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Applying Satellite Microwave Radiometric Methods to Analyze the Relationship of Tropical Cyclogenesis with Water Vapor Transport in the Atlantic

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Abstract—Some possibilities of using microwave radiometric measurements from the EOS Aqua and GCOM-W1 satellites to study the influence of tropical waves in the Atlantic on cyclogenesis processes in the Gulf of Mexico by monitoring the spatial and temporal variability of water vapor fields in the gulf are illustrated. Examples of the use of satellite images of atmospheric humidity fields obtained from DMSP and EOS Aqua satellites are given to demonstrate the processes of transformation of tropical waves into Atlantic hurricanes Bonnie (1998), Frances (2004), and Ivan (2004).

Keywords: Gulf of Mexico, tropical waves, tropical hurricanes, water vapor, satellite microwave radiometry

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INTRODUCTION

One promising field of research into the processes of tropical hurricane (TH) formation is monitoring atmospheric humidity fields in areas of cyclogenesis based on satellite measurement data on the intensity of natural microwave radiation—the brightness temperature of the ocean–atmosphere system in the spectral region of resonant absorption of radio waves in atmospheric water vapor (Grankov et al., 2022; Sharkov et al., 2012; Ermakov, 2021).

We have used this approach previously for studying cyclogenesis processes in the Gulf of Mexico by analyzing the response of total atmospheric water vapor (TAWV) content to these processes based on measurement data from the SSM/I (Special Sensor Microwave/Imager) and SSMIS (Special Sensor Microwave Imager/Sounder) microwave radiometers on DMSP satellites and the AMSR-E and AMSR-2 radiometers (Advanced Microwave Scanning Radiometer) on EOS Aqua and GCOM satellites.

The analysis of the spatial variability of TAWV fields during the periods of origin and development of THs Bret (1999), Humberto (2007), Lorenzo (2007), and Katia (2017) revealed their consistent changes not only in the areas of origin of these hurricanes, but also in the adjacent vast areas of the Gulf of Mexico (Grankov, 2021).

This result can be explained by the influence of tropical waves (otherwise known as African easterly waves (Thorncroft and Hodges, 2001)), formed in the tropical Atlantic during the period from April–May to October–November, propagating from the west coast of Africa to the Caribbean Sea and the Gulf of Mexico and carrying masses of warm air to the west by prevailing easterly winds along the tropics and subtropics near the equator. An illustration can be the arrival of a tropical wave in the Gulf of Mexico during the formation of TH Lorenzo in September 2007 (Franklin, 2007) (Fig. 1). TAWV variations observed by the AMSR-E radiometer on the EOS Aqua satellite at fixed locations in the gulf during the period leading up to the onset of the September 28 hurricane are presented here.

The figure shows a strong spike in the total vapor content of the atmosphere Q (at 25–30 kg/m^2) moving from the eastern part of the Gulf of Mexico in a westerly direction; this can be seen as a consequence of the approach of a tropical wave from the Atlantic to the Gulf on September 21.

A more complete understanding of the influence of tropical waves on the processes of cyclogenesis in the Gulf of Mexico, as well as in the tropical Atlantic, can be obtained based on data from the analysis of TAWV fields (images) from the DMSP, EOS Aqua, GCOM-W1, and Meteor-M satellites, which provide global information about this and other parameters of the atmosphere and ocean surface with a spatial resolution of 0.25° × 0.25° with daily regularity.

Below we will evaluate the possibilities of using satellite measurements to analyze the influence of tropi-

