ISSN 1075-7007, Studies on Russian Economic Development, 2023, Vol. 34, No. 6, pp. 738–745. © Pleiades Publishing, Ltd., 2023.
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CRITICAL INNOVATION PROJECT OF NATIONAL SIGNIFICANCE ON CLIMATE

Global Climate Change and the Oceans[1]

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Received June 15, 2023; revised June 29, 2023; accepted July 5, 2023

Abstract—The article analyzes the role of the ocean in climate change. The effects associated with the accumulation of anthropogenic heat by the ocean, as well as the formation of the ocean's own changes on a scale of decades, are discussed. The flows of climatically active gases between the ocean and the atmosphere are considered. It is shown that, being the most conservative component of the climate system, the World Ocean absorbs ~92% of excess heat entering the system as a result of anthropogenic activity. This determines approximately 50–60% of the contribution to the rise in the level of the World Ocean due to the steric factor. It is also substantiated that the ocean is the only component of the climate system that has internal (intrinsic) variability modes with long (from a decade to several decades) time scales. These modes of variability (for example, the Atlantic Multidecadal Oscillation) form responses in the atmosphere (during the processes of interaction at the ocean–atmosphere interface), whose superposition with global trends significantly reduces the accuracy of climate forecasts. Finally, it is shown that the oceans and seas are the most powerful net absorbers of climatically active gases, primarily CO_2. With the warming of the climate (and the simultaneous warming of the ocean and seas), the role of the ocean as a CO_2 sink is slowly weakening. Moreover, with an increase in storm activity in the oceans and seas, this role also weakens, since storm activity leads to an increase in emissions. Thus, global and regional balances of greenhouse gases cannot be reliably estimated without taking into account the role of the ocean.

Keywords: World Ocean, climate change, heat balance, sea level rise, greenhouse gas fluxes, monitoring system

DOI: 10.1134/S1075700723060060

Observed climate change. The climate changes observed today on Earth are unprecedented in terms of the intensity and speed of changes in key climatic parameters, primarily surface temperature. This conclusion is based on the conclusions of all assessment reports of the Intergovernmental Panel on Climate Change (IPCC), including the latest, sixth assessment report, released in 2021. The 2011–2020 decade was the warmest decade on record. Moreover, since the 1980s, each subsequent decade has been warmer than any previous one since 1850. Global surface temperature in 2011–2020 was 1.1°C higher than in 1850–1900, with warming over land (1.59°C) significantly greater than over oceans (0.88°C). Average rate of global warming during 1976–2020 amounted to 0.18°C/10 years on a global scale, and during this period alone, the global temperature increased by 0.8°C. It is important that the temperature increased especially rapidly in the Northern Polar Region, where, according to Roshydromet estimates, the linear increase in the average annual temperature over 30 years (1991–2020) was about 2.64°C with trends reaching more than 0.7°C in decade [1].

This heterogeneity of global warming has critical implications for the territory of Russia, where the increase in surface temperature significantly exceeds the global trend. According to the third Assessment Report on climate change and its consequences on the territory of the Russian Federation, released by Roshydromet in 2022, the territory of Russia is warming almost twice as fast as the land as a whole: 0.51°C per decade, and every decade from 1981–1990 warmer than the previous one, and of the ten warmest years, nine were observed in the 21st century.

Observed global climate change is also characterized by an increase in the atmospheric moisture content, an increase in the surface temperature of the ocean and its heat content, an increase in the global sea level (more than 3 mm per year over the past 30 years), as well as the melting of glaciers and a decrease in the area of sea ice (by about 40% in the Arctic) over the last 40 years. These climate changes are regarded by the climatological community as unprecedented, as

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[1] The main data obtained by the author and his colleagues as part of the implementation of the Most Important Innovative Project of National Significance and summarized in this article are used by specialists from the Institute of Economic Forecasting of the Russian Academy of Sciences and their colleagues in the Climate Economics consortium (see articles by M.G. Reshetnikov and A.A. Shirov in the same issue of the journal) in model calculations when constructing scenarios of socio-economic development to select its most sustainable trajectory for the long term.

such changes have never occurred so rapidly [1]. During the geological history of the Earth, there were periods when the temperature was, for example, 14°C higher than today (for example, the extreme of the early Eocene about 60 Ma ago), but the changes that occured took tens and hundreds of thousands of years.

