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Heat to work conversion during upward heat convection
Part II: Internally generated entropy method

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Abstract

The work produced in the atmosphere is calculated from the entropy produced when work dissipates. The work is equal to the product of the entropy produced and the temperature at which the work dissipates. The atmosphere exports more entropy to external sources than it imports from external sources because it gives up heat at lower temperature than it receives heat. The net entropy export is compensated for by entropy produced internally also called internally generated entropy.

Compensating for the net entropy export of the atmosphere requires an average work dissipation of approximately 25 W m^{-2}. The entropy increase during weather events is calculated from soundings taken before and after the events. The internally generated entropy is the observed entropy increase minus the net entropy received from external sources. The work dissipation during a sub-tropical squall and during a period of forenoon warming are calculated to be 600 W m^{-2} and 15 W m^{-2} respectively. The method could be used to calculate work produced and dissipated under a wide range of atmospheric conditions. Routinely calculating of the entropy and enthalpy of soundings could improve the understanding of atmospheric energetics.

1. Introduction

The determination of the heat to work conversion efficiency of the atmosphere is the fundamental problem of atmospheric energetics. Estimates of how much work is produced vary widely. In the long run the work produced must equal the work dissipated by friction. The conversion efficiency could be established by evaluating either the work

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produced or the work dissipated, but the determination of either is difficult. Schulman (1977) pointed out that evaluating the dissipation is limited by poor understanding of the dissipation process. Evaluation of the work produced is limited by poor understanding of the work generation process. Estimates of the work produced and dissipated usually range from 2 to 12 W m^{-2} (see Lorenz, 1967 and Schulman, 1977). The corresponding conversion efficiency based on a solar flux of 350 W m^{-2} is 0.6% to 3%.

This article presents a method of determining the conversion efficiency which avoids the difficulties inherent in calculating either the work production or the work dissipation. Prigogine (1961) states that the only general criterion of irreversibility is given by entropy production (see his p. 17). Work produced in the atmosphere is eventually dissipated by friction in irreversible processes. The entropy produced is equal to the work dissipated divided by the temperature at which the work is dissipated. The atmosphere exports more entropy to external sources than it imports from external sources because it gives up heat at lower temperature than it receives heat. The net external entropy export is compensated for by entropy produced when work dissipates.

Michaud (1995, M1 hereafter) showed that the work produced when heat is carried upward by convection is equal to the upward heat flux multiplied by the Carnot efficiency based on the temperature at which the heat is received and given up. M1 showed from energy conservation that the work must be between 20 and 30 W m^{-2}. The internally generated entropy method is a corollary of the Carnot efficiency method. The internally generated entropy method is used in this article to show that the average work produced is 25 ± 5 W m^{-2}. The conversion efficiency is thus 7% of the solar flux and 17% of the energy carried upward by convection.

Section 2 calculates the work dissipated in a steady state system. Section 3 presents estimates the work dissipated in a variety of weather conditions. Section 4 calculates the work produced and dissipated during a squall. Section 5 calculates the work produced and dissipated during the forenoon heating of the boundary layer. The conclusion suggests that the entropy produced technique could be extended to calculate the work dissipated under a wide range of atmospheric conditions.

2. Steady state entropy balance

The entropy of the atmosphere can be changed by entropy received from an external source or by internally generated entropy, Lesins (1990).

$$\Delta S = (\Delta S_{e-i} + \Delta S_{e-o}) + \Delta S_i = \Delta S_e + \Delta S_i \tag{1}$$

where ΔS is the change in the entropy of the atmosphere, ΔS_{e-o} is the entropy exported to external sources, ΔS_{e-i} is the entropy received from external sources. The term in the parenthesis is the net external entropy import, ΔS_e. ΔS_i is the internally generated entropy. The second law of thermodynamics requires that the internally generated entropy be positive. A change in the entropy of the atmosphere can be due to one of three processes. The entropy of the atmosphere can be decreased by infrared radiation to space. The entropy of the atmosphere can be increased either by external heating or by entropy generated internally.

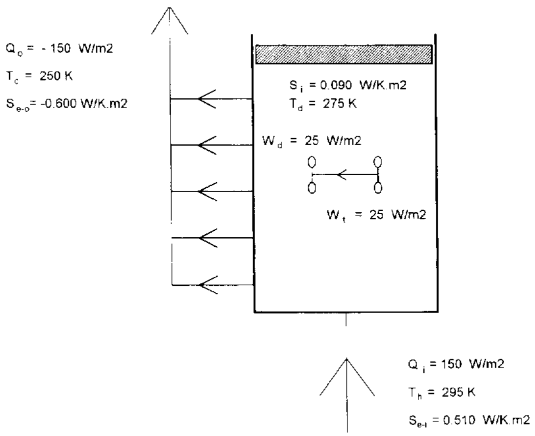

Fig. 1. Ideal steady-state thermodynamic system used to calculate work dissipation in the atmosphere. The system exports more entropy that it imports because it gives up heat at lower temperature than it receives heat. The net export of entropy is compensated for with internally generated entropy. The internally generated entropy is produced when the work produced within the system (w_t) dissipates (w_d). For the nominal heat flux shown, the work dissipation has to be 25 W m^{-2}.

