Математическое моделирование

PACS: 92.10.hp, 92.30.Np, 92.30.St, 92.30.Tq, 92.70.Mn, 92.70.Jw,
UDC 504.1,504.4,504.7,53.023

Simplified Sea Level Estimation Based on Logistic Equation and Paleoclimate Data

L. V. Sorokin

Economic and Mathematical Modeling Department
Peoples' Friendship University of Russia
6, Miklukho-Maklaya str., Moscow, Russia, 117198

During the pre-industrial period the variation of Global Surface Air Temperature on 1°C change Global Mean Sea Level on 24.79 m (SL $<$ 0) and in the modern time — 7.5 m (SL $>$ 0). For the global warming period the rising rate of the Global Mean Sea Level will slowing down in 3.3 times simultaneously increases the Global Surface Air Temperature rate in 3.3 times. In the present time the Global Surface Air Temperature is 0.8°C higher then pre-industrial level that will lead to the sea-level rise on 6 m. The logistic equation for the current climate conditions (global warming on 0.8°C) has provide us a solution that the sea level within next 95 years will rise up to +5 m and will stabilized at +6 m level within the relaxation time of 150 years. The EU Strategy on adaptation to climate change assume that the global warming must be limited to below 2°C above pre-industrial level, that within some ages will lead to the sea-level rise on 15 m (15 times grater than for the A1B scenario, with the Sea-level rise up to 1 m). So in the future conditions the EU Strategy on adaptation to climate change do not assume rapid climate changes that will significantly increase the economic losses from Sea Level Rise.

Key words and phrases: logistic equation, climate change, global warming, sea level, paleoclimate, glaciology, glacial cycles, glacial melting, ice-age, flood, economic losses.

1. Introduction

Since the midst of past Century, a deep global climate change accompanies the expanding industrialization of our economies. The speed of this change amplified in the beginning of the 2000's and it is associated with an increasing number of extreme weather related events: floods, droughts, typhoons, hurricanes, dust storms and forest fires, intense low and high temperatures. In the present time the Global Surface Air Temperature (GSAT) exceeds by 0.8°C [1] the temperature that prevailed in the era before the industrial development. In Europe, from 2002 to 2011, it increased by 1.3°C [2] mainly due to the industrial development, and this temperature is 1.625 times higher than in the whole planet. Furthermore, one can observe a rise of the sea level at the World level. Global warming, greenhouse effect and human activity associates with this increase.

From an economic viewpoint, it appears that the existing infrastructures (harbors, localization of roads, cities, airports, etc.) are weakening face to such quick and deep climate changes. Consequently, in a near future, populations have to expect expending huge financial resources to adapt and to modernize these infrastructures to these new climatic conditions. For instance, annual damages due to climate change are already estimated at 250 billions Euros in the middle of this century (2050) [1]. In response to these climatic hazards, the European Union is developing a global strategy for adaptation to climate change [3, 4]. In accordance with the parameters laid down in the EU strategy on adaptation to climate change, our work supplies the assessment of steady state, around, which tends the Global Surface Air Temperature (GSAT) and the Global Mean Sea Level (GMSL).

Received 15th June, 2015.

2. Adaptation to Climate Change

Within the framework of its adaptation strategy to climate change [4, p. 5], the EU adopted the upper limit of 2°C (UNFCCC, Cancun, 2010) as an allowable increase concerning the average air temperature of the planet. This decision aims at compulsorily reduce the most serious risks from climate change. Among these last ones, two of them represent the greatest danger on the magnitude of the economic damage: floods and changes in global sea level. Brown et al., (2011) [5] have made a thorough analysis of economic losses caused by climate change for the European Union and they assessed the effectiveness of measures to adapt to climate change. For the scenario A1B, under appropriate conditions of high and medium greenhouse gas emissions, Brown's analysis [5] carried out a rise in global sea level by one meter.

From the analysis of the EU Strategy on adaptation to climate change [4, p. 11–13], it is obvious that the adaptation process can compensate a rise in global sea level by 1 meter (scenario A1B), corresponding to half of flood damage and most of the damage from rising sea levels. But the consequences from the Sea-level rise higher then 1 meter were not investigated yet by the scientific community.

3. A Semi-Empirical Approach

Everything looks good until the sea level rise is limited to one meter. However, the situation could change when admitting the idea that the rise of the global sea level could be up to higher grades. Hence, Hansen (2007) [6] proposed to use an exponential growth model that considers the global sea level that doubles in 10 years. This design is consistent with the forecast that the level will rise to a 5 meters level in 2100. Modern researches in the climatology field require the construction of very sophisticated mathematical models. This leads to numerical solution using supercomputers. Computational experiment induces large errors and cannot fully describe the observed processes.

However, in some cases simplified models demonstrate their highly predictive value. Hence, a semi-empirical approach [7] proposed by Rahmstorf S. (2007) showed good concordance with the observed 50 years of ocean level. In our opinion, it is necessary to develop a simple and intuitive method for determining the boundaries of sustainable working of the systems, the variations of their parameters and reaching the stationary states. This paper proposes a quantitative assessment based on logistic equation and stationary solution of future changes in Global Mean Sea Level for long-term change (from a few hundred years up to the millennium) in Global Surface Air Temperature of the Earth.

