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Inter-annual variability of Baltic Sea water balance components and sea level

Valery N. Malinin, Alexei V. Nekrasov and Svetlana M. Gordeeva

Russian State Hydrometeorological University, Malookhtinsky Pr. 98, RUS-195196 St. Petersburg, Russia

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This paper discusses some estimates of the Baltic Sea water balance components for the period 1951–1990. A considerable discrepancy is found resulting from different causes**.** The features of the trends in the inter-annual variations of the vertical water exchange components are also discussed. Particular emphasis is placed on the inter-annual oscillations of sea level. The most important large-scale regularities of these oscillations are demonstrated for the period 1892–1994.

Introduction

In spite of a long history of investigations, in many respects the problem of formation and variability of Baltic Sea water balance remains unresolved. Among other issues, the question of the reliability of existing data on different items of water balance needs more attention. The temporal and spatial variability of various items should be studied in relation to this. The aim of this paper is to discuss some characteristics of the water balance variability with emphasis on trends of different items.

Material and methods

The water balance equation may be written as:

$$\Delta V = Q_f + U + P + E + F + \Delta V_d, \qquad (1)$$

where ΔV = intra-annual change of sea volume, Q_f = total river water supply, U = groundwater effluent, P = sea area precipitation, E = sea area evaporation, F = resultant water exchange through the Danish Straits, ΔV_d = sea volume increment due to density variations. It is known that to evaluate the reliability of the numerical values of the water balance components one should determine the discrepancy arising in Eq. 1 after independent calculation of all its components. From Eq. 1 it follows that

$$\Delta V_{ob} - \Delta V_{cal} = S(\Delta h_{ob} - \Delta h_{cal}) = \eta, \qquad (2)$$

where S = sea surface area, η = discrepancy; ΔV_{ob}, Δh_{ob} are the observed intra-annual changes of sea volume and sea level increments and ΔV_{cal}, Δh_{cal} those calculated from Eq. 1.

Discrepancy η was evaluated for the periods 1951–1960, 1961–1970, 1981–1990 and for 1951–1970. In the evaluation it was assumed that groundwater supply brings 10.3 km^3 year^{-1} and that inter-annual density change may be ignored. The volume changes were calculated from sea level data using procedure described by Gordeeva and Malinin (1999). Additionally, the averaged over the sea surface value for precipitation (P_{IA}) and for evaporation (E_{IA}) were calculated using data for the 1949–2000 period from 22 sea area grid points as given at http://ingrid.ldeo.columbia.edu/SOURCES/.NOAA/.NCEP-NCAR/.CDAS-1/.MONTHLY/?help+datasetdataselection, and described by Kalnay *et al.* (1996).

Other water balance components were taken from various sources (Mikulski 1974, Arsenieva 1978, Lazarenko and Alexeeva 1992, Omstedt *et al.* 1997). Some Q_f values were also taken from Dr. V. Babkin, State Hydrological Institute, St. Petersburg (pers. comm.). All these data, including η, are presented in Table 1.

To describe the inter-annual variations of a component $X(t)$, a statistic model represented by a sum of additive terms was proposed:

$$X(t) = T(t) + C(t) + E(t), \tag{3}$$

where $T(t)$ is a trend component, meaning a slow variation with a period exceeding the length of the initial realization, $C(t)$ is a component describing quasi-periodic oscillations, and $E(t)$ is a component characterizing random oscillations. Linear and non-linear trends for all components, except water exchange through the Danish Straits, were calculated for the period 1949–2000.

To examine the inter-annual variations of sea level, observational data from 28 shore stations taken from different sources were used, covering a period of 103 years (1892–1994).

