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Microwave Radiation of the Ocean-Atmosphere

Boundary Heat and Dynamic Interaction

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We dedicate this book of blessed memory of Prof. Anatoly Shutko

Preface

This monograph is dedicated to the elaboration of passive microwave (MCW) radiometric methods for the study of ocean-atmosphere interactions: it is a sequel to the monograph *Relation Between Natural Microwave Radiation of the Ocean-Atmosphere System with the Boundary Heat and Dynamic Interaction* by A.G. Grankov and A.A. Milshin published by Nauka (Moscow, Russia, 2004) with the support of the Russian Foundation for Basic Research. Later, in 2010, the Springer issued an expanded and revised edition of this book in English, titled *Microwave Radiation of the Ocean-Atmosphere: Boundary Heat and Dynamic Interaction*.

After publication of the book *Radioemission of the Earth as a Planet* by A.Je. Basharinov, A.S. Gurvich, and E.T. Egorov (Moscow, Russia, 1974), MCW radiometric methods based on the natural radiation of the earth and atmosphere achieved recognition and wide use. Ten years earlier, the monograph *Radiothermal Location* (*Passive Radiolocation*) by A.G. Nikolaev and S.V. Pertshev was published by Sovetskoe Radio; however, this monograph differed greatly because it could not display the results of the unique radiophysical experiment carried out from the satellite Cosmos-243 in 1968.

In this monograph, we discuss some possibilities for using the potential of satellite passive MCW radiometric methods in the analysis of variations of heat and dynamic processes in the ocean–atmosphere interface for a wide range of time scales—from *mesometeorogical* (of an hour), *synoptic* (of a week), and *seasonal* (of a month), to *interannual*. The methods for analysis of the processes of ocean–atmosphere interaction as a factor of seasonal and interannual variability is a very important component of international scientific programs, such as the Global Change Research Program and Earth Observing System (EOS). The need for high-resolution, accurate surface fluxes of heat, water vapor, and momentum over the global ocean has been articulated by numerous groups within the global climate community, including the World Climate Research Programme (WCRP) Working Group on Air–Sea Fluxes (WGASF), the WCRP Global Energy and Water Cycle Experiment (GEWEX) Radiation Panel, and the Climate Variations (CLIVAR)

Science Steering Group. The GEWEX Radiation Panel and the U.S. CLIVAR Committee have established a goal of 1° spatial resolution, 3- to 6-h time resolution, and accuracy of 5 Wm^{-2} for individual components of the surface heat budget. The actuality of these subjects has also been emphasized in special issues of Russian programs on ocean research and the development of systems for its studies.

As a result of the steady reduction of field measurements in the World Ocean, satellites have become the most important tools in its investigation. Measurements from vessels and buoys do not provide the required spatial resolution and time regularity for observations, whereas conventional estimates of global fields of the fluxes between ocean and atmosphere suffer from inadequate spatial and time sampling. Only a few exceptions exist, such as the network of meteorological stations in the equatorial belt of the ocean (TAO/TRITON) and the system of buoy stations in the Gulf of Mexico designed for the regular monitoring of ocean surface parameters and the near-surface atmosphere in active areas of the tropical cyclogenesis.

The parameters measured from satellites, such as vertical turbulent fluxes of sensible and latent heat and the impulse (momentum), are considered to be the so-called climatic-forming factors. The main problem in retrieving these parameters from satellites is as follows: an intensity of natural MCW radiation in the ocean–atmosphere system (SOA) results in information not only on near-surface atmospheric layers (which are most active in forming the processes of energy exchanges with the oceanic surface) but also on the higher layers. Therefore, satellite passive MCW radiometric analysis of climatic-forming parameters was recognized as an effective tool in the 1980s and 1990s (mainly in the United States, Russia, and Germany). Prior to this, in the 1960s and 1970s, some encouraging results were reported for the use of remotely sensed data in laboratory studies; in addition, measurements were obtained from aircrafts and floating platforms using microwaves and infrareds for the analysis of the heat and water exchange at the air–sea boundary.

In the twenty-first century, strong efforts have been made toward developing methods to determine geophysical parameters, such as water vapor content in the atmosphere and radiation fluxes, from geostationary and polar orbiting satellites. Retrievals developed for radiometers on the National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellites, such as the Advanced Very High Resolution Radiometer (AVHRR), the Special Sensor Microwave/Imager (SSM/I) on the DMSP program, and the instruments onboard the Tropical Rainfall Measuring Mission (TRMM) satellite are distinguished by an accuracy that is comparable to or better than in situ measurements.

