

# The Ocean Level and Models Simulating Its Oscillations

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## ABSTRACT

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General modes for simulating changes in mean sea level are expressed for different time frames that involve short- and long-term transgressive - regressive periods. Our investigations of variations in the global hydrologic cycle indicate that they are important factors in the long-term fluctuations of the world ocean level. It is suggested that anthropogenic factors are contributing to a world-wide increase in temperature that may in turn destabilize the western Antarctica ice sheet. A surge and melting of this vast ice mass might cause a rise in the world ocean level on the order of 5 to 7 meters.

**ADDITIONAL INDEX WORDS:** *Climate change; greenhouse effect; hydrological cycle; sea-level fluctuation; water balance; Weiner process.*

## INTRODUCTION

The changes in the world ocean level are closely associated with the changes in geophysical processes occurring at the surface of our planet, and serve as an integral factor of these changes. The controlling factors in the changes of the sea level over billions of years could have been the general evolution of the earth, the changes in its surface topography, development of the water expanse, and thermal fluctuations, among others (ARTYUSHKOV, 1970; VINOGRADOV, 1962; KATTERFELD, 1958).

Investigations of the distribution of sedimentary rocks (STRAKHOV, 1948; TERMIER, 1952), simulation models of the probable changes in the hydrosphere (SOROKHTIN, 1974) and the Earth's topography (KLIEGE, 1980), point to the gradual shrinkage of the ocean and expansion of the land area, which was concomitant with the increase in the total ocean depth, occurring at a rate of about 1 mm per thousand years. **GENERAL MODELS** The model simulating the ocean level variation in

time (T), for large scale geological periods, can be expressed in a general form as

$$H = 0.93 \int_{-\infty}^T 1 - \frac{(u+1.2)}{4.5} du - 2.5.$$

The data available from investigations suggest that during the entire period of existence of the world ocean its level should have experienced a steady tendency to rise, averaging a rate of about 0.6-0.8 mm/10<sup>3</sup> yr.

At the same time, as a result of tectonic processes, during certain periods, the sea level was subjected to large transgressions and regressions, occurring on the average at a rate of 4-5 mm/10<sup>3</sup> yr. The generalized model simulating the ocean level variations during the Phanerozoic can be expressed as follows:

$$H = 60 + (0.334 - 0.27 \cdot 10^{-3T})T$$

The tendency towards the leveling of the Earth's surface, as a result of tectonic processes, was noted for the Mesozoic-Cenozoic (WOLDSTEDT, 1955; KRIEGER, 1963; LEONTYEV, 1970) and particularly for the last 100 million years, the average rate approximating 2 mm per thousand years.

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## OCEAN LEVEL FLUCTUATIONS AND THE HYDROLOGICAL CYCLE

Investigations conducted in natural environments (MARKOV & VELICHKO, 1967; FAIRBRIDGE, 1961) indicate the development of a directional cyclic process during the Pliocene, involving the withdrawal of large volumes of ocean water and storage in ice-sheets. This period is characterized by a general trend toward the lowering of the ocean level, occurring at an average rate of about 0.4 mm/yr.

During the last large continental glaciation (16-18 thousand years ago) the ocean level was more than 100 m below the present level. About 16 thousand years ago the ocean level started to rise rapidly, due to the melting of the ice-sheets. The rate of rise averaged 10 mm, but during certain periods it could have exceeded 50 mm. About 6-7 thousand years ago the world ocean level neared its present position and became relatively stable, showing minor oscillations between several meters, with a slight tendency to rise at a rate of about 1 mm per year. The 3-7 m eustatic decline of the ocean level, observed during the last 5 thousand years, quite distinctly corresponded to the events of glacier advance (FAIRBRIDGE, 1961).

Tide gauge recordings in operation since 1700, show that the world ocean level is at the present time in steady state, which allows it to be used as a datum level in altimetric reference measurements. The mean annual level fluctuations, averaged in respect to the area, approximate 20 cm and are closely associated with the variations in the global water interchange system, which, in turn are of thermal control (KLIEGE, 1978).

### CLIMATIC CHANGE AND GLOBAL WATER BALANCE

Since the end of the last century the climate underwent a conspicuous warming, its maximum up to 1°C occurring during the 1930-1940s, which was of essential impact on the Earth's surface water regime. For instance, the present-day global water interchange is characterized by considerable replenishment of the world ocean, approximating 541 km<sup>3</sup>/year, and the rise of the ocean level by 1-2 mm/yr, resulting from the reduction of the water resources of

TABLE 1. Probable effects of the water-interchange on the ocean level during the period of 1900-1975.

