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Original article

The Recurrence of Winter Invasions of Cold Air over the Black Sea

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Abstract

Invasions of cold air masses into the atmosphere over the Black Sea in winter cause the intensive cooling of the surface water layer and contribute to the formation and development of a cold intermediate layer. Although such invasions are relatively rare, they regularly recur in winter. The article studies characteristics of the probability of cold invasions into the atmosphere of the Black Sea region. The article studies series of daily wind data, as well as data on sensible and latent heat fluxes and sea temperature in winter at various points in the west and east of the northern and central parts of the Black Sea. The cases of cold air masses invasion characterized by strong northerly winds were highlighted. The article considered statistical parameters of the winds in points characteristic of the north-westerly, northerly and north-easterly winds in the open central part of the sea and points in the coastal north-western and north-eastern regions. Wind roses and graphs of cumulative distributions were constructed for the offshore points which allowed determining the periods of recurrence of strong northerly winds in winter. A direct dependence of the magnitude of heat fluxes from the sea surface on the northerly wind speed in winter was revealed. It is shown that cold invasion led to seawater cooling as illustrated by the decrease in seawater temperature at the surface and at 50 m depth in 2012.

Keywords: Black Sea, cold invasions, northerly wind, recurrence period, heat fluxes, sea water temperature

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Повторяемость зимних вторжений холодного воздуха над Черным морем

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Аннотация
Вторжения холодных воздушных масс в атмосферу над Черным морем зимой являются причиной интенсивного выхолаживания поверхностного слоя вод и способствуют формированию и развитию холодного промежуточного слоя. Хотя такие вторжения относительно редки, в зимние периоды они регулярно повторяются. Статья посвящена исследованию характеристик вероятности холодных вторжений в атмосферу Черноморского региона. Исследованы ряды суточных ветровых данных, а также данных о потоках явного и скрытого тепла и температуре моря зимой в различных точках на западе и востоке северной и центральной частей Черного моря. Выделены случаи вторжения холодных масс воздуха, характеризующиеся сильными ветрами северного направления. Рассмотрены статистические параметры ветров в характерных для ветра северо-западного, северного и северо-восточного направления точках в открытой центральной части моря и в прибрежной северо-западной и северо-восточной областях. Для морских точек построены розы ветров и графики кумулятивных распределений, позволившие определить периоды повторяемости сильных ветров северного направления в зимний период. Выявлена прямая зависимость величины потоков тепла с поверхности моря от скорости северного ветра в зимний период. Показано охлаждение морской воды как результат холодного вторжения для случая 2012 г. на примере полей понижения температуры моря на поверхности и на глубине 50 м.

Ключевые слова: Черное море, холодные вторжения, северный ветер, период повторяемости, потоки тепла, температура морской воды

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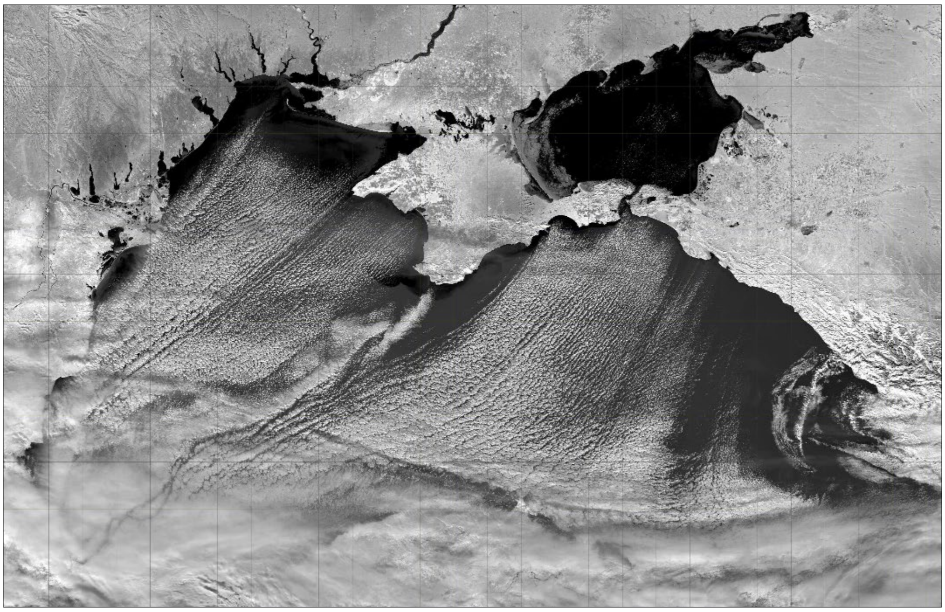
Introduction

The cooling of the Black Sea surface in winter is most intense when cold air masses invade across the northern boundary of the sea (1–5). While rare, cold air invasions into the atmosphere over the Black Sea are a recurrent phenomenon in winter. In the southern and especially the south-eastern part of the sea, such invasions are less pronounced and less intense.