The troposphere will be represented by the closed ideal steady-state stationary thermodynamic system shown in Fig. 1. The system receives heat from the bottom and gives up heat at higher level by infrared radiation to space. The analysis depends on the fact that the heat received at low level is transported by convection to the higher level where it is radiated to space. In the real atmosphere the net upward convective heat flux is equal to the net downward radiative heat flux. In a stationary system, the heat input is equal to the heat output and there is no change in the enthalpy or entropy of the system. The pair of propellers represents work production and dissipation. The shaft joining the propellers does not extend outside the system because the work which is dissipated is produced within the system. The object of the calculation is to determine how much work is produced (w_t) and dissipated (w_d). The system is surrounded by insulated vertical walls. The air above the tropopause does not take part in the rearrangement process and is replaced by a piston exerting a constant pressure in order to create a closed thermodynamic system.

The external entropy import is equal to

$$\Delta S_{e-i} = \frac{Q_i}{T_h} \tag{2}$$

where Q_i is the heat received and T_h is the temperature at which the heat is received.

The external entropy export is equal to

$$\Delta S_{e-o} = \frac{Q_o}{T_c} \tag{3}$$

where Q_o is the heat given up and T_c is the temperature at which the heat is given up. By convention, heat and entropy are positive when received by the system and negative when given up by the system.

The entropy produced when work dissipates is equal to the work dissipated (W_d) divided by the absolute temperature at which the work is dissipated (T_d).

$$\Delta S_i = \frac{W_d}{T_d} \tag{4}$$

The work can be considered to be dissipated by friction which produces internal heating and thus internally generated entropy.

Combining Eq. (1) to Eq. (4), the work which must be dissipated to make up for the excess of entropy export over entropy import is then

$$W_d = Q_i T_d \left(\frac{1}{T_c} - \frac{1}{T_h} \right) \tag{5}$$

An application of this equation is given in Fig. 1. The energy fluxes are based on Peixoto and Oort (1992) (see their fig. 15.2). The nominal heat input of 150 W m^{-2} is the observed average infrared radiation to space (238 W m^{-2}) minus the infrared radiation which does not have to be carried upward by convection, namely the 20 W m^{-2} of infrared radiation emitted directly from the earth surface to space, and the 68 W m^{-2} of solar radiation which is absorbed in the upper atmosphere. It will be shown later that heat emitted at the same temperature as it is received does not contribute to the production of work. The average temperatures at which heat is received (T_h) and given up (T_c) are about 295 K and 250 K, respectively.

Fig. 1 shows that the entropy received by the troposphere is 0.510 W K^{-1} m^{-2}, and that the entropy given up by the troposphere is -0.600 W K^{-1} m^{-2}. The internally generated entropy compensates for the net entropy export of 0.090 W K^{-1} m^{-2}. Taking the average temperature at which work is dissipated (T_d) as 275 K, the work (W_d), which must be dissipated to balance the external entropy export, is 25 W m^{-2}. The work dissipation efficiency (W_d/Q_i) is then 16.7%.

A dissipation temperature of 275 K was selected because it is roughly half way between the hot and cold source temperature. The efficiency is mainly determined by the temperatures at which heat is received and given up and only slightly sensitive to the temperature at which the work is dissipated. The conversion efficiency would be 15% if the work were dissipated at the cold source temperature, and 18% if the work were dissipated at the hot source temperature. The reason why the efficiency is higher when the work is dissipated at hot source temperature is that the work becomes additional heat which is eventually transported to the cold source. In the real atmosphere the work production and dissipation is distributed throughout the system.

Prigogine (1961) (chapter 3, p. 20) states that the internally generated entropy concept is of great importance. Splitting the entropy into externally supplied and internally generated portions permits extending the concept that the entropy of isolated systems can only increased to closed systems; the internally generated portion of the entropy can only increase. Prigogine (1961) (see his p. 84, eq. 6.41) shows that the entropy import in a closed stationary system is,

$$\Delta S_e = Q_i \left(\frac{1}{T_h} - \frac{1}{T_c} \right) \tag{6}$$

Since internally generated entropy is always positive, there must be a net export of entropy. Prigogine only considered processes where entropy is produced in non equilibrium processes, such as conduction, evaporation, and mixing. He did not specifically consider processes where entropy is produced by the dissipation of work (see his p. 29, eq. 3.52), but the internally generated entropy concept is applicable to work dissipation. It is estimated that about 90% of the entropy produced in the atmosphere is produced by the simple dissipation of mechanical energy. Taking the energy dissipated when a unit mass of air rises as 2750 J/kg (typical of CAPE) and the dissipation temperature as 275 K, the entropy produced when the work dissipates is 10 J K^{-1} kg^{-1}. The entropy produced when two masses of air with a 10 K temperature difference are mixed is about 0.15 J K^{-1} per kilogram of mixture. The entropy produced when 1 g of water is evaporated in air with 60% relative humidity is about 0.16 J K^{-1} per gram of water. Increasing CAPE by 2750 J kg^{-1} through water evaporation requires that about 6 g of water be evaporated per kilogram of air. The entropy produced in evaporating enough water to produce a CAPE of 2750 J kg^{-1} is thus about 1 J K^{-1} kg^{-1}, about 10% of the entropy produced by work dissipation. This article only considers the entropy produced by work dissipation.