4. Methods

In this paper we used the machine for linear regression analysis of paleoclimatic data and extrapolation of the results to date. The large depth of the sample (1.8 million years) will demonstrate that the observed nowadays climate change has repeatedly occurred in the past.

Dependence of the global sea level on the concentration of oxygen isotopes in sediments δ^{18}O Ocean can be expressed by the linear regression equation (3), (4), and the temperature of the deep water in the ocean by the equations (1), (2). Another regression equation (5) relates the average temperature of the air on the planet with a temperature of deep water in the ocean. However, despite the fact that these regression equations are linear, they express extreme climatic nonlinear transient processes in the ocean and the atmosphere. The explanation lies in the fact that the regression equations (1)–(5) does not describe the transient and steady state of the Earth's climate system to which it seeks a sufficiently large relaxation time (from a few hundred years up to the millennium). Thus, this applied approach gives an estimate of the stationary solution of the sea level rise (12), (13) because of a fixed air temperature change on overall planet in the long run.

But we need find a form and relaxation time for the sea-level rise function. Applying an empirical approach for finding the logistic equation (20) and tuning its coefficients we can achieve compliance with the historical data. This can help us to get the relaxation time and make forecast for the sea-level change in the nearest future.

The definition of the boundaries for the stationary state of the climate system in response to the fixed change of meteorological parameters allows verifying this hypothesis to assess the future damages and the effectiveness of the economic strategies for adaptation to this climate change [8].

5. Reconstruction of Paleoclimate

To define the parameters of the models of future climate, we can use the Earth's paleoclimate (Zachos et al., 2001 [9]; Zachos et al., 2006 [10]; Zachos et al., 2008 [11]; Hansen et al., 2008 [12]). Climatic conditions similar to the currently observed occurred during the Pleistocene: 124, 327, 405, 952 thousand years before present time (kyr BP); 1.07 and 1.23 million years before present time (Myr BP). At the times indicated the ocean level was slightly above the pre-industrial sea-level (PISL = 0). The near future seemed comfortable, but led to dramatic consequences. The Global Surface Air Temperature has grown and the earth's climate became warmer, and the Global Mean Sea Level continued to rise. However, after a few millennia it began to plummet, which marked the beginning of the next glacial period.

Paleoclimate reconstruction of Hansen et al. (2008) [12] was produced on the basis of the oxygen isotope concentration ^{18}O (Zachos et al., 2008) [11]. Concentration of stable oxygen isotopes ^{18}O and ^{16}O in the conglomerate of global ocean sediment cores depends on deep ocean temperature, and the total weight of ice on the planet. Model Hansen et al. (2008) [12] is built on communication δ^{18}O Global Deep Ocean Temperature (GDOT) — Tdo (°C), see equation (1), (2) and the Global Mean Sea Level (GMSL) — SL (m), see equation (3), (4). Equation (5) relates the Global Deep Ocean Temperature — Tdo (°C) with an average temperature at the surface of the planet (Global Surface Air Temperature) — Ts (°C). Equations (1)–(5) are taken from the work of Hansen et al., (2013) [13].

$$\mathrm{Tdo}\,(^\circ\mathrm{C}) = 5 - 8(\delta\,^{18}\mathrm{O} - 1.75)/3 \qquad (\text{for } \delta\,^{18}\mathrm{O} < 3.25), \tag{1}$$

$$\mathrm{Tdo}\,(^\circ\mathrm{C}) = 1 - 4.4(\delta\,^{18}\mathrm{O} - 3.25)/3 \qquad (\text{for } \delta\,^{18}\mathrm{O} > 3.25), \tag{2}$$

$$\mathrm{SL}\,(\mathrm{m}) = 60 - 40(\delta\,^{18}\mathrm{O} - 1.75) \qquad (\text{for } \delta\,^{18}\mathrm{O} < 3.25), \tag{3}$$

$$\mathrm{SL}\,(\mathrm{m}) = -120(\delta\,^{18}\mathrm{O} - 3.25)/1.65 \qquad (\text{for } \delta\,^{18}\mathrm{O} > 3.25), \tag{4}$$

$$\mathrm{Ts}\,(^\circ\mathrm{C}) = 2 \times \mathrm{Tdo} + 12.25^\circ\mathrm{C}. \tag{5}$$

A detailed analysis of the data and the reconstruction of paleoclimate ocean level on the basis of the concentration of oxygen-18 isotope in deep ocean sediments are presented in the work of Hansen, J. E., and Mki. Sato (2011) [14].

6. Regression Analysis of the Pleistocene Paleoclimate Data

We can estimate the parameters of the model for the future of Earth's climate using the data concentration $\delta\,^{18}$O (Zachos et al., (2008) [11] in the Pleistocene period (from 16 kyr BP to 1.8 Myr BP) and as reconstruction Hansen, J., M. Sato, G. Russell, and P. Kharecha (2013) [13].

Figure 3 shows a graph of the level of the World Ocean during the Pleistocene (from 16 kyr BP to 1.8 Myr BP), calculated according to the measurement of the concentration of oxygen isotopes in sediments $\delta\,^{18}$O Ocean (equation (3), (4)).

