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FORECASTING GLACIER MASS BALANCE VARIATIONS IN GLACIATED REGIONS OF THE NORTHERN HEMISPHERE

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Correlation analysis revealing a relationship between regionally averaged mass balance series for nine glaciated regions in the Northern hemisphere and insolation contrast has been carried out. Based on the regression equation, the forecast of changes in the regionally averaged total mass balance of glacier ice has been performed for these regions until 2050. It has been determined that the degradation of the contemporary mountain glaciation is associated with the enhancement of the inter-latitude heat transfer caused primarily by a decrease in the angle of the Earth's rotational axis tilt and concomitant increase in the meridional gradient of insolation (irradiance contrast).

Ice mass balance, glaciated regions, insolation, irradiance contrast, inter-latitude heat transfer, regression model, forecasting

INTRODUCTION

Prediction of variations in the ice mass balance in glaciated areas is important for two major reasons: glaciers serve as indicators of regional climate change; glaciers water resources have to be included into the strategy of the socio – economic development of mountainous and piedmont regions.

Multiyear variations in the ice mass balance in the glaciated regions of the Earth are primarily associated with variations in surface air temperature (SAT) as one of the basic indicators of climate change. The Sun's radiant energy is known to be the main source of heat on the Earth. The redistribution of energy coming to the Earth involves such important mechanisms of heat transfer defined [*Shuleikin, 1953*] as inter-latitude heat transfer ("heat machine of the first kind") and heat transfer between the ocean and the continents ("heat machine of the second kind"). Heat transfer in the global climate system is associated with the circulation processes in the atmosphere and ocean. Atmospheric circulation processes are liable for changes in daily, seasonal and annual variations of SAT. The atmospheric circulation processes are linked with the formation of precipitation pattern. The circulation processes thus affect the dynamics of major climate drivers that determine the conditions necessary for glaciers to form and develop, and are therefore an important factor (along with the incoming solar radiation) in the areal extent and global distribution of glaciers and their dynamics in time. At the same time, macrocirculation processes in the atmosphere are closely related to changes in insolation [*Fedorov and Kononova, 2014; Fedorov, 2015c*].

The astronomical theory of climate change based on the calculation of Earth's insolation was designed to explain the causes of Pleistocene continental glaciation [*Milankovitch, 1939; Imbrie and Imbrie, 1988*], which nevertheless somehow overlooks a relationship between glaciers mass balance dynamics and the Earth's surface insolation.

Given that the forecast depth is dictated by the duration of the time series containing the original glacier mass balance data, the unavailability of long-term series of original data on accumulation, ablation and mass balance represents one of the major challenges in studying the glaciers dynamics in the past and making future prognosis for their evolution. Statistically significant forecast is possible for a period not exceeding 1/3 of the original series duration. Therefore, the increased time series of instrumental observations is one of the primary tasks of geocryology and glaciology [*Serebryany et al., 1989*]. A basic approach to solving this problem consists in the creation of glaciological reconstructions. The one built by the author was based on the established relationship between glaciers mass balance dynamics and duration of the macrocirculation processes in the atmosphere [*Fedorov, 2006, 2007, 2009a,b, 2011a,b*], while the forecasts were calculated from the relationship between total (cumulative) mass balance of ice in the glaciated areas and irradiance contrast (IC).

RESEARCH METHODS

The research methodology for the glacier mass budget reconstruction included calculations of the weight coefficients of elementary circulation mechanisms (ECMs) taking into account the typification of circulation processes in the atmosphere [*Fedorov, 2006, 2007, 2009a,b, 2011a,b*]. The predictions were largely based on the calculated values of Earth's insolation in the Northern hemisphere [*Fedorov, 2012, 2015a,b, 2016a,b, 2018*].

Glacier mass balance reconstruction methods

The total ice mass balance reconstruction for the glaciated regions of the Northern hemisphere was derived from the macrocirculation models. We used the typification of circulation processes in the atmosphere, developed by B.L. Dzerdzeevskiy, V.M. Kurganskaya and Z.M. Vitvitskaya [*Dzerdzeevskiy et al., 1946*] and the Calendar of ECM sequential change with the data on the atmospheric circulation for a time period spanning from 1900 to present [*Kononova, 2003, 2009*; http://www.atmospheric-circulation.ru].

