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GEOPHYSICS

Variations in the Characteristics of Cyclonic Activity and Cloudiness in the Atmosphere of Extratropical Latitudes of the Northern Hemisphere Based from Model Calculations Compared with the Data of the Reanalysis and Satellite Data

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We performed analysis of variations in the characteristics of cyclonic activity and cloudiness, including their mutual variations in the atmosphere of the Northern Hemisphere (NH) from the tropical to polar latitudes based from model calculations under the condition of climate changes in comparison with the satellite data and reanalysis data [1]. According to the estimates, during global warming in the 21st century, a decrease in the total area of clouds at extratropical latitudes of the NH is associated with a corresponding decrease in the proportions of the extratropical latitudes covered by cyclones.

The objective of the joint analysis of variations in the characteristics of cyclonic activity and cloudiness during climate changes is related to the necessity of diagnosis the joint evolution and mutual influence of the general atmospheric circulation and radiation-cloudiness processes in the climate system [2–7]. Eddy activity (cyclonic and anticyclonic) is important both for the atmospheric dynamics as a whole and for realization of extreme local and regional regimes. The clouds, whose formation is essentially related to cyclonic conditions, have a key influence on radiation fluxes and, hence, on the temperature regime of the Earth as a whole, as well as on separate regions and on general atmospheric circulation.

In our analysis, we used the results of numerical simulations of the daily global fields at sealevel pressure (SLP) and cloudiness with the climate general calculation model (CGCM) IPSL-CM4 [8]. The (CGCM) IPSL-CM4 model includes models of the general atmospheric circulation LMDZ–4 (with 19 vertical levels in the atmosphere and horizontal spatial resolution 2.5° × 3.75°), ocean circulation model ORCA (with horizontal spatial resolution 2° and enhanced resolution up to 1° near the equator, and in the Mediterranean and Red seas), and the ORCHIDEE block for land and vegetation and the LIM block for sea ice.

In the calculation performed with the CMGH IPSK-CM4 model, we specified anthropogenic emissions of greenhouse gases and aerosol into the atmosphere based on the data of observations for the period 1860–2000 and according to the anthropogenic scenario SRES–A2 for 2001–2100.

Cyclones and anticyclones were distinguished as regions of low and high pressure, respectively, limited by closed contour lines (isohypses) based on the data of geopotential similarly to [9] (see also [10]). We analyzed the variations in the proportion of the area of the Earth's sphere (in particular, the area of extratropical latitudes of the NH) covered with atmospheric eddies (cyclones) or the density of package of cyclones on a sphere c according to the definition in [11].

We used for comparison the results of the analysis of cyclonic activity [9, 10] based on the NCEP/NCAR reanalysis data [12] of the general calculation model in the latitudinal range 20°–80° N with 2.5° × 2.5° resolution for each step during the period from 1952 to 2007. In addition, we used the satellite data of the International Satellite Cloud Climatology Project (ISCCP) in format D2 for the period 1983–2007 [13].

Figure 1 demonstrates the changes in the total cloudiness n and the density of cyclone coverage c at extratropical latitudes of the NH (20°–80° N) based on model simulations for the period 1860–2100. The variables in Fig. 1 are normalized by their mean values for the period 1961–1990. The model shows no significant

