UDC 551.576

A.M. Pirnach, *Prof., Sc.D.,* **S.M. Dudar**, **V.M. Shpyg**
Ukrainian Hydrometeorological Research Institute, Kyiv, Ukraine

NUMERICAL SIMULATION OF THE DANGEROUS EVENTS IN THE STEPPE PART OF UKRAINE

Abstract. *The three-dimension diagnostic and prognostic models of frontal cloud systems have been used for investigation of atmospheric phenomena connected with atmospheric fronts and their cloud systems that caused the damage events. Case of high convective cell caused aircrafts accident (August of 2006) will be presented in detail. It is found that is plausible to assume that crash was caused by conditions as follow: violent development of chimney clouds on the way of aircraft; cells of the strong vertical motions that can make the flight out of control; zones of instability that caused strong turbulence; chimney convective clouds with crystal tops and mixed layers that caused riming of aircraft.*

Keywords: *numerical simulation, frontal cloud system, aircraft crush, chimney clouds.*

1 Introduction

The paper continues theoretical investigations of different phenomena connected with atmospheric fronts and their cloud systems. In recent years numerical simulations of the various dangerous weather events caused the damages in frame aircrafts, agriculture, transport etc have been fulfilled in UHRI. Cases of strong shower, heavy convective and long lasting precipitation, spouts (as example in July of 1969, March of 2004) have been investigated [3-6]. Series of numerical experiments have been carried out with aim to research the key parameters caused formation of deep rotor cells and the phenomena accompanied it. Case with deep convective cell caused the aircraft accident will be below presented in detail.

2 Research methodology

The three-dimension diagnostic and prognostic models with non-elastic dynamics and detailed microphysics have been adapted for theoretical interpretation of the investigated phenomena. There is proposed research methodology based on numerical integration of dynamic and thermodynamic full equations jointly with kinetic equations for cloud particles distribution functions. Investigation of rotor structure of mesoscale phenomena have carried out by calculation and analysis of vertical component of vorticity and several components of the vorticity equation. Detail description of an evolution of cloud particles (cloud drops, rain drops, crystals, cloud and ice nuclei, etc.) are used to study the microphysical processes into widespread and convective frontal clouds [2, 4, 5, 6].

The purpose of this paper is to develop a methodology suitable for modelling of deep convective cells embedded in frontal cloud systems. Conditions of formation and development of cloudiness, precipitation, convective cells, and rotor cells were estimated for flat and complex terrain. Features of vortical movement in cumulus clouds and nearest environment were basically investigated in frame of vortex theory based on application the vorticity equation.

The developed models for complex relief use a terrain-following “Z-sigma” coordinate system that followed terrain relief and kept top coordinate surface on a target constant height. Coordinate system transformation has been used and Cartesian coordinates were replaced by a terrain-following sigma coordinates. Axes of x, y and z directed in east, north, and vertical respectively. x, y, z are the Cartesian coordinates, ξ, η, ζ are Z-sigma coordinates.

$$\xi = x, \quad \eta = y, \quad \zeta = \frac{z-\Gamma}{H-\Gamma} H . \tag{1}$$

Γ *(x,y)* is a relief function, H is highest ζ.

Clouds, vertical motions, rotor structure, relief were selected as key parameters for investigation. A relationship for calculation of vertical vorticity was used as follows:

$$\Omega_\zeta = \frac{\partial v}{\partial \xi} - \frac{\partial u}{\partial \eta} . \tag{2}$$

Ω_ζ is vertical vorticity, *u, v* are the horizontal components of wind velocity respectively calculated by integration of the full dynamic equation system [2,6]. Vertical motions have been calculated by integration of the system that included equations:

$$\frac{\partial^2 \rho u}{\partial \zeta \partial \xi} + \frac{\partial^2 \rho v}{\partial \zeta \partial \eta} + \frac{\partial^2 \rho \breve{w}}{\partial \zeta^2} = 0 , \tag{3}$$

$$\frac{d\breve{w}_i}{dt} = -g - \frac{1}{\rho}\left[\frac{\partial p}{\partial \zeta}\frac{1}{G_0}\right] + \Delta \breve{w} , \tag{4}$$

t is calculation time, p, ρ and $\breve{w}$ are pressure, air density and analogue of vertical component of wind velocity respectively. $\Delta\breve{w}$ and G_0 presented turbulence and $\partial\zeta/\partial z$ [5]. There are the *z*-integrated continuity equation (3) and full equation for vertical motion (4) that was used in different combination against different physical assumptions, type of cloudiness, calculation stage and features of modelling process. Total calculated scheme have been realized by splitting method. Description of schemes is in [2, 5, 6].

