Spatial structure and long-term variations of the atmosphere optical instability from NCEP/NCAR Reanalysis data

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Climatic distribution and long-term variations of optical instability of the Earth's atmosphere (OIEA), eddy activity of the atmosphere were studied by data of NCEP/NCAR Reanalysis. In the lower and middle troposphere the level of optical instability depends on the eddy activity and horizontal temperature gradients in the polar front area and at the "ocean–continent" boundary. In the upper troposphere and in the tropic regions the temperature variations are associated with changes in temperature occurring during vertical motions. In the lower stratosphere OIEA variations are caused by changes of the polar eddy and adiabatic changes of temperature. In the lower troposphere, variations of the OIEA and eddy activity are most closely connected in tropics and subtropics: in the South of Asia, in Africa, and South America. Some of favorable (from the viewpoint of astroclimate) regions in the Southern Hemisphere (South Africa, South America) in wintertime fall into the area of positive trends of OIEA. Variations of the OIEA and eddy activity might be caused by changes in the general circulation of the atmosphere, in particular, by strengthening the circum-Antarctic depression.

Introduction

The aim of this investigation is to work out an approach to interpretation and forecast of astroclimate variations. Even in the case when the main climate trends of a chosen region are known, the problem is not trivial, because the notion of astroclimate is complex and includes a series of characteristics depending on global and regional factors differently varying in time. Analysis of all these characteristics within the framework of a single study does not seem possible. In this paper, we consider in detail optical instability of the Earth's atmosphere (OIEA) as an astroclimate characteristic and focus on one of the main factors, which determines this characteristic, i.e., the eddy activity of the atmosphere.

By optical instability of the Earth's atmosphere we mean the degree of inhomogeneities of the refractive index under variations of the air density. The optical instability of the Earth's atmosphere is determined mainly by variability of the temperature integrated over the vertical coordinate. With increase of height and decrease of air density the contribution of temperature variations in layers of equal thickness decreases, but remains significant up to the heights of the lower stratosphere. Variations of temperature affect the optical instability to less extent under a high temperature background and to higher extent under low temperatures. The parameter, which is defined by the semi-empiric relation[1] OIEA ~ σ_T/T^2, where σ_T is the standard deviation of temperature calculated for about a month, T^2 is the square of average temperature during the same period, is one of the instability characteristics, taking into account all these features.

In such a way of estimation, the contribution to the calculated characteristic is yielded by both high- and low-frequency temperature variations. The subject of our inquiry is the low-frequency component. It turns out that low-frequency variations not only affect the observation quality themselves but are an indirect indicator for the influence of the high-frequency component.

Comparison of optical instability characteristics, which were computed by archive data and characteristics, obtained from data of direct optical and aerologic measurements at the territory of the former USSR[2] has demonstrated their good agreement. This made it possible to use this method for other regions. Just the connection between high- and low-frequency variations permits one, in principle, to hope for the possibility to forecast astroclimate components and to conduct diagnostic investigations with the archives of reanalysis, obtained by assimilation of the data of standard observations from a network of meteorological stations.

There are two reasons for the importance of the possibility to use present-day archives for astroclimate estimates. First, the archive data, if they are interpolated in the points of some regular grid, uniformly cover the whole surface of the earth sphere. Second, they are continuous in time, what makes it possible to apply them not only for diagnostics but also for solving prognostic problems. We used the data of the most frequently cited archive NCEP/NCAR Reanalysis accumulating a large array of various meteoparameters in the points of a 2.5×2.5° grid at 17 levels of the atmosphere.[3]

Eddy and wave activity of the atmosphere is the main weather factor affecting the temperature variability and optical instability. Cyclonic and anti-cyclonic

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perturbations prevail in the lower troposphere, stationary and moving planetary waves prevail at higher levels. In this paper we conventionally call them the eddy activity. Since the circulation of the atmosphere is approximately geostrophic in temperate latitudes, the velocity field can be expressed by pressure distributions or stream functions. Temporal variability of theses values is convenient for calculations, when it is estimated by variance of 24-hourly values of near-land pressure or geopotential during periods of about a month. In Ref. 4 this characteristic was called the eddy activity index and computed for the surface of 500 hPa.

