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LONG-TERM SALINITY TENDENCIES IN COASTAL WATERS OF ODESSA REGION, BLACK SEA NORTH-WESTERN PART[1]

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Long-term variability of coastal water salinity in the Odessa Region of the North-Western part of the Black Sea (NWBS) is studied using the available information on local river inflows, precipitation and wind regime. The study confirms a strong connection between the coastal water salinity in the Odessa Region, river runoff into the NWBS region and the regimes of atmospheric circulation over the North Atlantic and Europe. Using the concept of the Black Sea hydrological phases and their variations under the influence of long-term climate variability, it is predicted that the annual-mean salinity in the Odessa Region of the NWBS will increase in the coming 6-10 years. This prediction is based on the displacement of trajectories of the majority of cyclones during that period that propagate from the North Atlantic and pass over northern Europe. The displacement will favour a decrease in the Black Sea freshwater balance and, hence, an increase of salinity. In addition, the analysis of wind regime in the Odessa Region of the NWBS in 2000-2019 reveals a decreased frequency of westward winds and a significantly increased frequency of northerly winds. Assuming that these wind trends continue in the future, and taking into consideration the major hydrodynamic features of the NWBS, it is expected that it will lead to a blocking of freshwater inflow from the Dnieper River mouth into the northern and western coasts of the region. As a result, the increase of annual salinity in the coastal waters will intensify.

Key words: Marine salinity, North-Western part of the Black Sea, rivers discharge, climate changes, wind regime.

Introduction

Temporal variability of salinity in the **N**orth-**W**estern part of the **B**lack **S**ea (NWBS) became a hot research topic due to sharp changes of salinity values near the Odessa Bay coast, that had further intensified more recently (fig. 1). It is known that the physical characteristics of seas undergo changes at different time scales: short-term, synoptic, seasonal, multi-year, and secular. In the NWBS Odessa Region, salinity changes of different time scales can happen under the influence of wind, upwelling, river discharge, rainfall, Black Sea dynamics, phase of the Earth's revolution around the Sun, changes in solar radiation intensity, etc. An overlap of factors that have different time scales contributes to the complexity of salinity variations in the area.

Studies of long-term variability of salinity in the coastal zone of the NWBS Odessa Region have usually been based on observations performed at the Marine Hydro-Meteorological Station (MHS) Odessa-Port (Ковальчук 1985; Альтман и др. 1986; Альтман и др. 1988; Белевич, и Орлова 1996; Брянцев и др. 1991; Демидов 1991). The results of those studies (up to 2010) have been summarized by Dotsenko (Доценко 2010) in an unpublished monograph chapter of the Institute of Marine Biology (IMB). According to that work, during the 1948-1982 period the annual-mean salinity at the station had a negative trend. Then, from 1982 to 1986, the trend was positive, followed by salinity stabilization observed until 1994. Finally, from 1994 to 2010 the salinity trend was negative again (Адобовский и др. 2000; Доценко, и Рубан 2002; Доценко 2002,

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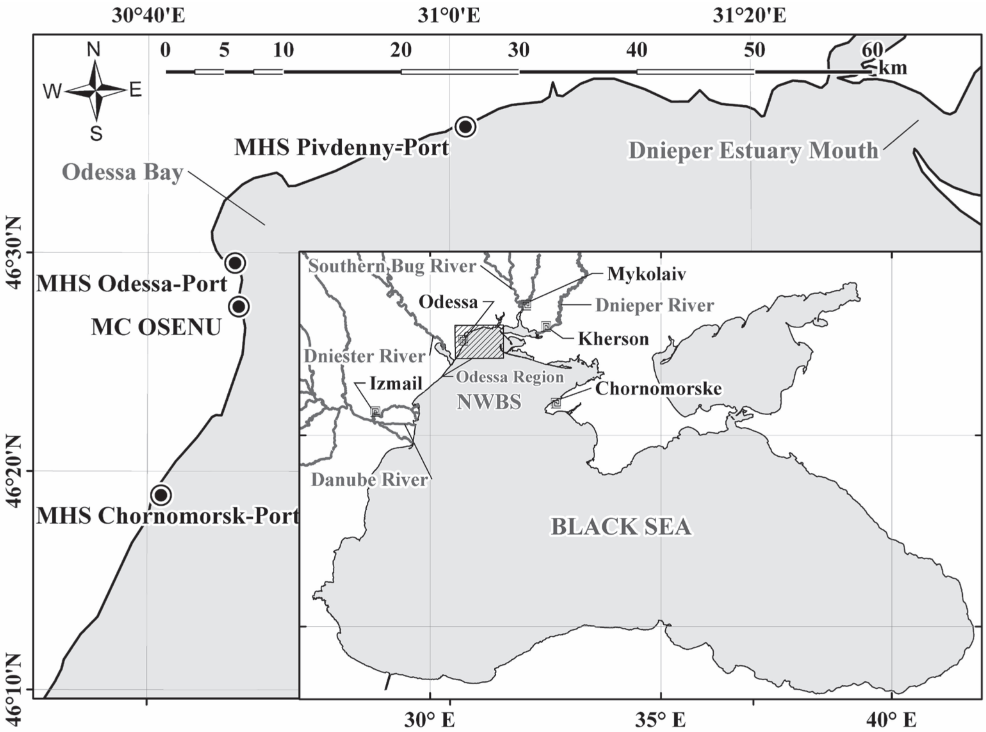