Various methods for estimation of the monthly mean latent heat fluxes at the SOA boundary and their seasonal variability have been proposed and approved. These methods are based on the direct (*physical*) or indirect (*correlative*) relationships between the SOA brightness temperatures measured from satellites and the most important components of heat and moisture exchange, such as the ocean (sea) surface temperature and the temperature, moisture, and wind speed of the near-surface atmosphere.

We examined the potential of the SSM/I radiometer for retrieval of the synoptic latent fluxes, but the results of these studies were not encouraging. Some research gaps should be addressed on the real and potential possibilities of satellite passive MCW radiometric methods in relation to an analysis of the heat and dynamic ocean-atmosphere interaction:

- The methods used are based on formulas of heat and water exchange between the ocean and atmosphere (*bulk formulas*), accounting for calculations of the near-surface air temperature and humidity, which are *indirectly* connected to the SOA brightness temperature.
- Usually, only the atmospheric characteristic of humidity, as measured from satellites in the spectral MCW band of water vapor absorption, is taken into consideration as the intermediate characteristic between the SOA brightness temperature and the surface heat fluxes.
- Relationships between the SOA's brightness temperature and the surface heat fluxes have a static characteristic, as they are based on *general* (climatic) regressions between the air integral and near-surface humidity, which do not reflect their effects on various mechanisms of heat and water transfer in the atmosphere (e.g., vertical diffusive, horizontal advective) in short timeframes.
- More importantly, specialists in the field of remote sensing of oceanological and climatic processes have not considered the possibility of using satellite MCW radiometric methods in *frontal* oceanic zones, where the effectiveness of bulk formulas is not yet clear.
- The potential of satellite passive MCW radiometric methods for the analysis of energy, circulation characteristics of the boundary layer of the atmosphere, and their influence on heat and water exchange at the boundary of the SOA have not been fully researched.
- Finally, for remote sensing of the World Ocean by means of passive radiometric MCW, infrared (IR), and other methods, researchers have lost sight of the urgent problem concerning the study of the initial role of the ocean and atmosphere in their heat and dynamic interactions at various spatial and time scales.

All of these circumstances were noted in our previous monograph (Grankov and Milshin 2004), which summarized the results of our work for the 20 years prior to its publication.

During 2008−2011, the scope of our interest was extended. We studied the ocean–atmosphere heat and dynamic interaction with MCW radiometric methods in midlatitude cyclones and the oceanic areas subjected to the impacts of tropical cyclones (hurricanes). In this period, several studies were conducted:

- Clarification of the role of *horizontal* (advective) heat transfer in forming the relationship between the intensity of the SOA's natural MCW radiation and the intensity of heat and moisture exchange at the ocean–atmosphere boundary.
- Study of the behavior of the SOA's oceanographical, meteorological, aerologic, and MCW radiation characteristics in areas of tropical cyclone activity, with a comparison to midlatitude North Atlantic cyclones.

- Analysis of the atmospheric dynamics and energy in oceanic (sea) waters for cyclonic (prestorm) conditions with data of simultaneous satellite MCW radiometric and station (buoy) meteorological measurements.
- Elaboration of the methods for determining heat and moisture content in the near-surface, boundary, and troposphere layers of the atmosphere with satellite and station (buoy) measurements.

A special aspect of these studies is the investigation of mechanisms of the SOA's natural MCW radiation reaction to heat property variations in the near-surface and boundary layers of the atmosphere, as well as the search for spectral intervals and suitable scales of space and time. Data from satellite measurements was averaged to provide an immediate (*direct*) connection between the SOA's brightness temperature measured from satellites and the intensity of heat and moisture exchange at the boundary of the system.

The atmosphere boundary layer plays a special role in our studies for the following reasons:

(a) Because of the processes of turbulent mixing, the atmosphere boundary layer's parameters are closely associated with the parameters of the near-surface layer (0−10 m), which affect the intensity of its heat and moisture exchange with the ocean surface.
(b) Within this layer, natural MCW radiation of the SOA is formed in a line of radiowave absorption in atmospheric water vapor (at a wavelength of 1.35 cm) and its vicinity.

At meetings and seminars, we are often asked why such a strong correlation is observed between the SOA's brightness temperature and heat processes in the atmospheric boundary and near-surface layers, and why the ocean surface temperature so weakly influences the near-surface heat fluxes at the synoptic range of time intervals. Answers to these questions will be given in this book.

Our studies were supported by the Russian Foundation for Basic Research (grant no. 94-05-16234a, 1994−1995). The Russian and American space agencies (Rosaviacosmos and NASA) sponsored our activity within the contract NAS 15-10110, 1996−1997). Later, the results were applied to studying the behavior of the SOA's natural MCW radiation characteristics in areas of tropical cyclone formation under the support of the International Scientific and Technological Center (grant No. 3827, 2008−2011).

