Oceanology, Vol. 44, No. 1, 2004, pp. 44–54. Translated from Okeanologiya, Vol. 44, No. 1, 2004, pp. 49–61.

MARINE PHYSICS

Use of the Data of Simultaneous Satellite Microwave Radiometric and Ship-borne Measurements for the Study of Air–Sea Interaction in the North Atlantic

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Received November 25, 2002; in final form, May 22, 2003

Abstract—A comparison of the ship-borne data obtained in the NEWFOUEX-88 and ATLANTEX-90 experiments from aboard the R/Vs *Viktor Bugaev*, *Musson*, and *Volna* in the Newfoundland energy-active zone in the North Atlantic and the data of the simultaneous measurements of brightness temperature of the microwave natural radiation of the ocean and atmosphere obtained with a SSM/I scanning radiometer from the US *F-08* DMSP meteorological satellite is presented. The brightness temperature was found to be clearly correlated with the synoptic variations of the heat and momentum fluxes at the interface between the ocean and atmosphere, the characteristics of the atmospheric boundary layer, and the characteristics of the trans-frontal heat transfer in the zone of the subpolar hydrological front. The potentialities of the use of the data of long-term microwave radiometric measurements from the DMSP satellites for the analysis of the annular and interannual variability of the monthly mean values of heat fluxes in the Norwegian, Newfoundland, and Gulf Stream energy-active zones in the North Atlantic are also illustrated.

INTRODUCTION

The development of methods for the analysis of air–sea interaction, which is a factor of the annual trend and interannual variability of climate, is an important aspect of study from the point of view of international programs such as the World Program of Climate Studies, International Geosphere and Biosphere Program, Global Change Research Program, Earth Observing System, and Climate Variability and Predictability. The fact that this field is important for the national interests of Russia is reflected in sections 3 and 10 ("Development of the United Federal Information System on the World Ocean Conditions") of the "Study of World Ocean Nature" Federal Purposive Program. The marked reduction of the expeditionary ship-borne observations of the World Ocean in Russia makes the use of a satellite the most promising solution to this problem. In addition, the onboard and mooring means are in principle not capable of providing the sufficient regularity of measurements required for a system of global observations.

Vertical turbulent fluxes of sensible and latent heat and momentum flux are among the most important characteristics of the heat and dynamic interaction between the ocean and atmosphere. Satellite microwave radiometric methods of the analysis of such parameters have been developed only beginning in the 1980s–1990s (predominantly in the USA, Russia, and Germany), whereas already in the 1960s–1970s, encouraging results of the use of remote microwave and IR radiometric methods for the analysis of heat exchange at the air–water interface in taking measurements in the laboratory, from floating platforms, and from aboard low-flying planes have been obtained.

In the recent years, experience has been accumulated on the use of the methods of satellite microwave and IR radiometry for the analysis of the heat interaction between the ocean and atmosphere on the basis of the data obtained with SSMR (*NIMBUS 7* and *SEASAT* satellites), SSM/I (DMSP), and AVHRR (NOAA) radiometers. Methods were developed and approved for the determination of monthly mean values of fluxes of latent heat at the air–sea boundary and their seasonal variability. The methods were based on direct or indirect relationships between the brightness temperature measured from a satellite and components of heat fluxes such as the ocean surface temperature, temperature, humidity, and wind speed in the near-surface layer of the atmosphere. More recently, the ability of these methods to estimate latent heat fluxes on synoptic time scales was studied from the SSM/I radiometer data. The results, however, were not too encouraging. At present, there is a set of marked white spaces in the study of the real and potential capabilities of satellite microwave radiometer methods for the analysis of the characteristics of heat and dynamic air-sea interaction:

—the methods used are based on the formulas of air–sea heat and water exchange (bulk-formulas), which contain temperature and humidity of the near-surface layer of the atmosphere only indirectly related to the brightness temperature of the system ocean–atmosphere (SOA);

—humidity characteristics of the atmosphere recorded by satellite microwave radiometers in the region of the resonance absorption of water vapor are the only characteristics used to relate the SOA brightness temperature in the microwave range to the heat fluxes at the interface of the system;

—the relationships between the brightness temperature and heat fluxes are steady-state in the sense that they use generalized (multi-year) regressions between the data of observations of integral and near-surface humidity which do not take into account the contribution of various mechanisms of heat and water transport in the atmosphere (vertical diffusion mechanism, horizontal (advective) mechanism, or any other) on shorter time scales.

A more important factor is that the world practice of remote sensing has yet not considered the possibility of using the data of satellite microwave radiometric measurements for the solution of such an important problem for oceanologists and climatologists as the analysis of the characteristics of air–sea heat interaction in the frontal zones, where the bulk formals are usually invalid. Up to now, the potential of satellite microwave radiometric methods for the analysis of the energy and circulation characteristics of the atmospheric boundary layer and the assessment of their effect on the heat and water exchange at the SOA interface have remained unknown. Finally, specialists on the remote sensing of the World Ocean by microwave, IR, and other radiometric methods have not considered the most important problem—the relative contributions of the ocean and atmosphere to the heat and dynamic interaction between them on various spatiotemporal scales.

In the present study, we demonstrate the possibilities of the present-day satellite microwave radiometric means for the solution of a set of applied problems in the frontal zones of the ocean and atmosphere and in the regions of activity of mid-latitude cyclones, where the use of classical formulas for the air–sea heat and momentum exchange is limited. The problems that are important from the point of view of oceanologists, meteorologists, and climatologists are as follows:

—the estimation of spatiotemporal variations of heat and momentum fluxes at the air–sea interface in the synoptic range of time scales;

—the analysis of the response of heat fluxes and enthalpy of the atmospheric boundary layer to the passage of the mid-latitude cyclones;

—the study of the dynamics of the temperature and humidity characteristics of the atmosphere, in particular, of the velocity of the atmospheric front movements in the middle and high latitudes of the ocean;

—the analysis of the characteristics of trans-frontal heat and water transfer and their effect on the intensity of the air-sea heat and dynamical interaction.