Fig. 1. Location of MHS Odessa-Port, MHS Chornomorsk-Port, MHS Pivdenny-Port and MC OSENU (Maritime Centre of Odessa State Environmental University) in the NWBS Odessa Region

2003; Доценко и др. 2009). Scientists have associated these salinity variations with long-term fluctuations of river runoff and precipitation, caused by global and regional changes as well as a succession of climatic periods.

In addition, a study of long-term salinity changes in the NWBS by (Ильин 2006) has demonstrated a strong dependence of salinity on river discharge and wind patterns. Periods of maximum (1966-1975) and minimum (1986-1995) surface salinity values were also established in (Шокурова и др. 2004), which is applicable to the entire North-Western shelf of the Black Sea, with the difference between the extreme salinity values being 0.3 g/kg.

In this work, analyses of time series and wind patterns in the area are combined to further explain the changes of coastal water salinity in the NWBS Odessa Region during different periods.

Materials and methods

The time series of salinity from the MHSs Odessa-Port, Chornomorsk-Port and Pivdenny-Port for 1949–2019 used in this study were kindly provided by Hydrometeorological Centre of the Black and Azov Seas (HMC BAS) (ГМЦ ЧАМ) and the data for 1951–2019 – by the Marine Centre of Odessa State Environmental University (MC OSENU) (ОДЕКУ). In addition, we also analyse annual discharges of the major rivers, such as Dnieper, Dniester, Southern Bug and Danube for 1921–2018 (ІМБ), climatic indices of the North Atlantic Oscillation (NAO), East Atlantic pattern (EA) and East Atlantic/West Russia (EA/WR) teleconnection for 1921–2019 (NOAA CPC), annual sum of atmospheric precipitation at the coastal stations in the NWBS for 1921–2019 (Погода и климат) and NCEP/NCAR reanalysis data for wind velocity for the period 1948-2019 (NCEP-NCAR), linearly interpolated from four points of a 2.5 x 2.5-degree box to the centre of Odessa Region of the NWBS.

To establish temporal periodicity of long-term variations of the analysed parameters, we apply several additional techniques: a harmonic analysis, diagrams of time dependence, deviations of 11-year moving average values from the mean value of the time series, linear and polynomial approximation, pair correlation, assessment of statistical significance of correlation coefficients, and regression equations.

Results and discussion

1. Analysis of marine water salinity dependence on river inflow and precipitation into the NWBS

Harmonic analysis of the time series of observations at the MHS Odessa-Port reveals periods of annual-mean salinity variations such as 4.0, 6.0 and 10.3 years; at MHS Chornomorsk-Port – 5.5 and 11.0 years; at MHS Pivdenny-Port – 4.0, 6.6 and 10.0 years; and at MC OSENU – 13.0 years. Moreover, using longer time series from the MHS Odessa-Port and MC OSENU

(71 and 69 years respectively), a period of salinity variations as long as 34–36 years is established.

Comparisons between the values of annual river runoff into the NWBS and average annual salinity at the above measuring stations demonstrate a considerable similarity between variations of these characteristics (table 1).

Maximum (statistically-significant) coefficients of pair correlation are found between annual discharges of the Dnieper River and annual-mean salinity at the MHS Pivdenny-Port (table 2), due to a close proximity of the river mouth and the station (38 km; Fig. 1). However, the correlation coefficients are not as high at the more distant from the river mouth MHS Odessa-Port and the MC OSENU stations. Using the values of pair correlation, it is found that during the above mentioned periods the salinity at the MHS Odessa-Port was influenced the most by water inflow from Dnieper (table 2), followed by inflow from Danube and Dniester. A somewhat different picture with the river influences on salinity values is observed at the MC OSENU: due to the geographical features of that station, the Dnieper influence was again the most significant, followed by the influences from Dniester and Danube.

The analysis of annual values (fig. 2) shows the following tendencies: a decrease of salinity at the MHS Odessa-Port by 0.020‰/year at P≥95% (in 1948–2019), a decrease of salinity at the MHS Chornomorsk-Port by 0.027‰/year at P≥90% (in 1999–2019), a decrease of salinity at the MC OSENU by 0.013‰/year at P≥95% (in 1951–2019), and an increase of salinity at the MHS Pivdenny-Port by 0.037‰/year at P≥95% (in 1999–2019). A linear trend of average annual values for the 1999-2019 period is negative for the MHS Odessa-Port (-0.015‰/year, P≥95%) and positive for the MC OSENU (+0.117‰/year, P≥95%). Thus, for this period the tendencies of annual-mean salinity from nearby stations can be opposite in sign (Fig. 1).