Results and discussion

It can be seen from Table 1 that the discrepancy η, which may serve as an independent test for the accuracy of Eq. 1, depends strongly on the data used. In general, the discrepancy exceeds in magnitude both the change in sea volume and in effective evaporation, and constitutes a considerable part of even the river water supply and the resultant water exchange (especially in 1961–1970). Furthermore, after analysis of the water balance for 1981–1990 using data for E and P from Omstedt *et al.* (1997), P_{IA} and E_{IA} also show that the discrepancy is significantly large and close to values obtained for the period 1951–1970. All this indicates that the accuracy of water balance calculation is low. To our mind, this must be mainly related to the errors in determining water exchange between the Baltic and the North Sea, where quantitative estimation cannot be made with sufficient accuracy. In other words, substantial progress in water balance calculation depends on development of more accurate methods for determining the water exchange. Furthermore, the errors in determining the vertical water exchange (P and E components show significant discordance) may be important.

The characteristics of trends obtained for different water balance components (including

Table 1. Baltic Sea water balance components (km^3 year^{-1}) with resulting discrepancies for different time periods. Digits in square brackets mean references number. [SHI] (= State Hydrological Institute) refers to personal communication mentioned in the text.

Water balance components	Period							
	1951–1960		1961–1970		1951–1970		1981–1990	
Q_f	444 [2]	435 [SHI]	433 [2]	428 [SHI]	438 [2]	432 [SHI]	436 [SHI]	
P	207 [3]	279	196 [3]	235	202 [3]	257	252 [7]	234
E	206 [3]	185	248 [3]	206	227 [3]	196	182 [7]	194
F	383 [4]		499 [4]		441 [4]		436	
U	10 [4]		10 [4]		10 [4]		10 [4]	
$S\Delta h_{ob}$	1		44		23		–22	
$\Delta V = S\Delta h_{cal}$	72	156	–108	–32	–18	62	80	50
η	–71	–155	152	76	41	–39	–102	–72

