The longtime global climatic consequences modeling of the Chicxulub asteroid impact event

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Abstract. Studies indicate the mass death of a significant number of biological groups on Earth, in particular - dinosaurs, at the end of the Cretaceous period 66 million years ago. Currently, there are two main theories: large-scale volcanic eruptions and the asteroid impact that formed the Chicxulub crater (Mexico). The production of sulfur-containing gases from the Earth's surface layers vapors during impact is considered a main source of climatic effects, as they form stratospheric sulfate aerosols that block sunlight and thus cool the Earth's atmosphere and interfere with photosynthesis. It is presented an application of the 3-D coupled global hydrodynamic climate model of intermediate complexity, including ocean model, sea ice evolution model and energy - moisture balance atmosphere model to study this asteroid impact effects on the Earth's climate. The model continents and ocean depths distribution corresponds to Cretaceous period. A series of calculations with different residence times and deposition times of the stratosphere aerosol have been carried out. It was found that, depending on the stratosphere aerosol time parameters, the global annual average surface air temperature decreased by 18°С - 27°С, remained below zero for 4 - 30 years, and a recovery time of more than 30 years was observed.

1. Introduction

On the Cretaceous-Paleogene boundary, a significant number of biological groups of animals, including large (non-flying) dinosaurs, other vertebrates, marine reptiles, invertebrates, and some species of plankton, suffered mass death. The severity of this event, recently dated 66.043 ± 0.043 Ma [1], and the fact that it marks the death of dinosaurs, explains the continued interest in understanding its origins. However, the ultimate cause of the extinction remains a matter of debate. Currently, most research focuses on two theories based on events that roughly coincide with disappearance. These are large-scale volcanic eruptions, and the main phase of the eruptions lasted from 66.3 to 65.5 million years ago [2]. These eruptions released sulphur dioxide and carbon dioxide, leading to climate change that could trigger a mass extinction. The second event - the asteroid impact that formed the Chicxulub crater (Mexico), led to sharp local and short-term consequences, and also produced a large amount of dust, sulphate aerosols and greenhouse gases that influenced the climate globally and over a longer period [3]. Model studies of environmental changes associated with these events can help evaluate these theories [4]. Here we use a coupled climate model to study the effects of this asteroid on Earth's climate. There are a number of hypotheses explaining the cessation of photosynthesis after impact [5, 6]. In recent considerations, the production of sulphur-containing gases from target vapors during
collision is considered to be the main source of climatic effects, since they form stratospheric sulphate aerosols that block sunlight and thus cool the Earth’s atmosphere and impede photosynthesis [7, 8].

The few existing studies on the aerosol effect used incomplete climate models [9] and were limited to short periods after exposure, without investigating long-term changes. The present calculations have shown a strong long-term cooling caused by the asteroid impact. Depending on the time spent in the stratosphere of the aerosol, the global mean annual surface air temperature decreased by at least 26°C over a period of 3 to 16 years and a recovery time of more than 30 years. Surface cooling caused vigorous mixing of the ocean, and a change in the meridional vertical circulation of the ocean. These dramatic environmental changes suggest a key role for the asteroid impact in the death of dinosaurs at the end of the Cretaceous.

2. Problem statement and results of climate modeling before and after the asteroid impact

Here we use a coupled hydrodynamic three-dimensional global climate model [10-12], consisting of a model of the World Ocean in the geostrophic approximation, taking into account the frictional term in the horizontal momentum equations, an energy-moisture balance model of the atmosphere and a thermodynamic model of sea ice to study the climatic effects of sulphate aerosols and CO₂ after the fall of the asteroid. The present study focuses on global and long-term changes and does not consider local and short-term events close to the impact site [3].

The ocean model equations are considered in the geostrophic approximation with the friction term in the horizontal momentum equations. The temperature and salinity values satisfy the advection-diffusion equations, which allow us to describe the thermohaline circulation of the ocean. Convective processes are also taken into account in an approximate manner [10–13].

