THE EFFECT OF THE NEGATIVE ENTROPY FLOW ON THE ORGANIZATION OF ATMOSPHERIC DISSIPATIVE STRUCTURES IN NON-EQUILIBRIUM CONDITIONS

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ABSTRACT

The entropy balance equation that describes the entropy budget of atmospheric systems is derived from the Gibbs relation. The distribution of the entropy flows of a west-Pacific typhoon and a Bengal-Bay cyclone is calculated and thus the dissipativity of the atmospheric systems is revealed.

I. INTRODUCTION

According to the Prigogine-School's theory of the dissipative structures (Nicolis and Prigogine, 1977), if a system deviates from its equilibrium with a certain distance (actually reaches a certain level of dissipation), the original system would often lose its stability and form some orderly structures in it. Considering that the entropy has the ability to describe the orderlessness of the system, some physicists, e. g. Schördinger, attributed the exchange between system and its environment to entropy exchange, and in the information theory, some authors even regarded information as negative entropy. On the other hand, inside any system there exist the irreversible processes producing the positive entropy. The orderedness of the system would be continuously weakened owing to the spontaneous entropy-increasing processes inside the system when no negative entropy enters the system from environments. To maintain the orderedness of the system, especially to make itself evolve from low-order into high-order states, it is necessary for the system to draw enough negative entropy from environments, causing entropy-decreasing movements inside (Nicolis and Prigogine, 1977).

In this paper, the dependence of the organization of orderly structures which occur frequently in the unstable non-equilibrium atmosphere, such as typhoons and cyclones, etc., on the negative entropy flow will be analysed in light of the theory of dissipative structures, so as to concretely reveal the dissipativity of the atmospheric orderly structures far from equilibria.

II. THE ENTROPY BALANCE EQUATION

The Gibbs relation for the total differential of the entropy per unit mass could be written as (Glansdorff and Prigogine, 1971)

$$T\delta s = C_v\delta T + p\delta a - \sum_r \mu_r \delta N_r, \qquad (1)$$

where s is the specific entropy, a the specific volume, μ_r the chemical potential for component r, $N_r=\rho_r/\rho$, the fractional mass for component r;

$$\sum_r N_r = 1,$$

the others are the symbols used commonly in the thermodyanmics. δ in formula (1) is the general increment, also represents the local change with respect to time. For the atmospheric system studied here, it would be convenient to change formula (1) into the entropy change equation for the mixed ideal gases

$$\delta s = \sum_r (N_r \delta s_r + s_r \delta N_r), \tag{2}$$

thus the specific entropy s for the mixed ideal gases could be expressed as (Iribarne and Godson, 1973),

$$s = \sum_r N_r s_r,$$

where

$$s_r = \int C_{pr} \frac{dT}{T} - R_r \ln p_r + s_{r0}$$

is the specific entropy for the rth ideal gases; C_{pr}, R_r, p_r and s_{r0} are the specific heat at constant pressure, gas constant, partial pressure and entropy constant for component r, respectively. As usual (Wang, 1979; Li, 1979), the entropy constants are all taken to be zero in this paper.

Starting from the Gibbs-relation for the specific entropy, omitting the contributions of both the chemical reactions in the atmosphere and inertial energy change, and assuming that there exist no diffusive flows between different components $(\boldsymbol{J}_r = 0)$*, for the travelling synoptic system, such as typhoons, cyclones etc., one could derive the entropy balance equation for the mixed ideal gases in the quasi-Lagrangian coordinates:

$$\frac{D\rho s}{Dt} = -\mathrm{div}\,(\rho s(\boldsymbol{V} - \boldsymbol{C}) - \rho R \boldsymbol{V}) - \boldsymbol{V} \cdot \nabla \rho R \tag{3}$$

$$\equiv CS + EP,$$

where D/Dt is the quasi-Lagrangian change rate following the travelling system, $\boldsymbol{C}$ the travelling velocity of the system, and R the mixed ideal gases constant . The term of div (i. e. the term of CS) is just the term of the entropy flow that we would mainly discuss in this paper and the term of EP is called the entropy production. In addition, ρs is the entropy

