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Long–Period Trends in Water Temperature Changes in the Northern Part of the Atlantic Ocean according to the Ocean Reanalysis Data

P. A. Sukhonos[a],*, **V. V. Ivanov**[b], **and N. A. Diansky**[b,c,d]

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Abstract—The results of assessing long–term changes in water temperature in the northern part of the Atlantic Ocean (0°–70° N, 8°–80° W) according to the data of ocean reanalyses and objective analyses for the periods of 1961–2011 and 1980–2011 are presented. The obtained estimates are based on the use of a nonparametric method of regression analysis (quantile regression) for the monthly mean ocean temperature for a quantile value of 0.5. In 1961–2011 the warming was mainly recorded in the upper 400-m layer in the region from the equator to 70° N. Over this 51-year period, the increase in the median monthly ocean temperature was ~0.5°C on average in the analyzed water area, while in the Gulf Stream–North Atlantic Current system, it was ~1°C. During the period of 1980–2011, the warming in the northern part of the Atlantic Ocean occurred mainly in the upper 1-km layer at high latitudes (50°–65° N). Over this 32-year period, the median monthly mean ocean temperature increased in the subpolar gyre in the upper 400-m layer by ~1°C.

Keywords: temperature, ocean reanalysis, quantile regression, the northern part of the Atlantic Ocean

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INTRODUCTION

The increase in today's temperature of the World Ocean leads to the destabilization of the global climate system. Its major consequences include ice melting, ocean level rise, an increasing frequency of extreme weather events, etc. [1]. Model and in-situ assessments indicate that global warming and associated changes in key climate parameters will intensify in the future. The variability of the ocean state and its circulation play an important role in redistributing global thermal energy. However, this assertion has still ben insufficiently substantiated, especially at the quantitative level, due to a lack of data on characteristics in the deep ocean layers. Reliable reconstruction of long-period changes in the ocean temperature is hardly possible, since the observational data are highly inhomogeneous, especially in the deep layers. Therefore, to obtain a realistic pattern of the evolution of the World Ocean's temperature and its separate regions over an extended period is crucial for understanding the causes of changes in today's climate.

Given the growing concerns about the adverse consequences of climate change and the significant role of oceans in the accumulation of excess heat and the absorption of the primary greenhouse gas (CO_2) from the atmosphere, substantial efforts were made to study variations in the thermal state of the oceans [2]. In recent decades, heat has primarily been accumulating in the upper layers of the ocean (upper 700 m), although about 30% of the accumulated heat is found in the intermediate layers between 700 and 2000 m [3, 4]. The results of numerous studies showed that the recorded change in the World Ocean's temperature is characterized by long-period trends caused primarily by human activities and periodic and aperiodic variability resulted from natural factors that have not been fully studied. The estimates of the warming rate of the World Ocean over several decades range within 0.08–0.10°C/10 yr in the upper 300-m layer [5]. In this case, the rate of ocean temperature increase may vary significantly due to the different durations of the analyzed time series.

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[a] *Institute of Natural and Technical Systems, Sevastopol, 299011 Russia*
[b] *Moscow State University, Moscow, 119991 Russia*
[c] *Marchuk Institute of Numerical Mathematics, Moscow, 119333 Russia*
[d] *Zubov State Oceanographic Institute, Moscow, 119034 Russia*
**e-mail: pasukhonis@mail.ru*

The observed ocean warming occurs unevenly in time. The warming trend detected in the 0–2000 m layer in the northern part of the Atlantic Ocean (0°–80° N) is 0.031 ± 0.006°C/10 yr for the period of 1920–2002 (0.043 ± 0.011°C/10 yr for the period of 1950–2002) [6]. However, there were periods in the 20th century, when short-period trends intensified significantly due to multidecadal variability [7]. About 60% of the total warming since 1970 is accounted for by this variability in the northern part of the Atlantic Ocean. The trend caused by internal multidecadal variability in the ocean does not contribute to the formation of long-period trends but can make a significant contribution to short-period trends. The long-period trend of the ocean surface temperature (OST) averaged over the water area for the period of 1946–2008 is 0.090 ± 0.013°C/10 yr, while the trend for the period of 1977–2008 is 0.145 ± 0.029°C/10 yr [8].