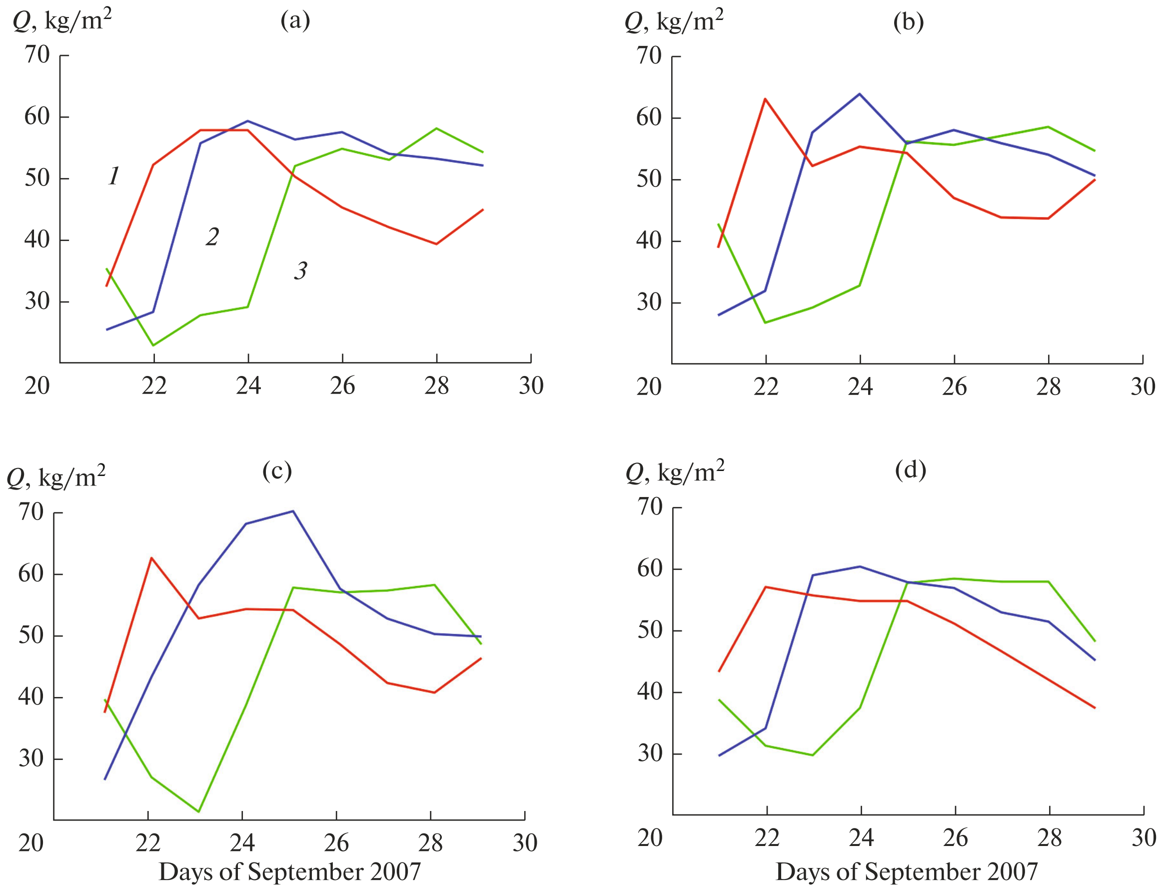

Fig. 1. Dynamics of TAWV (Q) in the period preceding the origin of TH Lorenzo in the Gulf of Mexico at grid points with longitude coordinates 85.5° W (*1*), 91° W (*2*), and 95.75° W (*3*) and latitudes 25° N (a), 24° N (b), 23° N (c), and 22° N (d).

cal waves on the formation of atmospheric humidity fields in the Gulf of Mexico during periods of the emergence of various tropical formations.

Within the framework of this task, not only are THs considered, but so are tropical storms, the frequency of which is several times higher; therefore, the volume of useful information for the analysis of cyclogenesis processes in the Gulf can be expanded.

RESPONSE OF ATMOSPHERIC HUMIDITY FIELDS IN THE GULF OF MEXICO TO THE APPROACH OF TROPICAL WAVES

Let us consider a number of examples of the use of satellite measurement data to analyze the influence of tropical waves on TAWV fields in the gulf during periods of the formation of local hurricanes and storms.

The Birth of Hurricane Lorenzo, September 2007

According to (Franklin, 2007), TH Lorenzo formed from a tropical wave that passed through the western coast of Africa on September 11, 2007, and formed initially as a tropical depression in the southwestern Gulf of Mexico on September 25, 2007, at point 21.8° N, 94.8° W, reaching hurricane stage on September 28 at point 20.5° N, 96.3° W.

Using measurement data from the AMSR-E radiometer of the EOS Aqua satellite (National Snow & Ice Data Center (NSIDC) archive), the spatiotemporal variability of TAWV in the Gulf of Mexico in the 20.75°–28° N, 97.75°–85.5° W region during the period of September 22–27, 2007, preceding the origin of TH Lorenzo, was studied, and the results are presented in Fig. 2. This area covers most of the Gulf of Mexico; its external boundaries were chosen in such a way that the coastal areas of the bay did not fall into the field of view of satellite radiometers.