These results were obtained from a joint analysis of the data of comprehensive NEWFOUEX-88 and ATLANTEX-90 experiments carried out from onboard R/Vs *Viktor Bugaev*, *Musson*, and *Volna* in the energy active zones (EAZ) of the North Atlantic and the data of microwave radiometric measurements from the US *F-08* DMSP satellite.

The possibilities of the use of the data of long-term microwave radiometric measurements from DMSP satellites for the analysis of the annual and interannual variability of the monthly mean values of heat fluxes in the Norwegian and Newfoundland energy active zones as well as in the Gulf Stream energy active zone and in the Gulf Stream region are also illustrated.

USING SATELLITE RADIOMETRIC DATA FOR ANALYZING HEAT FLUXES AT THE AIR–SEA INTERFACE

The principal difficulty in the use of satellite radiometric methods for an analysis of heat interaction between the ocean and atmosphere is that the characteristics of natural radiation in both the microwave and IR ranges measured from a satellite are formed not only in the near-surface 10-m layer of the atmosphere, but in the upper layers as well. There are different approaches to using microwave and IR radiometric measurements for the estimation of heat fluxes in the SOA. One of them is based on the retrieval of the vertical temperature gradient in the near-surface layer of the ocean, the sign and value of which, as is shown in [26], are related to the value of the vertical turbulent sensible heat flux. The efficiency of such a method in the IR range is supported by the results of a number of measurements under laboratory conditions, from stationary coastal points, from floating marine platforms, and from low-flying planes [2]. Some possibilities for the retrieval of the temperature profile near the ocean surface from the data of multi-frequency microwave radiometric measurements are studied theoretically in [23, 27]. Microwave radiometric methods for determining the vertical temperature profile of calm and rough water surfaces for the case of stationary and ship-borne measurements [3] are developed and approbated in the laboratory. At the same time, there is no evidence on the use of the IR or microwave radiometric methods of determining heat fluxes from the temperature profiles in the operative large-scale studies of the ocean, i.e. with the use of a satellite. The modern satellite IR and microwave radiometric facilities, which can determine the temperature of the water surface and its variations, in the best case, with an accuracy of 0.5–1°C, do not guarantee a reliable indication of not only the value, but of the sign of the temperature gradient in the near-surface layer of the ocean as well. A similar situation holds for the microwave and IR radiometric methods for the retrieval of vertical temperature and humidity profiles in the near-surface atmosphere in the spectrally localized absorption (radiation) bands of its gas components, water vapor, and oxygen, which are the most important from the point of view of heat and water transport. Due to the insufficient spectral resolution and sensitivity of radiometric instruments, these components have been considered only as potential sources of information on the processes of heat and water exchange in the SOA [19].

A more appropriate and, one can say, constrained (accounting for the present-day technique of remote sensing) approach to the determination of heat fluxes is based on the indirect (statistical) correlation between the integral (averaged over the height) values of the temperature and humidity in the atmosphere, whose variations are reliably retrieved from the data of satellite microwave and IR radiometric measurements in the given spectral bands, with the temperature and humidity in the lower atmospheric layers. This correlation is associated with the mechanism of turbulent mixing of heat and water (which is much more developed and intensive in the atmosphere than the ocean) in the near-surface and boundary air layers and is best manifested in their mean monthly (or decadal) values free from the effect of hourly and diurnal perturbations. Therefore, these are the time scales for which encouraging results were obtained in the use of satellite methods for the determination of heat fluxes at the SOA interface, in particular, for the determination of mean monthly values of fluxes of latent heat from the data of microwave and IR radiometric measurements obtained from onboard the *Nimbus 7*, DMSP, and NOAA satellites.

The availability of correlations between the temperature and humidity characteristics in various layers of the atmosphere permit the use of satellite radiometric methods for the determination of basic quantitative characteristics of the heat interaction between the ocean and atmosphere and the vertical turbulent fluxes of sensible (q_h) and latent (q_e) heat at the SOA boundary with the use of semi-empirical formulas, the so-called bulk formulas, obtained on the basis of the Global Bulk Aerodynamic Method. In accordance with this approach, q_h and q_e can be expressed as [18, 20]

$$q_h = c_p \rho C_T (T_s - T_a) V, \tag{1}$$

$$q_e = L \rho (0.622/P_a) C_E (e - e_0) V, \tag{2}$$

where T_a is the temperature, e is the aqueous tension, V is the wind speed in the near-surface air, T_s is the ocean surface temperature, and e_0 is the maximum humidity at the given value of T_s. Equations (1) and (2) also contain the coefficients of heat C_T (Schmidt number) and humidity C_E (Dalton number) exchange, the specific evaporation heat L, the specific heat capacity of air at a constant pressure c_p, and its density ρ.

The aerodynamic method allows a simple parametrization of the intensity of the mechanical (dynamical) interaction of the ocean surface and atmosphere by introducing q_V, which is the flux of momentum [18, 20]

$$q_V = \rho C_V V^2, \tag{3}$$

where C_V is the drag coefficient.

Equations (1)–(3) allows the assessment of not only "instantaneous", but also averaged over significant time intervals (e.g., mean monthly) fluxes of heat and momentum using the averaged parameters T_s, T_a, e, and V as initial data [1, 15, 22, 29]. This makes the aerodynamic method attractive for the assimilation of satellite radiometric measurements especially those containing the information on temperature and humidity of the near-surface atmosphere. As indicated by specialists on the air-sea interaction, the aerodynamic method, however, needs a set of conditions to be satisfied. In particular, the horizontal spatial gradients of parameters T_s, T_a, and e should not exceed some critical values, i.e. the applicability of the method to the ocean frontal zones is questionable [20]. Therefore, to determine the fluxes of sensible and latent heat and momentum at the interface between ocean and atmosphere, it is necessary to know the temperature of the ocean surface, the absolute value of the near-surface wind speed, and the temperature and humidity of the near-surface air. The estimates of parameters T_s and V can be obtained directly from the data of satellite radiometric measurements, while to determine parameters T_a and e, it is necessary to use their indirect correlation with temperature and humidity characteristics of the atmosphere, which are strongly correlated with the intensity of the microwave and IR self-radiance of the atmosphere in selected regions of the spectrum.

