Bursts in the turbulent medium and light propagation

Zeng Zongyong

Anhui Institute of Optical and Fine Mechanics, Academia Sinica, Hefei, China

Received September 10, 2001

It is shown by the results measured that the eddies with temperature sharp changing section viz temperature discontinuous surface (TDS) may frequently occur in a stratified turbulent medium. Because the TDS structure is very asymmetrical, the properties of light propagation would depart from the theory of isotropic turbulence. The appearance of TDS is probably related to removal of eddies in the vertical direction. The production and removal of these eddies can be named "bursts."

Introduction

So far as, the theory of light propagation in the turbulent medium was normally based on the theory of isotropic turbulence and the normal distribution of refractive index fluctuations was assumed. These theory and hypothesis have not been satisfied frequently in the practical turbulent flow, especially, in the turbulent atmosphere.

For example, "sheets" with strong inversion have been measured in the free atmosphere. The horizontal scale of a sheet is more than ten times longer than the vertical scale,[1] therefore the light transmitted horizontally would be more bended. The boundary of turbulent region and laminar region is irregular at the top of the convective boundary layer[2] so that the light through the top of the convective boundary layer would be jittering violently because the temperature gradient in different regions is different.

When the wind blowing through the boundary of water surface and land surface, because of the different temperature gradient above different surfaces and variation of temperature gradient due to fluctuations of the wind direction, the light transmitted along the prevailing wind direction would also be jittering violently. If one side of the boundary is an unstable turbulent region and another is stable, the local structure parameter[3] may have a longer spatial correlation scale which is about ten times as large as the outer scale. The correlation scale in the horizontal direction is often very short in the homogeneous turbulence.

Some organized eddies viz coherent structure have been frequently measured in the turbulent flow.[4] The "ramps" structure in the atmospheric convective boundary layer is a kind of a coherent structure.[5] The contribution of ramps to the second-order structure function of the refractive index is very small, as the scale of ramps is larger. The upwind edge of ramps where there is a sharp change in temperature may affect light propagation under the specific conditions.[6] A similar structure has been measured in the nocturnal stable boundary layer and the ramp structure has been measured in a water tank used for simulation of turbulence.[7]

The effects of bursts produced due to unstability of wind shear on light propagation were analyzed in this paper. The production and removal of eddies with sharp temperature changing section viz temperature discontinuous surface (TDS) in the stratified turbulent medium was named "bursts." In fact, these eddies were measured in the boundary layer many years ago.[8] In Ref. 8, wind and temperature sensors at different locations simultaneously received sharp changing signal, therefore the existence of TDS can be found. The response frequency of sensors is higher than 500 Hz, therefore the thickness of TDS is approaching the inner scale. In Ref. 8 the reflection of radar wave on the TDS and the variation of the probability distribution of wave front fluctuations were presented, but light propagation has not been analyzed. Although we don't understand clearly the structure of these eddies, effects of TDS asymmetry on light propagation can be analyzed.

1. Measurements

In this paper the bursts in the unstable stratified turbulent flow have been found by the traces of temperature fluctuations measured by balloon-borne thermometers. At the top of a gondola three temperature probes with a tungsten filament 10 μm in diameter and 2.4 cm in length were mounted along a horizontal line. The distances between probes were respectively, 1.07 m, 0.75 m, and 0.33 m. The noise of a probe was 0.002°C. The response frequency was 0.02–30 Hz. The sample rate was 25 Hz. The ascent speed of a balloon was about 5 m/s, so that the spatial resolution of the probes was 20 cm.

It was shown by results measured that $Ri < 0.25$ below the height of 12 km and $Ri < 0.1$ at some of heights; the temperature fluctuations in the vertical direction obey "$-5/3$" power law in the region of 0.2–20 m; the values of C_n^2 in the vertical direction were

0235-6880/02/04 332-04 $02.00 © 2002 Institute of Atmospheric Optics

roughly equal to the values in the horizontal direction. The detail can be referenced to Ref. 9. An example of bursts is given in Fig. 1.

Many positive pulses with violent fluctuations appeared on the gently varying temperature trace in Fig. 1. The rear edge of pulses is very steep and the edge width is often smaller than the probe resolution. The pulse amplitude is about 0.1–0.3°C. The details of face *A* and face *B* are given in Figs. 1*b* and *c*. The pulse edge was frequently measured simultaneously by three probes. This fact indicated that not only TDS is a horizontal plane but the TDS width is larger than 1 m and the TDS thickness is smaller than 0.2 m. Because the inner scale is about 5 cm, the TDS thickness may approach the inner scale. At least 45 of TDS's were observed in the atmospheric layer of 8500–10200 m. The average amplitude of temperature decrease at TDS is $a\sigma_T = 0.16$°C, where σ_T is standard temperature deviation, and $a = 2.6$. The contribution of 45 TDS's to σ_T^2 is only 1.4%. One third of all TDS's has a thickness smaller than 0.2 m and was a plane in the horizontal direction. A half of all TDS's has a thickness of 0.2–0.4 m and is mostly slant or bended. A threshold of 0.1°C was used for identification of a burst. Very slant TDS's have not been added up.