Water balance constituents	Volume changes (km <sup>3</sup> /yr)	Total volume changes (km <sup>3</sup> )	Ocean level changes (mm/yr)	Relative Ocean level change (%)
Lakes	- 63	- 4788	+ 0.17	+ 10.3
Subsurface waters	- 186	- 10336	+ 0.38	+ 22.3
Antarctica glaciation	- 315	- 23940	+ 0.87	+ 51.6
Greenland glaciation	- 82	- 6232	+ 0.23	+ 13.4
Arctic Island glaciation	- 12	- 912	+ 0.03	+ 1.9
Mountain glaciers	- 3	- 228	+ 0.01	+ 0.5
Water storage reservoirs	+ 69	+ 5244	- 0.19	- 11.5
World Ocean	+ 542	+ 41192	+ 1.50	+ 88.7

continents. About 75% of this recharge is derived from melt waters, resulting from deglaciation; 18% probably from the lowering of ground water levels, and 7% from waters drawn off from lakes (Table 1).

### Water Balance in Antarctica

Of essential importance is the problem bearing on the secular variations in the Antarctica water balance. This problem has not yet been solved. Because certain components of the water budget cannot be accounted for with precision, many investigators tend to regard the Antarctica regime as nearly stationary. However, the world-wide warming of the climate during the current century, that involved also the Southern Hemisphere including the coastal areas of Antarctica, should have exerted a definite influence on the water-glaciated conditions of the southern continent proper.

The evidence advanced by American glaciologists serves to indicate that the ice sheet, extending from the Ross Sea to the Wedell Sea over a vast area of about two-thirds of Western Antarctica, undergoes diminution during the current century. The rate of glacier retreat in this area, estimated by HUGHES (1975) at the junction of the ice-sheet with the Ross shelf glacier, approximates 70 mm/year. In Hughes' opinion, this should lead to the contribution of about 200 km<sup>3</sup> of fresh water per year to the world ocean causing changes in its level. Comparative analysis of the data available on the

changes in the Ward shelf glacier areas during 1966-1974 (MERCER, 1978) indicates shrinkage in its area of 600 km<sup>2</sup> by one fourth. The George VI shelf glacier undergoes a similar diminution.

Glacial investigations conducted in the northern part of Victoria Land (MAYEWSKI, 1978) provide evidence of the retreat of the Rennik glacier, reduction in lake depths in the area of the Reaves and Rennik glaciers, and shrinkage of snow caps in this area over a long time period.

According to the information obtained from satellite imagery on the changes in the movement of the Antarctica ice-front, the margin of the shelf glacier in the area of the Bellingshausen Sea underwent a retreat of 500-1200 m over the period of 31/2 years (1972-1975) (COLVILL, 1977). Estimates of the total water budget of Antarctica indicate that during the period 1900-1975 a negative balance prevailed, *i.e.* the rate of moisture draw-off was about 5% in excess of the water inflow. As a consequence, the reduction in the total water reserves should have been about 24,000 km<sup>3</sup>. Hence, the total reduction in the glacier volume during the last century approximated 31,000 km<sup>3</sup>.

### GLOBAL WATER BALANCE

Large-scale changes in the present day global water-interchange of the Earth result from the displacement of large water masses in high northern latitudes where long-term melting of the ice-sheets prevailed, towards the southern latitudes, as a result of increases in the ocean volume. This phenomenon should have retarded the Earth's rotation, supporting evidence for which is found in the investigations irregularities in long-term planetary rotation.

For instance, SIDORENKOV (1975) demonstrated that the rotational rate of the earth decreased by 0.01 sec during the last 100 years, and showed that the long-term nature of these changes is consistent with long-term changes in global water-interchange during the same period.

According to Sidorenkov, at the same time the North Pole underwent a shift towards Greenland, averaging about 10 cm per year, *i.e.* approximately 10 m during the last century. Investigations conducted in the laboratory of helio-space communication of the USSR Gos-

komgidromet, indicate that this polar shift could have been engendered by a considerable loss in mass resulting from melting of the Greenland and Antarctica (to a greater extent) ice sheets. These processes in turn were a controlling influence on the development of atmospheric circulation processes and on the global water-interchange.