The published assessments of climate trends in the temperature of the northern part of the Atlantic Ocean, which were obtained according to the data of various durations from different sources and are mostly confined to the ocean surface, have discrepancies and they are difficult to interpret. This leads to uncertainty in the structure and in the value of long-period changes in the ocean temperature. The aim of this study is to obtain a refined quantitative assessment of changes in water temperature in the northern part of the Atlantic Ocean based on several datasets over a long-period period. This study particularly focuses on the analysis of median trends. This seems expedient for time series with a non-stationary statistical structure, determined by the increase in the number of observations and by the overlapping of natural and anthropogenic processes in the second half of the 20th century. In this work, we use the term "long-period change in ocean temperature" without distinguishing between anthropogenic changes in ocean temperature and natural (more extended than multidecadal) variations in ocean temperature, which are not resolved by the datasets in use.

DATA AND METHODS OF PROCESSING

We employed monthly average ocean temperature data from the ocean objective analysis datasets, such as EN.4.2.2 (1945–2020) [9] and ISHII (1945–2012) [10], as well as ocean reanalysis datasets, including version 3S6m of GECCO3 (1948–2018) [11], ORAS4 (1958–2014) [12], GFDL (1961–2015) [13], ORA-S3 (1959–2011) [14], ORAS5 (1979–2018) [15], GODAS (1980–2021) [16], and version 3.12.2 of SODA (1980–2017) [17]. The study region is bounded by coordinates 0°–70° N, 8°–80° W.

The linear trend estimates of median values of this characteristic were used as a quantitative indicator of long-period changes in ocean temperature. Quantile regression is a procedure for estimating the parameters of regression (usually linear) for any quantile from 0 to 1 of the values of the dependent variable. The advantages of quantile regression analysis compared to other methods were discussed in [18, 19].

It is known that for random variable Y with probability distribution function $F(y) = Prob(Y \le y)$, the τth quantile is the inverse function $Q(\tau) = \inf\{y{:}F(y) \ge \tau\}$, where $0 < \tau < 1$. In particular, the median represents $Q(1/2)$.

The idea of using the quantile regression method for the linear model implies that for an arbitrary value of quantile $0 < \tau < 1$, we can introduce the concept of linear conditional function $Q(\tau | X = x) = x'\beta(\tau)$ for any value of $\tau \in (0, 1)$. This function was found by solving the optimization problem:

$$\beta(\tau) = \arg\min\left[\sum_{i:y_i \ge x_i'\beta} \tau|y_i - x_i'\beta| + \sum_{i:y_i < x_i'\beta} (1-\tau)|y_i - x_i'\beta|\right]. \qquad (1)$$

Here y_i and x_i' are the given values of the dependent and independent variables at the ith grid node, respectively.

We cannot calculate the value of $\beta(\tau)$, called the coefficient of linear quantile regression corresponding to some value of τ, analytically but can do that by the method of linear programming. In the special case at $\tau = 1/2$, minimizing of (1) reduces to finding β, which is the solution of the optimization problem $\beta(1/2) = \arg\min \sum_{i=1}^{n} |y_i - x_i'\beta|$, i.e., the sum of absolute deviations is minimized, which corresponds to regression based on the median absolute deviations.

The standard errors of quantile regression coefficients were determined by the bootstrap method [18], which can be the basis for obtaining the most realistic estimates of significance of linear trends [20]. Using the method of random tests, 1000 subsamples were generated, each representing a time series that did not have randomly excluded values (~30% of values were excluded from the time series) compared to the initial time series. Trends were calculated for each sample using the quantile regression method for quantile $\tau = 1/2$. The significance of the trend coefficients was assessed at a confidence level of $\alpha = 0.05$. We presented only statistically significant results.

The calculations were conducted for each dataset at each grid node at all depths from the surface to the bottom for the time intervals of 1961–2011 and 1980–2011. The first interval is a common period for most of the datasets. The second interval was chosen because it was since about 1980 when a rapid increase in global OST was observed, which was determined by the coincidence of an anthropogenic trend and natural multidecadal variability. Then, the coefficients of linear trends in ocean temperature were averaged zonally and in the layer of 10–400 m. The lower boundary of this layer was chosen by the results of the analysis of average zonal trends.

