Using the Results of Cloud Classification Based on Satellite Data for Solving Climatological and Meteorological Problems

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Abstract—Algorithms for classifying cloud images based on MODIS and VIIRS satellite data using artificial neural networks and fuzzy logic methods are considered. A combined classification of recognized cloud types is presented. The results of using the cloud classification for solving some problems of climatology and meteorology are analyzed. A statistical model of the image texture for various cloud types and physical parameters of clouds based on two-parameter distributions is proposed. A description of the algorithm for detecting weather fronts and determining their types from satellite data and the results of its testing for the territory of Western Siberia are presented. An approach to studying internal waves in the atmosphere based on the analysis of their cloud manifestation parameters is considered. The results are presented of studying the long-term variability for some of their parameters over the water area of the Kuril Islands. The methodology and results are discussed of studying the long-term variability of the structure of global cloud fields and their parameters over the natural zones of Western Siberia in summer during 2001 to 2019.

INTRODUCTION

The results of remote sensing of the Earth from space have been used for solving various scientific and applied problems since the launch of the first satellites [17, 29]. Such problems include studying cloud fields, which are among the main components of the Earth climate system. On average, every day clouds cover about 70% of the globe surface [37]. Cloudiness affects different processes in the "atmosphere–Earth's surface" system: water cycle, radiative transfer, aerosol transport, etc. [7]. In addition, clouds indicate the occurrence of such phenomena as internal gravity waves and Karman vortices [9].

The cloud field structure is heterogeneous. According to the modern WMO meteorological standard, 27 cloud types are distinguished including 10 main types, their subtypes and combinations [11], which are distributed among three levels (low, middle, and high) depending on their height. The division of clouds into types depends on their appearance and amount, which are directly associated with their formation mechanisms [19]. For example, the main cloud-forming factors are internal waves, convection, convergence, terrain, weather fronts, and cyclones [18]. At the same time, different cloud types affect the Earth climate system in different ways. Low-level clouds with a significant vertical extent impede the Earth's surface cooling, partly reflect solar radiation, and insignificantly absorb it [43]. High-level clouds, depending on microstructure, can retain outgoing longwave radiation in the troposphere, enhancing the greenhouse effect, or scatter shortwave radiation coming from space, reducing the Earth's surface heating [35]. Mid-level clouds have an essential effect on the radiation budget during the passage of weather fronts over a specific territory [40]. Another important parameter of cloudiness that directly determines the Earth biosphere state, is moisture content. Clouds are among the main factors of uncertainty in the climate change
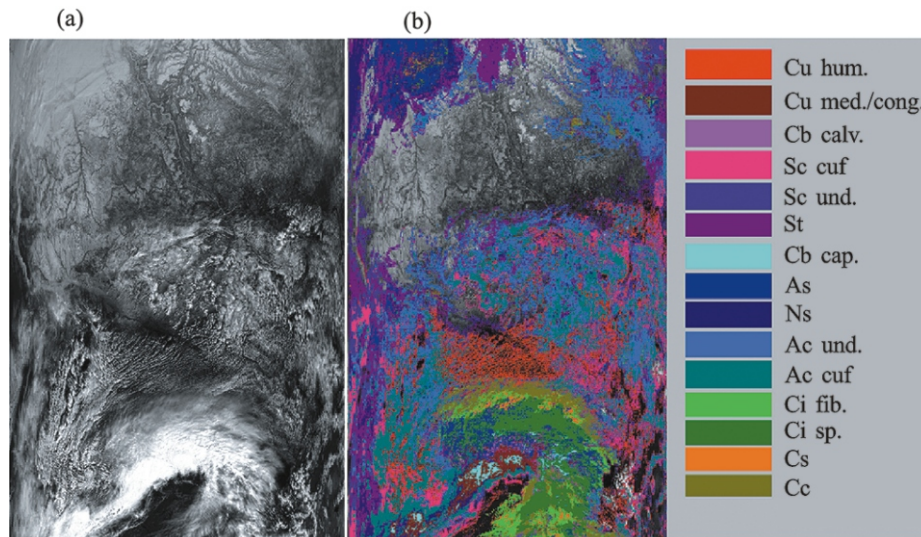
Fig. 1. (a) The daytime (05:50 UTC) MODIS satellite image of the territory of Western Siberia on May 3, 2008 and (b) the result of cloud classification based on this image.

