

# DETERMINATION OF THE ATMOSPHERIC DYNAMIC CHARACTERISTICS FROM THE MSG DATA IN ZONES OF DANGEROUS ATMOSPHERIC PHENOMENA

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## Abstract

On the basis of the method developed to determine the atmospheric dynamic characteristics with the use of the data of the radiometer SEVIRI water vapor channels of the European geostationary meteorological satellites Meteosat-8 and Meteosat-9 calculated were the fields of wind horizontal speed  $\mathbf{V}$ , the coefficient of horizontal turbulent diffusion  $K_d$  and vorticity ( $\text{rot}\mathbf{V}$ ) in the zones of jet fluxes and tropical cyclones. The horizontal dimensions of increased turbulence regions in the zones of jet fluxes in the upper troposphere and the coefficient of horizontal turbulent diffusion in them were determined. The calculated fields of  $\mathbf{V}$  and  $K_d$  were compared with the data of the baric topography maps. Revealed were the peculiarities of the coefficient of horizontal turbulent diffusion spatial distribution in the zones of tropical cyclones in the Atlantics.

## INTRODUCTION

The satellite methods used for determining wind fields in the atmosphere based on the Atmospheric Motion Vectors (AMVs) are widely applied in the operation practice and for scientific research. They give valuable information on horizontal wind vectors at different levels of the troposphere. At the same time it is known that many dangerous phenomena, in particular, intense atmospheric vortices, jet fluxes are characterized by the presence of zones of increased turbulence. These zones can be dangerous for aviation. Unfortunately, the methods used for the determination of the AMVs do not allow one to find the zones of increased turbulence and to obtain its quantitative characteristics. We have developed a method for determining dynamic characteristics of the atmosphere based on the use of the inhomogeneities of a conservative impurity concentration as tracers that make it possible not only to determine the wind horizontal speed vector but also the coefficient of turbulent diffusion. The method is described in the works by Nerushev et al., 2006 and Nerushev et al., 2007. The essence of the method is in the determination of kinematic characteristics of a random field by statistical methods. The motion of some separated volume element of a continuous medium is expanded into the transport (wind speed vector  $\mathbf{V}$  with components  $V_x, V_y, V_z$ ), rotation around an instantaneous axis going through its center ( $\text{rot}\mathbf{V}$ ) and deformation induced by, for example, diffusion processes. The use of the correlation-extreme algorithms makes it possible to determine the characteristics sought. The present paper gives the calculation results for the effective coefficient of horizontal turbulent diffusion based on the data derived from board the European geostationary meteorological satellites Meteosat-8 and Meteosat-9 for different regions of the atmosphere and different meteorological conditions. Main attention was paid to dangerous atmospheric phenomena – tropical cyclones and jet fluxes.

## METHOD FOR CALCULATING THE ATMOSPHERIC DYNAMIC CHARACTERISTICS

In the method applied by us a random field is the satellite-derived field of relative humidity  $U(x,y,t)$ , where  $x, y$  are the axes of the flat Cartesian coordinate system (positive direction  $x$  is towards the east,  $y$  – towards the north),  $t$  is time. The use of a two-dimensional (flat) model physically means that the effect of vertical motions in the field  $U$  can be neglected (Nerushev et al., 2007). The motion of

some separated region of the medium can be expanded into the transport (wind horizontal speed vector  $\mathbf{V}$ ), rotation around the immediate axis going through its center ( $\text{rot}\mathbf{V}$ ) and deformation induced, for example, by diffusion processes. The separation of a needed element of the medium volume (an “operation window”) is made by the operator  $H$ , being the spatial weight function and playing the role of a filter for the upper spatial frequencies. The procedure of matching of the areas of the field  $U$  during the time moments  $t_1$  and  $t_2$  made in such a way is in finding global extremes of mutual statistical characteristics.