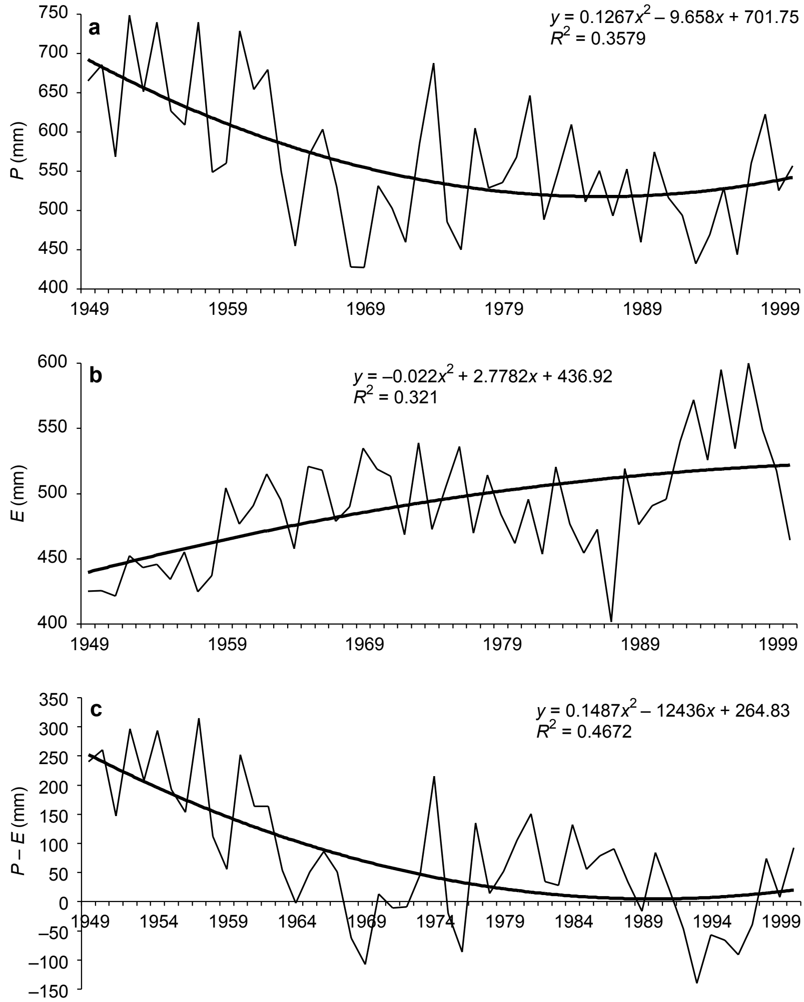

Fig. 1. Inter-annual variability of averaged water balance components and their nonlinear trends: — **a**: precipitation (P_{IA}), — **b**: evaporation (E_{IA}), — **c**: difference $P_{IA} - E_{IA}$.

Neva River discharge, Q_N) are summarized in Table 2. The trends are most distinct in the *P* and *E* components (Fig. 1). The amount of precipitation decreased to the end of the eighties but then showed a weak increase. On average, the decline in precipitation during 50 years amounted about 26%. Evaporation on the other hand showed a weak positive trend, rising 16% in 50 years.

Table 2. Trends in Baltic Sea water balance components.

Component	Observation period	Determination coefficient, R^2	Trend equation (mm year^{-1})	*t*-value
ΔV	1949–1994	0.11	$-53.56 + 17.38t - 0.428t^2$	2.44
Q_f	1949–1986	0.15	$106.86 - 1.004t + 0.030t^2$	2.99
Q_N	1949–1988	0.04	$19.821 - 0.172t + 0.004t^2$	1.27
P	1949–2000	0.36	$701.75 - 9.658t + 0.127t^2$	6.70
E	1949–2000	0.32	$436.92 + 2.778t - 0.022t^2$	5.94
$P - E$	1949–2000	0.47	$264.43 - 12.436t + 0.149t^2$	9.24

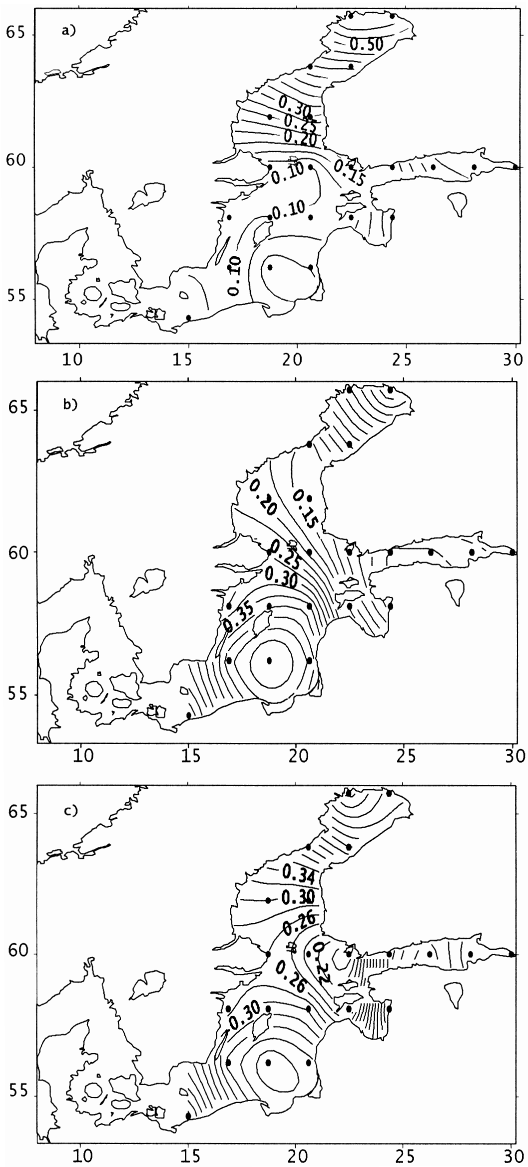

Fig. 2. Spatial distribution of determination coefficient (R^2) at the assessment of trends of water balance components: — **a**: precipitation (P), — **b**: evaporation (E), — **c**: difference $P - E$.