### CHANGES IN OCEAN LEVELS THROUGH TIME

Interesting results were obtained by applying comparative quantitative analysis of data on ocean level changes in respect to time-varying periods. The data considered for this purpose are ocean level data for different time intervals of: 600 million years (KLIEGE, 1980); 400, 000; 12, 000; and 3, 000 years (FAIRBRIDGE, 1966); mean ocean level values averaged for the period of gauge recordings; and ocean levels recorded at certain stations. A necessary requirement for the choice of the row rank is that each row series should be sufficiently complete, *i.e.*, each row series should be constructed of several tens of digitals (ordinates) of more or less regular time-distribution.

The quantitative analytical treatment of tide gauge data is based on the theory of stochastic processes. The primary constraint on the application of this theory in such events is that practically all the specified row series are not of full rank and consist only of several tens of digitals. Until recently, the application of stochastic methods to such row series was considered incorrect and not permitted. Only in recent years were new mathematical methods developed that considered these specific events largely eliminating this impendence. In these methods data processing follows the informative approach: the extraction of information of maximum reliability from the available data which helps to minimize *a priori* generalizations, *i.e.*, subjunctive assumptions. These methods are often termed "perturbation methods" or "methods of most informational entropy." They were originally introduced by Van der Bosse, Ulrich, Bishop and others. In the USSR, these methods were apparently first implemented by S. V. Muzilev and V. E. Prival'sky. In our investigations we employed the method of most informational entropy in Berg's modification. Finally, after processing a large

number of variants (and testing 42 different model-types for each) we obtained the optimal stochastic model describing each row series. The chief criteria for the judicious choice of the model are the prediction competency and validity of the parameter estimates of the model.

The stationary or, conversely, non-steady state of the models and series was checked by the deterministic autoregression equations. For calculations the Markward-Wilson optimization iterative algorithm was used. Darbin's recursion formulas and Akaike's criteria were used for testing models.

Let us now discuss the results obtained from analytical treatment of the gauge record data on the modern level fluctuations. In our opinion, these results are interesting because they indicate that the row series data from gauge stations, can be described by the stochastic mathematical model of a unique type. This model-type was thoroughly studied by Norbert Wiener and, accordingly, bears his name; it is termed the "Wiener process." The formula describing the Wiener is very simple in appearance:

$$X_{t+\Delta t} = X_t + a_t$$

where "t" is the time,  $\Delta t$  - discrete interval of the described row series;  $X_{t+\Delta t}$  - process index value (in the specific case - the level),  $X_t$  - Preceding level value;  $a_t$  - sequence of uncorrelated, stationary, normally distributed random values, averaging zero, *i.e.* the Gaussian distribution.

This mathematical model, notwithstanding its apparent simplicity, is not a trivial one and unexpectedly suggests even paradoxically, at a first glance, regularities in the ocean level fluctuations over the last few tens of years. This refers to the level increment - the amount of water that is added, or, conversely, removed from the ocean level (primarily drawn-off to the glaciers), which is, of course, stationary, fluctuating steadily around zero; there is an equal probability of water-draw-off from the glaciers to the ocean as water removal from the oceans to the glaciers. The level itself is in an essentially unsteady state, *i.e.*, it has no mean value, no so-called "adjustment level," to which it shows a tendency, drifting continuously in one or another direction. This feature is in the spirit of the Wiener process.

Another interesting feature of the modern eustatic level oscillations is that, despite the distinct manifestation of a non-steady process and the capability of unlimited long-term upward and downward movement of the level, its variations are not linear. This latter observation (absence of a linear trend) confirms the lack of components in the row series of mean world ocean levels, which is consequential on the geological and geomorphological trend, and reflects namely the eustatic denivellation of the water surface.

Supporting evidence to the Wiener nature of the modern long term oscillations of the mean ocean level is found also in the analysis of the components of the world water balance. For instance, the row series of those components that are accessible for evaluation (KLIEGE, 1979), such as the total flow into the ocean, ice-berg melt water runoff from such glaciers as the Greenland ice sheet, are in full agreement with our mathematical model of the Wiener process. The current Hasselman theory of climate control, can be described by the Gaussian processes. Such components of the world water balance that cannot be directly determined by gauge measurements, as for instance, the evaporation from the ocean surface, precipitation on its surface, apparently can be described also by the Gaussian model. The explanation for the variations in the components of the world water balance, naturally, can be found in the modern theory of climate control. This theory of dynamic-stochastic models was originally developed in recent years in Hamburg, in the Institute of Theoretical Meteorology, by Max Planck, and is of steadfast general recognition today. According to this theory, the energy source of large-scale hydro-meteorological processes, including those of large terms, are the baroclinical instability of the atmosphere, long Rossby waves and other processes of the same type.