According to the shifts of  $\Delta x$ ,  $\Delta y$ ,  $\Delta\varphi$ , at which a global minimum of the spatio-temporal structural function  $D(\Delta x, \Delta y, \Delta\varphi, \tau)$  is achieved, two components of the transport speed ( $V_x$  and  $V_y$ ) and vorticity ( $\text{rot}\mathbf{V}$ ) are calculated:

$$V_x = \Delta x / \tau, \quad V_y = \Delta y / \tau, \quad \text{rot}\mathbf{V} = \Delta\varphi / \tau, \quad (1)$$

where  $\tau = t_2 - t_1$ ,  $\varphi$  is the Eulerian angle of the coordinate system moving together with the separated region of the field. The calculation results refer to the time moment  $t = (t_2 + t_1)/2$ . The determination of the rate of the field ( $V_e$ ) temporal evolution caused by its “unfreeziness” is based on the analysis of the spatial and spatio-temporal structural functions. In this case  $V_e$  is calculated in the form of  $V_e = r_e / \tau$ , where  $r_e$  is the radius of the circle equivalent in the surface area to the cross section of the horizontal surface area of the spatial structural function  $D(\Delta x, \Delta y, 0, 0)$  for the time moment  $t_1$  at the level of the minimum of the spatio-temporal structural function  $D(\Delta x, \Delta y, \Delta\varphi, \tau)$  at  $\tau = t_2 - t_1$ . Note that the values of  $\mathbf{V}$ ,  $\text{rot}\mathbf{V}$  и  $V_e$  calculated in such a way reflect the effect of all the processes contributing to the displacement as a whole and the deformation of the medium range with the dimensions determined by the operator  $H$ . “Unfreeziness” of the random field and turbulent diffusion are different signatures of one and the same process – the temporal field evolution. Therefore, it is natural to assume the existence of a connection between the rate of evolution  $V_e$  and the coefficient of turbulent diffusion  $K_d$ . By interpreting  $V_e$  as an increment of the radius-vector of a spot diffusing per a time moment, one can easily show that for the two-dimensional diffusion model  $K_d = a \cdot V_e \cdot r_e$ , where  $a$  is the dimensionless coefficient equal to about unity.

## DETERMINATION OF THE COEFFICIENT OF TURBULENT DIFFUSION

For the determination of  $K_d$  the data obtained in the channels of water vapor (6.2 and 7.3  $\mu\text{m}$ ) of the radiometer SEVIRI based on board the geostationary satellites Meteosat-8 and Meteosat-9 were used. The satellite-derived information was received in Moscow in the Scientific and Research Center of Space Hydrometeorology “Planeta” (SRC “Planeta”) in the HRIT/LRIT formats. Most of the calculations were made with the “operation window” ( $H$ ) of the sizes of  $50 \times 50$  pixels. Fig. 1 presents the histograms of the coefficient of horizontal diffusion distribution for December 2005, January, February and March 2006 based on the data of the 6.2  $\mu\text{m}$  channel for the whole disk of the Earth. The number of calculation points for every month is within the limits of 1519-1556. The character of  $K_d$  distribution is practically the same for all the months: unimodal distribution with a maximum in the range of  $(2-6) \cdot 10^4 \text{ m}^2/\text{s}$ . Average values of  $K_d$  for December – March calculated from the histograms are within the limits from  $(9.0 \pm 0.2) \cdot 10^4 \text{ m}^2/\text{s}$  to  $(10.6 \pm 0.3) \cdot 10^4 \text{ m}^2/\text{s}$ . Rather a wide range of the  $K_d$  values obtained should be mentioned: maximum single values reached  $10^6 \text{ m}^2/\text{s}$ . Rather a long tail of the  $K_d$  distribution may reflect the effect of large vortices with the dimensions exceeding the value of  $H$ , but their contribution is negligible.

It is known that the value of  $K_d$  is the function of the scale  $r$ . To find a possibility to obtain the dependence  $K_d(r)$  from the satellite-derived data the calculations of  $K_d$  were made for the same regions but with different sizes of the operator  $H$ . The calculation results of average values of  $K_d$  for different values of  $r$  are shown in Fig. 2, the scale of  $r$  being matched with the linear size of  $H$ . The same figure demonstrated the theoretical curves for  $K_d$  from (Golitsyn, 2001). In this work analyzed are practically all available scarce experimental data for determining  $K_d$  in the atmosphere. It is concluded that the theoretical dependences rather adequately generalize the experimental data available. From Fig. 2 it follows that average values of  $K_d$  calculated from the satellite data for different seasons and different meteorological conditions, tropical cyclones in their number, are, on the whole, in good agreement with the theoretical curves for  $20 \text{ km} \leq r \leq 300 \text{ km}$ . The lower limit of the scale  $r \geq 20 \text{ km}$  is

determined by the spatial resolution of the radiometer SEVIRI (3 km in the IR spectrum range) and a used method of calculation. A quantitative comparison of the calculated  $K_d$  values with the theoretical ones for two ranges of  $r$  values is shown in the table. Note that we do not know other works where the values of  $K_d$  were determined from the satellite information.

