The Kinetic Energy Budget and Circulation Characteristics of the Tropical Storm Irma during AMEX Phase II

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ABSTRACT

By using the data from observation on the Chinese research vessel Xiang Yang Hong No.5 and other sources during AMEX phase II, the kinetic energy budget and circulation characteristics of the tropical storm Irma were analyzed.

Irma formed on the ITCZ of the Southern Hemisphere. During the formative stage of the storm, the SE trades and monsoon westerlies on both sides of the ITCZ strengthened, and more importantly, there was a strong divergent flow in upper troposphere. These contributed to the intensification of Irma. At the time when Irma formed, the Richardson number (Ri) in middle and lower troposphere was much smaller than that prior to and post the formation.

When Irma intensified rapidly, the area-averaged kinetic energy in the general flow increased in the whole troposphere . The largest contribution came from kinetic energy generation term, $-[\bar{v}\cdot\nabla\varphi]$,indicates that there existed a strong ageostrophic acceleration. As to the generation term , the conversion of available potential energy to kinetic energy, $-[\omega\alpha]$, made the largest contribution. This illustrates the importance of internal sources and of the ensemble effect of cumulus convection to the kinetic energy.

To the increase of area-averaged eddy kinetic energy during the rapid intensification of Irma, the most important source in the whole troposphere was the dissipation term $-[E']$, that should be interpreted as the feeding of eddy kinetic energy from smaller to larger scale disturbances. Another important source was generation term, $-[v'\cdot\nabla\varphi']$, in the lower troposphere. Rather small contribution came from the energy conversion from the kinetic energy of area-mean flow to eddy kinetic energy. Therefore, the eddy kinetic energy of the developing tropical disturbance extracted both from smaller and larger scale motions. The former was much more important than the latter. In addition, the disturbance acting as a generator and exporter, generated and exported eddy kinetic energy to the environmental atmosphere.

I. INTRODUCTION

During AMEX Phase II in Jan.–Feb., 1987, the research vessel Xiang Yang Hong No.5 of the PRC was sent to take the observation of tropical atmosphere and ocean in collaboration with scientists from other nations. For about one month, the Chinese vessel was fixed at about 11.5S,139.0 °E in the Gulf of Carpentaria to perform the atmospheric–oceanic observation and encountered with some interesting Southern Hemisphere weather systems. A study on these systems with the data observed by the ship was made and the results of the research on the tropical storm Irma, which is one of these systems, are presented in this paper.

Irma was a weak (formed on 19 January in the Gulf of Carpentariastorm) with the maximum wind speed only about 20 m/s^{-1} before its landfall. Fig.1 shows her track. In this paper, analyses of the kinetic energy budget of Irma and the large scale circulation characteristics of her formation are made

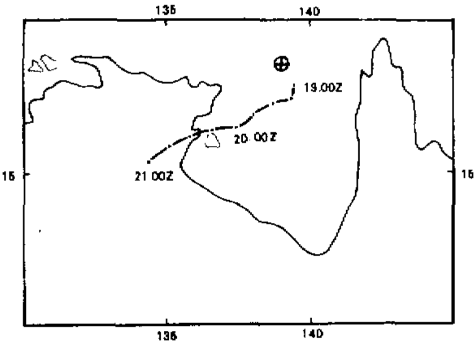

Fig.1. The track of the tropical storm Irma January, 1987. ⊕ indicates the location of the research vessel.

II. PATTERN OF LARGE SCALE FLOW INFLUENCING THE FORMATION OF TROPICAL STORM IRMA

Based on grid–point values at 5° Long. x 5° Lat. taken from the tropical objective analysis by ECMWF and NMC along with conventional daily rawinsonde data by the Chinese research vessel, the flow pattern of different standard pressure levels is analyzed. Only are streamlines of 850 hPa and 200 hPa at 1200 UTC, 19 January shown in Figs. 2a and 2b. Fig.2a shows that tropical storm Irma is originated onthe ITCZ of the Southern Hemisphere (or the monsoon shear line as named by Australian scientists, Mcbride et al., 1982). The westerlies to the north of the Southern Hemisphere ITCZ and the easterlies to the south of it are both intensified from 16 January as Shown in Fig.3. It is favorable for the intensification of the tropical cyclone by increasing shear vorticity and is in agreement with previous findings (Holland, 1983; McBride, et al., 1982).

Fig.2a. Streamline of 850 hPa, 1200 UTC 19 January 1987. ITCZ is denoted by dash–dotted line.