One should bear in mind that, generally speaking, there are some differences in the mechanism of the eddy activity influence upon temperature fluctuations at different levels of the atmosphere and in different latitude zones. In the lower and middle troposphere of temperate latitudes, it is mostly advective and is connected with the horizontal field of velocity. Its realization needs spatial gradients of temperature, which provide for the heat advection together with the eddy activity.

No doubt that formation of temperature contrasts and the eddy activity are connected, but, in the first rough approximation, these two factors can be analyzed separately on the base of the assumption that temperature contrasts are formed by the general circulation of the atmosphere. This is true to a certain degree, because temperature gradients along a meridian are a consequence of Hadley and Ferrel meridian circulation cells, and those along latitude circles are closely connected with monsoon effects at the "ocean–continent" boundaries.

In the upper troposphere and tropics the contribution of vertical motions increases. Variations of temperature in a descending or ascending air mass can be connected with release of heat of phase transitions, with variations of the radiation balance in formation or scattering of clouds in tropics, or with adiabatic fluctuations of the temperature. In the lower stratosphere, adiabatic variations become main factors.

Fluctuations of mean temperature can compensate or enhance the role of the eddy activity in the optical instability of the atmosphere to some extent. Certainly, the role of this factor seems to be considerable in seasonal OIEA fluctuations and in large spatial scales (ocean, continent). At short-time intervals and over a homogeneous surface, features of spatial OIEA distribution are most likely connected with distribution of the eddy activity. In the lower troposphere they seem to be significantly depended also on the distribution of horizontal temperature gradients.

To verify these rather common suppositions, we compared spatial distributions of OIEA and the eddy activity in different seasons at different heights of the atmosphere and in different regions of the Earth. To estimate the eddy activity index, height variances for the isobaric surface were calculated in grid points for monthly intervals. For the same intervals, the parameter of optical instability was also calculated by the above-mentioned formula. The computed characteristics were averaged for the period from 1950 to 2006. In addition to spatial distributions of optical instability and eddy activity, we studied connections between variations of the both characteristics and features of their long-term variations.

Spatial distributions of optical instability and eddy activity of the atmosphere

Figures 1*a* and *b* demonstrates near-surface climatic distributions of the OIEA parameter and the eddy activity in January and July.

The solid background represents the distribution of the optical instability of the atmosphere; the isolines present the distribution of the eddy activity index. One can clearly see seasonal variations of the both characteristics. In winter the eddy activity in temperate latitudes is higher than in summer, and mean temperature is lower. This additionally increases the contribution of the eddy activity. The level of OIEA is not high over oceans, although the eddy activity can be high. It seems that a homogeneous underlying surface smoothes temperature contrasts between air masses and decreases variations of temperature. Over continents, OIEA distributions are of quasi-zonal character and correspond to the latitude variation of the eddy activity distribution. Temperature gradients, which are especially high in the polar front area, also have latitude variations. Coastal areas of continents are special zones. Contrasts of temperature between dry land and ocean lead here to especially strong advective fluctuations of temperature and high values of OIEA.

Figures 1*c* and *d* presents spatial distributions of OIEA (background) and the eddy activity (isolines) in January and July at a level of 700 hPa, which approximately corresponds to a height of 3 km. One can see that the features of spatial OIEA distribution and the eddy activity at this level generally follow features of distributions near the surface. Thus, in the lower and middle troposphere, as expected, the effect of the eddy activity on optical instability is of advective character and depends on the spatial distribution of temperature gradients in the polar front area and at the "ocean–continent" boundary.

With increase of height, beginning from the upper troposphere, temperature fluctuations are already not of advective but of convective character and are connected with adiabatic variations at vertical motions. The role of horizontal temperature gradients and temperature distinctions of air masses decreases, and the connection with pressure fluctuations in Rossby waves increases. Generation of Rossby waves, as it is well-known, occurs in zones of aggravation of jet streams. As it should be expected, maximal OIEA values prove to be connected with these zones. This is illustrated by Fig. 2, which presents the distributions of the OIEA parameter and eddy activity at the level of 150 hPa lying just over the tropopause, in January and July.