The climatological seasonal cycle of salinity shows a clear link to the climatological cycle of river runoff (fig. 3). Minimal salinity values are found during April-June, with a sharp salinity decrease also seen in November. Maximum salinity values, along with the minimum values of river discharge, are found in September. The lowest salinity at the MHS Chornomorsk-Port can be explained by the close proximity of this station to the Danube mouth. It is also interesting to note that at the other stations, the seasonal cycles of salinity resemble each other more closely during the first half of year than during the second half.

Table 1

Periods of long-term variations of river inflow and mean annual salinity in Odessa region of the NWBS

River or station	Periods of variations, years						
Danube River	2.4	3.6	4.9	8.2	14.0	19.6	32.7
Dnieper River	2.2	4.7	5.8	9.8	12.3	24.5	32.7
Dniester River	2.4	3.6	5.5	10.3	14.4	24.0	36.0
Southern Bug River	2.3	4.2	6.0	8.4	14.0	21.0	42.0
Mean river discharge values	2.3	4.0	5.6	9.2	13.7	22.3	35.8
MHS Odessa-Port	2.4	4.0	6.0	10.3	14.4	-	36.0
MHS Chornomorsk-Port	-	4.4	5.5	11.0	-	22.0	-
MHS Pivdenny-Port	2.2	4.0	6.7	10.0	-	-	-
MC OSENU	-	-	-	-	13.6	-	34.0
Mean salinity values	2.3	4.1	6.1	10.4	14.0	22.0	35.0

Table 2

Coefficients of correlation between average annual salinity and annual river flow (the coefficients significant at P≥95% are shown in bold)

Stations	Dniester discharge	Southern Bug Discharge	Dnieper discharge	Danube discharge
MHS Odessa-Port (1948-2019)	-0.38	-0.08	-0.58	-0.47
	p=<0.001	p=<0.638	p=<0.0001	p=<0.0001
MHS Chornomorsk-Port (1999-2019)	-0.33	0.14	-0.34	-0.32
	p=<0.149	p=<0.559	p=<0.148	p=<0.159
MHS Pivdenny-Port (1999-2019)	-0.64	-0.34	-0.80	-0.72
	p=<0.002	p=<0.149	p=<0.0001	p=<0.0001
MC OSENU (1951-2019)	-0.40	-0.39	-0.51	-0.35
	p=<0.001	p=<0.011	p=<0.0001	p=<0.003

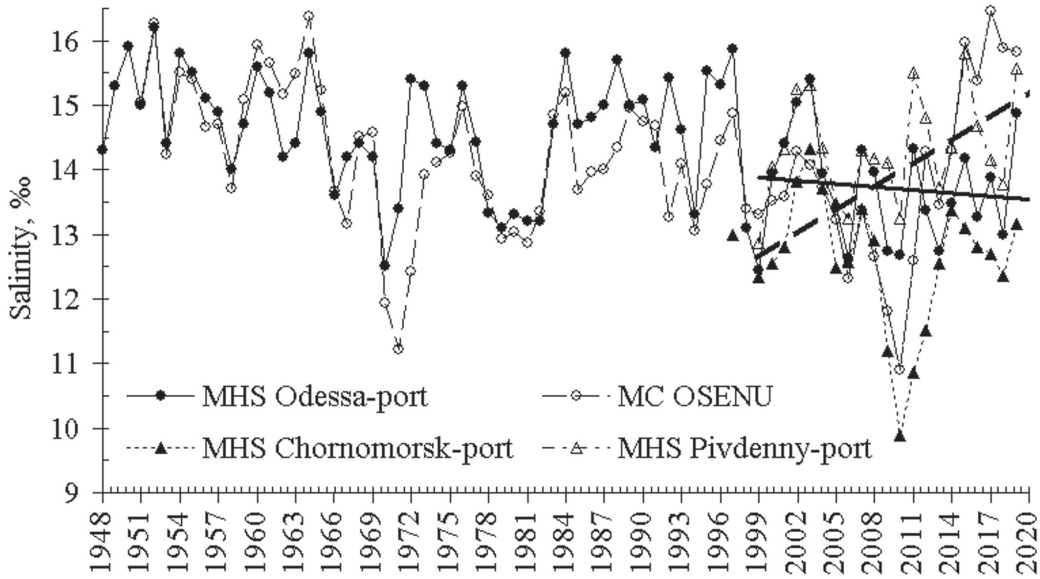

Fig. 2. Time series of annual-mean salinity at MHS Odessa-Port, MC OSENU, MHS Chornomorsk-Port, and MHS Pivdenny-Port