The results of our studies on the role of horizontal advective heat transfer in the atmosphere boundary layer in forming relations between its enthalpy and the SOA's brightness temperature in the synoptic range of time scales were included in the 1998 and 2012 annual reports of the Russian Academy of Sciences (RAS).

Our research was conducted mainly at the Institute of Radioengineering and Electronics of Russian Academy of Sciences. We are grateful to our colleagues N.A. Armand, A.M. Shutko, B.G. Kutuza, E.P. Novichikhin, N.K. Shelobanova, Ju.G. Tischenko, A.B. Akvilonova, N.K. Shelobanova, B.Z. Petrenko, B.M. Liberman, and S.P. Golovachev.

An important factor in these studies was our collaboration with Moscow scientific organizations, including P.P. Shirshov's Institute of Oceanology RAS (A.I. Ginzburg, S.V. Pereslegin, V.N. Pelevin), Russian Hydrometcenter (Ju.D. Resnyaskii), Rosaviacosmos (I.V. Cherny), Institute of Space Research RAS (Yu.A. Kravtzov, Je.A. Sharkov), Institute of Water Problems RAS (G.N. Panin), Institute of Numerical Mathematics (A.I. Chavro), and Moscow Physical and Technical Institute (P.P. Usov).

An invaluable contribution to the studies was made by the unique data of vessel experiments NEWFOUEX-88 and ATLANTEX-90, which were received from the P.P. Shirshov's Institute of Oceanology RAS (S.K. Gulev), and the archive data of satellite MCW radiometric long-term (10-year) measurements derived from the U.S meteorological satellite DMSP, which were given to us by the Marshall Space Flight Center. The oceanographic, meteorological, and satellite measurements accumulated at point "M" of the North Atlantic, as reported by Joerg Schulz (Germany), expanded our understanding of the dependencies of SOA's brightness temperature and boundary heat fluxes of the middle latitudes on the higher ones.

We also note that the unique and expensive (even by Soviet measures) experiments NEWFOUEX-88 and ATLANTEX-90 will let us—as specialists in the remote sensing of the ocean from space—rest upon the data of these experiments again and again.

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Contents

Chapter 1
Accessible Parameters for Satellite MCW Radiometers and Their Relationship with Ocean–Atmosphere Interactions

1.1 Methods for Surface Heat Flux Analysis Using Radiometric Measurements

1.1.1 Traditional Approach

In remote sensing of heat exchange processes at the ocean–atmosphere system (SOA) interface, the characteristics of natural microwave (MCW) and infrared (IR) radiation of the SOA are formed not only in the near-surface atmosphere layer (10–20 m thick) but also in higher layers (2–5 km), depending on the spectral bands used in satellite measurements. There are different approaches to using MCW and IR radiometric measurements for estimating heat fluxes in the SOA interface. For example, one method retrieves the vertical temperature profiles (gradients) of the oceanic surface layer; Khundzhua and Andreev (1973) used the magnitude and the sign to judge the intensity of the vertical turbulent flux of sensible heat. The effectiveness of an infrared approach has been confirmed by the results of numerous laboratory studies, stationary coast points, and floating sea platforms; these results are in good agreement with the data from aircraft measurements (Bychkova et al. 1988).

The potential for retrieving the vertical temperature profile of the sea subsurface layer was investigated theoretically by Sharkov (1978) and Mitnik (1979). These studies were continued by specialists who developed and tested the possibilities of retrieving the water surface vertical temperature profile of the ideal (flat) and natural (waved) sea surface (Gaikovich et al. 1987) in laboratory studies.

MCW and IR ranges have not yet been proven for the determination of heat fluxes based on water surface vertical temperature profiles from satellite measurements. Modern satellite MCW and IR means, which accurately retrieve ocean surface temperatures (OST) within 0.5–1 °C, do not provide sufficient estimates of OST values and their variations. This is even true of MCW and IR methods for retrieving air vertical temperature and humidity profiles in local bands of radiation

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(absorption) for the most important atmospheric components—water vapor and oxygen, whose accuracy estimates are insufficient due to low spectral resolution and the sensitivity of radiometers.

More perspective is the method for determining heat fluxes based on the statistical correlation between the integral (averaged over height) atmosphere characteristics, whose variations are neatly fixed from satellites with MCW and IR measurement data, and its temperature and humidity values. This correlation results from the air near-surface and boundary layer mechanisms of turbulent heat and water mixing. These processes are most typical and intense for the atmosphere (versus the ocean) and have apparent mean variations each month (or decade), independent of more short-term perturbations. Therefore, the best results for satellite radiometric methods are obtained by retrieving *monthly* mean SOA boundary heat fluxes. These results are based, for example, on MCW and IR passive radiometric measurements from the satellite Nimbus 7, as well as from the DMSP and NOAA satellites.