The basic equations system written in local Cartesian coordinates \((x, y, z)\), where \(x, y\) are horizontal coordinates and \(z\) is the height directed up, has the following form:

\[
-lv + \lambda u = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{1}{\rho} \frac{\partial \tau_x}{\partial z}, \quad l\mu + \lambda v = -\frac{1}{\rho} \frac{\partial \tau_y}{\rho} \frac{\partial \tau_y}{\partial z}.
\]

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0
\]

\[
\frac{\partial p}{\partial z} = -\rho g
\]

\[
\rho = \rho(S, T)
\]

\[
\frac{d}{dt} X = k_v \nabla^2 X + \frac{\partial}{\partial z} \left( k_h \frac{\partial X}{\partial z} \right) + C,
\]

in which \(u, v, w\) are components of the velocity vector, \(\lambda\) is the friction term, variable in space, increasing towards the coastal boundaries and the equator, \(T, S, p\) are water temperature, salinity, pressure, respectively; \(\tau_x, \tau_y\) - components of the wind friction stress; \(\rho\) - water density; \(l\) is the Coriolis parameter, \(g\) is the gravity acceleration, \(k_v, k_h\) are respectively the vertical and horizontal turbulent diffusion coefficients of the tracers \(X=(T,S)\), respectively, \(C\) determines the sources.

The condition of zero normal flow, heat and salt fluxes are required at all boundaries. The ocean is exposed to wind stress on the surface. The \(T\) and \(S\) flows are determined by the interaction with the atmosphere on the surface.

The equations are discretized on the Arakawa grid using simple central differences in space for diffusion and a scheme with weights upstream for advection. At each time step, the velocity field is determined diagnostically from the density field. Mathematical and numerical modeling is a powerful tool for studying the climate system and predicting climate change. Modern modeling is carried out using powerful software tools, including domestic ones, for example, to solve the problems of unsteady gas dynamics of multicomponent gas by various numerical methods [14 - 18].
Dynamic equations of the sea ice thermodynamic model [10, 11] are solved for ice compactness and for the average ice thickness. The ice growth and melting in the model depends only on the heat fluxes difference between the atmosphere, sea ice and ocean. The diagnostic equation is solved for the ice surface temperature. The energy and moisture balance model or the atmospheric general circulation model is used to describe the atmosphere processes [11].

All model blocks are coupled by the exchange of momentum, heat and moisture. The real continents configuration and the ocean depths distribution are used [7 - 9]. The vertical levels of the ocean model are evenly distributed in logarithmic coordinates. The horizontal grid is uniform in the longitude and sine of latitude coordinates, determining cells of the same area in space. This model uses 8 vertical levels for density. The maximum depth is assumed to be 5000 m.

Numerical experiments are based on the climatic state modeling of the end of the Cretaceous period using the configuration of the continents (figure 1) 66 million years ago [19].

![Figure 1. The distribution of the ocean depths (shown in different colors) and the continents (dark blue color) 66 million years ago.](image)

The equations in a spherical coordinate system are solved by a numerical finite-difference method. The initial state of the climate system is characterized by constant temperatures of the ocean, atmosphere and zero speeds of ocean currents. Calculations show that the model reaches equilibrium over a period of about 2000 years. The prognostic equations of the model are solved by the method of central second-order differences in space and simple forward-time differences. The model uses a finite-difference grid of 72 × 72 cells uniform in longitude and sine of latitude. The longitude resolution of the model is 5°, and in latitude it changes from approximately 1.5° at the equator to approximately 10° at the poles.

The original procedure for determining the wind velocities field from the atmosphere temperature field, based on the geostrophic approach, taking into account the thermal component of the wind, and introducing the mechanism of friction on the underlying surface is used. This method allows in general describe the wind speeds field depending on the state of the climate system.