The work production and dissipation in Fig. 1 is independent of any specific convection process, but it is useful to examine specific processes to see how the work is produced and dissipated. M1 analyzed several specific processes and showed that the work is always equal to the upward heat flux multiplied by the Carnot efficiency. M1 showed that the work produced when a unit mass of air is raised is equal to the reduction in its static energy, which is equal to the reduction in the enthalpy of the system. The entropy is produced when the work dissipates and not when the work is produced. No entropy is produced in a reversible constant entropy lifting process (table 1 of M1). Entropy is produced when work dissipates in an irreversible constant static energy process (table 2 of M1). In the irreversible process (table 2 of M1), the entropy of the raised unit mass increases from 243.4 to 246.9 J K^{-1} kg^{-1}, the product of the entropy increase 3.5 J K^{-1} kg^{-1} and the dissipation temperature (210 K) is equal to the work dissipated, 734 J kg^{-1}.

The principal work dissipation mechanism in the atmosphere is probably frictional dissipation between rising and descending air masses and their surroundings. Dissipation is low when convection is weak because dissipation is a function of shear. A steady horizontal wind requires little shear. Buoyant air masses reach a terminal velocity at which work dissipation equals the work production. A Convective Available Potential Energy (CAPE) of 2000 J/kg can theoretically produce a velocity of 60 m/s, but the upward velocity of buoyant updrafts rarely exceed 10 m/s, a kinetic energy of 50 J/kg. Raising a kilogram of air with a CAPE of 2000 J/kg produces 2000 J of work despite the fact that the kinetic energy of the air never exceeds 50 J. Once the terminal velocity is reached, the work is dissipated by friction as it is produced. The upward velocity increases until the work dissipated equals the work produced. M1 showed that a significant fraction of the work produced can be in the potential energy of condensed water. The dissipation mechanism for the potential energy of condensed water is similar to the dissipation mechanism for buoyant air masses. The potential energy of condensed water is dissipated either by the condensed water falling at its terminal velocity or by air masses becoming negatively buoyant as a result of in-mixing of condensed water and descending at their terminal velocity.

The efficiency of the atmospheric engine is a function of the temperatures at which heat is received and given up; the temperature of the sun is irrelevant. In thermodynamics engines it is the temperature at which the heat is received by the working fluid that is important. The atmosphere receives heat at the temperature of the air near the Earth's surface and gives up heat at the temperature at which radiation is emitted to space. The thermodynamic analysis of the system of Fig. 1 would be unchanged if the heating and cooling were done with heat exchangers instead of by short wave solar radiation and long wave terrestrial radiation. The working fluid is the air including its water content. The temperature at which latent heat is transferred from condensing water to air is also irrelevant. The efficiency is independent of whether the system contains pure air or an air water mixture. The bottom surface can be considered to be covered by a layer of liquid water which is part of the system and where heat can temporarily be stored.

Fig. 1 shows that the entropy exported by the atmosphere is 1.2 times the entropy received. Peixoto and Oort (1992) (see their fig. 15.2) used the temperature of the sun as the hot source temperature and concluded that the entropy exported by the Earth is 23 times the entropy received. The atmosphere is only a part of the universe, there is a further increase in entropy of the universe when short wave solar radiation is converted to long wave radiation, whether the conversion occurs on the Earth which has an atmosphere or on the Moon which has no atmosphere, but this further increase is not associated with dissipation in the atmosphere. Li et al. (1994) tried to separate the entropy production contribution of radiation, conduction, and condensation and found the entropy produced to be 0.76 W K^{-1} m^{-2}, which is much higher than the 0.09 W K^{-1} m^{-2} of Fig. 1.

Emitting heat at lower temperature than it is received requires that work be dissipated. There is no requirement that work be dissipated on the moon where heat is given up at about the same average temperature as it received. The Earth's atmosphere and its opacity to infrared radiation cause heat to be radiated at lower temperature than it is received, which requires that entropy be produced internally, and that work be dissipated, and thus requires that work be produced.

