Use of statistical models to predict how different regions of the Arctic and the Northern Hemisphere will reach an ice-free regime

V Malinin¹, A Averkiev¹, V Tsarev², E Istomin³ and Y Petrov³

¹UNESCO-IOC Department of Applied Oceanography and Integrated Coastal Zone Management, Russian State Hydrometeorological University, 79, Voronezhskaya Street, St. Petersburg, 192007, Russian Federation
²Department of Oceanology, Russian State Hydrometeorological University, 79, Voronezhskaya Street, St. Petersburg, 192007, Russian Federation
³Department of Applied computer science, Russian State Hydrometeorological University, 79, Voronezhskaya Street, St. Petersburg 192007, Russian Federation

E-mail: malinin@rshu.ru

Abstract. Estimates of reaching an ice-free regime in September for different regions of the Arctic and the Northern Hemisphere are presented on the basis of an additive statistical model that takes into account trends and cyclical fluctuations for the period 1979-2017, assuming that the current climate regime will be maintained in the future. It is shown that, due to the rather high stability of the trend estimates for the sea ice area in the Arctic regions, taking into account cyclical fluctuations does not go beyond the rms trend errors.

1. Introduction

Due to the accelerated rise in temperature rise in the Arctic compared to global temperature, the area of sea ice is rapidly decreasing. It is possible that the area of modern ice cover in the Arctic is the minimum for the last about 1500 years [1]. From the point of view of sustainable development of the territory, including the development of gigantic natural resources and the extension of navigation along the Northern Sea Route, long-term forecasts of the main elements of the climatic regime - air temperature and characteristics of sea ice - are needed. The forecast of the complete clearing of sea ice seems to be especially relevant. Obviously, this will happen in September, when the area of sea ice reaches the smallest size in the annual course.

However, forecasting the characteristics of sea ice for the long term, including until the end of the century, is extremely difficult due to insufficient understanding of the genesis of the formation and variability of natural processes in the Arctic. At present, hydrodynamic models of the general circulation of the atmosphere and ocean are widely used, with the help of which estimates of various characteristics of the global climate up to 2100 are calculated. Unfortunately, the errors of such forecasts are very large. For example, the possible error for the global near-surface air temperature in 2100 when comparing different models can reach 4.5 °C [2]. Even more significant errors due to the specificity of the natural conditions of the Arctic are inherent in the characteristics of its climate. So, according to the ensemble of models of the CMIP5 project, the spread of predicted estimates of the
disappearance of sea ice in the summer period is $\pm 75$ years [3]. Naturally, for practical purposes, such a forecast can hardly be of value.

Obviously, in addition to climate models, it is necessary to develop alternative methods for long-term forecasting of ice coverage, which can be statistical methods. For example, if linear (nonlinear) trends describe a significant part of the variance of the initial series, then taking the condition of climate stationarity, one can calculate long-term changes in hydrometeorological parameters for any year ahead [4].

The purpose of this work is to predict how the September ice coverage of different regions of the Arctic and the Northern Hemisphere as a whole reaches the ice-free regime based on a simple statistical model.

2. Methods and Materials

The main source of information on sea ice in the polar regions is satellite microwave radiometry data. In this work, a NASA product using the NASA Team (NT) algorithm was used to estimate the sea ice area. This algorithm, which is described in [5-6], is widely used in numerical calculations. Sea Ice Area (SIA) data are freely available on the NASA website for nine different regions of the North Polar Region (NPR) and five sectors of the South Polar Region (SPR) from October 1978 to 2017.

We represent interannual changes in the time series in the form of the following additive model:

$$X(t) = Tr(t) + C(t) + P(t)$$  (1)

Where $Tr(t)$ – trend component; $C(t)$ - cyclic component characterizing regular (cyclical) interannual fluctuations; $P(t)$ is the residual part characterizing irregular (random) interannual fluctuations. Obviously, from the point of view of the forecast, it is necessary to take into account the sum of the trend and cyclical components, which represents the deterministic part of the expansion (1), i.e. that part of the variance of the original series $X(t)$, which lends itself to interpretation and is strictly described by statistical methods.

At the first stage, the calculation of linear and nonlinear trends in the September ice coverage in 8 regions of the Arctic and the entire northern hemisphere was carried out. Pronounced negative trends in SIA are present in all regions of the Arctic. In terms of magnitude, the most intense trends are noted for the Bering, Barents and Kara Seas, and in terms of the contribution of trends to the variance of the initial time series ($R^2$), the highest estimates are characteristic of the Arctic Basin and the Bering Sea ($R^2 = 0.72$). The weakest SIA trends are in the Greenland Sea and in the Canadian Arctic Archipelago.