3. Statement of the problem and the results of climate modeling before and after the fall of the asteroid

The statement of the problem largely follows [20], however, the original model with a more detailed representation of the ocean block [11 - 13] is used. The solar constant is assumed to be 1354 W/m², based on today's solar constant of 1361 W/m². Orbital parameters coincide with modern ones. Estimates of CO₂ concentration in the atmosphere range from 500 to 1500 ppm for the Late
Cretaceous [21]. During the period immediately preceding the impact, they were probably below 800 ppm [22]. Therefore, we performed a baseline simulation with 500 ppm atmospheric CO$_2$ and a sensitivity experiment with a higher CO$_2$ concentration of 1000 ppm. Calculations before the fall of the asteroid were carried out for about 2000 model years, until climatic equilibrium is reached. Estimated global mean annual surface air temperature of 8,000 m at the end of the Cretaceous is 15.5°C, or about 4°C above pre-industrial temperatures for simulations of 500 ppm and 21.6°C, or about 7°C higher than pre-industrial climate for a model experiment with 1000 ppm. The results of geophysical collision modeling indicate that for the area of fall with a depth of 2.9 km, consisting of 30% of the evaporated substance and 70% of saturated with water, a mass of sulphur is formed of 100 Gt [8]. This corresponds to about 10,000 times the amount of sulphur released during the 1991 Pinatubo eruption. The results are not highly dependent on the exact amount of sulphur released during impact, since the radiative forcing does not increase for sulphur mass greater than 30 Gt [9]. Only stratosphere aerosols are taken into account, since aerosols are quickly washed away as soon as they enter the troposphere. The residence time of stratospheric tracers in the present-day steady-state atmosphere is about 2 years. We follow [9] and assume a possible longer residence time of the aerosol in the disturbed atmosphere after the collision. With this formulation of the problem, the solar flux on the surface decreases sharply immediately after the impact from the value before the impact of 169.5 W/m$^2$ to the minimum value of 2.28 W/m$^2$, which remains unchanged for 3 months, 1 year or 2 years, for various calculation options. The characteristic time of aerosol sedimentation is 3, 5, and 10 years for different variants of calculations. In addition to the effect of sulphate aerosols, an increased CO$_2$ concentration is expected as a result of the fall. For sulphur mass of 100 Gt, about 1400 Gt of carbon dioxide is injected into the atmosphere by 180 ppm. In addition, there may be additional CO$_2$ emissions from ocean degassing and disturbances in the terrestrial biosphere, so additional simulation experiments with 500 ppm, 800 ppm and 1200 ppm CO$_2$ have been performed as sensitivity experiments. It is assumed that both sulphate aerosols and CO$_2$ generated during the impact are distributed globally and evenly in our numerical experiments. The uniform distribution of aerosols is simplistic, but may be a reasonable approximation given the magnitude and location of the Chicxulub fall. It is assumed that the short-term dust effects are overlapped by the aerosol effect. In addition, we neglect water vapor because the amount obtained is uncertain and its residence time in the troposphere is very short. All asteroid impact experiments are performed for the end of the Cretaceous climate period with 500 ppm and 1000 ppm atmospheric CO$_2$ and are integrated over 100 years after exposure. The main result of climate modeling is strong and persistent global cooling for decades after exposure. The global annual mean surface air temperature and the global sea ice area for 30 years after the fall for atmospheric CO$_2$ concentration of 500 ppm before impact, for different residence and deposition times of aerosols and for different values of CO$_2$ emissions from the fall is presented in figure 2.
Temperature changes for different emissions of carbon dioxide caused by the fall are weakly dependent on its value. The following will focus on modeling representing an intermediate emission of 360 ppm. For a stratosphere aerosols deposition time of 3 years, which is the most conservative modeling assumption, the global mean annual surface air temperature decreases by 27°C, with a minimum temperature reached 3 years after impact. This temperature difference is not sensitive to the pre-exposure CO₂ concentration: in the case of concentrations up to 1000 ppm, the temperature drops to almost the same value from +22°C to -5.0°C. The global average annual surface air temperature remains below freezing for 5 years. For deposition times of 5 and 10 years, the minimum global mean annual surface air temperature is even lower (cooling by 30°C and 34°C, respectively) and is reached later (in the 4th and 7th years, respectively). In these calculations, with longer residence times, global mean annual freezing temperatures are maintained for 11 years and 25 years, respectively. The post-impact cooling observed in our calculations is accompanied by a noticeable expansion of the area of snow and sea ice. Average surface albedo increases from 0.13 to impact to 0.25 per year with maximum ice cover in our standard simulations (500 ppm CO₂ pre-impact, 3-year settling time, 360 ppm CO₂ due to impact). For a stratospheric aerosol deposition time of 3 years, the sea ice area increases by 30% and then decreases to its original value (figure 2). For a deposition time of 10 years, the sea ice area increases sharply after the initial cooling period (maximum 4 times after about 25 years), which indicates the beginning of a process caused by a positive ice-albedo feedback. However, this process eventually slows down and stops with a solar radiation increase. Note that the CO₂ release from the impact will result in warming compared to the pre-impact state after the initial cooling period. Table 1 summarizes the calculation results for all calculation options.