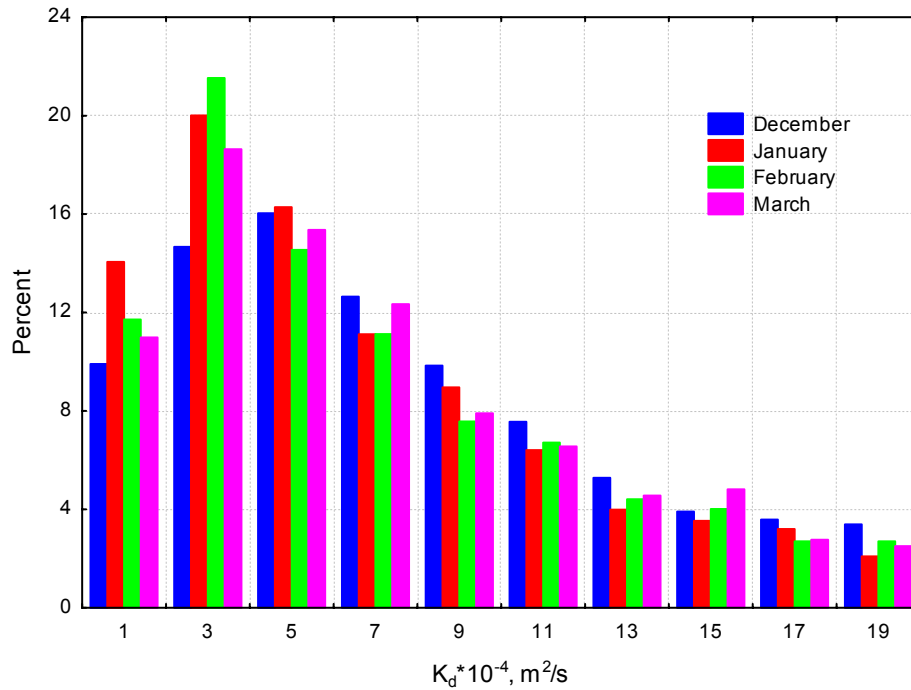


Figure 1: Histograms of the coefficient of horizontal turbulent diffusion distribution in the upper troposphere in winter and the beginning of spring of 2006 based on the calculation data for the whole disk of the Earth (6.2  $\mu\text{m}$  channel).

