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OBSERVATIONS OF TEMPERATURE MICROSTRUCTURE IN THE ATMOSPHERE

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ABSTRACT

In order to provide data of atmospheric temperature microstructure for the investigation of light propagation we measured fluctuations of atmospheric temperature below the height of 300 m with a platinum wire thermometer in Tianjin in May and September, 1980. The results measured in daytime revealed some properties of the temperature structure parameter and spectrum. It has been confirmed that there is a maximum in the profile of the structure parameter produced probably by the entrainment in the interfacial layer at the top of convective boundary layer. The average of $C_T{}^2$ in the interfacial layer and its Wyngaard calculating method are discussed, and the thickness of the interfacial layer is obtained.

It is shown by spectrum analysis that a wide inertial subrange exists in the convective boundary layer and the strong turbulent zone in the free atmosphere. The spectral law with the power of -2.5 was measured within the upper half of boundary layer over the sea in vicinity of Tanggu.

I. INTRODUCTION

A great number of soundings of temperature fluctuations in the atmosphere have been made by aircraft and balloon since the fifties and large quantities of data on the distribution of structure parameter C_T^2 or C_n^2 with height have been published[1,2]. Before using these data, it is desirable to understand in how wide range the value of C_T^2 would vary and what relationship is between C_T^2 and its mean field.

Besides, the properties of temperature spectrum in the convective boundary layer (marked by CBL) have particularly been investigated[3]. Kamail et al. described the forms of spectrum at various non-dimensional heights Z/Z_i (Z—height, Z_i—the depth of CBL). It is difficult to obtain a whole spectrum, for the signal of temperature fluctuation is often very weak and a continuous observation for a long period is hardly conducted. The several spectra obtained by different approaches are probably different, as given in papers[4,5]. Thus, we attempt to get a clearer understanding of the properties of temperature spectrum in the free atmosphere.

In addition to the values of temperature fluctuation measured by plane, the measurements obtained on the meteorological tower in Beijing have been used to analyse the variations of C_T^2 with height and the properties of temperature spectrum.

II. INSTRUMENTATION AND DATA PROCESSING

The self-made platinum wire thermometer is an A. C. bridge. Its output is proportional to the value of temperature fluctuation T', here $T'=T-T(t)$, T is the instantaneous temperature measured at a point in air and $\bar{T}$ (t) equals approximately the mean temperature of air. Due to using this system, the variation of T' with height during the aircraft rising or descending can be eliminated. The diameter of platinum wire is 10 micrometers. When the speed of aircraft equals 50 m/s, the frequency range of T' is probably 0.05—100 Hz. The temperature sensor is installed at the head of aircraft to ensure the sensor working in an undisturbed space.

The mean temperature is measured by semiconductor thermometer and its sensor is installed under the fuselage. The bump of aircraft is monitored by means of an aneroid barometer.

C_T^2 is calculated through the variance of temperature fluctuations and the results thus obtained are associated with the temperature spectrum and the frequency response of the thermometer[6]. If the frequency response of the system is H (n) (n—frequency), and Wyngaards' expression for one dimensional spectrum[7]

$$\phi_T(K_1)=0.25C_T^2K_1^{-5/3} \tag{1}$$

is assumed, we can obtain

$$C_T^2=a\bar{S}^2/(V^{2/3}\cdot b), \tag{2}$$

where ϕ_T is the temperature spectrum, K_1 wave number, $a=13.6$, $\bar{S}^2$ the mean square signal of temperature fluctuation, V the speed of plane, and

$$b=\int_0^\infty H^2(n)\cdot n^{-5/3}dn. \tag{3}$$

We measured the total frequency response of the system. Its half-power point is at 0.2 Hz. Integrating expression (3), we obtained $b=4.96$. In order to estimate the influence on C_T^2 of the lower frequency temperature fluctuations which does not satisfy expression (1), we also computed C_T^2 at the height of 200 m using another filter with the half power point being at 1 Hz. Both results are about the same, showing that the influence is negligible.