Typically, the cases of invasion of cold air masses correspond to the passage of a cold atmospheric front across the northern boundary of the sea. They are accompanied by an increase in surface wind speed up to 10–15 m/s and a decrease in air temperature down to –5...–10°C. As a result, intense convection and clouding develop in the cold boundary layer of the atmosphere above the relatively warm sea, the temperature of which in winter is in the range of 5–9 °C. A distinctive clouding pattern is observed in satellite snapshots, manifesting as cellular or roller structures [2]. Fig. 1 shows an illustrative example of such a snapshot.

In response to such events, the Black Sea exhibits lowering of the surface layer temperature, development of strong wind waves and wind currents and significant deepening of the upper quasi-homogeneous sea layer. Such an important feature of the vertical thermohaline structure of the sea as a cold intermediate layer (CIL) is formed. The water temperature minimum at depths of 50–70 m is believed to be formed in the open sea regions as a result of deep penetrating convection under conditions of large fluxes of sensible and latent heat from the sea surface [4, 6]. Advective transport of cold water from the shallow north-western region by the coastal western currents and further southwards by the Rim Current system is considered to be the second, less important cause of CIL formation [4, 8–11].

The characteristics and mechanisms of formation of the sea response to cold air mass invasion episodes require further study. The purpose of this work is to statistically assess the recurrence of such phenomena.



F i g . 1 . A satellite image of clouding during the invasion of cold air on 9 February 2012 (http://rapidfire.sci.gsfc.nasa.gov/imagery/subsets/)

Data and methods of study

To assess the characteristics of the probability of cold air invasion into the Black Sea region atmosphere, ERA5 reanalysis data (spatial resolution 0.25° × 0.25°) on wind speed at 10 m height and heat fluxes at the sea surface were used [12], as well as Copernicus climate reanalysis data (resolution about 10 km) on water temperature and surface wind speed [1)].

When identifying cases of cold air mass invasion, the northerly wind direction with a wind speed of at least 5 m/s at a height of 10 m was taken as a defining feature. Wind directions from strictly north-westerly to strictly north-easterly, i. e. inclusive of all angles within the selected range of 90°, were considered to be northerly.

Data series of the winter period (January and February) with a time interval of 1 day at selected points separately in the north-west and north-east of the Black Sea region were studied. These two points were selected taking into account the characteristic features of the Black Sea meteorological regime during the winter period. The data at the north-western point describe the invasions of cold air, which is formed at the south-eastern periphery of the anticyclone with the centre north-west of the Crimea [13], into the atmosphere of the northern boundary of the sea. The second point was selected due to its relevance to the phenomenon of cold north-eastern air invasion, which has been identified as a factor responsible for the development of the Novorossiysk Bora [2]. The choice of two winter months is related to the more general objective of studying the mechanism of deep cooling of the Black Sea, which is maximally developed in the second half of the winter period of the year [9, 11].

Our choice of criteria for determining the invasion of cold air masses is certainly quite arbitrary. Concurrently, an initial examination of synoptic data indicates that the predominant cooling of the sea takes place at north-easterly winds.

Obtained results and discussion

To determine the frequency of northerly winds, wind speed series were examined at points on the Black Sea northern coast at coordinates (46.7° N; 31° E) and (44.9° N; 38° E). The data set encompasses the winter months (January and February) between the years 1940 and 2022 (83 years), with a time interval of 1 day. The series comprises 4918 values pertaining to wind speed components. At the western point, 1727 instances of northerly winds were identified, 685 of which exhibited wind speeds of at least 5 m/s, with a maximum speed of approximately 14.3 m/s and an average speed of approximately 6.5 m/s. At the eastern point, 1009 instances of northerly winds were identified, with 117 days exhibiting wind speeds of at least 5 m/s. The maximum recorded wind speed was 9.6 m/s, while the average speed was approximately 6.1 m/s.

