Meteorologische Zeitschrift, Vol. **24**, No. 1, 61–82 (published online January 13, 2015)

WHITE – Winter hazards in terminal environment: An automated nowcasting system for Munich Airport

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(Manuscript received September 24, 2014; in revised form October 24, 2014; accepted October 27, 2014)

Abstract

Winter weather is a decisive factor affecting the daily course of action at airports and causing delays or even safety hazards. Snow covered or iced aerodrome movement areas or aircraft require an initiation of counteractions on time. In order to minimize economic loss and to maintain safety, winter weather situations within an investigation area around an airport have to be detected and forecasted as precisely as possible. At the Department of Transport Meteorology of the German Aerospace Center's (DLR) Institute of Atmospheric Physics the winter weather nowcasting system WHITE (Winter Hazards In Terminal Environment) has been developed kindly supported by Munich Airport operations. Designed as an automated system WHITE assimilates multiple real-time data sources and assesses problematic winter weather aspects like the differentiation between snow and liquid precipitation, the identification of freezing precipitation and icing plus the rating of surface conditions. The innovative approach of WHITE, combining critical parameters for different predefined winter weather scenarios by means of Fuzzy Logic, classifying hazardous regions and generating winter weather objects, enables the determination of precipitation type and hazard's intensity. By nowcasting the current situation over a period of two hours it is also possible to estimate the beginning and the duration of hazardous conditions within the investigation area. In addition to the nowcasting system a participatory sensing approach is integrated within WHITE as a second main issue. The idea of this user-centered approach is based on the recent spread of high-capacity sensor-equipped mobile phones and the pervasive willingness of using the devices. Performance optimization, output evaluation and simplified handling with the system's output are the benefits resulting from the participatory sensing approach. In this work the basics, the data sources and development of the nowcasting system and of the participatory sensing approach are described. Additionally the results of two test campaigns during the winter months of 2012/2013 and 2013/2014 are shown and the system's capability is demonstrated with the help of significant case studies.

Keywords: winter weather, nowcasting system, fuzzy logic, airport, participatory sensing

1 Introduction

Skiing on a perfectly prepared slope – ice-skating on a frozen lake – a snowball fight amidst winter scenery. Who does not have one of these pictures in mind when thinking about a winter day? But winter also implicates less enjoyable characteristics. Defrosting the car in early morning or fighting against masses of snow are just two examples of how winter weather negatively affects our daily routine. Besides these unpleasant consequences there are considerable winter weather impacts on efficiency and safety of road and air traffic. Especially when roads or runways are snow or ice covered, there are frequently delays and safety hazards. In order to minimize economic loss and to ensure the maintenance of safety in winter weather situations, it is necessary to identify and predict atmospheric conditions as precisely as possible. This knowledge will help airport and road service operators to react to hazardous situations in sufficient time or at best to initiate counteractions in advance. The knowledge also helps to avoid expensive unnecessary alerting and provision of personnel and equipment. A survey at Munich Airport traffic control center resulted in several key problems during winter weather situations. Of particular interest for all stakeholders is the short-term forecasting, or nowcasting, of (Tafferner and Keis, 2012):

- Onset, duration and type of precipitation
- Icing at the surface
- Aircraft icing at ground
- Freezing Fog
- Visibility

Driven by the demand to detect and forecast the critical conditions the winter weather nowcasting system WHITE (Winter Hazards in Terminal Environment) has been developed at the DLR (Deutsches Zentrum für Luft- und Raumfahrt – German Aerospace Center) Institute of Atmospheric Physics. The research focuses on the TMA (Terminal Manoeuvring Area) of Munich Airport. In order to identify and nowcast winter weather scenarios like snow, mixed precipitation, freezing precipitation, ice pellets or icing, multiple data sources are considered. The innovative approach of WHITE, combining critical parameters for several winter weather scenarios by means of fuzzy logic, classifying hazardous

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DOI 10.1127/metz/2014/0651
Gebrüder Borntraeger Science Publishers, Stuttgart, www.borntraeger-cramer.com

regions and generating winter weather objects, enables to determine the precipitation type. Within an investigation area around Munich Airport the current winter weather situation is analyzed and nowcasted for the following two hours. The meteorological background of the WHITE algorithm is described in section 3 of this paper. The development of the system can be found in section 4. In section 2 the impact of and the measures against winter weather hazards at Munich Airport are specified.

In addition to the nowasting system a participatory sensing approach is integrated within WHITE as a second main issue. The idea of this user-centered approach is based on the recent spread of high-capacity sensor-equipped mobile phones and the pervasive willingness of using the devices. Especially, the phone-positioning capabilities, such as built-in GPS, in combination with virtually pervasive mobile Internet access, provide new opportunities. This trend of using mobile phones as ubiquitous sensing devices is called participatory sensing (Burke et al., 2006). Performance optimization, output evaluation and simplified handling with the system's output are the benefits resulting from the approach. WHITE applies the participatory sensing concept and invites users to upload their current position and the observed weather condition via specifically developed web applications. The basic idea and the realized concept aim at a win-win situation: The user-based weather reports are used to evaluate the predicted weather scenarios and in exchange users receive a local weather prediction for their current position. This concept and its background are outlined in section 5.

From December 2012 until March 2013 and from December 2013 until March 2014 two campaigns were conducted in order to test both the nowcasting part and the participatory sensing concept of WHITE in a quasi-operational mode. The DLR Institute for Atmospheric Physics, the Munich Airport operations (FMG: Flughafen München Gesellschaft), the German Air Navigation Safety Service (DFS: Deutsche Flugsicherung) at Munich Airport and the Aeronautical Meteorological Forecasting Group of the German Meteorological Service (DWD: Deutscher Wetterdienst) at Munich Airport took part in the participatory sensing component of the campaigns. Two case studies originating from the campaign and demonstrating the system's capabilities are described in section 6.

Winter weather is an extensively elaborated research topic. Because of its diversity, it is impossible to present a comprehensive overview about the current state of research in the context of this work. Nevertheless some scientific publications, which had an inspiring influence on the development of WHITE are being addressed at this point, in order to conceive the basic ideas of WHITE and in order to classify the work in a greater context. An important basis for WHITE are the works of Tafferner et al. (2003) and Leifeld (2004) about the ADWICE (Advanced Diagnosis for Aircraft Icing Environments) system and the works of Bernstein et al. (2005) and McDonough et al. (2004) about the CIP/FIP (Current/Forecast Icing Potential) systems respectively. Both systems investigate, identify and predict potential icing volumes with super-cooled large drops. The arrangement into different scenarios depending on the formation processes is adopted by WHITE and experience, definitions and limiting values had influence on the development of the fuzzy logic algorithms. As icing is only one part of WHITE, there are also inspiring works about weather objects, nowcasting systems, fuzzy logic and the combination of different data sources. The work at hand was generated within the framework of the DLR-Project Weather & Flying. Works conducted within this project provide the basis for the development of WHITE (for example Forster and Tafferner, 2012; Gerz et al., 2012b; Tafferner and Keis, 2012; Tafferner et al., 2012). Additionaly thunderstorm nowcasting systems producing weather objects have been developed in the recent past at the DLR (for example Zinner et al. (2008); Kober and Tafferner (2009)). This idea of weather objects and its clearness and intelligibility for potential users was adopted by WHITE. The publications of Rasmussen et al. (2001); Rasmussen et al. (2003) about the WSDDM (Weather Support to Deicing Decision Making) system and about the derivation of radar displacement vectors helped to identify important issues in terms of winter weather. The same is true for the works of Zerr (1997), Hauf and Brown (1998), Theriault et al. (2006); Theriault et al. (2010) and Schuur et al. (2012). In these papers vertical profiles of temperature and humidity and their connection to precipitation type are investigated. Furthermore the AVISA-System (Airport Vicinity Icing and Snow Advisor) by Isaac et al. (2006) has a similar motivation and approach as WHITE. A main element of WHITE is the survey of various winter weather scenarios in terms of fuzzy logic. For example the publications of Hansen (1997); Hansen (2007) and Mueller et al. (2003) illustrate the benefit and the use of fuzzy logic for meteorology. In terms of combining different data sources and nowcasting key parameters the development of WHITE was inspired for example by Bailey et al. (2012) and Isaac et al. (2012).

2 Munich Airport and winter weather

In order to minimize economic damage, large airports have to be well prepared for typical weather situations of their climatic region. Thoroughly elaborated schemes provide for a standardized sequence of counteractions. Munich Airport, located in the northern mid-latitudes about 80 km north of the Alps in the south of Germany, has to deal periodically with winter weather impacts.

From December 1, 2011 to March 31, 2012 the runways at Munich Airport had to be closed 93 times on 24 days. The accumulated closing time was 36.5 hours. Overall 38.5 cm of snow were measured, of which 22.5 cm fell in February. A quantity of 7,724 de-icing and anti-icing actions had to be conducted.

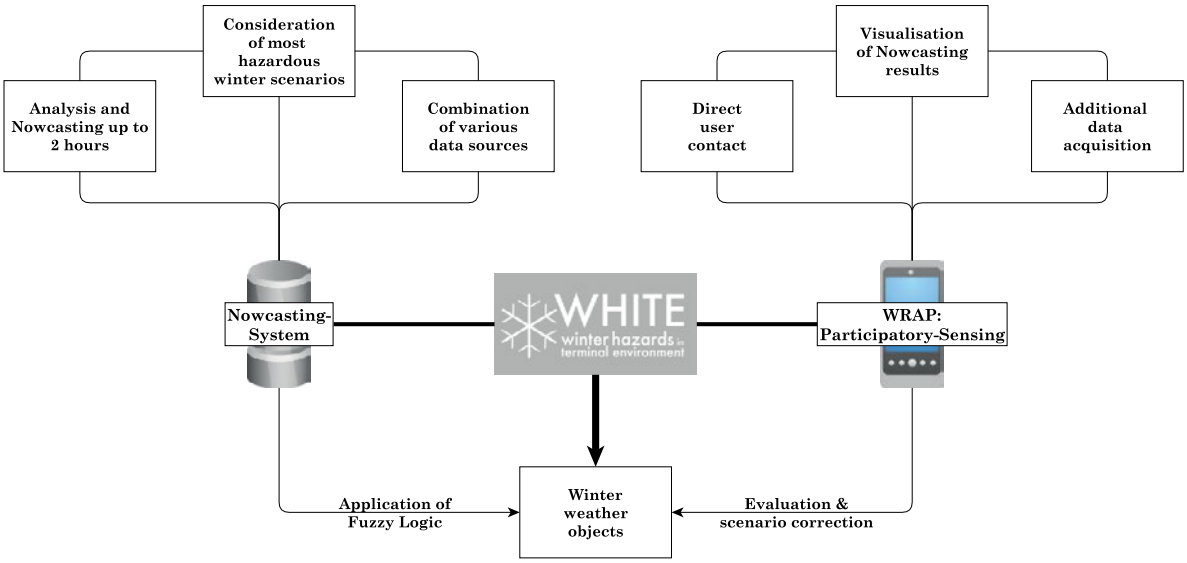

Figure 1: Schematic illustration of the WHITE system.

In statistical terms the winter 2012/2013 was one of the harshest since the construction of the new Munich Airport in 1992. The accumulated snow amount was 107 cm, 50.5 cm of which fell in February. On 72 days the runways had to be closed 158 times, the total closing time was 65.5 hours. In the investigation period, 13,096 aircraft had to be treated with de-icing and anti-icing fluid.

The winter 2013/2014 was somewhat out of the ordinary. Very little adverse effects were observed in these winter months. Only 15 cm of fresh snow were measured in the period from December to March. In the period January 25th until January 27th the amount of fresh snow alone was 11 cm. Overall the runways had to be closed 25 times on 14 days for an accumulated closing time of 8.3 hours. Because nearly all of the closing occurred during night, when there is very little traffic, no negative impacts could be observed. The number of icing actions was very small as well, compared to the previous years. Only 5,728 actions had to be conducted. In Fig. 2 the monthly total amount of de-icing actions and runway closures are shown for the three investigation periods.

If taxiways, apron areas or runways are snow or ice covered, the friction coefficient of vehicles is modified and the braking behavior is limited. In such a situation the weather-related closing of a runway is decided following the investigation of friction coefficients and braking values by test drives. In specified winter situations test drives are performed constantly. Measurements of visibility and height of surface contamination help to decide, whether a runway has to be closed and ploughed. For example at Munich Airport a runway is closed when more than 25 percent of its surface is covered by more than 15 mm of water, slush or wet snow and 60 mm of dry snow, respectively. In case of a winter hazard, several coordinated working teams are able to plough

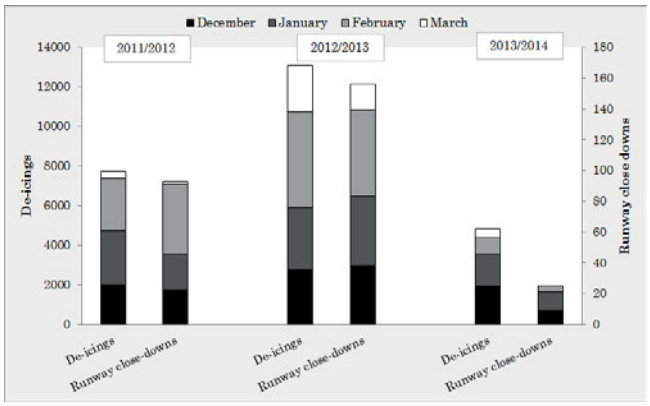

Figure 2: De-icing operations and runway closures at Munich Airport in the winter months of 2011/2012, 2012/2013 and 2013/2014.

one runway within twelve minutes. During ongoing hazardous conditions both runways are ploughed in turns, to maintain the airport operations as effectively as possible. The winter services are on standby from November 1st until April 30th. In case of a winter hazard the service is informed in time if possible. Then the service is able to best deal with the situation. For the operations there are more than 100 special-purpose vehicles like snowploughs, snowblowers and spreaders available. The collected snow is hauled to one of the six snow dumps with a total capacity of 87,747 m^3 (MUC, 2012).