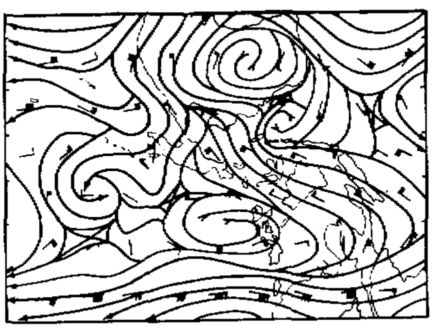

Fig.2b. Same as Fig.2a except for 200 hPa.

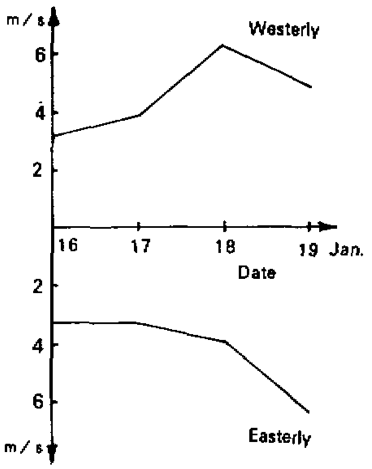

Fig.3. Averaged speeds of westerly (upper curve) and easterly (lower curve).Both are averaged from eight grid-point values of wind speed of westerly close to the north and easterly close to the south of the ITCZ at 1200 UTC from 135° —170° E.

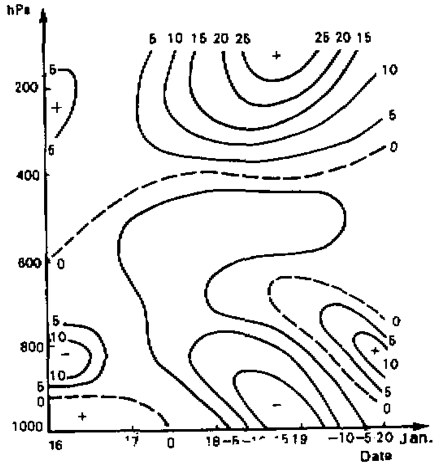

Fig.4. Time cross-section of area-averaged divergence at 1200 UTC over the Gulf of Carpentaria. Units 10^{-6} / s.

Perhapes the more important variation influencing the tropical storm formation took place in upper troposphere. Several days before, the regions of diffluent air flow at 200 hPa and 100 hPa were shifted westward from east of 150° E and arrived in the Gulf of Carpentaria on 19 January causing strong divergent southerly flow there (Fig.2b), which was favorable for the formation of tropical storm by offering a necessary outflow channel. The time cross-section of area-averaged divergence over the area of the Gulf of Carpentaria (Fig.4) shows obviously the variation of divergence and convergence patterns. Before 19 January the convergence in lower troposphere was increased in response to the strengthening of westerly and easterly as shown in Fig.3. However a spectacular change had taken place in upper troposphere and the divergence was increased sharply there.

The Gulf of Carpentaria is not an open ocean but the one surrounded by land and islands. According to climatological statistics (Holland, 1983; McBride et al., 1982), in this region tropical storms occur frequently. In the authors' opinion, this is due to that the Gulf of Carpentaria is usually located in the center of the subtropical high on the upper tropospheric climatological chart of the Southern Hemisphere (Sadler, 1975) or in the exit area between subtropical highs, hence the outflow in upper troposphere provides a favorable condition for the tropical storm development. On the other hand, in lower troposphere, the ITCZ of the Southern Hemisphere stretches there in this season (Atkinson and Sadler, 1970).

By using the upper-air data observed on the research vessel Xiang Yang Hong No.5, the Richardson number (*Ri*) is computed and the time cross-section of *Ri* is shown in Fig.5. On 19 January, the tropical storm Irma was located at about 100 km SSE from the research vessel. That was her shortest distance to the vessel in whole Irma's life cycle. The region of small *Ri* was limited only to cover the lower troposphere before Irma's formation and the region stretched to cover the lower and middle troposphere on 19 January, when Irma was developed rapidly. The deep region of small Ri provides a favorable condition for the convective activity of Irma.