3. Non steady state processes

In a non-stationary system, the heat input is not equal to the heat output; the enthalpy and the entropy of the system change with time. The average work production and dissipation in the atmosphere is 25 W m^{-2}, but the rate is far from uniform. Table 1 is the author's estimate of the work dissipation for a variety of weather conditions. The work dissipation can vary by over six orders of magnitude. The values in Table 1 are based on estimates of dissipation by friction, on the Carnot efficiency method, on the internally generated entropy method, and on the fact that the average dissipation in the atmosphere must be 25 W m^{-2}. The next two sections will verify two of the values in Table 1 using the internally generated entropy method.

Over the long run the incoming and outgoing external energy sources are equal.

Table 1
Estimated work dissipation for selected weather conditions

Work dissipation ($W m^{-2}$)	Weather condition
< 0.1	Calm air, no convection, night time radiative cooling over land
0.1–1	Light wind, little convection
1–10	Light wind, shallow convection
10–100	Some gusts, moderate convection, little or no precipitation
100–1000	Severe thunder storm with strong gusts and heavy precipitation
> 1000	Tropical cyclone, hurricane, or weak tornado
> 10,000	Strong tornado

However, the instantaneous values are rarely equal because of the daily variation in the solar radiation. The entropy produced by work dissipation is usually small compared to the entropy import or the entropy export. The fact that a small change in the heat input or output has as much effect on the entropy of the system as the nominal work dissipation makes determination of internally generated entropy difficult. A small measurement error in the heat input or the heat output can easily conceal the entropy increase due to work dissipation. Calculating the net heat input form the change in enthalpy between the initial and final sounding avoids the difficulty of accurately measuring heat input and heat output.

Analyzing closed ideal systems can be useful in understanding the atmospheric process in spite of the fact that the atmosphere is not a closed system. The following specific event technique is limited to systems that are uniform in the horizontal direction and that could be enclosed by vertical walls. The technique is not valid when there is a significant exchange of mass between the area of the event and adjacent areas. The technique would not be valid for the passage of a cold front where the air mass present after the passage of the front is not the same as the air mass before the passage of the front. The sub-tropical squall and the forenoon warming events were selected because they were uniform in the horizontal direction. In the squall case the conditions during the squall were not uniform in the horizontal direction, but soundings taken before and after the squall were representative of the area swept by the squall. The calculations are based on the assumption that the air present in the area is the same before and after the squall, that the air mass within the squall area has been rearranged without significant mass exchange with adjacent areas.

4. Work dissipation during a squall

4.1. Sounding analysis

Soundings taken before and after a severe squall will be used to estimate the work dissipated during the squall. The selected squall is a subtropical squall which was observed during the Taiwan Area Mesoscale Experiment (TAMEX) and which has been described by Wang et al. (1990). The center of the eastward travelling squall line passed over the small island of Makung located 40 km west of Taiwan. The squall line extended approximately 200 km north to south and was approximately 20 km wide. The

Table 2
Makung sounding. Pressure (P), temperature (T), dew point T_d, specific humidity (q), entropy (s) and enthalpy (h)

P (kPa)	T (°C)	T_d (°C)	T (K)	q (g/kg)	s (J/K·kg)	h (J/kg)
a. Pre-squall sounding						
101	25.5	24.8	298.65	19.473	260.8	74,736
90	20.5	14.0	293.65	11.108	205.1	48,566
80	13.0	11.0	286.15	10.258	205.5	38,826
70	8.0	−1.0	281.15	5.060	179.8	20,726
60	0.0	−2.0	273.15	5.486	199.0	13,721
48	−8.0	−11.0	266.15	3.434	214.4	528
40	−16.0	−19.0	257.15	2.129	223.7	−10,780
30	−32.0	−37.0	241.15	0.535	226.1	−30,827
20	−57.0	−63.0	216.15	0.041	227.3	−57,166
15	−64.0	−71.0	209.15	0.018	276.6	−64,254
		Sounding	Average	5.773	214.5	7884
b. Post-squall sounding						
101	23.5	23.0	296.65	17.457	236.8	67,612
86	19.0	11.0	292.15	9.538	199.3	43,094
73	10.0	7.0	283.15	8.647	206.4	31,558
67	7.0	−1.0	280.15	5.287	190.9	20,287
59	0.0	−1.0	273.15	6.007	208.5	15,023
50	−6.0	−8.0	267.15	4.176	217.1	4395
40	−16.0	−20.0	257.15	1.954	222.0	−11,215
30	−30.0	−35.0	243.15	0.653	235.6	−28,524
20	−56.0	−64.0	217.15	0.036	231.9	−56,174
15	−70.0	−80.0	203.15	0.005	247.2	−70,315
		Sounding	Average	5.814	216.6	8455