* The diffusion flow $\boldsymbol{J}_r$ for component r is defined as

$$\boldsymbol{J}_r = \rho_r (\boldsymbol{V}_r - \boldsymbol{V}),$$

where $\boldsymbol{V}$ denotes the velocity for the mass center (supposing that the system consists of n components):

$$\boldsymbol{V} = \sum_{r=1}^{n} \rho_r \boldsymbol{V}_r / \rho,$$

where ρ is the total density which relates with density ρ_r of component r by

$$\rho = \sum_{r=1}^{n} \rho_r.$$

Obviously, one has

$$\boldsymbol{J}_r = 0 \iff (\boldsymbol{V}_r - \boldsymbol{V}) = 0,$$

that is, no diffusion flows $(\boldsymbol{J}_r = 0)$ mean that there exist no relative movements between various components of the mixed ideal gases; for example, the velocity of vapour is regarded to be equal to that of the dry air which is mixed with the vapour:

$$\boldsymbol{V}_{\text{vapour}} = \boldsymbol{V}_{\text{dry}}.$$

per unit volume because s is the specific entropy. Therefore, the entropy balance equation in the form of (3), having been integrated over the whole volume (V), is very suitable for calculating the entropy budget of the travelling systems

$$\frac{DS}{Dt}=\iiint_V \frac{D\rho s}{Dt}dV$$
$$=\iiint_V (CS+EP)\,d\sum\left(-\frac{dp}{\rho g}\right), \tag{4}$$

where S denotes the total entropy of the system, $\sum$ the horizontal range occupied by the system, g the gravitational acceleration and, CS and EP could be written in the p-coordinates as

$$CS \equiv CS1+CS2+CS3+CS4+CQ,$$
$$EP \equiv -\rho \boldsymbol{V}\cdot\nabla R-\frac{2\rho}{T}\boldsymbol{V}\cdot\nabla\phi-R\boldsymbol{V}\cdot\nabla\rho-\frac{\omega}{T},$$

$$CS1 \equiv -\rho\frac{\partial}{\partial p}[\rho s(\boldsymbol{V}-\boldsymbol{C})]\cdot\nabla\phi,$$
$$CS2 \equiv -\rho(\boldsymbol{V}-\boldsymbol{C})\cdot\nabla s,$$
$$CS3 \equiv -s(\boldsymbol{V}-\boldsymbol{C})\cdot\nabla\rho,$$
$$CS4 \equiv R\boldsymbol{V}\cdot\nabla\rho+\frac{\rho}{T}\boldsymbol{V}\cdot\nabla\phi+\frac{\omega}{T},$$

$$CQ \equiv \rho\boldsymbol{V}\cdot\nabla R-\frac{\omega}{T}+\rho^2\frac{\partial R\boldsymbol{V}}{\partial p}\cdot\nabla\phi,$$

$$s=q(C_{pv}\ln T-R_v\ln e)+(1-q)(C_{pd}\ln T-R_d\ln p),$$
$$C_v=qC_{vv}+(1-q)C_{vd},$$
$$R=qR_v+(1-q)R_d,$$

where q is the specific humidity, e vapour pressure, C_{pd}, C_{pv}, C_{vd}, C_{vv}, R_d and R_v are the specific heat at constant pressure, specific heat at constant volume and gas constant for the dry air and vapour, respectively.

In the above expressions calculating the quantities like the specific entropy s etc., the contribution of the liquid water in cloud has been omitted because the liquid water content (about 5 g m^{-3} on the average over the tropics) is much less than the density of either vapour or dry air (Zou et al., 1982; Mason, 1971). Formula (4) is just the basic equation to calculate the entropy budget in this paper.