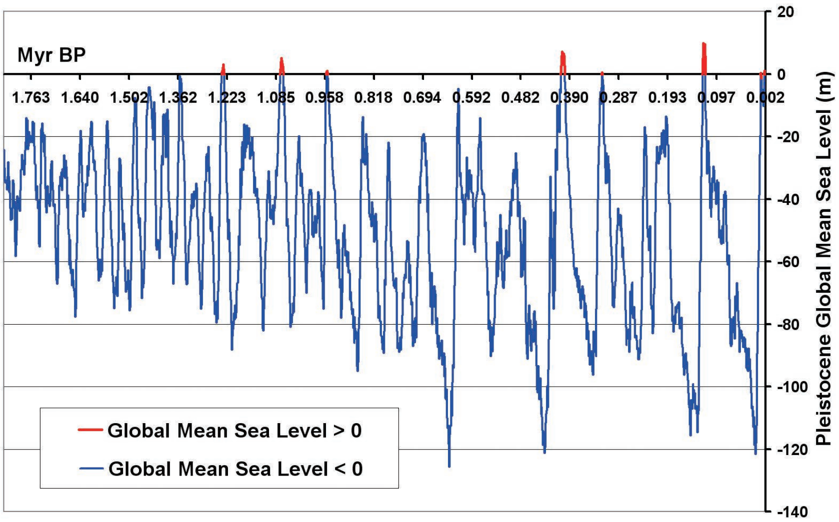

Figure 1. Changes in Global Mean Sea Level during the last 1.8 million years (based on the content of the isotope oxygen-18 in deep ocean sediments). The data source: Makiko Sato & James Hansen. Updating the Climate Science. What Path is the Real World Following? Columbia University Earth Institute. Data source: `http://www.columbia.edu/~mhs119/`

The blue color in Figures 1, 2, 3 shows the level of the oceans (GMSL $<$ PISL) in the era before industrial development (pre-industrial sea-level — PISL), and in red observed excess levels of the oceans border (GMSL $>$ PISL). The transition from $\delta\,^{18}\mathrm{O} = 3.25$ (equation (6)) the "zero" mark Sea-level (ZSL = 0 = PISL) is carried out by the formula (4). This point corresponds to the level of the world ocean in the late Holocene and is close to the level before the industrial development of our time.

$$\mathrm{SL}\,(\mathrm{m}) = 0 \qquad (\text{for } \delta\,^{18}\mathrm{O} > 3.25). \tag{6}$$

We are interested in dependence on the temperature level of the world ocean deep water. Write down the equation (1), (2) as a function of the Tdo and make their substitution in equations (3), (4).

$$\delta\,^{18}\mathrm{O} = (\mathrm{Tdo} - 9.666)/(-2.666) \qquad (\text{for } \delta\,^{18}\mathrm{O} < 3.25), \tag{7}$$

$$\delta\,^{18}\mathrm{O} = (\mathrm{Tdo} - 5.766)/(-1.466) \qquad (\text{for } \delta\,^{18}\mathrm{O} > 3.25). \tag{8}$$

Get the equation (9), (10):

$$\mathrm{SL}\,(\mathrm{m}) = 15 \times \mathrm{Tdo} - 15 \qquad (\text{for SL} > 0), \tag{9}$$

$$\mathrm{SL}\,(\mathrm{m}) = 49.587 \times \mathrm{Tdo} - 49.587 \qquad (\text{for SL} < 0). \tag{10}$$

For the transition from the regression equations (9), (10) linking the sea level (SL) with a temperature of deep waters (Tdo) in the ocean to equations depending on the average air temperature (Ts) at the planet, we look up (11).

$$\mathrm{Tdo}\,(^\circ\mathrm{C}) = \big(\mathrm{Ts}\,(^\circ\mathrm{C}) - 12.25^\circ\mathrm{C}\big)/2, \tag{11}$$

$$\mathrm{SL}_{\mathrm{St}}\,(\mathrm{m}) = 7.5 \times \mathrm{Ts}_t - 106.875 \qquad (\text{for SL} > 0), \tag{12}$$

$$\mathrm{SL}_{\mathrm{St}}\,(\mathrm{m}) = 24.793 \times \mathrm{Ts}_t - 353.306 \qquad (\text{for SL} < 0). \tag{13}$$

As a result we get equations (12), (13) linking the future sea level (SL) with the average air temperature (Ts) at the planet [8, 15]. The definition of the level for the stationary state solution of the Global Mean Sea Level (SL_{St}) in response to the fixed change of average air temperature (Ts_{t}) must conform to the main characteristics. The Earth's climate system to get the stationary state solution needs a sufficiently large relaxation time from a few hundred years up to the millennium. This applied approach gives an estimate of the upper bound of the sea level rise because of a fixed air temperature change on overall planet in the long run. The definition of the boundaries for the stationary state of the climate system in response to the fixed change of meteorological parameters allows verifying this hypothesis to assess the future damages and the effectiveness of the economic strategies for adaptation to this climate change [8].