Note: Thickened lines – trends at MHS Odessa-Port and MC OSENU in 1999–2019

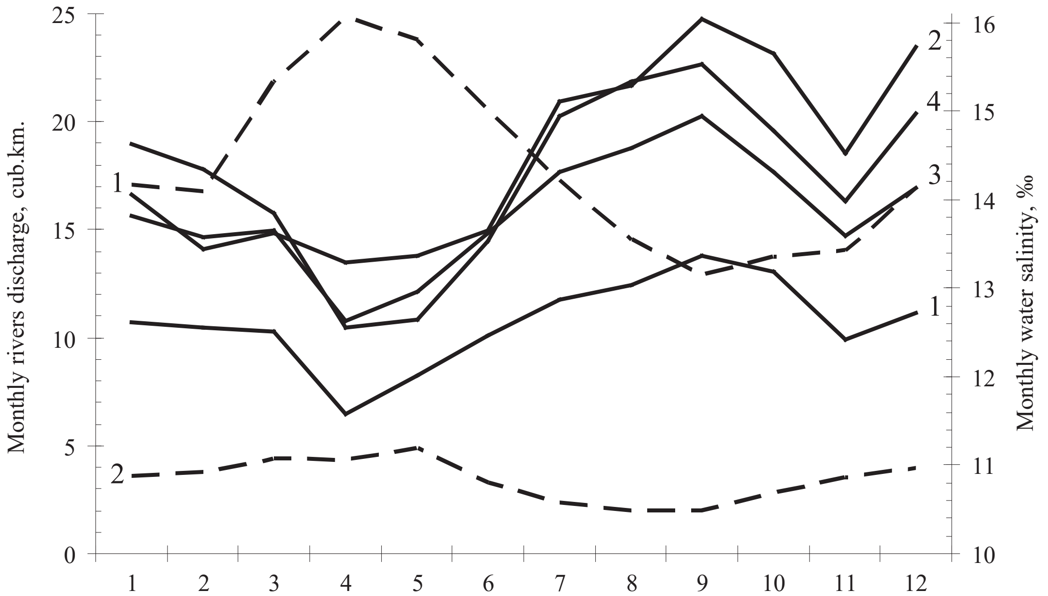

Fig. 3. Climatological seasonal cycles of salinity (solid lines) at the MHS Chornomorsk-Port (1), MC OSENU (2), MHS Odessa-Port (3), MHS Pivdenny-Port (4) and water inflows (dashed lines) from Danube (1) and Dnieper (2). The cycles are based on monthly values

Considering the datasets extended until 2019, the inter-annual variability of salinity at the MHS Odessa-Port, MC OSENU and river discharges are found to be synchronous and opposite in phase (fig. 4), consistent with (Доценко 2002, 2010). That is, the phases of increased annual river runoff correspond to the phases of decreased annual salinity and vice versa, which is expected based on the equations for salt balance and mass conservation (see Appendix). From 1951 to 1980, the salinity at these stations was declining, while the freshwater inflow into the NWBS from all rivers was increasing. From 1981 to 1990 the salinity was increasing, whereas the river discharge was decreasing. From 1991 to 2010 salinity was decreasing again, while the discharge from all the rivers was increasing. From 2011 to 2018, given the background decrease of runoff from all major rivers inflowing into the region of study, we observe a tendency towards increasing annual salinity in the MC OSENU area and stably low annual salinity values at the MHS Odessa-Port (Fig. 4).

Local precipitation directly affects river runoff into the NWBS. According to the data from the HMC BAS (ГМЦ ЧАМ), annual precipitation during 1921-2019 showed a general increasing tendency and was marked by significant decadal and inter-decadal fluctuations. The periods of these fluctuations are found to be close to the periods of river runoff variations: 6-11, 20-25, 40 years. According to (Доценко 2010), long-term oscillations of atmospheric circulation over Europe, including those connected to solar cycles, may have impacted both the variations of annual precipitation and river runoff. According to our observational estimates based on (Погода и климат), the linear trend of annual precipitation was positive in Odessa and Kherson (P≥95%), as well as in Izmail and Chornomorske (insignificant at P≥90%) during the last three quarters of the 20th century and at the beginning of the 21st century (fig. 1). However, considering only the 2010-2019 period, no significant positive trends of annual precipitation is revealed in the area. Moreover, negative trends are found in this case in Mykolaiv (-10.5 mm/year, P≥95%) and Odessa (-7.4 mm/year, P≥90%). It should also be pointed out that annual precipitation in Odessa in 2016 was the largest for the past 200 years. This points at irregularity of precipitation distribution in the NWBS area, including in the past decade.

