9.11 AIRCRAFT MEASUREMENTS OF REFRACTIVE AND CLEAR AIR TURBULENCE: SPECTRA, BUDGETS, AND THE PREDICTION PROBLEM

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1. Introduction.

Refractive Turbulence, the local fluctuations of the propagation speed of electromagnetic waves relative to speed in a vacuum, is associated with atmospheric density fluctuations and when it occurs with sufficient intensity is a main contributor to fast scintillation of laser communication, infra-red surveillance, and directed energy weapon systems. The goal of our direct airborne measurements of refractive turbulence is to investigate the structure and dynamics of strong refractive turbulence layers and determine what would be required in a model to predict the evolution of such strong atmospheric turbulence layers. For infrared (IR) and optical wavelengths the refractive turbulence parameter of primary concern is the temperature structure constant, C_T^2. Path weighted integrals of the Refraction structure parameter $C_N^2 = (80 \times 10^{-6} P/T^2)C_T^{\ 2}$ are used by propagation physicist to evaluate three quantities that define atmospheric seeing conditions: log amplitude variance (scintillation index), isoplanatic angle and Fried coherence length (Quirrenbach, 1999). Strong and/or thick turbulence layers increase the former and decrease the latter two. Obtaining refractive turbulence measurements in layers between 400 and 800 meters with peak C_T^2 values between 10^{-3} and 10^{-2} was of particular concern in planning our measurements and very difficult to realize in execution without an adequate turbulence prediction model.

The turbulence measurements were made with the GROB 520T EGRETT, a high altitude aircraft owned and operated by Airborne Research Australia (ARA). EGRETT was equipped with three NOAA/FRD built BAT turbulence sensors. The BAT probe is a 13 cm diameter pressure hemisphere with nine measurement ports. A micro-bead thermistor for temperature measurement is mounted in the central pressure port. The BAT probe is designed to be flown on aircraft without inertial navigation systems. Each probe contains a GPS receiver and three component accelerometers. For a more complete description of the BAT probe see Crawford and Dobosy (1992). A more recent description is available on the web site: http://www.noaa.inel.gov/frd/Capabilities/BAT/.

The three BAT probes on EGRETT were mounted with one under each wing and one at the top of the tail. The use of three probes was a response to several problems relative to high altitude turbulence measurements. The first is the averaging time problem discussed by Lumley and Panofsky (1964), and Wyngaard (1973). The second problem is flow distortion. It is hoped that the multiple probes will help in the identification of flow distortion affects on spectra. The final problem is to obtain measurements of vertical gradients of mean horizontal wind and mean potential temperature with comparable accuracy to the turbulence estimates. Both measurements are used to evaluate budgets of kinetic energy, temperature variance, and heat flux.

2. Where and When to Measure for Turbulence.

The determination of where to measure, in what season, and at what altitudes in order to capture the dynamics of strong turbulence layers is an unsolved problem. There are several new web sites that give forecasts of regions of expected clear air turbulence. Global predictions are available on the Turbulence Index site: (http://orbit-net.nesdis.noaa.gov/arad/fpdt/tifcsts.html). For the US alone the site: (http://www.rap.ucar.edu/project/itfa/turbdesc.html) Both sites are geared to commercial aviation altitudes. Our initial planning that lead to a decision on where to measure was greatly helped by use of climate data available on the NOAA web site (http://www.cdc.noaa.gov/HistData/). Using this database we concluded that it would be best to measure in winter subtropical jet stream near the south coast of Japan in February and in the Perth to Adelaide corridor in August.

Having made the turbulence measurements in these months in 1999, the NOAA database is still useful in estimating the order of magnitude of the horizontal shear and stratification production terms in the energy, flux, and temperature

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variance budgets. The upper troposphere and lower stratosphere are not homogeneous. The measurement flights where accordingly in the direction in which the atmosphere is most homogeneous, either upwind or downwind. The length of a constant altitude measurement was 1200 seconds, which is about 100 kilometers at EGRETT airspeed. In Japan the smallest separation of measurement levels was 660 meters and in Australia it was 330 meters.

3. Measurements

In Table 1 are summarized the structure function parameters for temperature for temperature and the three velocity components for most of the measurements made in Japan in February 1999. Also listed in the table are the ratios of pairs of structure parameters. C_U^2/C_T^2 is under Kolmororov scaling equal to the ratio $\alpha_1\,\varepsilon/\beta_1\,\chi$, the product of the kinetic energy and temperature variance dissipation ratio with the Kolmogorov spectral constant ratio. It shows great variability due to very reduced C_T^2 values. In the last column the estimates for turbulent dissipation (ε) are obtained from the relation: $C_U^2 = 2\,\varepsilon^{2/3}$. The ratio of the transverse velocity structure parameters to the longitudinal velocity structure parameter should be 4/3 if the inertial sub-range is locally isotropic. On average C_V^2 is about 4/3 while C_W^2 is not which indicates an absence of local isotropy for the vertical kinetic energy component. This same result was obtained for the measurements in Australia except for 6 August 1999, which are also shown in Table 1. On 6 August the measurement duration at level 9650 m was 3000 seconds in contrast to the other levels that day which all were for 1200 seconds. The time series for measurement flight at 9650 meters was dived into two sections. Section A is the eastern half and B is the western half. Level 9560B had the largest structure parameters EGRETT has measured to date. Correspondingly the vertical accelerometer data for section B was intermittently ± 1.5 g.