But not only the movement areas are impacted by winter weather. Aircraft residing at the airport at the time in question are affected as well. Even a fractional freezing on the wings can change the aerodynamics of the machine and reduce the lift or increase the drag. Both result for example in an increased stall speed and has to be compensated by amplified propulsion and additional fuel consumption. In addition to these aerodynamic impacts there are other potential dangers. For example ice

layers can break during take-off and be sucked into the engine causing damage. The icing of measuring instruments may cause incorrect information about altitude, speed or stalling angle. Icing of aircraft on the ground can occur at areas unprotected by integrated de-icing equipment. The influence on flight characteristics may not be tested and certified in a sufficient way (Cober et al., 2009). For this reason all aircraft are only allowed to take off, if both the wings and the fuselage are clear of snow and ice. In case of a winter weather situation, aircraft have to be de-iced before take-off. In specific hazardous situations they also have to be treated with anti-icing fluid afterwards, in order to prevent a renewed icing (ICAO, 2000). For this reason twelve de-icing areas exist at Munich Airport. They are located at the runway heads. So depending on the take-off direction, six of them can be in use simultaneously. In these areas aircraft are cleared of ice and snow close to take-off. The main advantage of the areas is their proximity to the runways. The hold-over time of the anti-icing fluid is usually not exceeded. For example a fatal aircraft accident at Denver, Colorado on November 15, 1987 illustrates the importance of complying with this hold-over time. After being treated with anti-icing fliud, the aircraft had to wait for the clearance for take off and the fluid's hold-over time was exceeded. During heavy snow a contamination layer accumulated on the maschine, which resulted in the airplane's crash shortly after take off (NTSB, 1988).

3 The meteorological basics of WHITE

Winter hazard is not a uniquely defined term. It paraphrases the phenomena snow and freezing precipitation, but it also paraphrases riming or icing in common usage. Not uncommonly a drop of temperature also can be described by the term winter weather succinctly. Within WHITE the winter hazards snow, freezing precipitation, ice pellets, mixed precipitation and icing with supercooled large drops and their formation mechanisms are covered. This section is supposed to present a meteorological basic understanding of the cloud physical and mesoscale processes in the atmosphere leading to winter hazards and to explain their threat for air traffic and airports.

Because winter weather occurs both in combination with liquid and solid precipitation, a basic outline about the formation of clouds and precipitation is necessary. For a cloud to form, it is necessary for a volume of moist air to be cooled below its dew point. In the atmosphere, the most prevalent mechanism for a parcel of moist air to be cooled below its dew point is via the approximately adiabatic expansion of ascending air, although it can be caused also by radiative cooling or due to the mixing of air parcels with different temperatures and moisture contents. In such a supersaturated air, cloud droplets may form by heterogeneous nucleation. This microphysical process describes the condensation of water on a foreign substance or surface. In the atmosphere aerosols like salt and dust particles, raised from the earth's surface by turbulences, sooty particles and ash, existing in the atmosphere due to forest fires, industry or volcanic events, and secondary particles, created by phase transformation processes of gaseous components of the air, serve as cloud condensation nuclei (CCN). At subfreezing temperatures ice particles are generated by homogeneous or heterogeneous freezing processes. Freezing of pure water drops doesn't occur at temperatures above about −40 °C and direct deposition of water vapor requires temperatures below −60 °C. Comparable to the CCN and their role at the drop formation process, ice nuclei (IN) serve as contaminants in the atmosphere and initialize the heterogeneous freezing process. There are several mechanisms of the heterogeneous freezing process: Contact freezing, immersion freezing, condensation followed by freezing and heterogeneous deposition. Although the appearance of IN is quite infrequent especially at high subfreezing temperatures, clouds typically hold a large amount of ice crystals at temperatures below −15 °C. Nevertheless supercooled liquid water still can be observed in the atmosphere down to temperatures of −40 °C.

After exceeding a critical radius, liquid cloud elements grow even without a further increase of the saturation ratio. However the development of rain drops exceeding a radius of 1 mm typically can't be explained by pure condensation processes. Even in advantageous circumstances only the formation of drizzle drops holding a radius of about 100 μm is comprehensible. The enormous growth of the droplets and the formation of precipitation in winter in the mid-latitudes typically are explained by the detour to the ice phase. Collision and coalescence are subordinated issues. After the development of first ice crystals in a cloud, there is no stable equilibrium between water drops and ice particles. The saturation vapor pressure over ice is lower than the saturation vapor pressure over water at low subfreezing temperatures. Each volume of moist air saturated with reference to water is supersaturated with reference to ice. A subfreezing cloud with both liquid and solid elements will turn into an ice cloud, because ice particles grow at the expense of the water drops. This process is called Bergeron-Findeisen-Theory. Depending on temperature and saturation ratio highly diverse shapes develop. These different particles can collide and aggregate with each other or with the remaining water droplets and grow to big snowflakes or porous sleet pellets respectively.

The development of clouds and precipitation is an elaborately investigated research topic. In this paper only a brief outline of the topic can be addressed. At this point the interested reader is referred to the specialized literature (e.g. Rogers and Yau, 1996; Pruppacher and Klett, 1997; Wallace and Hobbs, 2006). One main issue in winter weather research is the type of precipitation. In most cases the precipitation type reaching the ground is of interest. For aircraft crossing the clouds or the layers of air beneath a precipitating cloud, the dif-

ferentiation of precipitation types in upper air layers is important as well.

In subfreezing clouds liquid precipitating particles can exist. At temperatures below −25 °C only very few liquid elements can be found. A critical parameter is the cloud top temperature (CTT). If the CTT is low, ice crystals are likely to form and to initiate the icing process. By implication warm values of CTT are an indicator for the predominance of super-cooled liquid water (Politovich and Bernstein, 1995). If solid precipitation particles don't cross warm layers of air on their way down, snow is expected to be observed at the ground. But if the particles fall through a layer of air with positive Celsius temperatures, they will melt completely or partly depending on the extent and intensity of the warm layer and on the saturation ratio. At the ground mixed or even liquid precipitation can be observed. If the CTT is greater than about −15 °C but still sub-zero, the coexistence of liquid and solid particles inside the cloud is likely and mixed precipitation is possible. In combination with strong winds inside the cloud, small porous sleet pellets as an alternative variant of mixed precipitation can develop. The development of freezing precipitation is typically explained by a vertical temperature profile with an enclosed warm layer of air. Solid precipitation, originating from cold layers above, melts inside the enclosed warm layer and super-cools in the cold layer underneath without changing the phase again (Bourgouin, 2000). These super-cooled drops freeze at contact on the ground or even on aircraft and pose a significant threat for traffic. If the near-ground cold layer of air is of great extent or of great intensity or if the solid precipitation doesn't melt completely inside the warm layer, the super-cooled drops may refreeze to ice pellets (Zerr, 1997). A characteristic weather scenario producing such temperature conditions area-wide is the passage of a warm front in winter. Advected warm air masses are lifted at the prevalent cold air and create the corresponding weather situation with an enclosed warm layer of air. A further mechanism producing freezing precipitation is the development of super-cooled drizzle drops by the collision-coalescence process (Bernstein, 2000). Probably about 25 % of all freezing precipitation events observed are connected to this process (Huffman and Norman, 1988). There are several studies presenting approaches to explain the development of precipitating freezing drizzle. The interested reader is referred for example to Cober et al. (1996) or Korolev and Isaac (2000). Even if the super-cooled drops are not large enough to precipitate, they may pose a significant threat for aircraft crossing the cloud, as they freeze on contact as well. These super-cooled liquid water clouds, typically stratiform and characterized by a clearly delimited cloud top, may also touch the ground and display freezing fog.

Independent from the formation process super-cooled large drops (SLD) with radiuses greater than 30 μm pose the particular threat of inflight icing. Its impacts can be compared to the surface-bound aircraft icing described in section 2. Because of their inertia, the SLD don't follow the air-current around a flying aircraft. They collide with aircraft and freeze at contact or even worse flow around the body or the wing and freeze at areas unprotected by deicing systems, which naturally are installed at the wing leading edges.

4 The nowcasting system of WHITE

The nowcasting system is the main part of WHITE. Short-term two hour forecasts are calculated in addition to an analysis of the current winter weather situation. The system has a modular construction. Its schematic concept can be seen in Fig. 3.

4.1 Module 1: Data sources

To make a correct statement about winter weather on the ground for the daily routine, it is essential to include the air mass above the ground into the investigation where precipitation is generated and phase changes are occuring. In order to ensure a thorough investigation, a combination of various data sources available in near real-time is implemented within WHITE.

One data source is the regular groundbased observations and measurements from about 280 manned and unmanned weather stations of the German Meteorological Service (DWD) within the investigation area. Data at the bottom and the top of the hour were provided for the research on WHITE. Additionally data from the automated SWIS (Straßenzustands und Wetterinformationssystem – Road weather information system) stations, located at major roads and measuring temperature of air, surface temperature and humidity with a temporal resolution of 15 minutes, have been available as well.

In order to include information from upper layers of air, output from the numerical weather prediction model COSMO-DE is used. The non-hydrostatic COSMO model has jointly been developed by the Consortium for Small Scale Modelling and is operationally used by several European Meteorological Services. The COSMO-DE version is the high resolution model of DWD using a horizontal grid size of 2.8 km covering an area roughly 1,200 km ∗ 1,300 km in Central Europe (Steppeler et al., 2003). It is run every three hours and produces forecasts for the following 18 hours. WHITE uses the 30 lowermost main layers of COSMO-DE, which covers a height of about 8 km, and the newest forecasts of temperature and humidity available. Additionally surface temperature as well as temperature and humidity of air extrapolated for 2 m above the ground is used.

The third data source used in WHITE is the precipitation scan of the German radar composite RX. The precipitation scan is the radar measurement with the lowest elevation angle available and the best possible area-covering approach to the real precipitation situation. It is also provided by the DWD and is available each 5 minutes.

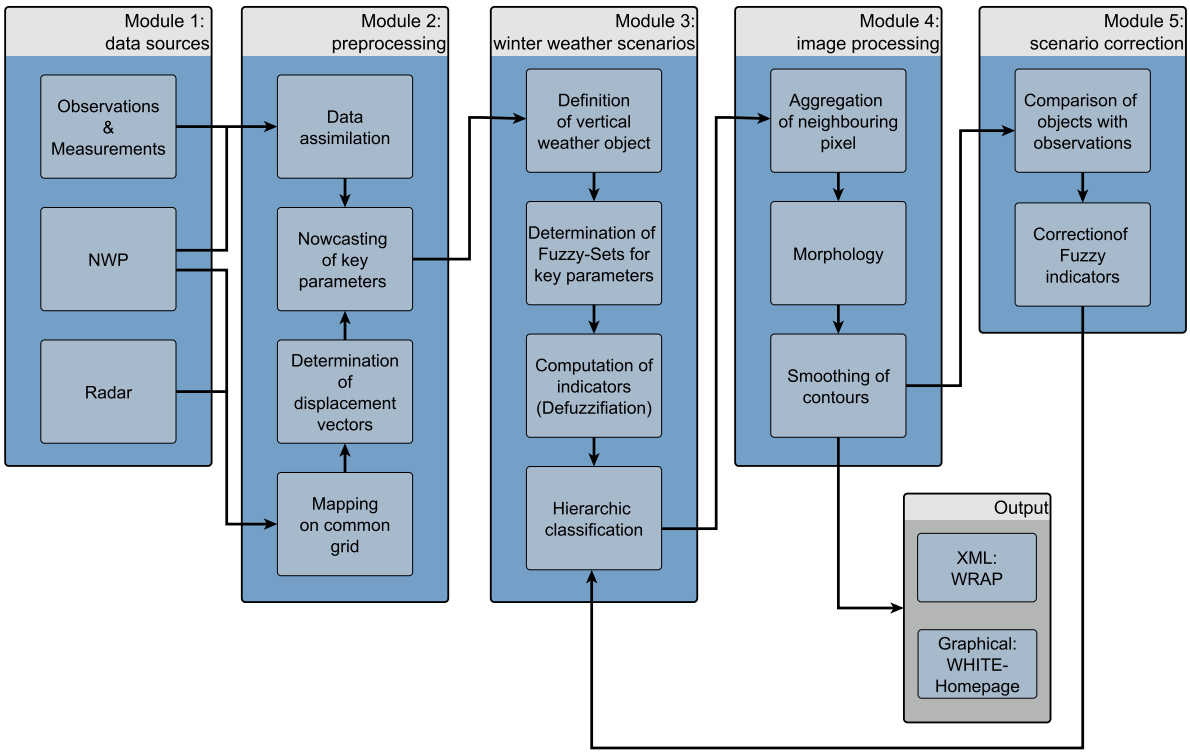

Figure 3: Schematic illustration of the nowcasting system of WHITE.

4.2 Module 2: Preprocessing and nowcasting of data

Typically very short range forecasts are derived from accurate assessments of current situations (Golding, 1998). But information from single points are insufficient in allowing weather nowcasting for a greater area. It is very difficult to derive forecasts only from measurements and observations, because advective processes or microphysical mechanism in upper layers of air remain unattended. There is lots of literature dealing with the derivation of area-wide information from local measurements of observation sites. Frequently a combination with NWP output is realized.

Prior to the fuzzy logic algorithms as core element of WHITE, all considered data are preprocessed. The aim of this preprocessing module is to obtain a uniform field of key parameters for each point in space and time and for each nowcasting time step. Within the WHITE algorithms the parameters temperature and humidity of air, surface temperature and radar reflectivity are processed. In order to get information from upper air levels, model forecasts from COSMO-DE are used as first-guess field. These first-guess fields are corrected by reference to the resource-efficient data assimilation technique of Cressman (1959) and extrapolated for the nowcasting time steps by reference to the ABOM (Adaptive Blending of Observation and Model) method of Bailey et al. (2012). The reflectivity field is mapped on the COSMO-DE grid and extrapolated for the nowcasting time steps by reference to the pyramidal image-matching algorithm of Mannstein et al. (1999).