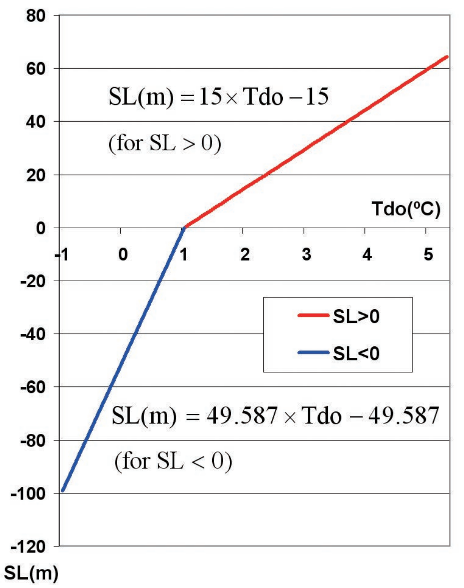

Figure 2. Linear regression equations (9), (10) connect the level of the World Ocean (SL) with the global ocean temperature-depth (Tdo) for the Pleistocene period

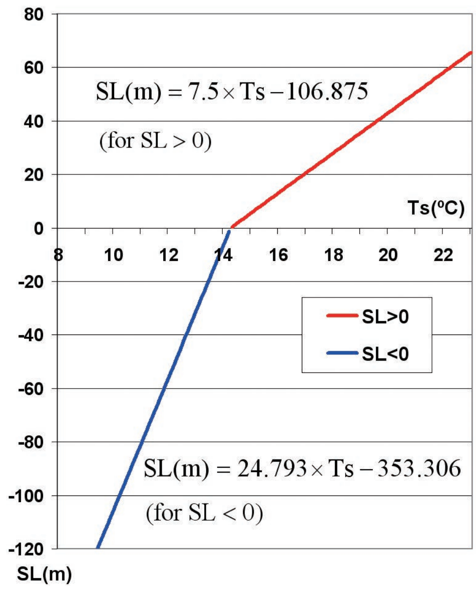

Figure 3. Linear regression equations (12), (13) connect the global sea level link (SL) with an average temperature of air at the surface of the planet (Ts) for the Pleistocene period

Figures 2 and 3 illustrate well the shift corresponding to the regression function when the ocean level is zero (SL = 0). The inflection point passes between 1940 and 1950. The linear regression equations (12), (13) show the relationship between the variation of average air temperature at the surface (Ts) of the planet and the corresponding changes in sea level (Fig. 3). In the present time the GMSL exceed the level of the World ocean in the era before industrial development at GMSL = 0.21 m. At the same time the value of the average global air temperature near the surface of the planet over to preindustrial level by GSAT=0.8°C (An EU Strategy on adaptation to climate change, 2013) [4, 15].

7. Future Sea Level rise

With the help of equations (12) and (13) we can estimate the up today climate parameters:

GSAT in the era before the industrial development (SL=0)

$$\mathrm{Ts}_{\mathrm{SL}=0} = 14.25°\mathrm{C}; \tag{14}$$

GSAT, corresponding to the current sea level $\mathrm{SL}_{(t=0)} = 0.21$ m;

$$\mathrm{Ts}_{\mathrm{SL}=0.21} = 14.278°\mathrm{C}; \tag{15}$$

GSAT in the present time ($t = 0$)

$$\mathrm{Ts}_{t=0} = \mathrm{Ts}_{\mathrm{SL}=0} + 0.8 = 15.05°\mathrm{C}. \tag{16}$$

In comparison with the era before the industrial development (SL=0) in the present time ($t = 0$) we have current climate conditions:

GMSL rise on

$$\mathrm{SL}_{t=0} = 0.21 \text{ m}; \tag{17}$$

due to the Global warming the GSAT exceeds by

$$\Delta T = \mathrm{Ts}_{t=0} - \mathrm{Ts}_{\mathrm{SL}=0} = 0.8°\mathrm{C}. \tag{18}$$

We can see from the equations (12) and (16) that GSAT increasing on 0.8°C is corresponding to the stationary Sea level at 6 m [15].

From the equations (12) and (15) it is clear, that for prevention of the Sea level rise and maintaining it on the current level (17) the GSAT in comparison with the era before the industrial development should be reduced by 28.5 times

$$\Delta T = \mathrm{Ts}_{\mathrm{SL}=0.21} - \mathrm{Ts}_{\mathrm{SL}=0} = 0.028°\mathrm{C}. \tag{19}$$

For the transient modeling of the Sea-level (GMSL) growth in response to the temperature (GSAT) jump it is reasonable to apply the saturation model, which can be formalized using the logistic equation [16]:

$$\mathrm{LE}_{(T,\,t)} = \frac{\mathrm{SL}_{(\mathrm{St})} \cdot \mathrm{SL}_{t=0} \cdot (1 + \Delta T)^{(t \cdot m_{(\Delta T)}/k)}}{\mathrm{SL}_{t=0} \cdot (1 + \Delta T)^{(t \cdot m_{(\Delta T)}/k)} + \mathrm{SL}_{\mathrm{St}} - \mathrm{SL}_{t=0}}. \tag{20}$$

The logistic equation (20) should meet the following requirements:

- t — time scale ($t = 0$ corresponding to the present time);
- equation (20) for the present time $t = 0$ is equal to $\mathrm{LE}_{t=0} = \mathrm{SL}_{t=0} = 0.21$ m;
- equation (20) at a value $\Delta T = 0.028$ is equal to $\mathrm{LE}_{(\Delta T=0.028,\,t)} = \mathrm{SL}_{t=0} = \mathrm{const} = 0.21$ m;
- equation (20) at a value $\Delta T = 0$, $a = (1 + \Delta T) = 1$, consequently $\mathrm{LE}_{(T,\,t)} = \mathrm{SL}_{t=0} = \mathrm{const}$;
- coefficients $m_{(\Delta T)}/k$ define the relaxation time for the transient function;
- on condition (17) the coefficients tuning $a = (1 + \Delta T)$, $m_{(\Delta T)}/k$ should initially provide an exponential growth model (20) up to the present time that considers the global sea level that doubles in 10 years [6];
- at a value $t \to -\infty$, equation (20) tends to zero $\mathrm{LE}_{(\Delta T>0,\,t\to-\infty)} = 0$;
- at a value $t \to +\infty$, equation (20) reaches the stationary level (12) $\mathrm{LE}_{(\Delta T>0,\,t\to+\infty)} = \mathrm{SL}_{\mathrm{St}}$.