Typification schemes of the atmospheric processes represent a continuous process of general atmospheric circulation in the form of interchanging repeated fragments, the homogeneous processes that cover the whole hemisphere or vast territories. In Russian meteorology there are two best known macroscaled atmospheric processes typifications: after G.Y. Vangenheim and A.A. Gears [*Gears, 1974*], and after B.L. Dzerdzeevskiy, V.M. Kurganskaya, Z.M. Vitvitskaya [*Dzerdzeevskiy et al., 1946*].

We use the Dzerdzeevskiy–Kurganskaya–Vitvitskaya typification in this work, due to the accurate formalization of circulation situations, time and space informativity (developed for the whole Northern hemisphere from 1899 up to present time) and general access to the Calendar of ECM sequential change [*Kononova, 2003, 2009;* http://www.atmospheric-circulation.ru]. This typification takes the correlation between zonal and meridional elements of circulation as profile characteristics. This ratio is regulated primarily by the amount of solar radiation hitting the Earth [*Fedorov and Kononova, 2014*]. There are 13 basic types of ECM and 28 variants of basic types based on seasonal or regional differences – a total of 41 ECM types.

Elementary circulation mechanism, in itself, is a single integrated macro process, during which the Northern hemisphere retains geographical distribution of the baric field of a certain type and the directions of the main transport of air masses. According to the interrelation of zonal and meridional transfers in the Northern hemisphere, ECMs are arranged in four groups: zonal group, zonal disturbance group, meridional northern and meridional southern groups. The groups classified as "zonal" and "disturbance of zonal (circulation group)" reflect zonal transport in the atmosphere, whereas "southern meridional" and "northern meridional" groups reflect meridional transport of the air masses.

The elementary circulation mechanisms (ECM), circulation groups and circulation seasons, being the main structural elements of the considered typification are thus defined within the continuous atmospheric circulation processes. Time, frequency, mode of manifestation and duration of the action of a particular ECM reflect the general atmospheric circulation features, and define the weather and climate patterns for each specific place. Application of the typification to analysis of glaciers mass balance indicators allowed developing the methodology for the glacier mass balance reconstruction, and to increase the duration of the mass-balance series. The reconstruction methodology was underlain by representations of the calculation of the weighting factors for each ECM in the processes of the glacier accumulation and ablation, using mass-balance characteristics obtained as a result of multiyear observations [*Fedorov, 2011b*].

The connection of the atmospheric circulation characteristics with climate was based on the assumption that each elementary circulation process in the hemisphere accounts for specific weather conditions in a particular place (thermal regime and precipitation pattern), governing thereby the glaciers' evolution. A relationship between the circulation characteristics (duration of the action time of ECM) and mass balance indicators was determined as the proportion of circulation contribution (weight ratios) of each ECM to the formation of the mass-balance indicator anomaly sign and value [*Fedorov, 2006, 2007, 2009a,b, 2011a,b*].

We determined the proportion of the contribution (weights) for the series of instrumental observations of accumulation and ablation by subtracting the average multi-year value from the series of mass-balance values, which resulted in obtaining the alternating function, the anomaly of the mass balance indicator (accumulation, ablation). Further, according to the Calendar of ECM sequential change [*Fedorov, 2006, 2007, 2009a,b, 2011a,b*] the total duration of the action time of ECM of all types (in days) during a certain period of the year (e.g., winter – for accumulation, and summer – for ablation) were calculated separately for years with positive and negative anomalies. Assuming that the weather conditions linked with certain types of ECM make a certain circulation contribution to the formation of both positive and negative anomalies of the annual glacier mass-balance indicators, we calculated (in unit fractions) the proportions of the circulation contribution (weights) from each ECM to the formation of the anomaly's sign and magnitude in accumulation and ablation.

The obtained proportions were verified using the values of the original instrumental series recovered from the Calendar of ECM sequential change [*Fedorov, 2011b*]. The correlation coefficient between the recovered and the original series and the divergences between such series were taken as the evaluation characteristics: in millimeters of water equivalent and as percent of the average module of the original series anomalies. The statistical significance of the correlation coefficient was determined based on the existing methods [*Tsymbalenko et al., 2007*] by substituting the date of the beginning and duration of the period (accumulation, ablation) in order to select the maximum for the correlation coefficient value, and the minimum for divergence. The recovered series was interpreted as a macrocirculation model of the mass-balance indicator.

