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ELECTRODYNAMICS AND WAVE PROPAGATION

Brightness Temperature of Microwave Self-Radiation Employed as Direct Characteristic of the Dynamic Interaction between the Ocean and Atmosphere

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Abstract—It is proposed and substantiated that, in the ocean–atmosphere system, the microwave self-radiation intensity (brightness temperature), which is measured by means of satellites in the millimeter and centimeter wave bands, can be used as the direct characteristic of the thermal and dynamic parameters of the system. The vertical turbulent fluxes of sensible and latent heat and momentum are determined at the ocean–atmosphere interface according to the data measured by the special sensor microwave imagers located on weather satellites created in the scope of the defense meteorological satellite program and the advanced microwave scanning radiometer installed aboard the EOS Aqua oceanographic satellite. For the first time, the integrated (annual) characteristics of heat exchange between the ocean and atmosphere are investigated in the energy-active zones of the North Atlantic with the help of long-term satellite microwave radiometric measurements.

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INTRODUCTION

The methods for analyzing the interaction between an ocean and the atmosphere are developed using the annual variations and interannual variability of the climate. Their development was and remains an important aspect of investigations from the viewpoint of international programs, such as the World Climate Research Program (WCRP), International Geosphere-Biosphere Program (IGBP), Global Change Research Program (GCRP), Earth Observing System (EOS), Climate Variability and Predictability (CLIVAR), etc. This theme is topical for national interests of Russia, as is confirmed by the federal targeted program "World Ocean" (Decree no. 11 of the President of the Russian Federation dated January 17, 1997), including subprogram "Research of the Nature of the World Ocean" with Section "Development of the Uniform State System of Information on a Situation in the World Ocean".

Even 20–25 years ago, when our country performed regular expeditionary shipborne observations, their volume and number were insufficient to solve a whole series of scientific and applied problems. However, on account of a drastic reduction in these observations, satellites whose functional capabilities (measurement accuracy, spatial resolution, and, mainly, the duration of operation life) improve continuously have begun to play an increasing role in the studies of the World Ocean in recent years. For example, during the last quarter of the 20th century, US satellites constructed according to the defense meteorological satellite program (DMSP) performed continuous microwave radiometric measurements of the intensity of thermal radio self-radiation of the Earth on diurnal and semidiurnal scales, ensuring specialists with global and regular meteorological and oceanographic information. It should be noted that, as compared to satellite monitoring in the IR range, the aforementioned measurements are practically all-weather.

At the beginning of 1980s, the specialists of Kotel'nikov Institute of Radio Engineering and Electronics, Russian Academy of Sciences, pioneered the transition from investigations into the opportunities of employing the microwave radiometric methods for determining the separate parameters of the ocean surface and atmosphere (ocean surface temperature (OST), near-water wind velocity, and atmosphere parameters) in the synoptic range of time scales according to fragmentary measurements performed by domestic Kosmos-243, Kosmos-1056, and Kosmos-1151 satellites to their immediate utilization in analyzing the variability of the integrated characteristics of the ocean–atmosphere system (OAS) (averaged over months, seasons, and years). At present, there is an impressive set of instruments intended for microwave radiometric monitoring of the ocean and atmosphere, including the MTVZA microwave scanning radiometers of domestic Meteor satellites, the special sensor microwave imager (SSM/I) of DMSP weather satellites, advanced microwave scanning radiometer (AMSR-E) of the EOS Aqua oceanographic satellite, advanced microwave sounding units (AMSUs) of National Oceanic and Atmospheric Administration (NOAA) satellites and others.

Modern Earth remote sensing satellite systems (at least microwave radiometers) differ little in performance characteristics (operating wavelength band, sensing angles and polarization types, spatial and temporal resolutions (details) of satellite data). In the last 20–25 years, the United States, Japanese, and Russian leading designers of satellite microwave radiometric facilities, which are intended for remote sensing of the ocean and atmosphere, have exhibited the so-called approachment (convergence) of design ideas and conceptions. To our opinion, we can establish, in particular, the fact that, at present, successful solutions to the problems concerning research into the thermal and dynamic interaction between the ocean and atmosphere and estimation of the parameters of the heat (energy) balance in the OAS on different time scales (synoptic, seasonal, and climatic) depend not only on technical aids themselves but is probably determined by the conception of their application.

1. CONCEPTION OF THE USE OF SATELLITE MICROWAVE RADIOMETRIC DATA IN THE ANALYSIS OF THERMAL INTERACTION BETWEEN THE OCEAN AND ATMOSPHERE

The conception is based on the use of atmospheric regions with resonant absorption (radiation) of molecular oxygen (5 mm) and water vapor (1.35 cm) as the “bridges” between the intensity of ascending OAS microwave radiation measured with the help of satellites and vertical turbulent heat and humidity fluxes in the system contact layer (interface) [1].