A number of studies are devoted to the analysis of the capabilities of satellite microwave and IR methods for the assessment of characteristics of the heat and dynamical air–sea interaction. For example, in [17], approximate estimates of the accuracy of the parameters of the active ocean layer were obtained, which are necessary for the determination of some characteristics of the balance in the SOA. The maximum values of the errors in determining the parameters T_s, T_w, and e, for which the estimates of q_h, q_e, and q_V obtained from the bulk formulas are valid, are calculated in [14]. The possibilities of the present-day satellite means and methods in the IR range are discussed from this point of view. In [37], on the basis of the data of the JASIN experiment on the study of mean monthly values of the fluxes of sensible and latent heat in the North Sea, information losses in the satellite estimates depending on the frequency of remote measurements are assessed. It was shown that, even at a measurement periodicity of 2 times per day, the relative error in the determination of heat fluxes can reach 10% for the parameter q_h and ~30% for the parameter q_e. The results of the experimental studies from *Nimbus 7*, DMSP (in the microwave range), and NOAA (in the IR range) satellites in various physico-geographical zones of the World Ocean [11, 35, 36] indicate that this method is appropriate. For example, the standard error in determining monthly mean fluxes of latent heat in 2–5-deg squares of the ocean from selected data (September 1987, global ocean [36]), February 1994, energy-active zones in the North Atlantic [11], 1982–1983, tropical zones of the Pacific Ocean, [35]) is 15–30 W/m^2 for their maximum mean monthly values of 150–250 W/m^2.

As it was noted, the aerodynamic method is hardly suitable for the retrieval of synoptic components of heat and water exchange in the SOA which are more dynamical in comparison with the seasonal components from the data of satellite microwave and IR radiometric measurements. This can be explained as follows. First, on the synoptic time scale, the stability (statistical significance) of the correlations between air temperature and humidity in the near-surface and upper layer of the atmosphere decreases in comparison with the seasonal time scale. As a result, the accuracy of indirect estimates of parameters T_a and e from (1) and (2) decreases. Second, on the synoptic time scale (in comparison to the seasonal one), the role of selected factors such as sea waves, cloudiness, and precipitation, which limit the accuracy of determining parameter T_s, is enhanced. Third, the ambiguity of the coefficients of heat C_T and water C_E exchange in equations (1) and (2) is more pronounced on the synoptic scale rather than on the seasonal one.

An efficient way of solving this problem is the use of the data of satellite microwave and IR radiometric measurements as direct characteristics of heat and dynamic interaction between the ocean and atmosphere. The reasonability of this approach was stated in [17] in discussion of the requirements to the composition and accuracy of satellite measurements for the analysis of the components of heat balance at the air–sea interface in the study under the auspices of the *RAZREZY* program and in [30] in the interests of numerical weather forecasting. It is shown in [21] that the intensity of natural radiation (brightness temperature) of the SOA in the centimeter wave range can be used as a direct characteristic of the rate of carbon dioxide exchange between the air and water surface. This approach corresponds to the concept developed at the Institute of Radio Engineering and Electronics, Russian Academy of Sciences, on the use of the data of remote measurements for direct determination of more general characteristics, e.g. the earth's radiation dryness factor [24, 25], rather than for their transformation into geophysical parameters such as temperature, humidity, wind speed, and others. Within the frameworks of this concept, it is shown, both theoretically and experimentally, that the characteristics of large-scale heat interaction between the ocean and atmosphere in the energy-active zones [4, 8, 9], the temporal and spatial variations of fluxes of the total (sensible and latent) heat on the synoptic scale [5, 7, 10, 12, 13, 31], and the multiyear variability of their monthly mean values in the mid and high latitudes in the North Atlantic [6] can be assessed without using the bulk formulas.

Below, we present initial satellite, ship-borne, and other data, which allow us to estimate the potentialities of the use of satellite microwave radiometric methods for the analysis of the processes of heat and dynamical interaction between the ocean and atmosphere for a set of situations and phenomena typical of these latitudes in the North Atlantic.

INITIAL SHIP-BORNE AND SATELLITE DATA

Synoptic Scale

To analyze the correlation between the characteristics of microwave natural radiation of the SOA and characteristics of heat and dynamic air-sea interaction in the synoptic range we used archive data of measurements obtained from onboard R/Vs *Viktor Bugaev*, *Musson*, and *Volna* of the State Oceanographic Institute in the region of the Newfoundland energy active zone of the North Atlantic during the stationary phases of the NEWFOUEX-88 and ATLANTEX-90 experiments (in March, 1988 and April 1990, respectively), as well as the data of simultaneous microwave radiometric measurements with a SSM/I radiometer from the US *F-08* DMSP meteorological satellite presented by the Marshall Space Flight Center, NASA.

The principal features of the ship-borne measurements in these periods are the high periodicity and regularity of observations and the possibility to study the proper temporal dynamics of the parameters of the ocean and atmosphere due to the fact that, at the steady-state phases, the vessel locations were fixed.

In these periods, the weather ships carried out measurements in three parts of the Gulf Stream delta: at the southern periphery of its major stream (R/V *Viktor Bugaev*), in the southern branch (R/V *Musson*), and in the eastern branch of the Labrador current (R/V *Volna*). This region of the ocean is characterized by a significant synoptic variability of the parameters of the ocean and atmosphere, which is caused by the closeness of the subpolar hydrological front formed by the cold Labrador current and the warm quasi-stationary anticyclonic gyre of the Gulf Stream [16].