For the current climate conditions we will estimate the future Sea level change, using the logistic equation (20) with parameters (12), (16)–(18) and coefficients $m_{(\Delta T)} = 9$, $k = 100$.

Figure 4 demonstrates the model of the future Sea level based on logistic equation (20) for two cases: for the current climate conditions with global warming on

0.8°C above pre-industrial level (18) and for the value of 0.028°C (19), 28.5 times less than the first one.

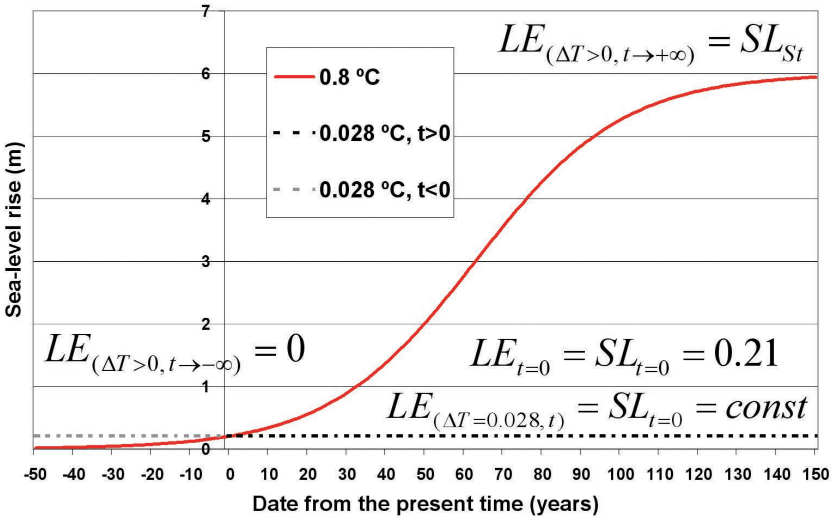

Figure 4. The future Sea level rise model based on logistic equation for the current climate conditions

From Fig. 4 we can see that, maintaining the global warming on the current value of 0.8°C within 95 years the Sea level will increase at +5 m and during the relaxation time of 150 years it will get to the +6 m level. In the case if the global warming will be reduced 28.5 times (19) to the value of 0.028°C, the Sea level will be stabilized on the current level at 0.21 m (black dotted line for $t > 0$, Fig. 4). The values marked by the gray dotted line for $t < 0$ (Fig. 4) are virtual due to the fact that we could not reverse the time.

This optimistic scenario are not real due to the EU Strategy on adaptation to climate change assume the 2°C global warming [4, p. 5]. If Earth's average temperature increase to 2°C above prior the industrial era, this will lead to an inevitable increase in global sea level by +15 meters. In the current time we have no data to estimate the relaxation time for sea-level rise on 15 m, but we will have three possible scenarios: the relaxation time does not change; it will happen faster or it will take more time.

8. Results

From the sea level at point zero (SL = 0), there are only two ways moving towards either the cooling or the warming of Earth. Equation (13) shows a downward trend in the level of the oceans to 24.79 m decrease in average temperature by one degree Celsius. This is the cold climate scenario or the onset of the next ice age. Equation (12) shows the trend of sea level rise at 7.5 m with an increase in the average temperature of one degree Celsius which corresponds to the scenario of global warming of the Earth's climate. Suppose that the world is entering an era of global warming. We get two pieces of news: the good one is that for the scenario of the Earth global warming, the rate of change in sea level over the long term slows down in 3.3 times which looks optimistic. The bad news is that the slowing rise in sea level would have to pay a higher rate of growth of the average temperature of the Earth, respectively, 3.3 times.

In accordance with the IPCC (2007)'s concept [17], the projected rate of increase of the oceans to 2100, should reach 29 cm (average range 20–43 cm, full range of 18–59 cm, for a variety of scenarios). In the case of a 59 cm rise in the sea level, it will be necessary to keep the Earth's average temperature by 0.08°C higher than in the era before the industrial development that means 10 times lower than the current value of 0.8°C [1].

Adopted at the moment, the short-term (up to 2100) EU's concept of adaption to global warming associates to a rise of one meter of the global sea level a temperature increase of 2°C [4]. If we assume that humanity will not be able to stop the rise in the Earth average temperature and, then will reach the milestone of 2°C, this fact leads in the long term to the inevitable increase in global sea level by +15 meters in accordance with equation (12). Such offensive from oceans will be disastrous for humanity and will flood most of the infrastructures, industrial and agricultural facilities. Implementing the EU's program and preparing infrastructures to a forecasted global sea level rise of 1 m (12) involves limiting the average increase of Earth's air temperature to a 0.133°C level. However, at this moment of the time; the average temperature on the planet increased at 0.8°C [1], which already should lead to global sea level rise of +6 m (12).

