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An Algorithm Predicting Upper Level Icing Potential by Fuzzy Set Theory and an Application with this Algorithm for Turkey

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Abstract: In this study, concerning with the icing phenomenon which is one of the most serious hazards for aviation, a system was developed providing predictions for the next 24 hours including location, level and time information. This system produces forecasts periodically and represents the results to users. The verification analysis is carried out by comparing the system output with real-time upper level atmosphere observations. After the verification analysis, it is found that the outputs which are produced by this study are practicable for operational meteorology.

Key Words: Fuzzy set theory, fuzzy inference system, upper level icing potential, icing forecast.

1. INTRODUCTION

Because of its characteristics, atmosphere may show considerable changes even in very short periods. Reducing the potential risks is possible only by predicting these rapid atmospheric changes and by taking measures according to these predictions. One of such changes which are required to be predicted is upper level icing probability. Upper level icing is accretion of ice on a solid surface as a result of transforming of supercooled water droplets into ice form by hitting to that solid surface [1]. This situation is a considerable threat for flight safety and it causes loss of altitude, reducing speed and loss of control. It is impossible to foresee the icing for the pilots. Because of these characteristics, it is very important to produce icing forecasts with high accuracy.

There are plenty of studies on icing potential. The first study on this subject was carried out by Schultz and Politovich in 1992. In this study, they evaluated icing by using the combinations of model temperature "T", relative humidity "RH", pilot reports (PIREPs) and Nested Grid Model outputs. They produced icing information with a progressive method based on T and RH threshold values [2].

Forbes *et al.* [3] and Thompson *et al.* [4, 5] furthered Schultz and Politovich's approach by characterizing four meteorological situations for icing, based on combinations of T, RH and vertical thermodynamic structure respectively in 1993 and in 1997.

Carriere *et al.* gathered T, RH and upwards vertical velocity for determining more intensive icing at 1997 [6].

Although these model based algorithms contain PIREPs, these algorithms usually tend to forecast icing, even for cloudless fields.

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Reisner *et al.* [7] developed an explicit microphysical parameterization in 1998, including ice physics and which includes three options of increasing complexity to represent the hydrometeor species. This study focused on the prediction of supercooled liquid water (SLW) by using microphysical classification.

Tremblay and Glazer [8] developed a new mixed-phase cloud scheme for improving the forecasts of various weather elements such as snow, rain or freezing precipitation in 2000.

Thompson *et al.* [9] evaluated the sensitivity of winter precipitation to numerous aspects of a bulk, mixed-phase microphysical parameterization in 2004.

Lee *et al.* [10] carried out a study on the potential for consistent, around-the-clock image products that can trace the movement and evolution of low, stratiform clouds in 1997.

Ellrod [11] developed an experimental satellite image product in 1996 for the detection of supercooled clouds conductive to aircraft icing.

Smith *et al.* [12] developed a technique for deriving cloud optical properties and, in particular, SLW, from high spatial and temporal resolution satellite data in 2002.

In these studies, the threshold values with certain borders were used for forecasting icing. For example; as the value of T= (-14,9) °C is an appropriate temperature, T= (-15,1)°C is not appropriate for icing according to these studies. That is, even very small changes in temperature, in relative humidity or in another parameter may cause unexpected changes on the icing fields forecasts. Briefly, these approaches are not adequate for representing expected and unexpected icing fields. Similarly with the other weather events, icing can have the characteristic of continuity or discontinuity both. One can encounter with unexpected discontinuities at cloud boundaries. In these fields, especially in vertical direction, considerable differences of icing may be encountered within the some hundred meters distance. Icing conditions may also differ according to degree and time. Because of these characteristics, it would be more effective and more reliable to use fuzzy logic instead of certain logic, on icing forecasts.

In this study, it is aimed to develop a software predicting icing potential for the next 24 hours. It is also aimed that to present these predictions in a user friendly form. Icing is directly related to temperature, water content of atmosphere, cloud top temperature and the vertical velocities of the particles in the atmosphere.