As satellite data we use the data of the measurements with a SSM/I microwave radiometer, which has successfully operated in space on operative meteorological satellites of the DMSP series from 1987 until now. The data of the measurements of the first satellite in this series, *F-08* satellite, are of particular interest since it was the only means of monitoring the ocean in the microwave range in 1988 and 1990, when the

Description of the data of direct and satellite measurements and their function

Type	Sources	Composition	Content
Meteorological observations	R/Vs *Viktor Bugaev, Musson, Volna*	Temperature of the sea surface wind speed in the near-surface atmosphere	More than 2000 observations with 1-h intervals
Aerologic observations	R/V *Viktor Bugaev, Musson, Volna*	Temperature, humidity, and air pressure within 10–16000 m at 20 levels	More than 400 observations with an interval of 6 h
Satellite measurements	F-08 DMSP satellite	Brightness temperature at frequencies 19.3, 22.2, 37, and 85.5 GHz for two types of polarizations	More than 20 sessions of measurements with an interval of about 24 h

NEWFOUEX-88 and ATLANTEX-90 experiments were carried out.

The SSM/I (Special Sensor Microwave/Imager) radiometer was designed to provide a global and synoptic determination of the following characteristics: water content in clouds; precipitation intensity; total water content in the atmosphere; velocity of the near-surface wind; ice coverage; their age and concentration; water equivalent of snow; and type, humidity, and temperature of the earth's surface. It features a scanning seven-channel four-frequency system that measures the brightness temperature of the SOA at an angle of observation of 52° on the vertical and horizontal polarization of radiation at frequencies of 19.3, 37, and 85.5 GHz (wavelengths of 1.55 cm, 0.81 cm, and 3.5 mm, respectively) and on the vertical polarization at a frequency of 22.2 GHz (1.35 cm) in the observation band 1400 km, providing global coverage of the earth every three days and incomplete coverage over a day [33]. In foreign publications, the corresponding channels of the radiometer are briefly denoted as 19V,H, 37V,H, 85.5V,H, and 22V depending on the type of the polarization used—vertical (V) or horizontal (H).

The description of the data of ship-borne and satellite microwave radiometric measurements used for the analysis of the correlation between the brightness temperature of the SOA and the intensity of the heat and dynamic air–sea interaction at the steady-state phases of the NEWFOUEX-88 and ATLANTEX-90 experiments is presented in the table.

Seasonal and Climatic Scales

In the study of the correlation of the characteristics of natural microwave radiation with characteristics of the heat and dynamic air–sea interaction on the seasonal and climatic scales, we used the archive data of the measurements with the SSM/I radiometer from DMSP *F-08, F-10, F-11, F-12*, and *F-13* satellites during the period from 1988 to 1996 presented by the NASA Marshall Space Center. This comprises more than 200 Gbit of archived information.

Fragments corresponding to our "regions of interest," the areas of the North Atlantic occupied by the Norwegian and Newfoundland energy active zones and the Gulf Stream energy active zone as well, were first extracted from the global database of the brightness temperatures. Series were then formed for the current (daily) and monthly mean values of the brightness temperature in the period from 1988 to 1998 for such turns of DMSP satellites which pass through more local regions (0.5° × 0.5° squares), whose centers coincide with the weather stations (vessels) M (MIKE, 66° N, 2° E), D (Delta, 44° N, 41° W), and H (HOTEL, 38° N, 71 W). To determine the oceanographic and meteorological parameters at these points, we used the recent permanently updated electronic archive NCEP/NCAR based on the database of reanalysis of the ship-borne and other measurements, which also includes the data of multi-year observations in various fields such as oceanography, climate and weather, hydrology and glaciology, biogeochemistry, and so on [34].

EXAMPLES OF THE USE OF THE SSM/I RADIOMETER DATA AS INDIRECT CHARACTERISTICS OF THE AIR–SEA INTERACTION

Use of the SSM/I Radiometer Data for the Estimation of Synoptic Variations of Heat and Momentum Fluxes

Figure 1 shows the results of a comparison of the ship-borne estimates of the total fluxes of heat q_{he} and momentum q_V recorded at the steady-state phase of the ATLANTEX-90 experiment with their satellite estimates obtained as linear combinations of the data on brightness temperature measured with various channels of the SSM/I radiometer, which carry information predominantly on the total water vapor concentration in the atmosphere (channel 22V), the integral water stock in clouds (37V,H), and the velocity of the near-surface wind (19V,H). As shown in [5, 10], for weak cloudiness, the brightness temperature in channel 22V and the brightness temperature (channel 19V,H) themselves are