## DISCUSSION

Now we can discuss the results obtained from studies of the ocean level oscillations during the geological past. The derived mathematical model can be applied in an attempt to extrapolate over past periods of the row series of mean ocean level oscillations. This extrapolation of the recorded present-time ocean level oscilla-

tions over past periods, seemingly involves the assumption that the components of the water balance were of the same behavior, and indicated the same regularities in past times as at present, although, naturally, this does not imply the *a priori* postulation of their past values.

The results shown in Table 2 compare the fundamental level parameters in past times according to the factual data advanced by different authors and the estimates obtained from our model. The major parameter which interests us is the deviations of the level during past periods from the present level. In our stochastic model this is the average value (mathematical expectations) of the deviations modulus.

As seen from Table 2, the observed and estimated values for thousand year time periods are quite similar. The similarity is extended over the time periods of tens to hundreds of million years ago (the coincidence in the values in certain instances, as, for example, 60, 64, 100 and 98 m, - is, of course, mere chance, but the fact that they are of the same order of magnitude is important.) For characteristic time periods of tens to hundred thousand years the values differ greatly. The observed amplitudes are considerably higher than those extrapolated. We call attention to the fact that the figures in the right column show the far-reaching results from continuance of the modern non-steady eustatic level oscillation process over past geological time-varying periods.

From a comparison of the past level values with those of the modern level oscillations a prudent working hypothesis can be suggested. It postulates that the modern type of global water interchange could have played and appreciable role in the ocean level fluctuations of several thousand years ago, and even tens to

hundreds of millions years ago, but it was probably of negligible effect in the event of tens to hundred thousand years, and seemingly a few million years ago.

It should be noted that the sea level row series from the Phanerozoic (up to 60 million years ago), as well as Fairbridge's row series (up to 3,000 years ago) are closely similar in construction to the same Wiener model, and the values in these row series are similar to those of the modern parameters.

## CONCLUSION

Investigations on the variations in the global waterinterchange system serve to indicate that they are controlling factors in the long-term changes of the world ocean level at the present time. Several investigators (BUDIKO, 1977; BOLIN, 1977; PEARMAN, 1977) present evidence which suggests that due to anthropogenic factors, a further world-wide temperature rise to 1°C or more can be expected in the near future. Such a rise should cause significant changes in the ice-conditions of Antarctica. Investigations conducted by HUGHES (1975), MERCER (1978), GROSSWALD and KOTLYAKOV (1978), and others, indicate that the more conspicuous changes resulting from a temperature increase can be expected in Western Antarctica where a considerable part of the ice-sheet is located below sea level. It is believed that even a relatively small increase in global temperature may destabilize the Western Antarctica ice sheet and initiate its disintegration into large ice-masses that could surge down into the sea. An event of this nature might cause a sharp rise of sea level on the order of 5-7 m. At the same time, a rise in mean sea level of only 5 cm would flood about 1 million

TABLE 2. Amplitudes of ocean level oscillations, according to paleodata (3) and the stochastic model of modern level fluctuations (4).

1 Author	2 Time	3 Level	4 Estimatees (Based on the Wiener model)
Fairbridge (1961)	- 1 Thousands of Years	0.40 m (-)	0.32 m
Fairbridge (1961)	- 3 Thousands of Years	1.60 m (-)	0.55 m
Fairbridge (1961)	- 12 Thousands of Years	75 m (-)	1.1 m
Fairbridge (1961)	- 400 Thousands of Years	100 m (+)	6.4 m
Fairbridge (1961)	- 40 Millions of Years	60 m (+)	64 m
Kliege, Shleynikov (1977)	- 100 Millions of Years	100 m (+)	98 m
Kliege (1980)	- 600 Millions of Years	280 m (-)	241 m

km<sup>2</sup> of land area, nearly the area occupied by the ten European countries of Austria, Albany, Bulgaria, Belgium, Hungary, West Germany, East Germany, Denmark, Netherlands, and Poland.

These estimates and the implications concerning the extent of the possible sea level variations in space, probably involving large-scale anomalies, are of essential importance.

From estimates of the probable climatic changes and their impact on the ocean level it becomes immediately apparent that they may be very significant in the near future, and lead to catastrophic consequences in coastal areas. This implies the necessity of obtaining high-precision estimates of future ocean level changes, and urgently calls for the organization of a complex investigation program on long-term ocean level fluctuations and the controlling factors in these changes, both at the present time and in past geological periods, taking into consideration the world-wide variations in the water-interchange at the Earth's surface.