The observed changes happen inhomogeneously on the Earth's surface. Air temperature increase trends are stronger in subpolar and polar latitudes than in the tropics (by about two to four times). The strongest increases in ocean temperature occur in the western tropical Pacific and eastern tropical Indian Ocean. The sea level also rises unevenly, with maximum trends in the tropics and polar latitudes and smaller values in the central Atlantic. In this sense, climate change in Russia is characterized by an average temperature trend of 1.3°C over the last century, with maximum changes observed in the northern subarctic regions and in the European part of the Russian Federation, and can exceed 2°C per century. It is important to note that in the last few decades, climate change trends have increased significantly – this applies to both global and regional changes. Thus, the temperature increase in Russia over the past four decades in some subarctic regions is up to 3.5°C in the winter season. In general, the intensification (or acceleration, amplification) of climate change is most pronounced in the Arctic region. In addition, long-term changes occur against the background of fairly strong interannual variability, which can be comparable in magnitude to long-term trends on the same time scale. Thus, interannual changes in the global average temperature can be several tenths of a degree, and interannual variations in the area of ice in the Arctic can be up to 10% with a long-term trend of 30%.

Therefore, climate change cannot be judged on the basis of short-term changes, both positive and negative. Equally, one cannot judge (or question) climate change based on consideration of changes in individual regions, since regional changes are associated with global ones. At the same time, regional changes are subjected to the most thorough analysis, since they affect the infrastructure, production activities, health and living conditions of the population.

The role of the ocean in global long-term climate change. Considering the role of the ocean in the global change in the state of the climate system, it should be noted that the key factor is the much greater conservatism of the ocean in relation to the atmosphere. The density of sea water is slightly higher than the density of fresh water and is on average 1026 kg/m^3. The density of air near the surface of the Earth can vary from 1.1 to 1.4 kg/m^3, averaging 1.2 kg/m^3. At altitudes, the air density is much less than at the ground, for example, at a height of ten kilometers it can be three to five times less. In the ocean, the density does not change as much as in the atmosphere (this does not mean that such small changes are not important, for example, for ocean circulation). But even if we compare the density at the surface, the density of ocean water is 850 times greater than the density of atmospheric air. The second important characteristic is the specific heat capacity, that is, the amount of heat that must be spent on heating a unit mass of air or water. For air, this value is slightly higher than 1000 J/(kg K); it is quite constant, being weakly dependent on temperature. For the ocean, the specific heat capacity ranges from 3800 to 4000 J/(kg K). Thus, we can roughly assume that the heat capacity of sea water is four times that of air. Multiplying 850 × 4 gives 3400, a very rough and notoriously low estimate of how much more conservative the ocean is than the atmosphere. That is, the ocean takes several thousand times more time than the atmosphere to change its thermal state. This, in fact, determines the most important role of the ocean in shaping the global climate.

Due to warming, approximately 92.5% of the additional energy in the Earth's climate system is absorbed by the ocean, increasing its heat content, which even gave rise to the meme "global warming is the ocean warming." The current increase in global temperature, including due to the anthropogenic factor leading to an accelerated increase in the concentration of greenhouse gases, is a response to a radiation imbalance in the Earth's climate system (the so-called Earth Energy Imbalance, EEI) associated with the excess of incoming solar radiation over outgoing long-wave and reflected short-wave radiation at the upper boundary of the atmosphere. This effect is shown in [2], a new version of the balance scheme [3], based on the most accurate estimates of all components of the energy balance in the atmosphere. For the period 2000–2012 the imbalance of incoming radiation (341.3 W/m^2) and outgoing shortwave and longwave radiation (340.4 W/m^2) is +0.9 W/m^2, which is different from estimates for the period from 1970 to 1990, when this value was about 0.2–0.3 W/m^2, although it is largely less accurate than estimates over recent decades.

As a consequence, excess heat accumulates in the Earth system, leading to the observed global warming [4, 5]. This, in turn, leads to destabilization of the global climate system, the main consequences of which are ocean warming, melting of the cryosphere, sea level rise, increase in air moisture content, and intensification of extreme climatic events (SREX, [6]). Predictions based on climate models [5] suggest that global warming and associated changes in key climate parameters will increase in the future. This implicitly implies an increase in the energy imbalance in the Earth's climate system. Therefore, the question of how this energy is redistributed, and how accurate estimates of this redistribution are, is key to understanding climate change.