III. CALCULATED CASES

Utilizing the entropy balance equation (4), we have calculated the structures of the entropy flow for the two travelling eddy systems: one is a Bengal Bay cyclone, and the other is a West-Pacific typhoon.

The Bengal-Bay cyclone analysed is a mid-level cyclone occurring during the second phase of the summer monsoon MONEX in July, 1979. On July 3 there existed a cyclonic circulation on the mid-troposphere (700—400 hPa) and, in the meantime there was only a monsoon trough below 700 hPa. This cyclone extended down to 850 hPa on July 5 and afterwards on the surface on 6th; maturated on 7th; arrived in the Indian Peninsula and tended to diminish on 8th. We have analysed the data set with the horizontal grid distance of one degree latitude and vertical resolution of 12 levels (100, 200, 300, 400, 500, 600, 700, 800, 850, 900, 950, and 1000 hPa), which comprises various information during the experiment period. The emphasis is put on the two times, one is July 6 when the system was developing and the other is July 7 when the system maturated.

The west-Pacific typhoon case selected is Typhoon 7507 occurring in August, 1975. From 00 GMT 17 August till 12 GMT 18 August the typhoon was in the disturbance phase; reached the critical strength typhoon at 00 GMT 19 August; afterwards it continued to develop and entered into the maturity phase at 12 GMT 21 August; and started to weaken at 18 GMT 22 August. For this typhoon, the data set with the horizontal grid distance of 1.5 degrees latitude and vertical resolution of 15 levels (50, 70, 100, 150, 200, 250, 300, 400, 500, 600, 700, 800, 850, 900 and 1000 hPa) comprises various information from the studied area (118.5—141.0°E, 16.0—42.5°N). Also, two times are chosen as the focal point to analyse, which are representative of the disturbance (formation) and prime phase, concretely, at 12 GMT 18th and 00 GMT 22 th, respectively.

For convenience, the area-integral of a quantity is replaced by the averaged value of 7×7 grid points. For the MONEX cyclone, it is corresponding to the area extending from its center outwards to 3.5 degrees latitude; for Typhoon 7507, to 5.25 degrees latitude; such a selection is very close to the real systems in area. As a result, the calculated values are actually the area-averaged ones.

IV. COMPUTATIONAL RESULTS

Table 1. The Entropy Budget for Systems (unit: cal K^{-1} s^{-1} m^{-2})

	July 6	July 7	August 18	August 22
$CCS1$	-0.1711×10	-0.8662	-0.4351×10	-0.2753
$CCS2$	-0.4630	-0.3324	-0.5089	-0.7338×10^{-1}
$CCS3$	0.9551	0.8850×10	-0.1155×10^{2}	-0.5057×10
$CCS4$	-0.6179×10^{2}	-0.4214×10^{2}	-0.9374×10^{2}	-0.2100×10^{2}
CCQ	0.2956×10	0.2090×10	0.4122×10	0.9255
FCS	-0.6008×10^{2}	-0.3239×10^{2}	-0.1060×10^{3}	-0.2534×10^{2}
$(FCS)'$			-0.1057×10^{3}	-0.2170×10^{2}
CEP	0.5997×10^{2}	0.4097×10^{2}	0.9052×10^{2}	0.2031×10^{2}

Table 1 shows the (area-averaged) volume-integrals of every term of the entropy change over the whole system for the computational days of the Bengal Bay cyclone (12 levels) and Typhoon 7507 (15 levels). As discussed above such values of integral are actually the area-averaged which are in nature the entropy flows and productions per unit (area) air column; among them the $CCS1$, $CCS2$, $CCS3$, $CCS4$ and CCQ are the area-averaged values of integrals of the term $CS1$, $CS2$, $CS3$, $CS4$ and CQ respectively, over the whole system, and

$$FCS = CCS1 + CCS2 + CCS3 + CCS4 + CCQ$$

is the (area-averaged) total entropy flow of the system; on the other hand, CEP is corresponding to area-averaged value of the integral of EP over the whole system.

