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STATISTICAL RADIOPHYSICS

On the Efficiency of the Integration of Satellite Microwave Radiometric Means for Monitoring Atmospheric Humidity Fields in the Zones of Hurricane Origin

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Abstract—Indicators of the completeness of the spatial survey and regularity of the time survey of atmospheric humidity fields in the Gulf of Mexico have been analyzed using the data of DMSP and GCOM-W1 polar-orbiting satellites during the origin and development of tropical Hurricanes Bret and Katia in the Gulf. During the monitoring of the total atmospheric water vapor content, estimates have been obtained for the size and frequency of occurrence of blind spots (gaps) that result from the divergence of scanning bands of microwave radiometers of satellites F11, F13, and F14 during Hurricane Bret and satellites F15, F17, and GCOM-W1 during Hurricane Katia. The data illustrating the improvement of indicators of the survey of atmospheric humidity fields at the transition from the single to group satellite measurements are presented.

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INTRODUCTION

At present, a survey of Earth's surface and atmosphere is made using polar-orbiting satellites DMSP, GCOM-W1, Meteor-M, and others, which are characterized by the occurrence of blind spots caused by the divergence of scan lines in the low-latitude areas. Gaps in the brightness temperature measurement data (or the results of their thematic processing) during satellite monitoring of tropical hurricanes (THs) can distort a picture of their origin and development, which can be effectively prevented using measurement data obtained from several satellites simultaneously. For example, the microwave radiometric measurement data from satellites F11, F13, F14, and DMSP give only a rough idea of the evolution of the brightness temperature field and its variation range at some stages of TH Bret's development, whereas the simultaneous processing of these data allows one to reconstruct a complete picture of hurricane transformation at different stages [1]. The quality (completeness and details) of the quantitative description of global fields of the brightness temperature and geophysical parameters, which depends on the spatial resolution of radiometers and trajectory characteristics of satellites, can be improved using special algorithms for the spatiotemporal interpolation of group satellite measurement data [2, 3].

In this study, we analyze indicators of the regularity of the time local survey and completeness of the spatial local survey of daily means of the total atmospheric water vapor (TAWV) content in the Gulf of Mexico using Scanning Sensor Microwave Imager (SSM/I) and Special Sensor Microwave Imager Sounder (SSMIS) radiometers of the DMSP satellites and an Advanced Microwave Scanning Radiometer (AMSR 2) of the GCOM-W1 satellite, which operated during TH Bret and Katia in the Gulf. These indicators play an important role in the analysis of the collective response of the TAWV field over the water area of the gulf to the TH generation and development processes [4].

The results obtained vizualize in situ the TAWV fields from individual satellites without involving special algorithms for correcting the satellite measurement data and demonstrate the possibility of improving the completeness of the obtained picture in group observations.

1. EXAMPLES OF THE REGULARITY AND COMPLETENESS OF THE GULF OF MEXICO SURVEY FROM THE DMSP AND GCOM-W1 SATELLITES

Let us consider the possibility of using modern microwave satellite radiometric systems for monitoring the TAWV daily means over the Gulf of Mexico by the examples of Hurricanes Bret (August, 1999) and Katia (August–September, 2017), the synoptic histories of which were described in [5, 6]. Bret was the strongest (wind speed of up to 230 km/h) among all the hurricanes that generated in the Gulf in 1995–2020 and Katia was included in the hurricanes