The heating of the ocean is manifested in an increase in its heat content. A consequence of the slow warming of the ocean is that the ocean continues to warm even during those relatively short periods when trends in global atmospheric temperature decrease, disappear, or reverse. Indicative in this sense is the period of the beginning of the 21st century (between 1998 and 2011), when a plateau was noted in the global atmospheric temperature trend, but the ocean continued to warm. Therefore, it is inappropriate to draw conclusions about stopping global warming based on short-term trends in air temperature. What matters for climate change is a rise in temperature from decade to decade, not fluctuations in the rate of warming over several years. The "Pause" in warming at the beginning of the 21st century has become the subject of much speculation by so-called climate skeptics who have declared the end of the era of global warming. However, it is the continued warming of the ocean during this period, along with the renewed trend of global atmospheric warming, which provides clear evidence of a long-term trend in global temperature change associated with an increase in greenhouse gas concentrations.

In this regard, an important question arises: where does this heat go, or what components of the Earth's climate system are heated most of all due to it? If we consider the atmosphere, the changes in heating due to short-wave radiation are very small. When comparing the various components of the short-wave radiative heat flux in the atmosphere, according to the data of different authors, it is clearly seen how stable the relative estimates of radiation transmission and accumulation remain, changing respectively in the ranges of 0.54–0.56 and 0.48–0.49, however, in sum always giving more than one, which, in fact, suggests the emergence of the so-called "missing energy" discussed above. If these estimates are to be believed, then a natural question arises: where does the missing energy go, and what component of the climate system receives mainly this energy? These components cannot be the atmosphere, cryosphere and land, since their storage capacity is rather low. Despite the possible uncertainties in the estimates for each of them (comprising no more than 10–15%), the total contribution of these three components is from 2 to 4% of the missing energy, the main sink of which is the ocean.

Indicative in this sense are the estimates that demonstrate changes in the heat balance at the upper boundary of the atmosphere, in comparison with changes in the heat content of the World Ocean for the upper 700-meter and 2000-meter layers, obtained from observational data (CTD + ARGO + AVISO) over the past 15 years. These estimates show that changes in the heat content of the ocean track well the imbalance at the upper boundary of the atmosphere. The discrepancy can be explained by the need to take into account changes in the deep ocean (deeper than 2000 meters), or energy exchange processes at the ocean-atmosphere boundary.

The ocean and interdecadal climate change. In addition to the role of a global accumulator of excess heat, the ocean also plays an important role as a generator of the so-called intrinsic variability, which forms a response in the atmosphere on scales smaller than long-term climate trends. One of the most important and little-studied phenomena of intrinsic variability in the ocean is the so-called Atlantic Multidecadal Oscillation (AMO), which is a periodic fluctuation of the ocean surface temperature in the North Atlantic, most clearly manifested in the middle latitudes with a period of 50–70 years [7–12]. In most climate models, the AMO is associated with changes in the Atlantic meridional circulation. This strong mode of natural variability is superimposed on the long-term trend associated with global warming and significantly modifies the spatial variability of the characteristics of this trend. This is clearly seen from both observational data and climate modeling data. In [10, 13, 14] shows that the AMO has a strong influence on the European and North American climate through the advection of heat and moisture from the North Atlantic. That is why it is necessary to study and understand this variability in order to separate the anthropogenic effect and natural fluctuations of the system [11].

The general concept of climate predictability and the role of the ocean in climate predictions is as follows: on time scales of several days, the predictability problem is mainly a problem of initial values, where the ocean (or rather its changes) plays a small role. On longer time scales, climate predictability depends mainly on external factors that influence the dynamics of the climate system (e.g., concentrations of greenhouse gases) and ocean signals. As a result, for time scales from a few years to a few decades, climate predictability is the worst, as ocean signals (such as AMO) are poorly understood for these time scales, which can significantly dominate anthropogenic trends. Thus, the possibility of 10-day climate forecasts strongly depends on the understanding and numerical description of the mechanisms of ocean variability. That is, the worst predictability on 10-day scales (several years–several decades) coincides with the maximum influence of the ocean on the climate.

The active role of the ocean in the processes of climate formation on a scale of decades was noted more than 50 years ago by Bjerknes (1964). He suggested that the nature of the large-scale interaction between the ocean and the atmosphere in the midlatitudes of the North Atlantic varies depending on time scales: the atmosphere regulates short-term changes in ocean surface temperature, while long-term changes in ocean surface and atmosphere temperatures are regulated by the ocean itself. During the last decades, Bjerknes' assumption has been tested using both models [15, 16] and observational data [10]. However, a detailed study of the formation of the internal variability of the ocean is associated with the role of synoptic and mesoscale water dynamics.