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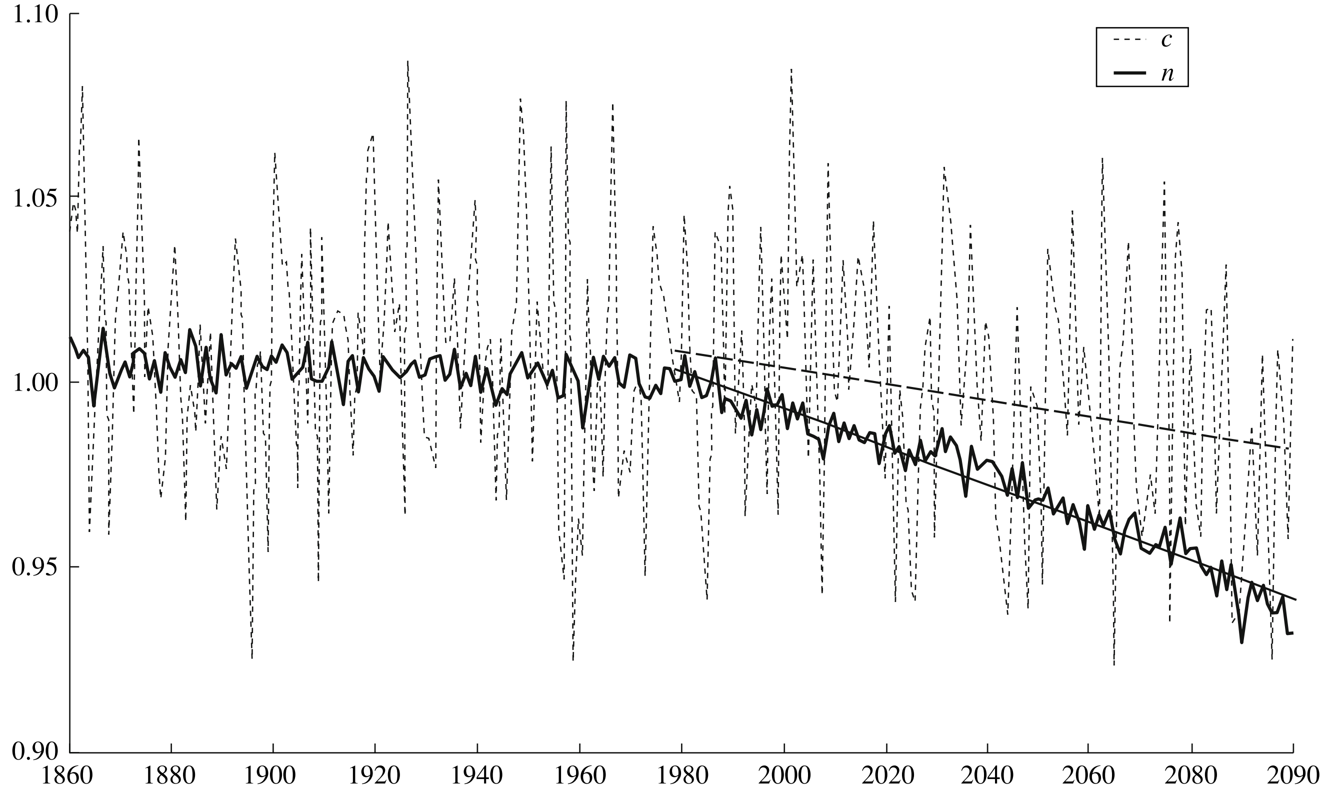

Fig. 1. Variations in annual mean normalized n and c for the latitudinal belt 20°–80° N based on model calculations for the periods 1860–2000 and 2001–2100 (under anthropogenic scenario SRES-A2 in the 21st century).

changes in n and c from the middle of the 19th century up to the end of the 20th century. Starting from the two last decades in the 20th century up to the end of the 21st century, both variables demonstrate a notable decrease. This tendency of decreasing is statistically more significant for cloudiness (with integrally smaller interannual variability). The trend in the proportion of area covered by cyclones based on the annual mean data for the 21st century $\frac{dc}{dt}$ was estimated at about –0.000038 yr^{-1} (or $c^{-1}\frac{dc}{dt} = -3.5\%$ in 100 years) with a correlation coefficient $r = -0.29$. The linear trend $\frac{dn}{dt}$ for the total cloudiness was obtained about –0.00037 yr^{-1} (or $n^{-1}\frac{dn}{dt} = -5.5\%$ in 100 years) with $r = -0.96$.

The tendency of the general decrease in the total density of covering the Earth's sphere with cyclones is related according to [11] (see also [14]) to the tendency of general weakening of the baroclinic instability mechanism during global warming. In this case, two opposite effects are pronounced in the variations of the baroclinic instability of the atmosphere, which leads to the generation of atmospheric eddies. On the one hand, a decrease in the meridional temperature gradient (temperature difference between the equator and pole) in the troposphere during global warming facilitates a decrease in the generation rate and the total number of eddies in the atmosphere. On the other hand, an increase in the related vertical gradient of temperature in the troposphere (see also [15]) and a decrease in its static stability lead to an increase in the rate of generation of eddies in the troposphere. The difference in the relative role of these competing factors in different regions and atmospheric layers (and for different seasons) should lead to different tendencies of change (by the value and sign) of the eddy activity in the atmosphere. If the decrease in the static stability of the troposphere is relatively low (and even if it is increasing), we should expect a decrease in the total number of eddies in the atmosphere during global warming.

