HAZARDOUS METEOROLOGICAL PHENOMENA FORECASTINGUSING REMOTE SENSING DATAAND PRODUCTS OF NUMERICAL WEATHER PREDICTION MODELS

I. Winnicki, J. Jasinski*, K. Kroszczynski, S. Pietrek

Military University of Technology, 2 Kaliskiego Str., 00-908 Warsaw, Poland
(ireneusz.winnicki, janusz.jasinski, k.kroszczynski, spietrek)@wat.edu.pl

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ABSTRACT:

The paper presents research concerning application of mesoscale models and remote sensing data to meteorological support of aviation. The software module developed for investigating hazardous weather phenomena manages, processes and visualizes products of COAMPS mesoscale non-hydrostatic model of the atmosphere, MSG satellite images and radar data. It enables complex analyses of data sets of miscellaneous information structure and to verify COAMPS results using radar and satellite data. Transformation of all elements of the database to the Lambert Conformal projection of COAMPS facilitates simultaneous interpretation and supports decision making processes for safe execution of aviation tasks. Verification of the forecasts includes research of spatial and temporal correlations of structures generated by the model and structures identified in satellite and radar images. The module determines meteorological parameters fields for vertical profiles of the atmosphere. Interpolation procedures run at user selected pressure or height levels of the model enable to determine weather conditions along any route of aircraft. Basic parameters of the procedures determining e.g. flight safety include: cloud base and cover, visibility, turbulence, precipitation and icing. The research includes also investigating new generation mesoscale models, especially remote sensing data assimilation, and developing the module to adapt the WRF model for the area of Poland which is suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometres. Appropriate validation of the mesoscale model performance is a separate task to be realized after an appropriate amount of computer simulations, synoptic, radar and satellite data have been collected.

1. INTRODUCTION

Meteorological conditions belong to the most important elements of the geographical environment because they have direct influence on numerous human activities, both civilian and military, in real situations and during training processes. The necessity to consider meteorological conditions in planning and realization of projects or training activities has been perceived since the very beginning of development of transportation means. They are important elements, especially of airborne situations, because they influence take-offs, flights and landings of aircraft. They have significant influence on safety, regularity and economy of aviation activities and its applications. They impinge on the airports state, aircraft and ground equipment exploitation. They determine properties of the flight-routes and their profiles, navigation methods and aircraft transportation capabilities. Airborne tasks realization is more effective if ground support personnel and the aircraft crew deciding about the flight have precise information concerning the current state and forecasted changes of weather conditions in the origin region, along the flight routes and in the vicinity of the destination. Meteorological conditions of flight - understood as the state of the atmosphere in a selected area, on defined flight levels and in fixed time or time range - are relevant elements characterizing the airspace in which the aviation operates or may operate.

Quality of meteorological support of aviation depends on prompt and effective forecasting of weather conditions changes.

Although various data are currently available for weather analysis and forecasting, they are still often insufficient for a specialized weather assessment and forecasts for specific air tasks, especially those that have to be realized in very difficult weather conditions, like airborne search and rescue missions. In such cases standard weather forecasts don't usually meet the requirements of the situation.

2. SPECIALIZED FORECASTS

2.1 Data Sources

Research concerning application of mesoscale models and remote sensing data to investigating hazardous weather phenomena for specialized weather forecasts has been conducted in the Faculty of Civil Engineering and Geodesy of the Military University of Technology, Warsaw, Poland. The research is based on data including products of COAMPS (Coupled Ocean/Atmosphere Mesoscale Prediction System) mesoscale non-hydrostatic model of the atmosphere developed by the US Naval Research Laboratory and satellite images from the MSG (Meteosat Second Generation) of the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT). The research also uses meteorological radars data acquired from the Institute of Meteorology and Water Management (IMGW), Warsaw, Poland.

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* Corresponding author.

The satellite images acquisition system and the COAMPS model are run operationally in the Faculty of Civil Engineering and Geodesy. The mesoscale model is run on IA64 Feniks multiprocessor 64-bit computer cluster.