2. Linking salinity changes in the region of study to climate indices

Climate studies often use climate indices based on analysis of atmospheric pressure fields. A study by (Репетин и др. 2006) shows that under positive phases of the NAO, the tracks of cyclones over Atlantic-European sector drift northward. This leads to more anticyclonic conditions with less precipitation over the Black Sea. Under negative phases of the NAO, the tracks of cyclones drift southward and warm air masses bring rainfalls to the Black Sea region. In a study by (Полонский и др. 2007), the authors find that the number of cyclones in the atmosphere over the Black Sea was decreasing from the second half of the 1960's to the early 1990's This, among other effects, resulted in a long-term weakening of wind-driven cyclonic circulation of the Black Sea. The authors associated these processes with the northerly drift of tracks of the North Atlantic cyclones, corresponding to a strengthening of NAO.

The phases of climate indices determine the type of atmospheric circulation in the region of study; i.e., either mostly zonal or meridional. Such a type is the main external factor regulating the changes of hydrological phases in the Black Sea (Белокопытов 2017). In general, freshwater balance of the sea declines when zonal circulation prevails, while it increases when meridional circulation prevails. During the positive NAO

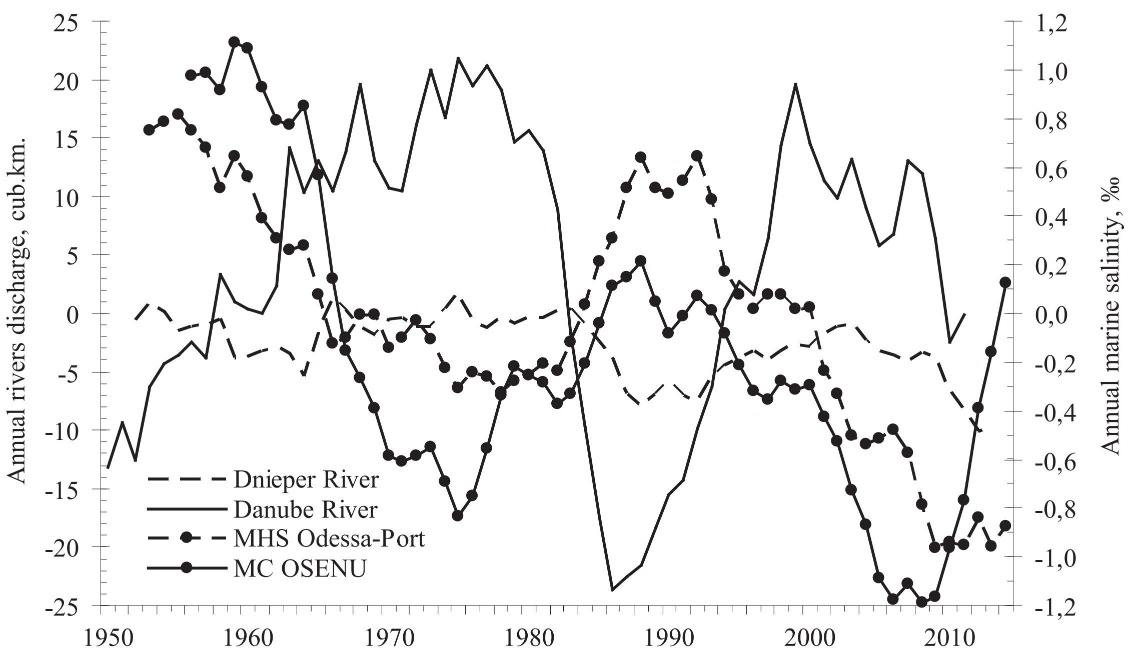

Fig. 4. Deviations of 11-year moving averages from river discharges and salinity at marine stations

phases (cold periods) the number of cyclones decreases and the river inflow declines. As a result, the freshwater balance of the sea declines. During the negative phases of NAO (and EA and EA/WR indices), and under the prevalence of meridional circulation of the atmosphere, the total number of cyclones over the Black Sea increases (Гирс 1971). This leads to a higher intensity of water circulation and to an increase of freshwater balance. The latter is associated with a more positive difference between precipitation and evaporation and also with an increase of river runoff into the basin. In contrast, the periods of prevailing zonal atmospheric circulation are associated with a decreasing freshwater balance, thereby leading to “salty” phases of hydrological regime of the sea (fig. 5).

As follows from the scheme of long-term changes of the Black Sea hydrological regimes proposed by (Белокопытов 2017), as well as from the changes of climate indices (NOAA CPC) (Fig. 6), the hydrological phase of the Black Sea during the 2015-2020 period can be assessed as being intensively warm and moderately fresh. Its change after 2020 is still unknown, but could be forecasted based on the intensively warm and salty phases.

The above assessment is consistent with the conclusions made in (Доценко 2010). According to this study, active cyclonic activity was forecasted for the Black Sea basin up until the end of the 1st decade of the 21st century. This was linked by the author to the prevalence of meridional transfer over Europe, significant rainfalls and increasing river runoff. The latter resulted in a decreasing tendency of annual-mean salinity in the NWBS. However, this process should change, as might be expected based on the multi-decadal variability (i.e., based on the 22 and 35 year-long cycles proposed by (Белокопытов 2017) for the long-term variations of salinity in the Black Sea shelf areas). That is, the annual-mean salinity in the region is expected to increase.