RESULTS AND CONCLUSIONS

The average zonal trends in the temperature of the northern part of the Atlantic Ocean are mostly positive over the period of 1961–2011 in the upper 400 m layer from the equator to 70° N. The quantile trend coefficients exceed 0.1°C/10 yr. Two areas of the highest warming are remarkable. One area is located in the Tropical Atlantic (0°–10° N) at a depth of about 100 m, with the quantile trend coefficients exceeding 0.25°C/10 yr. This area is weakly expressed in ISHII and GFDL. Another area is situated around 40° N in the layer of 10–200 m, with the quantile trend coefficients exceeding 0.2°C/10 yr. According to GECCO3, ORAS4, and ORA-S3, the average zonal quantile trends of ocean temperature are negative in several areas (with coefficients less than –0.1°C/10 yr). However, since these areas are recorded for only a half of the analyzed datasets and are located in different areas, a common pattern of ocean cooling cannot be identified.

In 1961–2011, long-period trends in the temperature changes of the northern part of the Atlantic Ocean in the layer of 10–400 m demonstrate positive coefficients of the quantile trend (exceeding 0.1°C/10 yr) almost throughout the entire basin (Fig. 1). The spatial distribution of areas with high coefficients of quantile trends varies slightly. In the vicinity of the Equatorial Counter Current and the Caribbean Current, all datasets show positive coefficients of quantile trends (>0.1°C/10 yr). In the vicinity of the Equatorial Counter Current, GECCO3, ORAS4, and ORA-S3 indicate coefficients exceeding 0.2°C/10 yr. Around the Caribbean Current, according to ORAS4, the coefficients exceed 0.2°C/10 yr, while according to GFDL, they are greater than 0.5°C/10 yr. Positive coefficients of the quantile trend >0.2°C/10 yr were recorded in the region of Canary Upwelling for all datasets, except ORAS4 and ISHII. According to ORAS4, the temperature increase is insignificant, while according to ISHII, the coefficients of the quantile trend are positive but <0.2°C/10 yr. In the Tropical Atlantic, the quantile trend showed significant negative coefficients (less than –0.1°C/10 yr) at 10° N only according to GFDL. In the Gulf Stream–North Atlantic Current system, all datasets in use indicate the warming in the layer of 10–400 m (with coefficients >0.2°C/10 yr). According to the data of all ocean reanalyses (but not ocean objective analyses), this region contains the segments where the coefficients of the quantile trend exceed 0.5°C/10 yr. However, the locations of these segments are different. The most contradictory estimates of the quantile trend coefficients appeared for the subpolar gyre. Overall, almost all datasets show small regions of cooling (with coefficients <–0.1°C/10 yr), but their locations are different. According to GFDL and ORA-S3, these regions are found at around 50° N, 30° W, while, according to other datasets, they occur southeastward. In the East Greenland Current, the long-period trends in ocean temperature changes are statistically significant in the layer of 10–400 m (the median trend coefficients exceed 0.1°C/10 yr in absolute magnitude) according to GECCO3 and ORAS4, but they are oppositely directed.

Average zonal trends in the temperature of the northern part of the Atlantic Ocean were mostly positive in 1980–2011. A common region of warming was identified for all datasets with the quantile trend coefficients greater than 0.3°C/10 yr in the upper 400 m layer in the latitudinal band of 50°–65° N. The thickness of the layer with the quantile trend coefficients exceeding 0.2°C/10 yr increases from the equator to 65° N. Exceptions are the average zonal trends according to GECCO3 and GODAS at 40° N, where near-zero coefficients of median trends were obtained. All reanalysis datasets, except for GFDL, presented the regions with negative average zonal ocean temperature trends (less than –0.1°C/10 yr). In the Tropical Atlantic (0°–25° N), a common region of cooling for most of the datasets appeared in the 100–150 m layer during the study period.

Over the period of 1980–2011, the temperature time series of water in the northern part of the Atlantic Ocean in the layer of 10–400 m demonstrate positive median trend coefficients (exceeding 0.2°C/10 yr) north of 30° N (Fig. 2). Exceptions are the central (according to ORAS5) and western (according to GODAS) segments of the subpolar gyre. In Fig. 2, the area of cooling is not visible in the 100–150 m layer in the Tropical Atlantic as the trend coefficients were averaged in a thick layer. It remains visible only according to GODAS and SODA3 data. The positive median trend coefficients in the 10–400 m layer in the Caribbean Current were detected by ORAS5 and GFDL. The warming in this current with intensity greater than 0.6°C/10 yr was recorded only by GFDL.