The role of mesoscale and synoptic dynamics in the atmosphere and in the ocean is very different. If we consider the spatial distribution of wind in the atmosphere at an arbitrarily chosen moment of time, then the general structure of the average large-scale circulation will be masked by synoptic movements, represented mainly by the movement of eddy formations, which dominate over large-scale (mainly zonal) transfers, which is especially pronounced in midlatitudes. At the same time, large-scale transfers in the ocean are clearly visible even for a very high-resolution model picture, which makes it possible to track the dynamics of ocean eddies. This shows that the spatial characteristics of the mesoscale dynamics in the atmosphere and in the ocean are very different. In the ocean, mesoscale variability cannot be described by analogy with synoptic variability in the atmosphere in terms of cyclones and their regimes. In the atmosphere, meridional heat transfer (MHT), especially at temperate latitudes, is carried out by synoptic eddies, while in the ocean, MHT is provided mainly by large-scale currents. This, at first glance, “small” role of mesoscale ocean eddies in the overall dynamics of the ocean was the reason that eddy-resolving ocean models developed much more slowly than high-resolution atmospheric models. This also emphasizes the very different role of synoptic and mesoscale eddies in the dynamics of the atmosphere and ocean, despite the fact that the processes of their formation for the atmosphere and ocean are very similar.

Since currents in the ocean near the western coasts are mainly represented by unsteady synoptic-scale eddies and meanders, the role of these eddies in the general circulation of the ocean is much more complex and less studied than the role of cyclones in the atmosphere. It is important to note that mesoscale and synoptic ocean eddies can significantly affect the interannual and long-term variability of ocean circulation and modulate strong low-frequency large-scale variability. This variability is clearly seen in ocean surface temperature measurements [17], hydrography [18], and ocean surface level altimetry [19]. It is also clearly seen in the structural changes in the continuation of the jet streams and in the corresponding recirculation zones of the main currents along the western coasts, such as the Gulf Stream and Kuroshio. Eddy-resolving ocean models with seasonal forcing clearly show the intrinsic low-frequency variability of mesoscale ocean dynamics [20], eddy heat transfer [21], sea level height [22], west coast currents [23], and meridional circulation [24], demonstrating the important role of oceanic mesoscale eddies.

Thus, the role of eddies in the ocean and atmosphere is essentially different. Ocean mesoscale eddies, playing, at first glance, a much smaller role in the global dynamics of the ocean, just form the long-term variability of the World Ocean on a scale of decades. In other words, it is the mesoscale dynamics of the ocean, being integrated over time, that ensures the formation of natural frequencies that prevent obtaining stable forecast estimates of climate change.

Observed effects of climate change. The consequences of climate change are, to a certain extent, difficult to separate from climate change itself, due to the fact that many of the consequences include feedbacks that affect them. Given this reservation, it is necessary to note the following important consequences of climate change for natural processes. First, these are significant changes in the frequency and intensity of extreme climatic events, primarily precipitation and related floods, as well as droughts. In many parts of the world, primarily in the middle latitudes and on the territory of Russia, the average precipitation values do not change very much, sometimes they remain quite stable, however, monthly precipitation amounts close in magnitude tend to fall during several extreme days, which leads to severe floods. In addition, an increase in the average global temperature, which is (see above) within one degree over recent decades, significantly affects the shift of cyclonic trajectories and, consequently, the removal of moisture from the oceans to the continents by cyclones, which leads to an increase in moisture in some regions and an increase in aridity in others. Another important factor is the impact of climate change on the state of permafrost soils. The reduction in the area of permafrost in Russia over the past decades has amounted to hundreds of thousands of square km, while an even greater reduction occurring for seasonally frozen soils. This directly affects infrastructure on permafrost. The stability of this infrastructure for many decades was guaranteed by the stability of the permafrost itself, and therefore its thawing undermines the stability of buildings, roads, mooring structures, etc. Considering the natural landscape complexes, we should note the progressive desertification of steppe landscapes, changes in the characteristics of soil fertility in various natural zones, possible growth of the swamp area (and the associated increase in methane emissions from the swamps), as well as changes in forest complexes.