It is easy to understand the production of the above TDS's. In the free atmosphere with stable stratification, because of unstable wind shear, the air parcel coming from the upper layer with the higher temperature has been entangled in the lower layer with lower temperature and the parcel mixed with ambient air so that many horizontal TDS's with large area were produced. The production and removal of eddies with TDS which have some characteristic structure can be named a burst.

The descend b of a warmer parcel can be calculated from the potential temperature gradient $d\theta/dz$

$$b = a\sigma_T/(d\theta/dz) \sim 50 \text{ m}. \qquad (1)$$

The odd-order moment of fluctuations with TDS is obviously not equal to zero. It was shown by results measured that the behavior of the odd-order structure function is not like that of the temperature ramps structure in the convective boundary layer. The detail about odd-order structure function of ramps structure can be found in Ref. 10. We do not understand clearly the structure of eddies with TDS, but the effects of TDS on the features of light propagation can be analyzed.

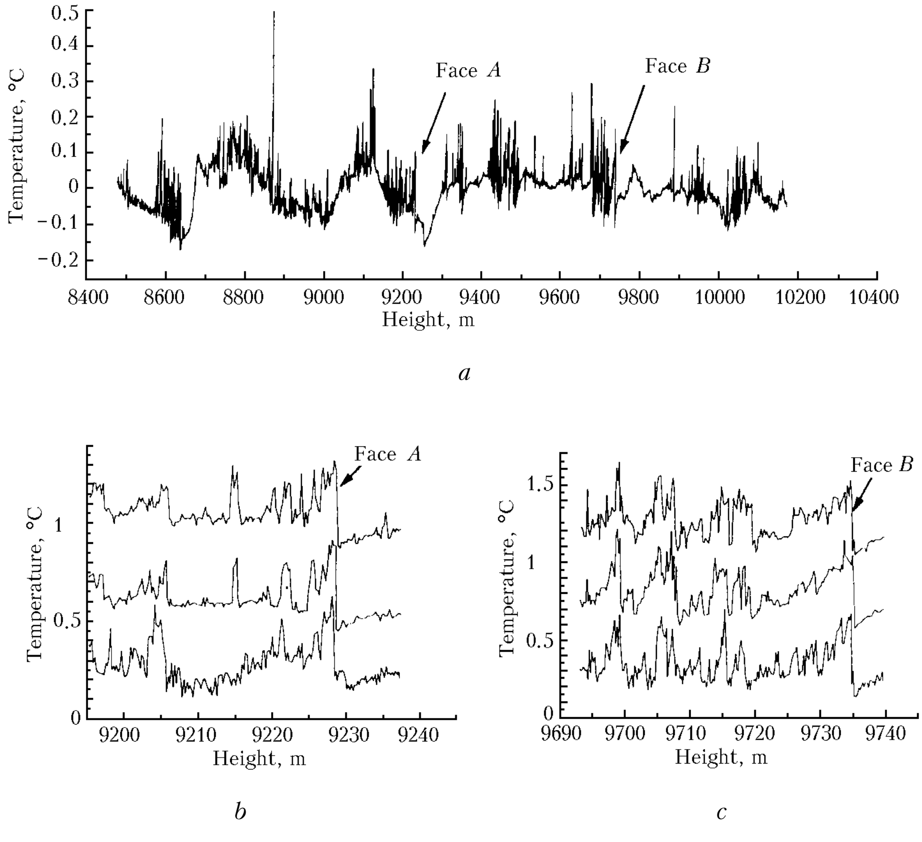

Fig. 1. The traces of temperature as measured by three balloon-borne thermometers: the middle sensor (*a*); panels (*b*) and (*c*) are, respectively, the details of face *A* and face *B* in the upper panel.