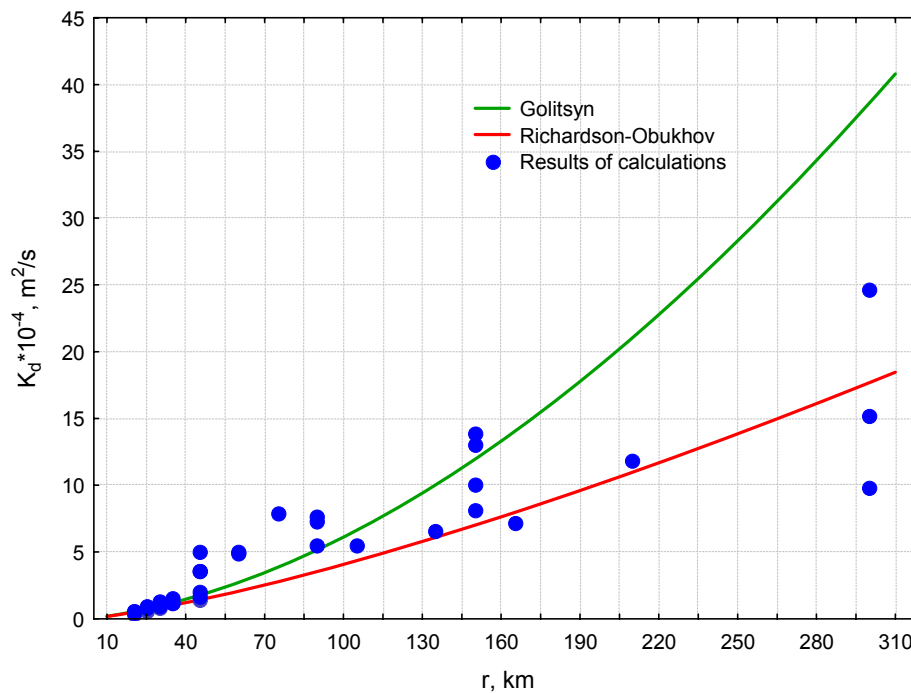


Figure 2: Comparison of mean coefficients of turbulent diffusion calculated from satellite data for different scales of  $r$  with the theoretical curves from (Golitsyn, 2001).

Variant	20 km ≤ r ≤ 150 km (n = 30)		20 km ≤ r ≤ 300 km (n = 35)	
	BIAS*10 <sup>-4</sup>	RMS*10 <sup>-4</sup>	BIAS*10 <sup>-4</sup>	RMS*10 <sup>-4</sup>
(Calculation) – (Golitsyn)	0.47	1.8	- 1.95	7.2
(Calculation) – (Richardson-Obukhov)	1.68	2.6	1.35	3.0

Table: Comparison of calculated mean values of  $K_d$  with the theory (n is the number of calculated mean values of  $K_d$ ).

## THE CALCULATION RESULTS FOR DYNAMIC CHARACTERISTICS IN THE ZONES OF JET FLUXES AND TROPICAL CYCLONES

It is known that in the zones of jet fluxes the regions of increased turbulence induced by large vertical and horizontal wind shifts are observed. They can be of great danger for aviation. From the data of scheduled flights and vertical soundings maximum repetition frequency of bumpiness in the upper troposphere caused by turbulence occurs at the altitudes of 8 – 12 km (Bogatkin, 2005). With the goal of searching the methods of objective revealing from the satellite-derived information of zones of dangerous atmospheric phenomena and determining their parameters we compared the calculated fields of  $\mathbf{V}$  and  $K_d$  with the data of the baric topography maps. Fig. 3 gives examples of calculation results for the atmospheric dynamic characteristics for 12:00 UTC based on the information from the satellite Meteosat-9 in the channels of water vapor (6.2 and 7.3  $\mu\text{m}$ ) obtained on 30.09.2007. The same figure show the prognostic map for the same period containing the information on jet fluxes, zones of increased turbulence, cloudiness, atmospheric fronts and maximum winds. Similar calculations and comparison with the maps were performed for 5 days more for other regions.