The identified form of the connection enabled reconstruction of the mass balance dynamics for 25 representative and reference glaciers of the Northern hemisphere with a long series of mass-balance observations [*Fedorov, 2011a,b*]. These region-specific data were supplemented by the results of mass-balance observations for another 100 glaciers of the Northern hemisphere. Then we calculated the region-averaged mass balance values for each area (all the glaciers encompassed by mass balance observations) and their total mass balance values. These series were used to predict the total glacier mass balance in glaciated regions of the Northern hemisphere.

CALCULATION METHODS FOR ERATH'S INSOLATION

The calculations of insolation of the Earth and its hemispheres served the basis for predictions of the total glacier mass balance. Previous calculations of solar radiation arriving to the outer fringe (on the upper boundary of the atmosphere or on the Earth's surface, in the absence of atmosphere) have been known since the appearance of the M. Milankovitch theory [*1939*]. His method for insolation calculations was employed primarily for explanation of the Pleistocene glacial/interglacial cycles. The method took into account three parameters of the Earth's orbital motion (eccentricity of the Earth's orbit, the slope of its rotational axis (axial tilt and the longitude of perihelion) spanning long periods of time (hundreds of thousands of years) and only for individual latitudes, assuming that the Earth's shape is a spheroid (although technically it is an ellipsoid). The calculations thus involved only secular variations in the Earth's orbital motion characteristics and the associated variations in the incoming solar radiation, whereas periodic changes in the elements of the Earth's orbit (orbital cycles) and tilt of the Earth's axis of rotation were ignored. Temporal resolution in the calculations made by Milankovitch and his followers [*Sharaf and Budnikova, 1968; Vernekar, 1972; Berger, 1978; Monin, 1982*] ranged from 1 to 5 thousand years. As such, the calculations could be useful in the analysis of paleoclimatic changes.

The analysis of modern climate requires calculations of insolation with a higher time resolution and taking into account periodic variations of insolation along with secular variations. The calculations of incoming solar radiation in the range of periodical disturbance were initiated at the Vojekov Main Geophysical Observatory, Russia (former USSR) [*Borisenkov et al., 1983*]. However, this research didn't get traction. Furthermore, research into high-frequency variations of insolation was consistently maintained at the G. Lemaitre Institute of Astronomy and Geophysics (Louvain-la-Nauve, Belgium) [*Loutre et al., 1992; Bertrand et al., 2002; Berger et al., 2010*]. Calculations of insolation (based on the solution of the problem of motion of two bodies) in this range were performed at the Institute of the Earth Cryosphere (Tyumen) by I.I. Smulsky and O.I. Krotov [*2013*].

Later, the author together with A.A. Kostin [*Fedorov, 2015a, 2018*; http://www.solar-climate.com] performed the calculations of insolation in the range of high frequency variations (high frequency solar flux measurements), based on the astronomical ephemeris [*Giorgini et al., 1996*; http://ssd.jpl.nasa.gov] for the entire Earth's surface (no atmosphere) for the period spanning from 3000 BC to 2999 AD. The initial astronomical data for the calculation of insolation were the declination and the ecliptic longitude of the sun, the distance from the Earth to the sun, the difference in the course of the uniformly current (average solar), and the world corrected time (true solar). The Earth's surface was approximated by ellipsoid (GRS80–Geodetic Reference System, 1980) with semi-axis lengths 6,378,137 m (big) and 6,356,752 m (small). The calculation algorithm can be generally represented by the expression

$$I_{nm}\left(\varphi_1,\varphi_2\right)=\int\limits_{t_1}^{t_2}\left(\int\limits_{\varphi_1}^{\varphi_2}\sigma(H,\varphi)\left(\int\limits_{-\pi}^{\pi}\Lambda(H,t,\varphi,\alpha)\,d\alpha\right)d\varphi\right)dt\ ,$$

where I – incoming solar radiation for elementary n-period of m tropical year (Joules), J; σ – square multiplier (m^2), by which square differential is calculated $\sigma(H,\varphi)d\alpha d\varphi$ – square of infinitely small rectangular ellipsoid cell; α – horary angle; φ – geographical latitude (Radians); H – height of ellipsoid surface relative to Earth surface (m); $\Lambda(H,\varphi,t,\alpha)$ – insolation at the stated moment at the stated ellipsoid surface point (W/m^2); t – time, s.