In fact, a stable increase of annual-mean salinity has already been observed at the MC OSENU station since 2014. However, at the MHS Odessa-Port station a significant salinity increase was found only in 2019, which can be explained by the strong influence of the Dnieper discharge on hydrological conditions at the station.

3. Linking salinity changes to wind patterns and hydrodynamics in the NWBS

Although river runoff is the main factor affecting water desalination in the NWBS, wind also is an important factor influencing salinity changes in the region. According to (Ильин 2006), wind patterns play the main role in transformation and distribution of water from the estuarine areas of major rivers to the central and eastern NWBS regions. In particular, during March – May a south-easterly wind prevails, driving freshwater from the rivers towards the north-western coast of the Odessa region. During June – July, north-westerly winds prevail, driving freshwater from the Dnieper mouth to

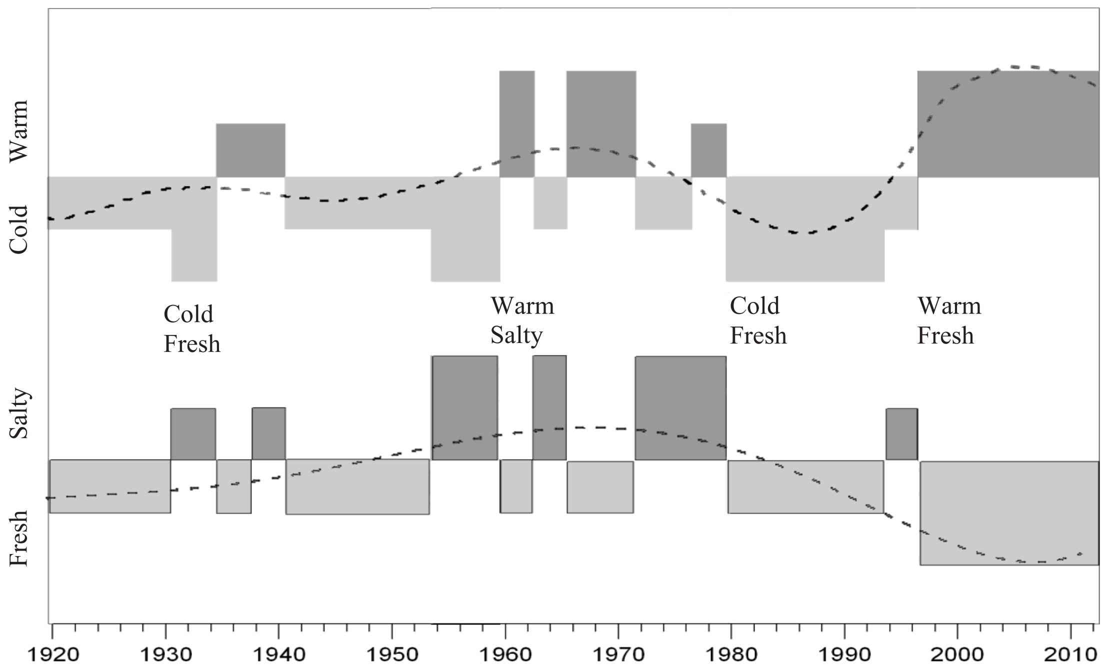

Fig. 5. Scheme of alternation of phases in the Black Sea hydrological regime (Белокопытов 2017)

Note: Height of columns presents 2 levels of intensity: moderate and intensive

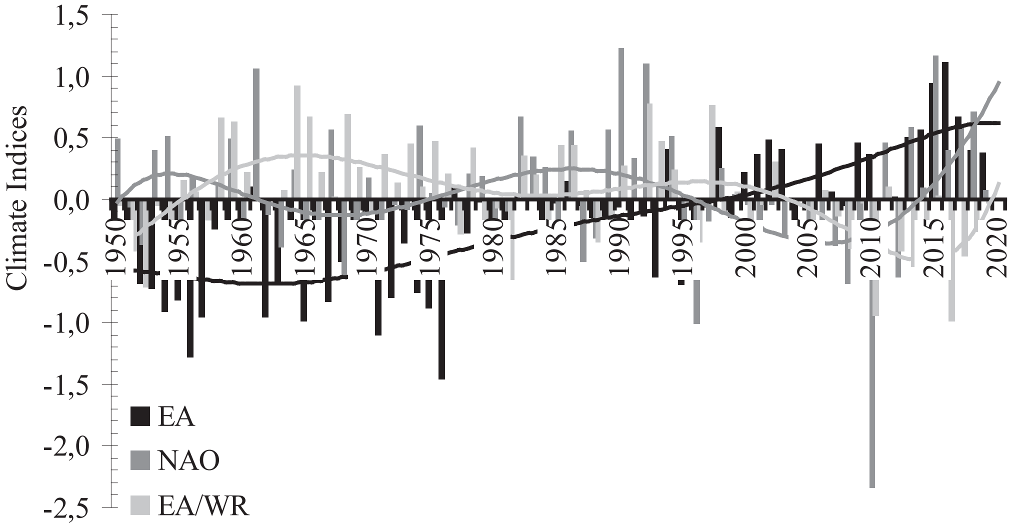

Fig. 6. Annual averages of climatic indices during 1950–2019

Note: Lines indicate approximation by the 6th order polynomials

the east and south-east, thereby increasing the low-salinity area in the NWBS.