2. Light propagation

As the bursts are a kind of eddies, the method of dealing with a coherent structure can be used. Fluctuations of a turbulent flow can be divided into two uncorrelated parts, for example, temperature fluctuations

$$T' = T'_{\mathrm{h}} + T'_{\mathrm{b}}, \tag{2}$$

where T'_{h} is the part which satisfies the condition of homogeneity and isotropy and T'_{b} is the burst part. Only the light propagation of the second part needs to be calculated. Because the inner scale is several centimeters in the free atmosphere, the method of geometric optics can be used in the range of several kilometers. First, the maximum value of arrival-angle fluctuations resulting from the TDS effect can be calculated

$$\alpha_{\max} = \int_L \frac{\delta N}{D}\, \mathrm{d}s, \tag{3}$$

where D is the diameter of the receiving aperture, δN is the change of the refractive index in the interval D in the vertical direction, L is the light propagation length, ds is a ray element. Assume that light propagates in the horizontal direction and TDS is a hemisphere with the thickness l_0 (inner scale) and diameter b. Furthermore the light beam received by a lens just passes through the TDS. Since $b \gg D$,

$$\alpha_{\max} = 2n\Delta N \sqrt{b/D}, \tag{4}$$

where n is number of TDS's passed through, ΔN is variation of the refractive index at the TDS.

$$\Delta N = a\sigma_T M, \quad M = \frac{\mathrm{d}N}{\mathrm{d}T}. \tag{5}$$

If the outer scale of isotropic turbulence is L_0, then C_n^2 can be written as

$$C_n^2 = 2\sigma_T^2 M^2 L_0^{-2/3}, \tag{6}$$

For *Kolmogorov* turbulence

$$\langle\alpha_{\mathrm{h}}^2\rangle = 2.91 D^{-1/3} C_n^2 L. \tag{7}$$

The ratio of two parts is

$$\frac{\alpha_{\max}^2}{\langle\alpha_{\mathrm{h}}^2\rangle} = 0.69 a^2 n^2 \left(\frac{b}{L}\right)\left(\frac{L_0}{D}\right)^{2/3}. \tag{8}$$

According to the data $L_0 = 30$ m. Suggest $D = 0.1$ m. When the light path length is hundreds meters, the probability of $n > 1$ is very small, then $n = 1$. The minimum value of L can be estimated as

$$L_{\min} = V \Big/ \left(\frac{g}{T}\frac{\mathrm{d}\theta}{\mathrm{d}z}\right)^{2/3}, \tag{9}$$

where V is the average wind speed, g is the acceleration due to gravity. Average values observed were substituted to Eq. (9), $L_{\min} = 1800$ m. According to the frequency of TDS occurrence $L_{\min} < 140$ m. Therefore $a_{\max}^2/\langle a_{\mathrm{h}}^2\rangle = 2.2$~29. The $L_{\min}$ value of 1800 m implies that the interval of the turbulent region is 1800 m. When the light propagates in the horizontal direction, C_n^2 can be much smaller than measurements in the vertical direction. Therefore some of intense arrival-angle fluctuations would appear. The duration of these fluctuations is about $D/V \sim \sqrt{b/D}/V =$ $= 0.004 - 0.08$ s. Therefore the frequency of these fluctuations is high. Some big salience on the trace of the high-frequency component would be found, if a wavelet transformation for arrival-angle fluctuations is finished. When the light propagation length is very long, probably $n > 1$ and $\alpha_{\mathrm{b}}^2 \gg \langle\alpha_{\mathrm{h}}^2\rangle$. Therefore normal distribution properties of wavefront fluctuations would be distorted. An experimental evidence can be found. There was a long tail on the probability distribution curve of arrival-angle fluctuations variation.[11] If TDS frequently appears in the light path, the relationship of C_n^2 and variation of arrival-angle fluctuations would be broken. For example, if the light beam passes through all of 45 TDS's on the path of 1.7 km, $\alpha_{\mathrm{b}}^2/\langle\alpha_{\mathrm{h}}^2\rangle \sim 0.7$. The variation of arrival-angle fluctuations measured would be larger than the value calculated by C_n^2.

The logarithm of light amplitude fluctuations resulting from TDS can be calculated by means of geometric optics

$$\chi_{\mathrm{b}} = \int_0^L \int_0^s \frac{\partial^2 N}{\partial z^2}\, \mathrm{d}s\mathrm{d}\xi. \tag{10}$$

The second-order differential of N in the vertical direction is a pulse with the amplitude of $\pm 2\Delta N/l_0$, l_0 is the inner scale of turbulence. If TDS is a level plane in width of C, then

$$\chi_{\mathrm{b}}^2 = 4\Delta N^2/l_0^4 = 4a^2 (C/l_0)^4\, \sigma_T^2 M^2, \tag{11}$$

For *Kolmogorov* turbulence

$$\langle\chi_{\mathrm{h}}^2\rangle = 2.46 C_n^2 L^3 l_0^{-7/3}, \tag{12}$$

then

$$\chi_{\mathrm{b}}^2/\langle\chi_{\mathrm{h}}^2\rangle = 0.81 a^2 (C/L)^3 (C/l_0)(L_0/l_0)^{2/3}. \tag{13}$$

Assume $l_0 = 0.1$ m and TDS is an arc. As above $C = 2\sqrt{b/l_0}$. Assume $L = 140$ m, then $\chi_{\mathrm{b}}^2/\langle\chi_{\mathrm{h}}^2\rangle \sim 0.047$. Therefore the TDS effect on scintillation is smaller. But if TDS has been encountered frequently, a projection could be found on the high end of the scintillation spectrum.