prediction [26, 42]. Therefore, studying cloud fields and their structure is needed to ensure effective solutions to various climatological and meteorological problems [10], but this is a laborious process complicated not only by the diversity of clouds but also by their multilayer nature, dynamics, regional dependence, and some other factors. Routine observations of cloudiness have been performed at the international network of ground-based and shipboard weather stations for more than 100 years [30]. However, due to the permanently decreasing number of such stations, an adequate evaluation of cloud fields is impossible, especially in high latitudes. In 1962, the paper [27] for the first time presented the estimation of the cloud field structure based on black-and-white satellite photographs taken with the TIROS-N instrument. In the next decades, the problem of analyzing cloud fields from satellite data have been intensively elaborated. Currently, a large constellation of geostationary and polar orbiting systems for remote sensing is in orbit, one of its main purposes is observing clouds in various spectral ranges [29]. The results of satellite observations allow not only the estimation of the cloud field structure but also the retrieval of cloud field parameters: optical thickness, effective radius of particles, waterpath, cloud top parameters (height, pressure, and temperature), etc. [25].

The paper considers the algorithms based on artificial neural networks and fuzzy logic methods for classifying clouds from MODIS and VIIRS satellite data at different time of the day, with a subsequent use of results for solving the following problems: studying the seasonal and latitudinal variability of statistical parameters for the physical features of cloud types, detecting weather fronts and determining their types, analyzing internal waves based on their cloud manifestations, and studying the variability of the structure and properties of cloud fields.

INITIAL DATA

A result of the cloud field structure determination (classification) based on satellite data is a false-color image (Fig. 1). Each of its pixels related to clouds is assigned (highlighted in color) to a certain cloud type in accordance with the selected legend. The present paper utilizes cloud classification algorithms developed using artificial neural networks and fuzzy logic methods [5, 21, 23]. Probabilistic and fuzzy neural networks, which have similar efficiency, are used as classifiers. A distinctive feature of the first approach is the actual absence of the learning procedure and a possibility of approximating the objective function of almost any complexity. The main disadvantage is the network size. It is large due to storing information about the whole learning sample in its structure, that is leveled by the use of parallel computing methods on general-purpose graphic processors. The second algorithm relates a classified sample to different classes simultaneously, but with a different degree of belonging. This option is caused by the set of fuzzy inference rules, which, in essence, simulate expressions like "if…, then…". In particular, this allows studying the structure of multilayer cloudiness in the presence of optically thin or broken clouds at overlying levels. The

Table 1. The cloud classification used in the present study

Cloud type	MODIS, VIIRS (summer, daytime)	VIIRS (winter/summer, nighttime)	MODIS, VIIRS (winter, daytime)
Towering vertical clouds			
Cu hum.	+	–/+	–
Cu med./cong.	+	–/+	–
Cb calv.	+	–/+	–
Cb cap.	+	–/+	–
Low-level clouds			
Sc cuf	+	+	+
Sc und.	+	+	+
St	+	+	+
Mid-level clouds			
As	+	+	+
Ns	+	+	+
Ac und.	+	+	+
Ac cuf	+	+	+
High-level clouds			
Ci fib.	+	+	+
Ci sp.	+	+	+
Cs	+	+	+
Cc	+	+	+

main shortcoming of the neural fuzzy classifier is a need in a priory information about the type of membership functions and laboriousness of its learning. At the same time, both approaches allow an effective application of truncated search methods for forming the sets of informative features, which is an important factor for solving the problems of cloud classification described by the set of parameters [23].