In the free atmosphere the temperature spectrum is often not $K^{-5/3}$, thus C_T^2 calculated from the spectrum has lost its original meaning. It only indicates a sort of average value of fluctuation energy. We still use C_T^2 as it can be compared with the previous data. However, we should notice that the C_T^2 value measured by a pair of probes represents the intensity of turbulence of various sizes.

The average values of C_T^2 within a layer of 100 m are computed from data obtained during the plane rising or descending, since the levels at which the plane flew horizontally are very few. The average values of C_T^2 represent the horizontal temperature fluctuations within the depth of 1.8 km if the plane rises or descends with the speed of 2 m/s. Because the error in height registered by the tape recorder can be as large as 100 m, the surface heat flux Q_0 is calculated by means of the values of C_T^2 measured on the horizontal flying at the height of 200 m.

The noise of our thermometer is 0.005°C. As there was a perturbance at 16 Hz during the flight, the noise could be as large as 0.01°C. Due to the bump of the plane, its altitude would have a random variation. The root mean square errors of temperature fluctuation and C_T^2 can be respectively calculated by the following forms

$$\delta_T=\gamma_a\cdot\delta_p\frac{dZ}{dp}, \qquad (4)$$

$$\delta_{C_T}=\delta_T\cdot(V\Delta t)^{-1/3}, \qquad (5)$$

where γ_a adiabatic lapse rate, δ_p the root mean square value of presure fluctuations, dZ/dp the variability of altitude with pressure, Δt the interval of reading pressure. The results calculated are listed in Table 1.

Because the average period of C_T^2 is shorter, there is a larger statistic deviation[4], particularly near the land.

Table 1 The Errors of Temperature Produced by Boump

Height (m)	200	400	800	1000	2000	3000
δ_T(℃)	0.033	0.027	0.026	0.031	0.013	0.0099
δ_{C_T}(10^{-2}℃ $m^{-1/3}$)	0.53	0.43	0.41	0.49	0.21	0.16
δ_T(℃)	0.017			0.0084	0.012	0.018
δ_{C_T}(10^{-2}℃ $m^{-1/3}$)	0.27			0.13	0.19	0.29

When vapour is not taken into account the refractive index structure parameter can be calculated by the following expression[9]

$$C_n=\frac{20\times10^{-6}p}{T^2}C_T, \qquad (6)$$

where p the pressure in hPa and T the mean temperature in K.

The signals of temperature fluctuations amplified by A. C. or D. C. amplifier were registered by a tape recorder, then brought into a square analyzer and digital frequency analyzer, thus $\bar{S}^2$ and temperature spectrum were obtained. The bandwidth of spectra was $n_c/3$ (n_c—central frequency).

III. DETAILS OF OBSERVATION

Only three of seven runs were used for analyzing because the ratio of signal to noise in the rest runs was not sufficiently large due to using a narrow bandwidth amplifier.

Although all the observations were conducted on clear day, the weather conditions were different in each run and the routes of the flight varied as well. It was at the edge of high pressure on 8 May and some Cu hum appeared during the course of observation. In this case the plane descended directly down through the cloud. On 13 May, Tianjin was located at the fore of warm front. There was an inversion which had a potential temperature jump ($\Delta\theta$) of 11.8 °C at the heights of 500 to 700 m. It was probably not the capping inversion of boundary layer produced by turbulent mixing ($\Delta\theta$ is approximately 3 °C)[9,10]. On 8 September Tianjin was just in the centre of high pressure. On 8 and 13 May the plane flew over the Tianjin city and its suburbs. On 8 September the plane flew over the sea 5—20 km off the coast of Tanggu, then it landed.

In Table 2, the surface temperature at the height of 1 m and the potential temperature jump $\Delta\theta$ of capping inversion of CBL were taken from the measurements, other parameters were calculated from C_T^2. The observations on the tower were also made in daytime.