2.2 General Synoptic Analysis

The atmospheric state is defined by a set of text and numeric values pertaining a number of meteorological elements. Good forecast of a synoptic situation usually corresponds with a good forecast of weather conditions. Synoptic situation forecast is preceded by analysis that pays special attention to processes in frontal zones where the greatest qualitative and quantitative changes in synoptic processes and weather conditions occur. As a result of synoptic situation analysis, the forecaster presents conclusions concerning development of synoptic processes. The conclusions are qualitative and so far have often constituted the basis for synoptic situation forecasts. Miscellaneous methods of quantitative calculations that complement these conclusions become more and more significant for weather forecasting.

High quality weather forecasts require acquisition and processing of large amounts of information. Data used for that purpose come mainly from the ground measurement networks, ships and aircraft, as well as from meteorological satellites. Increasing application of satellite images is a valuable complement of meteorological information from the ground measurement networks. The images are in practice the only regularly acquired information concerning selected weather elements from areas with a sparse measurement network or areas without such a network. In this context, dynamically developing satellite meteorology is very important.

Synoptic method, despite its imperfectness and significant dependence on the knowledge and experience of the forecaster, is still the leading forecasting method in many meteorological organizations supporting aviation. At present, effectiveness of the method also depends significantly on the number of charts prepared on the basis of numerical hydrodynamic methods and applied in the operational forecasting practice. Computer techniques are also used for automating acquisition, processing and archiving meteorological data.

2.3 Aircraft Icing

In winter it is necessary to pay special attention to forecasting of aircraft and runways icing which is one of the most dangerous threats to crews and passengers of all kinds of airplanes and helicopters. Most of the forecasting methods currently applied during meteorological support do not enable to determine the zones of icing and its intensity in an unambiguous way. Application of results of numerical models of the atmosphere and remote sensing data provides new capabilities of aircraft icing forecasting and enhances the methods used so far.

Depending on the phase state of water in the atmosphere, flight conditions and air temperature, aircraft icing is most often caused by:
- direct accumulation of ice or snow crystals,
- freezing of water droplets in clouds, rain or drizzle on surfaces of sub-zero temperature,
- resublimation of water vapor on the aircraft surface,
- freezing of super-cooled water droplets hitting the aircraft surface.

High humidity and temperatures below zero Centigrade are conductive to severe icing, especially in the following conditions:
- in clouds of super-cooled water,
- in air temperatures between 0 °C and –20 °C, with the most severe icing in air temperatures between 0 °C and –5 °C,
- in clouds of water-content exceeding 0,5 $g \cdot m^{-3}$ and cloud droplets exceeding 50 µm,
- in ascending air currents increasing super-cooled water content in clouds,
- in horizontally extended clouds increasing the flight time in icing conditions.

For icing forecasting it is necessary to determine relations between these conditions and actual processes in real atmosphere, i.e. determine synoptic situations conductive to aircraft icing which may occur both in cloud systems of uniform air masses and frontal zones, in precipitation as well as in cloudless areas.

Since icing severity depends on the microphysical structure of clouds determined by the processes of their formation and on the phase state of water constituting clouds, it is necessary to start the analysis from diagnosing the general structure of clouds in sub-zero temperatures. Three types of phase structure are distinguished (Brown B. G., 1997):
- clouds entirely consisting of super-cooled water droplets mixed with ice crystals,
- clouds consisting of water droplets in their lower part and of water droplets mixed with ice crystals in their middle part,
- clouds composed of numerous layers consisting of only water droplets or ice crystals.

Aircraft icing forecasting includes two stages: general synoptic situation analysis for assessment of possibility of occurrence of conditions conductive to icing, and detailed analysis for precise determination of areas and intensity.

General synoptic situation analysis is usually conducted using standard synoptic materials and it is often enhanced by analysis of various remote sensing data. For example, application of GOES satellite images (VIS channel - 0,6 µm and IR channels - 10,7 µm and 3,9 µm) to diagnosing and forecasting areas of aircraft icing is presented in (Ellrod G. P. , 1996).

Application of mesoscale numerical models of the atmosphere enables to predict the changes of the most relevant for icing meteorological elements – air temperature and humidity, water content in clouds, stability of the atmosphere.

2.4 Turbulence

Wind field data at selected flight levels in the form of wind vectors superimposed over terrain map or echoes from detected clouds are of great use for navigation. A weather forecast for aviation should include information concerning atmospheric turbulence as a part of wind field forecast. Turbulence occurs in complex wind fields where numerous vortices are generated due to significant differences of adjacent air streams velocities (Cebeci T., 1995). Aerodynamic forces are severely disturbed in zones of turbulence and so is the aircraft's flight. Additional unexpected accelerations conductive to rapid uncontrolled

movements of the aircraft in all directions are generated which is a threat to the structure of the aircraft.

