Peculiarities of the Dynamics of the General Atmospheric Circulation in Conditions of the Global Climate Change

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Abstract—In the last decades, poleward displacements of elements of the general atmospheric circulation such as the Hadley Cell and storm tracks have been observed. On the basis of results of the numerical modeling of climate dynamics using an idealized model of the climatic system, we showed that the tendency to the displacement of storm tracks to the poles in the Northern Hemisphere would continue under the conditions of climate warming (according to the RCP 8.5 scenario). We also discuss the other peculiarities of the dynamics of the general circulation under the conditions of variable climate, which were revealed in the numerical experiment.

Keywords: general circulation, atmosphere, storm track, climate, variation

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1. INTRODUCTION

A complete understanding of all peculiarities of the general atmospheric circulation mechanism may allow us to forecast its variations under the conditions of a varying climate. In this sense it is especially interesting to study the possible variations in the circulation of the tropical atmosphere, mid-latitude baroclinic turbulence and jet currents, temperature of the ocean surface and its energetic active zones, and the square of the sea-ice cover. In the 1980s, G.I. Marchuk suggested the “Razrezy” program\textsuperscript{1} of investigating energetic active zones of the ocean (EAZO), which have a strong influence on the global circulation. By means of the diagnosis of energetic active zones based on the theory of conjugated equations and a global model of the general atmospheric circulation\textsuperscript{2}, it became possible to distinguish two such zones, which we currently call regions of storm tracks: the Gulfstream and Kuroshio zones. These ideas were intensely developed in the works of Russian and foreign investigators\textsuperscript{3, 4}.

It is known that the tropical circulation, the Hadley Cell (HC), in the system of the general atmospheric circulation plays a key role in the formation of the Earth’s climate, transporting energy and angular momentum to the pole. The locations of the dry large-scale subtropical zones and main subtropical deserts on the globe are formed to a high degree by descending branches of the HC. The cell extends over the entire depth of the troposphere from the equator to subtropics (~30° N) in both hemispheres. The Hadley Cell appears as a response to intense warming by shortwave radiation in the intratropical convergence zone (ICZ) near the equator. The degree of displacement of tropics in the poleward direction depends on the determination of indicators of the width of the tropical circulation zone. For example, the global tropopause was considered in\textsuperscript{5} as an indicator of HC width. This indicator is based on the difference between the tropics, where the tropopause is high, and the extratropical zone, in which the tropopause is low. The advantage of this method is in the fact that the height of the tropopause (more exactly, the transition layer between the upper troposphere and lower stratosphere) is a relatively well observed peculiarity in the structure of the atmosphere and can be easily obtained from the analysis of the three-dimensional temperature field.