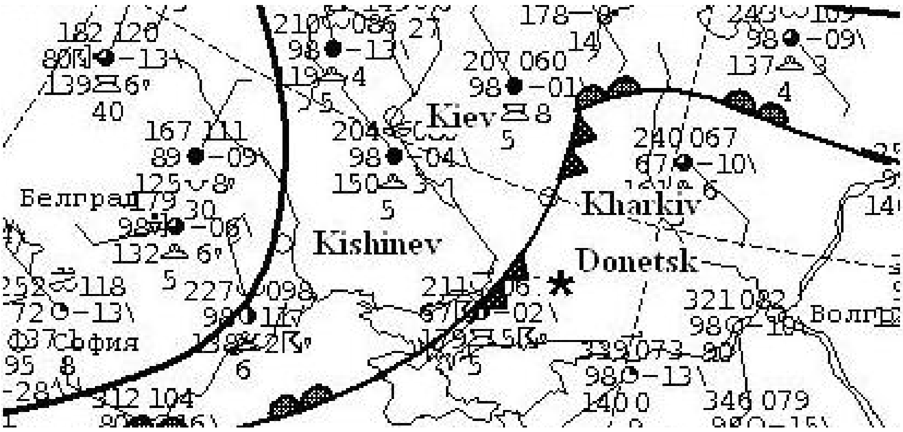
3 Initial data

Synoptic analysis and numerical modelling were used for description of current state of atmosphere at target time and space. Initialization of models was performed by rawinsond data from the regular network of Ukraine and neighbour stations of Europe and Asia obtained from INTERNET. 3-D diagnostic models were constructed and the received meteorological fields have been used for initialization of time development models. For the size distribution functions of cloud and participation particles the initial data were calculated by well-known empirical relationships, as an example, the Khrigian–Masin size distribution for cloud particles and Marshal – Palmer distribution for precipitation particles.

Initial stage ($t = 0$) of meteorological fields respectively is equal to 10:30 GMT. Origin of coordinates $(x, y) = (0,0)$ is Kryvyi Rig. Aircraft crash happened in 45 km from Donetsk in northwest direction. Area in frame $300 < x < 320$ km, $25 < y < 45$ km was selected for detail investigation. Nested grid were used in region $20 < x < 360$ km, $-10 < y < 50$ km. Steps of nested grid are $s_x = s_y = 1$ km, $s_z = 120$ m in *x, y, z* direction accordingly. In order to reduce description coordinates ξ, η, ζ are renamed as *x, y, z* respectively. In cases of complex relief $z = 0$ is located on earth surface, in case of Cartesian coordinates $z = 0$ is on sea level.

4 Synoptic situation

Analysis of all available meteorological information shows that Eastern part of Ukraine was under the influence of a cold front with possible lightings, thunderstorms and gusts (see Fig. 1,2).



Symbol ✱ represent Donetsk, (*x ,y)* = (338; 4 km).

Fig. 1 – Part of synoptic chart. Distribution of atmospheric fronts.

Available radar information shows that height of clouds reached up to 15 km, which is very rare over this region in summer time [1]. Observations of cloud evolution pointed to presence of deep Cb cells into accident region.

5 Diagnostic modelling

Diagnostic numerical modelling was used for construction of initial meteorological fields and analysis of weather conditions in investigation region. Weather situation was reconstructed by diagnostic model (calculation carried out in terrain-following “Z-sigma” and Cartesian coordinate systems). In Fig. 2 it is shown distribution of surface pressure and temperature; updraft z-maxima, and surface rotor were calculated for complex (first case) and flat (second case) relief at $t = 0$.