**Table 1.** Calculation results for all variants of the problem statement.

| Aerosol Deposition time (years) | The moment of reaching the min temperature (years) | Temperature minimum (°C) | Moment of reaching max sea ice (years) | Maximum sea ice area (cells) |
|---------------------------------|-----------------------------------------------|--------------------------|----------------------------------------|-----------------------------|
| 10                              | 6 - 7                                         | (-8.7) – (-11.6)         | 23 - 28                               | 260 - 500                   |
| 5                               | 3 - 4                                         | (-4.4) – (-9.7)          | 9 - 12                                | 170 - 230                   |
| 3                               | 2 - 3                                         | (-1.9) – (-8.8)          | 5 - 9                                 | 155 - 173                   |
Regional temperature changes caused by an asteroid impact are even more severe than global averages. Pre-impact surface air temperature maps and year of minimum global mean annual temperature indicate marked regional cooling, particularly in the continental and polar regions. In figure 3 shows the distribution of this temperature for 500 ppm CO$_2$ prior to the fall and figure 4 - after the fall for the 3 years deposition time and 360 ppm CO$_2$ for January month.

![Figure 3](image1.png)

**Figure 3.** Surface air temperature distribution before the fall of the asteroid, for 500 ppm CO$_2$.

![Figure 4](image2.png)

**Figure 4.** Surface air temperature distribution after an asteroid fall, for 500 ppm CO$_2$.

Due to the thermal inertia of the ocean, surface temperature changes propagate slowly into the deep ocean. In figure 5 shows the meridional profiles of the Pacific Ocean temperature change over two time intervals.
Figure 5. The meridional profiles of the temperature change in the Pacific Ocean 30 years (top) and 100 years (bottom) after the fall of the asteroid.

In the 30th year after the impact, strong surface cooling leads to very cold water masses in the upper 1000 m at all latitudes and down to the ocean floor at high latitudes. 100 years after the fall, the near-surface ocean shows signs of warming due to the release of post-impact CO$_2$, while masses of cold water reach deeper depths with clear cooling in the deep ocean at high latitudes.

4. Conclusions

Comparable studies in the field of modeling taking into account the effect of aerosols and using coupled climate models were carried out in [20, 23] and are consistent with the results presented here. In terms of geological and paleo data, it is difficult to compare the cooling found in our calculations because very high temporal resolution is required to record the rapid climate change associated with forcing. Our climate modeling study demonstrates the strong cooling and vigorous mixing of the ocean as a result of the Chicxulub fall. These results are generally consistent with paleo data, but detailed comparison is hampered by the temporal resolution of the empirical records, temperature calibration issues, and the low spatial resolution of our model. Although it cannot be inferred from our model results that the impact was solely responsible for the mass extinction at the end of the Cretaceous, the sharp drop in temperature and the expected deep disturbance of the marine biosphere due to changes in ocean circulation in our calculations certainly determines the key role of the fall on the extinction event.

Future research will need to explore in more detail the interactions between the two, as well as the effects on Earth's marine and terrestrial biosphere.

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