Steps during the integration: 1° latitude, 1° longitude, 1/360 length of tropical year [*Fedorov, 2013*]. Solar constant (mean multiyear total solar irradiance, TSI) was taken equal to 1361 W/m^2 [*Kopp and Lean, 2011*]. According to the results of calculations for the stated period from 3000 BC to 2999 AD, a publicly accessible database of incoming (no atmosphere) solar radiation upon the latitude Earth zones (5 degree step) with time step equal to 1/12 tropical year [http://www.solar-climate.com], which is used by the author in this work.

MAIN RESULTS

It has been established [*Fedorov, 2015a, 2018*], that during the time span from 3000 BC to 2999 AD, the solar radiation arriving to the Earth has decreased by only 0.005 %. However, the distribution of the annual incoming solar radiation across the latitude zones is found to be subjected to more profound variations (Fig. 1) [*Fedorov, 2014, 2015a, 2018*]. The incoming amount of solar radiation to equatorial regions shows an increasing trend (at least, in the span between 3000 BC and 2999 AD), while it is decreasing in polar regions of the Northern hemisphere (Fig. 1). This suggests an increase in the meridional gradient of insolation, which will result in the intensified inter-latitude heat transfer (between the Earth's warm (equatorial) and cold (polar) regions) both in the atmosphere and in the ocean, prompting the amplified performance of the "heat machine of the first kind" [*Shuleikin, 1953; Fedorov, 2014, 2018*]. The effect of increasing inter-latitude heat transfer in the atmosphere is echoed by the increasing trend in the duration of the meridional southern (MS) circulation group [*Kononova, 2003, 2009; Fedorov and Kononova, 2014*].

The discussed changes – intensified latitudinal contrast and smoothed seasonal differences in the Earth's insolation – reflect secular change tendency described as a decrease in the angle of the Earth's axial tilt caused by precession. The amount of solar radiation in polar regions increases with increased angle of axial tilt, implying that more tilt means more severe seasons (i.e. enhanced seasonal differences in both hemispheres), while latitudinal contrasts tend to be smoothed out. As the Earth's axial tilt decreases, the solar radiation received in the equatorial region increases and decreases in polar regions, meaning that less tilt means less severe seasons meaning less magnitude of seasonal change, while the latitudinal contrasts increase [*Milankovitch, 1939; Fedorov, 2018*].

Irradiance contrast (IC) was used to analyze changes in the surface air temperature (SAT): globally and for hemispheres. IC was calculated for hemispheres as the difference between solar radiation of the latitudinal zones of 0–45° and 45–90° (Fig. 2), while Earth's IC value was taken as mean annum hemispherical values.

The IC variations are linearly related to a change in the angle of the Earth's rotational axis tilt (correlation coefficient $R = -0.997$). Changes in the angle of tilt [*Fedorov, 2018*; http://ssd.jpl.nasa.gov] and the associated IC variations are determined from the planetary precession (trend) and nutation (19-year variations).

Since the glaciers' dynamics is largely governed by the thermal regime, a correlation analysis of the SAT anomaly values was carried out using the Hadcrut4 dataset, a collaborative product of the University of East Englia and Met Office Hadley Center [https://crudata.uea.ac.uk/cru/data/temperature/]. Given that 19-year variations are found to be representative neither in the SAT original series nor in the regionally averaged total ice mass balance, the series of angle of axial tilt (obliquity) and IC were smoothed out using a 21-year moving average. The reliability data analysis (1900–2016) [*Brohan et al., 2006; Jones et al., 2012; Fedorov, 2018*] showed a high correlation between the change in the axial tilt angle and the irradiance contrast and variations in SAT anomaly (Table 1). This indicates a positive relationship between the SAT anomaly and IC and a negative relationship between the SAT anomaly and the angle of the Earth's rotational axis tilt. In the dataset, the SAT anomaly is given relative to the average global temperature for the 1961–1990 period.