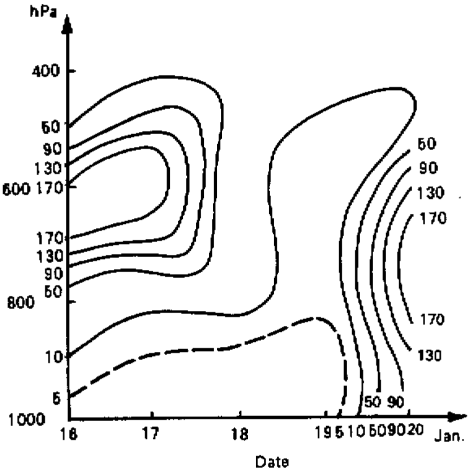

Fig.5. Time cross–section of Ri.

III. THE KINETIC ENERGY BUDGET DURING THE FORMING STAGE OF IRMA

For better understanding the intensification of Irma and gaining some physical insight into the development of Irma, the kinetic energy balance over a limited region is computed with the above–mentioned grid–point values by considering an area of 10° Long. × 10° Lat. enclosing Irma. The kinetic energy equations used in this study are similar to those given by Kung (1975).

The area–averaged kinetic energy equation of the general flow is

$$\left[\frac{\partial K}{\partial t}\right] = -\left[\nabla \cdot \vec{v}K\right] - \left[\frac{\partial \omega K}{\partial p}\right] - \left[\vec{v} \cdot \nabla \varphi\right] - [E]. \tag{1}$$

The eddy kinetic energy equation is

$$\left[\frac{\partial K_e}{\partial t}\right] = -[\nabla \cdot \vec{v}K_e] - \left[\frac{\partial \omega K_e}{\partial P}\right] - \left\{[u'\omega']\frac{\partial [u]}{\partial P} + [u'\omega']\frac{\partial [v]}{\partial P} - \left[\vec{v}' \cdot \nabla \varphi'\right] - [E']. \tag{2}$$

Where $[X]$ is the area–averaged of a variable X, the eddy quantity X' is the departure of X from the area–averaged. K and K_e are the kinetic energy and eddy kinetic energy per unit mass respectively.

$K = (u^2 + v^2)/2$ and $K_e = (u'^2 + v'^2)/2$. φ is the geopotential. The dissipation terms, $[E]$ and $[E']$, represent the effects of friction and the transfer of energy between grid and subgrid scales of motion due mostly to unresolved eddy process. The generation terms can b: written as

$$-\left[\vec{v} \cdot \nabla \varphi\right] = -\left[\nabla \cdot \vec{v}\varphi\right] - \left[\frac{\partial \omega \varphi}{\partial p}\right] - [\omega \alpha], \tag{3}$$

$$-\left[\vec{v}' \cdot \nabla \varphi'\right] = -\left[\nabla \cdot \vec{v}'\varphi'\right] - \left[\frac{\partial \omega' \varphi'}{\partial p}\right] - [\omega' \alpha'], \tag{4}$$

and the term C represents the energy conversion from the kinetic energy of area–averaged flow to eddy kinetic energy within the area

$$C = -[u'\omega']\frac{\partial[u]}{\partial p} - [v'\omega']\frac{\partial[v]}{\partial p}. \tag{5}$$

The vertical velocity ω is obtained by using the general kinematic method at first and then adjusted using a scheme proposed by O'Brien (1970) assuming that ω at 1000 and 100 hPa are equal to zero.

Each term in equations (1)–(4) is computed for 17–21 January. The terms $[E]$, $[E']$ and $-\left[\frac{\partial\omega\varphi}{\partial p}\right]$, $-\left[\frac{\partial\omega'\varphi'}{\partial p}\right]$ are obtained as residuals of the other terms in Eqs. (1),(2),(3) and (4).

In Irma's life cycle the most rapid intensification happened between 18 and 19 January as shown in Table 1 for area–averaged kinetic energy of the general flow and eddy over the Gulf of Carpentaria at different pressure layers . Only are the variation of kinetic energy between 18 and 19 January and related terms in Eqs. (1)–(4) within specified layers presented here (see Table 2) to demonstrate the characteristics of the kinetic energy budget during the forming stage of Irma. Because of shortcoming of data, there are some uncertainties in the result computed, but we believe that some useful physical clues can be extracted from it, at least in qualitative aspect.