In present time, the growth rate of global sea level has reached one of the maximum values for the entire Pleistocene period: 3.4 mm/year (Stefan Rahmstorf, 2007) [7]; 3.1 mm/year (Nerem et al., 2006) [18]; 3.1 ± 0.7 mm/year (TOPEX/Poseidon, 1993-2003) [19]; 1.98 mm/year (Simon Holgate, at al., 2007) [20]. Figure 5 clearly shows that our civilization has reached a maximum value of the growth rate of global sea level all over paleoclimatic records of the Pleistocene period (values in mm/year numerically correspond to m/millennium).

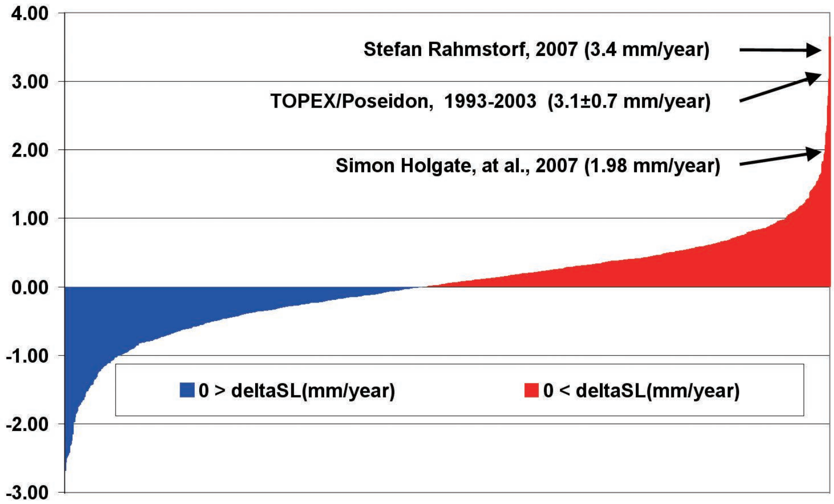

Figure 5. Annual increase in Global Mean Sea level in the Pleistocene period in comparison with the present growth rate (mm/year = m/millennium)

9. Conclusion

If Earth's average temperature increase to 2°C above prior the industrial era, this will lead to an inevitable increase in global sea level by +15 meters. That means that the score obtained by the authors is greater than 15 times the maximum rising oceans of 1 m allowed by the climate change scenario A1B. However, the EU's adaptation strategy to climate change does not accept such a development of events that could lead to a sharp increase in economic losses from rising sea levels. Currently, we can observe big discrepancies between the factual climate change and the planned measures to adapt to it. The current scenarios propose to invest in infrastructures that will be flooded without conditions. In this area, protected from flooding, are not funded properly, and their infrastructure is not adapted to the upcoming relocation. Under these circumstances, it is necessary to create an infrastructure in areas with an elevation of +15 m or above the level before the industrial era. How fast such catastrophic changes in the Earth's climate can occur? If Hansen (2007) [6] is right and if the rise of sea levels continue to double every 10 years and we can expected that the sea level will rise to a +5 meters level in 2100 compared to the preindustrial era level.

The logistic equation (20) for the current climate conditions (global warming on 0.8°C) has provide us a solution that the sea level within next 95 years will rise up to +5 m and will stabilized at +6 m level within the relaxation time of 150 years. If the global warming will get to the 2°C we will have three possible scenarios for sea level rise by +15 meters: the relaxation time does not change; it will happen faster or it will take more time. To answer this question we need get a new data on global warming and sea level rise.

The highest level of Pleistocene period sea-level rise was 9.8 m above the level before the industrial era. It means that we can fall in the next glacial period faster then reach the limit to below 2°C above pre-industrial level and corresponding for it sea-level increase of +15 m. In the millennium time scale the Global Warming and the Sea-level rise will provoke the next glacial period that starts with fast temperature falling down and the 7.5 m sea-level declining per 1°C (equation (12)) up to "zero" Sea-level and after that accelerating 3.3 times to 24.79 m per 1°C (equation (13)). The new infrastructure should be adopted both for 2°C higher temperatures as for the extreme low temperatures of the future glacial period.

References

1. EEA Report No 12/2012. Climate Change, Impacts and Vulnerability in Europe 2012 (2012).
2. Intergovernmental Panel on Climate (2012) Chapter 3: Changes in Climate Extremes and Their Impacts on the Natural Physical Environment in Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (2012).
3. An EU Strategy on Adaptation to Climate Change, 16/04/2013 - COM (2013). URL `http://ec.europa.eu/clima/policies/adaptation/what/docs/com\_2013\_216\_en.pdf`
4. An EU Strategy on Adaptation to Climate Change. Impact Assessment Part 2., 16/04/2013 - SWD (2013). URL `http://ec.europa.eu/clima/policies/adaptation/what/docs/swd\_2013\_132\_2\_en.pdf`
5. S. Brown, R. Nicholls, A. Vafeidis, J. Hinkel, P. Watkiss, Sea-Level Rise on Coastal Zones in the EU and the Costs and Benefits of Adaptation: Summary of Sector Results from the ClimateCost project, funded by the European Community's Seventh Framework Programme (2011).
6. J. E. Hansen, Scientific Reticence and Sea Level Rise, Environ. Res. Lett. 2 (2007) 024002. doi:10.1088/1748-9326/2/2/024002.
7. S. Rahmstorf, A Semi-Empirical Approach to Projecting Future Sea-Level Rise, Science 315 (2007) 368–370.
8. L. V. Sorokin, G. Mondello, The cost of adaptation for climate change, Bulletin of Peoples' Friendship University of Russia, Series Economics (S5) (2013) 63–72, in Russian. URL `http://elibrary.ru/item.asp?id=21074092`
9. J. Zachos, M. Pagani, L. Sloan, E. Thomas, K. Billups, Trends, Rhythms, and Aberrations in Global Climate 65 Ma to Present, Science 292 (2001) 686–693.
10. J. C. Zachos, S. Schouten, S. Bohaty, T. Quattlebaum, A. Sluijs, H. Brinkhuis, S. J. Gibbs, T. J. Bralower, Extreme Warming of Mid-Latitude Coastal Ocean During the Paleocene-Eocene Thermal Maximum: Inferences from TEX86 and Isotope Data, Geolog. Soc. Amer. 34 (2006) 737–740.

