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Article

Entropy Flow and the Evolution of a Storm

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Abstract: The universal principle that an open system can be driven to a state far from equilibrium, or organized, by strong negative entropy flow from its surroundings has been validated in numerous fields from physics and chemistry to the life science. In this paper, entropy flows for a severe storm are calculated via the entropy flow formula using the National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis data. The results show that the intensification of negative (positive) entropy flow entering into the storm preceded the strengthening (weakening) of its intensity, implying that entropy flow analysis can be used as a potential tool in forecasting changes in the intensity of a storm.

Keywords: Entropy flow, Storm, Forecast

1. Introduction

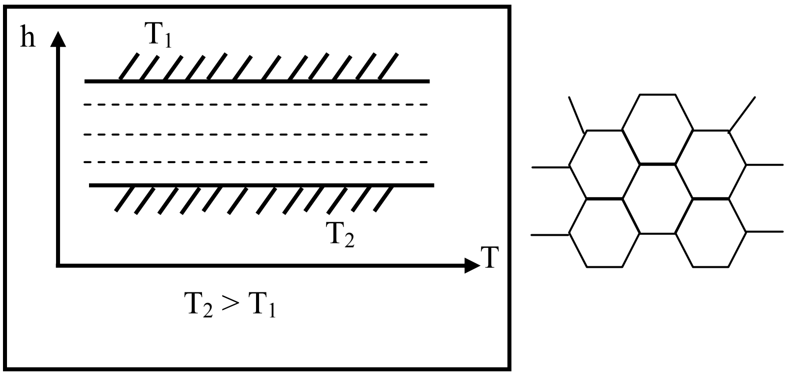
In recent years more attention has been paid to thermodynamics and statistical mechanics in the atmospheric sciences and other fields studying many-body systems like oceanography. In addition to the large number of journal articles [1-10], several monographs have been published in succession [11-13].

Early in the 1940s Eady pointed out the rather formidable task facing theoretical meteorology – that of discovering the nature of and determining quantitatively all the forecastable regularities of a “permanently unstable” (i.e., permanently turbulent) system, and firmly believed that “we can be certain that these regularities are necessarily statistical and to this extent our technique must resemble statistical mechanics” [14].

Entropy flow is a core concept in non-equilibrium thermodynamics just as entropy is in classical thermodynamics and statistical physics. According to the second law of thermodynamics, an isolated system will evolve spontaneously into the equilibrium with maximum entropy in which the order of the system is a minimum [15-16]. As a result, negative entropy is very important for an open system to remain far from equilibrium, which is also true in biological systems as reflected in the statement that life's existence depends on its continuous gain of "negentropy" from its surroundings [17-18].

The atmosphere has been likened to a giant thermodynamic engine in which disorganized heat energy is transformed into the organized kinetic energy of the winds. The general circulation of the atmosphere can be regarded as simply being driven by temperature differences between the polar and equatorial regions [19].

Figure 1. The schematic diagram for Bénard convection as the prototype of self-organization, showing that the temperature difference (T_2-T_1) reaching a certain critical value (threshold) will cause the macro-scale convection to occur within the system. Note that the temperature difference (T_2-T_1) > 0 will lead the entropy exchange $\delta s_e < 0$, meaning that the system gains "negative entropy". See text for details.



The classical Bénard convective system is driven by a vertical temperature difference, and well-organized hexagonal convective cells abruptly form within a thin layer of fluid originally at rest once the temperature difference reaches a certain critical value (see Figure 1). This system demonstrates that systems which get heat at a higher temperature and lose heat at a lower temperature will gain "negentropy" from its surroundings. The troposphere experiences a double negative entropy flow process, in the horizontal and vertical, since it gets heat at the tropics and the surface with higher temperature and loses heat at the poles and the tropopause which have lower temperatures, respectively. This suggests a possible explanation for the variety of weather in the troposphere.

In this paper, our starting point is based on the argument that negative entropy flow might drive a system to a state further apart from equilibrium in which its entropy reaches the maximum. It follows that negative entropy flow is important in the sense that it will favor the development or organization of a system such as storm.

In the field of the atmospheric sciences the theory of entropy has been mostly applied to global-scale and/or climatic investigations using the general circulation models or climatic models. For example, the entropy budget of the atmosphere as a whole has been estimated through the entropy balance equations and, the global climate system has been examined using the principle of minimum entropy exchange [20-22]. A number of more recent climate studies involve also entropy-flux and entropy production [23-25]. In addition to global-scale researches, a cloud ensemble model is used to study the entropy budget as well [26-27].

With respect to applications of entropy theory to numerical prediction, we would like to mention again the research in which the authors reviewed atmospheric systems in light of non-linear non-equilibrium thermodynamics and reached a series of results, including: numerical simulation of atmospheric circulation improved dramatically when the second law of thermodynamics is incorporated into a global spectrum model [10]; and, the forecast accuracy of a meso-scale numerical weather prediction model is noticeably enhanced by introducing a physics-based diffusion scheme [6-7]. Besides, precursors of cyclogenesis over a specific region have been investigated using the spatial distribution of the moist entropy although the physical connotation of this entropy in their context should be, in nature, different from that of the classical thermodynamic entropy [28].

