Weather Forecasting System for the Unmanned Aircraft Systems (UAS) Missions with the Special Regard to Visibility Prediction, in Hungary

Zsolt Bottyán, Zoltán Tuba and András Zénó Gyöngyösi

Abstract Nowadays, Unmanned Aircraft Systems (UAS) systems are playing more and more significant role in military and civil operations in Hungary. The proper, detailed and significant meteorological support system is essential during the planning and executing phases of the different UAS missions. Within such systems, it is very important to generate an accurate short-time visibility prediction. In order to develop a mentioned short-time hybrid visibility forecast, we combined an analog statistical and a high-resolution WRF-based numerical predictions which, are available around the four main airports in Hungary. In our work we show the detailed construction of hybrid visibility forecast. To publish our results we created a special web site where the adequate meteorological predictions can be access in some graphical, text and other forms via (mobile) internet connection.

Keywords Unmanned aircraft system · Hybrid meteorological modeling · Integrated weather prediction system · Visibility prediction · Meteorological support

1 Introduction

Remote piloted aviation is highly sensitive to the real weather situation, because the dynamic processes of flight depends on the present state of the atmosphere. The atmospheric influence on the mentioned type of aviation is more important than the

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normal flights one. Application of UAS systems, for both civilian and military purposes, is growing rapidly worldwide, due to lower operational costs of the airplanes, and these are going to decrease significantly in the near future [1]. The mentioned UAS systems are also playing more and more significant roles in military and civil operations in Hungary [2]. Aerial support for natural disaster management monitoring (earthquakes, floods and forest fire etc.), government and private survey (cartography, agriculture, wild life monitoring, border control, security and maintenance control for industrial companies, electricity cords network etc.) and defense of critical infrastructures may benefit from the on board instruments that might be the payload of such UAS's [3].

In spite of relatively easy control of most UAS systems, the weather hazards can be very dangerous for their flight like the manned ones, too. Despite the mentioned sensitivity of UAS systems to the dangerous weather phenomena—at present—there are few developed weather support systems for UAS handlers.

In order to decrease the weather-related risks during the UAS flights, we developed a complex meteorological support system for UAS users, mission specialists and decision makers. The mentioned system has to provide an adequate meteorological support during the planning and the flying phases of the UAS missions, with the special regard to the followings:

- Operational working during 0–24 h (always accessible)
- Readily accessible over the large geographical regions as far as possible, via internet connection (essentially everywhere, mainly via mobile net)
- Be simply installed in the other geographical regions (flexibility)
- In the final form it will contain a flight path optimization routine based on actual and predicted weather (future plan)

Finally, our developed meteorological support system can easily be implemented anywhere, since the applied meteorological data and numerical modeling system are mainly open-access!

2 Integrated UAS Weather Prediction System (IUWPS)

Forecasting the state of aviation meteorological variables is one of the greatest challenges for an operational forecaster [4]. For example, both visibility and ceiling (low clouds) are very difficult to predict even from the outputs of a very sophisticated high-resolution meteorological model.

Accordingly, the high-resolution numerical model output data should be processed parallel to statistical analysis of archive data base for a given weather situation and airports in order to yield the best forecast in a certain situation. This requires an integrated prediction system that consist both a suitable, specially tuned numerical model a statistical component, and—in addition—it is capable to generate an accurate hybrid (combined statistical and numerical) aviation meteorological forecasts.

There are some applied analog weather prediction procedures in an operational use, for example the Canadian fuzzy logic-based analog forecasting system called WIND-3 [5]. The success of the mentioned method gave us the motivation to develop a similar system in Hungary which is able to give effective meteorological support in UAS operations.

Visibility and ceilings play a key role in the success of UAS missions. Usually, the operational minimum of UAS flights is lower than the weather minimum of the special mission execution. For example, during reconnaissance or surveillance tasks, poor visibility and low ceilings can eliminate the mission but they do not restrict the UAS flight itself.

Our primary goal was to develop a hybrid forecasting system which is able to give accurate and timely forecasts of main airports with relevant climatic database to support UAS missions.