In figure 1 are vertical profiles for C_T^2, one from Japan and the one from 6 August in Australia. With the 660 meter separation between measurement levels in Japan it is possible that the peak value was not sampled. To capture the structure of these narrow layers of extreme turbulence future measurements should be no more than 200 meter separation in the vertical when extreme turbulence is encountered. Figure 2 contains the vertical profiles of the three components of velocity variance, temperature variance, and the vertical heat flux magnitude (note log plot of amplitude masks thinness of layer). Figure 3 contains the three Reynolds stress components in a linear plot that better sets off the turbulent layer. The curvature of the <uw> profile in the turbulent layer cannot be evaluated. If present it would act as a negative feedback and diminishes a positive mean vertical gradient of the mean wind that produces negative <uw>.

At low spatial wave-numbers, velocity and temperature spectra follow a k_1^{-3} power law and preliminary analysis with the scaling suggested by Lumley (1964) and Weinstock (1978) indicates a non-constant spectral constant in agreement with the aircraft turbulence measurements of Lilly and Lester (1974). This is an interesting result and is confirmed by EGRETT measurements for the University of Wales Aberstywyth in 2000 and 2001.

In Table two are presented various key turbulent parameter ratios and scale calculations. The first column the measured magnitude of "L" $=(C_T^2/(\partial\Theta/\partial z)^2)^{3/4}$. This is the magnitude of the critical length scale that would collapse all C_T^2 profiles with $\partial\Theta/\partial z$ scaling for fluctuating temperature. The column $<\theta^2>/w^2>$, the ratio of temperature variance to vertical velocity variance, is used to calculate L_E^2/L_B^2, the vertical heat flux Richardson number. The magnitude of which relative to unity indicates the dynamic role of the correlation of temperature with vertical gradient of fluctuating pressure. There are two columns for flux and gradient Richardson number and one for their rato K_H/K_m. The last column is the integral scale obtained from $((u^2+v^2+w^2)/2)^{3/2}/\varepsilon = q^3/\varepsilon$.

4. Scales and Budgets

TEMPERATURE VARIANCE BUDGET

$$\partial\langle\theta^2\rangle/\partial t = -\text{advection} - \langle w\theta\rangle\,\partial\Theta/\partial z\;(1 + \text{Horizontal Prod/Vertical stratification Prod}) + -\,\partial\langle w\theta^2\rangle/\partial z\;(1 + \text{Horizontal TT/Vertical TT}) - \chi$$

where χ ($\chi = \kappa\langle(\partial\theta/\partial x_t)^2\rangle$) is dissipation rate of temperature variance and TT stands for turbulent transport by third moments. The temperature structure parameter is obtained from the inertial sub-range temperature spectrum in the form

$$\Phi_T(k_1) = 1/4\, C_T^2\, k_1^{-5/3}$$

Under Kolmogorov scaling $C_T^2 = 4\,\beta_1\,\chi/\varepsilon^{1/3}$ and β_1 is the one dimensional Kolmogorov spectral constant. Under stationarity, horizontal homogeneity, and universal equilibrium, production and dissipation are equal so that:

$$-\langle w\theta\rangle\,\partial\Theta/\partial z = \chi = \kappa\,\langle(\partial\theta/\partial x_t)^2\rangle\;;$$

To derive C_T^2 divide by $\varepsilon^{1/3}/4\beta_1$. The resulting identity evolves as follows:

$$-4\beta_1/\varepsilon^{1/3}\ \langle w\theta\rangle\ \partial\Theta/\partial z = 4\beta_1 K_H/\varepsilon^{1/3}\ (\partial\Theta/\partial z)^2 = C_T^2$$
$$= 4\beta_1 \kappa/\varepsilon^{1/3}\ \langle(\partial\theta/\partial x_i)^2\rangle = 4\beta_1 L^{4/3}\ (\partial\Theta/\partial z)^2$$