c. Work dissipation calculations

$M = 8776$ kg m^{-2}

$I = 21{,}600$ s

$M/I = 0.406$ kg s^{-1} m^{-2}

$h_1 = 7884$ $h_2 = 8455$ $\Delta h = 571$ J kg^{-1}

$s_1 = 214.5$ $s_2 = 216.6$ $\Delta s = 2.18$ J K^{-1} kg^{-1}

$T_c = 250$ $T_h = 295$ $T_d = 275$ K

Case 1: $Q_o = -150$ W m^{-2}

$Q_n = 232$ W m^{-2}

$Q_i = 382$ W m^{-2}

$\Delta S_{ci} = 1.295$ W K^{-1} m^{-2}

$\Delta S_{co} = -0.600$ W K^{-1} m^{-2}

$\Delta S_c = 0.695$ W K^{-1} m^{-2}

$\Delta S = 0.884$ W K^{-1} m^{-2}

$\Delta S_i = 0.189$ W K^{-1} m^{-2}

$W_d = 52$ W m^{-2}

Case 2: $Q_o = 0$ W m^{-2}

$Q_n = 232$ W m^{-2}

$Q_i = 232$ W m^{-2}

$\Delta S_{ci} = 0.786$ W K^{-1} m^{-2}

$\Delta S_{co} = 0$ W K^{-1} m^{-2}

$\Delta S_c = 0.786$ W K^{-1} m^{-2}

$\Delta S = 0.884$ W K^{-1} m^{-2}

$\Delta S_i = 0.098$ W K^{-1} m^{-2}

$W_d = 27$ W m^{-2}

squall passed over Makung at 2300 local time. Soundings were taken at Makung at 2000 and 0200, 3 h before and 3 h after the squall.

Table 2a and b give the sounding data taken from figs. 6 and 7 of Wang et al. (1990). The thermodynamic properties were calculated using the equations given in M1 (see Appendix A of M1), except that the properties are divided by one plus the mixing ratio to give properties per unit mass of mixture instead of per unit mass of air, for convenience in calculating average sounding properties. The equations are based on Dufour and Van Mieghem (1975). Work dissipation calculations requires that the entropy and the enthalpy be calculated rigorously from the same sounding data. Approximate or inconsistent methods of calculating entropy and enthalpy would not give valid results. The average entropy and enthalpy of the sounding were calculated by trapezoidal integration.

The internally generated entropy and the work dissipated were calculated using the following equations in the order listed.

$$Q_n = (h_2 - h_1)\frac{M}{I} \tag{7}$$

$$Q_i = Q_n - Q_o \tag{8}$$

$$\Delta S = (s_2 - s_1)\frac{M}{I} \tag{9}$$

$$\Delta S_e = \frac{Q_i}{T_h} + \frac{Q_o}{T_c} \tag{10}$$

$$\Delta S_i = \Delta S - \Delta S_e \tag{11}$$

$$W_d = T_d\,\Delta S_i \tag{12}$$

Combining Eq. (7) to Eq. (12)

$$WDIS = W_d = T_d\left\{Q_o\left[\frac{1}{T_h} - \frac{1}{T_c}\right] + \frac{M}{I}\left[(s_2 - s_1) - \frac{(h_2 - h_1)}{T_h}\right]\right\} \tag{13}$$

Q_n is the net heat received by the sounding from external sources. s and h are the average entropy and enthalpy of the sounding. The subscripts 1 and 2 designate the pre-storm and post-storm sounding. M is the total mass of the sounding (8776 kg m^{-2}), the bottom pressure minus the top pressure divided by the acceleration of gravity taken as 9.8 m s^{-2}. I is the interval between soundings in seconds. Thermodynamic properties are per unit mass of substance. Entropy change and heat input are per unit area. Lower case letters are used for properties per unit mass, upper case for properties per unit area. The average temperature at which heat is received T_h, the average temperature at which heat is given up T_c, and the average temperature at which work is dissipated T_d will be taken as 295 K, 250 K and 275 K, respectively. The acronym *WDIS* will be used for work dissipated, W_d. The kinetic energy of the soundings is neglected because the difference between pre-storm and post-storm kinetic energy is not significant compared to the change in the enthalpy of the sounding. The kinetic energy produced during the interval between soundings is taken to have dissipated by the time of the final sounding.

The work dissipation calculations are given in Table 2c. The net heat received during the event is equal to the change in the enthalpy of the sounding. The average enthalpy of the sounding increased by 571 J kg^{-1} which corresponds to a net heating rate (Q_n) of 232 W m^{-2}. In addition to receiving heat from the underlying surface the sounding lost an unknown amount of heat from upward infrared radiative heat flux. Two cases will be considered: Case 1 where the upward radiative heat flux (Q_o) will be taken to be the nominal 150 W m^{-2}, Case 2 where the upward radiative heat flux is zero, the minimum possible value. Case 1 is more realistic, Case 2 shows how the heat loss assumption affects the work.