In the Gulf Stream–North Atlantic Current system, the values of median trend coefficients of ocean temperature significantly varied in 1980–2011 in the datasets. For example, EN4 did not show significant median trend coefficients in this region. South of 40° N, significant median trend coefficients were not detected according to GECCO3, ISHII, ORAS4, GFDL, ORA-S3, and ORAS5. However, GODAS recorded a region with high positive median trend coefficients (exceeding 1°C/10 yr) at these latitudes, while SODA3 revealed a region with high negative median trend coefficients (less than –0.4°C/10 yr). North of 40° N, the median trend coefficients of ocean temperature were negative with the values less than –0.4°C/10 yr according to GECCO3, but they

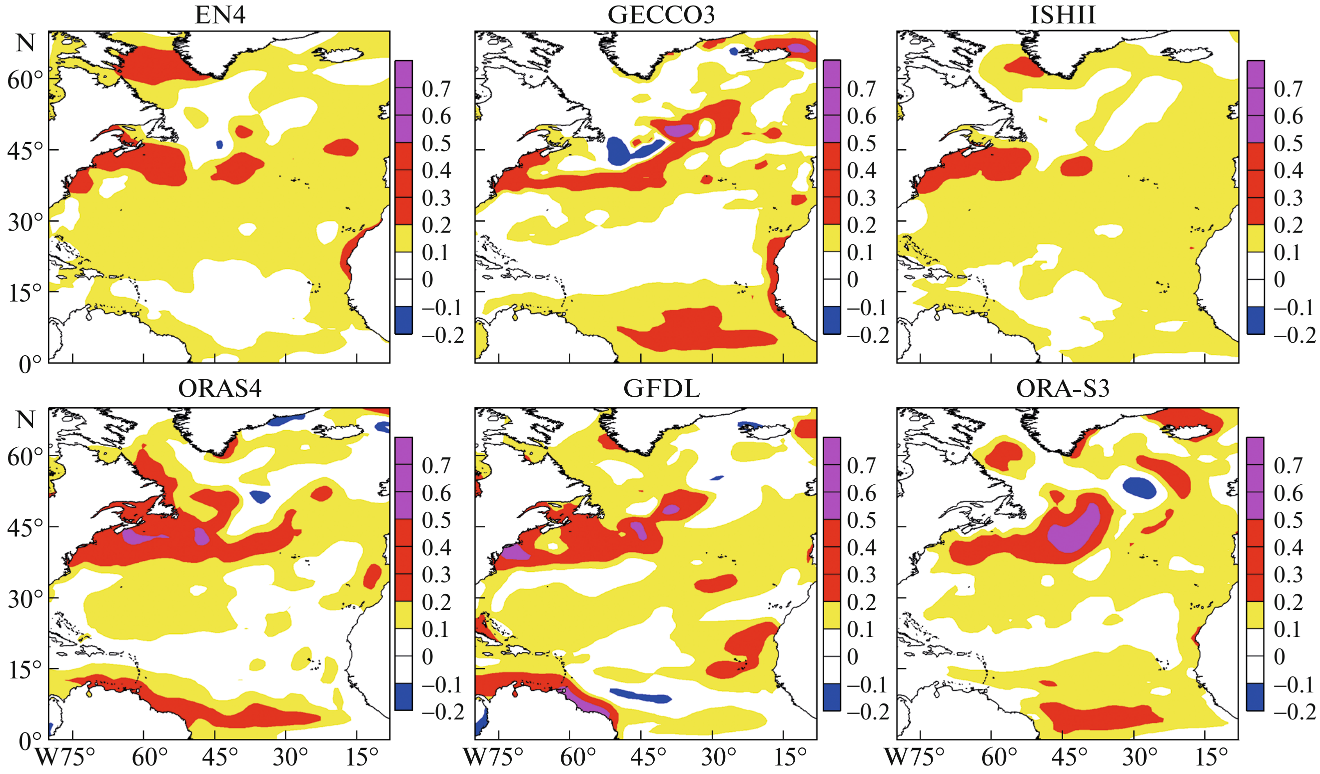

Fig. 1. Median trend coefficients of water temperature in the northern part of the Atlantic Ocean (°C/10 yr) for the period of 1961–2011, averaged in the 10–400 m layer.

were small and positive according to ISHII, ORAS4, GFDL, and ORA-S3. In this region, ORAS5 and SODA3 showed small alternating domains of positive and negative median trend coefficients of ocean temperature. However, according to GODAS, north of 40° N there is an area with high negative median trend coefficients of ocean temperature (less than –0.4°C/10 yr). Therefore, we cannot unambiguously determine the character of the ocean temperature trends in the Gulf Stream–North Atlantic Current system during the study period.