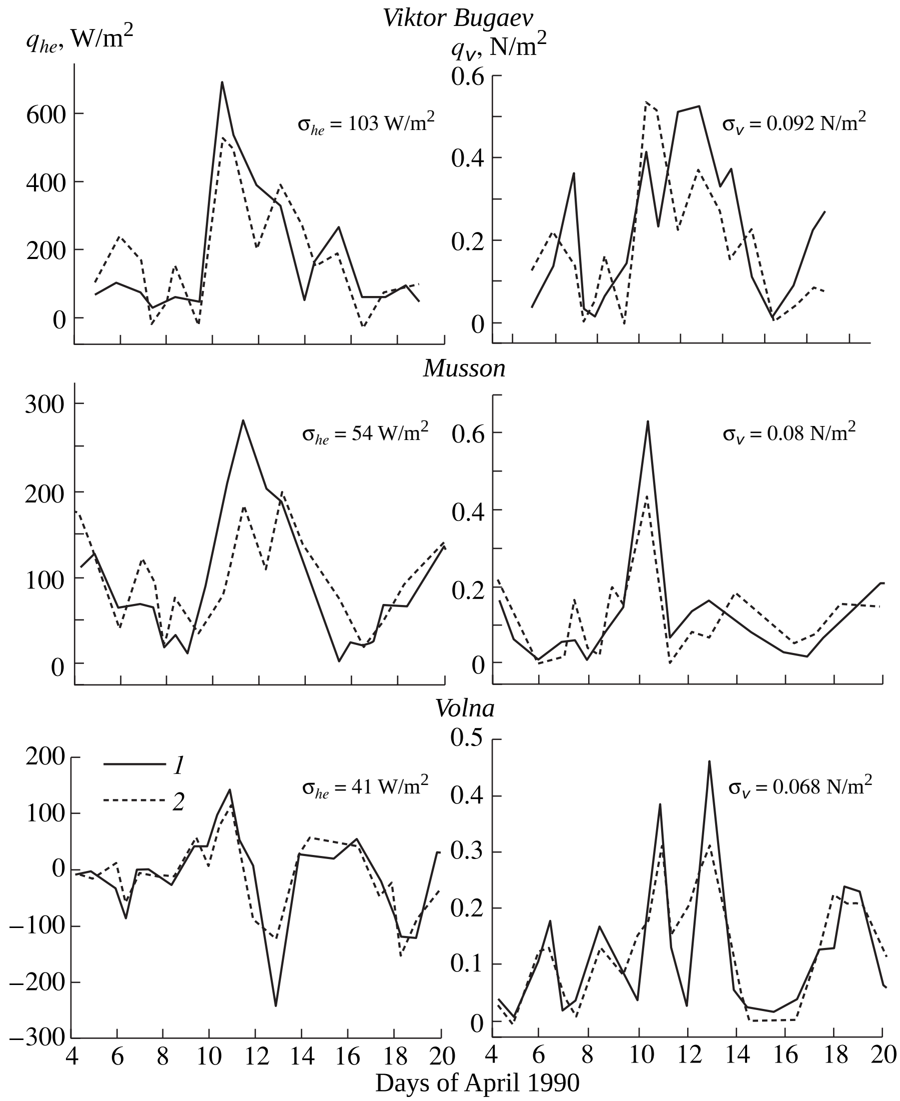

Fig. 1. Comparison of (*1*) the fluxes of total heat q_{he} and momentum q_V with (*2*) their estimates obtained with the use of a linear regression with the data of measurements of the channels of the SSM/I radiometer.

good qualitative characteristics of the heat and momentum fluxes, respectively. In the general case, however, it is necessary to use the additional data of the measurements of channels 37V,H, which allow for the effect of cloudiness.

In spite of the significant quantitative and even qualitative differences in the processes of heat and dynamic interaction between the ocean and atmosphere in the studied regions of the Newfoundland energy active zone of the North Atlantic, there is a good agreement between the ship-borne and satellite estimates of the parameters q_{he} and q_V. The correlation coefficient r between the heat flux values and their satellite microwave radiometric estimates reach 0.85 for R/V *Viktor Bugaev*, 0.73 for R/V *Musson*, and 0.84 for R/V *Volna*, and the corresponding values for momentum fluxes are 0.87, 0.81, and 0.84. The ratio of the root mean square differences σ_{he} and σ_V between the flux values recorded in the ship-borne measurements and their remote estimations to the maximum values of the natural variations of the fluxes varies from 12% (R/V *Viktor Bugaev*) to 19% (*Musson*) for the value of q_{he} and from 13% (*Musson*) to 18% (*Viktor Bugaev*) for the value q_V.

Examples of the Use of the SSM/I Data for the Analysis of Synoptic Variability of the SOA Parameters in the Region of the Subpolar Hydrological Front

A. The satellite images obtained with various channels of the SSM/I radiometer give visual representation of the characteristics of the subpolar hydrological front (SHF) such as the sizes and position of the frontal region in the synoptic range of time intervals. As an example, Fig. 2 shows black-and-white illustrations of

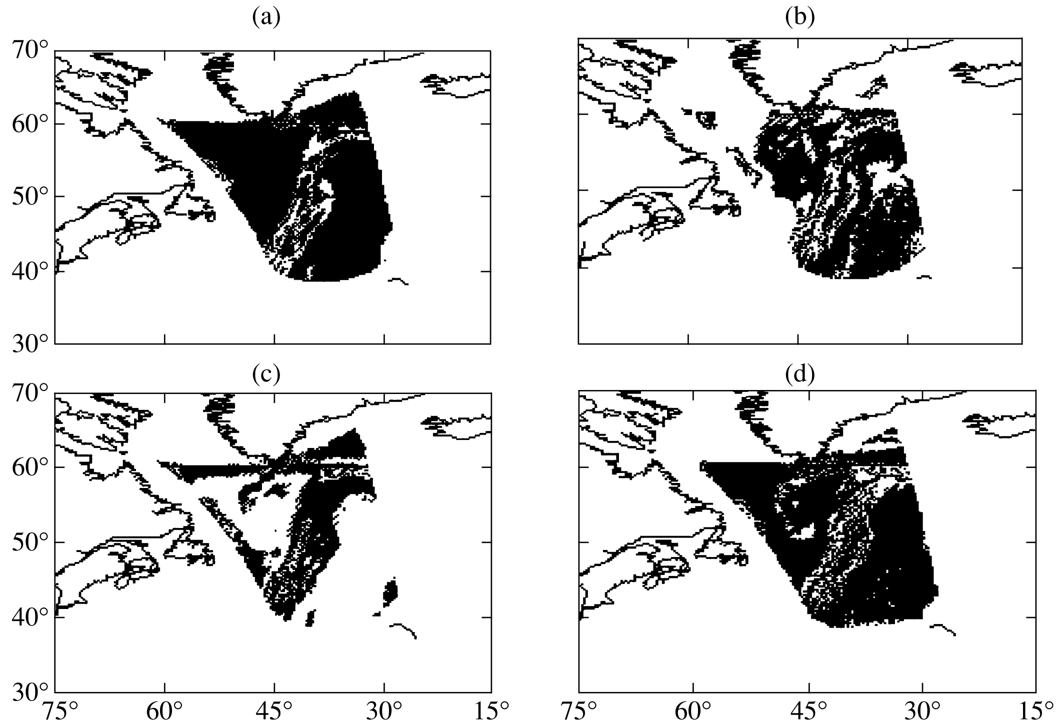

Fig. 2. Spatial distribution of the brightness temperature of the air–sea system in the region of the SHF on March 6, 1988, for various channels of the SSM/I radiometer: (a) 19V, 175–220 K; (b) 37V, 200–250 K; (c) 19H, 125–190 K; and (d) 37H, 150–230 K. The numerals along the axes are the latitude and longitude.

