,5	22,6	16,7	8,3	2,4	4,8	2,4	2,4	2,4	1,2	1,2		1,2
Moderate	47,2	8,3	12,5	8,3	6,9	2,8	4,2	4,2	2,8	1,4		1,4	
Heavy	22,2	11,1			55,6						11,1		
Total	39,4	15,8	13,9	7,9	7,3	3,6	3,0	3,0	2,4	1,2	1,2	0,6	0,6

October, 2012 was selected for the experiment using a mesoscale model based on the apparent climatic specifics of icing frequency.

3. RESULTS

Based on the weather forecast by PLAV Global Model of Hydrometeorological Centre of Russia [17], using mesoscale model TSU-NM3, icing was predicted in the atmospheric boundary layer (on 29 vertical levels) during the period between October 3 and October 16, 2012 in the vicinity of Tomsk aerodrome with 24 hours advance time. The assessment of accuracy of temperature and humidity calculations by this model is given in [18]. Predictions of TSU-NM3 Model represent hourly profiles of such values as specific humidity *q*(kg/kg), relative humidity (f, %), air temperature (*T, °C*), dew point deficiency (*D, °C*), saturation temperature above ice ($T_{a.i.}$, °C), and directly, signs of presence/absence of icing by Godske method, by NCEP method and based on the values of discriminant function L850.

Aggregate information on the above experiment is presented in Table 4, from which it follows that all the cases of the phenomenon presence manifested by inflight weather data coincided with the phenomenon forecast by numerical simulation. Specific nature of the in-flight information (few flights, ice detectors availability on the aircrafts, etc.) does not make it possible to assess icing forecast verification during the period of experiment with hourly discretization. In this situation the model adequacy may be assessed using qualitative analysis of meteorological and synoptical conditions.

Table 4 Aggregate information on icing from simulation results, inflight weather data and boundary layer state in the period from October 3 to October 16, 2012.

Date	Simulation						Inflight weather		
	Godske method		NCEP method		Method of Hydrometeorological Centre				
	Start/end points of time of the phenomenon, h, DST	Minimal lower boundary/upper boundary of icing stratum, m	Start/end points of time of the phenomenon, h, DST	Minimal lower boundary/upper boundary of icing stratum, m	Start/end points of time of the phenomenon, h, DST	L850	Time period of icing, hours, DST	Lower boundary/upper boundary of icing stratum, m	Intensity of the phenomenon
03	Phenomenon is not forecasted		00:00–14:00	2000/ 2300*	00:00–24:00	L<0	inflight weather data are not available		
04	Phenomenon is not forecasted		11:00–24:00	1800/ 2300*	06:00–24:00	L<0			
05	10:00–12:00	2100/ 2300*	00:00–24:00	1100/ 2300*	00:00–24:00	L<0			
06	00:00–24:00	500/ 2300*	00:00–24:00	500/ 2300*	00:00–24:00	L<0	04:30–07:00	600/ 1500	Сл.
							13:00–15:00	3500/ 4900	Сл.

07	00:00–22:00	350/2300*	00:00–24:00	300/2300*	00:00–24:00	L<0	inflight weather data are not available		
08	08:00–24:00	1000/2300*	00:00–24:00	800/2300*	02:00–24:00	L<0	10:30–13:00	2000/2300	Ум.
09	00:00–24:00	1000/2300*	00:00–24:00	900/2300*	00:00–24:00	L<0	inflight weather data are not available		
10	00:00–12:00	300/2300*	00:00–24:00	300/2300*	00:00–12:00 23:00–24:00	L<0	06:47–09:30	1500/2300	Сл.
11	08:00–12:00	500/1000	00:00–24:00	0/2300*	00:00–14:00	L<0	04:37–07:00	–/1000	Ум.
12	Phenomenon is not forecasted		11:00–24:00	1300/2300*	18:00–24:00	L<0	inflight weather data are not available		
13	Phenomenon is not forecasted		00:00–24:00	0/800	–	L>0			
14	Phenomenon is not forecasted		00:00–24:00	0/2000*	–	L>0			
15	02:00–24:00	1000/2300*	01:00–24:00	150/2300*	02:00–24:00	L<0			
16	02:00–09:00	2100/2300*	00:00–24:00	1000/2300*	00:00–24:00	L<0			

Note: DST is daylight saving time (local). 2300* is the upper limit of icing layer, it is determined by resources of the model.

It is noteworthy that on 3rd October, 4th October, and 12th October L850 calculation results and the NCEP method indicated icing while Godske formula indicated "no icing". In this case an unambiguous decision can be made based on a more detailed analysis of both synoptical and meteorological (air temperature and moisture) conditions. On 3rd October and 4th October Tomsk region was in the area of a cyclone and of front cross-sections of the cyclone but the air temperature in the boundary layer was positive up to 1800-2000 m. On 12th October, under anticyclonic conditions, dew point deficiency of $>2\ °C$ did not promote formation of icing according to Godske method while method of Hydrometeorological Centre and NCEP method showed potential icing above 1300 m.