Knowing the trend equation, it is easy to calculate the date of the ice-free regime of a given Arctic sea. For example, for the SIA of the Barents and Kara Seas ($A_{BK}$) in September for the period 1979-2017, we have $A_{BK} = a_0 + a_1 t = 0.432 - 0.009t$. From this it is easy to get that the exit to the ice-free regime will occur in 2026.

3. Results and Discussion

Table 1 shows the years of reaching the ice-free regime for different regions. The biggest uncertainty in such forecasting is the error due to the instability of the trend over time. This is due to the fact that the trend can change its intensity and even shape when the row length changes. Therefore, to test the degree of stability of the linear trend, the following experiment was performed. As the initial period, the time interval 1979–2010 was taken, for which the linear trend of SIA was calculated for all regions. Then, adding one year each time, the trends are calculated up to 2017. As a result, we get a set of 8 trends, from which its maximum and minimum estimates are selected. For example, if for the SIA of the Northern Hemisphere, the maximum trend was noted for the period 1979-2012 ($a_1 = -0.890$), then the minimum trend ($a_1 = -0.815$) was for 1979-2011, and the difference between them was only 9%. For the maximum and minimum trends, the dates of complete clearance of sea ice from the Arctic waters were also calculated (table 1).
Table 1. Estimates of reaching the initial year of ice-free ice coverage in different regions of the Northern Hemisphere based on the approximation of linear and nonlinear trends.

| Water surface          | Linear trend 1979-2017 | By the minimum trend  | By the maximum trend | Non-linear trend |
|------------------------|------------------------|-----------------------|----------------------|------------------|
| Barents, Kara seas     | 2032                   | 2026                  | 2024                 | 2018             |
| Bering Sea             | 2027                   | 2022                  | 2019                 | 2027             |
| Canadian archipelago   | 2094                   | 2107                  | 2114                 | 2060             |
| Labrador Sea, Baffin Bay| 2064                   | 2062                  | 2053                 | 2050             |
| Greenland sea          | 2089                   | 2080                  | 2070                 | 2046             |
| Hudson bay             | 2032                   | 2029                  | 2019                 | ----             |
| Arctic basin           | 2088                   | 2076                  | 2073                 | 2042             |
| North hemisphere       | 2081                   | 2074                  | 2066                 | 2040             |

As you can see from the table, reaching the ice-free regime of the northern hemisphere according to the maximum trend should be in 2066, and according to the minimum - in 2081, i.e. the discrepancy is only 15 years. Since the maximum discrepancy in the estimates of reaching zero is only 20 years (Canadian Arctic Archipelago), it can be confidently asserted that the linear trends in the Arctic SIA are stable in the period under consideration. As expected, the arrival of the ice-free regime in the Arctic waters along the nonlinear trend (table 1) occurs earlier.

At the second stage, the cyclic component in the expansion (1) is taken into account by calculating the significant harmonics of the time series by the method of spectral analysis or Fourier expansion. Then they are added to the trend component and the new time series (deterministic component) is extrapolated to the zero crossing of the abscissa. Obviously, it is impossible to predict a random component, especially for a long term. Therefore, one should expect the larger the contribution $\text{Tr}(t) + C(t)$ into dispersion $X(t)$, the more accurate the SIA forecast should be. However, for some regions, the role of random fluctuations in SIA is significant.

Let us turn to the results of the forecast of the transition to the ice-free regime of the Greenland and Barents seas with the Kara, for which the trend determination coefficient in September is small and amounts to 0.18 and 0.37, respectively. As a result of calculations, it was found that there are 4 reliable harmonics in the variability of the PML of the Kara and Barents Seas (3.2; 4.7; 6.3 and 9.5 years), the total contribution of which to the variance of the time series is 33.3% (table 2). The maximum contribution (9.4%) is made by harmonics with a period of 9.5 and 4.7 years. Taking into account the 3.2 year harmonic in the forecast is impractical due to its small amplitude and short period. Assuming the constancy of the first three harmonics in time, the $\text{Tr}(t) + C(t)$ components of the PML time series of the Kara and Barents Seas were extrapolated (Fig. 1). As seen from Fig. 1, the transition to ice-free mode occurs in 2021, that is, the deviation from the trend is five years and, in fact, does not go beyond the trend error.