The relations between these factors and the degree of effect to icing are the basis of developed forecast icing potential algorithm. The inputs for forecast icing potential system are gathered from the outputs of a numerical weather prediction model. This system produces icing potential probabilities for full area of Turkey with 7 km resolution grid area and for the 14 standard pressure levels up to 300 hPa. The system produces forecasts for every 3 hours up to 24 hours.

Linear methods and formula approach is insufficient for modeling meteorological conditions. Besides, expert opinions have considerable importance on meteorological forecasts. For these reasons, fuzzy logic is preferred as icing potential probability predicting method. In this study, a fuzzy inference system (FIS) based on basic fuzzy logic algorithm was designed. This FIS contains statistical data for icing potential inputs/outputs and expert experiences. After designing this FIS, software was developed for producing outputs with C++ programming language. For confirmation of produced outputs by the software, the same inputs were used at MATLAB program package's fuzzy logic tool and outputs were obtained. By comparing the results of manual computing, C++ program code run and MATLAB fuzzy logic tool calculation, the output validation operation was carried out for checking the C++ code against the possible code and computational errors.

The obtained outputs are compared with the real-time atmosphere sounding results for verifying analysis of the forecasts.

2. PREDICTING ICING POTENTIAL BY FUZZY LOGIC

It is suitable to use fuzzy logic for weather forecasting because there is a close relation between fuzzy logic and meteorology science by its nature. The reasons indicating fuzzy logic is the most ideal method for weather forecasts are given below;

a) The natural language in weather forecast reports contain fuzzy expressions such as cloudy, cooling after midnight, winds from western direction, regional shower, …etc.

b) Fuzzy logic was known by the studies on meteorology. For example; Bjarne Hansen designed a fuzzy system on marine forecasts in 1997 [13], and again designed a fuzzy system predicting cloud top and visibility correctly in 2000 [14]. Gottfried Shaffer formed a fuzzy logic system predicting temperature with 0.75°C accuracy and predicting icing on the roads in 1998 [15].

c) Finally, atmosphere and weather conditions meet the general conditions for fuzzy logic solutions such as;

- Approximate solutions are acceptable.
- The values and value intervals of some parameters such as wind direction, cloud cover and temperature can be displayed numerically.
- There is an input-output relation but this relation cannot be defined well and not stable. This input-output relationship differs according to the geographical conditions and seasons, besides, the same inputs may produce different outputs. A black box which is formed between inputs and outputs will provide flexibility for the model. For example; a forecast like "dry" and "humid" may be both correct for a period of 12 hours.
- There is no mathematical formula which produces desired outputs. Additionally, even the most improved computers fail in case of applying some algorithms to atmospheric models.
- As well as the whole accessible information desired to be used, this process produces a very complicated outcome.

One of the most important subjects which needed to be forecasted meteorologically is icing potential because of its great importance for aviation.

Forecast Icing Potential Algorithm

Algorithm Inputs

In this study, the parameters including temperature, cloud top temperature, relative humidity and vertical velocity which affect icing potential directly are used. The degree of effect of these parameters to icing and the relations between these parameters are evaluated with PIREP statistics and meteorological rules and the interest maps are prepared.

Interest Maps

Forecast icing potential (FIP) combines the model input data using fuzzy logic membership functions and a decision tree to estimate the potential for icing. The membership functions are based on cloud physics principles, forecasting and research experience, and a comparison of fields to icing PIREPs. They map data onto a 0 – 1 scale, which represents the expected likelihood of icing, given the value from that field [16].

The whole functions aim to behave like a forecaster. For example; the higher relative humidity value indicates the higher possibility of icing.

Temperature

Icing conditions are most common at temperatures close to freezing and become less likely with decreasing temperature, because the chance of significant ice crystal concentrations increase [17, 18]. Icing is relatively rare at temperatures below -25°C. The temperature membership function (T_{MAP}; Fig. **1**) was built with these factors in mind. Tmap also takes into account heating caused by the compression on the leading edge surfaces of an aircraft. This is the reason for the sharp decrease in interest as the temperature increases from -4°C to 0°C even though SLW is very likely at these temperatures [16].