Chaotic structure with several bands and spouts takes place for these fields for complicate relief. Closed area of low pressure and cold air zone are observed near to the crash point. Strong vertical motion; clouds and strong rotation have been found in calculation area nearby the place of investigated accident. Both anticyclone and cyclone formation occur in it. Bands of cyclonic cells can be reason why formation deep convective cells development very fast. The vertical vortices of cyclonic and anticyclone formation can coexist as paired formations or as chaotic formations. The organized structure (like bands) aligned along the inhomogeneous structures of relief are found.

Excluding of relief caused homogeneous cyclonic rotation. There are uniform decreasing of pressure from the west to the east and uniform increasing of temperature from the west to the east respectively. Chains of rotor cells and vertical motions were found on a south–east border of the investigated region at $y < 10$ km. There are isotherms and isobars are not parallel and baroclinicity reveal itself very clearly. Special consideration of the same structures will be given below.

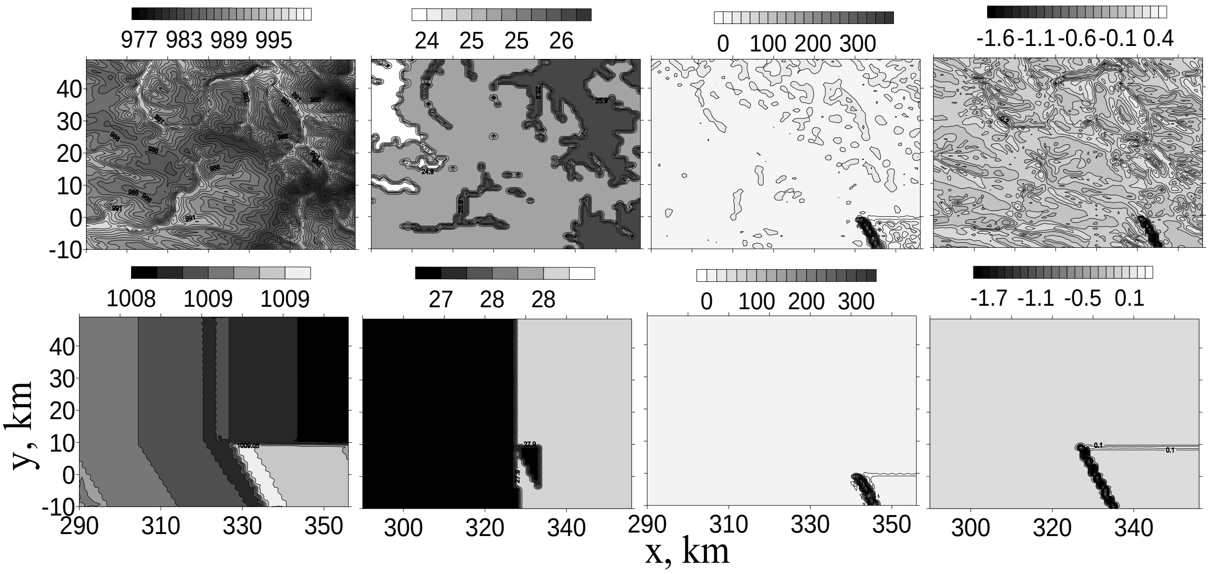


Fig. 2 – Initial distribution of meteorological fields. Surface pressure, hPa is first column; temperature, ^{o}C is second column; updraft z–maxima, cm/s is third column; rotor, 10^{-3}/s is fourth column. First and second rows present runs with and without relief account accordingly.

Ice supersaturation cells were not found in this region for both cases. Probably lack of observation data was not let them to reveal itself. Probably very strong activity of cloud and precipitation formation caused the total realization of the free water vapour. High temperature, zero isotherms ranged at the 3-4 km height caused the deep layers of subsaturation under bases of clouds and intensive evaporation of precipitation below clouds.