COSMO-DE produces forecasts eight times a day for the following 18 hours. WHITE is operated with a temporal resolution of 15 minutes. However, output from COSMO-DE is available only hourly. For the intermediate points of time, forecasts from two convenient model prediction fields are interpolated linearly. The same applies accordingly for the nowcasting time steps. The analysis first-guess fields of temperature and humidity, including extrapolated data fields for 2 m above the ground, as well as fields of surface temperature are corrected with current observations by reference to the Cressman interpolation-scheme. This scheme is sufficient for the WHITE system because of its low numerical effort and its efficiency in terms of computation time. For each point in the model grid, a weighted mean correction value is calculated from the surrounding measurements. Only measurements within a prior defined radius of influence are considered. The weight of the value for the bottom layer and the surface layer depends on the horizontal and vertical distance between grid point and observation site, in order to take into account the height differences of grid points near the Alps. This value is pro rata adopted for the remaining model layers depending on the current vertical pressure distribution.

According to the forecasting period either information from observation or from NWP output are appropriate to predict atmospheric changes. For a short period of time, forecasts derived from the persistence or the trend of observation are suitable, whereas for longer periods model output is the better approach. The period of time marking the boundary between the two methods is not an absolute term. It varies from case to case depending on time of the day, time of the year and weather situation. An effective blending method, which is the combination of observational information and model forecast, should consider this variability. The ABOM method calculates the accuracy of previous forecasts, taking into account the trend derived from successive analysis fields, the persistence of these corrected fields and NWP forecasts for the correspondent time step. The corrected analysis field of the current point of time is compared to the results of the different methods and standardized weighting factors for the blending of the different fields are defined for the nowcasting steps in consideration of absolute error and variance. Equation 4.1 illustrates the basic approach of the ABOM method.

$$V = O_O + q\Delta O_P + s\Delta O_T + r\Delta M, \qquad (4.1)$$

where V is the nowcasting value of a variable at a specified lead time, O_O is the present observational value of the variable, ΔO_P is the predicted change of the variable by observation persistence (by definition zero, but formally part of the equation), ΔO_T is the predicted change of the variable by extrapolating the observation trend, ΔM is the predicted change of the variable by NWP model and q, s and r are the weighting factors, which summate to 1. Additional details can be found in Bailey et al. (2012). The application of the ABOM method in WHITE produces nowcasting fields of all variables for each time step and lead time respectively. By checking these fields against groundbased measurements it can be shown that the forecast quality is improved compared to pure model forecast or pure extrapolation of observation trend (see Fig. 4a to c).

The precipitation scan reflectivity field from the German radar composite is mapped on the COSMO-DE grid. For each grid point of the COSMO-DE grid the nearest grid point of the higher resolved radar grid is identified and its reflectivity value is adopted. By this operation some raw information is lost, but, as no data are changed by interpolation, the general structure of the reflectivity fields is conserved. The nowcasting of the reflectivity fields is based on the pyramidal image-matching algorithm, which compares two consecutive data images and derives displacement vectors for each pixel by minimizing the squared difference between the pixel of both images or by maximizing the correlation coefficient. In order to consider that small scale developments of the precipitation field can be superposed by large scale synoptic fluctuations, a stepwise or pyramidal method is implemented. Initially images with a coarser resolution are produced from the original images by averaging over 2^N pixel. In these images coarse movement structures can be found. Each pixel is shifted to each horizontal direction and the best agreement with the consecutive image is determined. Afterwards the array of displacement vectors is interpolated to the maximum resolution. This procedure is repeated for N steps

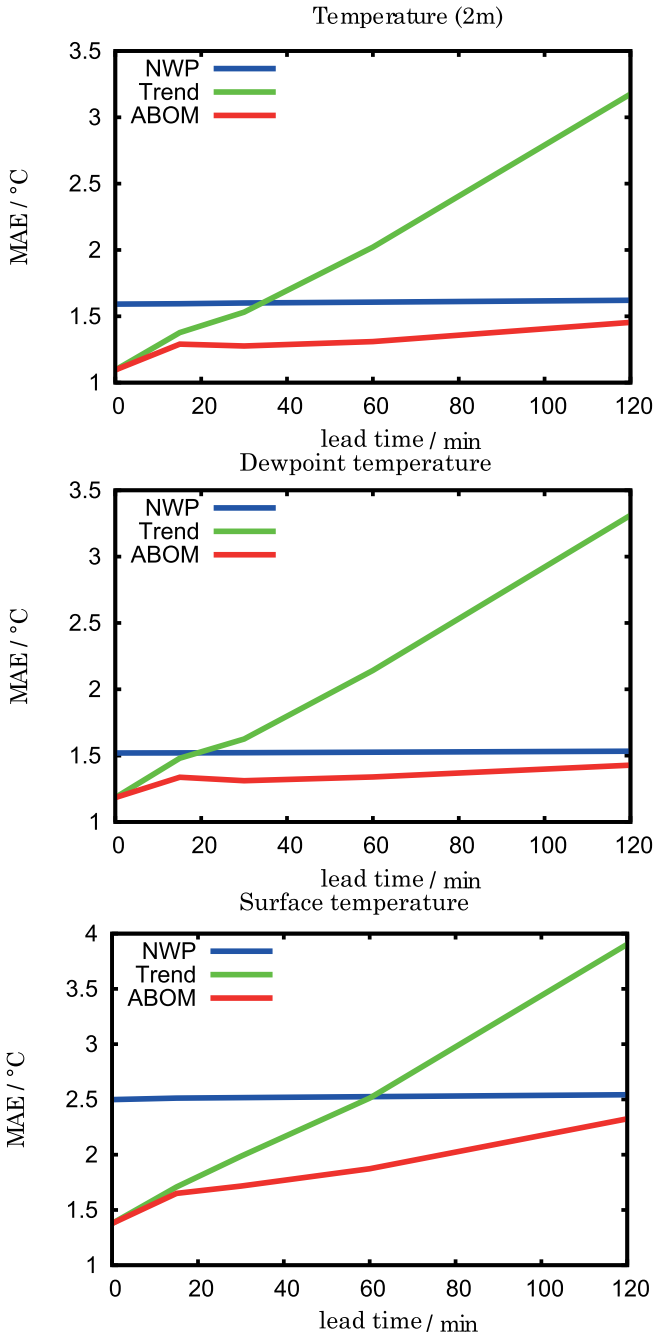

Figure 4: Mean absolute error (MAE) of different forecast methods. For the variables temperature in 2 m above the ground (a), dewpoint temperature (b) and surface temperature (c) nowcasting fields of ground near layers are compared to measurements. The errors are time-averaged over the period of the campaign 2013/2014 and spatially averaged over the investigation area. For short lead times the extrapolation of observation trend is predominating whereas for longer lead times the ABOM method tends to the model forecast. For all lead times the forecast quality is improved.

on gradual higher resolved images. The final displacement vector field includes information from different scale ranges and is extrapolated into the future. Additional details can be found in Zinner et al. (2008). In WHITE, extrapolated reflectivity fields for the nowcasting time steps +15, +30, +60 and +120 minutes are calculated by using a weighted mean of multiple consecutive preceding images and by implementing the pyramidal image-matching algorithm with $N = 3$ resolution iterations.

4.3 Module 3: Winter weather scenarios, the use of fuzzy logic and computation of vertical weather objects

WHITE considers the winter weather situations snow, mixed precipitation, freezing precipitation and icing with SLD. In order to best understand these situations, the independent scenarios *Warm Nose*, *Snow/Rain*, *Icing (SLD)*, *Evaporation* and *Surface* are defined, dissecting their microphysical formation processes into key parameters. The purpose of the system is the nowcasting of hazardous winter weather situations. So the decisive factor for all key parameters has to be their availability in near real-time. The determination of mathematical fuzzy sets and the calculation of indicators for each scenario are the next ingredients of the procedure. It is executed for both the corrected analysis arrays and the derived nowcasting fields alike. The basic idea of the scenarios is the investigation of vertical profiles of temperature and humidity and the identification of key sections. These sections are probably enclosed warm layers of air, cloud tops or cold layers of air on the ground. By identifying them, it is possible to define vertical weather objects for each profile, which clearly describe the weather activity in different height levels. By combining neighboring objects afterwards, it is possible to create horizontal polygons in each level and to conduct an area-wide investigation, including a prediction about propagation direction and speed or validity period.

In contrast to the conventional Boolean logic, where only the two statements "true" and "false" are allowed, fuzzy logic is capable of handling partial true or false. In certain situations fuzzy logic provides more opportunities than the Boolean logic and is applied as a matter of course in everyday life. For example, during a winter weather situation with very few snowflakes conventional logic only offers the two statements "snow" or "no snow", whereas fuzzy logic also enables statements like "marginal snow", "little snow" or "heavy snow". This common linguistic use of fuzzy logic is translated into mathematical terms applying the fuzzy set theory, which was first published by Zadeh (1965) almost 50 years ago. Since then, the fuzzy logic found its way into different fields of life like control engineering, traffic-control systems or meteorology. Fuzzy logic is also capable of handling various ambiguous input information and of producing one accurate output value. This output value indicates, which decision is to be expected under the existing initial situation and is called "indicator" in this work. The combination of input data can be described by three main steps:

- Fuzzyfication: Definition of membership classes and membership functions (also called fuzzy set functions) as fuzzy set for each input information
- Inference: Declaration of a combination rule-base and calculation of memberships to an output fuzzy set
- Defuzzification: Transformation of fuzzy information into a clear indicator

In WHITE symmetrical trapeze-shaped membership functions are used to assign membership grades of key parameters. The assignment and the combination rule base rest on cloud physical principles and on frequency distribution studies from data collected during winter 2011/2012 and 2012/2013 in the investigation area. The line of action and the realization of the three main steps are explained by means of the particular scenarios.

A typical feature of freezing rain formation is an enclosed warm layer of air. Solid precipitation originating in upper cold layers of air melts within the enclosed warm layer and becomes super-cooled in the bottom cold layer. Extent and intensity of both the warm layer and the bottom cold layer are the key parameters to determine the precipitation type on the ground and to distinguish between rain, freezing rain and ice pellets. Within the scenario *Warm Nose* the melting parameter β_m and the refreezing parameter β_f are introduced following the approach of Zerr (1997):

$$\beta_m = T_{\max} \Delta Z_m \tag{4.2}$$

$$\beta_f = T \Delta Z_f \tag{4.3}$$

The melting parameter is calculated onetime from the maximum temperature $T_{\max}$ within the warm nose and from the vertical distance ΔZ between the top and the bottom of the warm layer. In each model layer underneath an existing warm nose, the refreezing parameter is calculated analogously. The refreezing parameter is negative by definition, if the temperature has negative Celsius values, whereas the melting parameter is positive or nonexistent. Figure 5 shows schematically the definition of the vertical weather object within the scenario *Warm Nose*. On top of a warm layer with temperatures above 0 °C a relatively moist layer is searched where solid precipitation is likely to form.

In order to describe the key parameter's membership class, linguistic variables can be formulated. For example when considering freezing rain the melting parameter can be "too low", if solid precipitation is not melting completely inside the warm layer of air. On the other hand it can be "adequate", if the melting is thorough. The refreezing parameter can be "too low", if super-cooled drops refreeze to ice-pellets inside the bottom cold layer, or "too big", if the cold layer is not

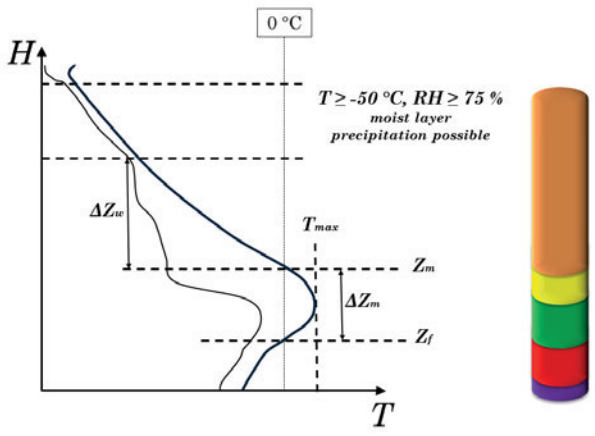

Figure 5: Vertical profiles of temperature (thick line) and dew point (thin line) as schematic illustrations of scenario *Warm Nose*. The color bars on the right symbolize the vertical weather object. Snow (orange) from upper air levels melts within the embedded warm layer of air to mixed precipitation (yellow) and to rain (green) afterwards. In the bottom cold layer this rain super-cools to freezing rain (red) and to ice pellets (purple).

sufficient to super-cool the melted elements. Alternatively it can have "adequate" values, if liquid precipitation elements become super-cooled within the bottom cold layer without changing the phase to solid. The formation of ice pellets and mixed precipitation follow the same principle. Ice pellets require at least a partial melting within the enclosed warm layer and an abundant refreezing layer. Incomplete melting facilitates refreezing, because in this case the partially melted particles still serve as IN. The refreezing parameter and melting parameter are either "adequate" or "too big". Mixed precipitation forms when the solid precipitation is not melted completely inside the warm layer and is not significantly super-cooled or further melted in the layers underneath. The refreezing parameter can be "too low", "adequate" or "too big", whereas the melting parameter has to regard "adequate" and "too big" values. The implementation of these membership classes, described by lingusitic variables, to fuzzy set functions is shown in Fig. 6 for each of the three sub-scenarios *Freezing Rain*, *Ice Pellets* and *Mixed Precipitation (WN)*. The definition of these membership functions is based on theoretical considerations, mainly oriented to results published by Theriault et al. (2006) and reviewed by case studies from winter 2011/2012 and winter 2012/2013.