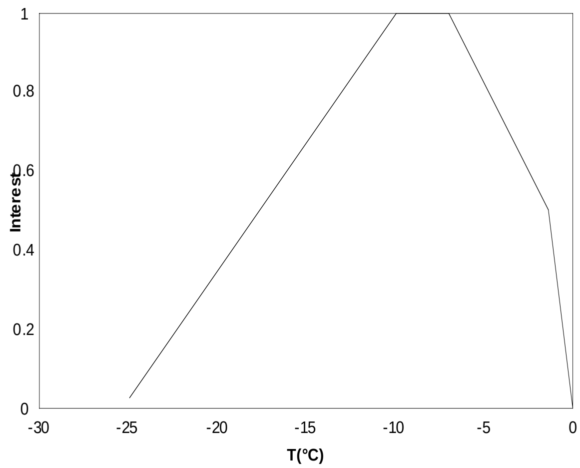

Fig. (1). FIP T_{MAP} membership function for temperatures from (-30) to 0°C.

Cloud Top Temperature

Because temperatures within a cloud layer are normally coldest at its top, cloud top temperature (CTT) can have a large effect on the chances for icing throughout a given cloud's depth. If cloud tops are cold enough to produce copious amounts of ice crystals, those crystals are expected to fall through the remainder of the cloud layer below, resulting in partial or complete glaciations. Warm topped clouds are likely to be dominated by liquid water, causing no glaciations below. This concept is reflected in the CTT membership function (CTT_{MAP}; Fig. **2**) [16].

CTT_{MAP} is set to 1,0 for CTT>0°C since such cloud tops will consist entirely of liquid, and remains 1,0 down to -12°C, because these tops are also likely to be dominated by liquid water droplets. CTT_{MAP} drops off with decreasing cloud top temperature, as cold tops are most likely to be dominated by the ice phase. CTT_{MAP} never becomes zero, even at very cold temperatures. Instead, it reaches a lower limit of 0,2 for CTT colder than -50°C. While very cold cloud tops certainly imply the presence of copious amounts of ice, the production of liquid water may exceed the depletion by scavenging in parts of the cloud, often due to strong lifting. Therefore, the icing potential cannot be completely shut off due to a low CTT [16].

Relative Humidity

The FIP relative humidity map (RH_{MAP}; Fig. **3**) represents the confidence that clouds (and thus, a chance for icing) are present between the cloud top and cloud or precipitation base. Ideally, the RH_{MAP} would be set to 1,0 for RH values of saturation only (100%) and 0,0 for all other values. However, moisture is a difficult field for the models to predict [16]. RH_{MAP} is generous. Distributions of positive icing PIREPs with model relative humidity have shown that icing is often reported with RH well below 100%. RH_{MAP} takes this into account, with interest beginning at 30%, growing

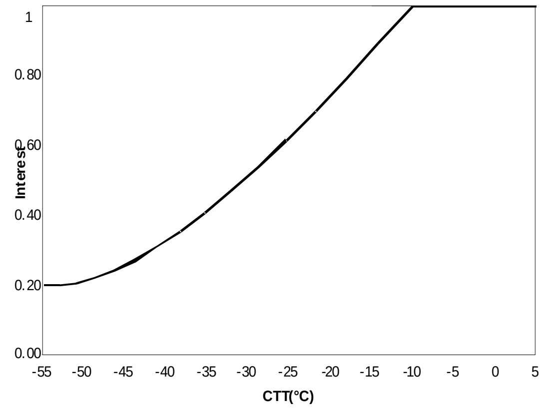

Fig. (2). FIP CTT_{MAP} for cloud top temperatures from -55 to 5°C.

slowly to 0,1 at 60%, and then ramping up quickly to a value of 1,0 at 95% [16].

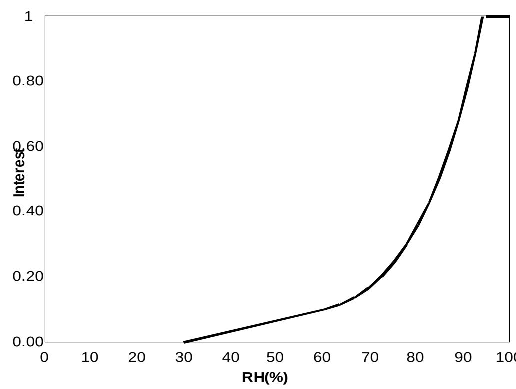

Fig. (3). FIP RH_{MAP}.