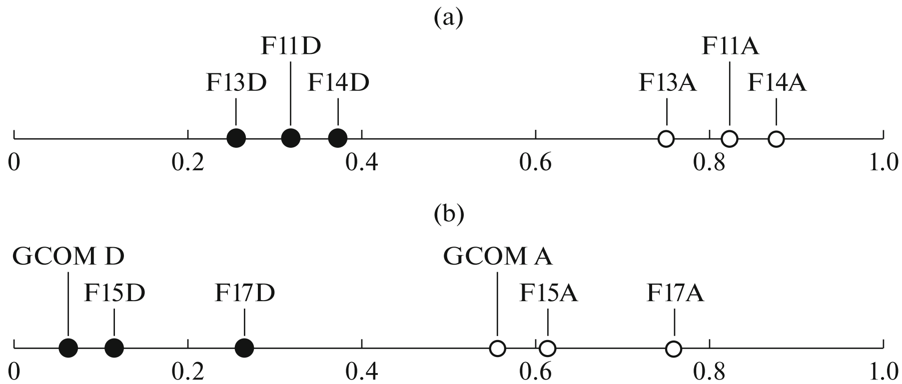

Fig. 1. Equatorial crossing time (in day fractions) for (a) satellites F11, F13, and F14 in 1999 and (b) satellites F15, F17, and GCOM in 2017 on ascending (A) and descending (D) orbits (time of approaching the TH Bret and Katia origination regions from the equator (6–7 min) is not taken into account; corrections for the dependence of the equatorial crossing time on the satellite lifetime by the hurricane survey time were made).

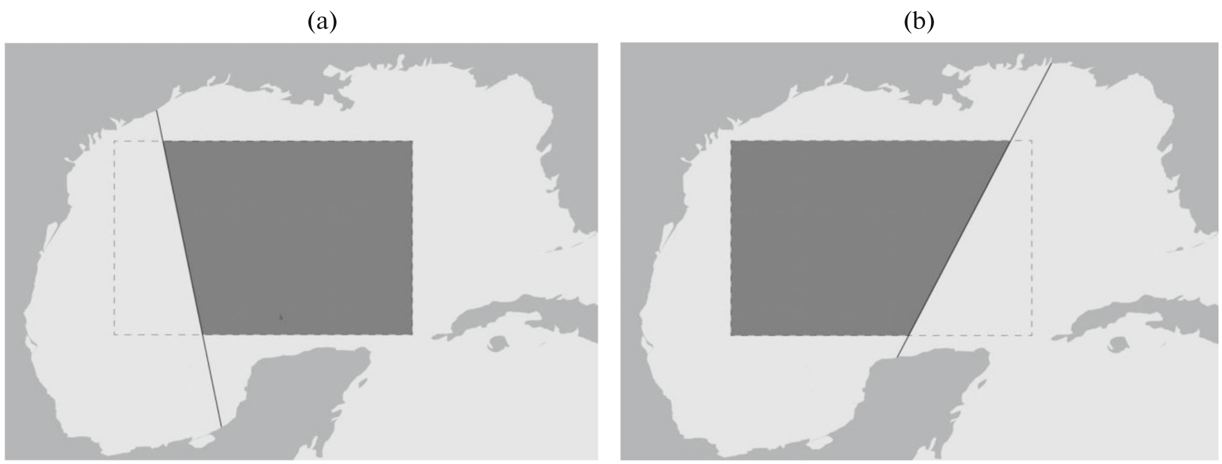

Fig. 2. Blind (unshaded) and visible (shaded) zones of the Gulf of Mexico in the investigated area during the monitoring by (a) satellite F13 (August 16, 1999) on the ascending orbit and (b) satellite F15 (September 5, 2017) on the descending orbit; the dashed line shows the investigated area and the solid line, satellite tracks.

marked as man-made disasters that led to irreversible changes in the thermohaline structure and current system of the Gulf of Mexico.

The satellite measurement data used to analyze the TAWV daily means in the Gulf during the periods of activity of these hurricanes are combined in two conditional groups:

(i) data from DMSP satellites F11, F13, and F14 (the SSM/I radiometer) obtained during TH Bret in August 1999 and

(ii) data from satellites F15 (the SSM/I radiometer), F17 (the SSMIS radiometer), and GCOM-W1 (the AMSR 2 radiometer) obtained during the TH Katia activity in August–September 2017.

In the first case, satellites F11, F13, and F14 were the only means for observing TH Bret; in the second case, TH Katia could also be observed using the measurement data from a WindSat radiometer of the Coriolis satellite and an MTVZA-GYa radiometer of Meteor-M No. 2 satellite, which were not used in our analysis.

Figure 1 gives an idea of the number of measurement sessions per day and their regularity that can be provided by the satellites chosen by us for monitoring the Gulf of Mexico during TH Bret and Katia.

