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Impact of Lunisolar Tides on the Iceberg Runoff in Antarctica

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Abstract—Regular variation in the solid runoff of Antarctic glaciers with the period of 18.6 years is revealed as a result of long-term observations. It is demonstrated that the periodicity of the solid runoff correlates with the 18.6-year periodicity of the Earth's angular velocity variations caused by the 18.6-year cyclicity of the variability of lunisolar tides. It is revealed that the vibratory gravitational sliding of glaciers to the sea is registered due to the tidal fluctuations along with many climate processes. The iceberg runoff lags as compared with the course of the variance of tidal fluctuations of the angular velocity approximately by six years.

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INTRODUCTION

The fluctuations of drifting parts (the shelf and outlet ones) of glaciers in Antarctica are associated with the peculiarities of climate changes and hydrology of the southern polar area. It is revealed that the change of alternating periods of the advance and subsidence of the edge of Antarctic glaciers as a result of the calving is associated with the periodic change of meridional and zonal types of atmospheric circulation, with the intensity of cyclonic activity, and with the variations of the precipitation amount and heat influx. The response of drifting parts of glaciers to the intensification of cyclonic activity and water pileup induced by the pressure waves of the cyclones is manifested in the acceleration of the movement of glaciers (surge) towards the sea. The periods of fluctuations of the edge of Antarctic glaciers indicates not only the type of atmospheric circulation and the snow accumulation conditions in the Antarctic but the prevailing long-term trends in the sea level fluctuations as well both in the separate areas and on the periphery of the glacier cover on the whole [11–15].

In the present paper, the relationship is demonstrated between the variations of the iceberg runoff in Antarctica and the 18.6-year cyclicity of lunisolar tidal forces. This discovery means that the iceberg runoff is generated by the vibratory displacement of glaciers. It enables to reconsider all relationships between the dynamics of shelf and outlet glaciers of Antarctica and the Arctic and the peculiarities of changes in the atmospheric circulation, climate, and hydrology of polar areas discovered before.

VARIABILITY OF LUNISOLAR TIDES

The lunar tidal force has the temporal variations of 13.65 days. This is a function of the declination and geocentric distance of the Moon varying in time in a complex way. An amplitude of monthly fluctuations of lunar declination varies from 29° to 18° with the period of 18.61 years due to the regression of lunar orbit nodes. The perigee of the lunar orbit moves with the period of 8.85 years. As a result, the amplitude of fluctuations of tidal forces has the temporal variations with the periods of 18.61, 8.85, 6.0, 1.0, and 0.5 years, as well as with the monthly, half-monthly, and many other less significant periods.

The variability of tidal forces is the most pronounced in the variations of the Earth's angular velocity. In [19, 24], the time series is computed of tidal fluctuations of the Earth's angular velocity from 1901 to 2011 with the daily time step. In Fig. 1 the graph of this series is given. Its analysis demonstrates that the amplitude of half-monthly fluctuations varies in a complex way. The upper envelope describes the waves with the period of 18.6 years and the lower envelope fluctuates with the period of 4.4 years.

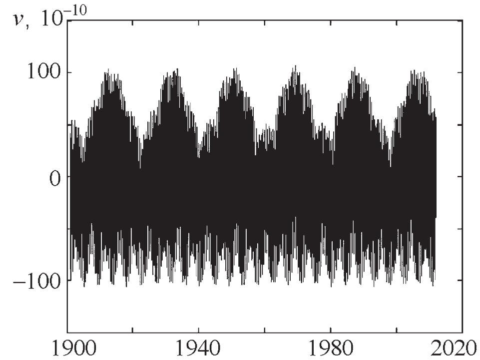

Fig. 1. Tidal fluctuations of the Earth's angular velocity from 1901 to 2011. Along the y-axis, the relative deviations in the angular velocity v of 10^{-10} are given.

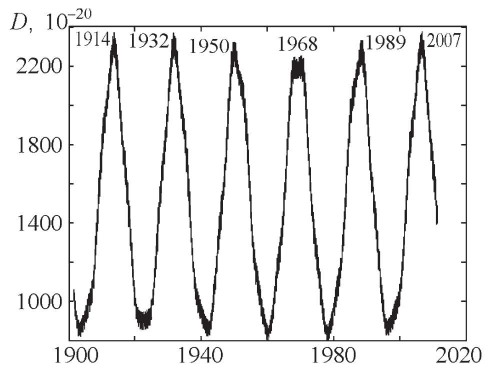

Fig. 2. Variance of tidal fluctuations of the Earth's angular velocity D in the sliding annual window for the period of 1900–2010.