It could be seen from the Table 1 that, as an open travelling system, either the Bengal-

Bay cyclone or Typhoon 7507 receives the negative entropy from environments, which is reflected in that the values of FCS for these four stages calculated are all negative. According to the theory of dissipative structures (Glansdorff and Prigogine, 1971; Hao et al., 1981; Nicolis and Prigogine, 1977), any irreversible process is always accompanied by entropy-increment, which is the fundamental implication of dissipation. If a system is not supplemented with enough negative entropy flows, its entropy and orderlessness would continually augment so that the system would tend to wither away. Our computations for the cases of synoptic systems would confirm this point from one aspect.

As mentioned above, the Bengal-Bay cyclone extended down gradually to the lower troposphere on July 6 and, continued to develop afterwards and reached its maturity on July 7. It could be seen, on the other hand, from Table 1 that the area-averaged entropy flow for the system corresponding to the developing phase (July 6) is -0.601×10^{2} cal K^{-1} s^{-1} m^{-2}, and that in the mature phase it has a much smaller valur of -0.324×10^{2} cal K^{-1} s^{-1} m^{-2}. We have noticed that since the negative entropy flow in the maturity decreased to almost the half of July 6, the strength of the cyclone weakened greatly on July 8.

For Typhoon 7507, the entropy flows of August 18 and 22 were calculated. The system was being in the eve reaching its critical typhoon strength at 12 GMT 18th and, developed into maturity at 00 GMT 22th. The computations show that the negative entropy flow on August 18 is considerably strong (for the typhoon, the integral in the vertical was made from the surface till 50 hPa; in addition, the values of the entropy flow given in Table 1 are the integration till 100 hPa $(FCS)'$ which are corresponding to those of the Bengal-Bay cyclone for comparison), having $(FCS)'=-0.106\times10^{3}$cal K^{-1} s^{-1} m^{-2} which is about one order of magnitude greater than that of the Bengal-Bay cyclone on July 6; on 19 August, the surface central pressure fell down to 990 hPa with a maximum wind velocity of 20 m s^{-1} near the center, reaching the critical typhoon strength. The maximum wind velocity near the center increased to 35 m s^{-1} at 00 GMT August 22 and maintained until 12 GMT August 22 when the negative entropy flow had a much smaller value of $(FCS)'=-0.217\times10^{2}$ cal K^{-1} s^{-1} m^{-2} and it was even smaller than that of the mature cyclone (the Bengal-Bay cyclone on July 7) so that the system tended to weaken.

In summary, as shown in Table 1, there is a common characteristic for the total entropy flow of these two atmospheric systems, that is, the entropy flow in the formation (disturbance) phase is larger than that of the maturity. It is easy to understand from the viewpoint of the open-system theory that an open system in developing phase would inevitably exchange much matter and energy with environments; only the strong negative entropy flow from the outside could balance the spontaneous entropy increment within the system and thus the system would gain the net negative entropy to augment its orderliness. However, the conditions are very different in the maturity when the circle symmetry of the system, especially the mature typhoon, strengthens greatly and the exchange of the matter and energy with the outside weakens noticeably, thus the system tends gradually to close. As a result, the negative entropy flow in the maturity is inevitably weaker than that in the developing phase.

The further analysis shows that there exists a close relation between entropy flow and dissipation of the system.