It can be seen in Fig. 1 that, at the same number of measurement sessions per day for both satellite constellations, the constellation of satellites F15, F17, and GCOM-W1 ensures the higher regularity of the Gulf survey.

The analysis of the characteristics of the spatial survey of the SSM/I, SSMIS, and AMSR 2 radiometers shows that the divergence of their scanning bands in the latitudinal zone of the Gulf of Mexico leads to the pronounced occurrence of blind spots (gaps). As an example, Fig. 2 shows blind spots in the rectangular area of the Gulf (21.75°–28° N and 85.5°–97.75° W) observed from satellites F13 and F15 during tracking the development of TH Bret on August 16, 1999 and

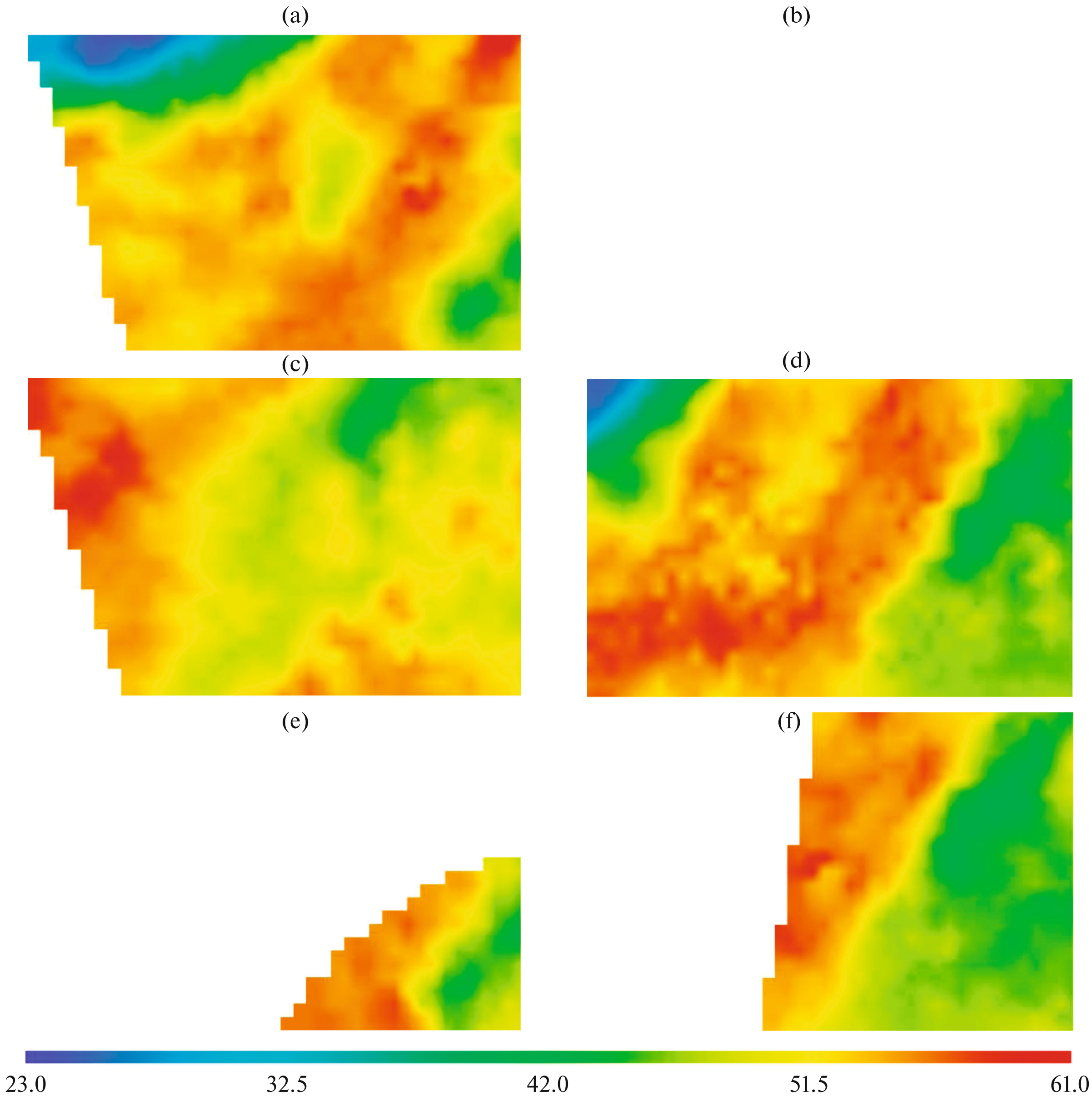

Fig. 3. Visible zones of distribution of the total atmospheric water vapor content (kg/m^2) in the selected area of the Gulf of Mexico surveyed by satellites (a, b) F11, (c, d) F13, and (e, f) F14 on August 16, 1999 on the ascending (on the left) and descending (on the right) orbits. The equatorial crossing times for the satellites are shown in Fig. 1.

TH Katia on May 9, 2017. This area covers a significant part of the Gulf of Mexico and is used by us as a testing area for studying the statistical characteristics of the TAWV spatial fields and the total water content of clouds and their correlation with TH origin and development processes [4].

The boundaries separating the visible and blind areas are the lines (satellite track projections) the positions of which are determined by the inclination of orbits and the nature of motion (ascending or descending) of the satellites.

We analyzed the blind and visible spots observed during the reconstruction of the TAWV fields from different satellites in the area of 21.75°–28° N, 85.5°–97.75° W of the Gulf of Mexico during the monitoring of the development of TH Bret on August 16, 1999 (Fig. 3) and TH Katia on September 5, 2017 (Fig. 4). The initial data were the TAWV daily means grouped in the 42 × 26 matrices on a spatial grid 0.25° × 0.25° in size taken from the National Snow & Ice Data Center (NSIDC), Remote Sensing Systems (RSS), and JAXA Data Providing Service archives.

In the presented figures, one can see that, in some cases (see Figs. 3e, 4d, and 4f), the shape and position of the boundaries of the visible regions differ from those determined by the trajectory characteristics of