The construction of our experimental complex Integrated UAS Weather Prediction System (IUWPS) is based on the following parts:

- Statistical Modeling Subsystem (SMS)
- Numerical Modeling Subsystem (NMS)
- Hybrid Modeling Subsystem (HMS)
- Post Processing Subsystem (PPS)

The important components of the UAS meteorological system and its relations to their different components are shown on Fig. 1. The mentioned experimental IUWPS has a modeling and a post-processing unit using both statistical and numerical outputs of its subsystems to produce the hybrid forecasts in case of visibility and ceiling. The IUWPS uses climatological data of mentioned parameters from the Statistical Modeling Subsystem and actual weather forecast data (basic meteorological

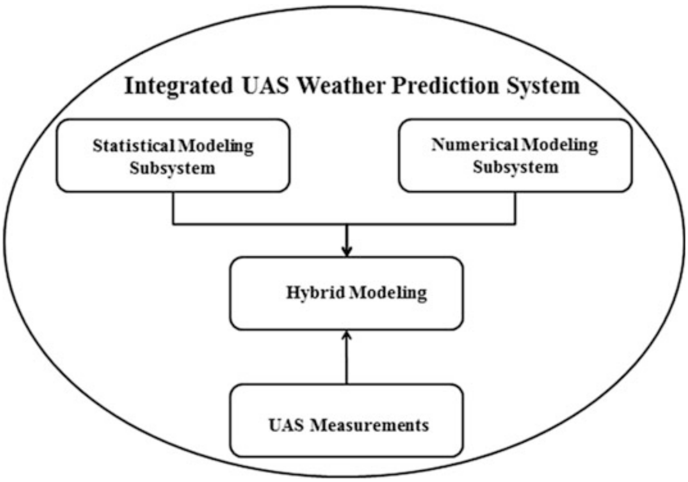

Fig. 1 Structural chart of the integrated UAS weather prediction system

variables) from the Numerical Modeling Subsystem. On the basis of mentioned parts IUWPS is able to produce the hybrid (combined) short-time predictions regarding both visibility and ceiling.

3 Statistical Modeling Within the IUWPS

The basic principle of analog forecasting is to find similar weather situations in the past to the current and recent conditions and rank them according to the degree of their similarity in the interest of giving relevant information for weather forecasts. (The phrase of weather situation means couple of hour continuous observations in this study.) Therefore, analog forecasting does not work without a relevant climatic database which contains the meteorological parameters planned to forecast in the future. We have set up an appropriate database for Hungarian military airbases (LHKE, LHPA and LHSN) and for the largest Hungarian international airport (LHBP). It is based on routine aviation weather reports (METAR's) [6]. The database contains the meteorological variables for every half an hour from 2006. It has more than 30 variables, because it includes the parameters in elemental and derived format as well (e.g. year, month, day, hour, minute vs. Julian date). The records are more than 99 % complete. We have to note such database is easily creatable for any airport with available METAR weather reports all over the world, of course!

The applied fuzzy logic-based algorithm is measuring the similarity between the most recent conditions and the appropriate elements of the database. During the examination of every single weather situation the model uses the current and the eleven previous METARs' content. The algorithm compares the meteorological variables of every examined time step using fuzzy sets.

The fuzzy sets—which are composed for describing the degree of similarity—used in this process are determined by experts (in this case: operational meteorologists), which is a common method in the development of such fuzzy systems [7]. These functions are applied for every compared parameter and their outputs give the similarity with a value between 0 and 1. The individual parameter values of a weather situation are examined one by one and the similarity value of a time step is given from weighted averaging of the individual similarity of the elements [8]. Obviously, we could improve the accuracy of the forecast of individual elements by using appropriate weights highlighting the importance of them during the fuzzy logic-based forecasting process [8].