Simulation results of October 13 and 14 are correlated by Godske method and method of Hydrometeorological Centre which both give prognostic statement of absence of icing. At that moment Tomsk region was under the influence of extensive and very violent anticyclone.

Thus, simulation results for October 5 to October 11 and October 15 and 16 pointed to potential icing probability. Supporting factual evidence on inflight weather of October 5, 7, 9, 15 and 16 is not available for technical reasons. The relevant confirmation of the phenomenon availability on October 6, 8, 10 and 11 is presented in Table 4. It is to be noted that NCEP method results indicated to potential icing on every day of the experiment; in this method this is due to a sufficiently wide range of temperature and moisture that promote icing. Temperature and moisture conditions ($-16\ °C \le T \le 0\ °C$ and $f \ge 63\ \%$) are quite typical for October in the boundary layer of the investigation area.

Let us examine in detail the calculation results for October 6 (Fig.1) when according to inflight weather data 2 icing cases were recorded (slight, in the clouds). On that day Tomsk region was the area of depression, of cold humid and unstable air mass after the Arctic front that passed about the territory on the previous day [19]. The calculation data of the model indicate to the 24-hour availability of icing according to Godske, NCEP and L850 methods. At the same time the lower limit of potential icing according to NCEP method is, on the average, located 100-200 m lower than by Godske method.

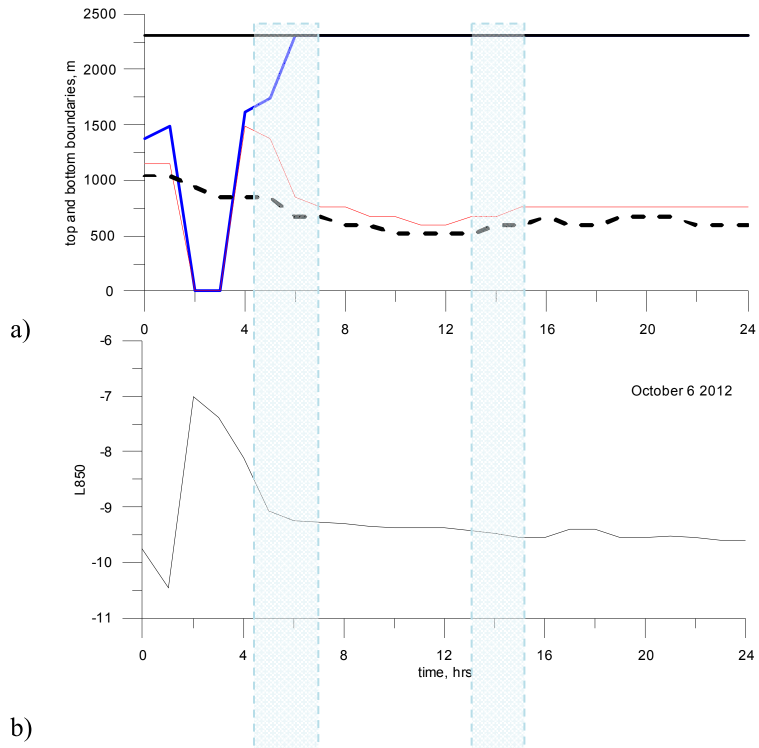

Figure 1 - Simulation results for October 6, 2012 : a) Godske formula (red line is the lower borderline of the layer, blue line is the upper borderline of the layer) and NCEP method (black dashed line is the lower borderline of the layer); (b) Hydrometeorological Centre method at 850 hPa level. The time when the fact of icing was confirmed is identified as a separate cluster block.

4. CONCLUSIONS

This work presents the results of forecasting meteorological conditions that promote aircrafts icing in the atmospheric boundary layer; the forecasting results were obtained based on mesoscale meteorological model, TSU-NM3. Godske formula which is based on the calculation of saturation temperature above ice, NCEP Method and statistical method of Hydrometeorological Centre of Russia were used as criteria of probability of aircraft icing during take-off or landing. Numeric weather prediction results were compared with physical observations made in the atmospheric boundary layer in October 2012 in the vicinity of Tomsk airport. The method of forecasting aircraft icing based on weather predictions by the numerical model TSU-NM3 demonstrated its effectiveness and may be taken as a basis for developing a regional method.

5. ACKNOWLEDGMENTS

This work was supported by the Ministry for Education and Science of the Russian Federation (No. 5.628.2014/K).

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