The convenient characteristic of the temporal variability of one or another variable is its variance computed in the sliding time window (for example, it is equal to a year). In Fig. 2 the temporal variations are presented of the variance D of tidal fluctuations of the Earth's angular velocity in the sliding annual window. The variance D varies three times: from the minimum in 1903, 1923, 1942, 1960, 1978, and 1997 to the maximum in 1914, 1932, 1950, 1968, 1989, and 2007 [19]. The minimum variance is observed, when the descending node of the lunar orbit coincides with the vernal equinox and the maximum variance, when the ascending node of the lunar orbit coincides with the vernal equinox.

VIBRATORY DISPLACEMENT OF GLACIERS

The tidal deformations are small but cyclic and permanent. They create the accumulating effects manifested in the transformation of vertical tidal shifts to the horizontal shifts of glaciers. During the low tides, the drifting parts of the Antarctic ice cover (shelf and outlet glaciers) overlie the subglacial bottom elevations slowing down their movement towards the sea. During the tide and sea level rise, the drifting parts of glaciers surface, tear off bottom elevations, and, not being subjected to the channel friction force, slide towards the sea influenced by the horizontal component of the pressure force of the ice mass from the internal areas of the cover. At the subsequent low tide, the drifting parts of Antarctic glaciers slow down again on the bottom elevations and at the tide, surface again and accelerate towards the ocean. In case of the maximum advance of glaciers towards the sea, the icebergs are torn off their edge part at the certain time moment.

Such type of the movement as applied to the mechanics is described in the papers of I.I. Blekhman [5, 6, 21] and is known as the "vibratory displacement." It is corroborated by the field observations of the dynamics of two reference glaciers in Antarctica and the Arctic. For example, it was revealed according to the data of hydrological stations located near the glaciers that the sea level rise (up to 40–60 cm) was really observed in the periods of the increase in the speed of movement of their edge and the sea level decrease was observed at the decrease in the speed [10, 11]. The mechanism of vibratory displacement consisting in the transformation of vertical tidal fluctuations of glaciers into their horizontal shifts towards the ocean is permanent. It has been demonstrated above that the tidal amplitude has the temporal variations with the period of 18.6 years. If the mechanism of the vibratory displacement of glaciers operates, the iceberg runoff should vary with the same cycle.

ICEBERG RUNOFF OF ANTARCTIC ICE COVER

According to the data of [2], the area of drifting shelf glaciers reaches 1653 thousand km^2 that is 11.8% of the area of the whole Antarctica. It was demonstrated before that the numerous and significantly fluctuating tongues of outlet glaciers amount only to 0.2% of the ice cover area or 1.3–1.6% of the area of its all drifting parts. Thus, the shelf glaciers make up more than 98% of the area of drifting formations in Antarctica [12].

For Antarctica as a whole, all available data on the horizontal movement of glaciers (fluctuations of the edge) are presented and analyzed in [12, 13]. Using the descriptions, maps, and satellite images, the dynamics of 88 glaciers was studied situated on the periphery of the main ice-catchment basins of the ice cover including 34 shelf glaciers (61% of the total number or 91% of the total area of the known shelf glaciers in Antarctica) and 54 outlet glaciers and ice streams. The total extent of the coastline under analysis amounted to 10000 km or 52% of the whole length of coasts of shelf and outlet glaciers.

All acquired data on the type of the dynamics and direction of fluctuations of glacier fronts (early and modern maps and numerous satellite images) were divided into two separate groups of time periods. The first group includes the data on the position of marine boundaries of glaciers at their maximum and intermediate movements towards the sea and the second group, at the extreme southern and intermediate recessions towards the land as a result of the calving. Until now, 10 periods of surges and recessions of the edge of shelf and outlet glaciers have been separated (two periods have been reconstructed due to the low provision with the historical data). The last period of the advance of shelf and outlet glaciers after the vast calving of large icebergs in 1996–2009 has not evidently ended yet.