It is accepted that the parameters determined by means of a satellite, such as turbulent fluxes of sensible and latent heat and momentum, refer to so-called climate-forming parameters. The main problem of their determination with the help of satellites is that microwave self-radiation field carries information on both the lower atmosphere participating directly in energy exchange with ocean surface and its higher layers. Hence, satellite microwave radiometry used to analyze climate-forming parameters has begun to actively develop only from the 1980s–1990s (predominantly in USA, Russia, and Germany) although the encouraging results gained when remote microwave and IR radiometric methods were applied to the analysis of heat exchange processes at the “water–air” boundary (in measurements under laboratory conditions and with the help of floating platform and low-flying aircrafts) have been already obtained in the 1960s and 1970s. The given conception is implemented using the following prerequisites:

(i) The components of heat and moisture exchange between the ocean and atmosphere (OST, air temperature and its moisture, and near-water wind velocity) participate directly in the formation and transformation of microwave radiation in the indicated spectral regions in near-water (10–20 m) and superjacent layers of the atmosphere.

(ii) In the given spectral regions, the thickness of the atmospheric layer with formed OAS microwave radiation is close to that of an atmospheric boundary (turbulent) layer (1000–1500 m) [1].

Below, we consider several examples demonstrating how satellite microwave radiometric methods are applied to the study of thermal and dynamic interactions between the ocean and atmosphere in the wide range of time scales: synoptic, intraannual (seasonal), and interannual. For these purposes, we employ the satellite data archive accumulated for 25 years of our activities (its description can be found in [2]).

2. EXAMPLES OF THE USE OF SATELLITE MICROWAVE RADIOMETRIC METHODS IN THE ANALYSIS OF THE THERMAL INTERACTION BETWEEN THE OCEAN AND ATMOSPHERE ON THE SYNOPTIC TIME SCALES

A. Newfoundland Energy-Active Zone in the North Atlantic

Basic results were obtained by comparing data of research weather ships (RWSs) Viktor Bugaev, Musson, and Volna, which were measured during NEWFOUEX-88 and ATLANTEX-90 experiments in the Newfoundland Energy-Active Zone (EAZ) of the North Atlantic, with microwave radiometric measurements performed by means of the SSM/I mounted on the US F-08 weather satellite (DMSP).

Satellite- and ship-borne measurements were planned and carried out independently by different scientific and industrial organizations of the USSR and USA in 1988 and 1990s. An idea of their comparison made it possible to obtain a number of useful results concerning the application of satellite microwave radiometry to the investigation of thermal and dynamic interactions between the ocean and atmosphere [1, 3].

The SSM/I is a scanning seven-channel and four-frequency system intended to measure the brightness temperature of microwave self-radiation of an OAS at an observation angle of 52° on horizontal and vertical polarizations at frequencies of 19.35, 37, and 85.5 GHz, as well as on vertical polarization at a frequency of 22.2 GHz in the observation band of 1400 km that ensures the global coverage of the Earth during three days and an incomplete coverage for twenty four hours [4, 5].