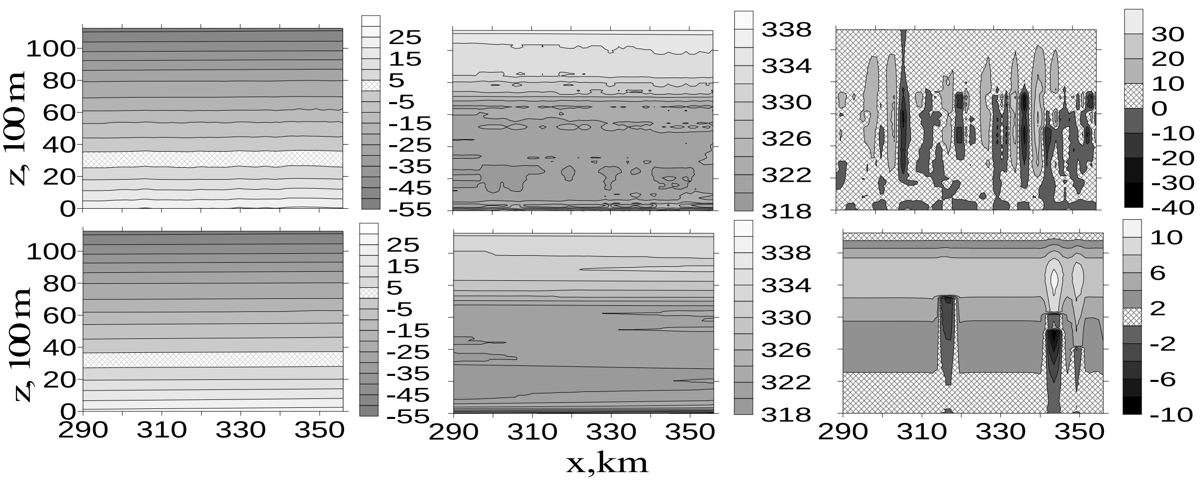


Fig. 3 – Vertical distributions of initial air features. Temperature, ^{o}C is first column; pseudo-equivalent temperature, K is second column and vertical motions, cm/s is third column at y = 31 km with (first row) and without (second row) relief account. Coordinates *ξ, η, ζ* are renamed as *x, y, z* respectively.

Figure 3 shows vertical structure of temperature and vertical motions into nested grid at y = 31 km. Vertical motions have the cell structure. Many deep columns of updrafts and the cell structure of pseudo-equivalent temperature depicted presence of deep chimney clouds in this region. Second row of this figure show a deep column of vertical motion nearby the accident place and two deep columns on the right board at $x = 318$ km and at $x > 340$ km. With including relief many dipoles of vertical motion have place. Pseudo-equivalent temperature (second column) confirm strong air instability both with and without of relief account. In first case more small instability cells have been observed and their number increased with including relief.

6 Evolution of cloud features accompanied aircraft crash

Runs for plate and complex relief shown the crucial role of relief in formation and development of chimney clouds (see Fig. 4). Relief caused the deep layers of mixing clouds that placed upon 0-isotherm and reached 9 km and ice cloud top exceeded 12 km and caused riming processes for aircrafts.