4.2. *Case 1*

Producing a net heat input (Q_n) of 232 W m^{-2} plus an outgoing heat flux (Q_o) of 150 W m^{-2} requires a heat input (Q_i) of 382 W m^{-2}. 382 W m^{-2} is somewhat higher that the nominal heating rate of 150 W m^{-2}, but is not unreasonable because a higher than average heating rate can be expected over the agitated sea during a squall. The average entropy per unit mass of the sounding (Δs) increased by 2.18 J K^{-1} kg^{-1}. The entropy of the sounding per unit area (ΔS) increased by 0.884 W K^{-1} m^{-2}, but the net entropy increase from external heat input (ΔS_e) was only 0.695 W K^{-1} m^{-2}. 0.189 W K^{-1} m^{-2} of entropy increase had to be produced internally. The work which has to be dissipated at 275 K to produce 0.189 W K^{-1} m^{-2} of entropy is 52 W m^{-2}.

The time interval between the soundings was 6 h, but the squall lasted less than 1 h. The squall travelled at 60 km/h and was approximately 20 km wide. The intense part of the squall had a duration of approximately 20 min. The average dissipation rate during the squall must have been 300 W m^{-2} and 1000 W m^{-2}, 6 to 20 times the average dissipation rate during the 6 h interval. Localized short duration peak dissipation rates may have been over 2000 W m^{-2}.

The entropy and the enthalpy of the pre-storm and post-storm soundings are shown in Figs. 2 and 3. The entropy and the enthalpy decreased near the bottom of the troposphere and increased in the middle troposphere. The storm transported energy upward. The change in the entropy and the change in the enthalpy divided by T_h are

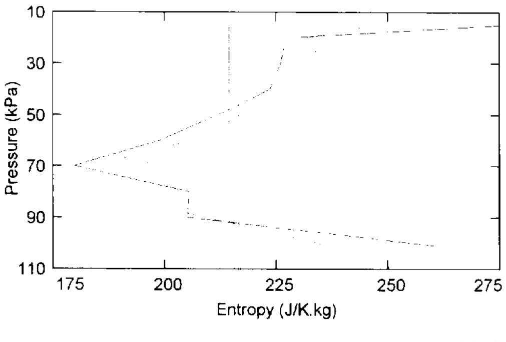

Fig. 2. Entropy of the Makung pre-squall and post-squall soundings. Solid line pre-squall, dotted line post-squall. Vertical lines average entropy of the soundings.

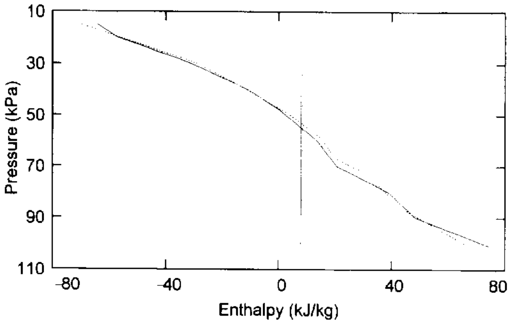

Fig. 3. Enthalpy of the Makung pre-squall and post-squall soundings. Solid line pre-squall, dotted line post-squall. Vertical lines average enthalpy of the soundings.

shown on Fig. 4. Normalizing by T_h makes the difference between the two lines on Fig. 4 correspond to the term in the second set of brackets in Eq. (13).

4.3. Case 2

When the heat output Q_0 is zero, the average work dissipation during the 6 h interval between sounding is 27 W m^{-2}, and the work dissipation during the 20 min duration of the squall is 482 W m^{-2}. The work, in Case 2, is the minimum work could have been dissipated because the work is at its minimum when the heat output is zero. When the heat output is zero, the internally generated entropy is equal to the small area between the two curves of Fig. 4. The entropy produced and the work dissipated both depend on the extent to which the entropy increase exceeds the enthalpy increase divided by the temperature at which the heat is received. The change in the average enthalpy of the sounding, 571 J kg^{-1}, is small compared to the uncertainty of the measurement, but the internally generated entropy is significant provided the change in entropy and in enthalpy are calculated from the same sounding data.

The initial and final sounding should contain the same quantity of air and water. It is fortunate that the two Makung soundings have approximately the same total water

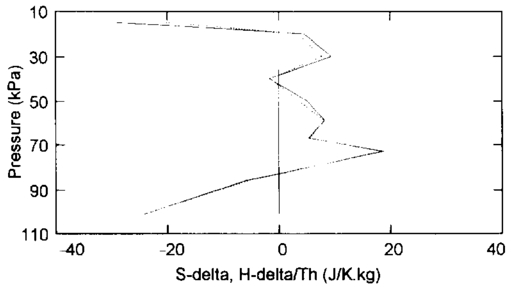

Fig. 4. Change in the entropy and enthalpy of the Makung sounding. Solid line entropy. Dotted line enthalpy divided by the hot source temperature, (h/T_h).

Table 3
Work per unit mass raised from the base to the top of the Makung sounding. Work of buoyancy w_b (CAPE), potential energy of condensed water (w_p), total work (w_t) and GCAPE. Based on no separation and no freezing

Pre-storm sounding	Work (J/kg)
w_b (CAPE)	1917
w_p (PE of condensate)	2746
w_t (Total work)	4662
GCAPE	75
Post-storm sounding	**Work (J/kg)**
w_b (CAPE)	−251
w_p (PE condensate)	2463
w_t (Total work)	2212

content. The levels in Table 2a and b were selected to correspond with inflections in the soundings. Work based on the original soundings data would be more accurate than work based on data taken from published sounding plots, but the effect should be no more than 25%.