#### LITERATURE CITED

- ARTYUSHKOV, E. V., 1970. Density Differentiation of Earth's Substances and Associated Phenomena. *Izv. AN SSSR, Fizika Zemli*, No.5. (In Russian).
- BOLIN, B., 1977. Critical evaluation of the carbon cycle models, IN: *Physical Principles of the Climatic Theory and Models Simulating Its Changes*. Leningrad: Gidrometeoizdat. (In Russian).
- BUDIKO, M. I., 1977. *Modern Climate Changes*. Leningrad: GIMIZ.
- COLVILL, J., 1977. Movement of Antarctic Ice-Fronts Measured from Satellite Imagery. *Polar Research*, 18 (115).
- FAIRBRIDGE, R. W., 1961. Eustatic Changes in Sea Level. IN: *Physics and Chemistry of the Earth*, Volume 4. New York: Pergamon.
- GROSSVALD, M. G. and KOTLYAKOV, V. M., 1978. Iminent Climatic Changes and Their Impact on Glaciers. *Izv. AN SSSR, ser. geogr.*, No/6.
- HUGHES, T., 1975. The West-Antarctic ice-sheet instability, disintegration and initiation of ice ages. *Review Geophysics and Space Physics*, 13 (4).
- KATTERFELD, G. N., 1962. *The Image of the Earth and Its Origin*. Moscow: Geografiz. (In Russian).
- KLIEGE, R. K., 1978. *Modern World Ocean Level Fluctuations. Water Level, Coasts and Ocean Floor*. Moscow: Nauka. (In Russian).
- KLIEGE, R. K., 1980a. History of Surface Water Formation of the Hydrosphere. Doctoral Dissertation, Moscow State University.
- KLIEGE, R. K., 1980b. *The Ocean Level in the Geological Past*. Moscow: Nauka. (In Russian).
- KRIEGER, N. I., 1963. Terrace Series. Results of Investigations. Moscow: Geografiz. (In Russian).
- LEONTYEV, O. K., 1970. *On the Changes in the World Ocean Level During the Mesozoic and Cenozoic.*, Number 2. (In Russian).
- MARKOV, K. K. and VELICHKO, A. A., 1967. *The Quarternary Period*, Volume 3. Moscow: Nedra.
- MAYEWSKI, P. A. and ATTIG, J. W., 1978. A recent decline in available moisture in northern Victoria Land, Antarctica. *Journal Glaciology*, 20: 84.
- MERCER, J. H., 1978. West Antarctica Ice-Sheet and CO<sub>2</sub> Greenhouse Effect. A Threat of disaster, *Nature* (London), 271.
- PEARMAN, C. L., 1977. The Carbon Dioxide-Climate Problem. *Clean Air*, 11: 2.
- SIDORENKOV, N. S., 1975. The irregular rotation of the earth as reflected by astronomical observations. *Astronomecheskii zhurnal*, 52 (5). (In Russian).
- SOROKHTIN, O. G., 1974. *Global Evolution of the Earth*. Moscow: Nauka. (In Russian).
- STRAKHOV, N. M., 1948. *Fundamentals of Historical Geology*. Gosgeolizdat. (In Russian).
- TERMIER, H. and TERMIER, G., 1952. *Histoire geologique de la biosphere*. Paris, Masson.
- VINOGRADOV, A. P., 1967. Origin of the ocean. *Izv. AN SSSR, ser. geolog.*No.4. (In Russian).
- WEERTMAN, J., 1976. Glaciology's great unsolved problem. *Nature* (London), 260 (5549) : 284-286.
- WOLDSTEDT, P., 1955. Interglacial transgression levels in northwestern Europe as indicators of tectonic and isostatic movements. IN: *Quarternary Geology Problems*. Moscow: Voprosi geologii chetvertichnovo perioda. (In Russian).

#### □ RESUMEN □

Se expresan formas generales de simular variaciones del nivel medio del mar para diferentes escalas de tiempo, periodos de corto y largo plazo, transgresivas y regresivas. Nuestras investigaciones sobre las variaciones del ciclo hidrológico global indican que aquéllas son un factor importante en las fluctuaciones de largo periodo del nivel del océano. Se sugiere que factores humanos contribuyen al ascenso de la temperatura de la tierra que finalmente puede desestabilizar el casquete de hielo del Oeste Antártico. Un deshielo de esa masa de hielo podría producir un ascenso del nivel medio del océano del orden de 5 a 7 metros.

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