In the above identity we have approximated mean-square gradients by the square of a mean gradient times a ratio equivalent to a Reynolds number: $K_{H/\kappa}\ (\partial\Theta/\partial z)^2 = \langle (\partial\theta/\partial x_i)^2\rangle$. The basic problem in modeling C_T^2 in stable stratification is to determine the magnitude of "L"$^{4/3}$ or $4\beta K_H/\varepsilon^{1/3}$ which has the dimension of $(\text{length})^{4/3}$. This is illustrated in figure 1 in Wyngaard et. al. (1971b). In our terminology this is a graph of "L" $^{4/3}/z^{4/3}$ versus Richadrson Number. The graph on the stable side would be a constant equal to 1 if the measured ratio $C_T^2/(\partial\Theta/\partial z)^2$ had been scaled by "L"$^{4/3}$ rather than $z^{4/3}$. Under stable stratification $C_T^2/(\partial\Theta/\partial z)^2$ is independent of z but not of "L"$^{4/3}$ which is now derived. By definition we have $K_H = -\langle w\theta\rangle/\partial\Theta/\partial z = -C_{w\theta}\,\sigma_w\,\sigma_\theta/\partial\Theta/\partial z$ and "L"$^{4/3}/4\beta$ or $K_H/\varepsilon^{1/3} = -C_{w\theta} L_E L_{I\,w}{}^{1/3}$ where $L_{I\,w}$ is equal to a vertical integral scale and L_E is the Ellison scale defined by $\langle\theta^2\rangle = L_E{}^2\ (\partial\Theta/\partial z)^2$. This scale ratio will be shown to arise naturally in the vertical heat flux conservation equation.

An alternative form for stratification production modeling of C_T^2 is obtained by replacing the vertical gradient of potential temperature by $N^2\ \Theta_o/g$ and not replacing the vertical heat flux by an eddy diffusion coefficient as follows:

$$-4\beta_1/\varepsilon^{1/3}\ \langle w\theta\rangle\ \partial\Theta/\partial z = C_T^2$$
$$-4\beta_1\ ({}_g/\Theta_o\ \langle w\theta\rangle/\varepsilon) N^2\ (\Theta_o/g)^2\ \varepsilon^{2/3} = C_T^2$$

The dimensionless combination, $g/\Theta_o\ \langle w\theta\rangle/\varepsilon$, is sometimes assumed to be a constant equivalent to a critical Richardson number. Table 2 shows this is nearly true in strong turbulence but not in weak. This results in a relation between C_U^2 and C_T^2 as follows: $-2\beta_1\ R_I c\ N^2\ (\Theta_o/g)^2\ C_U^2 = C_T^2$

This relation is sometimes used in analyses of radar data to derive C_U^2 or $\varepsilon^{2/3}$ from radar C_N^2. Note that the ratio $\varepsilon^{2/3}/N^2$ is $L_o^{4/3}$ where L_o is the Ozmidov length scale. Thus we also have the following alternative expression for C_T^2:

$$-4\beta_1\ ({}_g/\Theta_o\langle w\theta\rangle/\varepsilon) N^4\ (\Theta_o/g)^2\ L_o{}^{4/3} =$$
$$-4\beta_1\ (\partial\Theta/\partial z)^2\ ({}_g/\Theta_o\ \langle w\theta\rangle/\varepsilon)\ L_o{}^{4/3}$$

VERTICAL HEAT FLUX BUDGET

$$\partial\langle w\theta\rangle/\partial t = -\text{advection} - \langle w^2\rangle\ \partial\Theta/\partial z\ (1 + HP/VSP - g/\Theta\ \langle\theta^2\rangle/VSP + 1/\rho_o\langle\theta\partial p/\partial z\rangle/VSP) + 2\Omega\cos\varphi\ \langle u\theta\rangle - \partial\langle w^2\theta\rangle/\partial z\ (1 + HTT/VTT) + \langle w\theta\rangle(\partial U/\partial x + \partial V/\partial y)$$

where $VSP = -\langle w^2\rangle\ \partial\Theta/\partial z$, $g/\Theta\ \langle\theta^2\rangle/VSP = L_E^2/L_B^2$ and $1/\rho_o\langle\theta\partial p/\partial z\rangle/VSP = C_{\theta\pi}\ L_E/L_\pi$ and the symbol π represents $\partial p/\partial z$. In the stable boundary layer, Wyngaard et. al. (1971a) showed the vertical heat flux budget is a balance between a gain from stratification production ($-\langle w^2\rangle\ \partial\Theta/\partial z$) and loss from buoyancy ($+ g/\Theta\ \langle\theta^2\rangle$) and the fluctuating pressure term ($-1/\rho_o\langle\theta\partial p/\partial z\rangle$. The ratio of buoyancy to stratification production is equivalent to L_T^2/L_b^2 where $\langle w^2\rangle/N^2 = L_b^2$. For measurements at the Boulder Tower under conditions of stable stratification, Hunt et. al. (1985) found this ratio was 0.64 for all cases. In the 6 Aug clear air turbulence event this ratio was between 1.7 and 4.0 for the four strong turbulence levels. It is not completely clear at this time what the exact balance is between the turbulent transport and the fluctuating pressure gradient terms in maintaining the negative vertical heat flux. This is a goal of measurements in 2002.