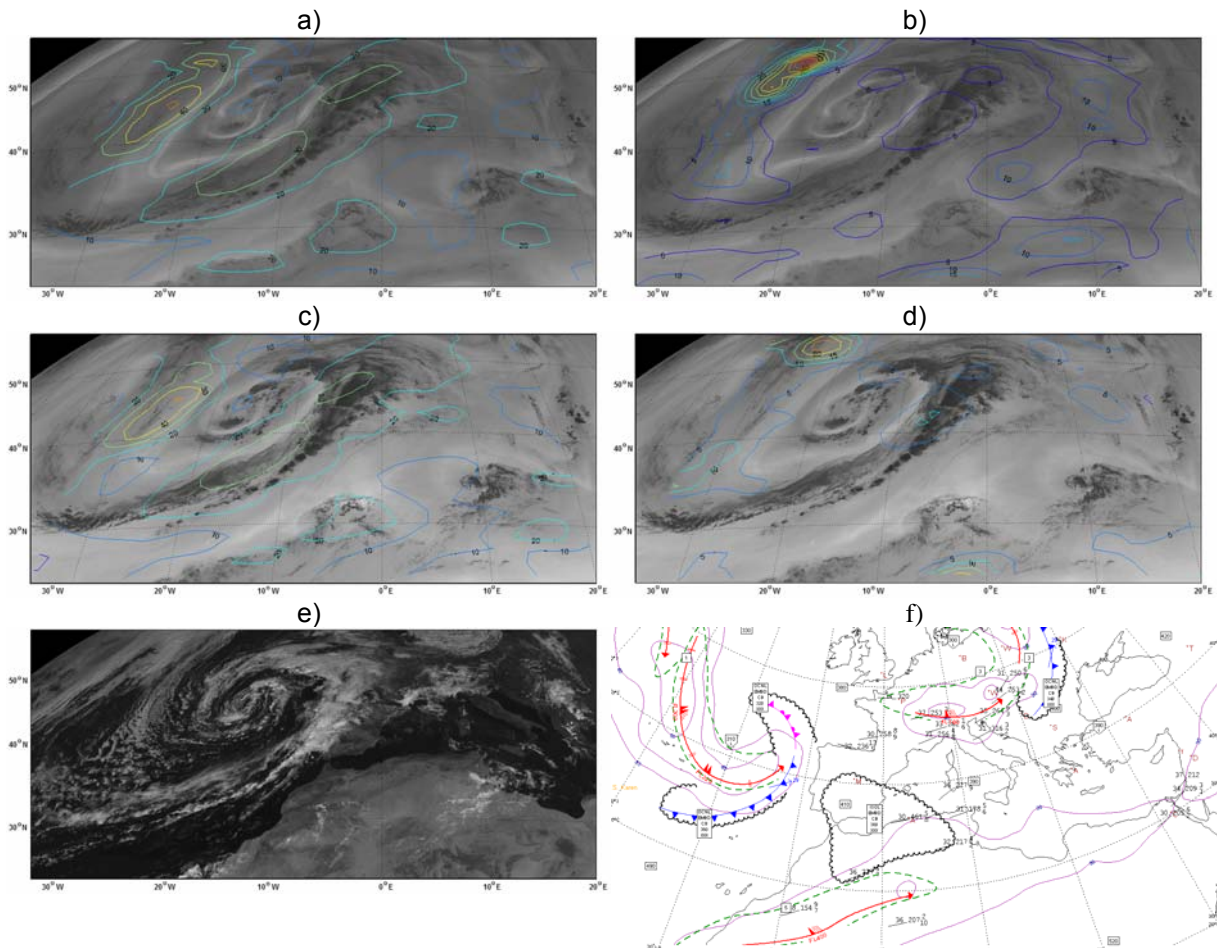


Figure 3. An example of atmospheric dynamic characteristics calculations in the regions of jet fluxes and zones of increased values of  $K_d$  connected with them for the image of Meteosat-9 of 30.09.2007, 12:00 UTC: a) isotachs (m/s), b) isolines of  $K_d \times 10^{-4} \text{ m}^2/\text{s}$  (6.2  $\mu\text{m}$  channel); c) isotachs (m/s), d) isolines of  $K_d \times 10^{-4} \text{ m}^2/\text{s}$  (7.3  $\mu\text{m}$  channel); e) a simultaneous image in the 0.6  $\mu\text{m}$  (visible range); f) the map constructed during the same period with a forecast of jet fluxes (red lines), zones of increased turbulence (green dashed lines), cloudiness (black wave lines), atmospheric fronts (blue and pink lines) and isotachs presenting the diagnosis of maximum wind at the level of maximum wind (violet lines).

A detailed analysis of the results obtained shows that there is good agreement both in the location of the zones of jet fluxes in the troposphere and the wind speeds in them. The locations of the calculated regions of maximal  $K_d$  values coincide with the zones of increased turbulence indicated on the maps. The calculated maximum values of  $K_d$  (the data of the 6.2  $\mu\text{m}$  channel) are by 8 – 10 times higher than its background values and reach  $6 \cdot 10^5 \text{ m}^2/\text{s}$ .

The regions with the values of  $K_d \geq 3 \cdot 10^5 \text{ m}^2/\text{s}$  are extended along the boundary of the jet flux and have for the case considered the dimensions:  $S_{\text{max}} = 1940 \text{ km} \times 590 \text{ km}$ ,  $S_{\text{min}} = 110 \text{ km} \times 50 \text{ km}$  at an average value of  $S_{\text{mean}} = 570 \text{ km} \times 240 \text{ km}$ .