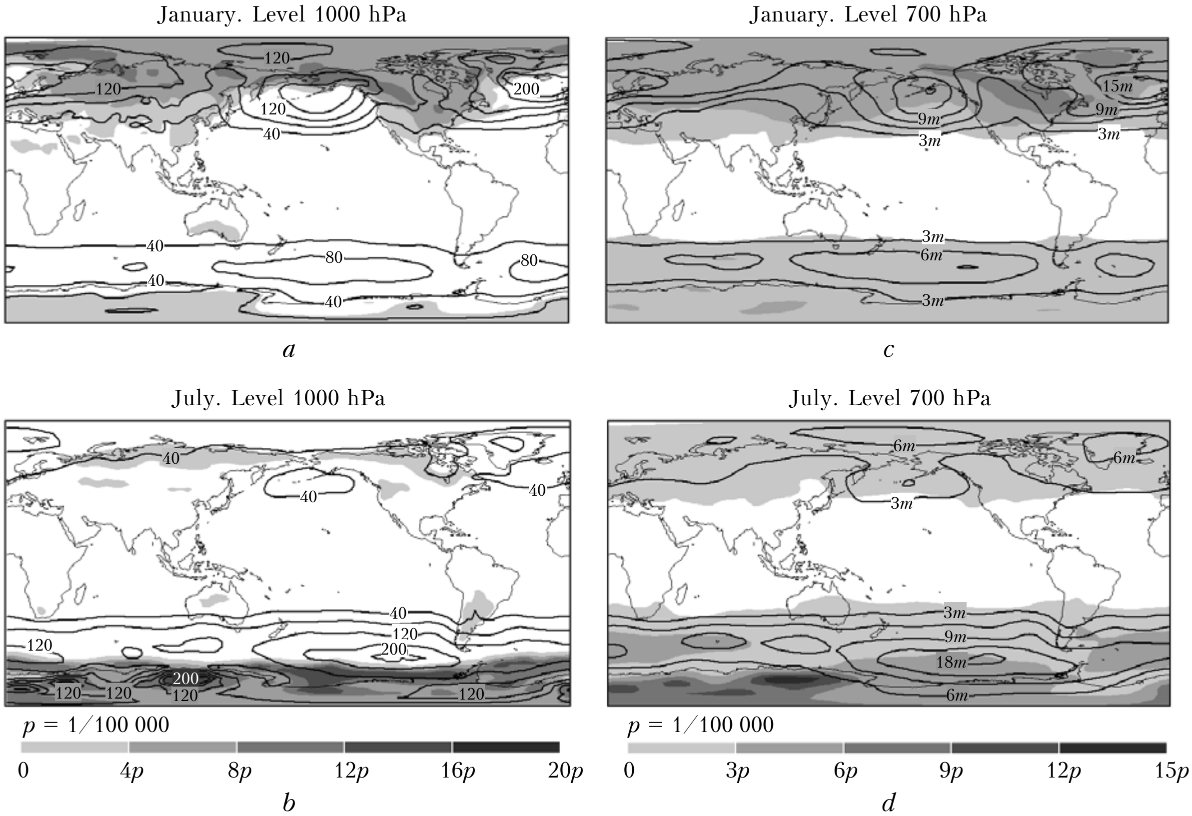

Fig. 1. Distributions of the OIEA parameter and the eddy activity at the ground level (*a*, *b*) and at the 700 hPa surface (*c*, *d*) in January and July. Isolines show the distribution of the eddy activity index with a discreteness of 40 m^2 (40, 80, 120...) at the ground level and with a discreteness of $3m$ ($3m$, $6m$, $9m$...), where $m = 1000$ m^2, at a level of 700 hPa. The solid background is the OIEA distribution in conventional units.

One can see that the maximal values are localized over the North Atlantics in the Northern Hemisphere and in the South of the Pacific Ocean in the Southern Hemisphere. These areas roughly correspond to the latitude of the polar-front jet stream. Over the East of Eurasia and West of North America, the optical instability is somewhat lower, apparently due to smaller velocities of jet stream velocities and the decreased wave activity over the homogeneous cold surface of the continent.