The purpose of this paper is to derive entropy flow equations for calculating the instantaneous entropy flow field and to discuss the relationship of entropy flow with the life cycle of an atmospheric system - a tropical storm (TS) - with the aim of revealing the dependence of the growth of the system on negative entropy flow. The TS selected for this study is tropical storm Bilis, hereafter called TS Bilis, which struck land on Fujian, China in 2006 and was the worst such disaster in Eastern China in the last ten years, as it caused the most deaths. The entropy flow computations for the various stages of its life-cycle are based on the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) 1°×1° (latitude-longitude) resolution reanalysis data [29].

1.1 Background

The second law of thermodynamics can be expressed in terms of the entropy balance equation provided local equilibrium is assumed [16]. The entropy change in an open system usually consists of two parts: one is entropy flow that is caused by the exchange of entropy in the system with its surroundings and the values of entropy flow can be either negative or positive; and, the other is positive definite entropy production caused by irreversible processes within the system.

The Gibbs relation under the assumption of local equilibrium [30] can be written in terms of the change of entropy per unit mass, s, with time

$$\frac{ds}{dt}=\frac{1}{T}\frac{dU}{dt}+\frac{p}{T}\frac{d\alpha}{dt}-\sum_k\frac{\mu_k}{T}\frac{dN_k}{dt} \tag{1}$$

where

$$N_k=\rho_k/\rho \tag{2}$$

and

$$\rho=\sum_k\rho_k \tag{3}$$

The three individual derivatives in the right-hand side of equation 1 can be found through the first law of thermodynamics, the continuity equation and the component balance equation. The first law can be written as

$$\frac{dU}{dt} = -\alpha div \vec{J}_q - p\frac{d\alpha}{dt} \tag{4}$$

where $\alpha = \rho^{-1}$ and $\frac{d\alpha}{dt}$ can be related to $div\vec{V}$ via the continuity equation

$$\frac{d\alpha}{dt} = \alpha div\vec{V} \tag{5}$$

where

$$\vec{V} = \sum \rho_k \vec{V}_K / \rho \tag{6}$$

and, the component balance equation can be written as

$$\frac{dN_k}{dt} = -\alpha div J_k + \alpha \sum_r v_{kr} m_k \omega_r \tag{7}$$

Substituting for the three individual time derivatives in the right-hand side of equation 1 by equations 4, 5 and 7 and turning the derivation of entropy into the local derivative, we have

$$\frac{\partial \rho s}{\partial t} = -div(\rho s\vec{V} + \frac{1}{T}\vec{J}_q - \sum_k \frac{\mu_k}{T}\vec{J}_k) + \sigma \tag{8}$$

where

$$\sigma = -\sum_k \vec{J}_k \cdot \nabla\frac{\mu_k}{T} + \frac{1}{T}\sum_k \vec{J}_k \cdot \vec{F}_k - \frac{1}{T}\sum_r\sum_k v_{kr}\mu_k\omega_r \tag{9}$$

is called entropy production while the “div” term is the entropy flow.

Usually the contribution of $\frac{1}{T}\vec{J}_q$ to the entropy flow in the atmosphere is neglectable compared with $\rho s\vec{V}$ while the diffusive flow $\vec{J}_k$ for component *k* can be defined as [31]

$$\vec{J}_k = \rho_k(\vec{V}_k - \vec{V}) \tag{10}$$

In this paper the component of liquid water has been omitted owing to the liquid water content (about 5 gm^{-3} on the average over the tropics) being much less than the density of either vapor or dry air [32-33] and only two components are therefore taken into account, that is, vapor and dry air. Usually the velocity $\vec{V}_q$ for vapor is assumed to be the same as $\vec{V}_d$ for dry air so that $\vec{J}_k = 0$ in this case. As a consequence, the entropy *s* per unit mass consists accordingly of s_q for vapor and s_d for dry air with all the corresponding entropy constants, s_{q0} and s_{d0}, to vapor and dry air, respectively, set to zero so that

$$s = s_q + s_d = q(C_{pv}\ln T - R_v \ln e) + (1-q)[C_{pd}\ln T - R_d \ln(p-e)] \tag{11}$$

The formulas above are derived based on Cartesian coordinates but the NCEP/NCAR reanalysis data used in this paper are on constant pressure layers, so it is necessary to transform the expression of entropy flow into that in the p-coordinates

$$-div\vec{J}_s = -\frac{\partial \rho s u}{\partial x} - \frac{\partial \rho s v}{\partial y} + \rho g\frac{\partial \rho s\omega}{\partial p} \tag{12}$$

Equation 12 is the fundamental formula for diagnosing entropy flow employed in this paper.

1.2 Case Description

TS Bilis struck land at Fujian, China on 14 July 2006, and caused direct economic losses of US$5.1 billion, 654 deaths and 208 missing persons. TS Bilis formed in the afternoon on 9 July 2006,