There is another approach, we can assign weighting to the meteorological variables. The higher the importance of the parameter, the larger the applied weight is. Because of the large number of variables the direct determination of weights was excluded. We applied a widely used technique in different fields of life except meteorology so-called Analytic Hierarchy Process (AHP) which was introduced by

Saaty [9]. This method is mainly used in multi-criteria decision making, especially in solving complex problems from most different fields [10, 11]. AHP was used only for determining the applicable weights for the different parameters as criteria. It is also necessary to apply pairwise comparison on criteria which is based on general definition. In our case these experts' judgments were assigned by operational forecasters' joint opinion. The ratios of pairwise comparisons can give the elements of a matrix. The best choice for the weight vector is the eigenvector belonging to the maximal eigenvalue of this matrix. For detailed description please refer Saaty's proof [8]. To determine the eigenvector we used the standard power iteration method. The received weights will be shown at the verification results. Obviously the matrix might be inconsistent due to the subjective comparisons. We found an inconsistency of 2.5 % which is less than the tolerable 10 %, so the results are significantly reliable [12].

4 Numerical Modeling Within the IUWPS

The Weather Research and Forecasting (WRF) model version 3.5 (release April 18, 2013) has been applied to generate numerical output for our general weather prediction system [13]. The WRF is a non-hydrostatic meso-scale meteorological model and its modularity and high flexibility with the wide global user experience suited well for the needs of our purposes. The modular structure of our development provides the possibility to exchange from one limited area model to another (e.g., HIRLAM/ALADIN, etc.) as a driver for the Numerical Modeling Subsystem unit of the system. Some successful experiments were conducted with CHAPEAU, the academic version of the ALADIN to verify the possibility of such replacement.

Input geographical data have been generated from two different sources. Land-cover/land-use information was taken from the CORINE 2000 (Coordinate Information on the Environment) database adapted and modified to be used in WRF [14]. The main advantage of this database with respect to the USGS data, originally used by WRF, is the much more realistic representation of land characteristic features (e.g., much better and more specified representation of various types of forests and shrub-lands; in addition to more than 3 times larger area specified as urban, etc.). These characteristics are essential in surface-atmosphere interactions and boundary layer processes, which are most important inputs for calculations of main aviation meteorology parameters.

Similarly, the original FAO (Food and Agriculture Organization) soil texture data has also been replaced by the DKSIS (Digital Kreybig Soil Information System, produced by the Centre for Agricultural Research, Hungarian Academy of Sciences) [15]. Contrarily to the CORINE database which can be applied to all model domains, the DKSIS covers only the area of Hungary so we were able to use it in the smallest (but highest-resolution) domain. In addition, soil hydraulic parameters were also adjusted according to Hungarian soil sample data (MARTHA and HUNSODA).

Within the whole prognostic area, which is located in the Carpathian-basin (centered at a location with geographical coordinates N47.43; E019.18), we applied a well-used three level telescopic nesting with 30 km horizontal resolution in the coarsest (d01) domain, 7.5 km in the intermediate (d02) domain and 1.875 km in the highest-resolution lowest level (d03) domain. The applied number of vertical levels was 44 and there were 24 levels in the lower troposphere under 2 km (Fig. 2).

In order to apply a setup tuned for the special requirements of the designated purpose, extensive tests were performed: 30 different combination of parameterization setups (ENS)—including 8 types of micro-physics (types 3–9 and 13), 6 types of Land Surface Models (types 1, 2, 4, 5, 7 and 10) and 8 types of PBL (1, 2, 4, 5, 7–10) schemes—have been tested. Tests have been performed for 9 selected weather situations in the model domain, which ones have strong aviation weather relevance (Table 1).

Model output has been compared to synoptic surface observations at 31 ground stations in Hungary and the operational radiosonde data of 4 stations located in the d02 domain. Temperature and dew point data have been evaluated using RMS error and the wind score derived with respect to wind speed and wind direction differences. Results showed that in the surface data there is a wide variation in humidity and temperature, while in the upper level data only wind speed and direction are significantly affected by the choice of the parameterization schemes. The final results of our parameter optimization procedure can be seen in Fig. 3.