A comparison of calculation results based on the data of the 6.2  $\mu\text{m}$  channel (maximum weight function for the moderate latitudes is at about 350 hPa) and 7.3  $\mu\text{m}$  (maximum weight function is at about 500 hPa) shows that when the fields of  $\mathbf{V}$  for them do not practically coincide (Fig. 3a and Fig 3c), the fields of the turbulent diffusion coefficient are noticeably different (Fig. 3b and Fig 3d). Maximum values of  $K_d$  at a lower atmospheric level (the 7.3  $\mu\text{m}$  channel) are by 2 times lower, and the region of increased values of  $K_d$  is significantly less in size (approximately  $1300 \text{ km} \times 800 \text{ km}$  for 6.2  $\mu\text{m}$  and  $600 \text{ km} \times 300 \text{ km}$  for 7.3  $\mu\text{m}$ ).

This agrees rather well with the corresponding theoretical consumptions of horizontal expansion and vertical thickness of zones with increased turbulence (Bogatkin, 2005). All the above-said gives a basis to think that the method used by us allows to reveal with the help of the satellite information the zones of increased turbulence and to obtain for them quantitative values of the coefficient of horizontal turbulent diffusion.

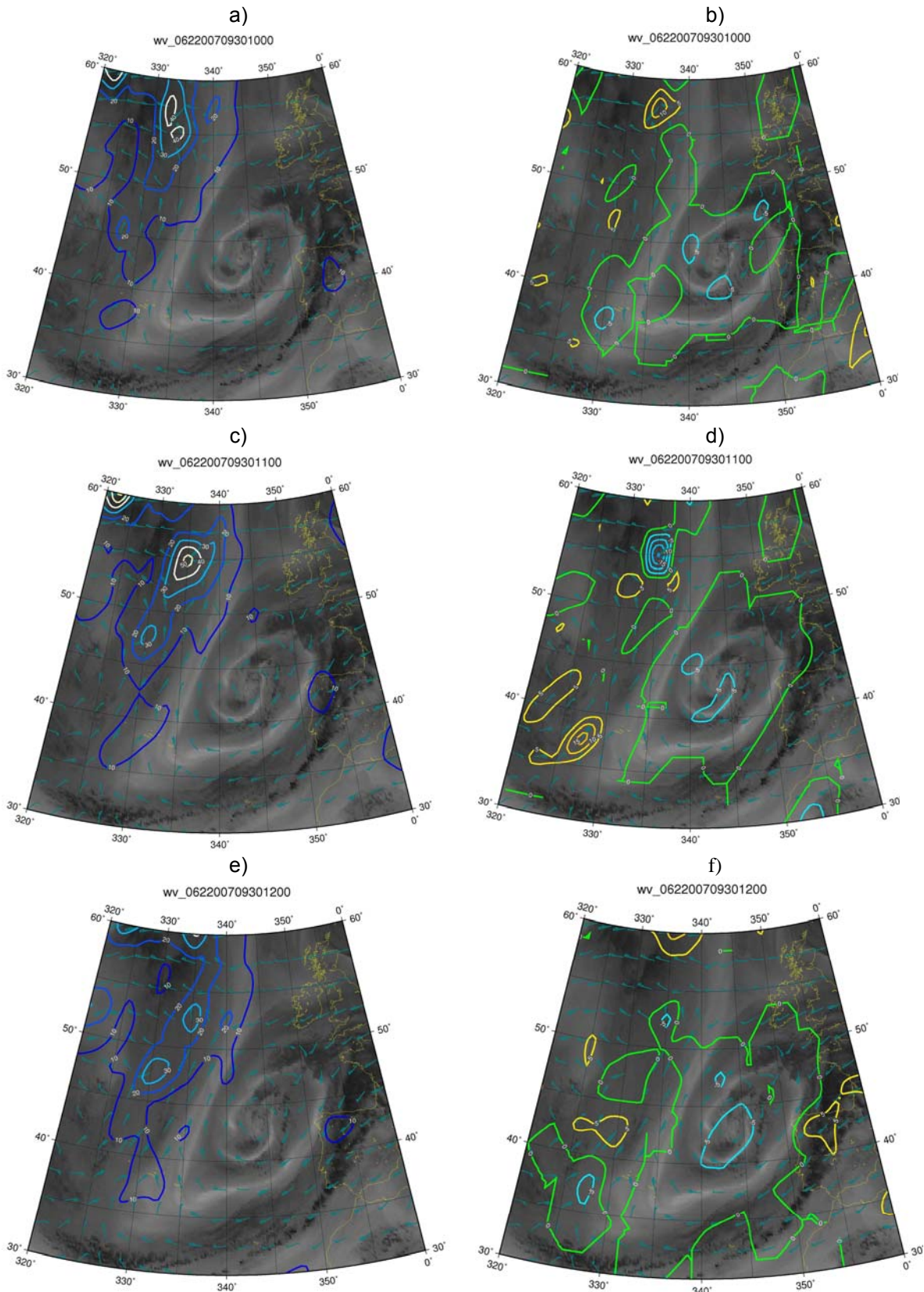
Fig. 4 gives an example of the dynamic characteristics ( $\mathbf{V}$ ,  $K_d$  and  $\text{rot } \mathbf{V}$ ) calculated from the data of the 6.2  $\mu\text{m}$  channel obtained on 30.09.2007 in the range of the atmospheric vortex in the Atlantic for three time moments: 10:00, 11:00 and 12:00 UTC. The sizes of the operator  $H$  are  $50 \times 50$  pixels. Note that all the atmospheric dynamic characteristics indicated are calculated simultaneously and independently on one another.