Table 2 The Parameters of CBL in Each Run

No	1A	1B	2A	2B	3A	3B
Date	8 May		13 May		8 September	
Time	8:35— 9:41	9:48— 10:17	10:50— 12:20	12:22— 12:44	8:56— 9:54	10:09— 10:42
Surface Temperature(℃)	17.0	19.5	21.0	23.0	21.8	25.3
$\Delta\theta$(℃)		4.4		11.8	4.0	1.2
Z_i(m)	700	700	600	600	600	1300
Q_t(℃ m/s)	0.036	0.039		0.027	0.14	0.063
W_* (m/s)	0.94	0.97		0.80	1.2	1.2
θ_*	0.038	0.041		0.033	0.10	0.045

IV. THE PROFILE OF STRUCTURE PARAMETER

1. *Distribution of Refractive Index Structure Parameter with Height*

In Table 3 we list the mean C_n^2 of each layer to be compared with the mean distribution given by Barletti et al. In general, C_n^2 measured in Tianjin is as small as half of Barletti et al. If we consider the fact that most of the depths of CBL which were observed in Tianjin were under 1000 m, but it could often be extended to 2000 m[3,10]. Therefore, it is possible to illustrate why mean C_n^2 at heights of 1—2000 m measured in Tianjin was very small.

Table 3 The Mean Distribution of C_n^2 (10^{-16} $m^{-2/3}$)

Height	0—1000(m)	1000—2000	2000—3000
Tianjin	5.4	0.26	0.31
Barletti	11	1.3	0.61

2. C_T^2 in CBL

C_T^2 reduced with $Z^{-4/3}$ in the lower half portion of CBL, but in the upper half portion a large peak occurred near the top of the boundary layer after a section of smooth varying. This phenomenon has already been observed by Kaimal Caughey.[10] Kuharetz[11] et al. Its existence is also confirmed by our data. The mean distribution of C_T^2 with height normalized by scales of mixed layer is given in Fig. 1. These scales are determined in the following way.

By now there is no generally accepted definition of the depth of CBL Z_i. The height of the capping inversion base is defined as Z_i by Kaimal et al[3]. But Kuharetz[11] regards Z_i as the height of inflection point on the profile of turbulent kinetic energy dissipation rate ε. In our data, the Z_i is taken to be 0.9 times the height of the peak of C_T^2. The difference between Z_i and the height of the capping inversion base is often smaller than 100 m. The scales of speed and temperature are respectively

$$W_* = [\theta_0 \cdot Z_i(g/T)]^{1/3}, \tag{7}$$

$$\theta_* = Q_0/W_* \tag{8}$$

Where g is the acceleration of gravity, and Q_0 is the surface heat flux and can be calculated from C_T^2 value by the following form

$$C_T^2 = 2.67 Q^{4/3}(T/g)^{2/3} Z^{-4/3}. \tag{9}$$

In Fig. 1 Kaimal's curve quoted from[3] and Kuharetz's curve is given by the following experimental expression[11]

$$\varphi_{C_T^2}(\xi) = K_1 \xi^{-4/3} + K_2 e^{-K_3(\xi-1.1)^2},$$

where

$$\varphi_{C_T^2} = C_T^2(\xi)/C_T^2(0.1), \xi = Z/Z_i, K_1 = 0.046, K_2 = 0.6 \text{ and } K_3 = 12.$$

The maximum of C_T^2 is often observed at the top of CBL and its appearance is naturally associated with the entrainment occurring in the interfacial layer between the boundary layer

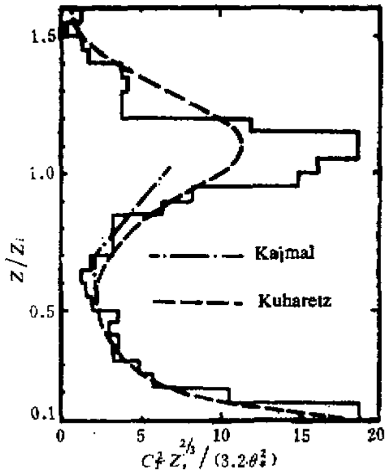

Fig. 1. The Mean Distribution of C_T^2 in CBL.

and the free atmosphere. The entraiment is the basic cause for C_T^2 peak. In the free atmosphere there is sometimes an inversion, but no C_T^2 peak is observed at the same place. This was also the case on 8 May.