The picture undergoes a notable transformation over the sea, where we examined the series of daily wind data for January and February over a 44-year period (1980–2023) at two sea points in the north-west (45.5° N; 31.5° E) and north-east (44° N; 37° E), situated in the almost central region of the sea. The series comprised

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[1)] E.U. Copernicus Marine Service Information: Global Ocean Physics Reanalysis. https://doi.org/10.48670/moi-00021

2607 values. At the western sea point, 870 instances of northerly winds were identified, of which 680 exhibited wind speeds of at least 5 m/s, with a maximum of 15.7 m/s and an average speed of 8.5 m/s. At the eastern point, 877 instances of northerly winds were identified, of which 623 exhibited wind speeds of at least 5 m/s, with a maximum of 19.4 m/s and an average speed of 8.4 m/s.

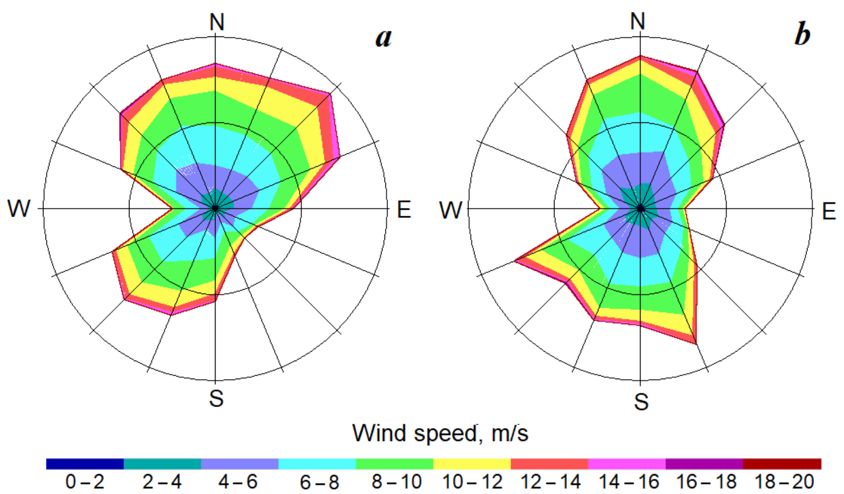
Fig. 2 shows wind roses constructed according to these wind data.

The wind roses display a notable discrepancy in their shapes. At the eastern point, there is a markedly higher prevalence of north-easterly winds, with speeds exceeding 6 m/s. Furthermore, both eastern and western points exhibit a minimal presence of westerly and easterly winds, with relatively weak winds constituting the predominant contribution. It should be noted that the distributions of surface wind speeds are considered, given that these are significantly dependent on the features of the atmospheric boundary layer, including orography and temperature contrasts between sea and land in coastal regions [14]. The discrepancy in the wind roses observed at two points over the sea situated approximately 600 km apart can be attributed primarily to the influence of boundary effects such as the impact of the elevated Crimean and Caucasus Mountains.

Generalized Extreme Value (GEV) distribution was used to assess important probabilistic characteristics such as return values and recurrence periods (i. e. values occurring once in a certain time period, the so-called recurrence period for a given return value)

$$F(x, \mu, \sigma, \xi) = e^{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi}},$$

where μ is position parameter; σ and ξ are scale and shape parameters, respectively.



F i g . 2 . Wind roses for offshore points in the west (*a*) and east (*b*)