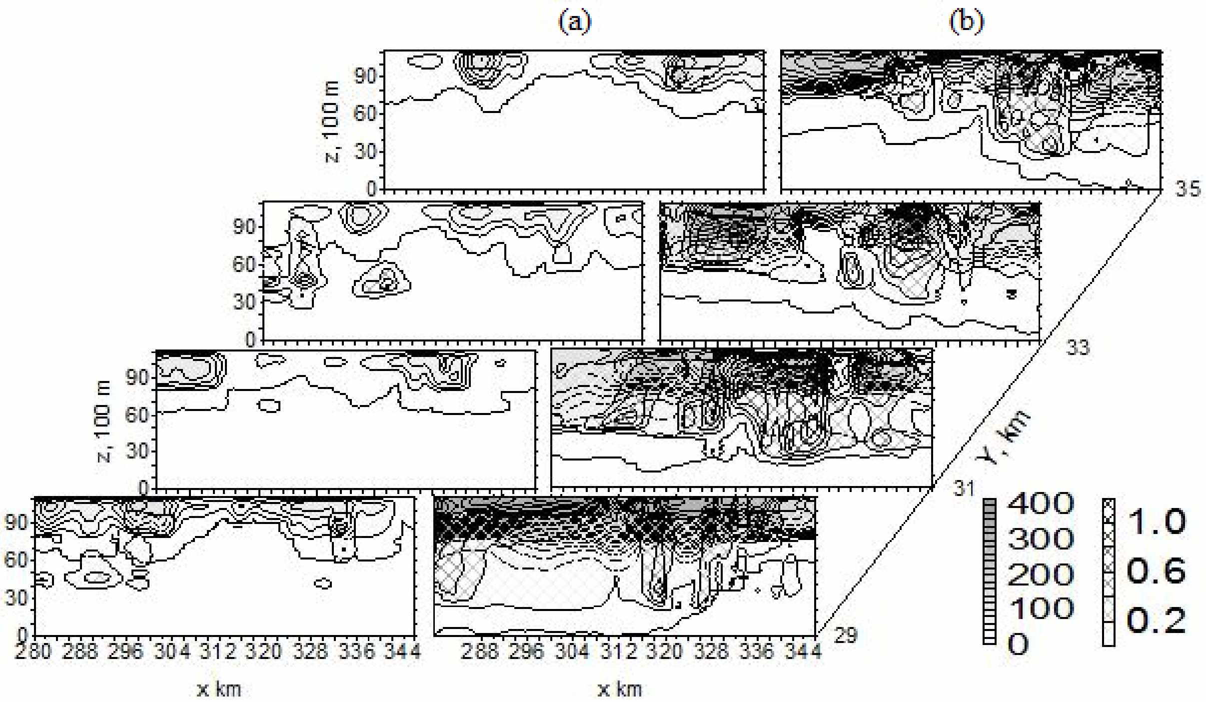


Fig. 4 – Space distribution of ice concentration and water content at 11:30 GMT. Ice concentration 1000/g is presented by numbers near 1st scale; water content, g/kg, is presented by numbers near 2nd scale. (a) numerical runs for flat relief; (b) numerical runs for complex relief.

Clouds ranged at heights that exceeded 5 km. z-maximums of water content were found at $8 < z < 9$ km. Presence of cloud drops at the very low temperature was very suitable for riming process and very dangerous for airplane flight. Ice concentration in tops of clouds exceeded 10^5/g and there were rich sources for seeding of mixing clouds and formation of precipitation. But deep layers of ice subsaturation take place below clouds and they let fall to the ground to the very large parts of precipitation only. With excluded relief from accounts clouds ranged higher and mixing clouds were thin and rare.

As we can see in Fig. 4 – 6 the powerful convective systems had formed less than 30 minutes from single clouds to the widespread convective systems with very great values of total water content. Chaotic rotor structures transform in ordered structures as band or as closed regions.