In the East Greenland Current, long-period trends in ocean temperature changes in the 10–400 m layer were significant and positive according to EN4, GECCO3, ISHII, GFDL, ORAS5, and SODA3. The median trend coefficients of the ocean temperature have values exceeding 0.6°C/10 yr according to GECCO3 and GFDL. However, ORA-S3 and ORAS4 mark significant negative median trend coefficients with values less than –0.4°C/10 yr in this current.

During the period of 1980–2011, the highest median trend coefficients (exceeding 1°C/10 yr) were found in all ocean reanalysis data, except SODA3. However, the regions with such median trend coefficients in different datasets were located in different places, which does not allow us to identify a universal pattern.

Thus, in 1961–2011, the warming in the northern part of the Atlantic Ocean was mainly observed in the upper 400 m layer from the equator to 70° N. During this period, the median monthly average ocean temperature increased by 0.5°C on average across the water area and in the vicinity of the Equatorial Counter Current, the Caribbean Current, and the Canary Upwelling, while in the Gulf Stream–North Atlantic Current system, it increased by more than 1°C. The quantile trend coefficients of the ocean temperature were higher on average in the reanalysis datasets than in the objective analyses. In 1980–2011, the intense warming in the northern part of the Atlantic Ocean primarily occurred in the upper 400-m layer at high latitudes (50°–65° N). During this period, the median monthly mean ocean temperature increased by 1°C in the subpolar gyre. The Gulf Stream–North Atlantic Current system showed significant variations in the values of median trend coefficients of the ocean temperature. Therefore, we cannot unambiguously determine the character of the ocean temperature trends in this region during the study period. The data of all ocean reanalyses, except SODA3, showed the regions where the warming was the most, almost 3°C in 1980–2011. However, they were located in the different datasets in the different places, which does not allow us to establish a common pattern.