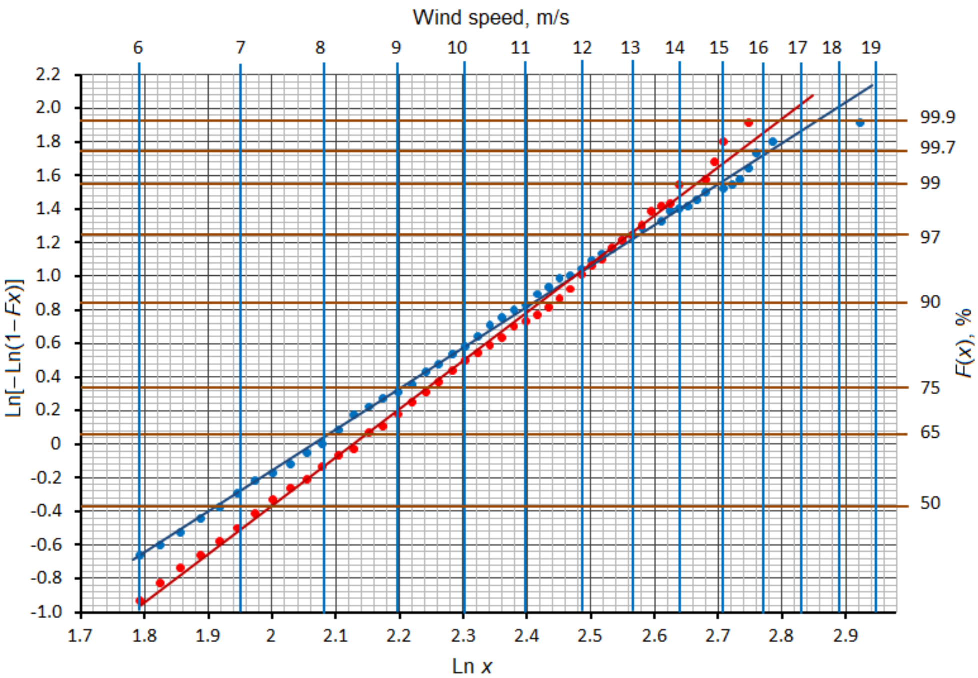
Return values and recurrence periods are related by the following relationship

$$F = (1 - 1/T(U)),$$

where F is probability density estimation (percentile) for the return value of estimated quantity U and its expectation time (recurrence period) T.

The GEV distribution enables the approximation of the so-called tails of the cumulative distribution functions for values exceeding a selected threshold value.

Fig. 3 shows cumulative distributions of northerly wind speed values at sea points in logarithmic coordinates from the threshold value of 6 m/s. The plots exhibit a slight elevation in wind speed probability within the range of approximately 12 m/s at the western point. Notably, the eastern point exhibited exceptionally high wind speeds, though the discrepancy was minimal. It is noteworthy that this eastern region of the sea is the location where strong wind phenomena, namely the Novorossiysk Bora, are observed during the winter season.



F i g . 3 . Cumulative distribution functions of wind speed values in logarithmic coordinates at offshore points in the north-west and north-east of the Black Sea. The blue dots are 44° N, 37° E; the red dots are 45.5° N, 31.5° E

Recurrence periods T (days) for the series of daily values of northerly wind speed at offshore points for January–February in 1980–2023

U, m/s	45.5° N, 31.5° E	44° N, 37° E
8	7.2	8.4
9	10.2	11.9
10	15.8	17.7
11	26.6	28.3
12	49.6	48.2
13	102.7	87.7
14	238	171
15	623	359

An important characteristic of wind speed anomaly is the recurrence period, which represents the expectation time for a particular extreme value. Approximations of this distributions allowed us to obtain estimates for the recurrence periods of high wind speeds. Estimates of the recurrence periods T for the return highest values of northerly wind speed at a height of 10 m U at these sea points are given in the Table.

