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Computing entropy change in synoptic-scale system

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HIGHLIGHTS

- We aim to analyze the entropy change of the synoptic-scale atmosphere as an open system.
- We found that a strong negative entropy flux will appear when the heavy rainfall is coming.
- Our results provide a further evidence for adding the entropy balance equation into the heavy rainfall forecast.

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ABSTRACT

Thermodynamic entropy is of great importance in the atmospheric physics and chemistry process, because it is a non-conserved state function which making a system's tendency towards spontaneous change. But how the entropy forces a synoptic-scale system is still not well known. In this paper, we analyzed the entropy change in atmosphere system, by calculating several examples of extra tropical cyclones over the Yellow River and its adjacent area in summer. The results show that a strong negative entropy flux appears over the north of a stationary front and the thresholds $F_e S \leq -280$ and $\partial s/\partial t \leq -50$ are satisfied. At the same time, the change of total entropy is smaller than zero. Therefore the cyclone developed quickly and daily precipitation reached 371 mm, which is heaviest rain over the Yellows River area in summer. We suggest the dynamical entropy should be developed to improve the forecasting technique of heavy rainfall event in synoptic-scale.

1. Introduction

Some previous researches show that the most extreme rainfall in most regions of the world will increase in intensity by 3 to 15% [1,2], and the observations are telling us there will be increases in extreme events at almost all latitudes [3,4]. However, it is much more difficult to answer what drives changes in heavy rainfall. Although a great deal of studies on extreme events were carried out, most of them considered atmospheric dynamics instead of thermodynamics. Some researchers realized the important role of thermodynamic entropy in atmospheric physics and chemistry progress. But the studies of entropy change in the climate system are more than that in the weather system [5,6]. Considering extreme events are usually related to weather system (that is synoptic-scale system), we analyzed the entropy change of the atmosphere in synoptic-scale system.

Thermodynamic entropy is a non-conserved state function that is of great importance in the atmospheric physics and chemistry [7]. Entropy can be defined from a classical thermodynamics viewpoint [8], in which the system is viewed

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from perspective of the gross motion of very large masses of molecules, but it is more generally defined from a statistical thermodynamics viewpoint [9–12], in which the molecular nature of matter is explicitly considered. Historically, the classical thermodynamics definition developed first, and it has more recently been extended in the area of non-equilibrium thermodynamics, the concept of entropy evolved in order to explain why some processes are spontaneous and others are not; systems tend to progress in the direction of increasing entropy, so entropy is the "time's arrow" [13]. Entropy is as such a function of a system's tendency towards spontaneous change [14]. Entropy sometimes increases more rapidly and at other times more slowly; only rarely does it remains constant. The weather is an important example of a non-equilibrium steady state system [15]. The physical quantity which is able to describe both the irreversibility (non-equilibrium) and the steadiness of the weather system at once is the entropy production rate of the system [16].

Many studies on the budgets of momentum, energy and heat of a synoptic-scale system have been made for understanding its motion and structure [17–20]. We focus on thermodynamics of the synoptic-scale system in view of an entropy change, so we first derive a computational scheme of entropy balance equation in the troposphere from thermodynamics, then some computations of the entropy change of extra tropical cyclones over the Yellow River valley were made. The fields of entropy change of them were analyzed in order to diagnose weather of extratropical cyclones and to improve the local weather forecast in the future.

As known in statistical thermodynamics, when a total entropy ds of a system is smaller than zero, i.e. $ds = d_e s + d_i s < 0$, where $d_e s$ is entropy exchange, $d_i s$ inner entropy production, i.e. the system gets a negative entropy flow from its environment, the system will develop. So a fundamental view of this study is to examine the change of negative entropy in the field with the motion of extra tropical cyclone over the Yellow River valley.