For the sake of control, the analysis of the data on the variations of the position of the edge of the glaciers under study was carried out two times. For the second time, the estimation of fluctuations of the edge of Antarctic glaciers was carried out for the reference (representative) shelf and outlet glaciers located circumpolarly on the periphery of Antarctica. The coefficient of correlation between the obtained series turned out to be equal 0.96 [13].

The following periods of fluctuations of the edge of studied glaciers are separated: 1893–1902, **<u>1902–1910</u>** (the data from 1912 to 1934 are missing), **<u>1935–1939</u>**, 1947–1949, **1955-1957**, **<u>1958–1960</u>**, 1961–1965, **<u>1970–1983</u>**, 1984–1988, **1989-1994**, 2001–2004, **<u>2005–2009</u>** (the periods of the maximum advance of the front of drifting parts of glaciers towards the sea are bolded and underlined, the intermediate periods of the advance are bolded only. The periods of extreme southern positions of glacier fronts at their recession after the calving are written with the common type).

Using all obtained data, the periodicity was specified of the surges of Antarctic glaciers as the area and volume of ice increase, as well as of the dramatic recession of the edge as a result of the separation of marine edges of glaciers in the form of icebergs.

On the whole, the peculiarities of the dynamics of the edge of Antarctic glaciers during the period under study can be characterized in the following way. The periods of the advance (surge) of glaciers are always tightly bound with the sea level rise. The response of drifting parts under these conditions is manifested in the increase in the speed of their movement towards the sea that results in the increase in the iceberg runoff. The periods of the slowing down of the movement of the glacier edges towards the sea and of the recession of fronts of Antarctic glaciers as a result of the calving are observed at the sea level decrease near the ice coasts [11, 13–15].

All available data on the dynamics and regime of shelf and outlet glaciers in Antarctica from 1893 to 2009 were used for estimating the iceberg (solid) runoff from the periphery of the ice cover as a whole. The data needed for this purpose (the length of the coastline for each type of ice coasts in Antarctica, the annual speed of their movement, and the thickness) were taken from [1, 4, 7–9, 17, 18, 20, 22]. Although the data of these authors were mainly obtained from the charts and aerial photographs of 1947–1969, they are widely used nowadays for computing the water-ice balance of Antarctica.

In the papers mentioned above, the length of different types of ice coasts in Antarctica, the speed of the edge movement, and the thickness of glaciers and continental ice selected for the computation differ. For example, the length of the coastline in [20] is estimated at 30030 km and in the computations of ice discharge [17], the length of the perimeter of 27610 km is taken. In view of this, there are differences in the computation of water-ice balance as well. The analysis demonstrated that the following relationships be-

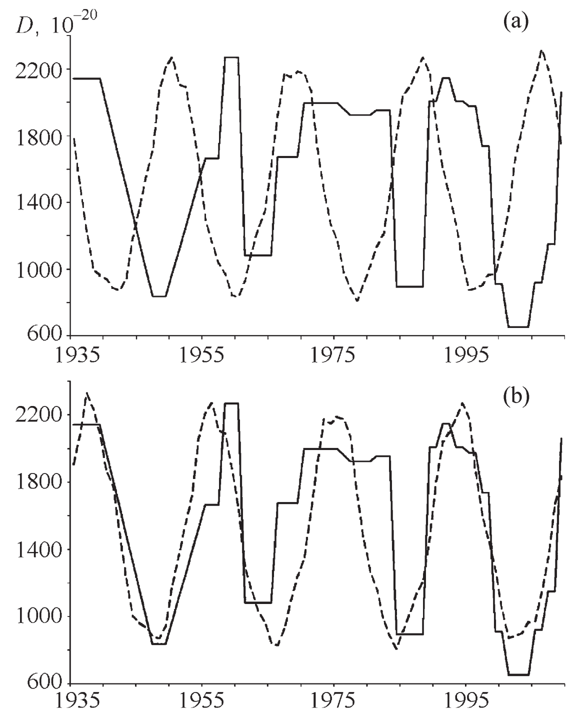

Fig. 3. (a) Synchronous variations of the total iceberg runoff of ice from the Antarctic ice sheet (block curve) and variance *D* of tidal fluctuations of the Earth's angular velocity (dotted line) for the period of 1935–2009 and (b) asynchronous variations of the same variables taking account of the ice runoff lag behind the variance *D* by six years. The time scale for the variance *D* is shifted to the right by six years.

tween the ice shores and coasts and the outcrop of bedrocks are the most optimal: 41.4% for the shelf glaciers, 37.4% for the continental ice or inland ice, 13.1% for the outlet glaciers, and 8.1% for the bedrocks.