In order to calculate concrete values indicating the likelyhood of formation of a certain weather situation, combination rules for each sub-scenario have to be defined. These rule bases represent conditional relationships, which consider meteorological expert knowledge, results from cases studies and longtime experience. The number of relationships matches the number of combination possibilities of the membership classes involved. For the formation of freezing precipitation and mixed precipitation there are $2 * 3 = 6$ relationships each, whereas the investigation of ice pellets requires $2 * 2 = 4$ equations. If a combination produces contradictory statements, it is allowed not to consider this possibility or to reduce its importance. In WHITE suchlike contradictory statements are avoided by the appropriate choice of key parameters. The conditional relationships of the scenario *Warm Nose* and of the scenarios following are illustrated in Fig. 7.

By executing the conditional equations an assessing output fuzzy set is created. This compilation is called inference. WHITE deploys the Min-Max-Inference. Each combination possibility is assigned to a membership class of the output fuzzy set, again described by a linguistic variable. The minimum membership grade, defined by the particular membership functions, determines the degree of assignment. After completing with all conditions, the maximum value of each output membership class is identified and by applying the center of area method (see e.g. Klir and Yuan, 1995; Ross, 2010) the significant indicator is calculated.

With the help of Fig.s 8a to c the proceeding is explained exemplarily. For sub-scenario *Freezing Rain* of scenario *Warm Nose* the fuzzy sets functions are defined. If the melting parameter has a value of 0.4 km°C, a value of 0.6 is assigned to the membership class "too low" and a value of 0.4 is assigned to the membership class "adequate". In this example the refreezing parameter has a value of −3.5 km°C. The membership value of class "adequate" is 0.25, whereas the membership values of the classes "adequate" and "too big" are 0.75 and 0 respectively. The rulebases from the first, the third, the fourth and the sixth line of the left part of Fig. 7a have to be considered. The degrees of assignment to the output membership classes are identified by the minimum membership grade of each rulebase:

$$\begin{aligned} FZ\ low &= min[too\ low(\beta_m), too\ low(\beta_f)] \\ &= min[0.6, 0.25] = 0.25 \\ FZ\ neutral &= min[too\ low(\beta_m), adequate(\beta_f)] \\ &= min[0.6, 0.75] = 0.6 \\ FZ\ neutral &= min[adequate(\beta_m), too\ low(\beta_f)] \\ &= min[0.4, 0.25] = 0.25 \\ FZ\ very\ high &= min[adequate(\beta_m), adequate(\beta_f)] \\ &= min[0.4, 0.75] = 0.4 \end{aligned}$$

There are two entries to output class "FZ neutral" in this example, from which the maximum value is used. The value of class "FZ neutral" is assigned with $max[0.6, 0.25] = 0.6$, whereas the classes "FZ low" and "FZ very high" are allocated with 0.25 and 0.4 respectively. These values are used during the defuzzification and transformed to a clear indicator by applying the center of area method. As graphically depicted in Fig. 8c the output fuzzy set's triangles are cut off at this membership value and trapezoids of different heights evolve. These trapezoids are taken as connected area

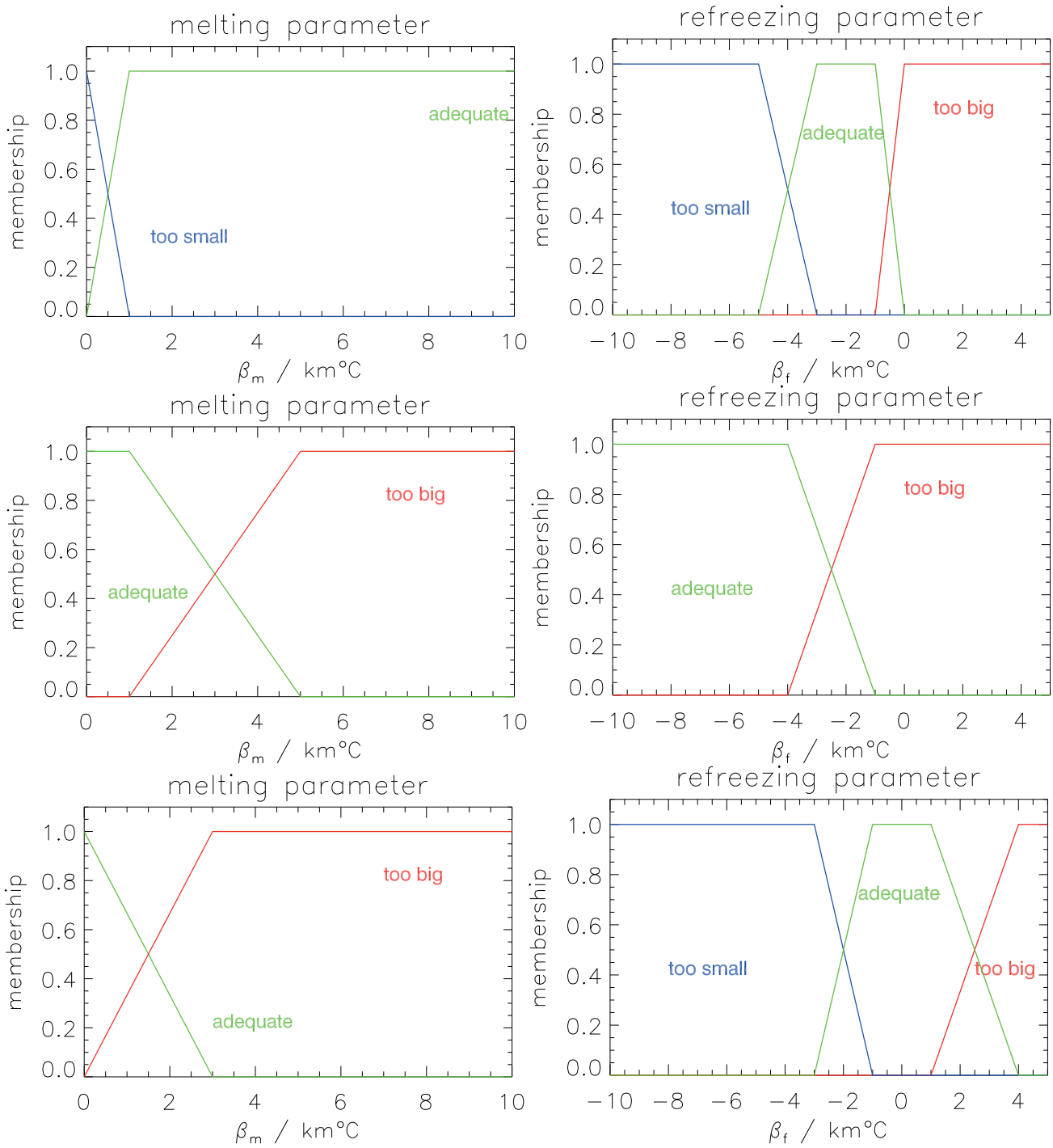

Figure 6: Fuzzy set functions for WHITE scenario *Warm Nose*. (a) and (b) show the functions for melting and refreezing parameters for the formation of freezing rain. (c), (d) and (e), (f) show both parameters for the formation of ice pellets and mixed precipitation, respectively.

and the center of area is calculated. The center of area's X-coordinate finally marks the defuzzification's output value.

The Scenario *Snow/Rain* describes the classical case of formation of snow or super-cooled liquid water via the cold-rain-process as addressed in section 3. Figure 9 shows schematically the approach of this scenario. In a super-cooled cloud solid precipitation particles are formed. In the example of Fig. 9 these solid particles melt within a bottom warm layer to mixed precipitation particles at first and with increasing fall distance to rain. As main key parameter the melting parameter is calculated in each model layer beneath the freezing line. As described in section 3 the CTT has a decisive influence on the precipitation type. So the CTT is identified as second main fuzzy input parameter. A cloud is assumed as moist layer of certain vertical extend. In winter, weather situations which possess several horizontal stratiform cloud layers one upon the other, are likely to exist. So within WHITE, the profile is searched for fur-

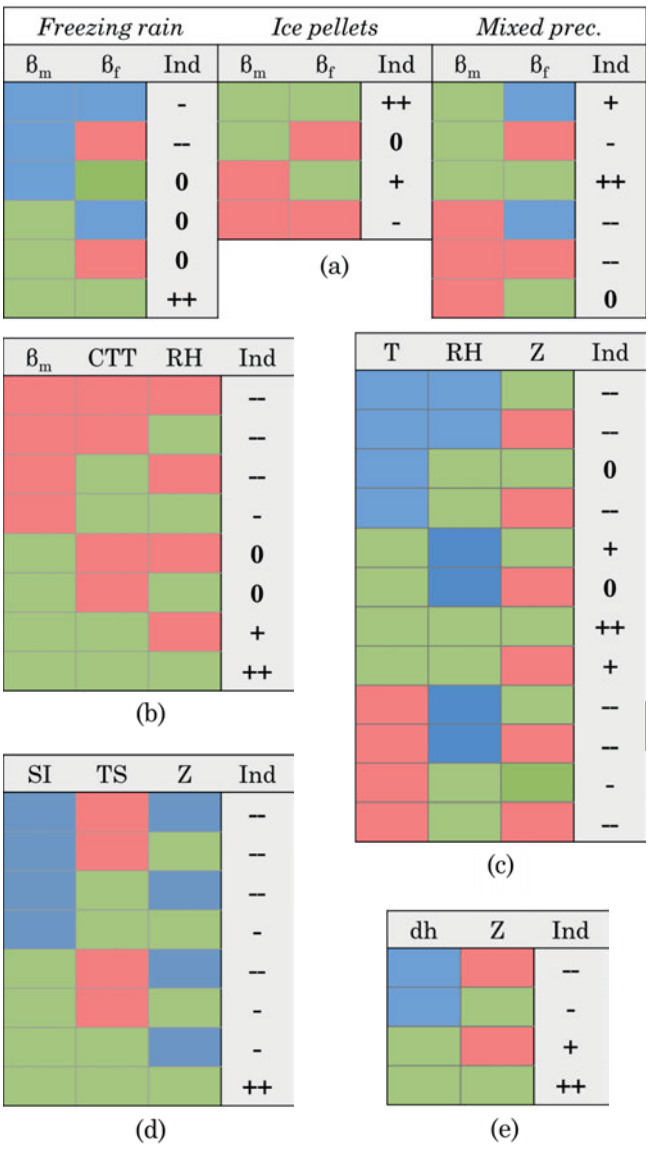

Figure 7: Rulebases of WHITE scenarios (a) *Warm Nose*, (b) *Snow/Rain*, (c) *Icing (SLD)*, (d) *Surface - Fresh Snow* and (e) *Evaporation* for the combination of the fuzzy set functions. Key parameters are melting parameter (β_m), refreezing parameter (β_f), cloud top temperature (CTT), relative humidity (RH), radar reflectivity (Z), indicator of scenario *Snow/Rain* (SI), surface temperature (TS) and vertical extend of a dry layer of air (dh). Colors correspond to linguistic variables used in the membership functions of the particular Fuzzy Sets (see Fig.s 6, 10, 12, 14 and 15). Each combination is assigned to a triangular output membership function, that can be described by the linguistic variables membership very low (–), membership low (-), membership neutral (0), membership high (+) and membership very high (++).

ther cloud layers and the CTT of the top layer is used. The third key parameter used by this scenario is the relative humidity in each layer of air. In a saturated environment no water evaporates, no heat is exchanged and the probability for further phase changes is decreased. Figure 10 shows the fuzzy set for the scenario *Snow/Rain*. For each parameter fuzzy set functions, described by the linguistic variables "adequate" and "too big", have to be regarded as described in terms of the scenario *Warm Nose*. In Fig. 7 the $2*2*2 = 8$ conditional relationships are illustrated. The further approach of calculating the significant indicator mirrors the line of action explained during the description of scenario *Warm Nose*. Similar to scenario *Warm Nose* the definition of the membership functions is based on theoretical considerations and reviewed by case studies from winter 2011/2012 and winter 2012/2013. The same is true for the adjacent scenarios.

A third scenario of WHITE covers the potential occurrence of SLD in stratified clouds. The basic idea of this scenario *Icing (SLD)* is the formation of nonprecipitating SLD via the coagulation mechanisms. As supercooled liquid water appears preferably at slightly negative Celsius temperatures, the temperature in each layer of air beneath the cloud top is identified as first key parameter. The cloud top in this scenario is defined by a distinct moisture gradient and a coexistent temperature inversion (see Fig. 11). The second key parameter is the relative humidity. The assumption is: The higher the degree of saturation, the higher the liquid water content. This simplified assumption is supplemented by the inclusion of radar reflectivity as third key parameter. Even SLD reaching a radius of about 30 μm are too small to produce clearly observable reflectivity structures. So a high value of reflectivity indicates a different formation process.

As illustrated in Fig. 12, three fuzzy set functions, described by the linguistic variables "too cold", "adequate" and "too warm", with regard to the temperature, two functions, described by the terms "too small" and "adequate", with regard to relative humidity and two functions, described by the terms "adequate" and "too big", with regard to reflectivity have to be considered. The $3*2*2 = 12$ relationships are illustrated in Fig. 7.

At low precipitation rates, liquid and solid elements can evaporate during their fall without reaching the surface. An enclosed or near-ground dry layer of air is required to observe this phenomenon. In the scenario *Evaporation* a dry layer is defined as volume with a relative humidity of less than 75 % (see Fig. 13).

The key parameters are the vertical extent of the dry layer and the radar reflectivity. The lower the reflectivity and the larger the dry layer of air, the more likely the evaporation process occurs. So two fuzzy set functions, described by the terms "adequate" and "too big", for the reflectivity and two functions, described by the terms "too small" and "adequate" for the vertical extent are used. The $2*2 = 4$ conditions and the fuzzy set are shown in Fig. 7 and 14 respectively.