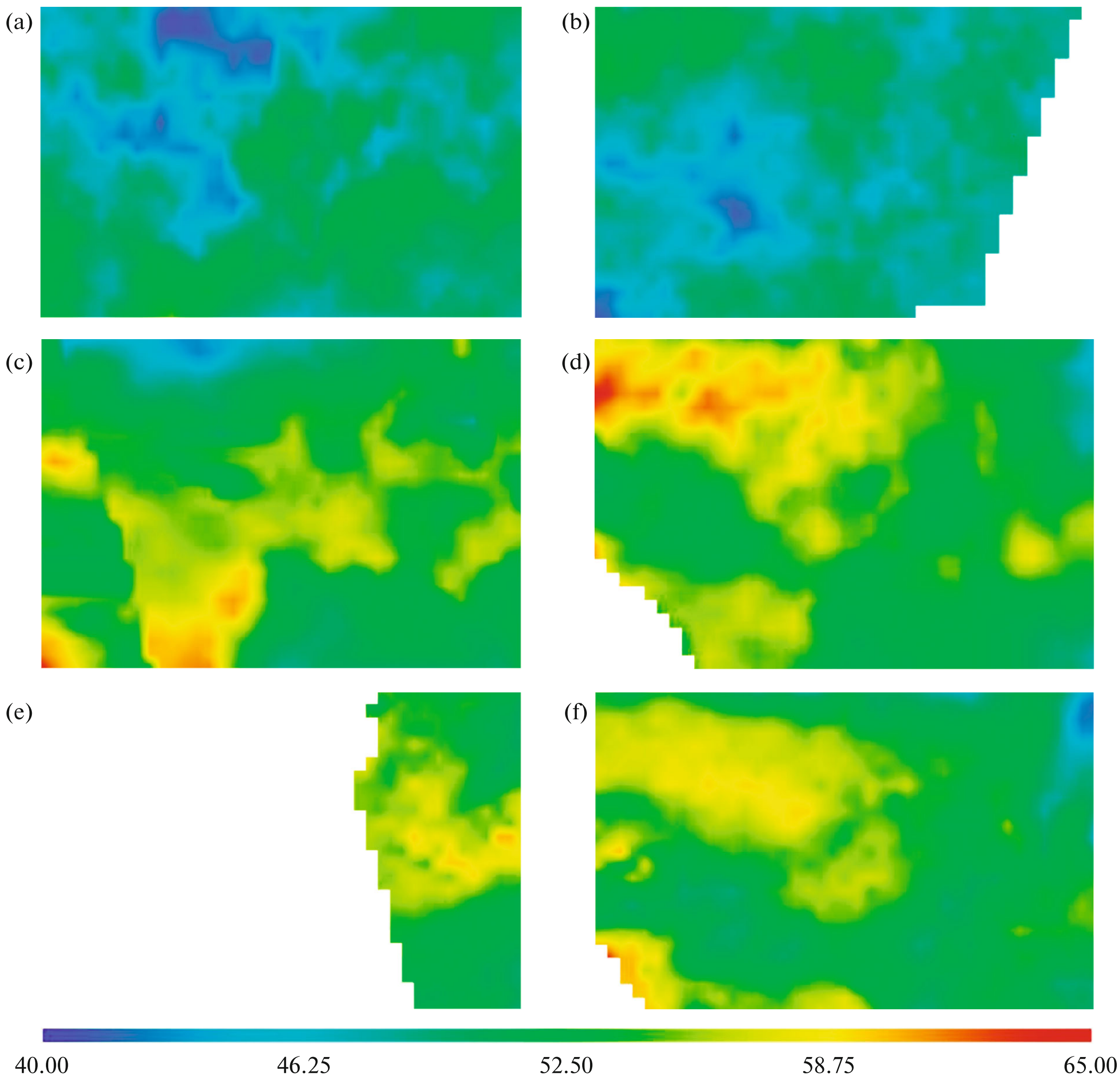

Fig. 4. Visible zones of distribution of the total atmospheric water vapor content (kg/m^2) in the selected area of the Gulf of Mexico surveyed by satellites (a, b) F15, (c, d) F17, and (e, f) GCOM on September 5, 2017 on the ascending (on the left) and descending (on the right) orbits. The equatorial crossing times for the satellites are shown in Fig. 1.

the satellites. This may be due to various interferences, which cause the rejection of brightness temperature measurement data and products of their processing in the satellite archives. These are telecommunication radio-frequency noise, heavy cloud cover, precipitation, and solar radiation. These factors additionally increase the sizes of gaps in the satellite images of the TAWV distribution over the Gulf of Mexico.

The above examples show that the gaps of data are observed over a significant part of the Gulf of Mexico (especially for satellites F11, F13, and F14) and can heavily distort the estimated TAWV content over its water area. The observed variation in the TAWV fields in different periods of TH Bret and Katia showed that the location, size, and frequency of the occurrence of gaps strongly change and statistical analysis is needed to give a comprehensive idea of these characteristics.

2. STATISTICAL ESTIMATION OF THE SIZE AND FREQUENCY OF THE OCCURRENCE OF BLIND SPOTS IN THE GULF DURING BRET AND KATIA

We statistically analyzed the indicators of the completeness of spatial survey and regularity of time survey of the TAWV content in the Gulf of Mexico using satellites F11, F13, and F14 and F15, F17, and GCOM-W1.