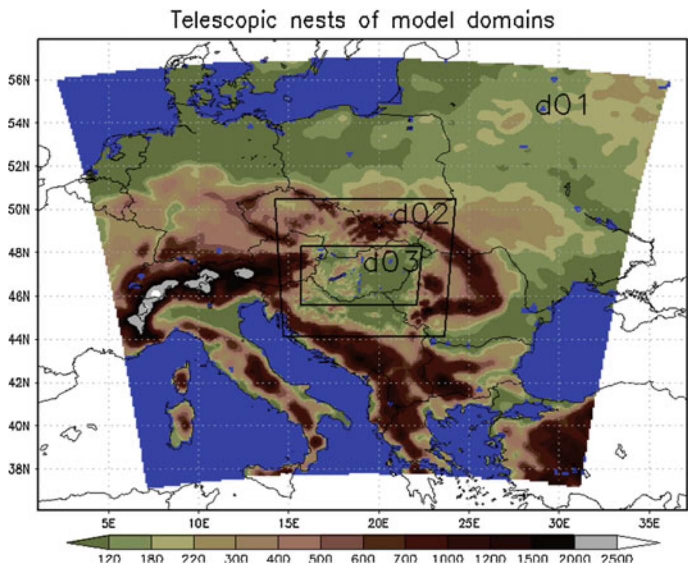

Fig. 2 The applied telescopic nests of WRF model in the numerical modeling subsystem

Table 1 The applied case studies and their dates during WRF optimization procedure

#	Dates	Description
1	20121027	Widespread precipitation from a Mediterranean low pressure system
2	20120920	High horizontal pressure gradient situation with strong winds, with a special wind-pattern
3	20120119	Significant low level inversion during winter period
4	20120908	High pressure ridge transition resulting in significant and rapid change in wind direction
5	20120729	Deep convection resulting in local and heavy showers that were not well resolved by most operational models
6	20120512	Significant change in wind direction following a cold front
7	20120122	Well documented severe icing case weather situation
8	20120216	Convective precipitation from a high level cold vortex, temperature in the mid-troposphere less than—25 °C
9	20121206	UAV test flight case for direct verification purpose

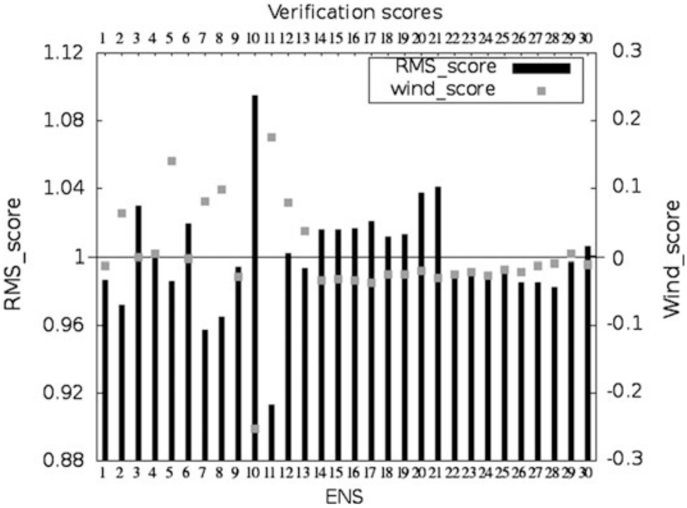

Fig. 3 Final results of the parameterization optimization procedure of the WRF model. We have to note that in case of RMS scores the smaller values are the better ones, but in connection with wind scores the larger values are the better ones

On the basis of our analysis of the mentioned results, Bretherton and Park JC (9) PBL scheme [16], WSM Single-Moment 3-class (3) micro-physics scheme [17] and the Noah scheme [18] for land-surface processes were the best options. In addition, RRTM (Rapid Radiative Transfer Model) for long-wave radiation [19], Dudhia's scheme for short-wave radiation and a modified version of the Kain-Fritsch scheme for cumulus convection have been applied in the complete WRF model parameterization [20].

In our Numerical Modeling Subsystem 0.5° by 0.5° GFS data is applied as initial condition and boundary conditions for the limited area integration of the outermost domain every 3 h, with no additional data assimilation. Input data is preprocessed with WPS, the vendor preprocessor of the WRF system.

Integrations running for 96 h lead times are performed two times a day, initialized from 00 UTC and 12 UTC at 04:00 UTC and 16:00 UTC, respectively. Model products are delivered to the users through the web interface of the integration server itself 6 h after the observation of the input data.