Table 1. Area–Averaged Kinetic Energy of the General Flow and Eddy for 1200 UTC 17–21 January over Gulf of Carpentaria (Unit: $10^5 J/m^2$)

Pressure Layer (hPa) \ Date		17	18	19	20	21
$[K]$	200—100	0.58	0.59	1.00	1.11	0.91
	500—200	1.19	0.74	1.58	1.50	1.51
	700—500	0.33	0.45	1.12	0.88	1.00
	850—700	0.27	0.37	0.72	0.85	0.95
	1000—850	0.15	0.23	0.41	0.66	0.87
	Total	2.52	2.38	4.83	5.01	5.23
$[K_e]$	200—100	0.15	0.16	0.25	0.27	0.21
	500—200	0.38	0.47	0.97	0.78	0.84
	700—500	0.31	0.41	0.90	0.75	0.77
	850—700	0.25	0.36	0.65	0.73	0.59
	1000—850	0.12	0.21	0.38	0.54	0.47
	Total	1.20	1.61	3.14	3.07	2.88

It can be seen from Table 1 that the eddy kinetic energy is the same order of magnitude as the kinetic energy of the general flow and only slightly smaller in values. It is just the characteristics of a strong synoptic disturbance like this case. Because, in general, the eddy kinetic energy should be one order of magnitude smaller than the kinetic energy of the general flow (Tsui and Kung, 1977).

Table 2. Kinetic Energy Balance During the Forming Stage of Irmea (for 00 UTC, 19 January., Unit: 10^5 J / m^2 for K.E., W / m^2 for other terms)

Presscure Layer (hPa)	$\left[\frac{\partial K}{\partial t}\right]$	$\left[\nabla \cdot \bar{v}K\right]$	$-\left[\frac{\partial \omega K}{\partial P}\right]$	$-\left[\bar{v} \cdot \nabla \varphi\right]$	$\left[\omega\alpha\right]$	$-\left[\nabla \cdot \bar{v}\varphi\right]$	$-\left[\frac{\partial \omega\varphi}{\partial P}\right]$	$-\left[E\right]$	
Upper Troposphere 500—100	1.41	0.21	0.12	202.81	278.99	−457.16	380.99	−201.74	
Lower Troposphere 850—500	1.19	−0.29	−0.07	28.17	154.99	66.61	−249.75	29.72	
Boundary Layer 1000—850	0.20	0.13	−0.05	1.79	17.69	20.40	−36.30	−1.67	
Total 1000—100	2.84	0.05	0.00	176.44	451.66	−370.15	94.93	−173.65	
	$\left[\frac{\partial K_e}{\partial t}\right]$	$-\left[\nabla \cdot \bar{v}K_e\right]$	$-\left[\frac{\partial \omega K_e}{\partial P}\right]$	$-\left[\bar{v}' \cdot \nabla \varphi'\right]$	$-\left[\omega'\alpha'\right]$	$-\left[\nabla \cdot v'\varphi'\right]$	$-\left[\frac{\partial \omega'\varphi'}{\partial P}\right]$	$-\left[E'\right]$	C
Upper Troposphere 500—100	0.69	−0.09	0.15	−0.83	−0.63	−0.28	0.08	1.39	0.08
Lower Troposphere 850—500	0.90	−0.23	−0.08	0.49	−0.06	−0.06	0.61	0.70	0.04
Boundary Layer 1000—850	0.19	0.13	−0.06	0.19	−0.19	0.04	0.35	−0.08	0.01
Total 1000—100	1.77	−0.19	0.00	−0.15	−0.89	−0.30	1.03	2.00	0.12

The area–averaged budget of kinetic energy in the general flow is shown in the upper half of Table 2. The major terms are the generation term $-[\vec{v}\cdot\nabla\varphi]$ and the dissipation term $-[E]$. During the forming stage of Irma, $[K]$ increases in the whole troposphere. The largest contribution to the increase of $[K]$ comes from generation term $-[\vec{v}\cdot\nabla\varphi]$ almost all generation being produced in upper troposphere, but at other days, the term is negative (not shown) there. It is suggested that in the upper troposphere the ageostrophic deceleration changes into a stronger ageostrophic acceleration of the flow when the tropical storm develops. But a great portion of generation of kinetic energy is transferred into other scale energy or dissipated to smaller–scale motion through term $-[E]$, mainly at upper layer. Only is a small residual between the generation and dissipation terms used to increase the kinetic energy. The horizontal and vertical transport terms are contributed insignificantly to the budget with a tendency to transport the energy from the lower half of troposphere to the upper half. Therefore we can conclude that kinetic energy contributing to the development of the tropical storm Irma comes from the internal sources rather than external ones.

As for the generation term $-[\vec{v}\cdot\nabla\varphi]$, the largest contribution comes from the $-[\omega\alpha]$, conversion of available potential energy to kinetic energy with a maximum in the upper troposphere, which shows a negative correlation between an excess of temperature and vertical p–velocity. The result indicates the importance of the ensemble effect of warming and strong upward motion at upper levels associated with active cumulus convection in Irma. But a great part of the converted energy is exported in upper troposphere from the study area through $-[\nabla\cdot\vec{v}\varphi]$.