As is shown by calculations [*Fedorov, 2018*], in the original time series of the SAT anomaly (for Earth and hemispheres) the variability is dominantly represented as trends (from 69 % for the Northern hemisphere to 85 % for the Southern hemisphere). Note that the trend reflects the main tendency in the time

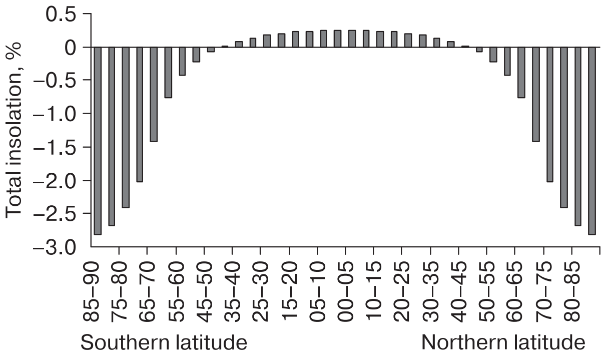

Fig. 1. Variation in the Earth's insolation in the period from 3000 BC to 2999 AD across latitudinal zones (relative to average for respective insolation latitudinal zones).

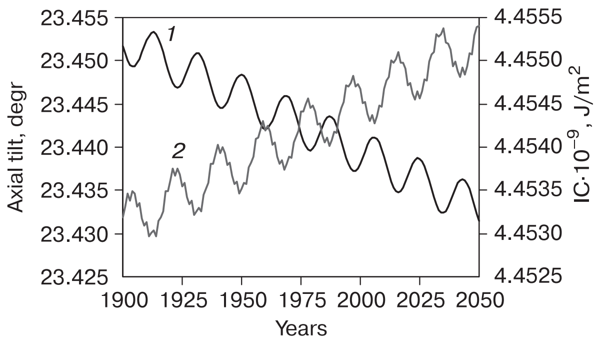

Fig. 2. Changes in the angle of the Earth's rotational axis tilt (line *1*) and irradiance contrast (line *2*).

Table 1. **Correlation coefficient values (*R*) for the angle of the Earth's rotational axis tilt and irradiance contrast (IC) with the surface air temperature anomaly (SAT)**

Insolation parameter	SAT anomaly		
	Earth	NH	SH
Axial tilt angle	−0.888	−0.832	−0.914
IC	0.888	0.833	0.914

Note. NH, SH are Northern and Southern hemispheres.

series of a variable. Trends can be described by various equations: linear, logarithmic, power, polynomial, etc., while the trend type is determined by the selection (statistical methods) of a function that most accurately describes the trend, or by smoothing out the original data of the time series. The values of regionally averaged values for the total ice mass balance were obtained from the mass balance data (instrumental observations and reconstructions) for each of the 9 glacial regions in the Northern hemisphere (Fig. 3). They were calculated by averaging the total annual mass-balance values for respective years for all glaciers in the area encompassed by the mass balance observations. The data from the "Fluctuations of glaciers" series (I–IX) [*Dyurgerov, 2002*] including instrumental mass balance measurements of 125 glaciers in a total of 9 glaciation areas, and the reconstruction data for 25 glaciers of the Northern hemisphere [*Fedorov, 2011a,b*] were used for calculations. The obtained regionally averaged series (with account of the reconstruction data) cover the period spanning from 1900 to 2005 (Fig. 3). The reconstruction derived from the macrocirculation model [*Fedorov, 2006, 2007, 2009a,b, 2011a,b*] spans the period from 1900 until the beginning of instrumental balance observations in the region. The results obtained show

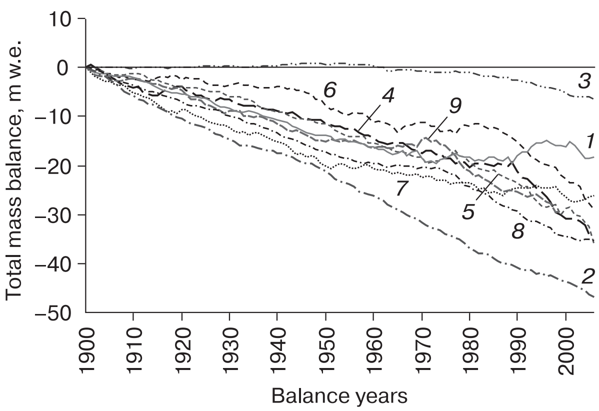

Fig. 3. Regionally averaged total ice mass balance dynamics over the 20th century in glaciated regions of the Northern hemisphere:

1 – Scandinavia; *2* – Spitsbergen; *3* – Canadian Arctic archipelago; *4* – Alaska; *5* – Cordilleras; *6* – Alps; *7* – Caucasus; *8* – Tien-Shan; *9* – Pamir-Alai.