According to the available data, during the periods of the general advance of shelf and outlet glaciers in Antarctica (surges), the speed of the movement of their front can increase by 70–100% as compared with the speed of the glacier front movement during the recession periods. For example, the speed of the movement of the front of one of the largest shelf glaciers in Antarctica, the Ronne Ice Shelf, amounted to 2200 m/year from 1947 to 1956 (surge) [7] and 1100 m/year in 1980–1984 (the deceleration of the movement before the calving) [16]. The analogous data are also available for other ice shelves. According to the authors' computations, the speed of the advance of the Filchner Ice Shelf front during the advance period up to 1986 amounted to 2000–2500 m/year [12] and in 1986–2000 after the catastrophic calving of three large icebergs (40 × (90–100) km), it did not exceed 1000 m/year. The speed of the movement of the Shirase outlet glacier front during the same periods increased from 1800–2000 to 3150–3820 m/year [12, 23].

The mentioned characteristics of the dynamics of the edge of Antarctica could not be taken into account during the previous computations of the iceberg runoff because they have become widely known only in recent 15–20 years.

Taking account of the weighted averages of the speed of the movement of undifferentiated edge of the ice sheet of 100 m/year, of the speed of the movement of the edge of outlet glaciers of 600 m/year, and of the ice thickness near the edge of ~300 m accepted in accordance with [3, 4, 8, 9, 17, 18] and if the total length of these coasts is known, the mean value of the iceberg runoff can be obtained for each type of ice edges. Hence, the total value of the ice discharge on these coasts of Antarctica indicates the ice discharge due to the calving (at the ice density of 0.88 g/cm^3).

Unlike the known estimates of the iceberg runoff in Antarctica, the authors distinguish the runoff during the periods of the glacier advance activation (in case of surges) from the runoff during the periods of the slowing down of the movement of the glacier edge caused, as it was revealed from the data of independent research [25], by the tidal fluctuations of the Earth's angular velocity.

The obtained data were compared with the curve of the variance of tidal fluctuations of the Earth's angular velocity. The analysis of the curves demonstrated that the relationship between the dynamics of drifting parts in Antarctica and the variability of lunisolar tidal fluctuations was clearly observed in 1893–1910 (the data for the period from 1911 to the early 1930s are absent) and this dependence was permanently manifested from 1935 to 2009, i.e., almost during 75 years (Fig. 3).

It was revealed as a result of the research that the periods of the general advance (surge) of shelf and outlet glaciers in Antarctica are manifested approximately in six years after the maximum variance *D* of tidal fluctuations of the Earth's angular velocity and the periods of the general recession of the edge of shelf and outlet glaciers as a result of the calving, in six years after the minima of the dispersion *D* (Fig. 3).

The crosscorrelation analysis of time series of the total solid ice runoff from the ice sheet of Antarctica (km^3 of water per year) and of the variance of tidal fluctuations of the Earth's angular velocity for the period of 1935–2009 (Fig. 3) demonstrated the maximum correlation equal to 0.74 ± 0.56 at the shift of the curve of the variance *D* by six years back. The iceberg runoff lags behind the variations of the variance *D* by six years and the 18.6-year periodicity of two processes under consideration is traced reliably.

CONCLUSIONS

It can be stated that the lunisolar fluctuations cause the vibratory displacement of Antarctic glaciers towards the ocean and control the ice discharge as a result of the iceberg runoff. The variations of the total iceberg runoff from the Antarctic ice sheet (the edge of dynamic drifting parts and sedentary continental ice) are mainly associated with the 18.6-year cycle of the variability of lunisolar tidal forces. The iceberg runoff lags behind the variations of the variance *D* of tidal fluctuations by six years.

The lunisolar tides affect the atmospheric and oceanic processes [24]. They are the external factors which, on the one hand, generate the vibratory displacement of glaciers and the iceberg runoff and, on the other hand, influence the atmospheric and oceanic processes. That is why there are numerous relationships between the dynamics of shelf and outlet glaciers in Antarctica and the peculiarities of variations of atmospheric circulation, climate, and hydrology in the southern polar area.

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