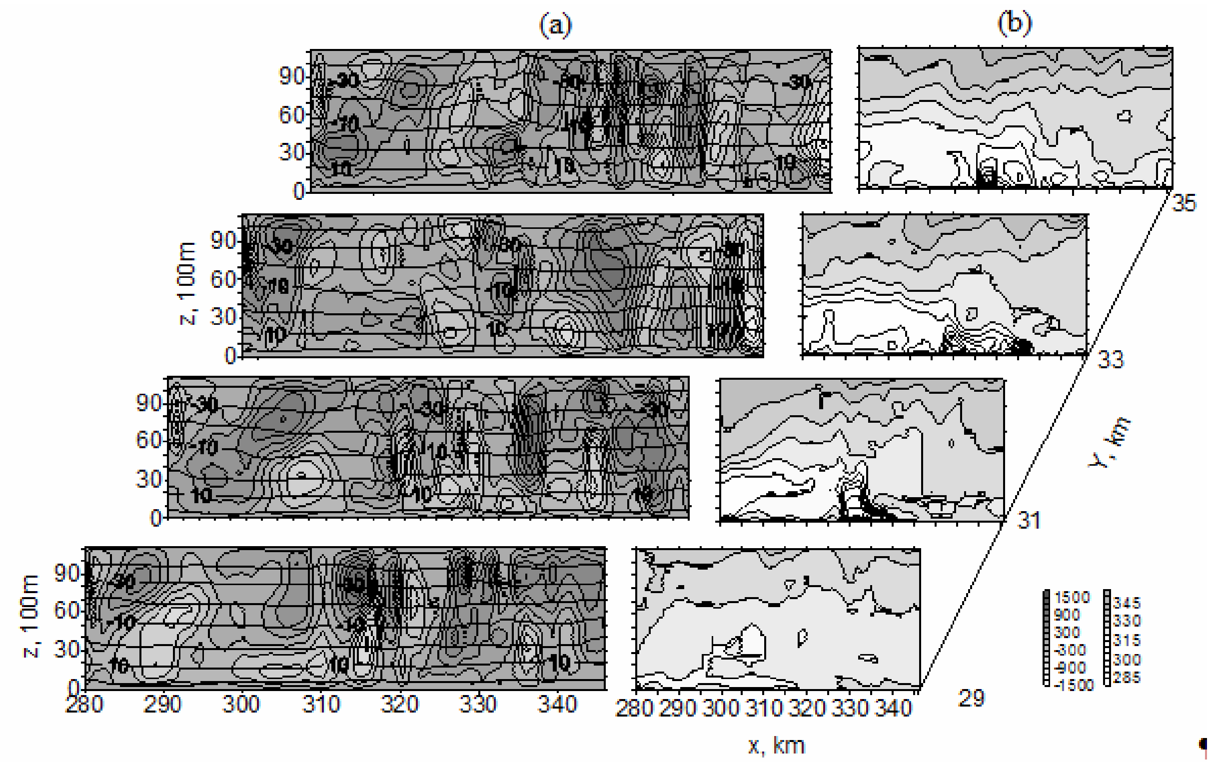


Fig. 5 – Space distribution of vertical motion and temperature at $t = 1$ hour. (a) temperature, °C, numbers near isoline; vertical motion, cm/s, numbers near 1st scale; (b) pseudo-equivalent temperature, °K, numbers near 2nd scale.

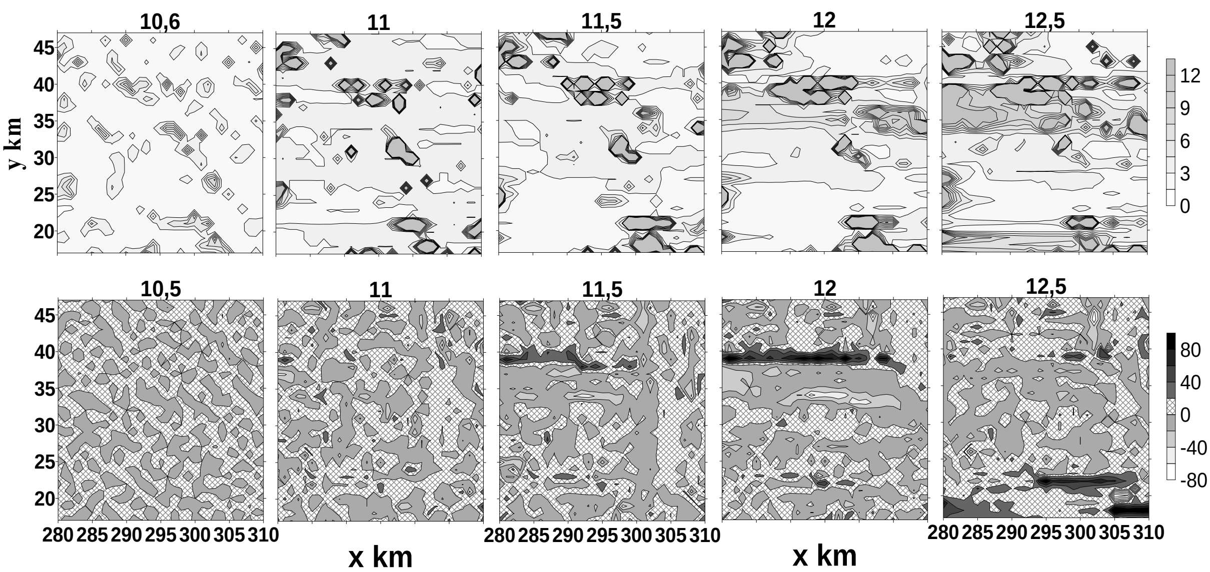


Fig. 6 – Cloud and rotor temporal and spatial evolution. Ice and water content z-integral presented as precipitation sum, mm (first row) and vortex temporal and spatial distribution Ω, 10^{-3}/s (second row). Numbers at top are GMT (aircraft-crash time is 11:38).