As for the ocean, an important consequence of climate change is a significant decrease in the area of Arctic ice [25]. In recent decades, there has been a steady decrease in the total amount of ice in the Arctic basin, associated with global warming. Over the past forty odd years (since 1980), the September area of Arctic ice (the so-called summer minimum) has decreased from 7.7 to 4.5 million square km, that is, we have lost about 40% of the summer ice cover. In winter, this decrease is about 20%. This is one of the ways the formation of stronger changes form in the global climate in the Arctic compared to other regions of the globe due to feedbacks between albedo and temperature and the influx of heat from the Arctic Ocean into the atmosphere. The forecast estimates of the Intergovernmental Panel on Climate Change and the National Report on Climate Change in Russia show that this trend will continue in the coming decades in almost all scenarios of economic development. This significantly affects the navigation situation on the Northern Sea Route (NSR), which is a promising transport artery, at first glance, more economically attractive than transit from Southeast Asia to Europe through the Indian Ocean.

However, the prospects for using the NSR for transit cargo transportation, as well as for transportation from the Russian Far East to the European part of the Russian Federation, should be treated with caution. Predictive estimates, for example, show that by 2050, if the current trends in the development of the economy, characterized by the most intense anthropogenic impact on the climate system (business as usual), continue, we can expect the complete disappearance of ice in the Arctic basin in the summer season, and under moderate scenarios, free from the ice of the NSR also in the summer season. However, in forecast estimates, we are talking about the occurrence of periods lasting 2 to 3 years, when this will be observed, that is, such periods will be interspersed with periods with relatively high ice cover. By the way, this is still observed, for example, the record negative anomalies of 2007 and 2012 interspersed with relatively high ice cover in 2014 and 2021. Besides, the metric of "no ice" in climate forecasts is the concentration of ice at the level of 15%, that is, there will still be floating ice.

Another important consequence of climate change is the rise in ocean levels, which is regarded as one of the strongest pieces of evidence of global warming. The rise in the level of the World Ocean has been occurring throughout the last century, and in recent decades it has increased significantly. Since 1993, when the ocean level began to be measured by high-precision satellite systems, its annual increase has been 3.1 mm, which has led to an increase in the level of about 10 cm over the past 30 years [25].

The two main causes of global sea level rise are thermal expansion caused by ocean warming (because water expands as it warms) and increased melting of land ice – continental glaciers and ice sheets. Estimates of the relative role of these two processes range from 50/50 to 60/40 in favor of the melting of continental ice, but the relative role of the thermal expansion of the oceans has increased somewhat in the last decade. With continued ocean and atmospheric warming, sea levels are likely to rise at a faster rate in the future than in the current century. Sea level rise at certain locations may be greater or less than the ocean average, for example due to the effects of regional ocean circulation. The strongest level increase in recent decades has been noted in the western equatorial Pacific Ocean (more than 7 cm over the past two decades), while in the eastern Pacific Ocean there has even been a decrease in level by 2–3 cm over the past 22 years.

Rising ocean levels pose a huge challenge to the world's coastal regions, which are exceptionally densely populated; more than half of the world's population lives here, producing more than 70% of the world's gross product. Moreover, coastal zones are deeply integrated into the economy even of areas far from the coast, and stresses on coastal zones seriously affect the economy and living conditions away from them. The main threats to coastal areas are rising sea levels and changes in the intensity of storm activity, leading to flooding and coastal erosion. Of particular danger is the rise in the level of the ocean for low-lying island territories, in particular, for the tropical islands of the Pacific Ocean, large areas of which are located a few centimeters above sea level. Rising mean sea levels also increase the risk of extreme sea level rises, such as storm surges, which will develop against higher mean levels. Sea level rise also affects water resources and the ecological balance of coastal areas, including both coastal sea areas and adjacent land areas. In this regard, coastal lowland ecosystems (salt marshes and mangroves) are particularly vulnerable, as they are only a few centimeters above sea level. These lowlands are the habitat of many species of animals and plants, they play an important role in the accumulation of nutrients. Moreover, it is here that intensive economic activity takes place, covering hundreds of millions of people, including, in particular, the construction, creation and maintenance of transport infrastructure, high-tech sectors of the economy, and tourism.

Against the background of a general rise in sea level, there is an increase in the frequency and intensity of extreme sea level rises, as well as the intensity of storms, which affects navigation and marine activities in the coastal zone and the open ocean, in particular, in winter, there is an aggravation of conditions conducive to icing of ships and platforms, first of all, in the Arctic basin, as well as the lengthening of periods with unfavorable conditions for navigation. Finally, climate change has a significant impact on ocean ecosystems, including as a result of the so-called ocean acidification. This leads to a shift in the areas of traditional fishing (for example, in the Barents Sea, most of the Arctic species have already been replaced by Atlantic species), as well as to the disappearance of certain species in the commercial volume.