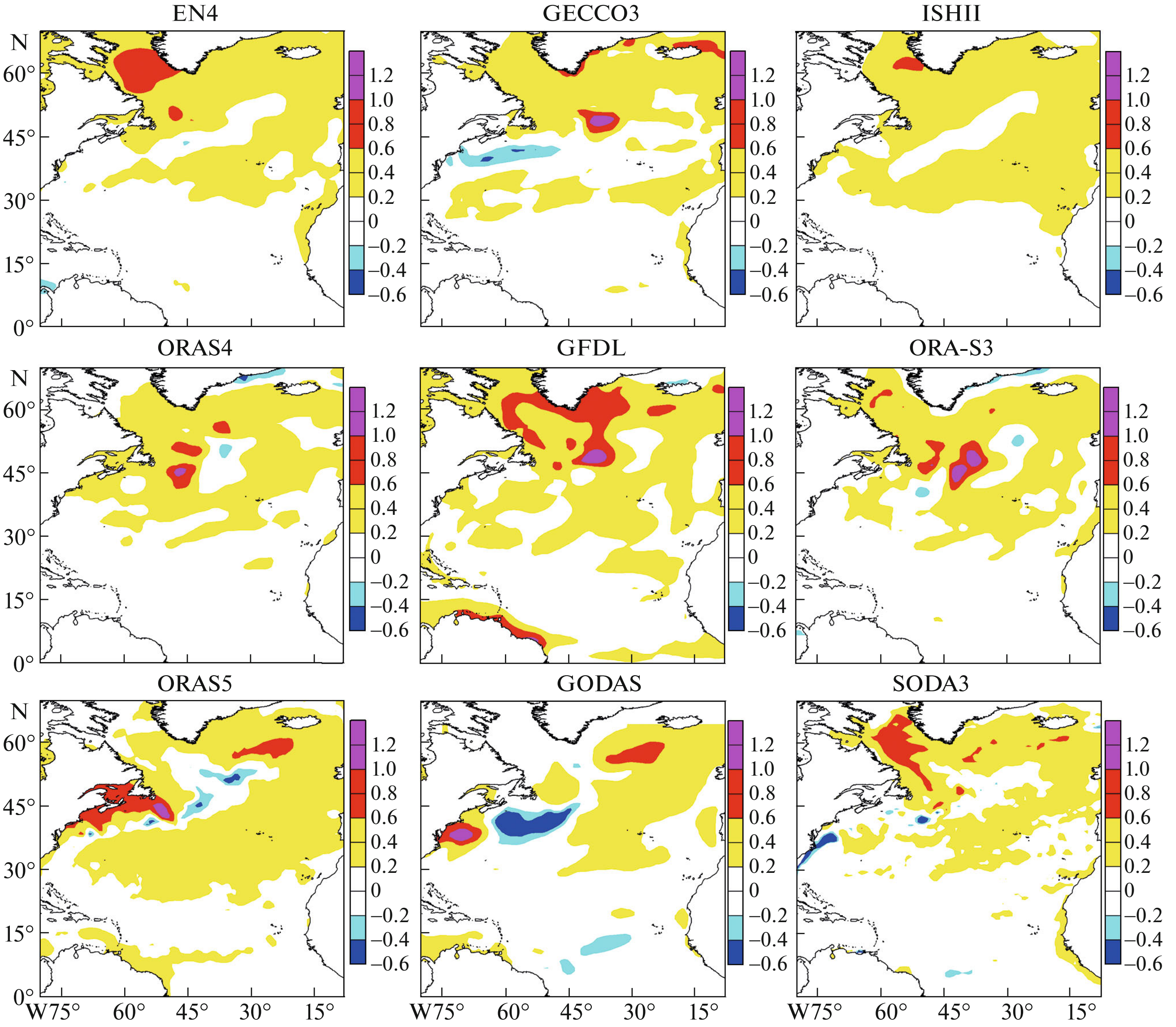

Fig. 2. Median trend coefficients of water temperature in the northern part of the Atlantic Ocean (°C/10 yr) for the period of 1980–2011, averaged in the 10–400 m layer.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

REFERENCES

1. S. A. Dobrolyubov, Partnerstvo Tsivilizatsii, nos. 1–2, 174–178 (2020).
2. Core Writing Team, in *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the 6th Assessment Report of the Intergovernmental Panel on Climate Change,* Ed. by H. Lee and J. Romero (IPCC, Geneva, 2023), pp. 1–34
3. S. Levitus, J. I. Antonov, T. P. Boyer, et al., Geophys. Res. Lett. **39** (10) (2012).
4. V. A. Bagatinsky and N. A. Diansky, Moscow Univ. Sci. Bull. **77** (3), 564 (2022).
5. J. M. Lyman and G. C. Johnson, J. Clim. **27** (5), 1945–1957 (2014).
6. I. V. Polyakov, V. A. Alexeev, U. S. Bhatt, et al., Clim. Dyn. **34**, 439–457 (2010).

7. S. K. Gulev, M. Latif, N. Keenlyside, et al., Nature **499** (7459), 464–467 (2013).
8. T. De Sole, M. K. Tippett, and J. Shukla, J. Clim. **24** (3), 909–926 (2011).
9. S. A. Good, M. J. Martin, and N. A. Rayner, J. Geophys. Res.: Oceans **118** (12), 6704–6716 (2013).
10. M. Ishii, M. Kimoto, and M. Kachi, Mon. Weather Rev. **131** (1), 51–73 (2003).
11. A. Köhl, Quart. J. R. Meteorol. Soc. **146** (730), 2250–2273 (2020).
12. M. A. Balmaseda, K. Mogensen, and A. T. Weaver, Quart. J. R. Meteorol. Soc. **139** (674), 1132–1161 (2013).
13. Y.-S. Chang, S. Zhang, A. Rosati, et al., Clim. Dyn. **40** (3–4), 775–803 (2013).
14. M. A. Balmaseda, A. Vidard, and D. L. T. Anderson, Mon. Weather Rev. **136** (8), 3018–3034 (2008).
15. H. Zuo, M. A. Balmaseda, S. Tietsche, et al., Ocean Sci. **15** (3), 779–808 (2019).
16. D. W. Behringer and Y. Xue, in *Proc. 8th Symp. on Integrated Observing and Assimilation Systems for Atmosphere, Ocean, and Land Surface* (Am. Meteorol. Soc. Seattle, WA, 2004). http://ams.confex.com/ams/pdfpapers/70720.pdf.
17. J. A. Carton, G. A. Chepurin, and L. Chen, J. Clim. **31** (17), 6967–6983 (2018).
18. R. Koenker, *Quantile Regression* (Cambridge, 2005).
19. A. A. Timofeev and A. M. Sterin, Russ. Meteorol. Hydrol. **35** (5), 310–320 (2010).
20. D. B. Kiktev and V. N. Kryzhov, Meteorol. Gidrol., No. 11, 27–38 (2004).

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