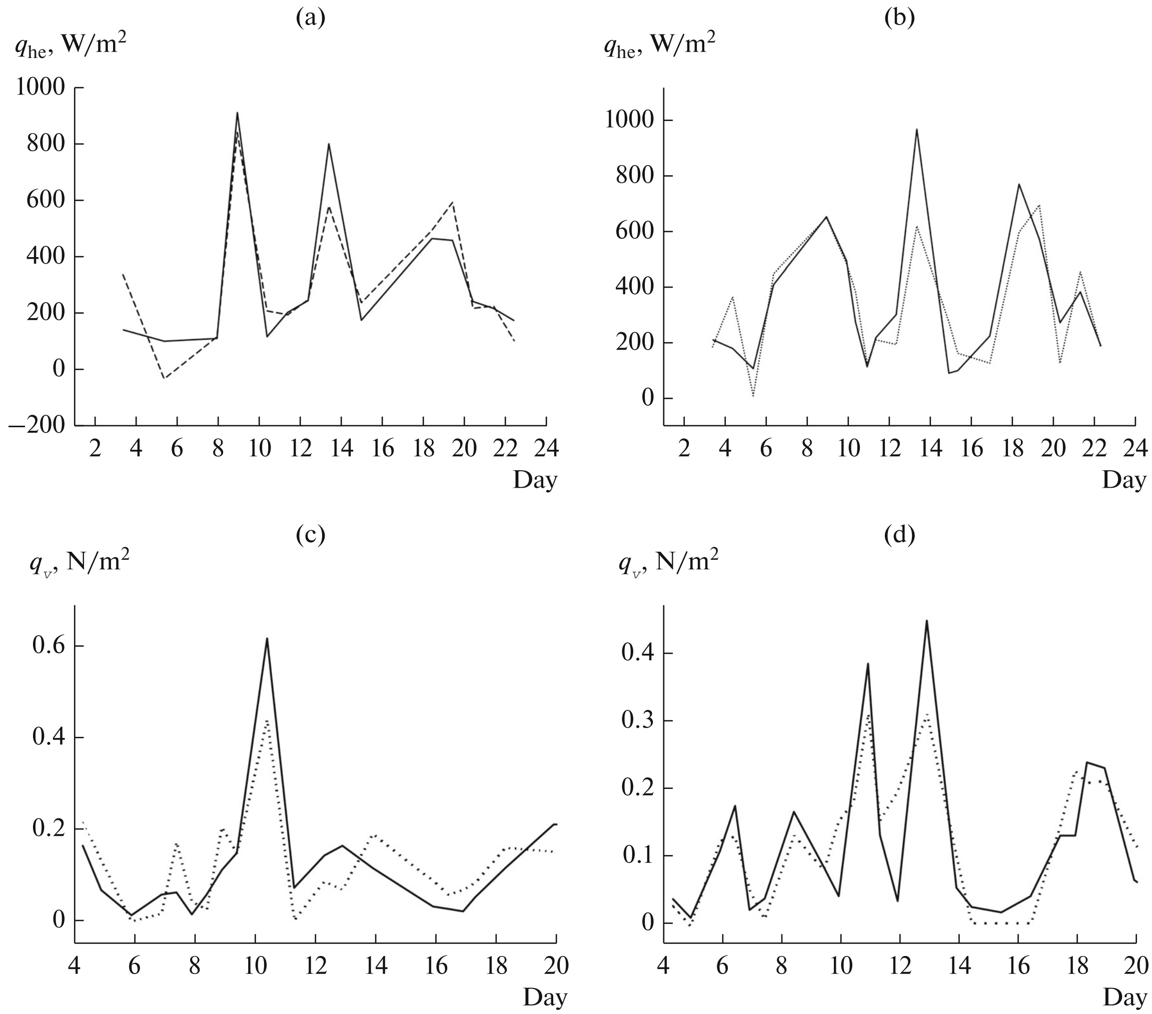

Fig. 1. Comparison between the direct (shipborne) estimates of the total heat and momentum fluxes (q_{he} and q_v, respectively) (continuous lines) and their satellite-borne microwave radiometric estimates obtained with the help of linear regressions and the brightness temperatures measured by the SSM/I instrument (dashed lines) in the Newfoundland EAZ near RWSs (a, c) Musson, (b) V. Bugaev, and (d) Volna during (a, b) NEWFOUEX-88 experiments performed in March, 1988 and (c, d) ATLANTEX-90 experiments in April 1990. In this case, σ_{he} = (a) 121 and (b) 143 W/m^2 and σ_v = (c) 0.08 and (d) 0.068 N/m^2.

Relying on the huge data archive collected over the entire period of the NEWFOUEX-88 and ATLANTEX-90 experiments, we chose only data on their stationary phases (in this case, RWSs remained immovable for a long time) distinguished by the following features [6, 7]:

(i) The largest periodicity and regularity of meteorological and aerological observations in this period (24 and 4 times per day, respectively).

(ii) The opportunity of investigating the time dynamics of ocean and atmosphere parameters in pure form due to the fixed position of RWSs.

In this period, RWSs performed measurements at three points of the Gulf Stream delta: in the southern periphery of the Gulf Stream (RWS V. Bugaev), in the southern branch of the Gulf Stream (RWS Musson), and in the eastern branch of the Labrador Current (RWS Volna). The given ocean region is characterized by a substantial synoptic variability in ocean and atmosphere parameters, which is associated with the proximity of the subpolar hydrological front caused by both the interaction of the cold Labrador Current with a warm thermal quasi-stationary anticyclonic vortex of the Gulf Stream and the vigorous activity of mid-latitude cyclones [7].

Figure 1 presents the examples of linear regression analysis between the total (sensible and latent) heat and momentum fluxes (q_{he} and q_v, respectively), which were recorded in NEWFOUEX-88 and ATLANTEX-90 experiments, and their remote estimates obtained as the linear combinations of the brightness temperatures measured in the channels 22.2V, 37V, and 37H of the SSM/I instrument (symbols V and H designate the vertically and horizontally