Table 2. **Correlation coefficient values (*R*) for total ice mass balance in glaciated regions with IC and determination coefficient (R^2) for the same original series**

Glaciated regions	*R*	R^2	
		Linear trend	Polynomial trend
Scandinavia	−0.787	0.840	0.964
Spitsbergen	−0.885	0.997	0.997
Canadian Arctic archipelago	−0.688	0.577	0.940
Alaska	−0.874	0.947	0.975
Cordilleras	−0.883	0.975	0.987
Alps	−0.841	0.890	0.946
Caucasus	−0.845	0.940	0.992
Tien-Shan	−0.887	0.985	0.987
Pamir-Alai	−0.875	0.960	0.962
Average	*−0.841*	*0.901*	*0.972*

good agreement with the previous reconstructions, model experiments and historical evidence for glacier dynamics [*Fedorov, 2011b*].

The analysis was carried out for time series which included instrumental observation values for the total mass balance and reconstruction data. All of the 9 glaciated regions exhibited a close relationship between changes in the total ice mass-balance and IC (Table 2).

In the original series of the regionally averaged total mass balance, variability is taken into account predominantly by trends (Table 2; Fig. 4). The presented values of the determination coefficient (R^2) show the proportion of the total mass balance variability reflected in the trend.

Thus, more than 90 % of the variations in the initial data on the total mass balance (used for the forecast) is taken into account by the trend. In this regard, the correlation comparison between these trends and the those for the angle of the Earth's rotational axis tilt and IC (83–85 % of the variance in these series are also taken into account by the trends) appears reasonable as explaining the reasons for more than 90 % variations in the regionally averaged total ice mass balance.

The regression equations (linear and polynomial – second degree polynomial) for the total mass balance and IC were constructed based on the found correlation with IC (Table 3). The determination coefficient is viewed as the main indicator reflecting the quality measure of the regression model describing the relationship between the dependent and independent variables of the model. The determination coefficient derived from the factors included in the model (the closer R^2 to 1, the higher the quality of the model) shows the fraction of variation in the explained variable taken into account in the model.

The forecast was carried out for the ensemble of linear and polynomial solutions by successive alge-