It is worth noting that, despite the general trend of decreasing density of coverage of the Earth's sphere with cyclones when the general temperature difference in the troposphere decreases during warming, it is not excluded that special regimes exist in separate regions and atmospheric layers as well as for separate ranges of the distribution functions of cyclones depending on the power and size. In particular, an increased role of intense cyclones and an increase in temperature gradients, for example in the upper troposphere, are not only not excluded but quite real. The latter is real in relation to the cooling of the stratosphere and mesosphere during global warming at the surface and in the troposphere in general, in particular in the case of anthropogenic impacts when the concentration of greenhouse gases in the atmosphere increases. In this case, intensification of the subtropical jet stream with the maximum in the tropopause discontinuity and manifestation of this effect also occur in the troposphere when, for example, the zonal wind velocity increases at the surface in some bands of midlatitudes. In general, during the general warming of the troposphere, it should be expected a general decrease in the zonal geostrophic wind velocity.

A large uncertainty exists related to the total cloudiness in the estimates of the tendencies of its change during global warming both on the basis of observations and modeling even in the sign of possible cloudiness changes. This is related to different mechanisms of formation of different types of clouds and different effects of their influence on the climate system dependent, in particular, on the regions and seasons.

Figure 2 shows the dependence of the proportion of cloudy the sky n on the proportion of sky covered by cyclones c in the band of latitudes 20°–80° N based on annual mean data of model calculations for the 21st century under the anthropogenic scenario SRES–A2. According to Fig. 2, in the 21st century, a general correlation is seen between n and c.

It is worth noting that mean values of the proportion of the sky covered with clouds and occupied by cyclones are different. Figure 3 presents the latitudinal distributions of c and n for the period 1984–2000 based on model calculations compared with the NCEP/NCAR data (for c) and satellite ISCCP data (for n). According to the model results, $n \sim \frac{2}{3}$, and $c \sim 10^{-1}$, which generally agrees with the satellite and surface based observations for cloudiness and estimates of the density of the Earth's coverage with cyclones based on the data of observations and reanalysis (see [2, 11]). These values in the period 1984–2000 based on the data of NCEP/NCAR reanalysis are $c = 0.10$, and based on the ISCCP data $n = 0.66$. The ratio $\frac{c}{n} = 0.15$; i.e., the sky coverage with clouds exceeds the corresponding coverage with cyclones 6–7 times. According to the model calculations for the period 1984–2000 $c = 0.14$, $n = 0.64$, and $\frac{c}{n} = 0.22$. The latter estimate corresponds to the fact that sky coverage with clouds exceeds the corresponding coverage with cyclones approximately 5 times.

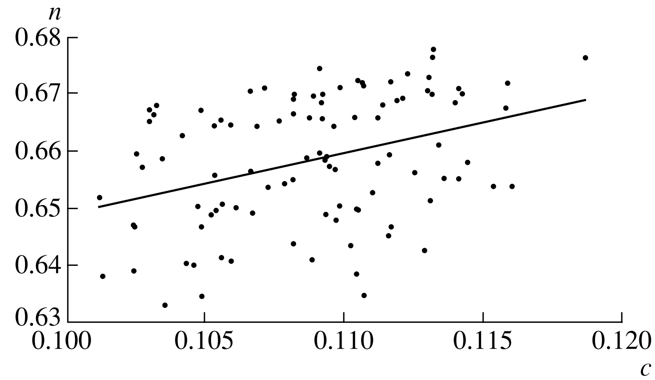

Fig. 2. Proportion of the sky covered with clouds n versus the proportion of the sky coverage with cyclones c in latitudinal belt 20°–80° N based on annual mean data from model similations for the 21st century under anthropogeic scenario SRES-A2.

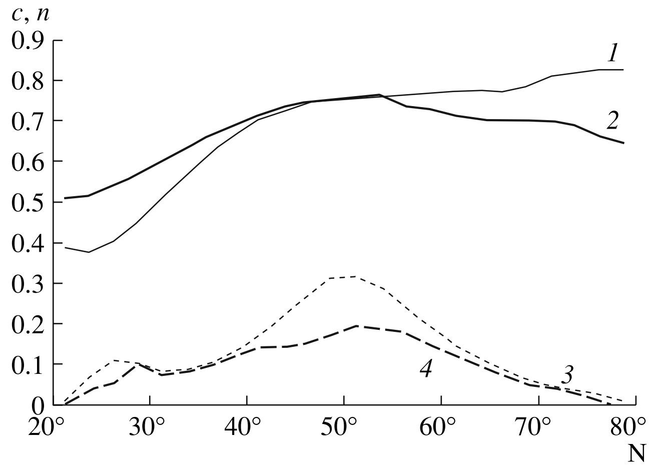

Fig. 3. Latitudinal distributions of c (*3*) and n (*1*) for the period 1984–2000 based on model calculations compared to the data of NCEP/NCAR reanalysis for c (*4*) and ISCCP satellite data for n (*2*).