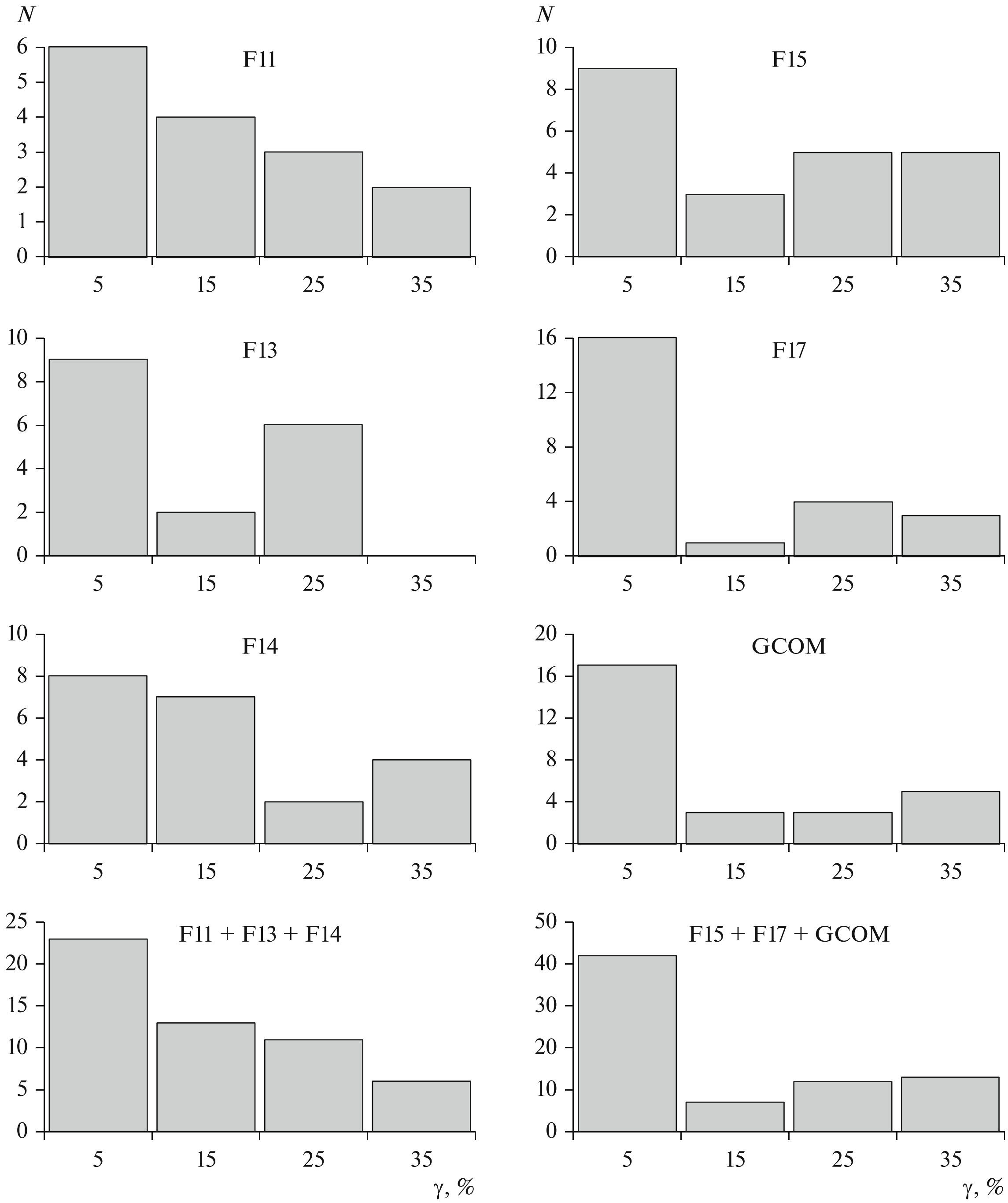

Fig. 5. Frequency *N* of the occurrence of gaps in the Gulf of Mexico versus their relative size γ (the ratio of the area with gaps to the total survey area in the Gulf) during TAWV monitoring by satellites F11, F13, and F14 in the period of August 8–31, 1999 and satellites F15, F17, and GCOM-W1 in the period from August 25 till September 10, 2017.

The frequency of occurrence of gaps and their sizes in the area of 21.75°–28° N, 85.5°–97.75° W of the Gulf of Mexico were estimated (Fig. 5).

The upper limit of the investigated changes in the relative area of the gaps is a threshold of $\gamma = 40\%$, above which, according to our estimates, the trust in the reliability of the reconstruction of the TAWV daily means in the areas with gaps is lost.