The developed algorithms make it possible to identify 9–15 cloud types from MODIS and VIIRS satellite data, with a probability of correct classification from 0.79 to 0.87 depending on observation conditions, time of day, and snow cover presence [5, 21, 23]. The description of cloudiness was based on the textural features of its images and physical parameters retrieved from satellite-based data products. The cloud texture features were calculated using the Gray-Level Co-occurrence Matrix [34], Gray-Level Difference Vector [41], Sum and Difference Histogram [39], and One-Dimensional Signal Histogram [13] methods. In total, 132 textural features were used taking into account their different angular directions. The optical thickness, effective radius of particles, waterpath, cloud top features, etc. were considered as physical parameters. This information is contained in standard MODIS and VIIRS data products [25]. The joint use of the mentioned parameters allows recognizing in satellite images not only the main cloud types but also some of their subtypes, for example, Sc cuf and Sc und., which basically differ in the texture of their images. Table 1 presents the unified classification of cloudiness depending on the instrument used and observation conditions, that was proposed by the authors in accordance to [5, 21, 23]. This cloud division into types was based on the WMO meteorological standard [11], as well as on the possibility of their recognition in the images from space taking into account the task equipment characteristics [3]. For example, the absence of information about the waterpath at night in VIIRS products does not allow reliable discrimination between As and Ns, and the similarity of the texture for daytime (nighttime) images does not allow discriminating between Cs and Cc [21]; therefore, they were united into one class, as shown in Table 1. A reason for excluding towering vertical clouds from the MODIS/VIIRS classification for the winter period is their low frequency of occurrence in high and middle latitudes during the periods with the snow cover (<2% of the total number of cloud observations per month) according to [18, 19]. The mentioned methods were tested

Table 2. The fragment of the statistical model for high-level clouds for the summer

Cloud type	Zone, n		r_{ef}, m	P, g/m^2	h_{ct}, m
Ci fib.	N, 208	Nakagami (2.45; 6.21)	Normal (11.6; 37.9)	Gamma (5.74; 9.39)	Inverse Gaussian (7.4 $\times$ 10^5; 8.7 $\times$ 10^3)
	S, 215	Normal (0.66; 2.60)	Log-logistic (9.56; 41.1)	Nakagami (4.70; 4.5 $\times$ 10^3)	Erlang (40; 234)
Ci sp.	N, 450	Pearson (5.25; 90.92)	Logistic (5.20; 39.76)	Log-gamma (164.75; 0.04)	Weibull (8.43; 8.7 $\times$ 10^3)
	S, 450	Pearson (5.91; 102.03)	Normal (8.43; 38.75)	Lognormal (0.45; 6.08)	Normal (1.1 $\times$ 10^3; 9.4 $\times$ 10^3)
Cs	N, 450	Log-gamma (1.37; 3.04)	Weibull (5.39; 47.5)	Erlang (4; 26)	Gumbel (min) (845; 8.3 $\times$ 10^3)
	S, 450	Lognormal (0.46; 1.21)	Normal (9; 42)	Gumbel (max) (37; 74)	Weibull (9.55; 9.4 $\times$ 10^3)

N and S are the northern and southern zones of Western Siberia, respectively; the description of the parameters is given in the text.

using satellite images for different regions of the Russian Federation, but they can also be adapted for other regions of the globe.

There are many cloud classification algorithms based on various satellite data, which can be used for solving some climatological and meteorological problems considered in the present paper. Paper [38] presents the fullest overview of foreign studies in the field of cloud type identification covering the period since the late 1980s. Papers [8, 15, 16] stand out among Russian studies, the results of developing cloud classification algorithms obtained in different regional centers of Planeta State Research Center on Space Hydrometeorology (independently of each other). It should be noted that the proposed parameterization of cloud fields is more detailed (in terms of the number of recognized cloud types) and extends the scope of possible applications of the results.