We shall now discuss the budget of $[K_e]$. Because the area covered by the closed circulation of Irma's forming stage is about 1000 km in diameter, the eddy kinetic energy, defined by the departure of the grid–point values at 5° Long. × 5° Lat. spacing from a 10° × 10° area–averaged value seems to resolve properly the tropical disturbance with the scale like Irma's.

The lower half of Table 2 shows the area–mean eddy kinetic energy balance during the forming stage of Irma (00 UTC,19 Jan.) and Table 3 the interdiurnal variation of some terms.

From Table 2, during the forming stage of Irma, the increase of $[K_e]$ in the whole troposphere is similar to $[K]$. It is interesting to note that the local time changes of $[K]$ and $[K_e]$ have the same magnitute order but the value of the latter is slightly smaller than that of the former. It is reasonable that there is a strong disturbance in this case.

Tables 2 and 3 show that in the balance of $[K_e]$, except term C which is one magnitute order smaller than other terms, the rest terms have the same orders of magnitute. The two major terms are the generation term, $-[\vec{v}'\cdot\nabla\varphi']$, and the dissipation term, $-[E']$.

Table 3 shows that in the lower troposphere and boundary layer, the generation terms, $-[\vec{v}'\cdot\nabla\varphi']$, are positive and increase for most part, indicating that there is a strong ageostrophic eddy acceleration in lower half of the troposphere to generate eddy kinetic energy. It is consistent with the case that Irma is not a deep tropical disturbance. But in upper troposphere, the values of generation term decrease from positive to negative and the minimum value appears on 19 January. It indicates that when Irma intensifies rapidly, a strong ageostrophic eddy deceleration and adiabatic destruction of eddy kinetic energy are engendered by a strong divergence in upper half of the troposphere and the sum of generation of eddy kinetic energy in upper and lower troposphere is negative, i.e, the destruction in upper troposphere overcomes the generation in lower troposphere.

Table 3. Interdiurnal Variation of Some Terms in Area-Averaged Eddy Kinetic Energy Budget of Irma (1200 UTC, Unit: w/m^2)

Pressure Layer (hPa) \ Date		17	18	19	20	21
$-[\vec{v}' \cdot \nabla\varphi']$	Upper Troposphere 500—100	0.73	0.39	−2.07	−1.49	−1.12
	Lower Troposphere 850—500	0.21	0.21	0.65	0.80	0.89
	Boundary layer 1000—850	−0.11	0.15	0.21	0.54	0.38
	Total 1000—100	0.84	0.76	−1.21	−0.15	0.15
$-[\nabla \cdot \vec{v}K_e]$	Upper Troposphere 500—100	0.05	−0.09	−0.32	−1.07	−0.28
	Lower Troposphere 850—500	0.16	−0.12	−0.56	0.75	−0.80
	Boundary layer 1000—850	0.02	0.09	0.20	0.67	−0.09
	Total 1000—100	0.24	−0.13	−0.68	0.35	−1.16
$-\left[\frac{\partial \omega K_e}{\partial P}\right]$	Upper Troposphere 500—100	0.07	0.07	0.35	0.27	0.25
	Lower Troposphere 850—500	−0.03	−0.07	−0.17	−0.07	−0.09
	Boundary layer 1000—850	−0.04	−0.01	−0.18	−0.20	−0.16
	Total 1000—100	0.00	0.00	0.00	0.00	0.00
C	Upper Troposphere 500—100	−0.02	0.03	0.17	0.15	0.00
	Lower Troposphere 850—500	−0.03	0.00	0.09	0.06	−0.11
	Boundary layer 1000—850	0.00	0.00	0.01	0.00	0.00
	Total 1000—100	−0.05	0.04	0.27	0.21	−0.11

We must pay special attention to dissipation term $-[E']$, the time variation of which is shown in Fig.6. Except in boundary layer, $-[E']$ increases before 19 January and reaches peak values both in lower and upper troposphere on 19 January when Irma develops most rapidly, and it should be interpreted that a large amount of eddy kinetic energy from smaller to larger-scale disturbances must be feeded to sustain Irma's development. After 19 January $-[E']$ decreases to negative in lower troposphere but the large positive values still remain in the upper troposphere. It seems to be the result from conversion of kinetic energy from subgrid scale to large scale due to cumulus convection activity during Irma's forming and maturing stage. The small negative values of $-[E']$ in boundary layer indicate that there exists a frictional dissipation.