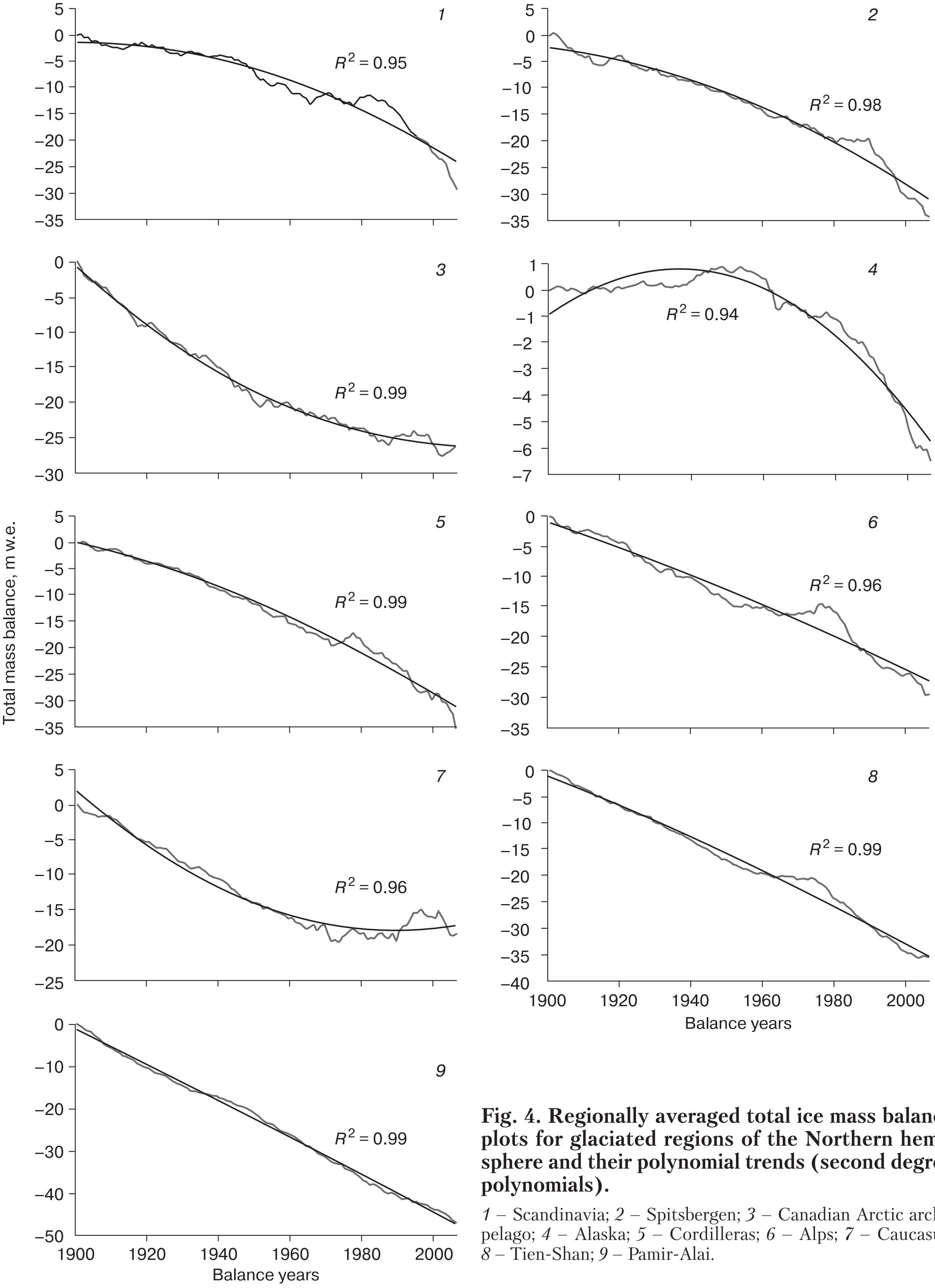

Fig. 4. Regionally averaged total ice mass balance plots for glaciated regions of the Northern hemisphere and their polynomial trends (second degree polynomials).

1 – Scandinavia; *2* – Spitsbergen; *3* – Canadian Arctic archipelago; *4* – Alaska; *5* – Cordilleras; *6* – Alps; *7* – Caucasus; *8* – Tien-Shan; *9* – Pamir-Alai.

Table 3. **Determination coefficient values (R^2) in linear regressions and dispersion relations (D) for ensemble regression equations**

Glaciated regions	R^2		D
	Linear regression	Polynomial regression	
Scandinavia	0.827	0.963	0.929
Spitsbergen	0.992	0.992	0.992
Canadian Arctic archipelago	0.580	0.942	0.942
Alaska	0.946	0.976	0.946
Cordilleras	0.973	0.983	0.980
Alps	0.887	0.941	0.928
Caucasus	0.932	0.986	0.973
Tien-Shan	0.983	0.984	0.984
Pamir-Alai	0.960	0.902	0.961
Average	*0.898*	*0.963*	*0.959*

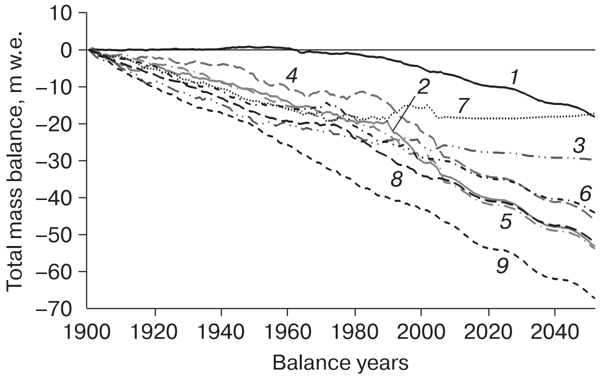

Fig. 5. Regionally averaged total ice mass balance dynamics during the 20th century and in the first half of the 21st century in glaciated regions of the Northern hemisphere.

For legends see Fig. 3.

braic addition of the calculated annual total ice mass balance values (starting from the final value in the 2005 initial series) to the total mass balance of the initial series (Fig. 5). Whilst annual values were calculated on the basis of the regression model values for regionally averaged total ice mass balance. The variations pattern for the regionally averaged (from 1900 to 2050) total ice mass balance for nine glaciated regions of the Northern hemisphere is shown in Fig. 5.

Thus, the maximum ice mass loss over the period of 1900–2050 obtained for a region's average glacier from those encompassed by mass balance observations are: 67.9 m w.e. (water equivalent) for Svalbard; as a linear dependence of the total ice mass balance on the irradiance contrast (to be regionally averaged) – for Spitsbergen; significant ice loss (53.6 m w.e.) for Alaska; 54.2 m w.e. for the Cordilleras; 52.4 m w.e. for the Tien-Shan. Slightly lower values over the century and a half of weight loss of ice is expected in the Alps (46.3 m w.e.) and the Pamir-Alai mountains (44.5 m w.e.).