According to (Доценко, и Тучковенко 2006), who analysed the long-term MHS Odessa-Port data, the frequency of winds of northerly, north-westerly and westerly directions accounts for 48-57% from July to September. The winds of these directions cause surface negative surges and coastal upwelling, thereby increasing surface water salinity (by bringing higher salinity water from the Black Sea interior to the region). This phenomenon can be either local or it can cover a significant part of the coastal zone in the Odessa region.

Water circulation in the Odessa region near the NWBS can be explained, at least in part, by its bottom topography. Indeed, this is a semi-enclosed basin, with a large shallow region (Odessa Bank) in its northern part, stretching from the west to the east and separated from the northern coast by deep trough-like depression. These features determine the overall domination of wind-driven circulation over the density-driven currents in the region (Доценко 2003; Тучковенко 2002). Using general circulation models, it has been found that during westerly (easterly) and north-westerly (south-easterly) winds, an anticyclonic (cyclonic) eddy-like circulation dominates in the region. In the case of southerly (northerly) and south-easterly (north-westerly) winds, an anticyclonic (cyclonic) eddy-like pattern dominates the circulation in the eastern part of the region, while a cyclonic (anticyclonic) gyre forms over the Odessa Bank.

Our analysis of wind components over the Black Sea, using the NCEP/NCAR reanalysis data (NCEP-NCAR), gives the following behaviour of wind trends for the 1948–2019 period (fig. 7). During the 1957–1995 period, the wind over the sea had linear trends (see also Ильин (2006)): (0.03) m/s and (-0.03) m/s per year for zonal and meridional wind components, respectively. However, for the 2000-2019 period the trend lines change their inclination considerably. Only negative tendencies are observed during that period: (-0.03) m/s per year for the zonal wind component and (-0.06) m/s per year for the meridional component. Thus, for most of the 2000–2019 period, we find a decreasing frequency of westerly winds (for 2019, the percentages of frequency of westerly and easterly winds are equal) and an increasing frequency of northerly winds in the Odessa region of the NWBS.

Taking into consideration the system of currents and water transport simulated by the model experiments presented in (Доценко, и Тучковенко 2006), as well as the sea bottom topography in the Odessa region of the NWBS, it can be suggested that, if the present tendency for the near-surface wind is to persist, this will lead in the future to a blocking of freshwater inflow from the Dnieper mouth to the Odessa coastline area. In this case, water would be more actively transported to the NWBS central part under the joint influence of anticyclonic eddy-like circulation over the Odessa Bank and cyclonic circulation over the eastern part of the Odessa region. Should this happen, it would seem reasonable to expect (forecast) an increase of annual-mean salinity in the Odessa Bay; i.e., in the western part of the Odessa Region of the NWBS.

Conclusions

Changes in the global-scale atmospheric circulation can tell us about long-term tendencies of hydrometeorological

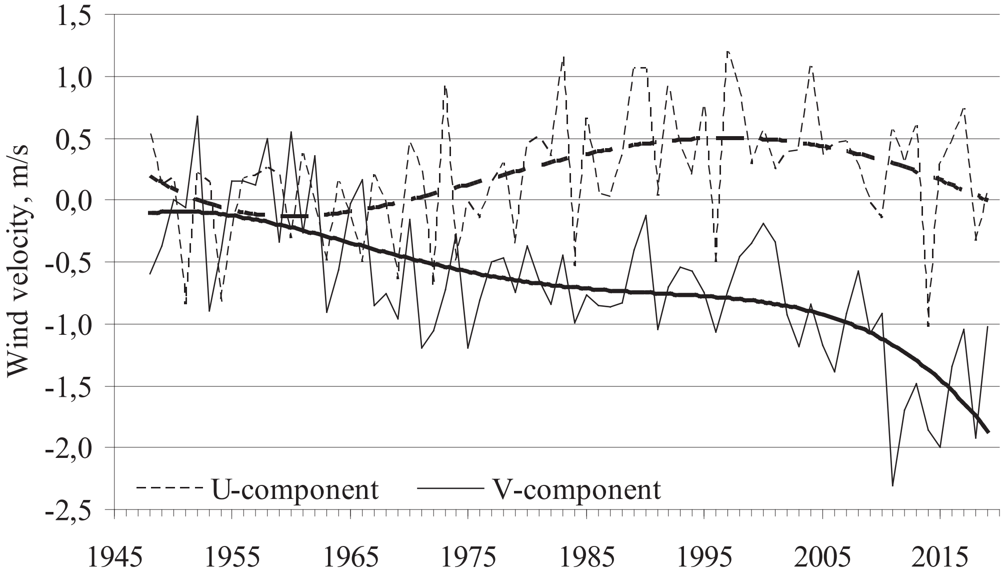

Fig. 7. Time series of the annual means of U-component (dashed lines) and V-component (solid lines) of wind velocity in the region of study during 1948–2019