As can be seen from Fig. 2, the arrival of a tropical wave in the Gulf of Mexico is accompanied by the appearance of an area with a high content of water vapor in the atmosphere in its eastern part, moving to the west, as well as its further localization in the southwestern part of the Gulf (the zone of origin of Hurricane Lorenzo).

Origin of Tropical Storm Matthew, October 2004

Tropical Storm Matthew formed from a tropical wave that passed through the western coast of Africa on September 19, 2004, and finally formed in the

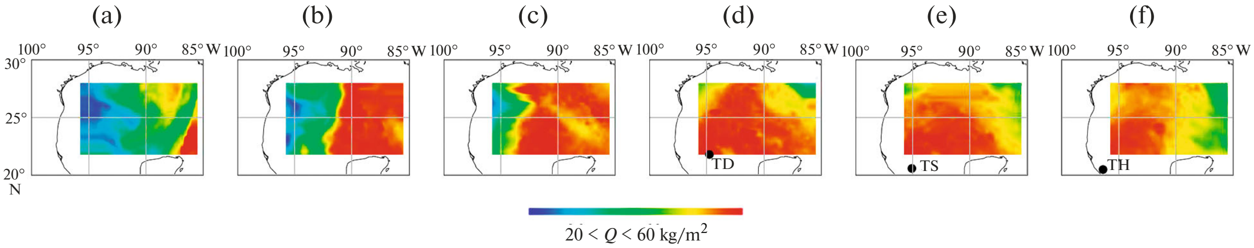

Fig. 2. Dynamics of changes in the TAWV field (Q) in a selected area of the Gulf of Mexico during the period preceding the emergence of TH Lorenzo in September 2007: (a) September 22, (b) September 23, (c) September 24, (d) September 25, (e) September 26, and (f) September 27. Time of arrival of a tropical wave to the Gulf of Mexico on September 21. TD is the beginning of the tropical depression stage, TS is the beginning of the tropical storm stage, and TH is the beginning of the TH stage (Franklin, 2007).

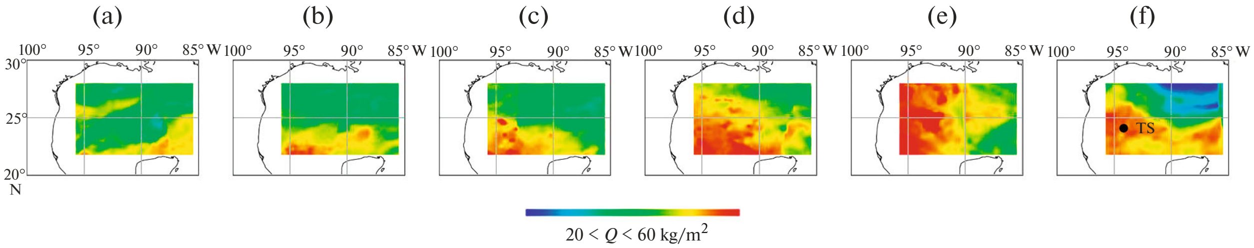

Fig. 3. Dynamics of the TAWV field (Q) in the Gulf of Mexico during the period preceding the emergence of Tropical Storm Matthew in October 2004: (a) October 3, (b) October 4, (c) October 5, (d) October 6, and (d) October 7. The arrival time of a tropical wave in the Gulf of Mexico is October 3. TS is the beginning of the tropical storm stage (Avila, 2004).

southwestern Gulf of Mexico on October 8 at point 24.1° N, 94.2° W (Avila, 2004).

Using measurement data from the AMSR-E radiometer of the EOS Aqua satellite (NSIDC archive), estimates of the spatiotemporal variability of TAWV in the 20.75°–28° N, 97.75°–85.5° W region in the Gulf of Mexico in the period preceding the formation of Tropical Storm Matthew on October 3–7, 2004, were obtained (Fig. 3).

The illustration shows that, as a result of the arrival of a tropical wave in the Gulf of Mexico, an area with a high total vapor content of the atmosphere is formed, which consistently moves in a northwesterly direction towards the area where the storm originates.

Origin of Tropical Storm Colin, June 2016

The origin of Tropical Storm Colin can be traced to a tropical wave that passed off the west coast of Africa on May 27, 2016, and reached the Caribbean Sea by June 1 (Pash and Penny, 2017). Its final formation occurred on June 5, 2016, in the southern Gulf of Mexico at point 22.4° N, 87.9° W.