2. Models and computational formula

Entropy is a thermodynamic quantity that helps to account for the flow of energy through a thermodynamic process. Originally, entropy was defined as a summation of heat supplied divided by its temperature [21]. If a certain small amount of heat δQ is supplied reversibly to a system with the temperature T, the entropy of the system will increase by an amount [22,23]

$$\Delta S = \int_{\mathrm{is}}^{\mathrm{fs}} \delta Q/T, \tag{1}$$

where ΔS is the incremental entropy of the system between the initial state (is) and the final state (fs) of the process, and δQ is the infinitesimal small change of one path function.

Heat is supplied by radiation, convection, or conduction. When the heat is extracted from the system, the same amount entropy of the system will decrease correspondingly. This is not a violation of the second law of thermodynamics, since the entropy in the surrounding system increases. For an open system which exchanges heat and mass with its surrounding system, the entropy of can either increase or decrease, depending on the direction of the heat transported. Generally speaking, the second law, the law of entropy increase, is valid for a whole isolated system. It remains reasonable for open systems when the system and its environment/reference state are considered as a whole system [24]. So the total change in entropy must be non-negative when we sum up all the entropy changes of interacting subsystems.

Considering that heat can flow from the hot reservoir B to the cold reservoir A which are connected by a small system C, the change rate of entropy of the whole system A+B+C by the heat flow is given by [25].

$$\frac{\partial s_{\mathrm{whole}}}{\partial t} = \frac{\partial s_a}{\partial t} + \frac{\partial s_b}{\partial t} + \frac{\partial s_c}{\partial t} = \frac{F}{T_c} - \frac{F}{T_h} = \frac{T_h - T_c}{T_h T_c} F \geq 0, \tag{2}$$

where $\partial s_{\mathrm{whole}}/\partial t$ is the change rate of the entropy in the whole system, and $\partial s_a/\partial t$, $\partial s_b/\partial t$ and $\partial s_c/\partial t$ are those in the subsystems A, B and C, respectively. F is the flux of heat through the system per unit time. According to Eq. (1), F/T_c is the increased entropy of the cold reservoir A, and $-F/T_h$ are is the decreased entropy of the hot reservoir B since the heat is flowing out from the hot reservoir to the cold. The inequality in Eq. (2) corresponds to the second law of thermodynamics and is a consequence of the fact that heat flows from hot to cold ($F \geq 0$). For a considerably long period of time ($t \to \infty$), the heat of the whole system transport will make the temperature difference negligible, resulting in the entropy of the whole system at a maximum. This final state is called thermodynamic equilibrium.

It is worth mentioning that the maximum work is not attainable generally, because irreversible processes of natural systems are always inevitable. These irreversible conversions of mechanical energy into heat energy (δQ) lead to additional contributions to the entropy production ($\delta Q/T$) in Eq. (1) [26]. In principle, due to some irreversible processes associated with turbulence in a fluid system, the ratio of entropy production can be given by a sum of the change rate of entropy in the system and its surrounding system, which exchanges heat with the system as:

$$\frac{\partial s_{\mathrm{turb}}}{\partial t} = \frac{\partial s_{\mathrm{whole}}}{\partial t} = \int_{\Omega} \frac{1}{T}\left[\frac{\partial(\rho c T)}{\partial t} + \mathrm{div}(\rho c T \vec{V}) + p\,\mathrm{div}\vec{V}\right] d\Omega + \int_{A} \frac{F_{\mathrm{sur}}}{T} dA, \tag{3}$$

where $\partial s_{\mathrm{turb}}/\partial t$ is the rate of entropy production due to turbulence, ρ is the fluid density, c is the specific heat at constant volume Ω, T is the absolute temperature, $\vec{V}$ is the velocity of the fluid, p is the pressure, Ω is the volume of the fluid system, A is the surface surrounding the system, and F_{sur} is the heat flux at the surface, defined as positive outward. (Material fluxes can also be taken into account by means of chemical potential [27]. The first term represents the change rate of entropy of the fluid system, and the second term represents that of the surrounding system.