At a level of 20 hPa (Fig. 3), maximal OIEA values almost uniformly fill the whole polar area with a local maximum over the North-East of Eurasia and a minimum over Greenland and Spitsbergen. The local maximum seems to be connected with predominant localization of points of the stratospheric warming. The appearance of the minimum of the optical instability is more difficult to explain. The climatic distribution of the temperature at this level (not presented in this paper) demonstrates a temperature minimum near Spitsbergen, what must favor the increase of the optical instability. However, the eddy activity also has a sufficiently complex distribution in this region. This probably compensates the influence of the temperature factor. On the whole, homogeneity of distributions (see Fig. 3) points to the fact that the polar stratospheric eddy is a localized object, within which all meteoparameters vary synchronously. In other words, distributions of the eddy activity and OIEA in the lower stratosphere are determined already by fluctuations of the whole polar eddy.

Thus, our initial prerequisites are verified in general. The factors, which have an effect on the optical instability of the atmosphere in temperate latitudes can be systematized as follows: the eddy activity and horizontal temperature gradients (advection) for the lower troposphere; Rossby waves in zones of higher baroclinicity, and vertical motions for the upper troposphere; large-scale low-frequency variability and vertical motions for the lower stratosphere.

Connection between variations of optical instability and eddy activity of the atmosphere

Now we turn to the study of optical instability variations. To simplify the problem, we restrict ourselves by consideration of the OIEA connection with the eddy activity only at one level, in the lower troposphere. This layer of air is especially important, because it yields the main contribution to image quality, and its study is impeded by the necessity to take into account additional factors: the orography,