Estimates of the spatiotemporal dynamics of TAWV Q are obtained in the area 20.75°–28° N, 97.75°–85.5° W in the gulf for June 1–6, 2016, preceding the formation of Tropical Storm Colin (Fig. 4). For these purposes, data from the satellite radio thermal imaging geoportal were used (https://fireras.su/tpw/Fields.aspx) (Ermakov et al., 2013), obtained based on measurements of the AMSR-2 radiometer of the GCOM-W1 satellite.

The illustration shows that, as a tropical wave approaches in the Gulf of Mexico, there is an accumulation of atmospheric water vapor in the area where Tropical Storm Colin originates.

The examples of satellite monitoring of the Gulf of Mexico show that, in the periods preceding the emergence of Hurricane Lorenzo and tropical storms Matthew and Colin, under the influence of tropical waves there was “pumping” atmosphere with water vapor, and areas with high TAWV values were formed, which moved within 5–6 days to the bay areas and became centers of their formation. This effect allows us to explain the close connection noted in (Grankov, 2021) between the spatial characteristics of TAWV fields and the processes of generation of THs Bret, Humberto, Lorenzo, and Katia in the Gulf of Mexico.

ATMOSPHERE HUMIDITY FIELDS AS INDICATORS OF THE TRANSFORMATION OF TROPICAL WAVES INTO ATLANTIC HURRICANES

Tropical Hurricane Ivan, September 2004

According to optical and infrared images obtained from the geostationary satellites GOES-12 and MODIS, TH Ivan formed from a tropical wave that passed

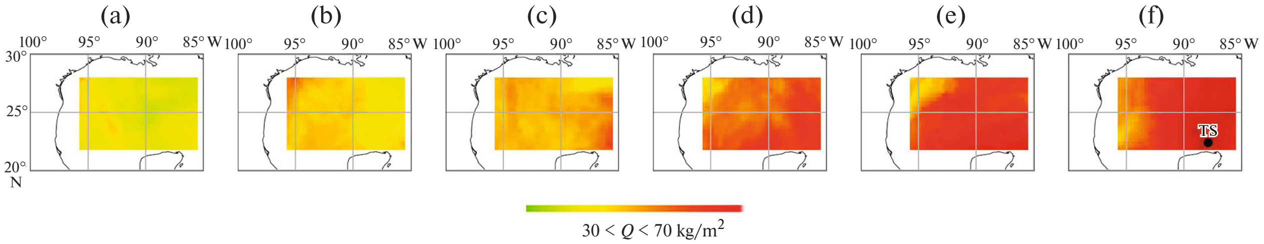

Fig. 4. Dynamics of the TAWV field (Q) in the Gulf of Mexico during the period preceding the emergence of Tropical Storm Colin in June 2016: (a) June 1, (b) June 2, (c) June 3, (d) June 4, (d) June 5, and (e) June 6. TS is the beginning of the tropical storm stage (Pash and Penny, 2017).

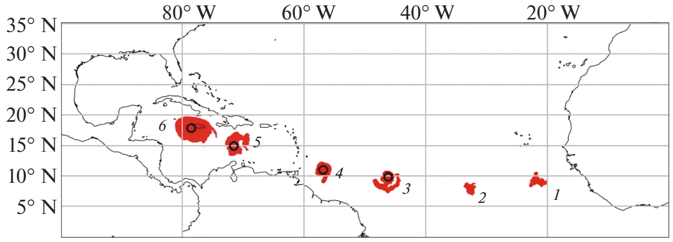

Fig. 5. Tropical wave transformation in TH Ivan, 2004: (*1*) September 1, (*2*) September 3, (*3*) September 5, (*4*) September 7, (*5*) September 9, and (*6*) September 11. The selected areas are characterized by a TAWV of 60 kg/m^2 or higher. The circles reflect the spatial position of the eye of the hurricane at midday (according to data from the AMSR-E radiometer of the EOS Aqua satellite).

through the west coast of Africa on August 31, 2004, and finally formed in the tropical Atlantic on September 5 at point 9.5° N, 43.4° W (Stewart, 2011). The hurricane corresponds to intensity category 5 on the Saffir–Simpson scale with a maximum near-surface wind speed of 270 km/h.