We adopt the height of the half-peak of C_T^2 as the unit to measure the width of interfacial layer, the results are shown in Table 4. The range of relative width is approximately within 0.3—0.4. The margin of interfacial layer is so distinct and C_T^2 varies so greatly that the width determined by the various multiples of the C_T^2 peak can not greatly differ from each other.

Table 4 The Width of Interfacial Layer ($\Delta h/Z_i$)

No.	1A	1B	2A	2B	3A	3B	Mean Distribution	Caughey et al.	Kuharetz
$\Delta h/Z_i$	0.4	~0.4	~0.4	0.4	0.1	0.3	0.3	0.3	0.48

Wyngaard et al.[12] derived the formula calculating the average value of C_T^2 (marked by $\langle C_T^2\rangle$) within interfacial layer under the influence of entrainment. If humidity is neglected,

$$\langle C_T^2\rangle=\frac{0.5\Delta\theta\theta_*}{Z_i^{2/3}}. \tag{11}$$

The C_T^2 value can be calculated by using values in Table 2 and its results are shown in Table 5.

Table 5 $\langle C_T^2\rangle$ in the Interfacial Layer under the Influence of Entrainment

No.	1B	2B	3A	3B
$\langle C_T^2\rangle$ (10^{-4}°C m$^{2/3}$)	11.7	31.8	70.3	1.9
Peak of C_T^2	21.0	24.3	2.0	0.4

All measurements except 1B can not well coincide with $\langle C_T^2\rangle$. On 13 May (case 2B) the strong inversion at the top of CBL was probably related to the frontal surface, and it seems that expression (11) was not suitable for this situation. On 8 September while the plane was rising there was a west wind blowing towards sea in lower layer and when the plane flew from the coast towards the sea at the height of 200 m, the measured temperature dropped by 1.5°C at 20 km off the coast. It seems that a new inversion formed over the sea, and the increased value of C_T^2 was twice more than that at the height of 200 m over the coast. It varied with height from 200 m to 400 m much quicker than $Z^{-4/3}$ (see Fig. 2). In this situation, it was not suitable to calculate the parameters of mixed layer from C_T^2 above the sea. For this reason, the C_T^2 value in 3B would be larger than measurements.

In order to explain $C_T^2\propto Z^{-4/3}$ at the lower part of CBL, we give the measurements on the tower in Beijing (see Fig. 3). The observations were performed one after another at different altitudes. The average time was 5 min at each altitude.

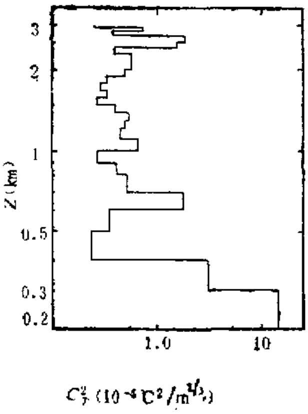

Fig. 2. The Profile of C_T^2 measured by the rising plane over the sea on 8 May.

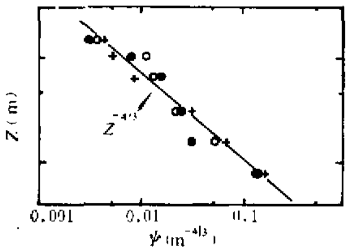

Fig. 3. C_T^2 value measured on tower in Beijing.

V. TEMPERATURE SPECTRUM

Within the lower half of CBL and the strong turbulent zone in the free air the measured spectra satisfy expression (1), but within the interfacial layer where turbulence has clear intermittence the measured spectra satisfy expression (1) as well. The spectrum in Fig. 4 is such an example.

However, there is an exception within the upper half of the boundary layer, a spectrum law with the power of -2.5 is measured (see Fig. 5).

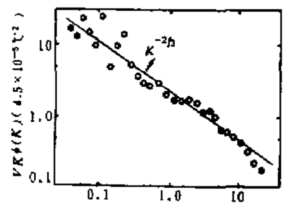

Fig. 4. The Temperature spectrum at the top of CBL. Time: 12:39 LST 13 May;Height: 600—700 m;Average Period: 80 sec.