In the present paper, the main source of information about clouds is the results of MODIS and VIIRS satellite observations. Both visible (0.6–0.7 m) images with a spatial resolution of 250 and 375 m and M(O/Y)D06_L2 and CLDPROP_L2 data products containing data on cloud parameters with a spatial resolution of 750 and 1000 m are used, as well as georeferencing files. The MODIS and VIIRS satellite data were extracted from the open NASA service for their search and download, with a preview option included [34]. In addition, other data on environmental conditions, for example, the results of ground-based meteorological observations and radiosonde data were used to solve the climatological and meteorological problems discussed in the present paper.

CLIMATOLOGICAL AND METEOROLOGICAL PROBLEMS

One of the directions for applying the results of the detailed cloud classification based on daily satellite imagery over a long-term period is studying the statistical features of cloud type parameters over a separate region or the whole globe. The construction of statistical models for cloud features and texture is associated with the selection of two-parameter distributions and the estimation of their parameters [12] proceeding from the Kolmogorov–Smirnov statistic minimum:

$$D_n = \max_i \left| F(t) - \Phi(t) \right|$$

where $F(t)$ and $\Phi(t)$ are the empirical and theoretical distribution functions, respectively. More detailed description of this technique is given in [2]. Statistical models can be constructed both for macroregions and for individual natural zones and territories.

Table 2 presents the fragment of the statistical model for the characteristics of high-level clouds observed over the northern (>65 N) and southern (<60 N) parts of Western Siberia in summer. For its construction, the sample datasets obtained from 2010 to 2019 were used, where the number of samples (sample volume n) varies from 200 to 450 for different cloud types depending on their frequency of occurrence over the considered parts of the target region. The datasets were formed using the technique for comparing archival weather station data for Western Siberia with satellite observations for similar time. Here, the

Table 3. The typical alternation of cloud types for different types of frontal systems perpendicular to the conditional line separating the warm and cold air masses

Front type	Sequence
Warm	Ci fib. Cs As and Ns St
Cold (1st kind)	St As and Ns Cs Cu
Cold (2nd kind)	Sc, Ac and Cc Cb cap. Cb calv. Cu med./cong. Cu hum.
Occluded warm	Cu Sc Cs As and Ns Cb calv. Cs St
Occluded cold	Cu, Ac and Cs Cb calv. Cb cap. Cu med./cong. Cs Cb calv.

distribution laws and estimates of their parameters (in brackets) are given for the optical thickness , effective radius r_{ef}, waterpath P, and cloud top height h_{ct}. As clear from Table 2, some parameters have similar values in both zones of Western Siberia (for example, the optical thickness of Ci sp.), and other parameters slightly differ (for example, the cloud top height). Similar models were also constructed for other physical parameters of clouds and textural features of their images. The selected distribution laws for cloud characteristics and textural features were used to initialize membership functions of the neural fuzzy classifier in [23]. This actually eliminated the procedure of its learning and improved considerably the results of cloud type identification from MODIS data. In addition, the comparison of the statistical models of clouds observed over different regions revealed their regional peculiarities [4].

The analysis of literature [7, 18, 19] revealed another area where the results of the detailed cloud classification could be applied. For example, during the passage of a weather front, a certain alternation of cloud types is observed in front of the zone separating the warm and cold air masses and behind it, the extent of the transition zone can reach several thousand kilometers. These series of cloud types may vary depending on the air movement mechanisms. There are five types of weather fronts, each characterized by the mesoscale cloud system: the warm front, the cold fronts of the 1st and 2nd kind, and the warm and cold occluded fronts. Table 3 presents typical alternations of cloud types (in accordance to Table 1) in an order of its observation in front of the zone separating warm and cold air masses and behind it. Some cloud types may be absent in real conditions, and other types may be not observed from space due to nontransparency of the overlying layer. However, the general structure of frontal mesoscale systems remains invariable, because the mechanisms of their formation and propagation are unchangeable.