The large variety of cloud types is related to different mechanisms of their formation and dynamics. The formation of clouds depends on more than just the realization of cyclonic regimes with ascending air motion from the surface and further condensation of water vapor in higher and cooler layers of the troposphere. Moreover, clouds are related to more than the local mobile cyclones. A large proportion of cloudiness is formed in large-scale regions of quasi-stationary atmospheric formations with a pressure minimum at the surface and ascending flows including those at the branches of meridional and zonal cells of the general circulation (Hadley cells at low latitudes and at the boundary of the polar cell and Ferrel cell in subpolar latitudes, Walker circulation) in cyclonic atmospheric action centers (Iceland and Aleutian minima, summer South Asia and North America cyclones). Cloud regimes typical for the regions of frontal activity in the atmosphere.

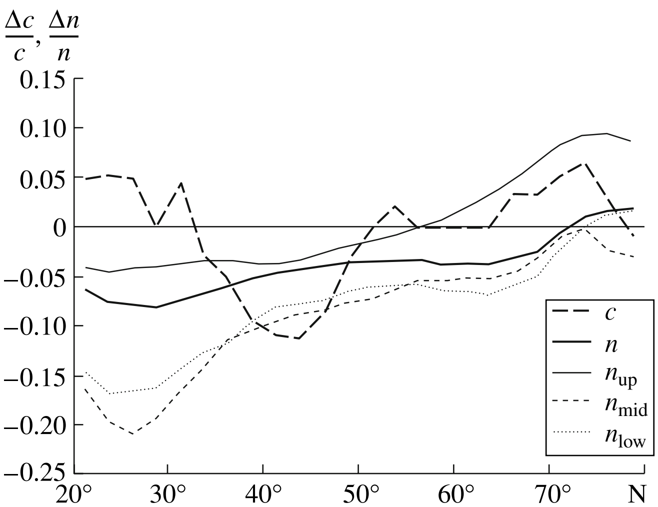

Fig. 4. Latitudinal distribution of relative $\left(\frac{\Delta c}{c} \text{ and } \frac{\Delta n}{n}\right)$ changes of c and n and the corresponding changes in the clouds for different layers: low (n_{low}), middle (n_{mid}), and high cloud (n_{up}) in the 21st century compared with the 20th century based on model calculations under the SRES–A2 scenario.

Despite the large variety of the types of clouds and the difference in the mechanisms of their formation, according to Fig. 2, the proportions of sky coverage with clouds and cyclones generally have a positive correlation (correlation coefficient is 0.36) based on the model calculations for the 21st century at extratropical latitudes. The coefficient or linear regression n with respect to c is practically equal to 1. This evidences that, in the model under global warming in the 21st century, a decrease in the total area of clouds at extratropical latitudes in the NH is related to a similar decrease in the proportion of the coverage of extratropical latitudes with cyclones.

No significant correlation between n and c in the interannual variations at extratropical latitudes of the NH was found in the model for the 19–20th centuries. No notable correlation was found between the estimates of c based on the NCEP/NCAR reanalysis data and n based on satellite ISCCP data during the short common period 1983–2000 that was analyzed.

A detailed analysis is needed to find what type of cloud is related to the revealed model tendencies. The correlation between the tendencies of climate in the proportion of coverage of extratropical latitudes in the NH with cyclones and the corresponding change in different cloud levels can be estimated from Fig. 4 based on numerical calculations with a concrete climate model [8]. Figure 4 presents latitudinal distributions of relative $\left(\frac{\Delta c}{c} \text{ and } \frac{\Delta n}{n}\right)$ changes in c and n (as well as corresponding changes in the clouds of different layers: low (n_{low}), middle (n_{mid}), and high (n_{up})) in the 21st century compared to the 20th century based on model calculations under the SRES-A2 scenario. According to Fig. 4, peculiarities in the structure of the general atmospheric circulation and its changes during global warming are manifested as relative changes in c. The greatest changes of the proportion of sky coverage with cyclones (a decrease) were found at mid-latitudes and subtropical latitudes.

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