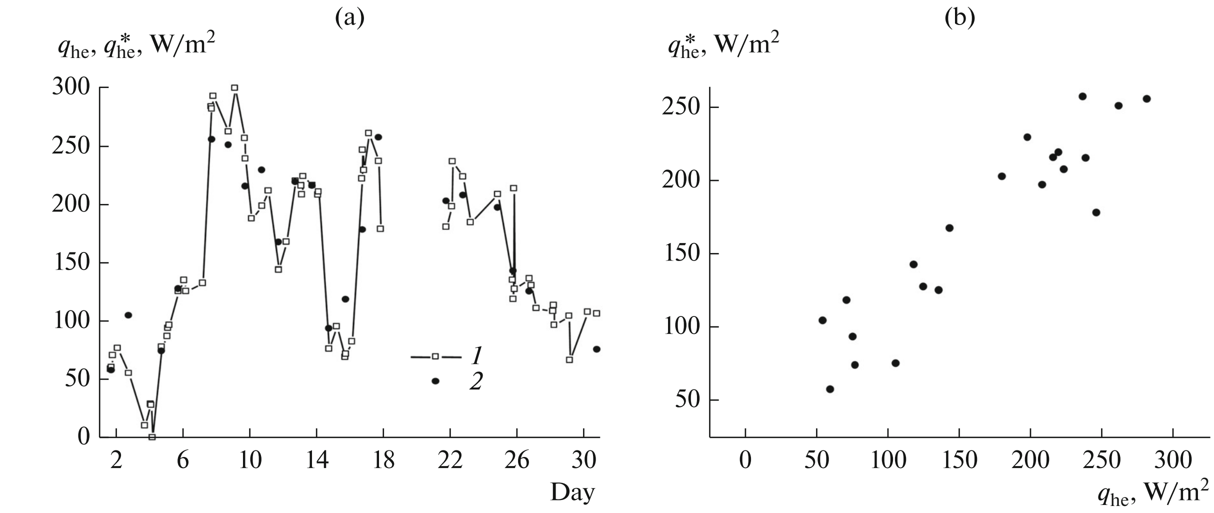

Fig. 2. Comparison between (a) direct (shipborne) and (b) satellite estimates q_{he} of total heat fluxes q^*_{he} at point M of the North Atlantic: (a) variations in parameters q_{he} and q^*_{he} in April, 1988 and (b) linear regression between parameters q_{he} and q^*_{he}, namely, $q^*_{he} = 32.83 + 0.81\ q_{he}$, $r = 0.93$, and $\sigma = 24.6$ W/m^2.

polarized radiation received by the given instrument), which ensures the least mean-square difference (residual) with the original values of q_{he} and q_v.

B. Norwegian Energy-Active Zone in the North Atlantic

There is a close interrelation between the shipborne estimates of total heat fluxes in the Norwegian–Greenland EAZ (materials were submitted by Iorg Schultz, Germany) and the satellite-borne estimates obtained via linear regressions with simultaneous measurement data in the channels 22.2V, 37V(H), and 19.55V of the SSM/I of the F-08 satellite (Fig. 2). The coefficient r of correlation between direct and remote estimates of fluxes is 0.93. In this case, the residual is $\sigma = 24.6$ W/m^2, and the ratio between this quantity and the heat flux variation is 8.2%.

We note that strong variations in OAS meteorological parameters are accompanied by considerable changes in the brightness temperature of the system. This facilitate the problem regarding the interpretation of satellite microwave radiometric measurement data if an indispensable condition is to allow for the microwave radiometer sensitivity and measurement calibration errors.

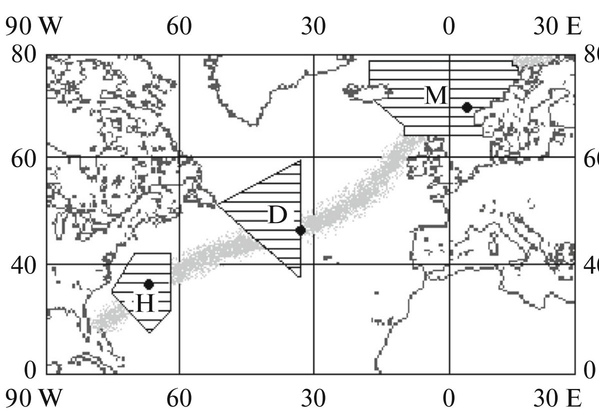

Fig. 3. Arrangement of the (H) Gulf Stream, (D) Newfoundland, and (M) Norwegian–Greenland EAZs with respect to the Gulf Stream and the North Atlantic Current.

3. BRIGHTNESS TEMPERATURE AS THE CHARACTERISTIC OF THE THERMAL INTERACTION BETWEEN THE OCEAN AND ATMOSPHERE IN THE GULF STREAM ACCORDING TO THE DATA OBTAINED FROM THE AMSR-E OF THE EOS AQUA SATELLITE

A. Area of Interests in the North Atlantic

Using the global data array of satellite microwave radiometric measurements [3], we extracted the fragments corresponding to the areas of interest, which, in the given case, are the North Atlantic regions occupied by Norwegian (M: MIKE 66° N and 2° E), Newfoundland (D: DELTA 44° N and 41° W), and Gulf Stream (H: HOTEL 38° N and 71° W) EAZs (see Fig. 3). These zones affect deeply weather conditions and climatic characteristics in Europe and the European territory of Russia. Afterward, the series of the daily and monthly brightness temperatures, which were measured by means of the SSM/I instrument and