With a summary drop of 250 mm in 50 years, the vertical water exchange ($P - E$) decreased and approached zero.

Peculiarities of spatial distribution of values R^2 (determination coefficient) characterizing the trend over sea area can be seen in Fig. 2. The maximum values of R^2 (showing the contribution of trend to initial data variance) for precipitation are found in the Gulf of Bothnia ($R^2 = 0.55$), while minimum values ($R^2 < 0.10$) are found in the central and south-western Baltic (Fig. 2a). For evaporation, the spatial distribution of R^2 is, in many respects, opposite to that of P, with maximum values of R^2 in the southern Baltic ($R^2 = 0.45$) and minimum values in the Gulf of Finland (Fig. 2b). The determination coefficient for $P - E$ combines the features of that for P and E (Fig. 2c).

The spatial distribution of the temporal means of the water balance components may be of some interest, since it shows that precipitation is most abundant in the Gulf of Bothnia and the Gulf of Finland, and most scanty in the Sea of Åland, and that evaporation is maximum in the south-eastern Baltic and at the head of the Gulf of Riga and the Gulf of Finland. The standard deviation for the temporal means of P and E (σ_P and σ_E) was found to be 86.1 and 43.8 mm year^{-1} respectively. The net (multi-annual mean averaged over the sea area) vertical water exchange $P - E$ is positive ($P > E$) and equals 73 mm year^{-1}. The spatial distribution of $P - E$ is very diverse, showing areas with $P - E$ values exceeding 600 mm year^{-1} (Gulf of Bothnia) and, on the other hand, areas where the predominance of E over P ranges up to 200 mm year^{-1}. Thus, the scatter of $P - E$ values over the sea area is very large with the standard deviation ($\sigma_{(P-E)}$ = 110.3 mm year^{-1}) exceeding its mean value.

When analysing the inter-annual variations of sea level in the Baltic Sea it appears reasonable to separate these into two main parts: (1) long-period (background) variations due to variations in the level of the North Atlantic, and (2) short-period (regional) oscillations related to the variability of Baltic Sea water balance components and other regional factors. Spatially averaged observational sea level data show a negative trend measuring –0.6 mm year^{-1} that contributes about 60% to the total variance. Consideration of this trend prompts the two main factors influencing Baltic Sea level long-term variability: global ocean level rise and Baltic shore tectonic movements, which can be estimated, according to Lazarenko and Alexeeva (1992), at +0.9 and –1.5 mm year^{-1} respectively.

After subtracting the trend from the data matrix, the latter can be decomposed into its 'principal components'. As a result, the following representation of the Baltic Sea level temporal variations was obtained:

$$h(t) = T_h(t) + A_1(t) + A_2(t) + \Sigma A_j(t) \quad (4)$$

with $h(t)$ = sea level average for station data, $T_h(t)$ = sea level trend component, $A_1(t)$ and $A_2(t)$ = first and second principal components, contributing 76% and 8% respectively to the variance of the initial data field (trend removed), and $\Sigma A_j(t)$ = the sum of remaining components (much less significant) together describing about 16% of the initial variance.

The geographic distribution of the first principal component demonstrates the considerable homogeneity of the A_1 loading. In contrast, the A_2 loading shows a considerable difference between the northern and southern parts of the Baltic. Analysis of the temporal variability characteristics of the principal components shows that in $A_1(t)$ the constituents with 4.5 and 3.6 year periods play a considerable role while in $A_2(t)$ small-scale non-regular oscillations are predominant.

Regression models were proposed for describing the basic properties of the principal components. It was found that the most significant predictors for $A_1(t)$ are the index of the North Atlantic Oscillation, Icelandic Pressure Depression and water exchange through the Danish Straits. Some other less significant factors may have some relevance. For $A_2(t)$ the most significant predictors were found to be the characteristics of the water balance.

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