The main meaning of the method for determining weather front types is the analysis of the structure of frontal mesoscale cloud systems. The zone separating the warm and cold air masses is localized by identifying in satellite images the zones with the highest probability of heavy precipitation based on the waterpath values (>300 g/m^2) according to [14]. In most cases, these zones are elongated, their extent is up to several thousand kilometers. Then isobars and isotherms are drawn using satellite-based data products. Such information is needed for preliminary assessment of the observed weather front type. At the final stage, the structure of cloudiness in front of the frontal zone, inside and behind it is determined, and the comparison of the results with the data from Table 3 is provided. The mentioned procedure is implemented on the basis of the decision tree in the automated mode. More detailed description of the method for determining weather front types is presented in [22]. Since standard nighttime MODIS and VIIRS data products do not contain information about the waterpath, the proposed technique is applicable only for the daytime satellite scenes.

Figure 2 presents the example of identifying the occluded warm front over Western Siberia on the border between the Tomsk oblast and Khanty-Mansiysk autonomous okrug based on MODIS satellite data for March 22, 2016. The results of the cloud classification in Fig. 2b demonstrate that the cloud systems of the warm (the left corner of the image) and the cold front of the second kind (at the bottom in the middle of the image) are at the stage of merging. Figure 2c clearly demonstrates the zones separating the warm and cold air masses. This fact is confirmed by the isotherms shown in Fig. 2e, which indicate an essential difference in the Earth's surface temperature (about 13 K) in front of the cold front and at its rear. In addition, Figure 2d clearly demonstrates the low-pressure zone (trough) at the point of merger of two frontal systems. Since the extent of weather fronts can reach several thousand kilometers, one more limitation of the method for their identification is the satellite scene size.

Besides a direct contribution to the terrestrial climate system, cloudiness is a marker of some processes and phenomena in the "atmosphere–Earth's surface" system, one of which is atmospheric internal waves. Among the diversity of wave motions in the atmosphere, clouds are formed mainly due to the disturbance of stability of inversion air layers under the influence of different processes (convection, convergence,
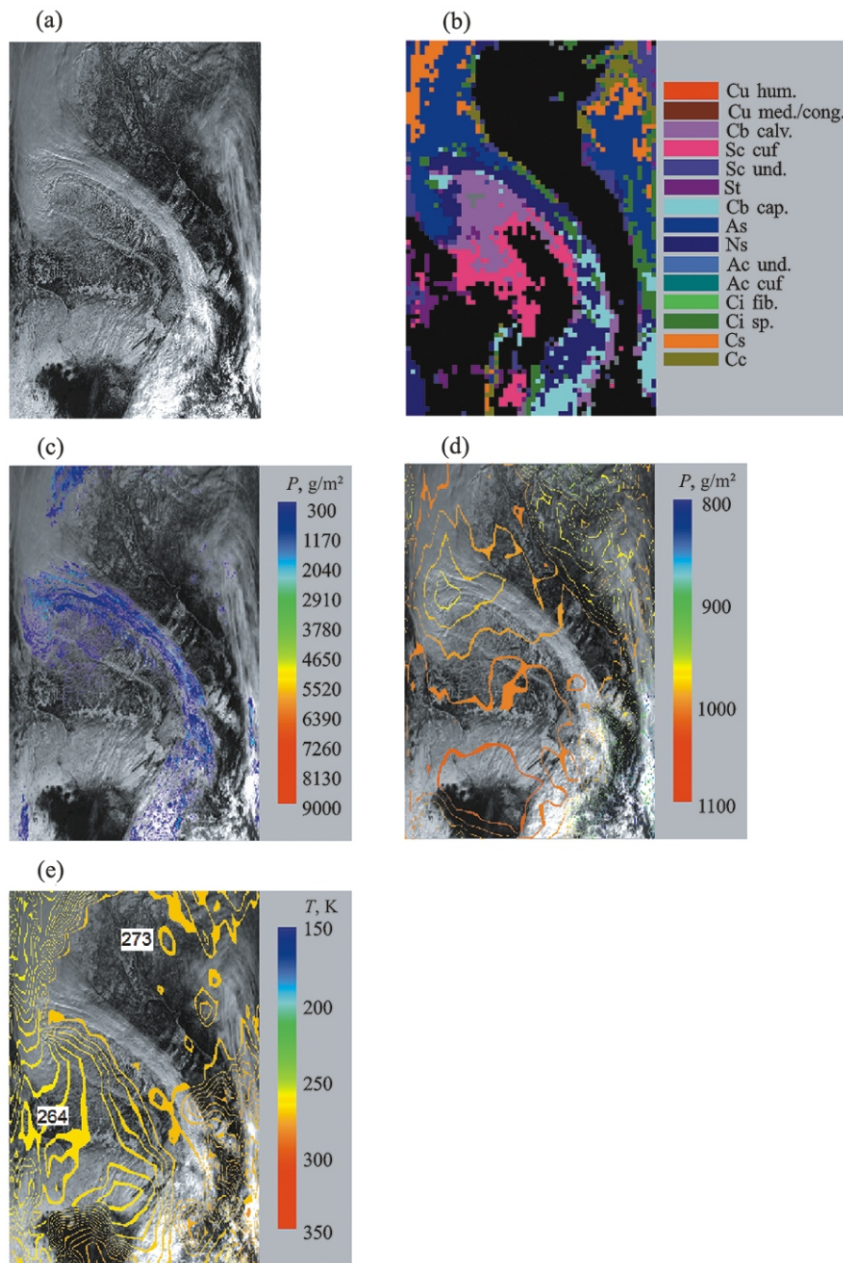
Fig. 2. (a) The satellite image of Western Siberia on March 22, 2016 (05:50 UTC) and the identification of (b) the occluded warm front and (c) frontal zones, the drawing of (d) isobars and (e) isotherms based on this image.