The presented results allow us to draw the following conclusions:

(i) An increase in the number of satellites from one to three leads to a decrease in the number of gaps by a

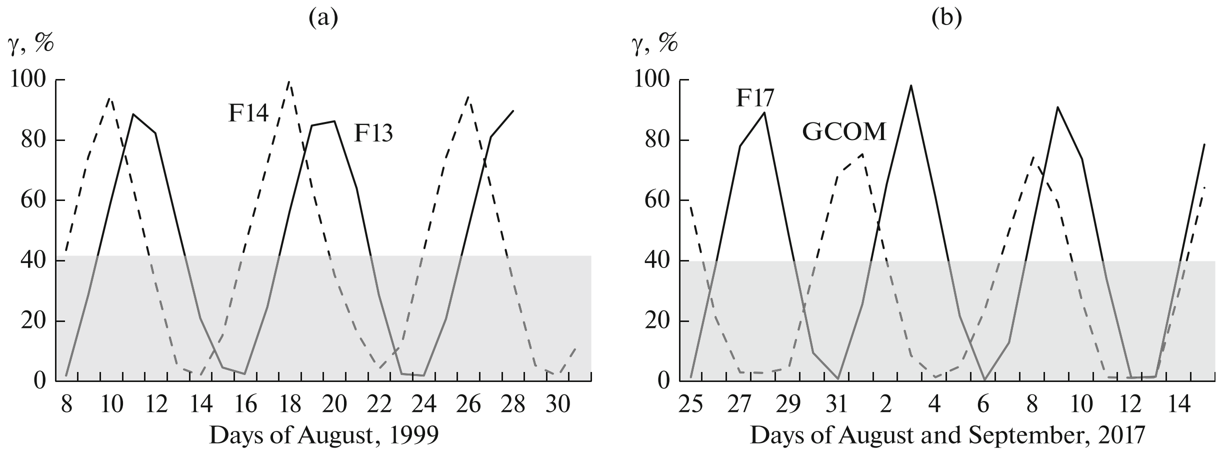

Fig. 6. Relative size γ of gaps in the Gulf of Mexico during the TAWV monitoring on the descending orbits of satellites (a) F13, F14 and (b) F17, GCOM-W1.

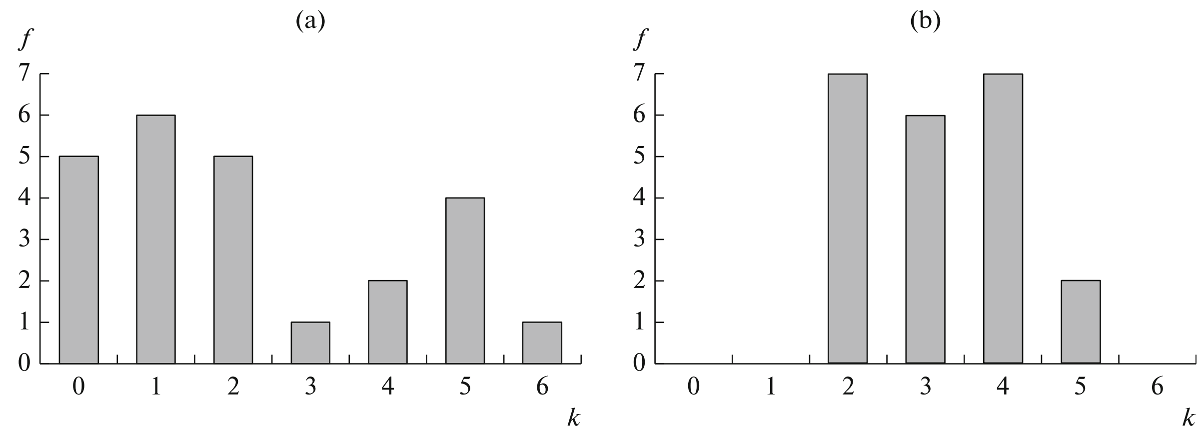

Fig. 7. Frequency f of cases with number k of the daily TAWV satellite readings in the Gulf of Mexico (a) in the period from August 8, 1999 till August 31, 1999 from satellites F11, F13, and F14 and (b) in the period from August 25 till September 10, 2017 from satellites F15, F17, and GCOM-W1.

factor of 2.5–3.5 during the observation of TH Bret and Katia development.

(ii) The number of informative areas, which bring information on the TAWV value, in the Gulf of Mexico for the 17-day observation of TH Katia development by satellites F15, F17, and GCOM-W1 is greater than that for the 24-day observation of TH Bret development by satellites F11, F13, and F14 by a factor of 1.4.