The role of the ocean in the balance of greenhouse gases in the atmosphere. The main cause of observed climate change over the past 170 years is emissions of climate-active (or, as they are sometimes called, greenhouse) gases into the atmosphere, the main of which are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The effect of these gases, which are called well-mixed long-lived gases, is due to the fact that they prevent long-wave solar radiation from escaping from the climate system. An additional effect is also created by halogen gases (CFCs, HCFCs, HFCs, PFCs, SF_6), whose influence on the climate is somewhat less. The sources of emission of climatically active gases into the atmosphere are, firstly, human anthropogenic activity, and secondly, natural sources associated with biogeochemical processes in the Earth's climate system. Anthropogenic influence on the emission of climatically active gases is created by energy generation, transport, agriculture, and various industries, the relative role of which in emissions may vary from country to country, although the main source of emissions in most countries is energy production. Another way of anthropogenic influence on the emission of climatically active gases is the change of landscapes and land use practices. Atmospheric concentrations of three major greenhouse gases have increased since the preindustrial era: CO_2 by 46%, CH_4 by 157%, and N_2O by 22%.

In this sense, the ocean is the most important and powerful regulator of CO_2 content in the atmosphere. Along with land ecosystems, the ocean absorbs a significant portion of carbon dioxide. The Sixth Assessment Report of the IPCC showed that under the "business as usual" scenario (SSP1-8.5), land and ocean ecosystems can only "cope" with 38% of greenhouse gas emissions into the atmosphere. Under the scenario of immediate and sharp reduction of emissions (SSP1-1.9), this value is 70%. In other words, to achieve carbon neutrality, 62% of emissions in the first case and 30% in the second must be utilized both by the use of new industrial technologies and the introduction of ecosystem technologies. Given the practical impossibility of implementing the SSP1-1.9 scenario in full, we should focus on at least the intermediate scenarios SSP1-2.6 or SSP2-4.5, which assume the need for industrial and ecosystem technologies to utilize 35 and 46% of greenhouse gas emissions, respectively.

The exchange of gas between the atmosphere and the ocean is a physicochemical process that is governed by the difference in gas concentrations between air and water and the exchange coefficient, which determines how fast gas molecules can move across the ocean–atmosphere interface. In this sense, the flow of gases between the ocean and the atmosphere is turbulent and is similar to the process of exchange of heat and moisture by turbulent flows. The ocean plays a huge role in the global CO_2 balance and other climatically active gases and is their global regulator. CO_2 is a soluble gas that dissolves in the oceans and is absorbed by marine plants, in particular phytoplankton. During natural CO_2 cycles absorbed by the ocean from the atmosphere in cooler and more biologically active areas and released back into the atmosphere in warmer and less biologically active areas. The most intensive absorption of CO_2 by the ocean from the atmosphere occurs in the North Atlantic. The total balance for today is such that the ocean is a net sink of CO_2, providing about 30% of global carbon dioxide uptake.

Observed ocean uptake of anthropogenic CO_2 is primarily a physical response to an increase in its concentration in the atmosphere. When the partial pressure of a gas increases in the atmosphere above a body of water, the gas begins to diffuse into the water until the partial pressures at the air–water interface are balanced. However, since the global carbon cycle is closely linked to the physical climate system, there are several strong feedbacks between the two systems. For example, an increase in CO_2 changes the climate, which in turn affects the circulation of the ocean and therefore the absorption of CO_2 by the ocean. Thus, the heating of the ocean leads to the expansion of areas of warm and unproductive waters and the reduction of areas of relatively cold waters, which leads to a decrease in the absorption capacity of the ocean. Another factor influencing the process of absorption of CO_2 by the ocean is storm activity. With climate warming, the intensity of storms may increase, and their intensification, and, as a result, the speed of a sharp increase in wind waves and their collapse, leads to a local increase in CO_2 flux from the ocean to the atmosphere, regardless of temperature. Thus, in the course of observed climate changes, the ocean, albeit very slowly, weakens its role as a CO_2 sink. Changes in marine ecosystems as a result of increased CO_2 emissions and/or climate change may also lead to changes in CO_2 between atmosphere and sea. These feedbacks could change the role of the oceans in absorbing atmospheric CO_2, making it very difficult to predict how the ocean carbon cycle will work in the future.