etc.), as well as terrain (mountain systems and islands). The first clouds are called gravity waves, and the second ones are orographic waves. In both cases, oscillatory motions are generated in the troposphere, moisture is condensed on wave crests, and clouds of different types are formed. There are suppositions that such wave processes are associated with various environmental phenomena, for example, with hurricanes and tsunami [28]. Atmospheric internal waves are aviation hazards due to high wind speed gradients and affect the refraction index modulation leading to the distortion of optical and radio signals [1]. The basic approach to studying the mentioned wave processes is the use of results of the laser sounding of the atmosphere, that provides routine but rather local observations of these processes [6].

In visible satellite images, atmospheric internal waves are manifested as quasiparallel bands with an extent to several hundred kilometers (Figs. 3a and 3b), which are formed of low- and mid-level clouds; therefore, the information about the structure of cloud fields and their parameters can be used for the
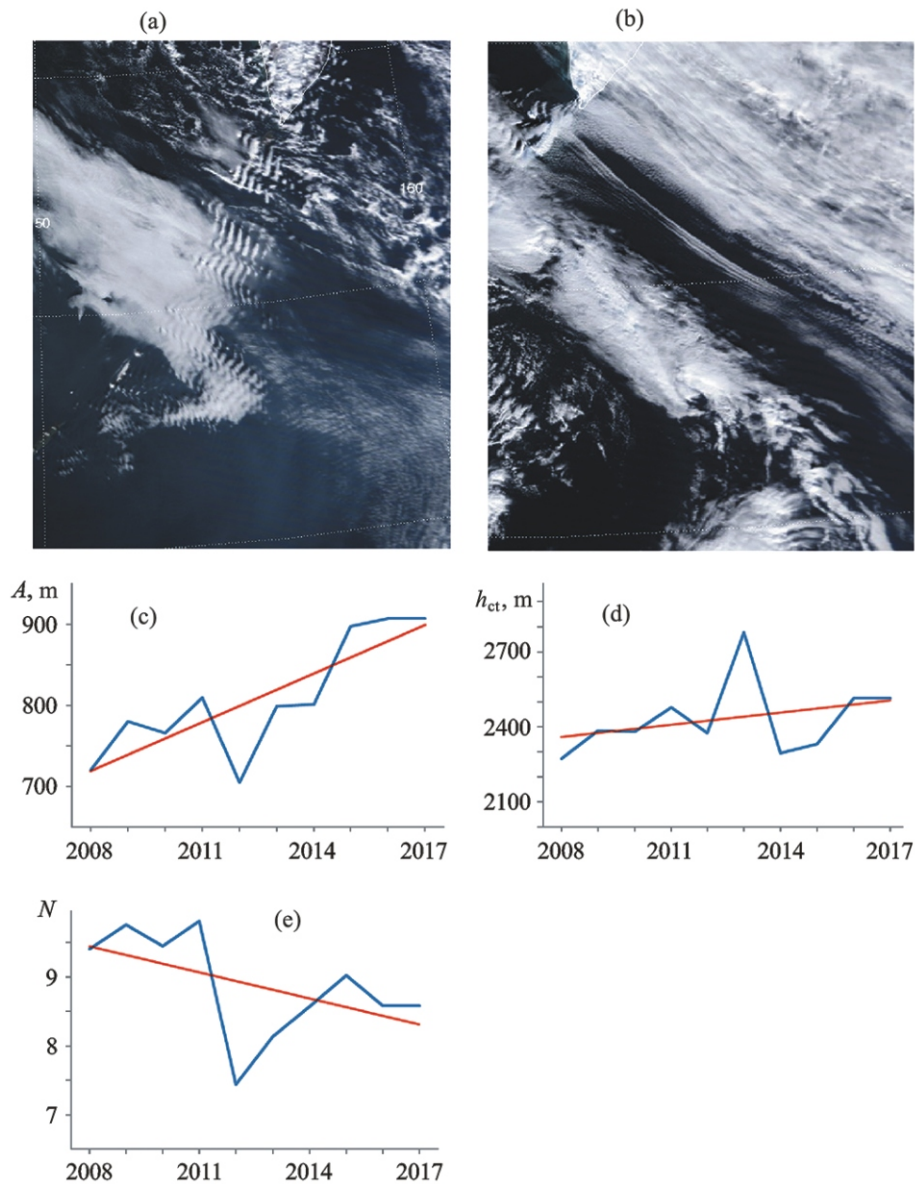
Fig. 3. The signatures of atmospheric (a) orographic and (b) gravity waves in the MODIS images for November 4, 2015 (01:15 UTC) and January 13, 2017 (00:50 UTC), respectively, as well as the long-term variability of (c) the amplitude, (d) cloud top height, and (e) number of quasiparallel bands for the analyzed wave processes over the Pacific coast of the Russian Federation in the daytime. In figures (c)–(e), the red line is the trend.

analyzed wave processes. For example, the authors of [24] proposed methods for retrieving geometrical and physical parameters of atmospheric internal waves and their signatures based on the complex use of MODIS information and radiosonde data from the ground-based weather station network. The main essence of the mentioned approach consists in analyzing the location of quasiparallel bands of cloud manifestations of the analyzed wave processes in satellite images and in comparing the cloud top features with the profiles of meteorological parameters (wind speed, wind direction, relative humidity, etc.) retrieved for similar time. The average values of cloud top height and respective points of the profile were considered for all quasiparallel bands. It is noteworthy that according to geostationary systems, the direction and speed of propagation of cloud manifestations of the analyzed wave processes generally remain constant for several hours. This technique was tested for the episodes of observing atmospheric internal waves over the Pacific coast of the Russian Federation during 2008 to 2017. The average annual frequency of occurrence of cloud manifestations of the analyzed wave processes in the mentioned region determined from daytime MODIS

ASTAFUROV, SKOROKHODOV

scenes is one of the highest and equals 95 days [36]. Figure 3 shows the typical signatures of atmospheric internal waves observed over the Kuril Islands and the graphs of long-term variability for some of their characteristics.