5 Hybrid Forecasting of Visibility in IFS

As we mentioned earlier, the visibility and ceiling predictions are very difficult. In order to create well-used operational short-time (up to 9 h) forecasts we developed a hybrid (combined) method to predicting of these parameters for UAS users and specialists.

First, we had to make the detailed verification of both prediction of visibility at the four airports. Heidke Skill Score (HSS) using all of the elements of a special contingency table and it is correct with verification of rare events, which is a typical in case of low visibilities [21]. According to the reasons stated above, we present the HSS values of the examined methods. Some naive forecasts (e.g. persistence) can be a standard of reference or in other words a competitive benchmark in the field of short term forecast verification [21], [22].

In order to show our verification results of persistence forecast, we generated the statistical visibility forecast for every third hour of the control period applying the 30th and the 40th percentiles of the analog situations. Then we calculated the HSS verification parameter mentioned above for both percentiles of statistical predictions and also for numerical and persistence forecasts in case of all of the examined ICAO category limits (800, 1500, 3000 and 5000 m). In this work we present our results regarding to the 1500 m category limit only (Fig. 4). As we can see in this figure during the first nine hours the statistical predictions are much better than the

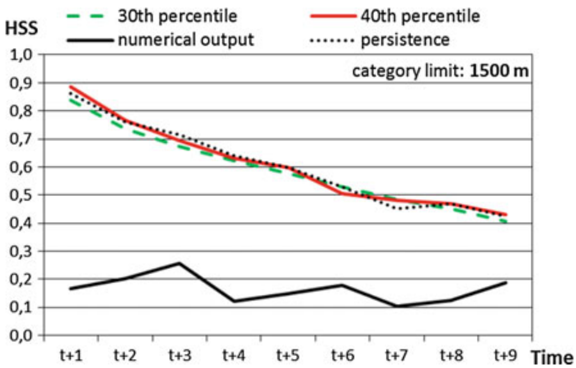

Fig. 4 The HSS values as a function of prediction time of different visibility forecasts in case of 1500 m category limit

numerical one but the difference of accuracy between them are sharply decreasing after six hours. We gave very similar results in case of other examined category limits so this means the statistical predictions accuracy after nine hours not significantly better than numerical ones.

Applying our results mentioned above we created an experimental hybrid visibility forecast method based on our 40th percentile analog forecast with AHP weight and modified numerical WRF prediction. The construction of a hybrid forecast, is based on the followings:

$$VIS_{HYBRID} = \mathrm{a} \cdot VIS_{STAT} + \mathrm{b} \cdot VIS_{NUM} \quad (1)$$

where $\mathrm{VIS}_{\mathrm{HYBBID}}$, $\mathrm{VIS}_{\mathrm{STAT}}$, and $\mathrm{VIS}_{\mathrm{NUM}}$ are the hybrid, the 40th percentile AHP analog and the WRF numerical visibility forecasts, respectively. The constants (a, b) are weights of the statistical and numerical forecasts. The applied values of the weight of $\mathrm{VIS}_{\mathrm{STAT}}$ (a) are found in a weight matrix represented by Table 2. The columns of this matrix are the time steps of forecasts (in hour) and its rows are the absolute category differences of the measured and numerical predicted visibilities at initial time (t + 0). If the difference value of the measured and numerically predicted visibility is within the 0–800 m, 800–1500 m, 1500–3000 m, 3000–5000 m and 5000–70,000 m intervals initially, the absolute category difference will be 0, 1, 2, 3 and 4, respectively. Obviously the weight b = 1 − a.

As it can be seen in the left hand side of Fig. 5 in the LHKE airport the measured (3000 m) and the numerical predicted visibilities (10,000 m) are highly different so the absolute category difference is 4 in this case. Contrarily in the right hand side of Fig. 5 the measured and numerically forecasted visibilities (10,000 m) at the LHSN airport are equal so the applied absolute category difference is 0. Accordingly the calculated $\mathrm{VIS}_{\mathrm{HYBRID}}$ forecasts are based on Table 2 and represented by the green columns (every column means one hour). Within the red rectangles we can also see the statistical (black line) and numerical (blue line) visibility forecasting based on Statistical and Numerical Modeling Subsystem of IUWPS. We have to note from t + 10 h the hybrid forecast will be the original numerical one because the accuracy of statistical predictions—by this time—is not enough to taking account of it to product more accuracy hybrid forecast (hence at t + 10 h the green column and black line show the same value of visibility).