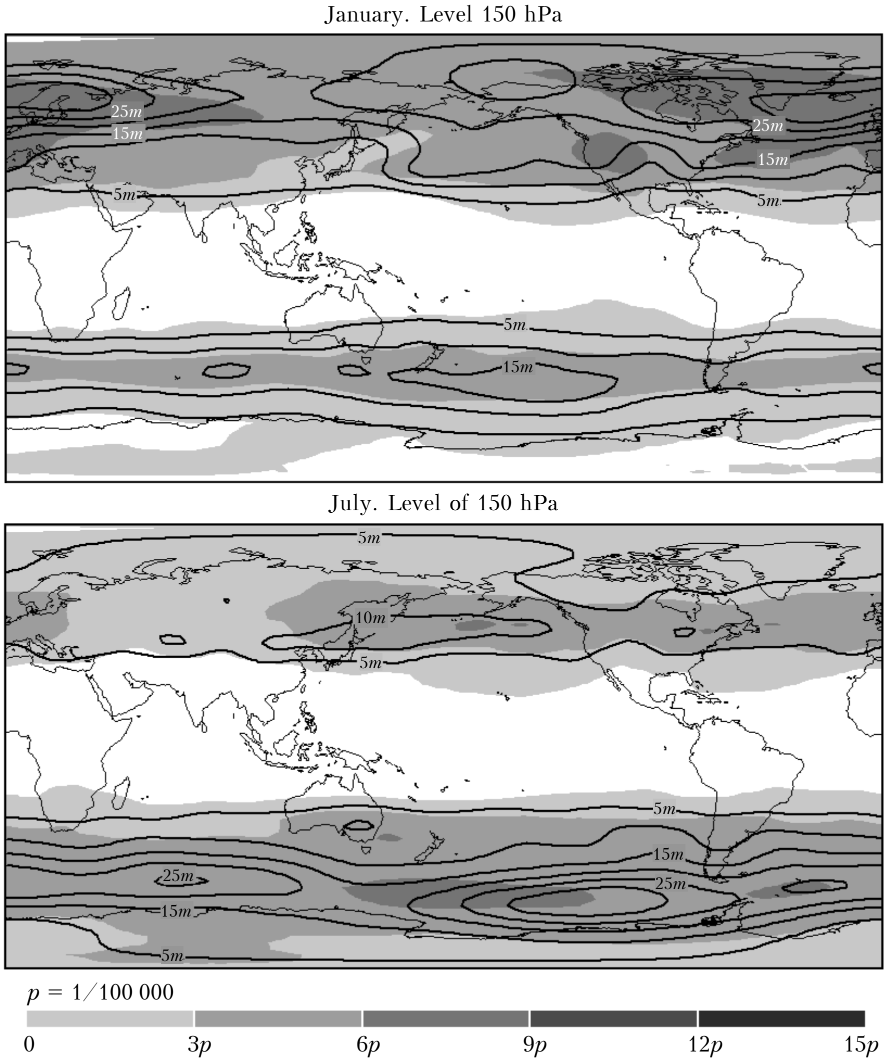

Fig. 2. Distributions of the OIEA and eddy activity in January and July at a level of 150 hPa. Isolines are the distribution of the eddy activity index with discreteness of $5m$ ($5m$, $10m$, $15m$...), $m = 1000\ \text{m}^2$. The solid background is the OIEA distribution in conventional units.

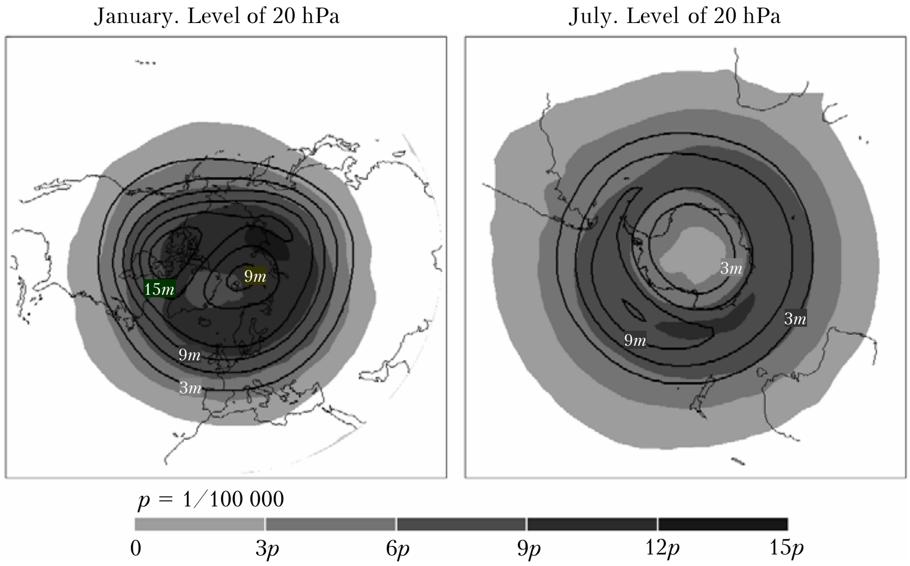

Fig. 3. Distributions of OIEA and the eddy activity in January and July at a level of 20 hPa. Isolines are the distribution of the eddy activity index with a discreteness of $3m$ ($3m$, $6m$, $9m$...), $m = 10000\ \text{m}^2$.

which influences spatial distribution of horizontal temperature gradients, differences in properties of synoptic formations, and general circulation of the atmosphere of temperate and tropical latitudes. Since these factors vary in time differently, the field of coefficients of correlation between OIEA variations in time and the eddy activity has a rather complex spatial structure. This is clearly seen from Figs. 4*a*, *b*, which presents distributions of coefficients of correlation between inter-annual variations of monthly average OIEA values and the eddy activity in January and July.

Although the spatial structures of OIEA and the eddy activity are close in temperate and high latitudes, correlation between these values proves to be stronger in tropics and subtropics, far from areas of big horizontal contrasts of the temperature. Correlation coefficients are in interval 0.5–0.7 in the south of Asia, in Africa, and in South America. This is probably connected with the fact that temperature fluctuations in these regions are already determined to large extent not by advection, which depends not only on eddy activity, but also on the distribution of horizontal temperature gradients, but by convection and factors of heating and cooling which are connected with vertical motions. In contrast to the horizontal field of temperature, which varies in time almost independently on variations of the eddy activity, the convective factors of heating and cooling are closely connected with variations of the eddy activity. This determines the high level of statistical connection between OIEA and variations of the eddy activity.