4.4. *Source of the work which is dissipated*

It is interesting to examine the source of the work dissipated. The work comes partly from the available energy of the initial condition and partly from the heat received during the storm. In a steady-state process where the entropy and enthalpy of the system are constant, the term in the second part between brackets of Eq. (13) is zero, and the work is produced from heat received during the convection process. In a process without external heat input or output, the entropy produced is equal to the observed entropy increase, and the work is produced from available energy of the initial condition. For the Makung soundings, the contribution of the two terms of EQ. (13) are approximately equal. The work was produced partly from heat received during the storm and partly from the previously stored energy.

Table 3 shows the work of buoyancy (w_b = CAPE), the potential energy of condensed water (w_p), the total work (w_t), and the GCAPE of the pre-storm and post-storm soundings. CAPE is the work of buoyancy produced when a unit mass of air is raised to its level of neutral buoyancy. GCAPE is the work of buoyancy produced when the system is brought to its reference state. CAPE is per unit mass of air raised; GCAPE is per unit mass of air in the system. CAPE and GCAPE are defined in Randall and Wang (1992). The three work terms are defined in M1. The CAPE of the sounding decreased from 1917 J kg^{-1} for the pre-storm sounding to −251 J kg^{-1} for the post-storm sounding indicating that the available work has been reduced to close to zero during the storm. The CAPE values are based on true adiabatic expansion without separation or freezing and would be somewhat higher with freezing and separation. The GCAPE of the initial sounding is 75 J kg^{-1}. GCAPE does not include the potential energy of condensed water. When the potential energy of condensed water is included the total available work could be as high as 400 J kg^{-1}. Releasing all the available work over the 6 h interval would produce 160 W m^{-2}. Converting 15% of the heat received during the storm to work would produce an additional 60 W m^{-2}.

The work dissipated (52 W m^{-2}) is considerably less than the total work available (220 W m^{-2}) because the convection is shallow and does not extend to the top of the troposphere. Bringing the sounding to the reference state would require that the bottom 6 kPa of the sounding be raised to the 15 kPa level. Fig. 3 shows that the average convection extended to the 60 kPa level. The work actually produced was much less than the total available work because the convection did not extend high enough to reach the reference state. GCAPE is the maximum work of buoyancy which can be produced by bringing a sounding to its reference state. WDIS is the work which is actually dissipated. GCAPE only considers work of buoyancy; WDIS includes the work of buoyancy (w_b) and the potential energy of condensed water (w_p).

Emanuel (1988) compared the maximum energy conversion efficiency of hurricanes to the Carnot efficiency. He used the temperatures at the bottom and top of the troposphere as the hot and cold source temperatures. He used a Carnot like cycle and calculated an energy conversion efficiency of 33%. Fritsch et al. (1994) discuss Emanuel's article and speculate on whether the kinetic energy of tropical depressions comes from the pre-existing CAPE or from heat supplied from the warm sea during the storm. The internally generated entropy method has the potential of distinguishing between work produced from pre-existing CAPE and work produced from heat received during a storm.

5. Work dissipation during forenoon heating

This section calculates the work dissipated during the forenoon heating of the mixed boundary layer. The selected soundings were described by Telford (1992). The soundings reconstructed from Telford Fig. 2 are given in Table 4a and b. The soundings were taken over land at 0940 and 1055 local time. Telford pointed out that forenoon heating increased the temperature below 94 kPa and increased the moisture between 93 and 89 kPa. The thermodynamic system will be considered to be covered by a piston at the 88.66 kPa level above which there is no increase in temperature or humidity. The heat radiated by the system is negligible compared to the heat received from the surface and will be considered to be zero, in which case the first part between brackets of Eq. (13) is zero.

The calculation results are in Table 4c. The heating calculated from the change in the enthalpy of the sounding is 690 W m^{-2} which is consistent with forenoon insolation. The entropy of the sounding increased by 2.37 W K^{-1} m^{-2} of which 2.32 W K^{-1} m^{-2} came from external entropy import. The internally generated entropy is 0.048 W K^{-1} m^{-2}. The work dissipation averaged 15 W m^{-2} or 2.2% of the heat received. The efficiency calculated from the entropy produced is the same as the Carnot efficiency. The heat to work conversion efficiency is only 2.2%, but additional work would be produced sometime later when the heat is carried to higher levels.