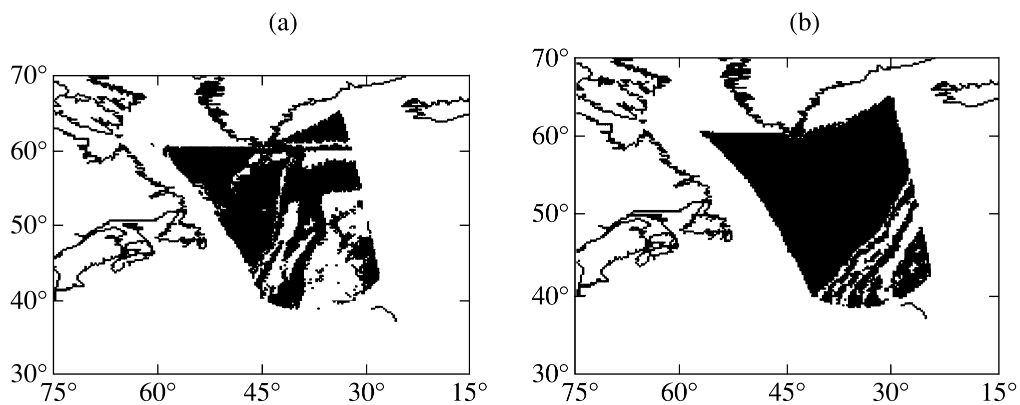

Fig. 3. Spatial distribution of the brightness temperature of the air-sea system in the channel 22V of the SSM/I radiometer in the region of the SHF in the range 180–240 K: (a) at 8 a.m. on March 3, 1988; (b) at 8 a.m. on March 7, 1988. The numerals along the axes are the degrees of latitude and longitude.

the results of the measurements of the spatial distribution of the brightness temperature in channels (a) 19V,H and (b) 37V,H in the region of the SHF during the passage of an intensive cyclone on March 6, 1988 (the value of the brightness temperature increases from darker to lighter gradations). The quantitative analysis shows that, depending on frequency, the values of spatial contrasts in the brightness temperature are 45–50 K on the vertical polarization and 65–80 K on the horizontal polarization; they are localized in an extended narrow region of the ocean 500–700 km in width which corresponds well to the location of the SHF.

B. The regular microwave radiometric measurements from the *F-08* satellite provide evidence on the intensity of the horizontal circulation of the atmosphere (in particular, on the dynamics of the development of cyclones) with a resolution of one day. For example, the brightness temperature of the SOA in channel 22V of the SSM/I radiometer deployed on the *F-08* satellite, which mainly characterizes the total water content in the atmosphere, is clearly related to the evolution of a cyclone in the region of SHF from the morning of March 6 to the morning of March 7, 1988 (Fig. 3). A comparison of Figs. 3a and 3b shows that the atmospheric front in this period moved toward the Azores Islands with a velocity of ~30 km/h.

C. We studied the possibility of analyzing the spatial distribution of the intensity of heat and dynamical interaction between the ocean and atmosphere along the satellite sections of the SHF across the regions of the locations of the R/Vs *Viktor Bugaev, Musson*, and *Volna*. For this purpose, we determined the coefficients of regressions between the values of the brightness temperature measured by different channels of the SSM/I radiometer and the intensity of the vertical turbulent fluxes of the total heat q_{he} and momentum q_V at the interface of the SOA calculated from the data of the ship-borne measurements from March 3 to March 23. The local regression relationships were then used for the retrieval of the variations of heat and momentum fluxes along the satellite sections across the SHF. Figure 4 shows the results of the use of such a procedure for a satellite section through the regions of location of the R/Vs *Viktor Bugaev* and *Volna* in the morning and in the evening of March 6. As can be seen from the figure, the variations of the parameters q_{he} and q_V are clearly traced in the warm region of the SHF formed by the southern periphery of the Gulf Stream, which is associated with the influence of the cyclonic activity of the atmosphere.

D. The SHF is characterized by the dependence of the characteristics of the heat interaction between the ocean and atmosphere in the areas adjacent to it not only on the intensity of the flow of the air masses but also on its direction with respect to the front. On the basis of the data [16], we studied the effect of the velocity and direction of the wind on the synoptic variability of the meteorological parameters of the near-surface air layer, total heat fluxes, and brightness temperature of the SOA at the steady-state phase of the ATLANTEX-90 experiment in the cold ocean waters in the region of the location of the R/V *Volna* 200 km away from the SHF.

The regression analysis of the relationships between the parameters mentioned above shows that the variability of the temperature and humidity of the near-surface air in this region of the North Atlantic is determined by the joint effect of velocity and direction of wind characterized by the value of the projection of wind speed $V_\perp$ on the normal to the curve describing the location of the SHF and passing through the R/V *Volna* site.

Figure 5 shows the results of the comparison of the variations of the fluxes of total heat and brightness temperature of the SOA for a wavelength of 1.35 cm measured by channel 22V of the SSM/I radiometer with the variations of parameter $V_\perp$ during the passage of a powerful cyclone typical of this region.

It was found that there is a close correlation between the diurnal values of the total heat fluxes and the brightness temperature, measured from the *F-08* satellite with a periodicity of about once a day, with the mean daily values of parameter $V_\perp$ during the entire steady-state phase of the ATLANTEX-90 experiment: the values of the correlation coefficients between the parameters q_{he} and $V_\perp$, and T_b and $V_\perp$ are 0.85 and –0.73, respectively.