For the airport operations, knowledge about the surface conditions on movement areas is significant. These conditions strongly depend on the surface temperature and on the precipitation type and intensity. In WHITE the accumulation of fresh snow and the danger of black ice are considered within the scenario *Surface*. Within the sub-scenario *Fresh Snow* surface temperature, radar reflectivity and the indicator of the scenario *Snow/Rain*,

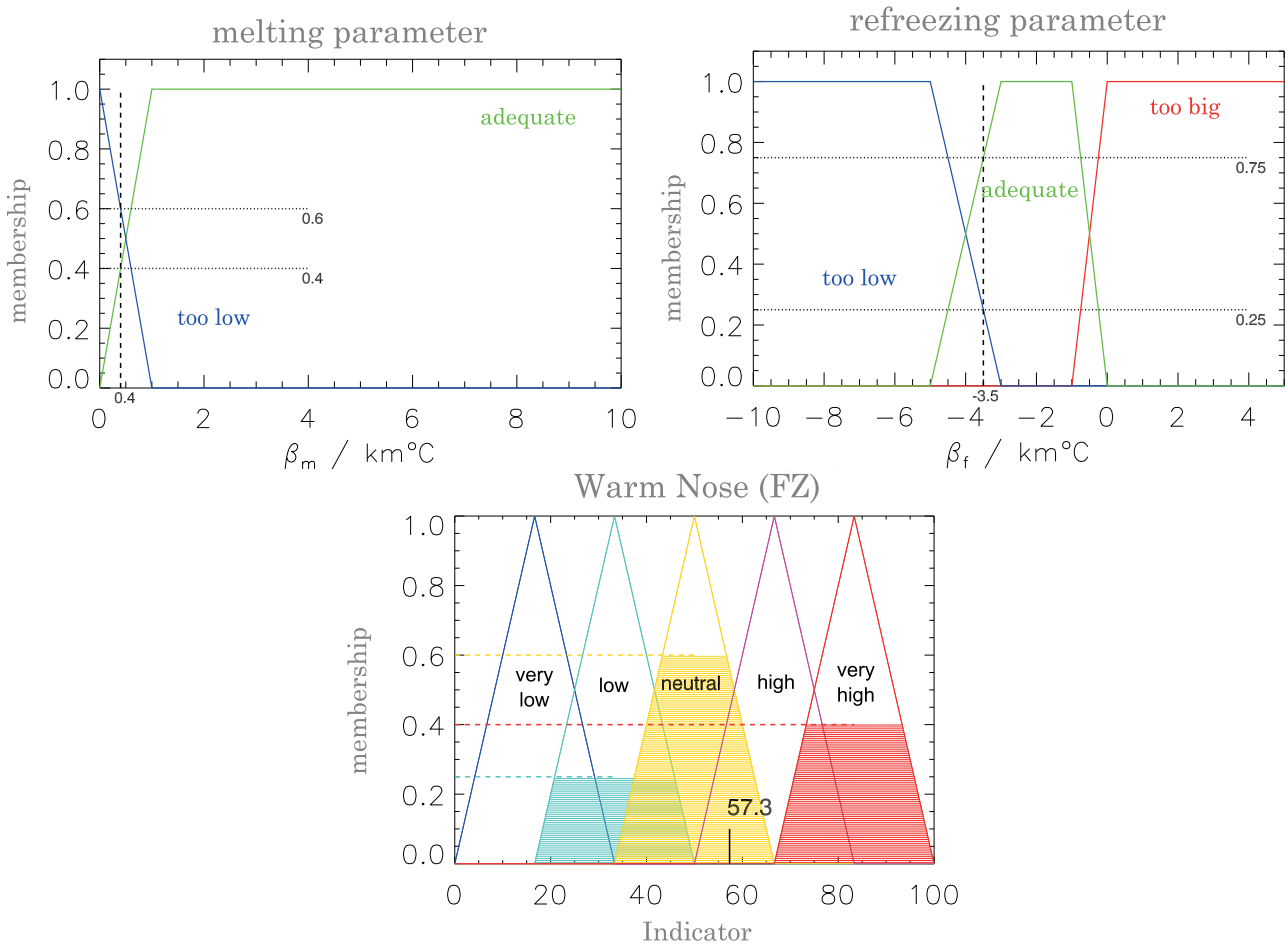

Figure 8: Examplaric illustration of fuzzification, inference and defuzzification in sub-scenario *Freezing Rain* of scenario *Warm Nose*. Figures (a) and (b) show the fuzzy sets for melting and refreezing paramters including example values. (c) shows the output fuzzy set for this sub-scenario. An indicator of value 57.3 is calculated as center of area from the combined trapezoids "FZ low", "FZ neutral" and "FZ very high".

Table 1: Main features of the nowcasting system of WHITE: Scenarios, key parameters and possible winter weather classes.

Scenario	Key parameters for fuzzy logic	Additional parameters	Possible winter weather class
Warm nose	melting paramter	radar reflectivity	*Freezing Rain*
	refreezing parameter	upper limit of humid volume of air	*Ice Pellets*
			Mixed Precipitation
Snow/Rain	cloud top temperature	radar reflectivity	*Snow*
	relative humidity	upper limit of humid volume of air	*Mixed Precipitation*
	melting parameter		
Icing (SLD)	temperature		
	radar reflectivity	highest stratiform cloud top	*Icing*
	relative humidity		
Evaporation	vertical extend of dry volume of air	lower limit of humid volume of air	
	radar reflectivity		
Surface	surface temperature		*Fresh Snow*
	radar reflectivity	indicators scenario warm nose	*Black Ice*
	indicator scenario Snow/rain		

calculated for the bottom model layer, are used as key parameters. The fuzzy set functions can be seen in Fig. 15, whereas the corresponding $2 * 2 * 2 = 8$ relationships are illustrated in Fig. 7. The sub-scenario black ice goes without fuzzy logic. A high indicator for freezing precipitation in the lowermost grid plane in addition with cold surface temperatures ($T_S < 1\,°C$) results in a black ice warning. The same is true, if warm liquid precipitation is expected and the surface temperature is less than 0 °C.

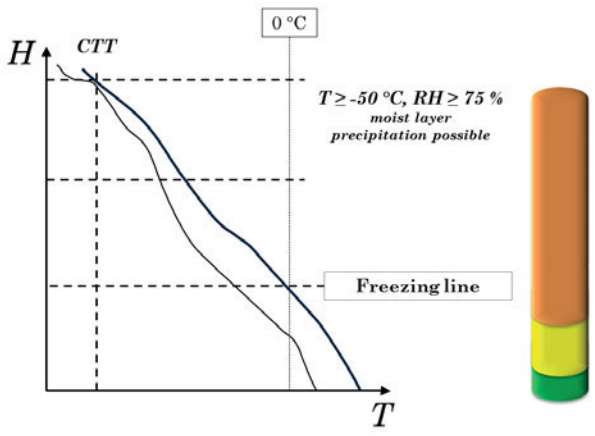

Figure 9: Vertical profiles of temperature (thick line) and dew point (thin line) as schematic illustrations of scenario *Snow/Rain*. The color bars on the right symbolize the vertical weather object. Snow (orange) from upper air levels melts within the warm layer of air to mixed precipitation (yellow) and to rain (green) afterwards.

The utilization of fuzzy logic results in significant output values, named as indicators in the framework of this paper. On the basis of these indicators a classification method is developed and applied in order to assign one explicit weather scenario to each grid point and to deduce vertical weather objects for each column. The tree structure of the classification is illustrated in Fig. 16. For grid points lying underneath the particular cloud top and above any evaporation layer, the classification is conducted. In order to gather a clear classification and to simplify the system's output with regard to potential users, boundary values (GW) for each scenario are introduced. During the quasi-operational testing phase of WHITE the value 50 for GW_{mix} and the value 66.66 for GW_{fz}, GW_{ip}, GW_{sn}, GW_{sld}, GW_{mp} were used. Ongoing studies at DLR are aimed at detecting the optimum value for each scenario. As can be seen in Fig. 16 the classes *icing in clouds*, *freezing rain*, *ice pellets*, *snow* and *mixed precipitation* can evolve. The precipitation situations *freezing rain*, *ice pellets*, *snow* and *mixed precipitation* are associated with a reflectivity greater than 1 dBZ and 7 dBZ respectively. *Freezing rain* is rated most hazardous for airports, so this branch of the classification tree is entered first. The indicators for *ice pellets*, *snow* and *mixed precipitation* are considered consecutively. The class *icing in clouds* is the only one using the reflectivity as part of the fuzzy logic method, so its classification is independent of reflectivity boundary values and conducted separately. Grid points classified as *icing in clouds* can be overwritten by any other class, because precipitation is regarded as more hazardous for air traffic and airports. If no indicator suggests a certain scenario but precipitation is observed by the radar network, the correspondent grid point is classified as rain.

4.4 Module 4 – Aggregation to horizontal weather objects

In order to receive area-wide information, grid points within one model layer sharing the same classification are aggregated to horizontal weather objects. The aggregation is conducted separately for each weather class and for each nowcasting time step. In a first step, each class is regarded as a binary image. Grid points holding a certain class get the value 1, the remaining pixels get the value 0. By Gaussian filtering the binary images created are smoothed and interfering structures are removed. The next step within this module is a dilatation. Dilatation is morphological image processing technique, which expands the binary objects systematically and closes perforated structures within the objects. Nearby objects are merged. In addition to the weather classes the surface layer is investigated and treated in an analogous manner. As the scenario *Surface* is directly linked to the output of the scenarios *Warm Nose* and *Snow/Rain* the surface objects perfectly correspond to the horizontal weather objects. A further layer of information can be attached.

4.5 Module 5 – Scenario correction

The precipitating weather objects *snow*, *freezing precipitation*, *mixed precipitation* and *ice pellets* of the lowermost model layer are checked for consistency with observation in this module. As *icing in clouds* by SLD is not directly linked to a clear weather observation it is excepted from the module scenario correction. The hourly observations originate from the manned and automated weather stations within the investigation area. Theoretically reports gathered by WRAP (see section 5) could be included here as well. The goal of this module is the correction of wrongly classified analysis objects. For each observation the nearest grid point is searched. If there is no matching object calculated for this gridpoint, the $11 * 11$ neighborhood of the grid point is scanned, in order to check if the object is only spatially displaced. If so, the classification of the $5 * 5$ neighborhood of the grid point and the corresponding vertical columns are adapted to the grid point column, where the classification was found to match the observation. For the nowcasting time steps the same grid points are adjusted. The same is true for the surface objects.

On the other hand, if there is a WHITE object calculated for the observational grid point, although no winter weather situation is observed there, the WHITE object is reduced accordingly. Analogously not the complete $11 * 11$ neighborhood may be located within the object and the $5 * 5$ neighborhood is adjusted to the values of the grid point column without classification.

After the classification adjustments the grid points are aggregated to horizontal weather and surface objects again. Module 4 is reapplied.

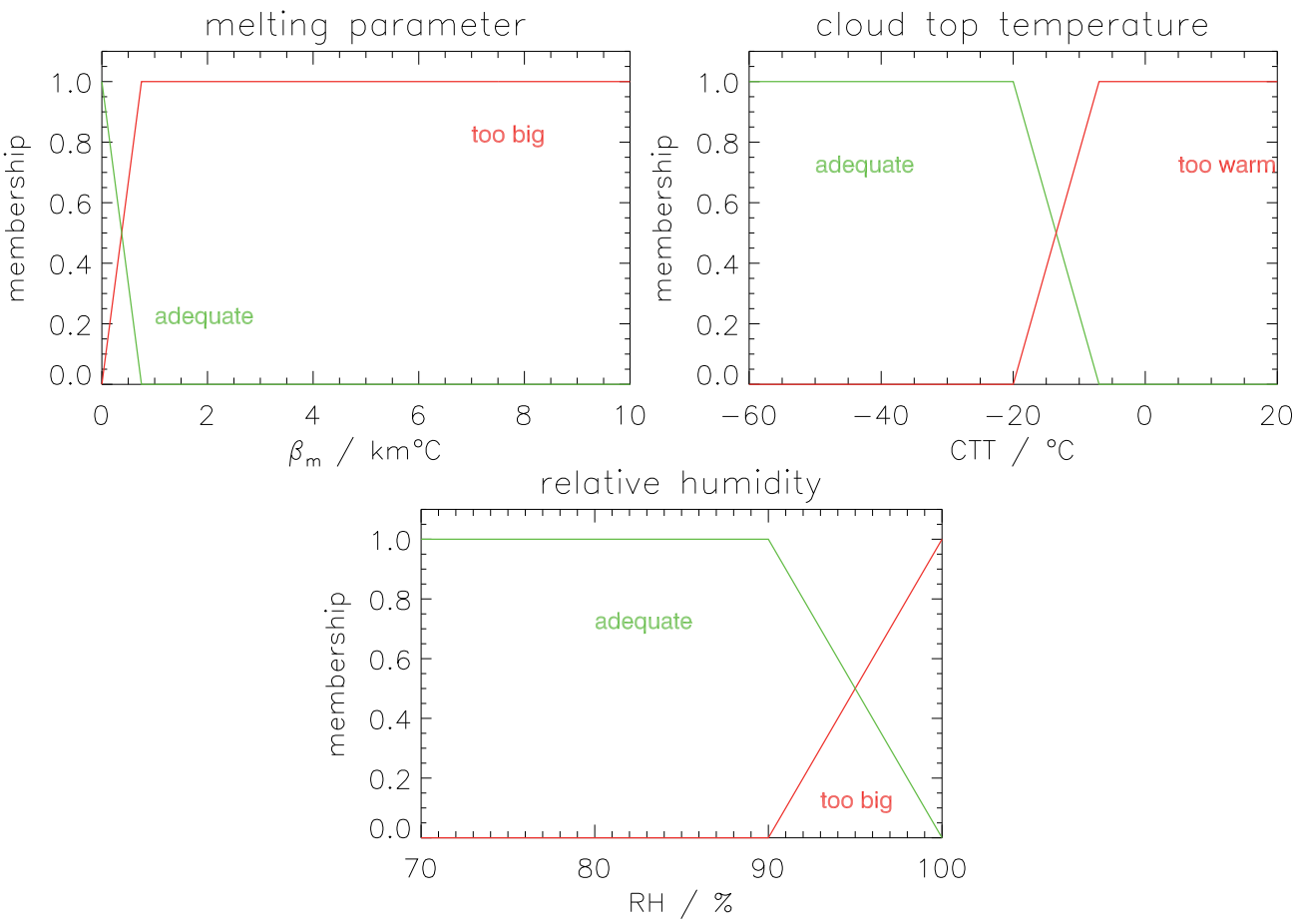

Figure 10: Fuzzy set functions for WHITE scenario *Snow/Rain*. (a) shows the functions for the melting parameter, (b) the functions for cloud top temperature (CTT) and (c) the functions for the relative humidity.