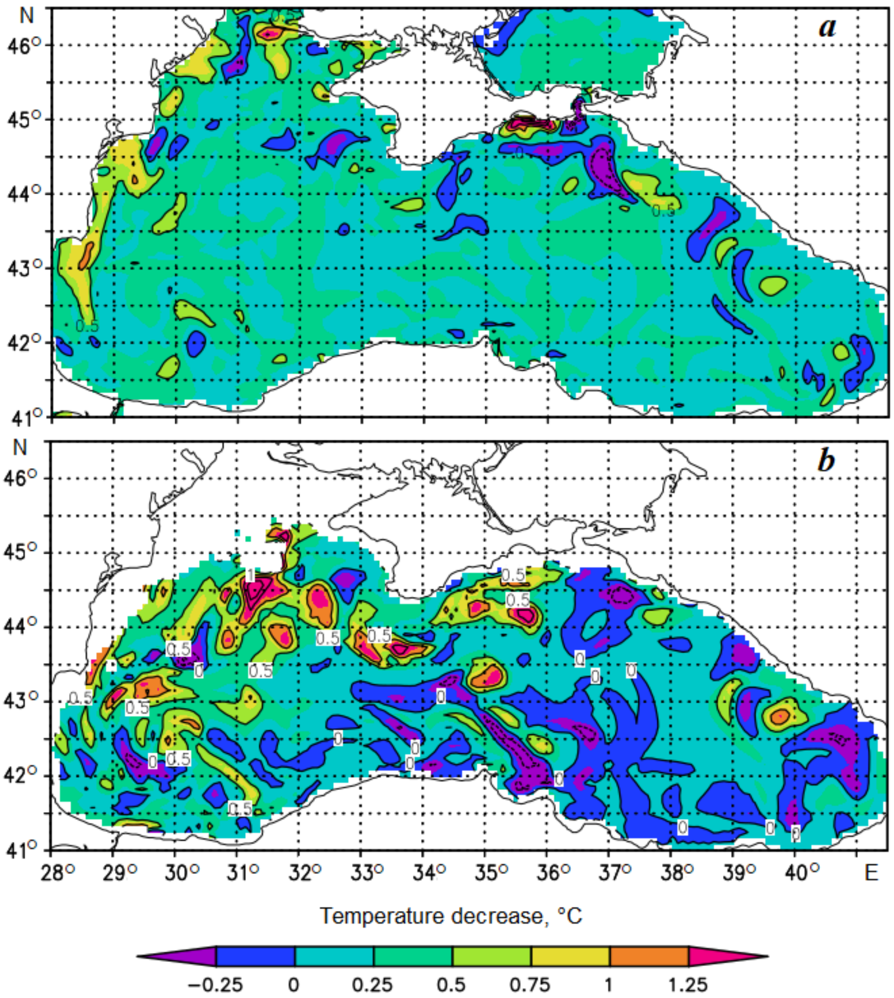
The results indicate that episodes of cold air invasion with speeds exceeding 8 m/s have an average recurrence period of approximately 8 days. It can be observed that higher wind speeds exhibit a longer recurrence period. Episodes of cold air invasion with speeds exceeding 14 m/s recur infrequently in the eastern part of the sea, with a recurrence period of approximately 5.5 months. This interval encompasses the winter periods of January and February. At the western point, the recurrence period is even less frequent, occurring once every 8 months (approximately once every 4 years).

A direct dependence of the sensible and latent heat fluxes from the sea surface on the northerly wind speed value was revealed, and a linear relation between them was obtained: $H = 37.9\,U$, where H is total heat flux; U is wind speed.

Given the rather high correlation between wind speed and total heat flux (approximation reliability R ~ 0.5), the main attention was paid to the response of sea temperature to wind speed perturbations.

Episodes of cold invasions, despite their short duration (usually not more than 2–3 days), have a noticeable impact on the temperature decrease in a sufficiently deep water layer. The case of the cold invasion on 8–9 February 2012 was selected according to the data of the Copernicus climate reanalysis using the above criteria.

As can be seen from Fig. 4, the temperature decrease spread in the upper layer up to 50 m depth. At the same time, the distribution of the sea surface temperature decrease is spatially much more homogeneous compared to the temperature decrease field at a depth of 50 m. Generally speaking, the physical mechanism of deep penetrating cooling in the winter period manifested in the inhomogeneities of the temperature field requires a separate consideration.



F i g . 4 . Decrease of the Black Sea water temperature at the surface (*a*) and at a depth of 50 m (*b*) during two days of the cold air invasion of 10 February 2012

Conclusion

The invasion of cold air across the northern, north-western and north-eastern boundaries of the Black Sea in winter, usually accompanied by increased wind speeds and decreased temperature values, can be classified as an extreme meteorological phenomenon that requires further investigation. The ERA5 reanalysis and Copernicus climate reanalysis data sets with increased spatial resolution were used for their study.

Two points were selected, situated in the eastern and western regions of the northern Black Sea basin, in close proximity to the centre. The distribution functions of extreme wind speed values were constructed for each location.

The recurrence periods of high wind speeds during the winter invasion of cold air from the north were estimated.

It is shown that the cases of invasions with significant increases in wind speed and decreases in air temperature are relatively rare events. However, they lead to a noticeable decrease in sea temperature from the surface down to depths of 40–50 m. As an example of a cold invasion case on 8–9 February 2012, data on changes in sea temperature at the surface and at a depth of 50 m for two-day period are presented.

A more detailed analysis of the physical mechanisms of the Black Sea response to episodes of cold air invasions, highlighted using the derived estimates, based on the WRF-NEMO coupled atmosphere-sea model is beyond the scope of this paper and will be presented later.

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Vladimir V. Efimov – problem statement, article text preparation

Olga I. Komarovskaya – calculations, preparation of graphic materials, text editing

All the authors have read and approved the final manuscript.