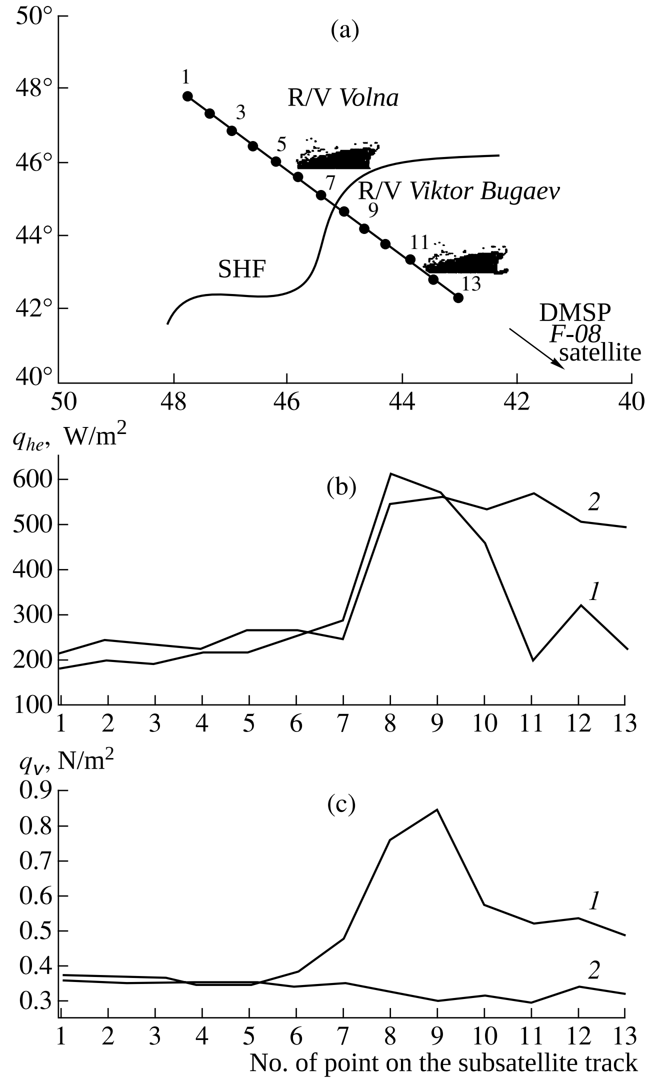

Fig. 4. (a) Schematic of the SHF section over the subsatellite track of the *F-08* satellite passing through the regions of the location of the R/Vs *Volna* and *Viktor Bugaev* on March 6, 1988 and estimates of the variations of the fluxes of total (b) heat q_{he} and (c) momentum q_V: (*1*) at 8 a.m., (*2*) at 10 p.m. the dots denote the satellite samples. The numerals along the axes are the degrees of latitude and longitude.

Using the Data of Long-Term Measurements with the SSM/I Radiometer for the Analysis of Interannual Variability of Heat Fluxes in the Energy Active zones of the North Atlantic

We studied the possibilities of using the data of long-term measurements with the SSM/I microwave radiometer from DMSP meteorological satellites for the analysis of annual and interannual variability of the

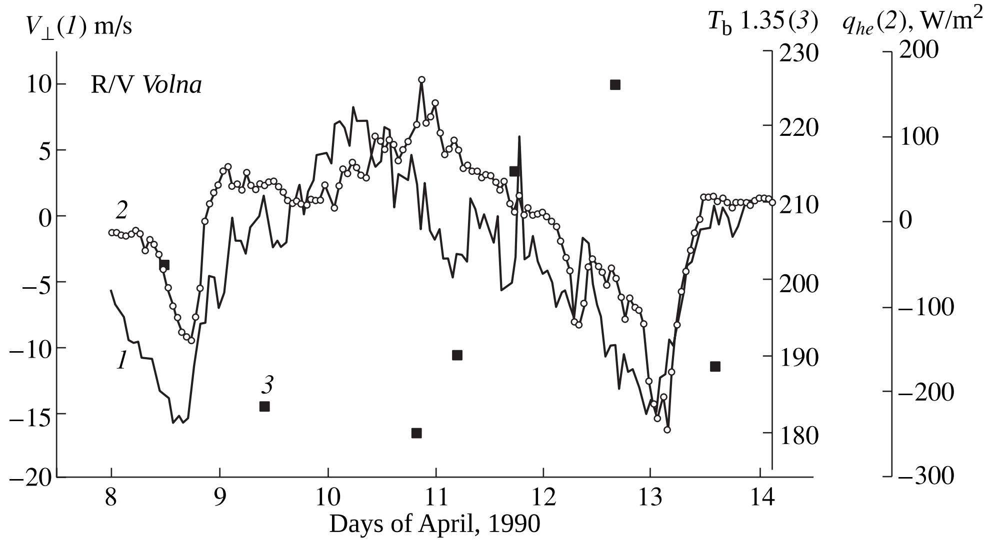

Fig. 5. Response of the brightness temperature T_b at a wavelength of 1.35 cm and the fluxes of total heat q_{he} to the variations of parameter $V_{\perp}$ during a cyclone passage on April 8–13, 1990.

intensity of heat interaction between the ocean and atmosphere in the Norwegian, Newfoundland, and Gulf Stream energy active zones of the North Atlantic. It was found that in these zones, there is a strong correlation between the monthly mean values of the brightness temperature of the air–sea system at a wavelength of 1.35 cm and heat fluxes (Fig. 6).

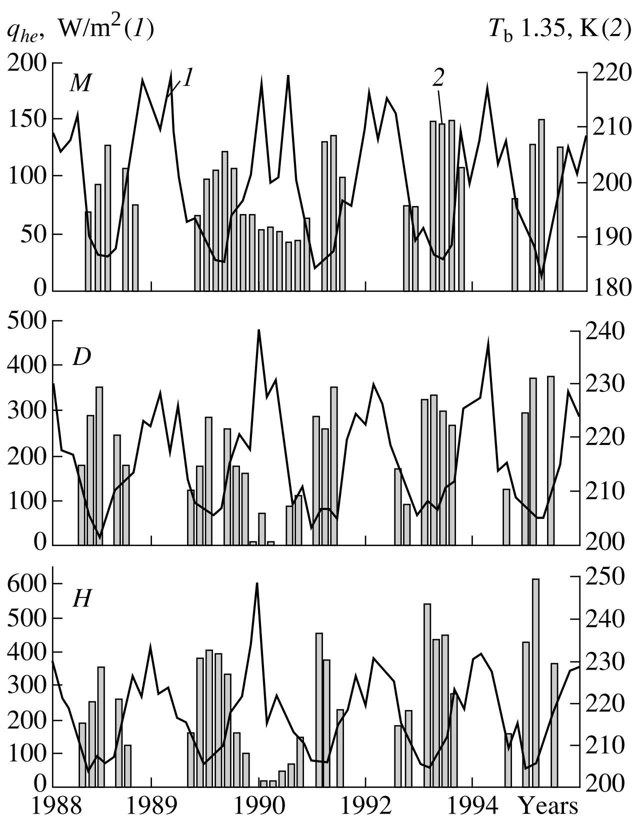

Fig. 6. Results of a comparison between the monthly mean values of (*1*) the fluxes of total heat q_{he} and (*2*) the brightness temperature T_b at a wavelength of 1.35 cm at points *M*, *D*, and *H* in the North Atlantic from 1988 to 1994.