Table 2 The applied values of the weight of $\mathrm{VIS}_{\mathrm{STAT}}$ (a) statistical visibility prediction for hybrid forecasting

		t + 1	t + 2	t + 3	t + 4	t + 5	t + 6	t + 7	t + 8	t + 9
Absolute category difference	4	1.00	1.00	1.00	0.90	0.80	0.65	0.50	0.35	0.20
	3	1.00	1.00	0.90	0.80	0.70	0.55	0.45	0.30	0.20
	2	1.00	0.90	0.85	0.75	0.65	0.50	0.40	0.25	0.15
	1	0.90	0.85	0.80	0.70	0.60	0.45	0.35	0.20	0.10
	0	0.90	0.80	0.70	0.60	0.50	0.40	0.30	0.20	0.10

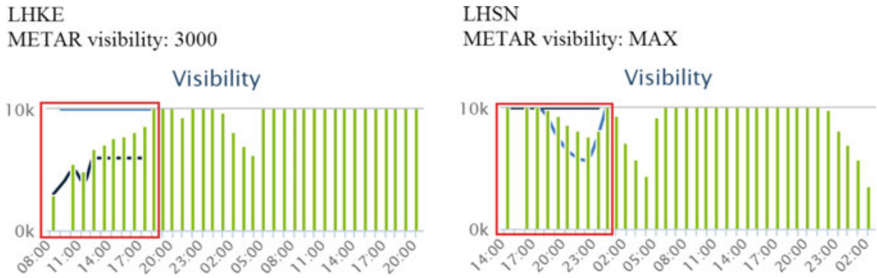

Fig. 5 Visibility forecasts are calculated by IFS for two different initial situations. *Left* LHKE airport with measured 3000 m and numerical predicted 10,000 m visibilities. *Right* LHSN airport with measured 10,000 m and numerical predicted 10,000 m visibilities. Hybrid, statistical and numerical forecasts are represented by *green columns*, *black lines* and *blue lines*, respectively. The *red rectangle* shows the first ten forecasting hours. On the vertical axis 10 k represents 10,000 m visibility value

In order to permit of wide access of our weather predictions—with the special regards to hybrid visibility forecasts—we developed an experimental (in this time with restricted access) web-based weather information center for UAS users. It is a special web site, where the appropriate meteorological information will be accessed in a graphical, text and other formats via (mobile) internet connection in the future.

6 Summary

An accurate, detailed and significant meteorological support system is essential during the planning and execution phases of UAS missions. In such systems it is very important to generate an accurate short-time visibility prediction. The IUWPS is able to give this meteo support and is based on the followings main parts:

- An adequate data base of the main four Hungarian airports which contains the freely accessible METAR data (this data base can be extensible similarly)
- The applied analog statistical model with AHP weights can help to give accurate prognostic information about visibility for the first nine hours (Statistical Modeling Subsystem)
- The WRF based numerical weather model can give us high resolution complex weather prediction (of course also the visibility forecasts) over the Hungary with the maximum horizontal resolution of 1.8 km (Numerical Modeling Subsystem)
- The applied post-processing methods—are based on the mentioned statistical and numerical visibility products—to predict the combined hybrid visibility forecast for the first nine hours at the region of four Hungarian airports (Hybrid Modeling Subsystem)

- A special web site where the adequate meteorological information can be access in some graphical, text and other formats via (mobile) internet connection (Post Processing Subsystem)

In the future we would like to develop an UAS flight path optimization, which is based on our predicted 3D weather situation and the planned UAS flight. We will also continue the development and testing of our Hungarian Unmanned Meteorological Aircraft System (HUMAS) which will be able to help verify and improve our weather prediction capability.

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