The relationship between temperature and humidity in various atmospheric layers is the starting point for using satellite radiometric data to analyze the sensible (q_h) and latent (q_e) vertical turbulent heat fluxes at the SOA boundary, if we use semi-empirical formulas (bulk formulas) based on the global bulk aerodynamic method. In this method, the values q_h and q_e are given by the following formulas (Ivanov 1978; Lappo et al. 1990):

$$q_h = c_p \rho C_T (t_s - t_a) V; \quad (1.1)$$

$$q_e = L \rho (0.622/P_a) C_E (e - e_0) V, \quad (1.2)$$

From these formulas, one can see that the values of q_h and q_e depend on parameters of the SOA, such as temperature (t_a), water vapor pressure (e), and wind speed (V) in the near-surface atmosphere, as well as oceanic water surface temperature (t_s) and the maximum for this value, air humidity (e). The parameters used in bulk formulas (1.1) and (1.2) are the numbers of Schmidt (C_T), Dalton (C_E), the specific heat of evaporation (L), the specific air heat under constant pressure (c_p), and the air density (ρ).

The aerodynamic method also allows one to obtain the simple parameterization of the relationships between the intensity of a *dynamic* air–sea interaction characterized by the turbulent flux of impulse (momentum) (q_v), which can be calculated as follows (Ivanov 1978; Lappo et al. 1990):

$$q_v = \rho C_v V^2, \quad (1.3)$$

where C_v is the drag coefficient.

The formulas (1.1)–(1.3) enable one to determine not only "instant" heat and impulse fluxes, but also those averaged over considerable time periods. For example, it is possible to estimate the monthly mean heat and impulse fluxes using the monthly mean parameters of t_s, t_a, e, and V as the input data (Ariel et al. 1973; Esbensen and Reynolds 1981; Larin 1984; Gulev 1991).

This peculiarity of the global bulk aerodynamic method has attracted the attention of specialists in the fields of oceanology, meteorology, and climatology who are interested in remote sensing, especially for information on the near-surface atmosphere air temperature t_a and humidity e. However, this method has limitations. For example, the horizontal spatial gradients of the parameters t_s, t_a, and e must not exceed their critical values (Lappo et al. 1990). Consequently, the possibilities of its realization are unclear in the oceanic frontal zones, which have significant geophysical and brightness temperature spatial and temporal contrasts.

Formulas (1.1)–(1.3) show that the water surface temperature t_s, the near-surface air temperature t_a, humidity e, and wind speed V are the main factors in air–sea interchanges. Estimates of the parameters t_s and t_a can be obtained directly from satellite MCW radiometric measurements. To estimate the parameters t_a and e, one should use some correlative relations between these parameters and the intensity of the SOA natural MCW and IR radiation, which manifest only in some spectral intervals.

Extensive studies have analyzed the potential of satellite MCW and IR methods for estimating the characteristics of heat and dynamic interactions between the ocean and atmosphere. For example, Dymnikov et al. (1984) obtained some proximate estimates of oceanic layer parameters that are closely related to the SOA radiation balance. Grishin and Lebedev (1990) found the maximal values of errors of the parameters t_s, t_a, V, and e, when the estimates of the fluxes q_h, q_e, and q_v were calculated with bulk formulas; these are useful for oceanologists and climatolologists with regard to the possibilities of modern satellite MCW and IR radiometric instrumentation. Taylor (1984) studied satellite-derived monthly mean heat and latent heat fluxes, as well as their sampling frequency, during the JASIN experiment in the North Sea. The results of this study estimated the relative error of heat flux determination to be $\sim$10 % for the parameter q_h and 30 % for the parameter q_e when oceanic areas were observed from satellites every 12 h.

The results of experimental measurements derived from the Nimbus 7, DMSP (microwaves), and NOAA satellites (infrared) within various physical and geographical zones of the World Ocean (Schulz et al. 1997; Grankov et al. 1999a, b; Liu 1995; Grassl et al. 2000) justify the effectiveness of this approach. For example, the square root estimate of the monthly mean latent heat fluxes averaged over $2° \times 5°$ squares for selected satellite data [September 1987, Global Ocean (Schulz et al. 1997)] is $\sim$15–30 W m^{-2}. Similar results were obtained by Grankov et al. (1999a, b; in some energy-active zones of the North Atlantic in February 1994) and Liu (1995; in tropical zones of the Pacific Ocean).

An important step in remote sensing for the processes of heat and dynamic ocean–atmosphere interaction characteristics should be considered. An atlas of the monthly mean sensible and latent heat fluxes, as well as some other parameters of the SOA that are typical for the global ocean, were collected during the period from July 1987 to December 1998 (Grassl et al. 2000). These results are based on satellite MCW and IR measurements. An analysis of the potential of satellite MCW