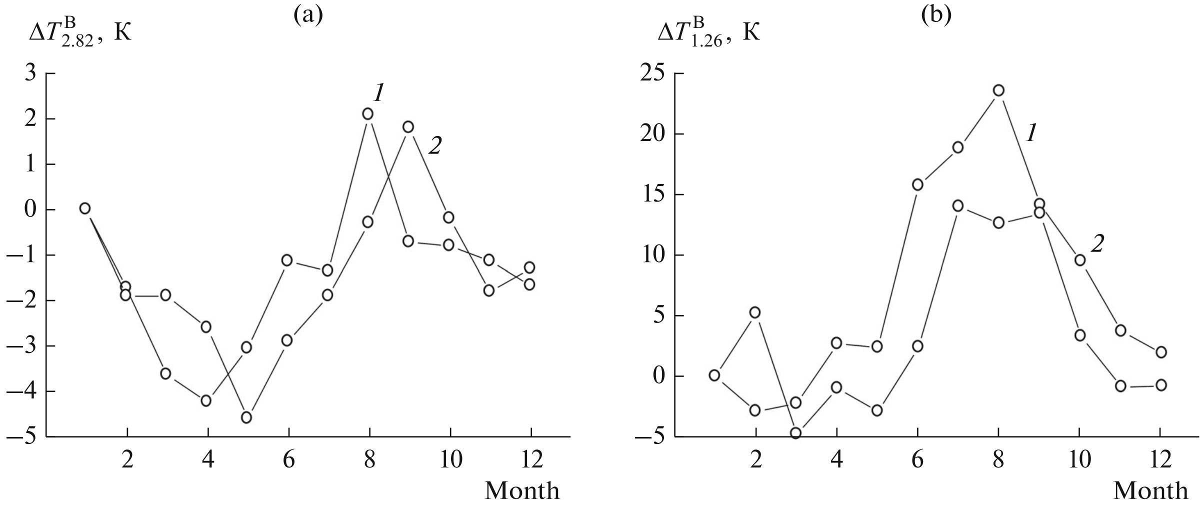

Fig. 4. Variations in the monthly brightness temperatures observed at wavelengths of 2.82 and 1.26 cm in region D: (a) 2010 and (b) 2005. Data were combined in the single scale.

the AMSR-E in different time intervals (they passed through more local regions (squares of 0.5° × 0.5°), namely, M, D, and H), were formed.

In old days, shipborne weather stations guaranteed oceanographic and meteorological data measured at these points, which were most numerous, regular, reliable, and, consequently, most attractive for the interpretation of satellite microwave radiometric measurements. The number of satellite orbits above the aforementioned North Atlantic regions varies from 17 to 34 in month, ensuring the quite satisfactory quality of determining the characteristics of the thermal and dynamic interaction between the ocean and atmosphere and estimating their seasonal and interannual variabilities [1].

B. Seasonal Variability of the Brightness Temperature in the Regions H and D of the Gulf Stream

For the different North Atlantic regions belonging to the Gulf Stream area, the seasonal variabilities of the monthly brightness temperatures measured in different years by means of the channels 10.65V (2.82 cm) and 23.8V (1.26 cm) of the AMSR-E were comparatively analyzed. Since 2002 until now, the AMSR-E installed on the EOS Aqua satellite ensures regular monitoring of the Earth surface. As compared to the SSM/I instrument, this instrument is equipped with long-wavelength channels of 2.82 cm (10.65 GHz) and 3.45 cm (6.9 GHz). Its technical characteristics were described in [8].

In the region of relative transparency of the atmosphere, channel 10.65V measures the brightness temperature related predominantly to the OST. In the absorption (radio self-radiation) region of the atmospheric water vapor, and the data recorded in channel 23.8V carry information on its thermal (temperature and humidity) characteristics. V-type channels are chosen because the OAS microwave self-radiation of the vertical polarization is less critical to the wind state (degree of roughness) of the ocean surface as compared to H-type channels, which measure the OAS brightness temperature on the horizontal polarization. In this case, the system's thermal properties manifest themselves to a better extent at the background of its other characteristics.

Figure 4 illustrates the results obtained from the comparative analysis of the seasonal dynamics of the OAS brightness temperature at wavelength 2.82 and 1.26 cm (in 2005 and 2010) in the region D of the Newfoundland EAZ. Data obtained in April 2010 during emergency oil spill in the oil-producing regions of the Gulf of Mexico, which partially retarded the transport of the warm Gulf Stream to the Europe coast, stand out against the background of ordinary 2005, which differs little from average climatic norms. This effect was detected by Dr. Gianluigi Zangari from the National Institute of Nuclear Physics, Frascati, on the basis of satellite IR radiometric measurements.

The reference points were the brightness temperatures observed at wavelengths of 2.82 and 1.26 cm in region D of the North Atlantic in January 2010.

The maximum range of seasonal variations in the monthly brightness temperatures of the OAS varies from 7 K (in region D) to 9 K (in region H) at a wavelength of 2.82 cm and, respectively, from 20 to 30 and 30 to 35 K at a wavelength of 1.26 cm. This coincides well with the known information on the predominance of heat and moisture exchanges (in particular, vapors) in low latitudes as compared to middle latitudes. In region D of the North Atlantic, the time delay (by one month) between the response of the OAS brightness temperature in the OST variation (at a