Based on NSIDC archive data, the spatiotemporal variability of TAWV in the 0°–35° N, 0°–100° W region in the Atlantic was studied during the period from the initial stage of tropical wave propagation (1) (south of the Cape Verde Islands) to the emergence of TH Ivan (3) and its maximum development (6) in the Caribbean Sea (Fig. 5).

Figure 5 demonstrates the existence of an area in the Atlantic with a high total vapor content of the atmosphere (over 60 kg/m^2) and its spatial evolutions, which coincide with the trajectory of the tropical wave from the western coast of Africa to the area of origin of TH Ivan and further with the trajectory of its propagation described in (Stewart, 2011).

Tropical Hurricane Bonnie, August 1998

According to optical and infrared surveys from the geostationary satellite GOES-8, TH Bonnie formed from a tropical wave that passed through the western coast of Africa on August 14, 1998, and finally formed in the tropical Atlantic northeast of Haiti August 22 at 21.1° N, 67.3° W (Avila, 1998).

Based on measurement data from SSM/I radiometers of the DMSP F11, F13, and F14 satellites (Remote Sensing System (RSS archive)), the spatiotemporal variability of TAWV was studied in the 0°–35° N, 10°–80° W region in the Atlantic (Fig. 6).

Figure 6 illustrates the movement of an area of high atmospheric moisture content in the tropical Atlantic (60–70 kg/m^2), the spatial evolutions of which coincide with the trajectory of the tropical wave from the western coast of Africa to the area of origin of TH Bonnie and further with the trajectory of its propagation described in (Avila, 1998).

Tropical Hurricane Frances, August–September 2004

According to optical and IR images from geostationary satellites GOES-12 and MODIS, hurricane Frances was formed under the influence of a powerful tropical wave that began its movement from the west coast of Africa on August 21, 2004, towards the Bahamas, reaching hurricane stage on August 26 in the area of 13.3° N, 45.8° W in the Atlantic and gaining full strength on September 2 off the coast of Haiti (wind speed 230 km/h) (Beven II, 2014).

Based on measurement data from the AMSR-E radiometer of the EOS Aqua satellite (NSIDC archive), estimates of the spatiotemporal variability of the total atmospheric moisture content and near-surface wind speed in the 0°–35° N, 20°–100° W Atlantic region were obtained during the period of time from