Turbulence zones may be detected by means of meteorological radars with Doppler channel. The Doppler shift of frequency recorded by the measurement system's receiver is a measure of the velocity of cloud particles or atmospheric heterogeneities providing backscatter of the emitted electromagnetic waves.

For frequencies of the emitted pulses of f_o=5 GHz, the Doppler change of frequency of the received backscatter is a few hundred Hertz (e.g. Δf=500 Hz). Comparison of these two numbers indicates that it is necessary to detect a change of the initial value by a very small fraction ($\Delta f/f_o \approx 10^{-7}$). This requires high stability of frequency and a reference frequency.

Measurement data from scanning the atmosphere in the range of 100 km every 10 minutes are processed by a specialized system. The RAINBOW system used in the Polish network of meteorological radars provides the users with graphical products of the wind field, e.g. wind speed and direction at selected levels, horizontal gradient of wind at the levels, vertical gradient of wind in selected layers of the atmosphere (direct indicator of turbulence) and vertical profile of wind speed and direction in the vicinity of the radar. Analysis of the products enables to determine the impact of the wind field on the aircraft flight both from the point of view of navigation and the aircraft reaction to the turbulence zones.

2.5 Data Analysis and Processing Tools

Meteorological values computation by means of numerical methods in general consists in solving hydrodynamic equations systems at an appropriate time step and with appropriate assumptions. Numerical methods use numerical input data concerning physical state of the atmosphere and provide (by means of mathematical operations) forecasted values of specific meteorological factors in various points at defined periods of time.

A computer module consisting of programs and scripts for managing, processing and visualizing meteorological and remote sensing databases was developed in the Faculty of Civil Engineering and Geodesy. The research version of the application was developed in Matlab® for Windows®. The basic task of the module is to enable complex analyses of data sets of miscellaneous information structure and to verify COAMPS results using radar and satellite data.

The program assists multi-variant objective analysis and forecast of the atmospheric state in the area covered by the COAMPS mesoscale model. It enables full analysis of the space structure of meteorological data, i.e. free operation on multiple vertical or horizontal cross-sections (pressure or height) of meteorological parameters. Using nonstandard information, the forecaster has the opportunity to conduct multi-variant analysis which significantly improves decision making concerning forecasting. Comprehensive analysis based on computer processing of synoptic information enables objective assessment of relations between physical processes in the atmosphere. Complementary usage of meteorological information from the COAMPS mesoscale model enables preparation of miscellaneous specialized forecasts.

The research is conducted using uniform cartographic projection of all elements of the database. Satellite images and radar maps are transformed to the Lambert Conformal projection used by the COAMPS. This facilitates simultaneous interpretation and supports decision making processes for safe execution of aviation tasks. Verification of forecasts includes research of spatial and temporal correlations of structures generated by the model, e.g.: cloudiness, meteorological phenomena (fogs, precipitation) and structures identified in current satellite and radar images.

3. SPECIALIZED WEATHER FORECAST EXAMPLE

The following set of the developed module products presents an example of practical operational application of the model data to preparation of a forecast for aviation: for an aircraft flight over the territory of Poland from Krakow to Warsaw.