11. J. C. Zachos, G. R. Dickens, R. E. Zeebe, An Early Cenozoic Perspective on Greenhouse Warming and Carbon-Cycle Dynamics, Nature 451 (2008) 279–283.
12. J. Hansen, M. Sato, P. Kharecha, D. Beerling, R. Berner, V. Masson-Delmotte, M. Pagani, M. Raymo, D. L. Royer, J. C. Zachos, Target Atmospheric CO_2: Where Should Humanity Aim?, Open Atmos. Sci. J. 2 (2008) 217–231. doi:10.2174/1874282300802010217.
13. J. Hansen, M. Sato, G. Russell, P. Kharecha, Climate Sensitivity, Sea Level, and Atmospheric Carbon Dioxyde, Phil. Trans. Roy. Soc. A 371 (2013) 20120294. doi:10.1098/rsta.2012.0294.
14. J. Hansen, M. Sato, Paleoclimate Implications for Human-Made Climate Change. In Climate Change: Inferences from Paleoclimate and Regional Aspects, Springer, 2012. doi:10.1007/978-3-7091-0973-1_2s.
URL http://www.springer.com/environment/global+change+-+climate+change/book/978-3-7091-0972-4
15. L. V. Sorokin, G. Mondello, The Cost of Adaptation for Climate Change: Future Sea Level Estimation, in: I. Stošić, et al. (Eds.), Economic Sciences on the Crossroad: Proceedings from the International Conference / International Scientific Conference on the Occasion of the 55th Anniversary of the IES, Institute of Economic Sciences, Belgrade, 2013, pp. 557–565.
URL http://www.ien.bg.ac.rs/images/stories/Izdavastvo/IEN/economic_sciences_on_crossroad13.pdf
16. L. V. Sorokin, Simplified Sea Level Estimation Based on Logistic Equation, in: Abstracts of the LI All-Russia Conference on Problems in Dynamics, Particle Physics, Plasma Physics and Optoelectronics Russia, Moscow, 12-15 May 2015, Moscow, 2015, pp. 63–65.
17. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, H. L. Miller (Eds.), IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment. Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.
18. R. S. Nerem, E. Leuliette, A. Casanave, Present-Day Sea-Level Change: A Review, Comptes Rendus Geoscience 338 (2006) 1077–1083.
19. TOPEX/Poseidon - sealevel.jpl.nasa.gov/missions/topex/.
URL sealevel.jpl.nasa.gov/missions/topex/
20. S. Holgate, S. Jevrejeva, P. Woodworth, S. Brewer, A Semi-Empirical Approach to Projecting Future Sea-Level Rise, Science 317 (2007) 1866.
URL http://www.sciencemag.org/content/317/5846/1866.2.full.pdf

УДК 504.1,504.4,504.7,53.023

Упрощённая оценка уровня мирового океана с использованием логистического уравнения и данных палеоклимата

Л. В. Сорокин

Кафедра экономико-математического моделирования
Российский университет дружбы народов
ул. Миклухо-Маклая, д. 6, Москва, Россия, 117198

Вариация глобальной средней температуры Земли на 1°C приводит к изменению уровня Мирового Океана в эпоху до индустриального развития на 24,79 м (SL < 0), а в настоящее время — 7,5 м (SL > 0). Для сценария глобального потепления климата Земли темп изменения уровня мирового океана замедлится в 3,3 раза, что приведёт к повышению скорости роста средней температуры Земли соответственно в 3,3 раза. В настоящее время средняя температура воздуха на планете превышает на 0,8°C значение в эпоху до индустриального развития, что может привести к повышению уровень мирового океана на 6 м. Применив модель переходного процесса на основе логистического уравнения для достигнутой на настоящее время величины потепления климата в 0,8°C можно ожидать, что через 95 лет уровень Мирового океана достигнет величины в +5 м, а за 150 лет стабилизируется на уровне +6 м. Стратегия по адаптации к изменению климата Евросоюза предусматривает рост средней температура воздуха Земли на 2°C, которая в долгосрочной перспективе приведёт к повышению уровня мирового океана на 15 м, что в 15 раз превышает величину 1 м (сценарий A1B). Стратегия адаптации к изменению климата Евросоюза не предусматривает быстрых климатических изменений, что приведёт к резкому увеличению экономических потерь от подъёма уровня мирового океана.