Vertical Velocity

Upward vertical motion lifts air, cools it, and increases its relative humidity, implying a stronger chance for SLW production. Downward vertical velocities tend to cause clouds to dissipate and SLW to decrease. Politovich *et al.* (2002) showed that 74% of icing PIREPs occur in rising air motions forecast by the Rapid Update Cycle (RUC) numerical model. The vertical velocity membership function (VV_{MAP}; Fig. **4**) reflects this, with positive (negative) interest for upward (downward) motion [16].

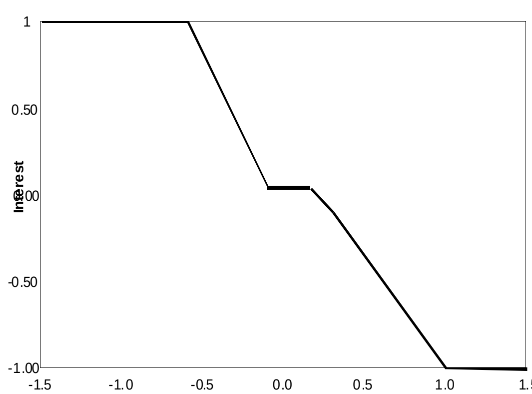

Fig. (4). FIP VV_{MAP} , negative VV values represent upward vertical motion.

In this study, fuzzy logic is used as a decision making method. Upper level icing potential forecast is selected as application subject and a method is developed for this forecast. Forecasting the meteorological processes such as icing which are very critical for aviation is always very difficult. For the difficult forecast conditions it is desired to combine the experiments of forecasters with some algorithms by technological developments on meteorology. Fuzzy logic has enough properties for meeting this requirements and it is a method of calculations based on a set of algorithms which mimic natural problem solving methods.

There are a lot of incomprehensible situations in weather forecasting. In some cases decision trees or flow charts are used. However, all these methods are based on classical logic.

In this study, the reason for selecting icing as a meteorological event is its critical role in aviation and the insufficiency of the currently used methods. Designed fuzzy inference system is explained in the annex.

The Software Calculating Icing Probability for Turkey

This software is developed in C++ programming language. The inputs for this program are temperature, cloud top temperature, relative humidity and vertical velocity values which obtained from a numerical weather prediction model called MM5. The software produces forecasts for the next 24 hours and for different standard atmospheric pressure levels. Horizontal resolution of forecasts is 7 kilometres. That is, the software produces outputs for every point on Turkey map with a space of 7 kilometres. After producing, these outputs are saved in a text file. The saved text files firstly converted into binary form by using a script [1] under Linux operation system. After converting the format into binary, by using a mapping library, coloured maps for every level and every time period is prepared again under Linux.

Standard pressure levels are used for meteorological applications generally. These standard levels are; 1000, 925, 850, 700, 500, 300, 200 and 100 hPa levels. In this study 1000, 925, 850, 800, 750, 700, 650, 600, 550, 500, 450, 400, 350 and 300 hPa levels are used. Because of there is no icing above 300 hPa level, the levels above 300 hPa is not considered.

Output Verification

There are two kinds of data which are used for icing information. The one of this data is real-time upper level atmospheric observations (SkewT LogP diagrams) which are carried out from the fixed stations for whole world. And the other is icing prediction information which is created by some algorithms using numerical weather prediction models' outputs as input. In Turkey, Turkish State Meteorological Service uses SkewT LogP diagrams for determining and forecasting icing. This method is based on atmospheric soundings which carried out from only 7 stations and twice in a day. This method is insufficient for representing the whole Turkey region and representing the future icing condition.

The software which created for this study uses MM5 numerical weather prediction model's outputs and produces outputs covering the whole Turkey region for the next 24 hours. MM5 numerical model produces outputs periodically for the fixed times of a day.