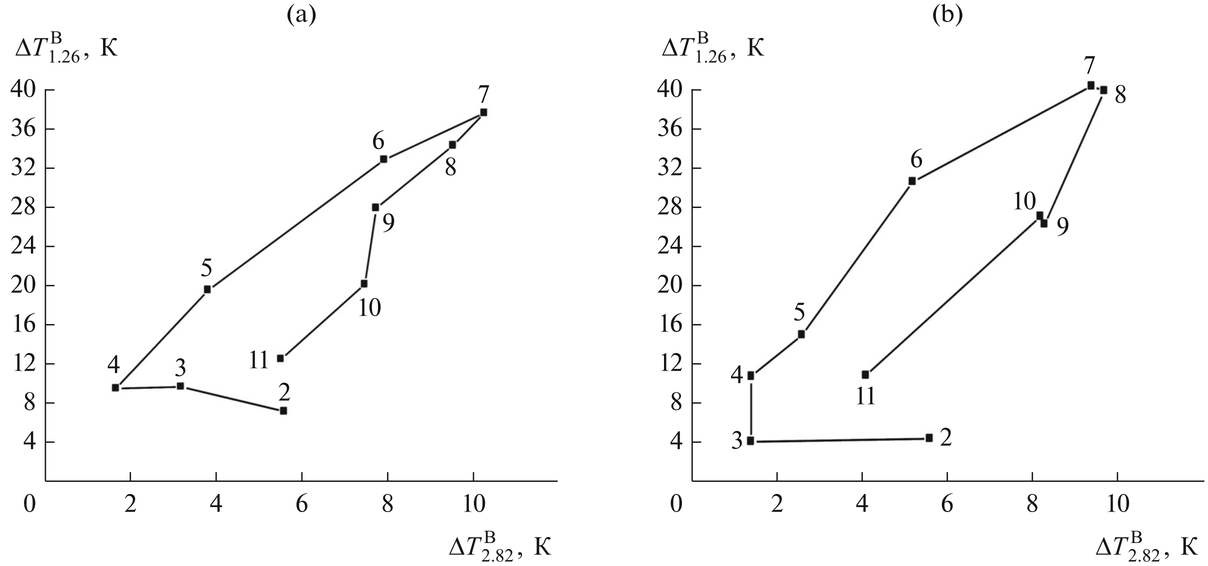

Fig. 5. Annual trajectories of the brightness temperature observed at wavelengths of 1.26 and 2.82 cm. Data were obtained in region H of the North Atlantic: (a) 2010 and (b) 2005. Numerals 2–11 designate months of the year.

wavelength of 2.82 cm) and the response of the brightness temperature of the variation in the total content of atmospheric water vapor (at a wavelength of 1.26 cm) is distinctly observed. In connection with this, as was demonstrated in [1], there is the possibility of constructing the microwave radiation (radio brightness) images of the annual dynamics of the heat exchange between the ocean and atmosphere in different EAZs of the North Atlantic in the form of the trajectories (loops) of the OAS brightness temperature.

C. Annual Cycles (Loops) of the Brightness Temperature in Regions H and D of the Gulf Stream

The technique for calculating the integrated (averaged over a year) sensible and latent heat fluxes inherent to the ocean–atmosphere interface, which are commonly used in climatic investigations, was proposed in [6]. The given approach is based on the important statement made by the authors, according to which the integrated heat flux depends not only on the monthly OST t_s and the near-water atmosphere temperature t_a, which play a crucial role in heat exchange processes, but is also determined by the advance (delay) of variations in one of them with respect to variations in the other in the course of a year. This circumstance is related to the fact that parameters t_s and t_a are adapted to each other if the averaging period is one year or more. In the case of seasonal scales, to determine the heat-exchange intensity and its character (heat transfer from the ocean to atmosphere or vice versa), the degree of matching (mismatching) must be taken into account. The given technique is easily implemented in graph form because the intensity of heat and moisture exchange between the ocean and atmosphere can be described by pairs of quantities in the form of phase trajectories (t_s and t_a loops), the geometric characteristics of which, particular, the loop area, its orientation, and the degree of loop-shape divergence from a rectangular configuration, make it possible to compare integrated (annual) fluxes in the different regions of the world ocean and estimate their interannual variability [6].

Owing to the OAS microwave self-radiation field response to variations in OST and near-water atmosphere temperature, it is possible to construct the radiation images of annual t_s and t_a loops with the help of OAS brightness temperatures, e.g., in a spectral range of 3–5 cm, where the brightness-temperature sensitivity to changes in OST is a maximum, and at a wavelength of 1.35 cm characterized by close correlation between the brightness temperature and the thermal behavior and moisture characteristics of the atmosphere.

Such an approach was examined and substantiated in [1]. In particular, it was demonstrated that, in the Gulf Stream, Newfoundland, and Norwegian EAZs of the North Atlantic, the annual areas of radio-brightness loops differ considerably. Moreover, for these EAZs, their ratios are close to those of average long-term annual heat fluxes at the ocean–atmosphere interface. In so doing, the OAS brightness-temperature estimates were calculated from archival data on oceanographic and meteorological parameters with the help of known radiation models. Since the global data array of satellite microwave radiometric measurements has been created in the last 25 years, these problems can be now solved experimentally.