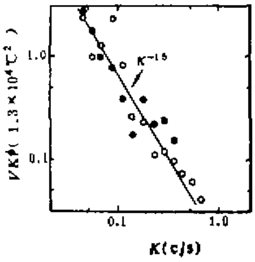

Fig. 5. The spectrum at the upper Half of the Boundary Layer at the shore at 9:00 LST 8 September.

We have made a statistics on some of the temperature spectra of quasi-laminar flow above the boundary layer. The results are listed in Table 6. The stratification was unstable on 8 May but stable on 13 May and 8 September. All the absolute values of spectrum slope rate are smaller than $|-3|$. From that table, it can be seen that there is always $|\beta|<|-3|$

in case of the stable stratification. When Cu hum occurs and the stratification is slightly unstable, the peak appears at some individual wave numbers. This is quite similar to the conclusion in Ref. [4]. This dispersion on spectral power law seems to be related to turbulent intemittence in quasi-laminar flow. It can be seen clearly from the original temperature record in Fig. 6, that the portion of high wave number possesses significant intermittence. The spectral slope rate at the place where the temperature varies smoothly is definitely steeper than that at the place where the temperature has a significant high frequency variation. In this case it is not clear whether the spectrum of $K^{-5/3}$ can be obtained by increasing average time. Because the spectra given by Vinnichenko[5] include measurements under different weather conditions, only a general trend is illustrated.

Table 6 The Number of Each Sepctral Power Law Occurring in the Quasi-laminar Flow

Date \ β	$\lvert\beta\rvert>\lvert-2\rvert$	$\lvert-5/3\rvert<\lvert\beta\rvert<\lvert-2\rvert$	$\lvert\beta\rvert<\lvert-5/3\rvert$	
8 May	6	2	—	6
13 May	9	4	—	—
8 Sept.	10	5	1	1

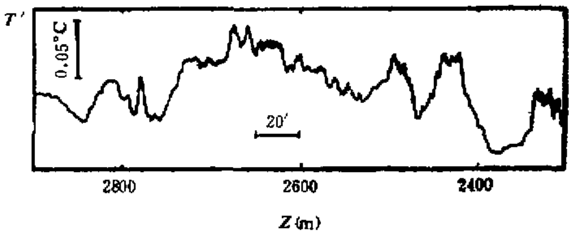

Fig. 6. Fluctuation of temperature at the 2300—2900 m, 12:22—12:26 LST, 13 May.

VI. DISCUSSION

(1) The temperature structure parameter in the lower half of CBL decreases in pace with $Z^{-4/3}$.

(2) A big peak of C_T^2 occurs at the interfacial layer on the top of the boundary layer due to entrainment. When the underlying surface is uniform and the interfacial layer is on the top of CBL, the mean C_T^2 in this region can be calculated by Wyngaard's formula. The thickness of interfacial layer is usually within 0.2—0.4 Z_i.

(3) Above CBL and below the height of 3000 m except that there may exist a strong turbulent zone, the value of C_n^2 generally varies within (1—5) $\times 10^{-17}$ ($m^{2/3}$).

(4) The temperature spectrum within CBL has a wider inertial range, even if it is at the inversion base where a turbulent intermittence exists. However, when there is land breeze over the inshore, the stratification of the surface layer will become stable, the turbulence of

upper half of the boundary layer will be weakened and the spectral law of power will be larger than $-5/3$.

(5) When the stratification becomes stable, most of the spectral laws of power is between $-5/3$ and -3 in the free atmosphere. When the stratification is slightly unstable, the temperature spectrum with multi-peak value occurs. The intermittence of temperature fluctuation becomes very clear in the free atmosphere.

Being short of the information on mean field and wind, it is necessary to further study the physical process within the boundary layer and the intermittence of turbulence in the free atmosphere. The theoretical spectrum about buoyancy subregion needs to be varified.

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