It should be noted that the frequency of occurrence of gaps in the Gulf of Mexico for satellites F15, F17, and GCOM-W1 in the single survey mode is lower than that for satellites F11, F13, and F14 by a factor of ~1.5.

Figure 6 illustrates the variability in the relative gap size in the Gulf of Mexico during TAWV monitoring during TH Bret from satellites F13 and F14 and during TH Katia from satellites F17 and GCOM-W1.

It can be seen in Fig. 6 that, in both cases, the visible areas alternate with gaps; the GCOM-W1 satellite ensures the smallest TAWV data loss in the gaps (the shortest time of exceeding a threshold of $\gamma = 40\%$).

Figure 7 gives an idea of important efficiency criterion for the satellite monitoring of the TAWV fields in the Gulf of Mexico: the maximum number of daily readings during TH Bret and Katia development.

We note some of the most significant results.

(1) The presence of gaps is especially pronounced when the constellation of satellites F11, F13, and F14 is used; in this case, one can observe single daily sessions (6 times during 24 days of observation) and even their skips (5 times during 24 days).

(2) The use of the constellation of satellites F15, F17, and GCOM-W1 for the main part of TAWV readings (20 of 22 days) ensures a regularity of 2–4 sessions per day.

CONCLUSIONS

The analysis of sample data on the spatial distribution of the total atmospheric water vapor content in the Gulf of Mexico obtained from the DMSP and GCOM-W1 satellites during the generation and development of Hurricanes Bret and Katia showed the presence of blind spots in the TAWV images related to the divergence of the scanning bands of microwave radiometers. In some cases, the gaps additionally increase, which can be explained by the fact that the brightness temperature measured from the satellites and the results of its thematic processing are affected by several factors, including heavy cloud cover, precipitation, telecommunication radio-frequency noise, and solar radiation. It was shown that the modern satellite microwave radiometer archives make it possible to compare both the individual DMSP and GCOM-W1 satellites and their constellations in terms of completeness and regularity of data on the atmospheric humidity fields in the Gulf of Mexico. There are similar possibilities for analyzing the efficiency of their use in studying the hurricane origin and development processes in the period of 2002–2011 from EOS Aqua and Coriolis satellites since 2003 and Meteor-M no. 2 satellite since 2014.

The integration of satellite microwave radiometric tools makes it possible to significantly reduce the number of gaps in the TAWV spatial distributions during the monitoring of Hurricanes Bret and Katia. In our case, we managed, if not to eliminate, then to smooth out the contradiction of group satellite measurements between the completeness of the survey of the investigated area and its time regularity, which arises in the analysis of the dynamic processes of the origin and development of tropical formations. Indeed, despite a significant difference between the atmospheric humidity fields observed by different satellites at different times of the day on August 16, 1999 (see Fig. 3) and September 5, 2017 (see Fig. 4), the difference between their statistical characteristics averaged over the water area of the Gulf of Mexico and the standard deviations considered by us as indicators of the collective atmospheric response to the hurricane generation process [4]) are not so significant. In particular, the spread of the estimated spatial variability (dispersion) of the TAWV content in the Gulf between the data of satellite F11 on the ascending orbit and satellite F13 on the ascending and descending orbits (relative gap size γ for these trustworthy samples is no more than 40%) is 1.1 kg/m^2, while the interdiurnal variation in the spatial dispersion in the period from August 14 to August 21, 1999 preceding the onset of TH Bret attains 7.3 kg/m^2. The spread of the estimated TAWV spatial dispersion between the data of satellites F15 and F17 on the ascending and descending orbits and a GCOM-W1 satellite on the descending orbit is 0.5 kg/m^2 and the interdiurnal variation in the dispersion of the atmospheric humidity field in the period from September 1 to September 5, 2017 preceding TH Bret origin attains 4.5 kg/m^2.

The issues raised in this study and the results should be considered as the first step in evaluating the impact of the completeness and regularity of the satellite monitoring of atmospheric humidity fields in analyzing the hurricane origin and development processes. In the future, we should focus not so much on determining the number and size of gaps in satellite measurement data, but on analyzing their role in obtaining the most complete idea of these processes in various ways of assimilation of satellite information.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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