Figure 5 presents the annual trajectories (loops) of the monthly OAS brightness temperatures, which

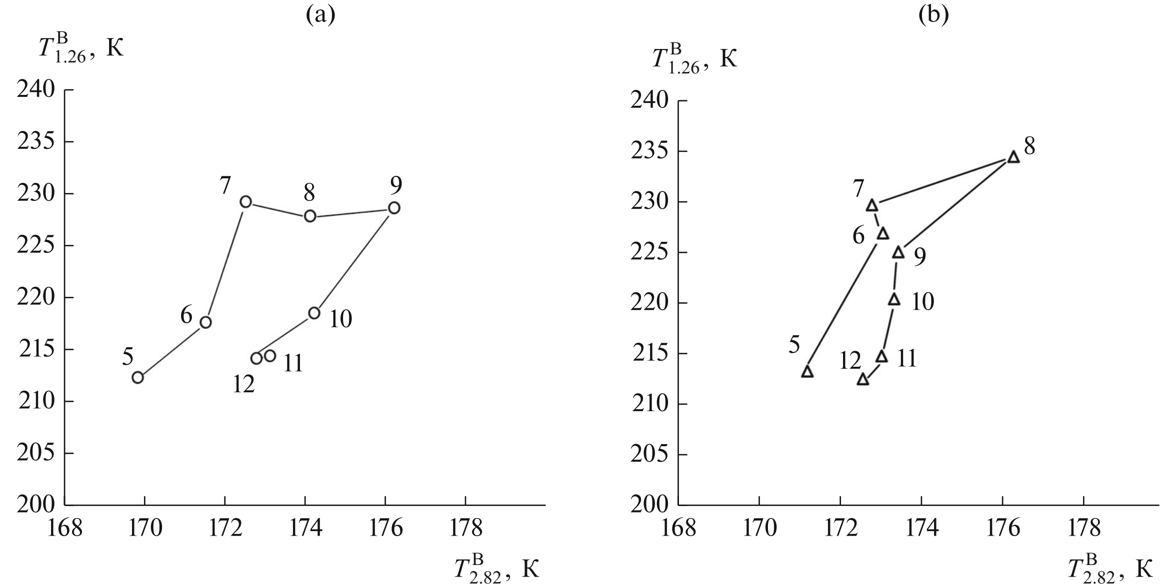

Fig. 6. Annual trajectories of the brightness temperature observed at wavelengths of 1.26 and 2.82 cm. Data were obtained in region D of the North Atlantic: (a) 2005 and (b) 2010. Numerals 5–11 designate months of the year.

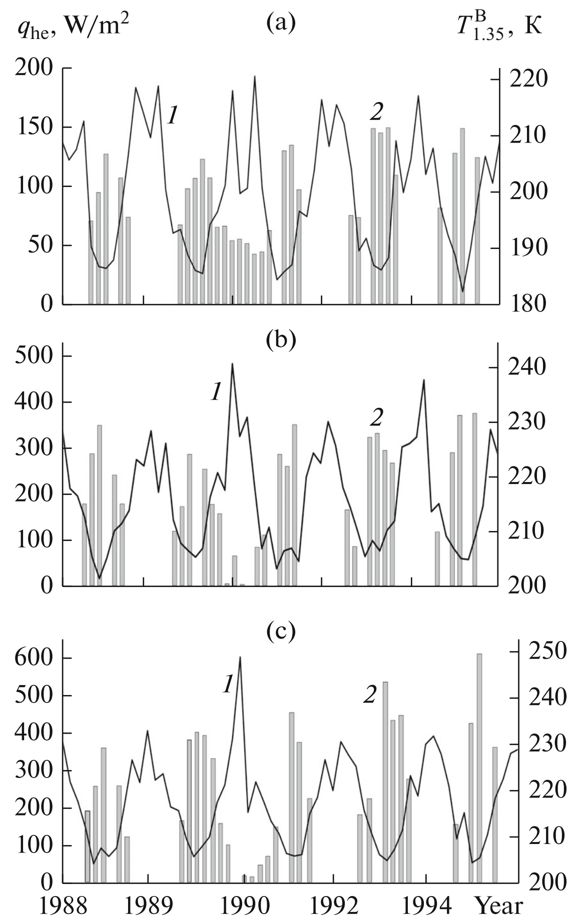

Fig. 7. Comparison between (*1*) the monthly total heat fluxes q_{he} and (*2*) the brightness temperatures $T^{B}_{1.35}$ at points (a) M, (b) D, and (c) H.

were measured by the AMSR-E in the Gulf Stream EAZ of the North Atlantic in 2005 and 2010.

In addition, there are the features of the 2010 annual cycle of the brightness temperature in region D of the Gulf Stream on the path of heat transit between southern and northern latitudes (Fig. 6).

Our estimates indicate that, in this zone of the North Atlantic, the ratio of the radio-brightness loop areas (i.e., the equivalent integrated (annual) heat flux through the OAS) diminishes 1.7-fold in the period from 2005 to 2010. The appreciable contrast of thermal and microwave radiation characteristics, which was observed in region D between 2010 and 2005, can be explained by the oil spill appeared in the Gulf of Mexico, as was mentioned above.