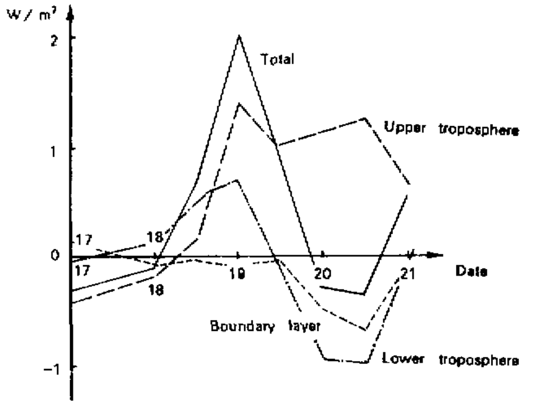

Fig.6. Interdiurnal variation of the dissipation term, $-[E']$, in the budget of area–averaged eddy kinetic energy of Irma. Unit: w/m^2.

Therefore, from 18 to 19 January when Irma developes most rapidly, the conversion from subgrid scale to large–scale kinetic energy is the uniquely important eddy kinetic energy source, because the generation term produces a net adiabatic destruction in the whole troposphere. It demonstrates the critical role of cumulus convection in the formation process of a tropical storm.

It can be seen from Table 3 that on 19 January the divergence of horizontalflux, $-[\nabla \cdot \vec{V}K_e]$ is negative and reduces to a minimum, suggesting that besides increasing eddy kinetic energy of itself, the tropical storm exports eddy kinetic energy to environmental atmosphere in its developing stage. On the other hand, the divergence of vertical flux, $-\left[\frac{\partial \omega K_e}{\partial p}\right]$ transports eddy kinetic energy from boundary layer and lower troposphere to upper troposphere by cumulus convection. This is the common characteristics of intense tropical disturbance because the same finding was obtained even from the study of averaged conditions over a period (Ding and Reiter, 1983; Kung 1975).

The term of energy conversion from the kinetic energy of area–mean flow to eddy kinetic energy, C is a minor source for Irma's development. It increases earlier and then achieves a maximum on 19 January although its magnitude is rather small. Hence during the forming stage Irma obtains the eddy kinetic energy both from smaller and larger scale motions but the former is much more important.

IV. CONCLUTIONS

The most significant findings related to the formation of tropical storm Irma and its kinetic energy budget are as follows:

1. Tropical storm Irma was formed on the ITCZ of the Southern Hemisphere. Strengthening of easterly trade to the south and westerly monsoon to the north of the ITCZ is

favorable for the formation of Irma. However, the more important variation occurs in upper troposphere, that is the strong divergence prompting a necessary outflow aloft.

2. During the period of most rapid intensification of Irma, the Richardsonnumber (*Ri*) in middle and lower troposphere is much smaller than that prior to and post the intensification.

3. During the forming stage of Irma, both the area–averaged eddy kinetic energy and its local time variation achieve the same magnitude order as the kinetic energy of the general flow and its time variation respectively. The kinetic energy generation of upper troposphere makes the largest contribution to kinetic energy increase of the general flow when Irma develops most rapidly. It is suggested that there exists a strong ageostrophicacceleration of the flow in upper troposphere when the tropical storm intensifies. For the generation of kinetic energy, the largest contribution comes from the conversion of available potential energy.

The results indicate the importance of the internal sources and the ensemble effect of active cumulus convection on kinetic energy increase of the general flow.

4. For the eddy kinetic energy balance, the generation and dissipation of the kinetic energy are two major terms. The generation term is positive and contributes to kinetic energy increase mainly in lower troposphere, denoting that a strong ageostrophic eddy acceleration exists in lower layer to generate eddy kinetic energy.

The dissipation term reaches peak values both in lower and upper troposphere when Irma develops most rapidly. It should be interpreted as the feeding of a large amount of eddy kinetic energy from smaller to larger–scale disturbance to sustain tropical storm development. The energy conversion of kinetic energy of area–mean flow into eddy kinetic energy is another but minor source for Irma's development. Hence Irma's formation obtains the eddy kinetic energy both from smaller and larger–scale motions.

Besides eddy kinetic energy generation, the disturbance exports the eddy kinetic energy to environmental atmosphere, and plays a role in general circulation as a generator and exporter of eddy kinetic energy.

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