Table 4

Telford Fig. 2. Pressure (P), temperature (T), specific humidity (q), entropy (s) and enthalpy (h)

P (kPa)	T (K)	q (g/kg)	s (J/K·kg)	h (J/kg)
a. 0940 LST sounding				
99.60	296.16	13.71	207.1	57,688
95.08	292.26	13.03	201.1	51,990
93.70	292.02	10.88	185.9	46,341
92.62	291.74	11.27	191.7	47,041
89.76	290.20	10.39	187.7	43,265
86.66	288.46	10.20	190.0	41,009
	Average	11.73	195.06 *	48,431 *
b. 1055 LST sounding				
99.60	297.86	13.71	212.8	59396
95.08	293.93	13.22	208.6	54176
93.70	292.71	13.22	208.6	52937
92.62	291.74	13.12	207.8	51707
89.76	290.20	10.88	191.9	44496
86.66	288.46	10.20	190.0	41009
	Average	12.39	203.16	50788

c. Work dissipation calculation

$M = 1320$ kg m^{-2}

$I = 4500$ s

$M/I = 0.293$ kg s^{-1} m^{-2}

$h_1 = 48{,}431$	$h_2 = 50{,}788$	$\Delta h = 2357$ J kg^{-1}
$s_1 = 195.06$	$s_2 = 203.16$	$\Delta s = 8 \cdot 10$ J K^{-1} kg^{-1}
$T_c = 291$	$T_h = 297$	$T_d = 295$ K

$Q_o = 0$

$Q_i = 690$ W m^{-2}

$\Delta S_{ei} = 2.32$ W K^{-1} m^{-2}

$\Delta S = 2.37$ W K^{-1} m^{-2}

$\Delta S_i = 0.048$ W K^{-1} m^{-2}

$W_d = 15$ W m^{-2}

$n = W_d / Q_i = 2.2\%$

$n_c = 1 - T_c / T_h \approx 2.3\%$

* Average includes 0.66 g/kg of liquid water with entropy of 0.22 J/K.kg and with enthalpy of 64 J/kg.

The work in the forenoon heating case is not due to a fortuitous choice of soundings. Heating the atmosphere from the bottom produces entropy because the temperature at which the heat is supplied is higher than the temperature of the air whose enthalpy is increased. The technique could be applied to the heating of numerous uniform air masses. Soundings taken throughout the day should show that the conversion efficiency increases with cloud height. Telford provided sounding taken at 0940, 1015 and 1055. The internally generated entropy method shows that the conversion efficiency was lower during the earlier interval than during the later interval.

The term in the second set of Eq. (13) is zero when the heat is received at the average temperature of fluid. No entropy is produced when air is heated by the direct absorption of radiant energy with no re-arrangement because the temperature at which the energy is received is the temperature of the heated air. No entropy is produced by radiative cooling because the temperature at which the energy is emitted is the temperature of the cooled air. No work is produced by heat which is emitted at the same temperature as it is received. For these reasons, the infrared radiation emitted at the same temperature as the corresponding solar radiation is received was omitted in Fig. 1.

There are several ways of calculating the work dissipated in irreversible processes. The statement that the work dissipated is the product of the internally generated entropy and temperature at which the work is dissipated is the simplest and the most elegant. Dufour and Van Mieghem (1975) (see their p. 37) used the *Clausius reduced heat* concept instead of the internally generated entropy concept. *Reduced heat* is the heat received divided by the temperature at which heat is received; *reduced heat* is entropy. In a reversible cycle, the reduced heat given up is equal to the reduced heat received, there is compensation. In an irreversible cycle, the reduced heat given up is greater than the reduced heat received, there is no compensation by external heat input. The *Clausius reduced heat* output which is not compensated by external heat input is compensated by internally generated entropy.

6. Conclusions

The steady state model of Fig. 1 has been used to show that the average work dissipation in the atmosphere is 25 ± 5 W m^{-2}. Two of the work dissipation rates in Table 1 have been verified. The dissipation was found to be 15 W m^{-2} during the forenoon warming of the boundary layer, and 300 to 1000 W m^{-2} during the sub-tropical squall. It has been shown that the work produced in the atmosphere can be calculated from the entropy produced when the work dissipates. The fact that the work dissipation calculated from entropy produced increases with turbulence is an indication that the method is valid and practical. The main internal entropy production process in the atmosphere is the simple dissipation of work. The dissipation rates estimated in Table 1 needs to be verified by applying the technique to a wide selection of weather conditions. The method could be applied to a succession of soundings to see how the work dissipation changes as a weather event progresses.

The internally generated entropy method could be extended to cover systems that are not uniform in the horizontal direction. When the system is not uniform in the horizontal direction, the definition of the system has to be large enough to eliminate mass exchange with the surrounding areas. Calculating the enthalpy and entropy of a non uniform system would require many soundings. Routine calculations of the enthalpy and entropy of soundings could lead to a better understanding of atmospheric energetics. A planned future article, Part III: the efficiency field, will show that the energy conversion efficiency is essentially the Carnot efficiency based on the temperature at which the heat is received for the hot source temperature, and the average temperature at which heat is radiated by the atmosphere (250 K) for the cold source temperature.

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