In our opinion, this result is sufficiently important, because it permits one to investigate temporal OIEA dynamics by analysis of a single factor, i.e., the eddy activity in areas, which are most interesting from the viewpoint of astronomical observations, i.e., tropics and subtropics of the both hemispheres. The use of the eddy activity index is especially convenient due to the fact that there are many investigations devoted to its properties, and, what is most important, one can try to associate this parameter with characteristics of the general circulation of the atmosphere.

Long-term variations of optical instability of the atmosphere

Now we turn to analysis of general trends in variations of the OIEA and eddy activity. Long-term variations of the eddy activity in the lower troposphere were analyzed in Refs. 5 and 6. It was found that the eddy activity was on the average higher in the Southern Hemisphere than in the Northern Hemisphere and rapidly increased from the middle 70s. Note that in the Southern Hemisphere the amplitude of stationary waves also increases.[6] This fact remains unexplained. At present, all these changes occur in high latitudes, far from main observatories.

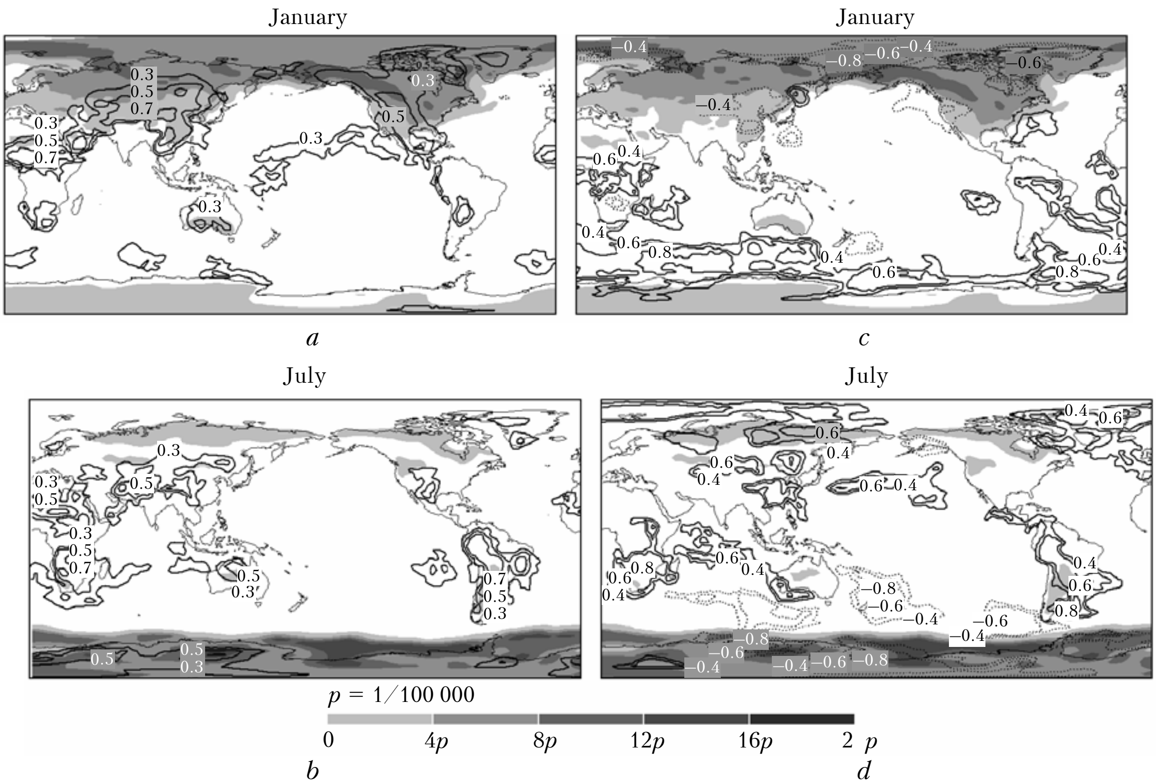

Fig. 4. Distributions of the coefficients of correlation between inter-annual variations of monthly average OIEA values and variations of the eddy activity (*a*, *b*) and a linearly increasing function (*c*, *d*) in January and July from 1950 to 2006. The solid background is the distribution of the OIEA parameter at the ground level.