After the related inputs provided, the system processes these inputs and then produces "icing potential probability" output for several grid points covering whole Turkey with 7 kilometres resolution. The produced outputs are combined in an icing map. That is, system produces outputs for not only one point but for several points with a fixed resolution.

The outputs of icing potential are compared with the currently being used SkewT LogP diagrams. Besides, these outputs are compared with the icing probabilities created by European Centre for Medium-Range Weather Forecasts (ECMWF) and MetOffice (England) by using some formulas with numerical model outputs.

The produced icing potential outputs for the same date, time, location (İstanbul, Samsun, Ankara cities) and level with the mentioned three methods are compared with each other. Comparison was made with upper level atmospheric observation results for observation times. And for the time period which there is no real-time observation is available the comparison was made with ECMWF and MetOffice predictions. After these comparisons, it is determined that there is harmony between forecasts and real-time observations for forecast periods coinciding with real-time observations. The comparison results are given below in Table **1**.

The software was represented to Turkish State Meteorological Service Numerical Weather Prediction Department and then it is evaluated that this software can be used operationally after a trial period.

The advantages which are provided by this program are listed below;

- A new product which currently not exist
- Real-time observation data belong to current or past time and incapable to represent future situation. With this software it is possible to provide information belong to "future"
- Currently the upper level atmosphere observations are carried out from only 7 points but icing potential predicting algorithm produces several data covering Turkey with 7 kilometres
- It is possible to improve the algorithm by changing or rebuilding the rules
- An alternate to classical methods using linear equations and formulations which are insufficient to represent meteorological conditions
- In future, by using the algorithm explained in this study, it is possible to predict some other meteorological parameters

CONCLUSION

Nowadays, aeronautical transportation is indispensable for mankind. In spite of being the most reliable and fastest transportation kind, aviation has some disadvantages such as causing considerable loss of life and property in any risky

[1] Small command sets which works without compiling and operates specific functions or different program codes

Table 1. Comparison of Outputs Obtained from 3 Different Methods

Source of Icing Data	Location	FL100 (700mb) T+24	FL050 (850mb) T+24	FL100 (700mb) T+18	FL050 (850mb) T+6
Current Situation	**İstanbul**	No icing	%85	Observation is not made on this hour	Observation is not made on this hour
	Samsun	%20	%34		
	Ankara	%84	%54		
ECMWF	**İstanbul**	No icing	No icing		
	Samsun	No icing	No icing		
	Ankara	No icing	No icing		
MetOffice (England)	**İstanbul**			No icing	%70
	Samsun			No icing	%70
	Ankara			%70	No icing
Fuzzy Logic Algorithm	**İstanbul**	No icing	%38	No icing	%56
	Samsun	No icing	%55	No icing	%75
	Ankara	%65	%63	%70	%46,5

situation. From the aspect of aviation, one of the most important risks is icing. Icing causes loss of height, loss of control, impossibility of landing in case of accumulation on glass and in some cases falling down. Because of these considerable risks, icing prediction has vital importance.

In Turkey, for upper level atmospheric observations, 14 radiosonde balloons and transmitters are launched through the atmosphere daily. The approximate cost for one balloon and transmitter is 300 USD and this equipment is only for one use. That is, the total daily cost for radiosonde observation is about 14 x 300 = 4200 USD for Turkey. Because of being a member of World Meteorological Organization (WMO) Turkey has the liability of carrying out radiosonde observations. Besides, these observations provide input for the numerical weather prediction model. For these reasons radiosonde observations have to be maintained. Although it is impossible to cut off real-time observations, it might be possible to reduce observation number to one daily by this study.

By using satellite and radar data as additional inputs, more sensitive and more consistent predictions on icing may be provided for shorter periods (up to 30 minutes). For providing predictions covering longer periods and for increasing the reliability, some additional parameters such as water vapour extent in atmosphere and supercooled liquid water content may be included as inputs to icing potential prediction algorithm. Besides, the dimension of the liquid particles may be determined by using radar data and with this information icing severity information may be provided as an output.

With a different approximation, the steps of icing potential prediction algorithm may be used for cloud prediction with related inputs. After cloud prediction, by applying additional processes for the cloudy fields, more specific and more reliable icing potential prediction results may be obtained.

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