Two interesting events have need to attention. At $t = 11{,}5$ h a cyclonic rotor band near $y = 40$ km accompanied chain of convective clouds. After $t = 12{:}30$ GMT the cyclone rotor band disappeared and the cloud chain take up by a new development cloud system. At that time near y = 30 km an anticyclone rotor band accompanied spot of clouds that development in single cloud. After t = 12 h cloud began to decrease and disappeared after 12:30 in new cloud system. The organized anticyclone rotor domain destroyed. Similar process with a cyclonic rotor band begin at t = 12,5 h at y = 20 km. Corresponding convective cloud in this case have been formed at t = 11 h. Probably deep clouds caused the organized rotor structure.

7 Conclusions

Numerical simulation frontal cloud systems accompanied aircraft crush in steppe part of Ukraine were fulfilled. Convective cells and widespread cloudiness developed in central Ukraine on August of 2006 have been considered in detail. Numerical experiments with using two coordinate systems were carried out and influence of relief on the cloud and precipitation development was investigated.

Conditions of formation and development of high convective cells and rotor cells have been analyzed for plate and complex terrain. It is found that in many cases the relief was the crucial reason why chimney convective clouds were developed.

It is found that is plausible to assume that crash was caused by conditions as follow: violent development chimney clouds on the way of aircrafts; cells of the strong vertical motions that can make the flight out of control; zones of instability that caused strong turbulence; chimney convective clouds with crystal tops and very high deep mixed layers that caused riming of aircraft.

References

1. *Kryvobok, O., L. Savchenko* (2007) Analysis of satellite data on 22 August 2006 (plane-crash over eastern part of Ukraine). 4th European Conference on Severe Storms, 10 – 14 September 2007, Trieste, Italy.
2. *Pirnach, A.* (1998) Construction and application of the various numerical models for study the cloud dynamics and structure of the frontal rainbands. J. Atmos. Res., pp. 45–47.
3. *Пірнач Г.М., Заболоцька Т.М., Підгурська В.М., Шпиталь Т.М.* Чисельні та експериментальні дослідження фронтальних хмарних систем, які зумовили небезпечні явища на Україні. – Наук. праці УкрНДГМІ, 2002, вип. 250, с. 42 -60.
4. *Пірнач Г.М., Білокобильский А.В.* Чисельне моделювання літніх фронтальних хмар. – Наук. праці УкрНДГМ, 2000, вип. 248, с. 5–21.
5. *Пірнач Г.М.* Моделювання фронтальних хмар із сильними опадами для рівнинних та гірських рельєфів. – Наук. праці УкрНДГМІ, 2005, вип. 25, с. 37–50.
6. *Пірнач Г.М., Шпиг В.М.* Моделювання потужних конвективних хмар – Геоінформатика, 2007, № 4, с. 86–94.

Численное моделирование опасных явлений в степной части Украины

Аннотация. *Трехмерные диагностические и прогностические модели фронтальных облачных систем были использованы для исследования опасных атмосферных явлений, связанных с атмосферными фронтами и их облачными системами. В статье проведен анализ эволюции сверхмощной конвективной ячейки обусловившей аварию самолета в августе 2006 года над Донецком. Были сделаны предположения, что возможными причинами аварии самолета могли быть такие факторы: взрывное развитие мощных кучевых облаков вертикального развития на пути полета самолета; зоны неустойчивости, обусловившие сильную турбулентность; мощные слои смешанных облаков при низкой температуре, которые могли обеспечить быстрое обледенение самолета.*

Ключевые слова: *численное моделирование, фронтальные облачные системы, авиационные катастрофы, дымовые облака*