Ключевые слова: логистическое уравнение, изменение климата, глобальное потепление, уровень океана, палеоклимат, гляциология, цикл оледенения, таяние ледников, ледниковый период, наводнение, экономические потери.

Литература

1. EEA Report No 12/2012. Climate Change, Impacts and Vulnerability in Europe 2012. — 2012.
2. Intergovernmental Panel on Climate (2012) Chapter 3: Changes in Climate Extremes and Their Impacts on the Natural Physical Environment in Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. — 2012.
3. An EU Strategy on Adaptation to Climate Change. — 16/04/2013 - COM. — 2013. — http://ec.europa.eu/clima/policies/adaptation/what/docs/com_2013_216_en.pdf.
4. An EU Strategy on Adaptation to Climate Change. Impact Assessment Part 2. — 16/04/2013 - SWD. — 2013. — http://ec.europa.eu/clima/policies/adaptation/what/docs/swd_2013_132_2_en.pdf.
5. *Brown S., Nicholls R., Vafeidis A. et al.* Sea-Level Rise on Coastal Zones in the EU and the Costs and Benefits of Adaptation: Summary of Sector Results from the ClimateCost project, funded by the European Community's Seventh Framework Programme. — 2011.
6. *Hansen J. E.* Scientific Reticence and Sea Level Rise // Environ. Res. Lett. — 2007. — Vol. 2. — P. 024002.
7. *Rahmstorf S.* A Semi-Empirical Approach to Projecting Future Sea-Level Rise // Science. — 2007. — Vol. 315. — Pp. 368–370.
8. *Sorokin L. V., Mondello G.* The Cost of Adaptation for Climate Change // Bulletin of Peoples' Friendship University of Russia, Series Economics. — 2013. — No S5. — Pp. 63–72. — ISSN 0869-8732. — http://elibrary.ru/item.asp?id=21074092. — In Russian.
9. Trends, Rhythms, and Aberrations in Global Climate 65 Ma to Present / J. Zachos, M. Pagani, L. Sloan et al. // Science. — 2001. — Vol. 292. — Pp. 686–693.
10. Extreme Warming of Mid-Latitude Coastal Ocean During the Paleocene-Eocene Thermal Maximum: Inferences from TEX86 and Isotope Data / J. C. Zachos, S. Schouten, S. Bohaty et al. // Geolog. Soc. Amer. — 2006. — Vol. 34. — Pp. 737–740.
11. *Zachos J. C., Dickens G. R., Zeebe R. E.* An Early Cenozoic Perspective on Greenhouse Warming and Carbon-Cycle Dynamics // Nature. — 2008. — Vol. 451. — Pp. 279–283.
12. Target Atmospheric CO_2: Where Should Humanity Aim? / J. Hansen, M. Sato, P. Kharecha et al. // Open Atmos. Sci. J. — 2008. — Vol. 2. — Pp. 217–231.
13. Climate Sensitivity, Sea Level, and Atmospheric Carbon Dioxyde / J. Hansen, M. Sato, G. Russell, P. Kharecha // Phil. Trans. Roy. Soc. A. — 2013. — Vol. 371. — P. 20120294.
14. *Hansen J., Sato M.* Paleoclimate Implications for Human-Made Climate Change. In Climate Change: Inferences from Paleoclimate and Regional Aspects / Ed. by A. Berger, F. Mesinger, D. Šijački. — Springer, 2012. — Pp. 21–48. — http://www.springer.com/environment/global+change+-+climate+change/book/978-3-7091-0972-4.

15. *Sorokin L. V., Mondello G.* The Cost of Adaptation for Climate Change: Future Sea Level Estimation // Economic Sciences on the Crossroad: Proceedings from the International Conference / International Scientific Conference on the Occasion of the 55th Anniversary of the IES / Ed. by I. Stošić et al. — Belgrade: Institute of Economic Sciences, 2013. — Pp. 557–565. — http://www.ien.bg.ac.rs/images/stories/Izdavastvo/IEN/economic_sciences_on_crossroad13.pdf.
16. *Sorokin L. V.* Simplified Sea Level Estimation Based on Logistic Equation // Abstracts of the LI All-Russia Conference on Problems in Dynamics, Particle Physics, Plasma Physics and Optoelectronics Russia, Moscow, 12-15 May 2015. — Moscow: 2015. — Pp. 63–65.
17. IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment. Report of the Intergovernmental Panel on Climate Change / Ed. by S. Solomon, D. Qin, M. Manning et al. — Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2007. — ISBN 978 0521 88009-1 Hardback; 978 0521 70596-7 Paperback, 996 p.
18. *Nerem R. S., Leuliette E., Casanave A.* Present-Day Sea-Level Change: A Review // Comptes Rendus Geoscience. — 2006. — Vol. 338. — Pp. 1077–1083.
19. TOPEX/Poseidon - sealevel.jpl.nasa.gov/missions/topex/. — sealevel.jpl.nasa.gov/missions/topex/.
20. A Semi-Empirical Approach to Projecting Future Sea-Level Rise / S. Holgate, S. Jevrejeva, P. Woodworth, S. Brewer // Science. — 2007. — Vol. 317. — P. 1866. — http://www.sciencemag.org/content/317/5846/1866.2.full.pdf.