As for the Greenland Sea, as expected, the fundamental harmonics play a significant role in its interannual SIA variability in September, describing about 50% of the variance of the time series (table 2). At the same time, the largest harmonic (4.7 years) is only slightly inferior to the trend in its contribution. For the SIA of the Greenland Sea, the extrapolation of the $\text{Tr}(t) + C(t)$ components reaching the ice-free regime was also performed. At the same time, it was revealed that taking into account short-period harmonics (5.4 and 4.7 years) can be ignored without compromising the forecast accuracy. Therefore, in the final calculations, only “long-period” harmonics (9.5 and 12.7 years) were used. Taking into account these harmonics, it was found that the complete clearing of ice in September in the Greenland Sea should be noted in 2075 (figure 2). Hence it follows that the discrepancy with the results of the trend method is only 5 years.
Table 2. Estimates of the contribution to the variance of the time series of the September harmonic values and the trend for the SIE of the Barents and Kara Seas and the Greenland Seas for the period 1980-2017.

| Barents and Kara seas, September | Greenland Sea, September |  
| Harmonic period, years | Contribution to the variance of the series, % | Harmonic period, years | Contribution to the variance of the series, % |
|-----------------------------|--------------------------|-------------------------|
| 9.50                        | 9.4                      | 12.67                   | 9.7                      |
| 6.33                        | 7.3                      | 9.50                    | 9.0                      |
| 4.75                        | 9.4                      | 5.43                    | 16.2                     |
| 3.17                        | 7.2                      | 4.75                    | 13.0                     |
| Trend                       | 37.3                     | …                       | 18.4                     |
| Total                       | 70.6                     | …                       | 66.3                     |

Figure 1. Results of extrapolation of the September SIE in the Barents and Kara Seas. 1 - actual values of SIE, 2 - calculated values of SIE (trend plus harmonics 9.5; 6.3 and 4.7 years), 3 - trend line.

Figure 2. Results of extrapolation of the September SIE for the Greenland Sea. 1 - actual values of SIE, 2 - calculated values of SIE (trend plus harmonics of 12.7 and 9.5 years), 3 - trend line.
4. Conclusion
In conclusion, we emphasize that predictive estimates of SIA were obtained under the assumption that the present climate regime will be preserved in the future. If warming in the Arctic continues at a faster pace, then the Arctic water area reaching an ice-free regime in September may accelerate.

5. References
[1] Kinnard C, Zdanowicz C M, Fisher D A, Isaksson E, Vernal de A and Thompson L G 2011 Reconstructed changes in Arctic sea ice over the past 1,450 years. Nature 479 509–512
[2] Stocker T F, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V and Midgley P 2013 The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press) 1535
[3] Semenov V A, Martin T, Berens L K, Latif M and Astaf’eva E S 2017 Changes in the area of Arctic sea ice in the ensembles of climate models STIP3 and STIP5. Lyod and Sneg. 57(1) 77-107
[4] Malinin V N and Vajnovskij P A 2019 When will the ice-free regime of the Arctic regions come? Study Notes of the Russian State Hydrometeorological University 56 98-109
[5] Cavalieri D J, Parkinson C L, Gloersen P, Comiso J C and Zwally H J 1999 Deriving long-term time series of sea ice cover from satellite passive-microwave multisensor data sets. J. Geophys. Res 104(15) 803-15
[6] Cavalieri D J, Parkinson C L, DiGirolamo N and Ivanoff A 2012 Intersensor calibration between F13 SSMI and F17 SSMIS for global sea ice data records. IEEE Geosci. Remote Sens. Lett. 9 233–236
[7] Flaksman A S, Kokurin D I, Khodzhaev D K, Ekaterinovskaya M A, Orusova O V and Vlasov A V 2020 Assessment of prospects and directions of digital transformation of oil and gas companies. IOP Conference Series: Materials Science and Engineering 976 012036
[8] Gubanov M M, Morkovkin D E, Begmurodzoda E, Sharipov F F and Romanova J A 2020 Differentiation of power supply systems for consumers in the Arctic zone. IOP Conference Series: Materials Science and Engineering 837(1) 012011
[9] Gubanov M M, Potemkin V V, Shmanev S V and Morkovkin D E 2020 Raising funds for the development of distributed generation in the Far East and the Arctic. IOP Conference Series: Materials Science and Engineering 976(1) 012039