CONCLUSIONS

The examples presented demonstrate the possibilities of the use of the data of microwave radiometric measurements for solving problems of the analysis of the heat and water exchange between the ocean and atmosphere (in the form of heat and momentum fluxes), of the dynamics of atmospheric and oceanic fronts, and of the trans-frontal heat and water transport. It should be noted that the characteristics of the natural microwave radiation of the air–sea system can serve as direct characteristics of these processes in a wide range of time scales: from the synoptic scale to the climatic one. Such an approach is different from the traditional ideas of oceanologists, according to which the satellite methods should be used only for the estimations of a set of intermediate parameters of the ocean and atmosphere involved in the calculations of heat fluxes (bulk-formulas).

The strong correlation between the brightness temperature of the natural microwave radiation of the air–sea system with the characteristics of the heat interaction between the ocean and atmosphere observed on the synoptic timescale in the middle and high latitudes of the North Atlantic can be explained by the intensive processes of large-scale horizontal transport of heat and water in the atmosphere inherent in these areas. Precisely these processes govern the heat and humidity regimes of the atmospheric layers, which take place in the heat and water exchange with the ocean surface and in which the SOA radiation is simultaneously generated.

A set of reasons responsible for the discrepancy between the satellite microwave radiometric data and direct (ship-borne) measurements on the synoptic scale can be indicated:

(1) The presence of significant horizontal gradients of the heat and momentum fluxes in the regions of the location of the R/Vs *Victor Bugaev, Musson*, and *Volna*. For instance, the data from [16] suggest that, in the region of the location of the R/V *Viktor Bugaev*, which was the closest to the subpolar hydrological front, the value of the horizontal gradient of the parameter of the total heat flux can reach 2–5 W/m^2 per kilometer. Thus, within the field of view of the receiving antennas of the radiometer, whose linear sizes are 15–30 km, the ambiguity of the estimate of the q_{he} parameter can reach 30–150 W/m^2.

(2) The presence of a time lag (up to 30 min) between the data of satellite and ship-borne measurements, which, in our opinion, gives an additional error in their comparison, reached 20 W/m^2 for parameter q_{he} and up to 0.03 N/m^2 for parameter q_V.

In addition, the specialists in the interaction between the ocean and atmosphere have different opinions on the accuracy of the methods used for the calculation of heat fluxes above the ocean, estimated at 30% in [32] and more in [28].

An important role of the total concentration of the water vapor in the atmosphere as a direct quantitative characteristic of the process of the heat interaction between the ocean and atmosphere on various timescales should also be noted.

There is no doubt that the SSM/I radiometer can be used for the assessment of annual and interannual variability of the characteristics of the air–sea interaction in the North Atlantic. These results should be discussed separately since it is believed that the retrieval of heat fluxes at the air–sea interface needs to use not only the results of meteorological probing of the SOA but the also the estimates of the surface temperatures, which can usually be obtained either in the 3–8-cm band of the microwave range or in the 8–12-μm band of the IR range, which are absent in the SSM/I radiometer. This question was posed in the analysis of the role of various parameters of the ocean and atmosphere in the formation of correlations between the brightness temperature and heat fluxes on the synoptic timescale [10] when it became clear that, in this case, the contribution of the surface temperature is minimal in comparison to the atmospheric parameters. Having discussed this result with V.N. Pelevin and S.V. Pereslegin, specialists of the Institute of Oceanology, Russian Academy of Sciences, we concluded that it can be explained by the inertia of the heat regime of the sea surface with respect to the rapidly altering heat and dynamical processes in the atmosphere inherent in the synoptic timescales. Why is this behavior retained on longer periods, where the microwave radiation characteristics of the SOA are clearly affected by the annual and interannual variability of sea surface temperature, still remains the subject of further study. An answer to this question is important both from the scientific point of view (what factors are primary in the processes of the large-scale heat interaction between the ocean and atmosphere) and from the point of view of practice (to what extent the use of meteorological satellites is efficient for the analysis of the intensity and dynamics of the heat and water exchange in the SOA on decadal and other timescales).

The experience obtained in the study shows that for the further improvement of the satellite microwave methods for analysis of the heat and dynamical interaction between the ocean and atmosphere it is necessary to take into account the following conditions and requirements:

(1) The methods should preferably be based on the models of correlation between irradiative and heat characteristics of the SOA, which have a clear physical sense and include a minimum of intermediate parameters, e.g. they can be based on simple (low-dimensional) parameterizations;

(2) The model used should include, if possible, those parameters of the SOA that are best scanned by satellite methods and, in particular, provide the strongest response of the field of the natural microwave (IR) radiation to their variations with respect to other parameters;

(3) The parameterizations used should be rather universal in order to allow their adaptation to various regions of the World Ocean (at least in the middle and high latitudes) for various seasons; they should also be valid in the cyclonic and frontal zones of the ocean, where the classical ideas on the heat and water exchange between the ocean and atmosphere (bulk-parameterization) are poorly efficient; and

(4) The satellite estimates of the characteristics of the heat and water exchange in this region of the ocean at a given moment of time should be useful even in the case when the mean values obtained during multi-year ship-borne, satellite, and other observations are used as base data.

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