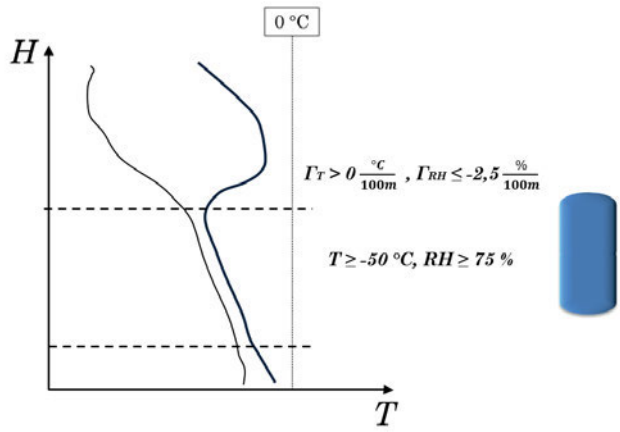

Figure 11: Vertical profiles of temperature (thick line) and dew point (thin line) as schematic illustrations of scenario *Icing (SLD)*. The color bars on the right symbolize the vertical weather object. Beneath a clearly defined cloud top there is icing hazard (blue) within the cloud.

5 The participatory sensing approach of WHITE

In addition to the nowcasting system a participatory sensing approach is integrated within WHITE as second main element. The idea of this user-centered approach is to simplify the data exchange between the nowcasting system and the participants of the campaigns and to simplify the handling of the system's output. An ancillary effect is the collection of additional data, which can be used for evaluation and for real-time correction of the WHITE objects. In fact, observations of the current weather situation are solely made half-hourly or to some extent even hourly. Hence a certain ambiguity about the system's reliability always remains for some part of its output. In order to reduce this limitation, the web application WRAP (Weather Report Application) was developed in the course of the WHITE research. The underlying idea is based on the recent spread of high-capacity sensor-equipped mobile devices that allow users to report weather observations from any location at any time. Especially, the phones' positioning capabilities, such as built-in GPS, in combination with virtually pervasive mobile Internet access, provide new opportunities. This trend of using mobile phones as ubiquitous sensing devices is called participatory sensing. WHITE applies the

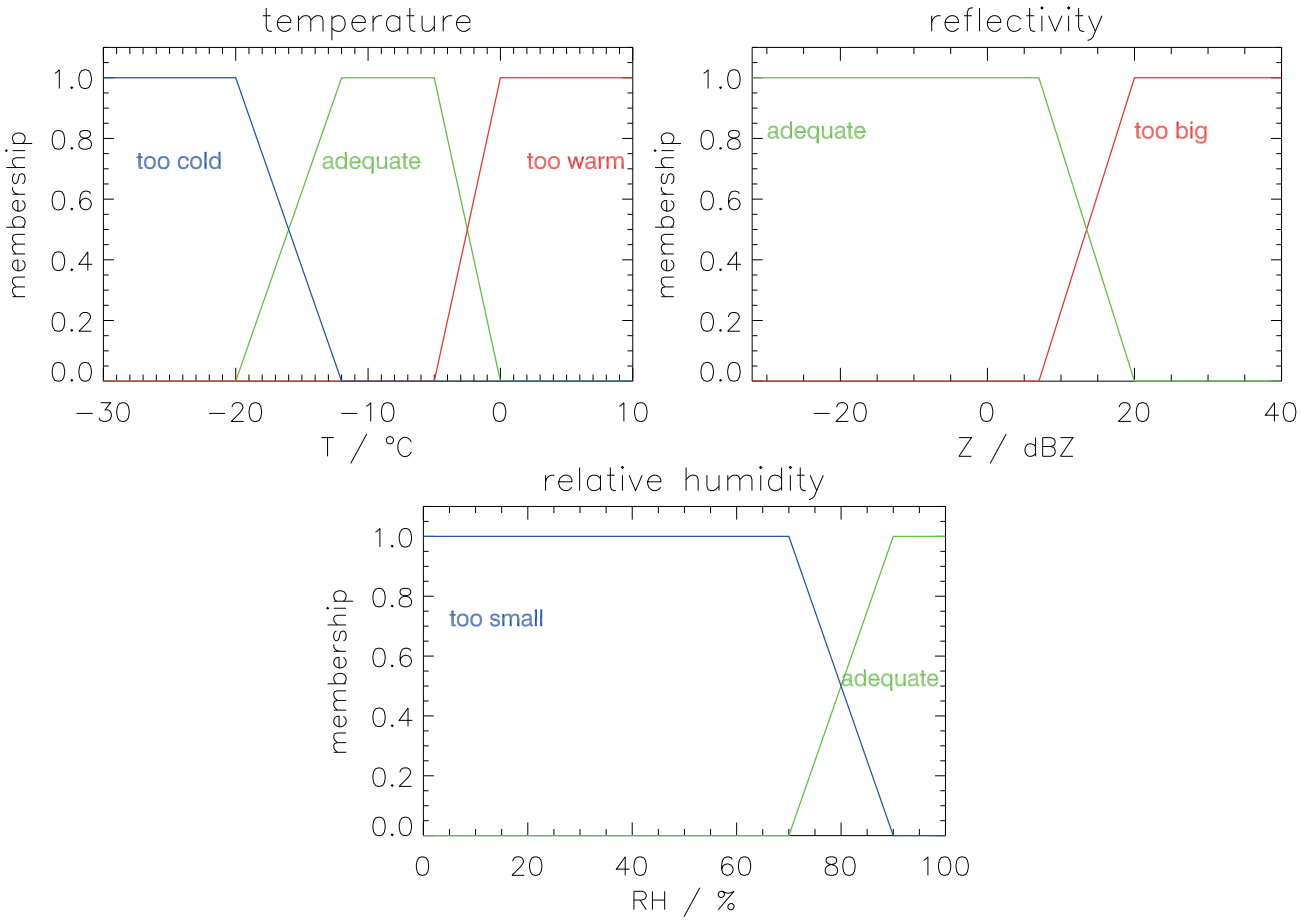

Figure 12: Fuzzy set functions for WHITE scenario *Icing (SLD)*. (a) shows the functions for the temperature, (b) the functions for radar reflectivity and (c) the functions for the relative humidity.

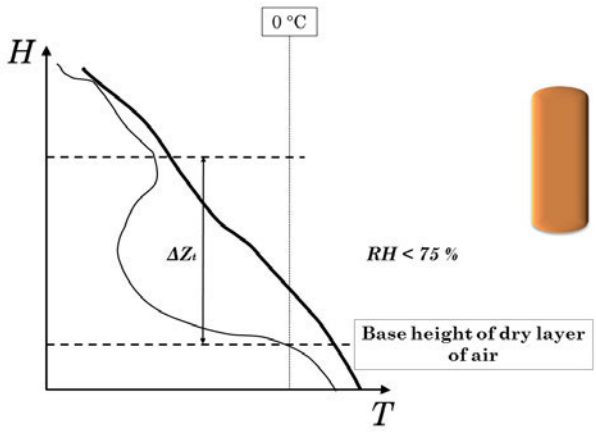

Figure 13: Vertical profiles of temperature (thick line) and dew point (thin line) as schematic illustration of scenario *Icing (SLD)*. The color bars on the right symbolize the vertical weather object. Snow (orange) from upper air levels evaporates within the dry layer of air.

participatory sensing concept and invites users to upload their current position and the observed weather condition via WRAP. The mobile version of WRAP is implemented as a HTML5-based web-app, that provides an adapted visualization for the users' local weather predictions. As response to submitted reports, users receive a local weather prediction for their current position from the nowcasting system. The basis for this data exchange is a PHP-based software accessing the XML files created by the WHITE nowcasting algorithm and saving the weather report information to the DLR system. The data transfer is implemented in AJAX, whereas the user interface is built using jQuery Mobile, a touch-optimized web framework for smartphones and tablets. The application and the participatory sensing approach is elaborately described in Keis and Wiesner (2014). During the campaign in the winter months of 2013/2014 the WRAP reports have been integrated tentatively in real-time into the WHITE module scenario correction. The reports gathered from both the campaign in the winter months 2012/2013 and 2013/2014 were used to extend the evaluation of the nowcasting system's output.

6 Case studies of WHITE

During two DLR-campaigns in the winter months of 2012/2013 and 2013/2014 WHITE was testet in a quasi-operational mode. Both the nowcasting system and the

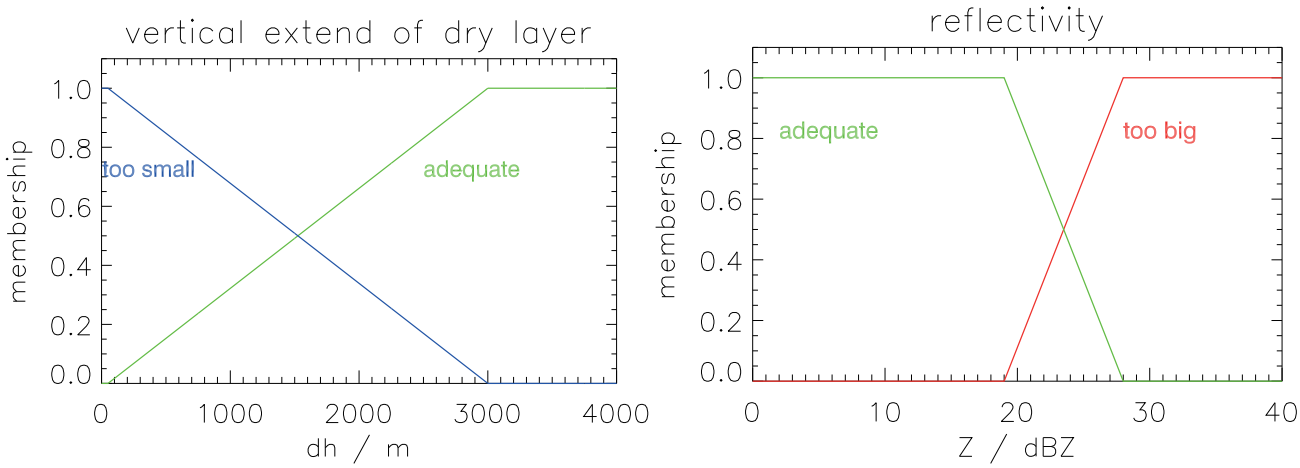

Figure 14: Fuzzy set functions for WHITE scenario *Evaporation*. (a) shows the functions for the dry layer's vertical extend and (b) the functions for radar reflectivity.

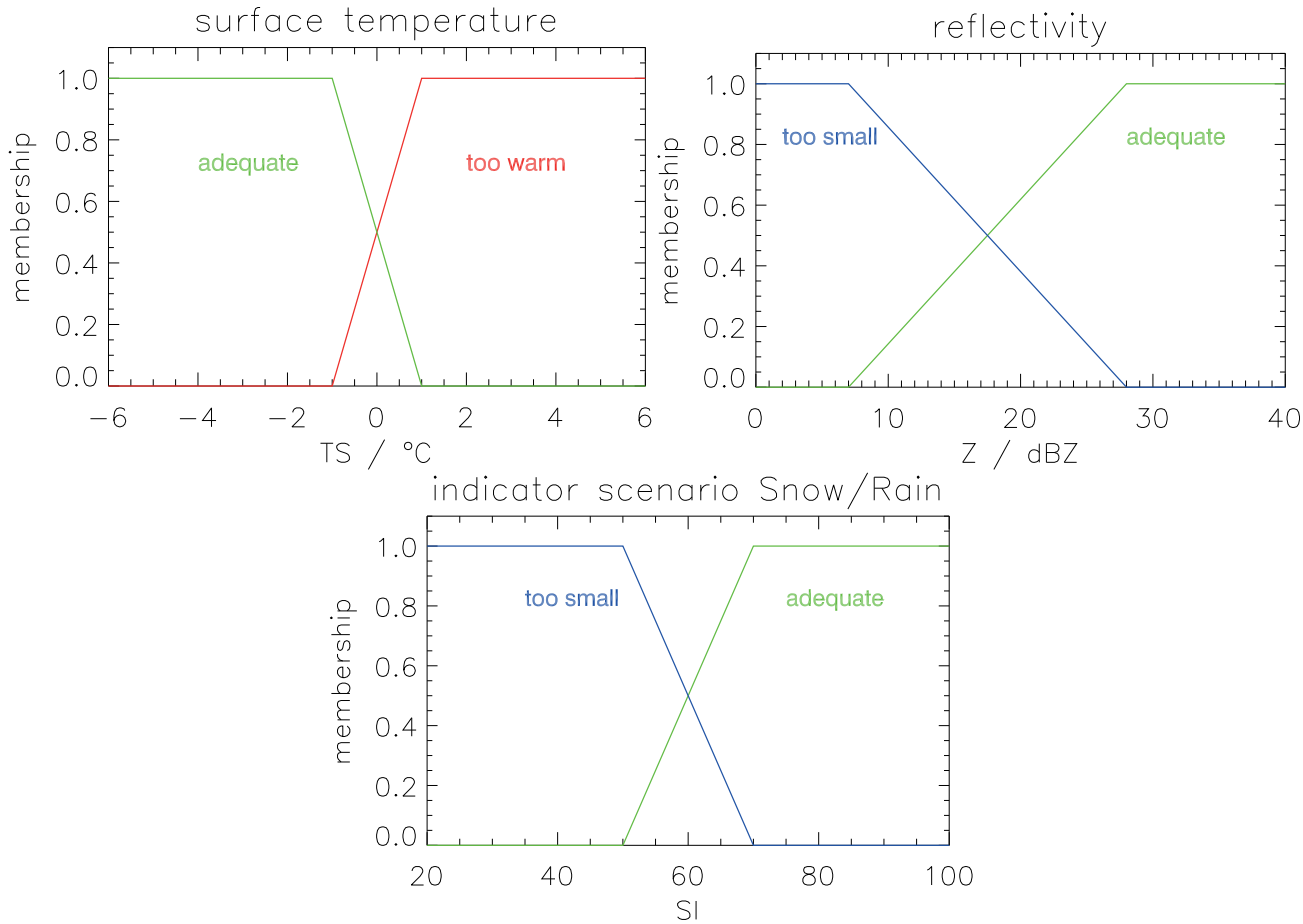

Figure 15: Fuzzy set functions for WHITE sub scenario *Surface – Fresh Snow*. (a) shows the functions for the surface temperature, (b) the functions for radar reflectivity and (c) the functions for the indicator of scenario *Snow/Rain*.

particpatory sensing approach have been employed. Obtaining an analysing of quality and familiarising the system and its concept to potential users were the goals of the campaigns. In this work the system's capability is demonstrated with the help of case studies. Because there haven't been significant case studies in Winter 2013/2014 within the investigation area, both cases shown in this work are from Winter 2012/2013 and have been postprocessed subsequently with the most up-to-date system version of WHITE.