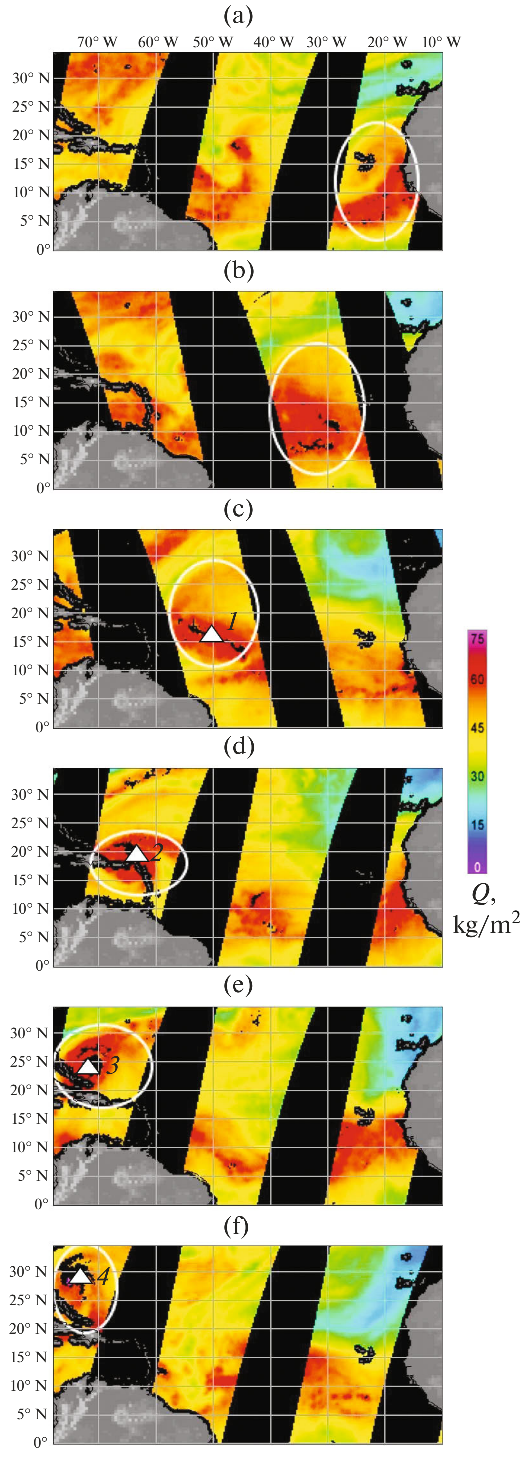

Fig. 6. Evolution of the TAWV field (*Q*) in the tropical zone of the Atlantic according to measurements from SSM/I radiometers of satellites F11, F13, and F14 on ascending (A) and descending (D) orbits in the period preceding the birth of TH Bonnie: (a) August 15 (F14 D), (b) August 17 (F14 A), (c) August 19 (F11 A); (d) August 21 (F13 D) and during its development: (e) August 23 (F14 D) and (f) August 25 (F13 D). (*1*) Tropical depression, (*2*) tropical storm, and (*3, 4*) tropical hurricane (according to (Avila, 1998)). Blind areas (outside the visibility of radiometers) are highlighted in black.

the initial stage of tropical wave propagation to the origin of TH Frances and its maximum development.

An area characterized by high values of total vapor content of the atmosphere (60 kg/m^2 and more) and near-surface wind speed (more than 25 m/s) moving from the west coast of Africa to the Florida Peninsula in the period August 27–September 3, 2004, was identified (Fig. 7). It follows from the illustration that the trajectory of movement of this area in the period of August 26–30 coincides with the trajectory of movement of a tropical wave from the Atlantic to the area of origin of TH Frances and then with the trajectory of its spread described in (Beven II, 2014).

CONCLUSIONS

The results of satellite monitoring of the Gulf of Mexico show that, in the periods preceding the emergence of Hurricane Lorenzo and tropical storms Mathew and Colin, under the influence of tropical waves, the "pumping" of the atmosphere with water vapor occurred and areas with high TAWV values were formed that moved within 5–6 days to the bay areas, which became the centers of occurrence of these tropical formations. This effect explains the close connection noted in (Grankov, 2021) between the spatial characteristics of TAWV fields and the processes of generation of THs Bret, Humberto, Lorenzo, and Katia in the Gulf of Mexico.

Using the examples of the stories of the emergence and development of THs Ivan, Bonnie, and Frances, one can see that satellite microwave radiometric measurements make it possible to identify zones in the tropical Atlantic with a high content of water vapor in the atmosphere (60–70 kg/m^2), the trajectories of which correspond to the trajectories of the propagation of tropical waves from the western coast of Africa to the areas where THs originate, determined from satellite optical and infrared survey data. The results shown for TH Frances indicate that tropical wave propagation can be observed not only as evolutions of the atmospheric water vapor field, but also the near-surface wind speed field.

In all the cases considered, the trajectories of further propagation of areas with high localization of water vapor in the atmosphere coincide with those given in (Stewart, 2011; Avila, 1998; Beven II, 2014) of the development trajectories of THs Ivan, Bonnie, and Frances (Best Track Positions), illustrating the spatiotemporal dynamics of the appearance and movement of zones of minimum atmospheric pressure and maximum wind speed.

The results indicate the important role of the transatlantic transport of atmospheric water vapor in the processes of cyclogenesis in the Gulf of Mexico and the Atlantic, as well as the possibility of using its integral (total) content in the atmosphere as an indicator of tropical wave propagation trajectories.