Figs. 1 and 2 show the distribution of the entropy flow with height for the Bengal-Bay cyclone and Typhoon 7507, respectively. It could be seen from the figures that the entropy exchange of the system with environments in the formation (developing) phase is stronger than that in the maturity almost at every level. On the other hand, the theory of dissipative

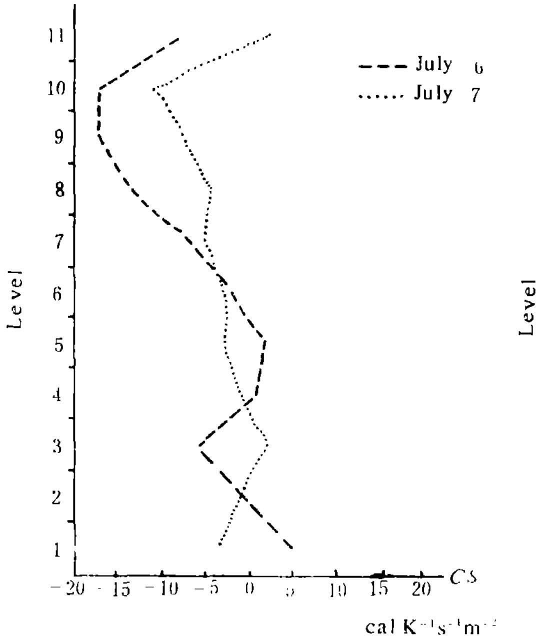

Fig. 1. The distribution of the entropy flow with height for the Bengal-Bay cyclone.

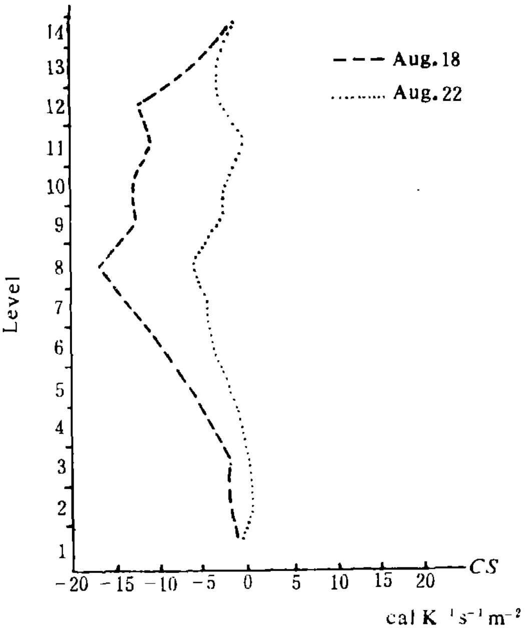

Fig. 2. As in Fig. 1, but for Typhoon 7507.

structures points out that (Nicolis and Prigogine, 1977) the maintenance of a dissipative structure produced by the continuous negative entropy flow from the outside needs a critical distance from the equilibrium, i. e., a minimum dissipation level. In other words, a system would tend to augment its dissipation when it evolves into a new stable regime. Our computations have confirmed this point (figures omitted). Either the Bengal-Bay cyclone or Typhoon 7505, which is far from the equilibria, when entering into the mature phase, will have its entropy be smaller than that in the formation or developing phase. Therefore, these two computed cases show that the process which gets the large negative entropy flow from the outside would experience the large dessipation; if the dissipation of the system is not large enough, that means its departure from the equilibrium is not far enough (as Hao et al. (1981) pointed out the entropy production of a system that is disturbed and departs from the steady state is necessarily larger than that in the steady state and, the equilibrium is the special case of the steady state). If so ,it follows that the entropy change of the system must obey the principle of the minimum entropy production in the linear non-equilibrium regime and finally it would regress to the equilibrium.

V. CONCLUSION

In this paper, in light of the theory of the dissipative structure and starting from the Gibbs relation, we derive an entropy balance equation which is suitable for describing the entropy budgets of the atmospheric system and, is used to diagnose the distribution of the entropy flow for the west-Pacific typhoon and Bengal-Bay cyclone. The calculated results confirm the dissipativity of these atmospheric systems and their maintenance must be supplied with the continuous negative entropy flow from environments. In addition, a system that gets the large negative entropy flow must experience the large dissipativity, the level of dissipation just reflects the distance from the equilibrium. Once the negative entropy flow decreases or, even there is a positive entropy flow from the outside somewhere in the system, the weakening of the system would follow.

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