The general synoptic situation indicated that the flight route lay in a trough related with a low pressure area with its center over western part of Czech. Advection at 850 hPa: direction 180°, speed 20 km/h. Advection at 700 hPa: direction 190°, speed 30 km/h. Advection at 500 hPa: direction 200°, speed 35 km/h. Isotherm 0°C at 1500 m. Isotherm -20°C at 4900 m. A waving cold front in the zone of the flight produced characteristic distribution of surface air temperature presented in Fig. 1, low clouds cover presented in Fig. 2 and horizontal visibility presented in Fig. 3. Lines A and B in Fig. 1 indicate vertical cross-sections locations for obtaining vertical profiles of meteorological elements values for the specialized forecast.
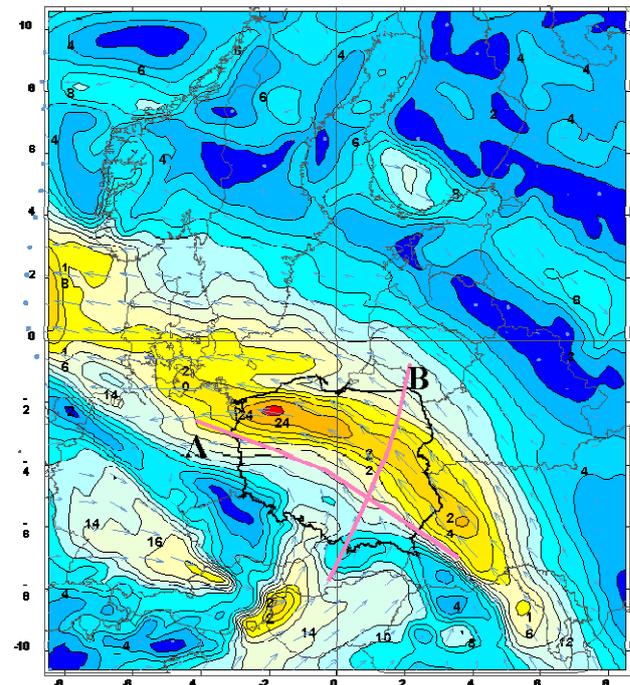

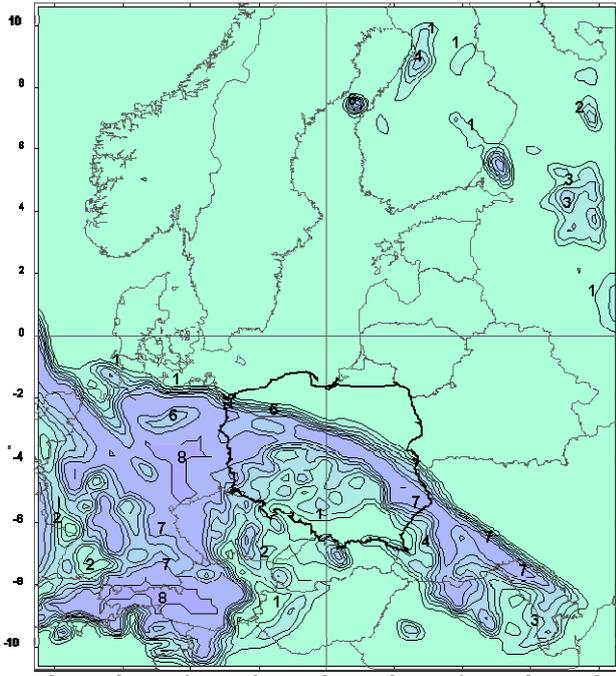Figure 1. Air temperature field at the surface.
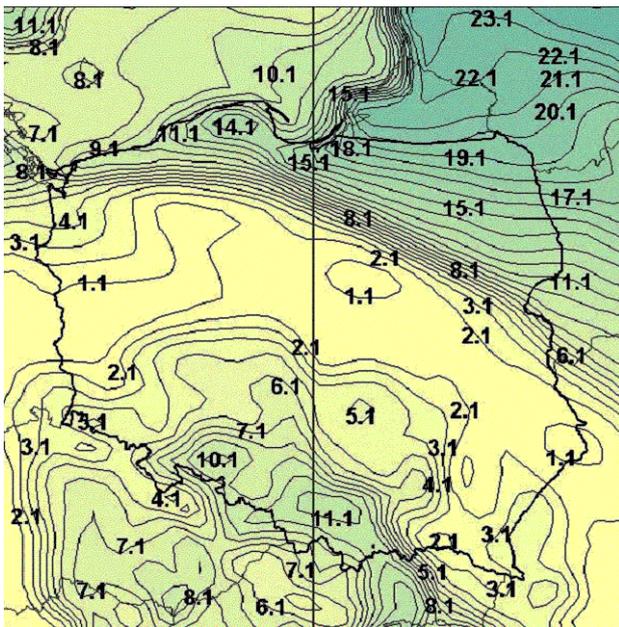
Figure 2. Low clouds cover.

Figure 3. Horizontal visibility.