The analysis of the calculation results obtained for the time interval from 9:00 to 14:00 UTC with the time scale  $\Delta t = 15 \text{ min}$  demonstrates a different character of spatiotemporal variability of calculated mesoscale dynamic characteristics of the atmosphere. The field  $\mathbf{V}$  changes slightly during this time period. The zone of increased  $K_d$  values changes its configuration – separate centers of  $K_d$  local maxima appear in it and migrate. Most significant spatiotemporal variations are observed in the vorticity field ( $\text{rot } \mathbf{V}$ ). Local mesoscale regions of relative extreme values of  $\text{rot } \mathbf{V}$  with positive and negative vorticity appear, as a rule, in the zone of enhanced turbulence.

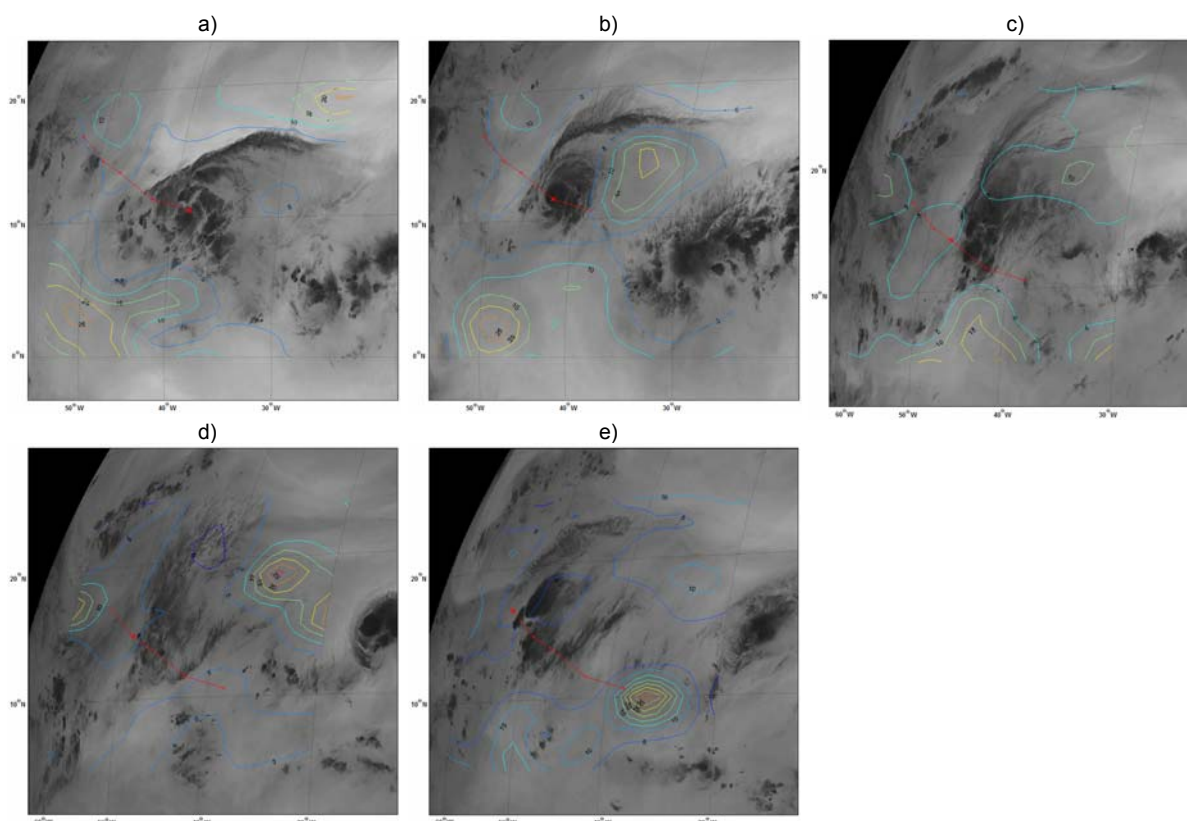
Fig. 5 gives a spatial distribution of  $K_d$  in the zone of tropical cyclone action in the Northern Atlantic Karen (September 2007) for 5 days of its lifetime – from 25 to 29 September. The tropical cyclone (TC) was at that time at the stage of tropical storm (25-28 September) and tropical depression (29 September).