An analysis of the radiosounding and reanalysis data demonstrated that the tropics have been widening since 1979 approximately at a rate of 0.4° of latitude during each decade. A similar widening is manifested also in the modeling data obtained as a result of using the IPCC climatic scenario, during which the radiation forcing is specified according to its historical value\textsuperscript{6, 7}. In addition, weakening of the tropical circulation intensity during climate warming was demonstrated in a number of publications\textsuperscript{8–13}. It is possible to distinguish several possible causes of the
HC motion to the poles: this is global warming in the troposphere, stratospheric cooling, variations in the temperature of the oceans (for example during El Niño—Southern Oscillation (ENSO)). The influence of the stratospheric circulation on the troposphere is confirmed by the data of observations and by the results of numerical experiments [14–15]. The width of the Hadley Cell is determined by the geographical latitude, in which the regime of the convective instability changes to the regime of the baroclinic instability. During global warming, the static stability of the atmosphere and the height of the tropopause increase; hence, the region of baroclinicity is displaced to the north. The authors of [16, 17] suggested a theory which establishes the relations between the static instability and the width of the tropical zone (the Hadley Cell), which explains the displacement of the HC upper branch to the north on the basis of the conservation of the angular momentum. According to this theory, the air flux increases the velocity shear of the zonal wind until it reaches the baroclinic instability and starts breaking. This determines the width of the HC boundary and the beginning of the mid-latitude baroclinic zone, in which the storm tracks are formed. Storm tracks are regions of strong baroclinicity (maximum of the meridional temperature gradient), which are determined on the basis of eddy statistics such as eddy fluxes of the angular momentum, energy, and moisture (using a band filter). Global warming is related to an increase in the static stability and suppressing of the baroclinic instability in the lower troposphere; hence the HC is displaced to the higher latitudes together with the poleward displacement of the storm tracks. Some peculiarities of the HC and tropopause dynamics related to the climate variation with the account for the stratosphere were considered in [18–23]. In this work we focus on the results of modeling of storm track dynamics in the winter period and also on their analysis at different climatic regimes when radiation forcing increases and then decreases (owing to the increase in the CO₂ concentration and gradual trend in the concentration to the preindustrial level). Two main storm tracks exist in the Northern Hemisphere in the regions of the Atlantic and Pacific oceans. One can use \( \sigma_E \sim \frac{g}{N} \left| \frac{\partial T}{\partial y} \right| \) as an estimate of the degree of baroclinicity, which is the maximum rate of the baroclinic wave increase in the Eadi problem [24]. The interaction between the waves and the mean flow at midlatitudes leads to low-frequency variations in the latitudinal location of the jet. One can suppose that small climate variations can significantly influence the locations of the jets and related locations of the storm tracks. It is known that the baroclinic instability is the main mechanism responsible for the generation of eddies [24, 25], which is maximum at the eastern coasts of Asia and North America. This instability is maintained by a strong heating source at the surface that appears owing to the temperature contrast between the ocean and continent: between the warm Kuroshio and Gulfstream currents in the east and cold continental air in the west [26, 27]. The storm tracks as the regions of the maximum variation of unstable stream function or eddy kinetic energy are concentrations of baroclinic eddies dominating in the atmosphere dynamics of extratropical latitudes, which significantly influence the climate. A problem arises as to whether climate change would significantly influence the location and intensity of midlatitude storm tracks and related jet currents. One of the basic concepts in the study of storm-track dynamics is the eddy development cycle, which consists of the baroclinic stage of increase, subsequent quasi-barotropic evolution, and barotropic decomposition. The baroclinic increase is accompanied by cyclogenesis at the surface with the further increase of the eddy at the upper levels. After this, saturation is gained first at the surface and then also at the upper levels [28, 29]. The jet can be displaced to the equator or to the pole from its initial position. This will depend on what type of wave breaking is realized: cyclonic or anticyclonic, respectively. The degree of baroclinicity intensity at the lower level is the determining factor for the type of wave breaking at the upper levels. In the case of weak or moderate intensity, the \( \beta \) effect would generate an anticyclonic type of wave breaking and displacement of the zonal jet to the pole owing to the spherical form of the surface. However, there is a strong difference between the weak and moderate intensities. In the first case, the centers of anticyclones are intense enough to cause the compression of the cyclonic centers in the northwestern—southeastern direction and the extension of the eddy in the other direction, which in turn leads to the positive eddy fluxes in the north, negative fluxes in the south, and poleward motion of the jet. In the second case, the centers of cyclones become significantly more intense than the centers of anticyclones; hence, they can deform anticyclones so that positive eddy fluxes appear in the south and the jet is displaced to the equator. Strong baroclinicity at the entrance of the storm track leads to a small displacement of the jet current to the equator. A weaker baroclinicity in the second part of the storm track causes anticyclonic wave breaking and displacement of the jet to the pole.

2. DESCRIPTION OF THE EXPERIMENT

A numerical experiment was conducted to study the response of the storm tracks on climatic variations. In this experiment we used the Planet Simulator global larch-scale climatic model of intermediate complexity [3] and one of the new climatic scenarios (RCP 8.5) belonging to the RCP family [31]. This model consists of a number of modules of differing complexity: atmospheric, oceanic, soil, biosphere, models for sea ice, and land surface modeling. It is a model of an intermediate complexity. It allows us to model a sufficiently