The module provides forecasts of vertical profiles of selected meteorological elements along the flight route, e.g. air temperature (Fig. 4), liquid water content in clouds (Fig. 5), ice crystals content in clouds or vertical air movements velocity. The presented profiles indicate that the flight planned along the route marked with '+' signs took part in an air mass of temperature around 0 degrees Centigrade and significant water content. This suggests high risk of aircraft icing.
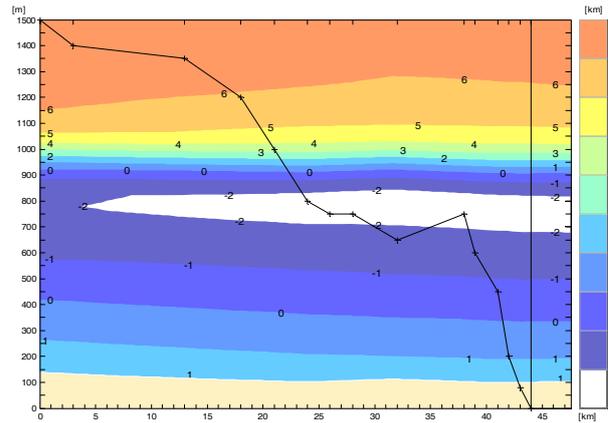

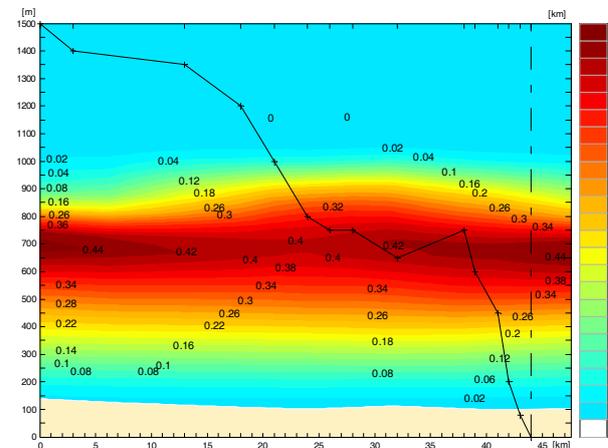Figure 4. Vertical profile of air temperature.

Figure 5. Vertical profile of liquid water content in clouds.

Vertical profiles of wind velocity in selected layers of the atmosphere are available using Doppler radars sounding results. These are of significant importance for wind shear analysis at the most crucial phase of aircraft approach to landing. Wind shear analysis in the layer between 1 and 3 km above the ground is presented in Fig. 6. Positive values of the gradient indicate increase of wind velocity with altitude of the aircraft.
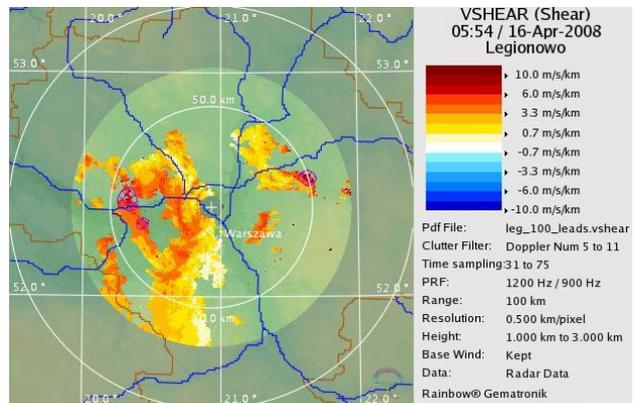

Figure 6. Vertical profile of wind velocity (www.imgw.pl).

4. CONCLUSION

Appropriate validation of the mesoscale model performance is a separate task to be realized after an appropriate amount of computer simulations, synoptic, radar and satellite data have been collected. The archived information is also a base for research concerning remote sensing data assimilation in the model which is important from the point of view of determining the atmospheric state. The developed module determines meteorological parameters fields for vertical profiles of the atmosphere. Interpolation procedures run at user selected standard (pressure) or height levels of the model enable to determine weather conditions along any route of aircraft. Basic parameters of the procedures determining e.g. flight safety include: cloud cover, cloud base, visibility, turbulence coefficient, icing and precipitation intensity. Determining icing and turbulence characteristics is based on standard and new methods (from other mesoscale models). The research also includes investigating new generation mesoscale models, especially remote sensing data assimilation. This is required by necessity to develop and introduce objective methods of forecasting weather conditions. Current research in the Faculty of Civil Engineering and Geodesy concerns developing the module to adapt the WRF (Weather Research and Forecasting) model for the area of Poland. It was designed to serve both operational forecasting and atmospheric research needs. WRF is suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometres.

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