Of attention are distinctly seen peculiarities of a spatial distribution of  $K_d$  as to the TC trajectory: local  $K_d$  maxima are located to the right and to the left of the trajectory, and the minima – along the trajectory. Maximum and minimum values of  $K_d$  differ by 5 – 7 times. Similar peculiarities are noted for all 5 TC of the Northern Atlantic of 2006 – 2007 that were in the zone of the radiometer SEVIRI viewing.

On the basis of these results one can make a conclusion that the above-mentioned peculiarities of the spatial distribution of  $K_d$  can be considered as prognostic signatures of a direction of a TC movement. But this conclusion should be supported by the calculation results for a considerably greater number of TC with various types of trajectories.



**Figure 4.** Spatiotemporal distributions of the coefficient of turbulent diffusion (isolines of  $K_d \times 10^{-4} \text{ m}^2/\text{s}$  at a, c, e), of vorticity (isolines of  $\text{rot}V \times 10^5 \text{ s}^{-1}$  at b, d, f) and of the wind speed vector  $V$  based on the data of the 6.2  $\mu\text{m}$  channel as of 30.09.2007 in the region of the atmospheric vortex at 10:00, 11:00 and 12:00 UTC. Yellow curves refer to positive vorticity, blue ones are for negative vorticity.



**Figure 5.** Successive photos of TC Karen from board the Meteosat-9 in 6.2  $\mu\text{m}$  channel of (25 – 29).09.2007, 12:00 UTC, (a) – (e), correspondingly, with isolines for  $K_d \times 10^{-4} \text{ m}^2/\text{s}$ . The red line indicates the TC motion trajectory, the circles show the TC center on the days mentioned, the cross refers to the TC location on the current day.

## CONCLUSION

The results presented here make it possible to draw the following basic conclusions:

1. The method used by us to determine the atmospheric dynamic characteristics allows one with the data of water vapor channels of the radiometer SEVIRI of the European geostationary meteorological satellites to find the zones of increased turbulence in the upper troposphere that are dangerous for aviation, to determine their horizontal dimensions and the coefficients of turbulent diffusion in them.
2. The regions of increased turbulence in the zones of jet fluxes in the upper troposphere, as seen from the calculations, have significant horizontal dimensions – more than 1000 km. The maximum values in them of  $K_d$  are by 8 – 10 times higher than its background values and can reach  $6 \cdot 10^5 \text{ m}^2/\text{s}$  and more.
3. In the zones of enhanced turbulence local mesoscale regions of relative extreme positive and negative vorticity values ( $\text{rot}\mathbf{V}$ ) are observed as a rule.
4. The spatial distribution of the coefficient of horizontal turbulent diffusion  $K_d$  in the upper troposphere in the zones of action of the Atlantic cyclones has distinctly seen peculiarities. Local maximum  $K_d$  are located to the right and to the left of a TC trajectory, and minimum – along its trajectory. In such a case minimum and maximum  $K_d$  values differ by 5 – 7 times.

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