In the Caucasus, the ice mass loss during this period are assumed to be about 30 m w.e. Minimum ice mass loss since the beginning of last century until the present time is reported from Scandinavia and the Canadian Arctic archipelago: 17.4 and 18.3 m w.e., respectively. Scandinavian glaciers are found to be largely influenced by the Atlantic (Iceland's minimum atmospheric pressure), which is caused by the cyclonic transport of maritime air masses from the west and south-west along the Iceland-Kara valley [*Chizhov, 1976; Koryakin, 1988*].

Therefore, the loss of ice mass here driven by an increase in global SAT (ablation) is largely compensated by an increase in precipitation (accumulation). Insignificant loss of ice mass in the Canadian Arctic archipelago can be explained by low values of mass-balance indicators (accumulation and ablation).

In the period from 2017 to 2050, the stationary (or close to it) state of the regionally averaged total ice mass balance is expected for Scandinavia and the Caucasus. In Scandinavia, the loss of ice mass during this period will be 1.3 m w.e., and about 2.0 m w.e. in the Caucasus. Minimum loss of ice mass in these areas may be accounted for by increased cyclonic activity and the transfer of maritime air masses across Scandinavia from the Atlantic, and in the Caucasus – from the Mediterranean sea. Thus, the implications of the increasing SAT associated with the increased inter-latitude exchange of heat on glacier dynamics (ablation) in these areas are largely compensated by the increased precipitation (accumulation). An increase in atmospheric precipitation is also dictated by increased inter-latitude heat transfer, specifically, by the duration of the action of southern meridional (SM) circulation group [*Kononova, 2009*].

In other glacial areas of the Northern hemisphere, the average ice loss during this period will be in the range of 9–10 m w.e. (the Canadian Arctic archipelago, the Pamir-Alai regions) up to 12–14 m w.e. (the Alps, Alaska, the Cordillera, Spitsbergen). Thus, in genetic terms, the development of Scandinavian and Caucasian glaciers in the context of increased meridional heat and moisture transfer is more affected by atmospheric precipitation (accumulation), and to a lesser extent by heat transfer (ablation). In the rest of the glaciated regions of the Northern hemisphere, the trends in the total ice mass balance are controlled by the heat transfer (ablation) with concomitant increase in the inter-latitudinal heat transfer as a result of a decrease in the angle of the Earth's rotational axis tilt.

CONCLUSIONS

A correlation between the total ice mass balance calculated for an average glaciated area and solar irradiance contrast (negative) and the change in the angle of the Earth's rotational axis tilt (positive) is interpreted as remarkable. Inasmuch as the variability of the averaged total ice mass balance is by 90–95 % taken into account by the trend, the obtained high correlation indicators bear evidence for the causation and incidence relationships in the trends for variations in the total ice mass balance and irradiance contrast (IC). The total ice mass balance trends in the glaciated regions of the Northern hemisphere are thus driven by an increase in irradiance contrast, which is caused by a decrease in the angle of the Earth's rotational axis tilt. An increase in IC is liable for the intensified performance of the "heat machine of the first kind" [*Shuleikin, 1953*] and heat and moisture transport (vortex and circulation atmospheric flows, ocean currents) – from low to high latitudes.

The result is an increase in temperature in the areas of heat flow, an increase in evaporation and water vapor content in the atmosphere, which significantly contributes to the greenhouse effect and to the air temperature warming in the heat outlet zone. These factors are largely responsible for the processes of degradation of modern glaciation in the Northern hemisphere. In some glaciated regions (Scandinavia, the Caucasus), the effect of increased heat transfer (ablation) on the ice mass dynamics is in part offset by increased moisture transfer – precipitation (accumulation), which may result in a slowdown in the degradation of glaciation. The obtained trends in the degradation of modern glaciation in the Northern hemisphere are determined by natural drivers, primarily, by a decrease in the angle of the Earth's rotational axis tilt. The results obtained are important for the generalized estimation of future variations in ice resources, and of their contribution to changes in the level of the world ocean and to the climate changes monitoring in the Northern hemisphere.

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