6.1 January 20, 2013

On this day big parts of Germany had to deal with the consequences of freezing precipitation. At Frankfurt

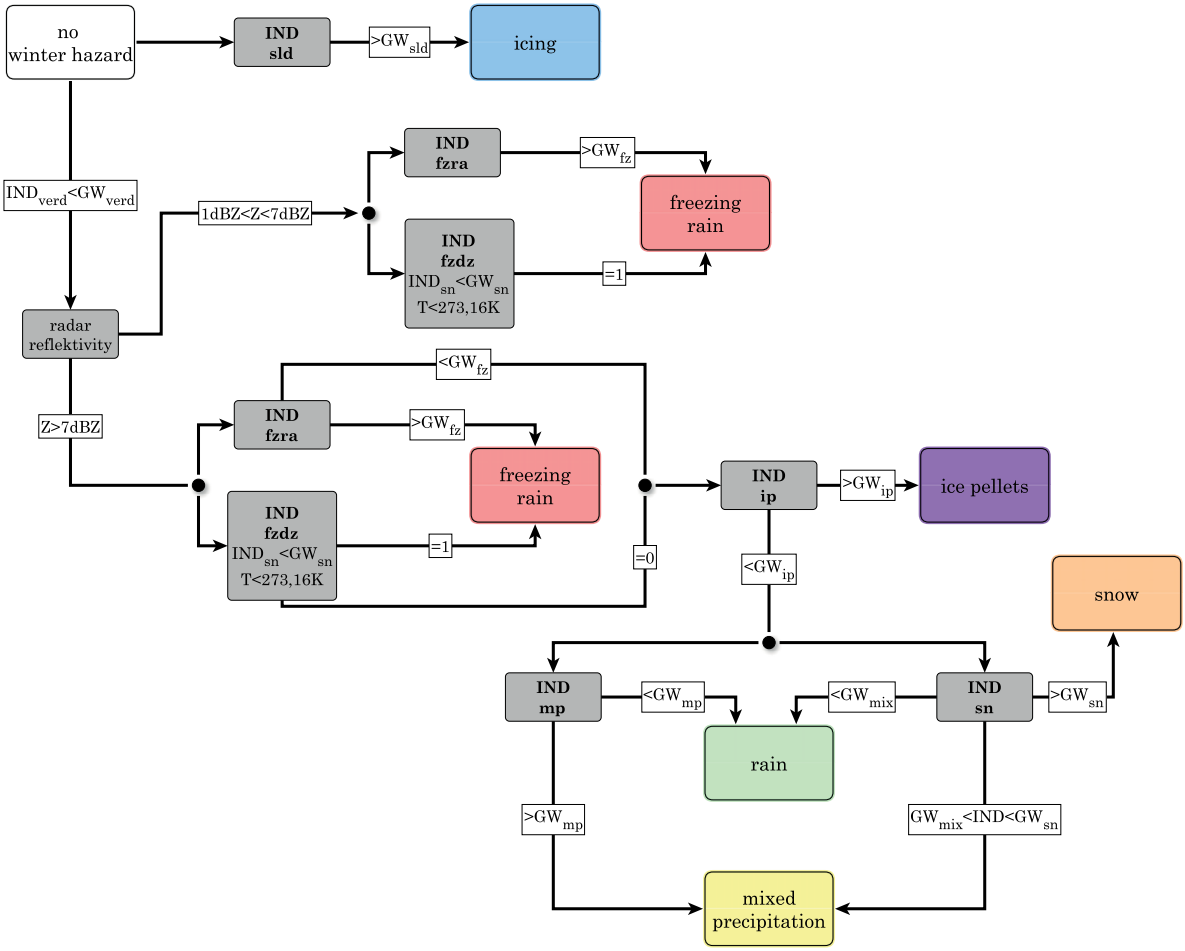

Figure 16: Tree structure of the classification.

Airport the flight service had to be suspended for several hours in the afternoon, because aircraft de-icing wasn't possible any more. About 400 flights had to be cancelled. At Munich Airport there was a weather warning of freezing precipitation for the period from 15:30 UTC until 18:00 UTC. In fact only at 17:00 UTC freezing drizzle and no accompanying adverse effects of the operating schedule could be observed (see Fig. 17). Nevertheless this case study demonstrates the mode of operation of the WHITE weather class *freezing rain* and shows, that this hazardous situation was assessed correctly by the nowcasting system.

The freezing precipitation on this day was caused by the low-pressure system Gong located over the Ligurian Sea. Warm air originating from Spain arrived in Germany in the course of its warm front. Because of a coexisting stable high pressure system over Scandinavia a north-western continental cold air stream still predominated in the bottom layers of air. In the afternoon of January 20 the temperature in several elevated Alpine valleys averaged to 5 °C. At the same time temperatures of −5 °C were measured in the lowlands. Near the Alps, snow originating from upper air layers not only melted but also evaporated within the dry bottom layer.

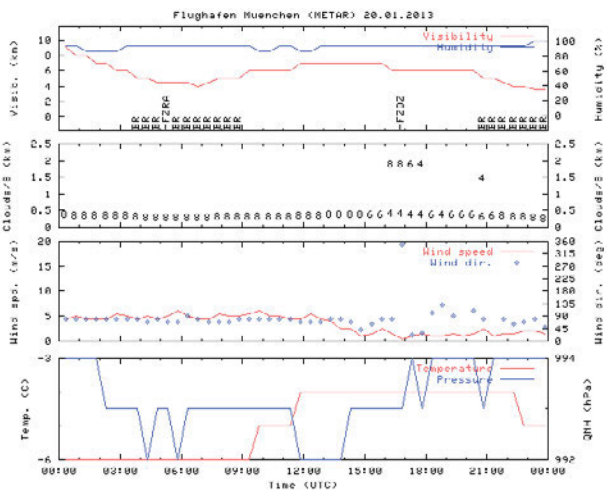

Figure 17: Munich Airport METAR reports from January 20, 2013.

On the ground no precipitation could be observed, although radar reflectivity was measured in these areas.

In Fig. 19 the weather situation in the lowermost model layer (2 m above the ground) at 16:30 UTC is shown as calculated by WHITE. Additionally the nowcasts for the following 15 minutes, 30 minutes and

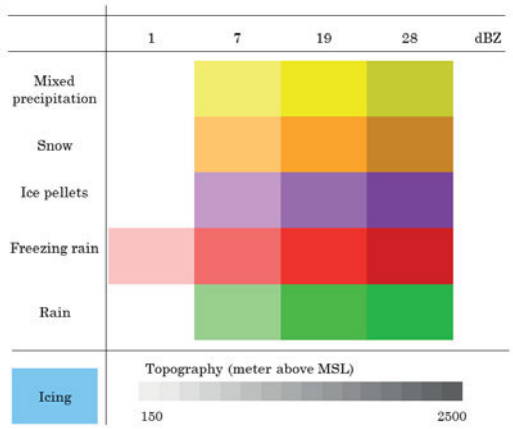

Figure 18: Color key for WHITE case studies. Colors represent different weather classes. Shading of colors result from corresponding radar reflectivity value.

60 minutes are plotted. At the analysis time, a south westerly warm air stream poured into the investigation area. The uplift of this stream over the prevailing cold air resulted in the formation of the distinct warm front. Solid precipitation melted or even evaporated within the embedded warm air and super-cooled in the bottom cold air (see vertical profiles and nowcasts of the weather object at Munich Airport in Fig. 20). At 16:30 UTC WHITE calculated no hazardous situation on the ground for Munich Airport. The nowcast of 15 minutes and 30 minutes produced *freezing rain*, whereas the nowcast of 60 minutes resulted in a nonhazardous situation assessment for the airport as well. A comparison with the original measurements of the radar precipitation scan (green areas in Fig. 19) proves that WHITE is able to detect areas without precipitation. Based on the precipitation scan alone one couldn't provide a sufficient situation assessment. The WHITE weather objects (red areas/black contour lines in Fig. 19) however provide nowcasts, that are consistent to weather observation at Munich Airport. When looking at Fig. 19 the spacious areas of freezing precipitation in northern Central Franconia and western Upper Palatinate stand out. Also these areas can be found in the weather observations. For example at Nuremberg Airport freezing precipitation was observed at 16:00 UTC, 17:00 UTC and 18:00 UTC. At 17:00 UTC and 18:00 UTC freezing precipitation was reported from the city of Regensburg. At 16:00 UTC cloudy sky without precipitation was reported from there. At 18:00 UTC the freezing precipitation arrived at the city of Straubing. The southerly object's delimitation can be traced with the aid of several weather observations. For example at the smaller airfields of Niederstetten (about 85 km southwest of Nuremberg) and Neunburg on the Danube (about 45 km northeast of Augsburg) no significant winter weather was observed throughout the afternoon.

6.2 March 18, 2013

Weather-determining on March 18, 2013, was the occlusion of a low-pressure area centered on the Gulf of Genoa. Westerly cold and moist air steadily arrived at the investigation area. Light to moderate rain originating from the frontal stratiform clouds could be observed throughout the day. At about 16:00 UTC this rain changed into mixed precipitation and at about 18:00 UTC into snow.

Figure 21 shows the atmospheric situation as calculated by WHITE in the lowermost model layer at 16:00 UTC, 17:00 UTC, 18:00 UTC and 19:00 UTC. WHITE summed up the situation in compliance with weather observations at Munich Airport (see Fig. 22). At 16:00 UTC the boundary line between rain and *mixed precipitation* is located in close vicinity to the airport. Rain is assumed when WHITE calculates no winter weather but there is precipitation observed by the radar network. The melting layer is specified short of the ground (see vertical profiles and nowcasts of the weather object at Munich Airport in Fig. 23). The nowcasts for Munich Airport show, that within an hour the melting layer was expected to descend and a change from rain to *mixed precipitation* on the ground was calculated. The outcome of the WHITE run at 17:00 UTC indicates *mixed precipitation* at Munich Airport. At 18:00 UTC and 19:00 UTC the weather class *snow* was calculated. When comparing the WHITE objects with observations from the remaining investigation area the results are confirmed. For example at 16:00 UTC mixed precipitation was reported from the weather stations in Nuremberg and Augsburg, wheras snow was observed in Regensburg. In the cities of Straubing and Fürstenzell rain was registered at the same time. At 17:00 UTC there was snow in Nuremberg and Regensburg as well as rain in Straubing, Fürstenzell and Augsburg. At 18:00 UTC and at 19:00 UTC the WHITE objects were in compliance with weather observations in Nuremberg (snow), Regensburg (snow), Fürstenzell (rain), Augsburg (rain) and Straubing (rain at 18:00 UTC, snow at 19:00 UTC).