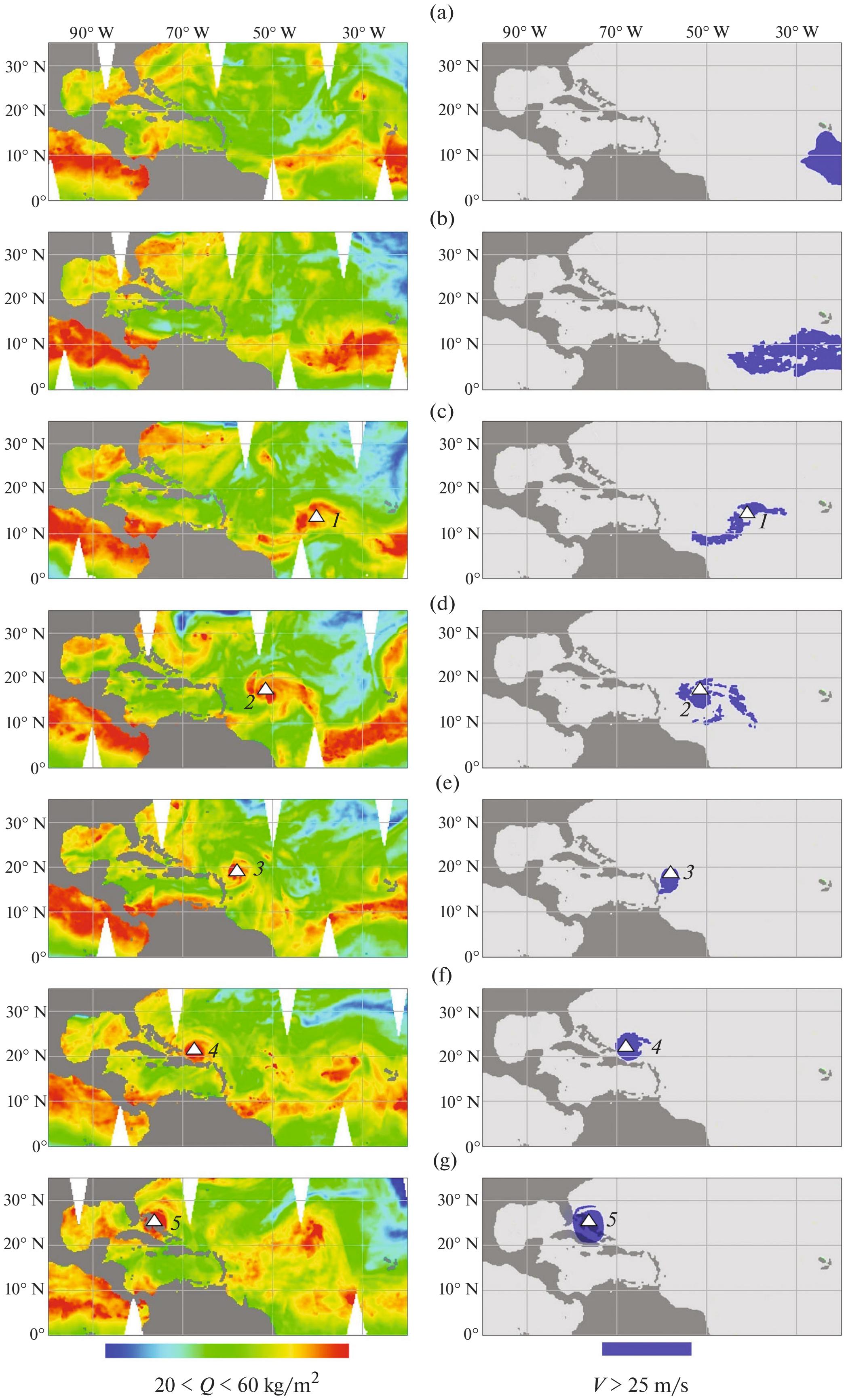
(a)
(b)
(c)
(d)
(e)
(f)
(g)
90° W
70° W
50° W
30° W
30° N
20° N
10° N
0°
1
2
3
4
5
20 < Q < 60 kg/m2
V > 25 m/s

Fig. 7. Evolution of atmospheric humidity fields (Q) and near-surface wind (V) in the Atlantic according to data from the AMSR-E radiometer in the period preceding the birth of TH Frances: (a) August 22; (b) August 24 and its development: (c) August 26, (d) August 28, (e) August 30, (f) September 1, and (g) September 3. (*1*) Tropical storm; (*2, 3, 4, 5*) tropical hurricane (according to (Beven II, 2014)). The white wedge-shaped areas are the blind spots of the AMSR-E radiometer.

From the examples discussed, it also follows that satellite monitoring of atmospheric water vapor makes it possible to trace the origins of hurricanes and storms that started in the Gulf of Mexico and the tropical Atlantic to East African waves, which expands the potential for early prediction of their occurrence. At the same time, it should be considered premature to use the total moisture content of the atmosphere as a universal and long-term predictor of the formation of THs and storms, since East African waves do not lead to their formation in all cases; alternatives are also observed when the final result of their activity is the emergence of only tropical depressions.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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