4. OAS BRIGTHNESS TEMPERATURE AS THE CHARACTERISTIC OF INTERANNUAL VARIABILITY IN THE THERMAL CORRELATION BETWEEN THE OCEAN AND ATMOSPHERE

Monthly vertical turbulent fluxes of the total (sensible and latent) heat corresponding to the ocean–atmosphere interface at points M, D, and H of the North Atlantic were estimated according to long-term OAS brightness-temperature measurement data in the different channels of SSM/I instruments located aboard F-08, F-10, F-11, F-12, and F-13 satellites. The results of comparison between the monthly fluxes at these points and the monthly brightness temperatures at a wavelength of 1.35 cm, which are closely related to the total moisture content of the atmosphere, are depicted in Fig. 7. The result of the regression analysis of the ratios between the monthly total

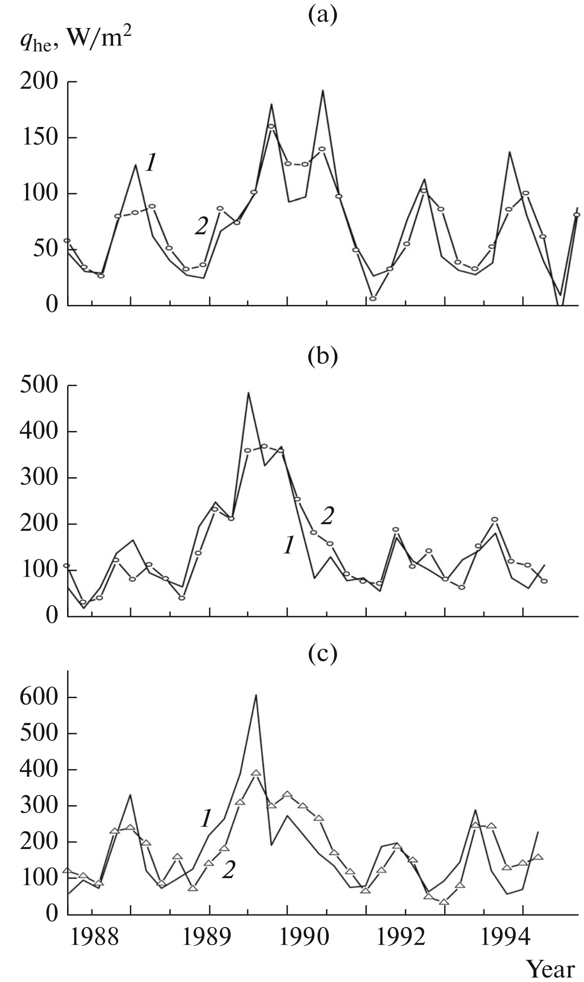

Fig. 8. Correlations between (*1*) the monthly total heat fluxes and (*2*) their satellite estimates at points (a) M, (b) D, and (c) H. The correlation coefficient is r = (a) 0.86, (b) 0.90, and (c) 0.81.

heat fluxes and their satellite estimates obtained from the data of radiometric channels 22.2V, 19.55V, and 19.55H are presented in Fig. 8.

Using the results shown in Figs. 7 and 8, we can definitely suppose that the OAS radio-brightness temperature can be employed to estimate the intra- and interannual variability of monthly heat fluxes at the system interface in the North Atlantic.

CONCLUSIONS

In the case of millimeter and centimeter wave ranges, the direct relation between the intensity of microwave self-radiation of the ocean–atmosphere system and the intensity of thermal processes in its contact layer (interface) is observed in the wide interval of time scales, namely, from synoptic to seasonal and interannual. This effect manifests itself especially distinctly in the line of resonant absorption of system radiation in the atmospheric water vapor at 1.35 cm and in the neighborhood of this wavelength.

In due time, NEWFOUEX-88 and ATLANTEX-90 experiments have played an important role in understanding the nature of synoptic processes characterizing the interaction between the ocean and atmosphere in middle latitudes. However, their results continue to be valuable in studying the opportunities to analyze these processes by means of satellite microwave radiometric instruments and methods. From the combined analysis of archival data of the ATLANTEX-90 experiment and the F-08 satellite, it is easy to make sure that data on scientific expeditionary and operational satellite investigations of the ocean can be efficiently interconnected even if they are planned and implemented independently of each other.

The method for analyzing the integrated (annual) characteristics of the thermal interaction between the ocean and atmosphere is proposed and substantiated. According to this approach, the criteria of their intra- and interannual variability are constructed using the data of the long-term (lasting of many years) satellite microwave radiometric measurements of OAS radiobrightness temperatures, rather than calculated results. The given method is employed to examine the dynamics of monthly brightness temperatures in the Gulf Stream and Newfoundland energy-active zones of the North Atlantic in 2010 that was noteworthy due to emergency oil spill in the Gulf of Mexico.

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