We also tried to highlight the trend component in OIEA variations. For this purpose, we obtained distributions for coefficients of correlation between OIEA variations in grid points in January and July and variations of a linearly ascending function (Figs. 4*c* and *d*). Such a way of estimation is rather rough but easy-to-interpret and makes it possible to estimate general trends in dynamics of parameters throughout the Earth. One can see that the areas of positive trends in January in the Southern Hemisphere are situated mostly in the Indian and Atlantic sectors of the circum-Antarctic depression. The optical instability decreases in high latitudes of the Northern Hemisphere, in polar areas of Canada, and near Chukotsk. These areas, however, are not of great interest because they are in regions with high climatic OIEA level far from big observatories. In July the areas of positive trends in the Southern Hemisphere prove to be shifted to lower latitudes – to South Africa, center of the Indian Ocean, and South America. One can suppose that the present-time deterioration of astroclimate conditions, observed at South America observatories, is a consequence of these trends. The maps, which are presented in Figs. 4*a* and *b* demonstrate that long-term variations of OIEA in this region are caused mainly by variations of the eddy activity. Variations of the eddy activity itself are probably caused by changes in the general circulation of the atmosphere, in particular, by strengthening of the circum-Antarctic depression and transfer of a part of the air mass to tropics and subtropics.[7]

Conclusions

In this paper we studied climatic distribution and long-term variations of the optical instability of the atmosphere as one of important characteristics of astroclimate. The eddy activity of the atmosphere was considered as one of the main factors having an effect on the OIEA. In the lower and middle troposphere, together with the eddy activity and Rossby waves, the level of the optical instability depends on horizontal temperature gradients in the polar front area and at the "ocean–continent" boundary. In the upper troposphere and tropics, temperature fluctuations are already not of advective character and are connected with variations of temperature at vertical motions. In the lower stratosphere, OIEA variations are caused by polar vortex fluctuations and adiabatic variations of the temperature.

In the near-land layer, variations of OIEA and the eddy activity are most closely connected in tropics and subtropics: in the south of Asia, in Africa, and in South America. This permits one to investigate temporal OIEA dynamics by analysis of a single factor, i.e., the eddy activity in areas, which are most interesting from the viewpoint of astronomical observations, i.e., tropics and subtropics of the both hemispheres. In the Southern Hemisphere in winter some regions, which are promising from the viewpoint of astroclimate (South Africa, South America) fall to the area of positive trends in OIEA variations. Long-term variations of the eddy activity and optical instability in these regions seem to be caused by changes in the general circulation of the atmosphere, in particular, by the strengthening of the circum-Antarctic depression.

Reference

1. V.I. Tatarskii, *Propagation of Waves in a Turbulent Atmosphere* (Nauka, Moscow, 1967), 548 pp.
2. P.G. Kovadlo, Atmos. Oceanic Opt. **11**, No. 9, 831–835 (1998).
3. E. Kalnay, M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Wollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K.C. Mo, C. Ropelewski, J. Wang, A. Leetma, R. Reynolds, R. Jenne, and D. Joseph, Bull. Amer. Meteorol. Soc. **77**, No. 3, 437–471 (1996).
4. J.M. Wallace and H.N. Hsu, J. Atmos. Sci. **40**, No. 9, 2211–2219 (1983).
5. E.V. Devyatova, P.G. Kovadlo, and V.I. Mordvinov, Solar-Terrestrial Physics, Is. 12 (2008) (In print).
6. V.I. Mordvinov, I.V. Latysheva, A.A. Karakhanyan, and A.S. Ivanova, Geogr. Prirod. Resursy, No. 3, 156–159 (2003).
7. E.V. Devyatova, V.I. Mordvinov, A.S. Ivanova, and I.V. Latysheva, Atmos. Oceanic Opt. **18**, Nos. 1–2, 131–134 (2005).