An important consequence of ocean absorption of CO_2 is ocean acidification, which significantly affects ocean biota and ecosystems. Therefore, being a powerful absorber of carbon dioxide, the ocean generates processes that are dangerous for many ecosystems. Ocean acidification is already affecting many species, especially organisms such as oysters and corals, which form hard shells and skeletons by absorbing calcium and carbonate from seawater. As ocean acidification increases, fewer carbonate ions are available for such organisms to build and maintain their shells and skeletons, which can cause them to begin to dissolve.

Observations of CO_2 fluxes between the ocean and the atmosphere are more technically complex and much more expensive than observations of thermal energy flows. Today, the number of observations of CO_2 fluxes on the surface of the ocean is ten times less compared to the number of observations of other ocean parameters. The development of satellite methods makes it possible to obtain indirect flux estimates, but validation of satellite measurements requires direct observations, which so far exist only in a limited number. As a consequence, our understanding of CO_2 fluxes at the ocean–atmosphere boundary are an order of magnitude less accurate than those for thermal energy fluxes.

The need for ocean monitoring. The described climatic changes in the World Ocean require the organization of long-term monitoring of all thermodynamic and biogeochemical characteristics of the ocean. Currently, within the framework of the Most Important Innovative Project of National Significance, aimed at creating a unified national monitoring system for climate-active substances, and within the framework of the Federal Scientific and Technical Program in the field of environmental development of the Russian Federation and climate change for 2021–2030, the system of such monitoring is being built within the framework of a separate consortium. The task of the consortium is to form a system for monitoring climate change, hydrophysical and biogeochemical characteristics, as well as energy flows and flows of climatically active substances based on the use of buoys, marine observatories, ship and coastal observations, which ensures prompt receipt of reliable and publicly available data on the dynamics of climatic characteristics and greenhouse gas flows, including the operational formation of retrospective analyses (reanalyses), in key areas of the World Ocean, seas and coastal areas of the Russian Federation, which are long-term grid arrays of all ocean characteristics with a resolution of at least 10 km in space and 1 day in time.

The implementation of the consortium's work will make it possible to create integrated monitoring systems for the subpolar North Atlantic and the northwestern part of the Pacific Ocean in order to reduce uncertainties in assessing the role of the ocean in climate change and the balance of climatically active gases; build multicomponent monitoring systems for the Russian seas, taking into account regional specifics to ensure the effectiveness of adaptation solutions; as well as to create operational reanalyses of the state of the World Ocean and the seas of Russia, including the characteristics of energy flows and climatically active gases, combining the capabilities of various types of data and modeling.

This is necessary because in Russia today there are neither integrated systems for observing the state of the ocean, seas and coastal areas, nor models with data assimilation systems and, as a result, long-term reanalyses of the ocean and seas. In modern conditions, we are also cut off from foreign reanalyses and data flows for assimilation. This leads to large (up to 70%) uncertainties in assessing the role of the ocean and seas in climate formation and the balance of greenhouse gases, making it impossible to make sound adaptation decisions, including for the development of all sectors of the economy related to the ocean and coastal areas.

Objective data on the state of key regions of the World Ocean and Russian seas based on measurements of buoys, satellites and ships, providing information flows for assimilation by model systems created during the operation of the consortium, will allow verification of earth system models and regional climate models, which will lead to the improvement of national climate prediction systems. This data will be used to create national measuring complexes for the oceans and seas, as well as to develop national systems for remote monitoring of climate active substances, which will eliminate the dependence of national monitoring systems on the EU and the United States.

Verified estimates of long-term changes in ocean dynamics, ocean–atmosphere energy flows, absorption and emission of greenhouse gases in the World Ocean and Russian seas based on reanalysis will be used to obtain operational assessments of the state of marine systems, included in information bases when developing scenarios for the development of the economy and used to justify adaptation measures in coastal areas and coastal zones.

FUNDING

This work was carried out within the framework of the Federal Scientific and Technical Program in the field of environmental development of the Russian Federation and climate change for 2021–2030 (FMWE-2023-0002). The analysis of global energy flows in the ocean–atmosphere system was supported by the Russian Science Foundation, grant no. 23-47-00030.

CONFLICT OF INTEREST

The author declares that he has no conflicts of interest.

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