Note: Bold lines indicate approximation by the 4th order polynomials

characteristics over Europe and also about variations of hydrological phases in the Black Sea. In the long run, the latter affects salinity in the coastal area of the Odessa Region of the NWBS. This includes salinity variations associated with multi-decadal, decadal, inter-annual and seasonal variability, as well as synoptic changes linked mainly to short-term wind fluctuations.

According to our analysis, an intense phase of the warm and saline hydrological regime of the Black Sea should be expected to develop from about 2020 onward. This phase will last not less than 6–10 years. During this period, annual-mean salinity in the Odessa Region of NWBS will increase. This salinity increase will be associated with strengthening of the positive phase of the NAO index and with high values of the EA index. The corresponding tracks of cyclones, propagating from the North Atlantic, will shift more to northern Europe. As a result, there will be less precipitation over the watershed areas of the Danube and Dnieper rivers, thereby decreasing freshwater balance in the NWBS.

Moreover, if the frequencies of westerly and easterly winds remain at their present level and the frequency of northerly winds gets higher, then the inflow of transformed low-salinity water from the Dnieper River mouth to the northern and western coast of the Odessa Region of the NWBS will be blocked. Should this happen, it would further contribute to the expected increase of annual-mean salinity in the coastal waters near Odessa.

Appendix

A close relation between salinity changes and river runoff, including on inter-annual time scales, may be expected based on the basic equations of salt balance and mass conservation. Essentially, over a broad enough and well-mixed region, the evolution of salinity and mass (volume) conservation can be written as follows $\frac{\partial S}{\partial t}=-\vec{u}\cdot\nabla S$ and $\nabla\vec{u}=0$, where S is the salinity, $\vec{u}$ is the velocity vector and ∇ is the gradient operator. Combining these equations, using the divergence theorem (also known as Ostrogradsky's theorem), and assuming that the net river inflow R (in $m^3 s^{-1}$) at the boundary is a much larger contributor to the local salinity changes than is the difference between precipitation and evaporation, the evolution of the salinity averaged over volume V (in m^3) is given approximately by $\frac{\partial \bar{S}}{\partial t}=-\frac{R}{V}S_o$, where S_o is some constant reference salinity (e.g., mean salinity of the water that must flow out of the region to balance the water inflow from the river runoff). Integrating the latter equation in time from $t=0$ to $t=T$ leads to $\bar{S}(T)=\bar{S}(0)-a\langle R\rangle$, where $\langle R\rangle$ is the time-mean river runoff and $a=\frac{S_o}{V}T$ is the dimensional coefficient.

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ТЕНДЕНЦІЇ ЗМІНИ СОЛОНОСТІ ПРИБЕРЕЖНИХ ВОД ОДЕСЬКОГО РАЙОНУ ПІВНІЧНО-ЗАХІДНОЇ ЧАСТИНИ ЧОРНОГО МОРЯ

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На основі наявної інформації про стік річок, атмосферні опади і вітровий режим розглядається багаторічна мінливість солоності прибережних вод в Одеському районі північно-західної частині Чорного моря (ПЗЧМ). Дослідженням підтверджено суттєвий зв'язок величин солоності води біля узбережжя Одеського району з обсягами річкового стоку в ПЗЧМ, які залежать від характеру циркуляції атмосфери над Атлантикою і Європою. Використана концепція зміни гідрологічних фаз в Чорному морі під впливом багаторічних змін клімату в регіоні, на основі якої зроблено прогноз збільшення середньорічних значень солоності моря в Одеському районі ПЗЧМ у найближчі 6-10 років. Ця тенденція обгрунтовується на зміщенні траєкторій більшості циклонів в цей період з Північної Атлантики на північ Європи і, як наслідок, зменшення прісного балансу Чорного моря. Аналіз вітрового режиму в Одеському районі ПЗЧМ виявив у 2000–2019 рр. ослаблення повторюваності вітрів західного напрямку і значне збільшення повторюваності вітрів північного напрямку. Збереження цієї тенденції в майбутньому в силу особливостей гідродинаміки в ПЗЧМ буде провокувати блокування надходження трансформованих розпріснених вод від гирла р. Дніпро до північного і західного узбережжя району, що також буде інтенсифікувати збільшення середньорічних величин солоності прибережних морських вод.

Ключові слова: морська солоність, північно-західна частина Чорного моря, стік річок, кліматичні зміни, вітровий режим.