7 Summary and outlook

The nowcasting system WHITE was developed with the aim to support Munich Airport stakeholders for decision making in winter weather situations. Various data sources are considered and fused by an innovative fuzzy logic approach. Hazardous winter weather situations like freezing precipitation, snow or icing with SLD are covered by the system. In addition to the nowcasting part, an innovative particpatory sensing approach was implemented and tested during two campaigns in winter 2012/2013 and 2013/2014. Both campaigns were conducted from December 1st until March 31st within an investigation area around Munich Airport. In this period of time, WHITE was operated in a quasi-operational mode with a temporal resolution of 15 minutes. Model data used was the latest COSMO-DE output available. Radar

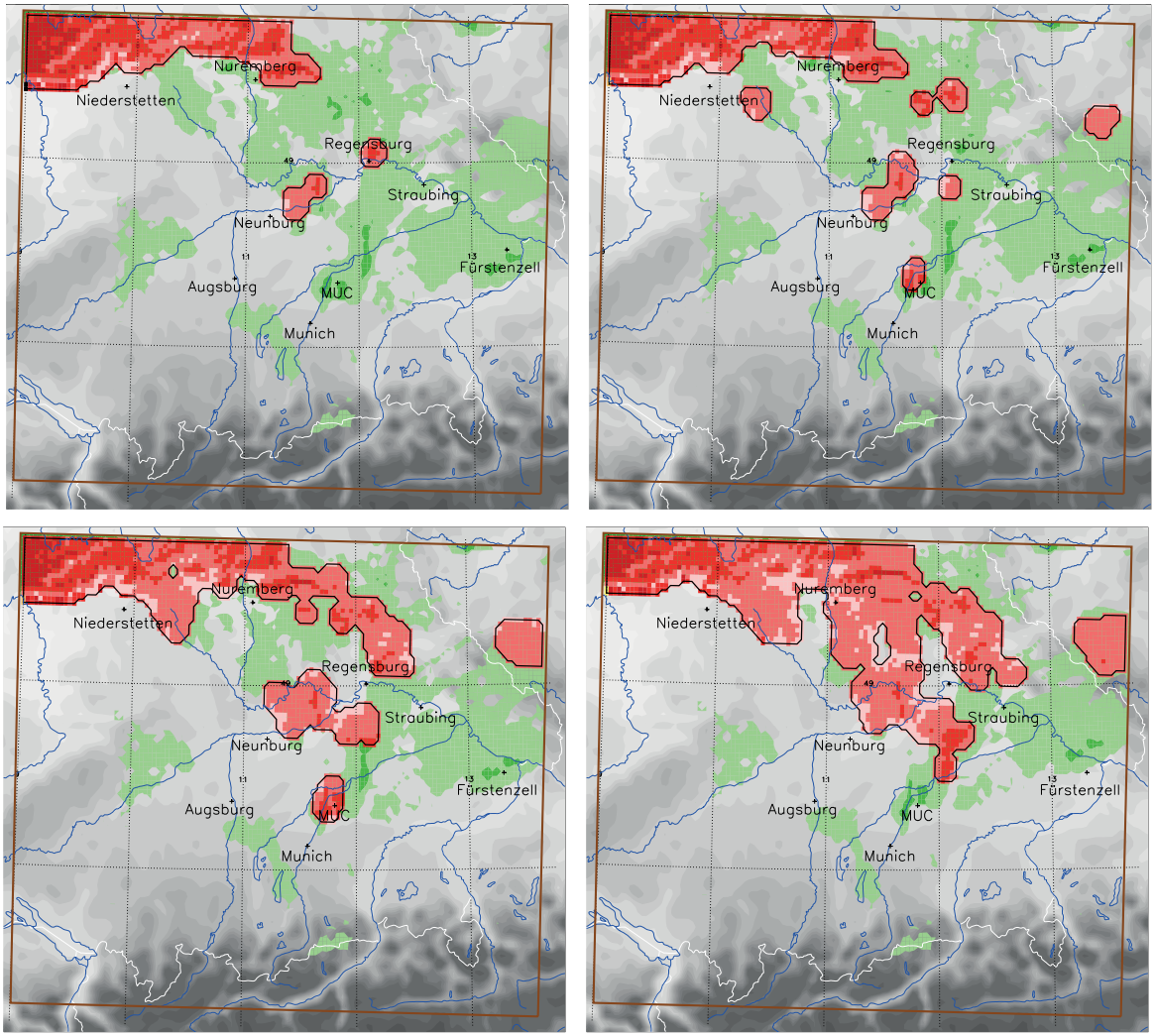

Figure 19: Illustration of WHITE winter weather objects of lowermost model layer (2 m above the ground) for January 20, 2013, 16:30 UTC in the investigation area. Colors represent different weather classes as explained in Fig. 18. Shading of colors result from corresponding radar reflectivity value. WHITE objects are additionally black-rimmed. Green shaded areas represent the raw reflectivity data measured from the German radar composit. (a) shows the situation at the time of analysis, (b) shows the nowcasting +15 minutes, (c) the nowcasting +30 minutes and (d) the nowcasting +60 minutes.

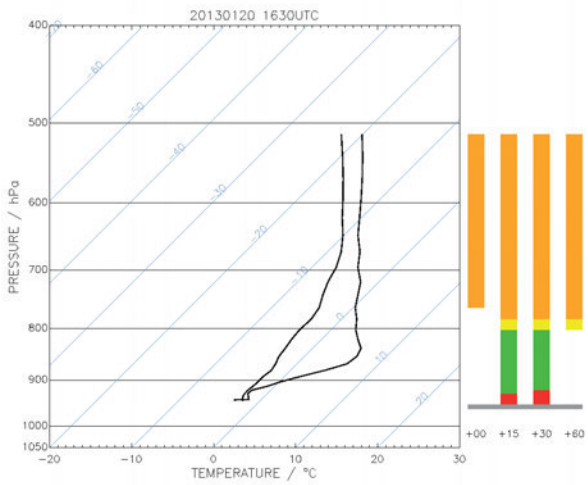

Figure 20: Profiles of temperature and humidity of January 20, 2013, 16:30 UTC at Munich Airport illustrated by a simplified Skew-T diagram. The color bars on the right symbolize the vertical WHITE objects at this location for the time specified. Colors correspond to the centered color key of Fig. 18 without color shading.

data and observation data from weather stations were available within the investigation area for each time step. Staff from the DLR Institute for Atmospheric Physics, the Munich Airport traffic control, the German Flight Navigation Service at Munich Airport and the Aeronautical Meteorological Forecasting Group of the German Weather Service at Munich Airport took part in the participatory sensing concept of WHITE and used WRAP to send 595 reports in winter 2012/2013 and 372 reports in winter 2013/2014 respectively. Additionally current analysis and nowcasting objects of WHITE were published on a specifically designed web page. In winter 2013/2014 the web page was accessed 664 times. In order to evaluate the quality of the nowcasting, data from all time steps were stored on the DLR system. As the campaign in winter 2013/2014 was supposed to evaluate and optimize the system, but suffered from the weather conditions, no significant statistics could be calculated yet. The campaign in winter 2012/2013 was primarily meant to calibrate and test the algorithms. Further cam-

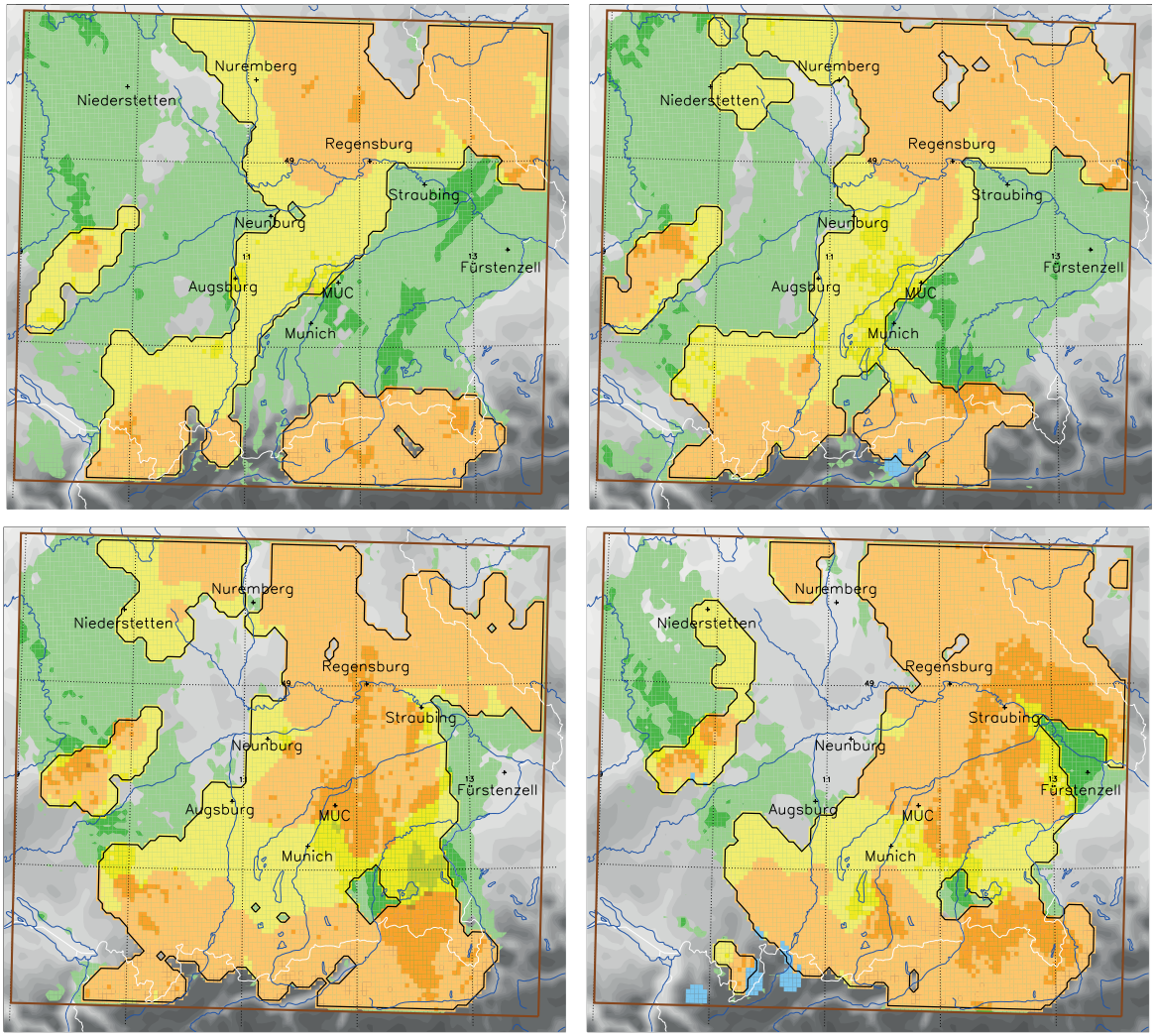

Figure 21: Illustration of WHITE winter weather objects of lowermost model layer (2 m above the ground) for March 18, 2013, 16:00 UTC (a), 17:00 UTC (b), 18:00 UTC (c) and 19:00 UTC (d) in the investigation area. Colors represent different weather classes as explained in Fig. 18. WHITE objects are additionally black-rimmed. Green shaded areas represent the raw reflectivity data measured from the German radar composit. Shown are the situations at the time of analysis in each case.

paigns in the following winter months are planned to rectify the statistics. Several enhancements of the system are discussed or projected in this context:

- Utilization of a model ensemble forecasting or a best member selection, in order to improve the first-guess fields.
- Use of the COSMO-MUC (Gerz et al., 2012a) model instead of COSMO-DE, in order to improve the first-guess fields.
- Integration of anonymized AMDAR (Aircraft Meteorological Data Relay) data or data from radio soundings in real-time, in order to improve the correction of vertical profiles in upper air layers.
- Application of MSG (Meteosat Second Generation) satellite data, in order to identify cloud-free areas and to derive cloud top temperatures.
- Implementation of a real time quality check for WRAP data and integration of the observations into the WHITE module 5.
- Realtime use of measurements gathered by state of the art mobile devices with integrated thermometer, barometer and hygrometer, in order to improve the correction of the first-guess model parameters.
- Implementation of a real-time nowcast verification and of flexible adapted classification limit values (for example BIAS-Tuning).
- Expansion of the investigation area to other airports.

In conclusion, the WHITE system and its innovative approach shows promising first results. The nowcasting system is able to analyze and nowcast hazardous winter weather situations within the terminal maneuvering area of an airport and to facilitate the decision making for traffic control. Even at this early stage of development, the system enjoys broad interest of potential prospective users. Especially the mobile application draws the attention and was a very useful tool during the DLR winter weather campaigns.

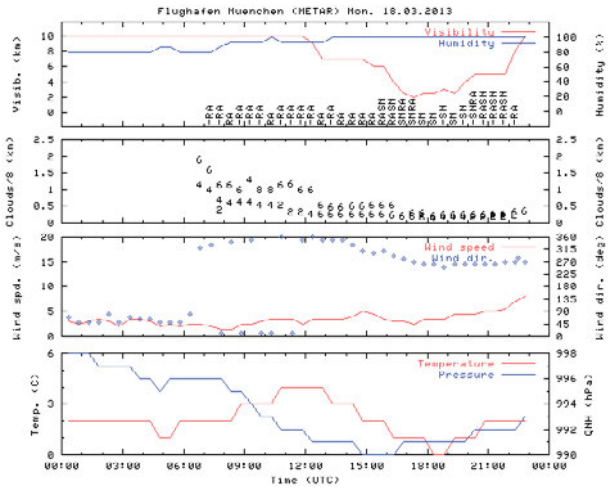

Figure 22: Munich Airport METAR reports from March 18, 2013.

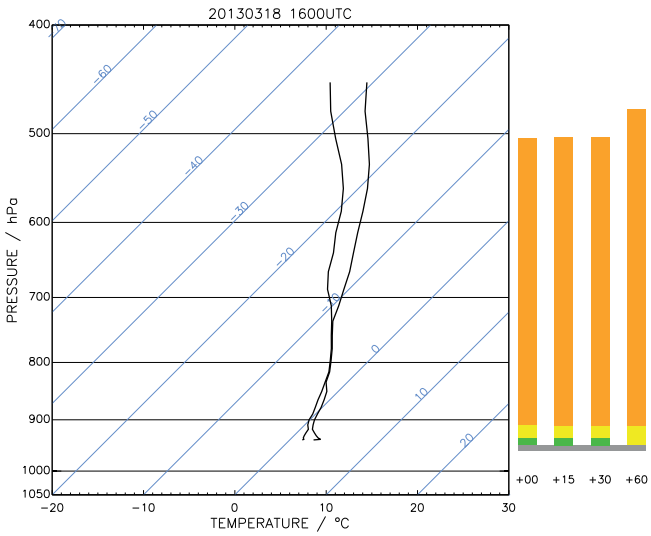

Figure 23: Profiles of temperature and humidity of March 18, 2013, 16:00 UTC at Munich Airport illustrated by a simplified Skew-T diagram. The color bars on the right symbolize the vertical WHITE objects at this location for the time specified. Colors correspond to the color key of Fig. 18 without color shading.

Acknowledgments

This work was done within the framework of the DLR-Project Weather & Flying. Especially staff from the Departement of Transport Meteorology of the Institute for Atmospheric Physics helped to realize the project. At this point I would like to express my special gratitude to Arnold Tafferener for his contribution to the development of the system. Special thanks must also be given to Jörg Simon (FMG), Frank Depping (DFS), Hans-Dieter Saffran (DWD) and their colleagues for the oppurtunity to test the system under real-life conditions at Munich Airport and for their participation in the campaigns. Finally I wish to thank the DWD for providing acess to their databases during this research project.

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