When a light beam passes through a turbulent medium, some characteristic structure can be seen in the light pattern under the condition of weak turbulence. A real light pattern cannot be drawn by the theory of isotropic turbulence.[12] In Fig. 2 an example is given. In the pattern of a collimated laser beam passing through the top of the convective boundary layer simulated in a water tank, there was a dark line on the upside of Fig. 2 followed by a bright line below which a convective eddy arriving inversion layer is outlined. According to the distribution of the refractive index at TDS and Eq. (1), this structure can be explained easily. The structure in which a bright line was followed by a dark line below can seen easily when a laser beam passed through the convective turbulent flow simulated in a water tank.

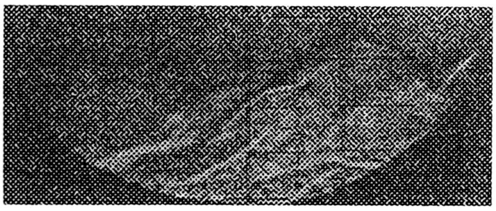

Fig. 2. The light pattern of laser beam passing through the top of the atmospheric convective boundary layer simulated in a water tank. At the upside a dark line is followed by a bright line below which a convective eddy arriving inversion layer at the top of convective boundary layer is outlined. The scale is 1 cm.

3. Conclusion and discussion

The existence of bursts with sharp temperature change section in the stratified turbulent medium was shown by the results measured in the atmosphere and the properties of light propagation through TDS were analyzed. It is very different from the isotropic turbulence that the TDS structure is very asymmetrical. The scale is very small, but the change of the refractive index is very large in the normal direction of TDS. The scale is very large and the correlative distance is very long in the tangent direction of TDS. Therefore some characteristics of light propagation were caused by TDS. If there are many TDS's number on the light path and the scale is large and TDS parallels light beam, not only a projection may appear at the high end of scintillation or arrival-angle fluctuations spectrum, but more intense and higher frequent fluctuations of arrival-angle more frequently appear so that the probability distribution of arrival-angle fluctuations may be distorted. Furthermore the variation of arrival-angle fluctuations measured may be larger obviously than the value calculated by C_n^2.

According to the characteristic structure of the light passing through a turbulent medium, we may find some large eddy in the medium. Analyzing the light pattern to find out the structure of the turbulent flow is a convenient method.

Some features of turbulence such as the isotropy of dissipation may be broken in the turbulence flow where bursts or coherent structure dominate.

Because of complexity of the turbulent flow, especially, the atmospheric turbulence, the eddies with TDS probably existed in the other environment widely.

References

1. F. Dalauder et al., J. Atmos. Sci. **51**, 237–248 (1994).
2. N.K. Vinichenko, *Turbulence in Free Atmosphere* (Gidrometeoizdat, Moscow, 1990).
3. V.I. Tatarskii, Radio Sci. **22**, 859–865 (1987).
4. U. Frish and S.A. Orszag, Physics Today **43**, 24–32 (1990).
5. R.A. Antonia, A.J. Chambers, et al., J. Atmos. Sci. **36**, No. 1, 99–107 (1979).
6. Yuan Renming and Zeng Zongyong, Acta Optica Sinica (submitted).
7. Yuan Renming and Zeng Zongyong, Acta Mechanica Sinica **32**, No. 3, 257–263 (2000).
8. Zeng Zongyong, Proceedings SPIE **1114**, 23–27 (1989).
9. Zeng Zongyong, Zhang Jun, et al., Scientia Atmos. Sinica **21**, No. 3, 380–384 (1997).
10. R.A. Antonia and A.J. Chambers, Boundary Layer Meteorology **23**, 395–403 (1982).
11. Zhang Jun and Zeng Zongyong, Acta Optica Sinica **17**, No. 12, 1259–1264 (1997).
12. Z. Zongyong, W. Ninguan, Z. Jun, and W. Yingjian, Atmos. Oceanic Opt. **5**, No. 12, 843–845 (1992).