Figure 3a shows that one of the key factors for the formation of the observed atmospheric waves is the island ridge. In Fig. 3b, the signatures of the wave process are perpendicular to the coastline, which rules out the contribution of the Kuril Islands to its generation and propagation. The application of the technique for retrieving the parameters of atmospheric internal waves from long-term radiosonde and satellite data allows not only revealing their typical values but also assessing their interannual variability. Data in Figs. 3c, 3d, and 3e lead to the conclusion that over the decade of observing the analyzed wave processes, their average annual amplitude increased by more than 200 m, the cloud top height almost did not change, and the number of quasiparallel bands formed by them decreased. The obtained information may be used for revealing regional features and factors of generation of atmospheric internal waves, as well as for assessing their impact on various environmental processes.

Another direction in using the detailed classification results is the investigation of the cloud regime over separate regions based on long-term satellite data. For this purpose, the information about the daily, seasonal, and long-term variability of cloud types and their parameters with a high spatial and temporal resolution is required. In general, a change in the cloud regime may be both a marker of climate change and its key factor. For example, the variation in the frequency of occurrence of different cloud types indicates the intensification (or weakening) of prevalent processes in the "atmosphere–Earth's surface" system over the target region during the analyzed time period. Therefore, the long-term (several decades) variability of the cloud structure indicates global impacts on climate, the seasonal variability reflects mesoscale phenomena, and daily variations indicate a response of the system to fast processes, for example, to the passage of weather fronts and the formation of self-organized convective cells [32].

Studying the cloud regime over separate regions of the globe is based on using the results of the cloud classification from the set of daily satellite images. These data allow obtaining reliable estimates of predominant cloud types over the study area during a month, a season, or a year, as well as their mean parameters, despite the frequency of occurrence of the orbits of satellites with the MODIS and VIIRS instruments that is 16 days [33]. After processing all sample data, the trends in the cloud parameters are constructed, and their variability over the analyzed time intervals is evaluated. For example, the estimates were obtained for the variability of some cloud type parameters over the natural zones of Western Siberia during 2001–2019 in summer (June to August) based on MODIS satellite data. The most frequent cloud types over the analyzed period were Cu hum., Sc, and Ac cuf. At the same time, a significant latitudinal dependence of the cloud regime is observed over Western Siberia. For example, the frequency of occurrence of towering vertical clouds in summer over the natural zones of tundra and forest tundra is much lower than over the rest of the territories in the analyzed region, and the frequency of stratiform clouds (St and As) is higher. The possible reasons for that are the advection of heat from the low latitudes and the proximity of the Arctic.

CONCLUSIONS

An attempt is made to outline the range of climatological and meteorological problems, which can be solved using the detailed results of the cloud classification from daily satellite imagery as the main or auxiliary data. The statistical information on the structure of cloud fields and their parameterers (Table 2), as well as on their variability allows revealing regional features of their formation. These data can be used as a priori information for solving various applied problems in many areas, as well as for the indirect assessment of environmental changes. In addition, the presence of typical structures of mesoscale cloud systems (Table 3) is often an effect of processes in the "atmosphere–Earth's surface" system, such as the passage of weather fronts, which may form the base for determining their location and type. There are many natural phenomena associated with the characteristics of air and its movement, for which cloudiness is a kind of marker. In particular, they include atmospheric internal waves accompanied by the formation of cloud manifestations (Fig. 3). Therefore, the information on these signatures may be used to improve understanding of the mechanisms of formation and propagation of the mentioned phenomena.

It is obvious that the present paper covers not all possible application areas for the results of the cloud classification based on satellite data. In particular, the following problems were not discussed: radiative effects of clouds, the transport of aerosol particles by them, the formation of latent heat in them due to phase transitions, the estimation of contribution of their individual types to the water cycle, etc. However, the presented approaches highlight the urgency of studying cloud fields and their structure based on the results of remote sensing with modern satellite systems.

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