5. Conclusions

EGRETT measurements strongly suggest that clear air and refractive turbulence should be sought in the strong shear layers (≥ .03 Hz.) found above and below the jet core of the winter sub-tropical jet stream in both hemispheres. Local anisotropy, as represented by C_w^2/C_u^2 - the ratio of vertical to longitudinal turbulence, is not present this ratio is less than 1.33. Egrett measurements show this is sometimes as small as 0.1. One cannot determine the presence of strong C_w^2 and C_T^2 from gradient Richardson number calculations from radiosonde data. Turbulence data, represented by flux Richardson number and L_E^2/L_B^2 is needed. More investigation of the role of the correlation fluctuating vertical pressure gradient with temperature (any scalar) and fluctuating vertical velocity.

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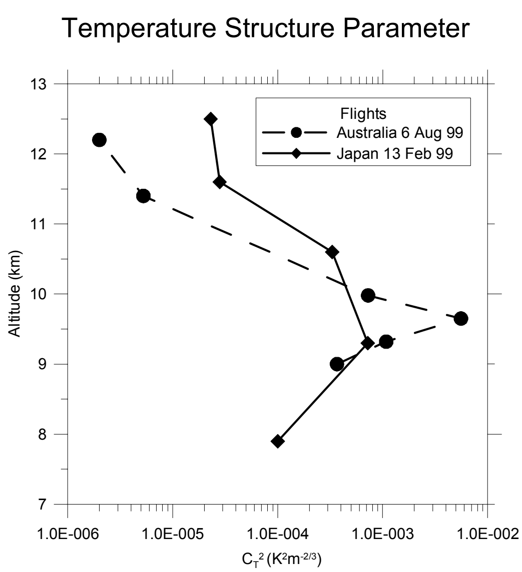

Figure 1. Vertical Profiles of Temperature Structure Parameter.

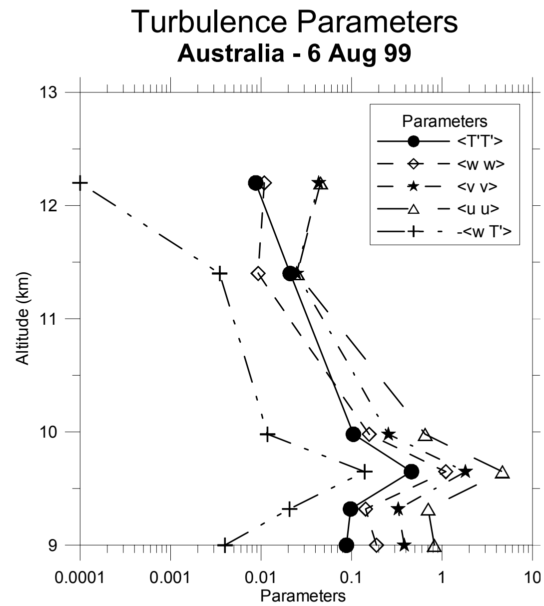

Figure 2. Vertical profiles of temperature variance, turbulent velocity components, and the vertical heat flux (multiplied by −1).

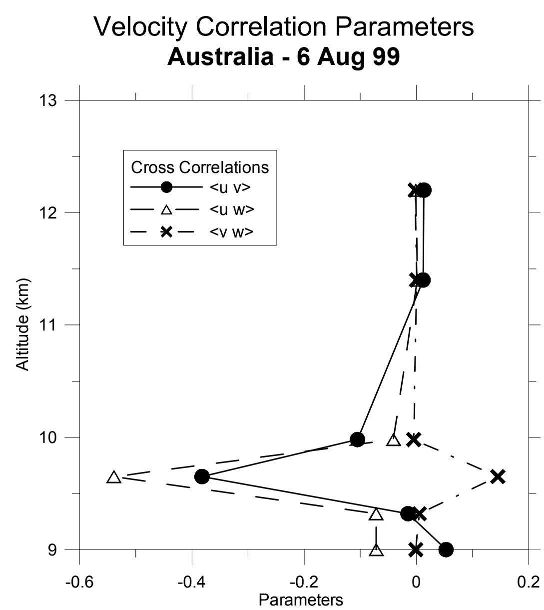

Figure 3. Vertical Profiles of Three Components of Reynolds Stress.

Table 1. Structure function parameters and ratio

Date	Altitude	C_T^2	C_u^2	C_w^2	C_v^2	Cu2/Ct2	Cw2/Ct2	Cw2/Cu2	Cv2/Cu2	ε
Japan	(meters)									(m^2/s^3)
12-Feb-99	11,849	1.40E-04	1.20E-03	5.90E-04	1.50E-03	8.6	4.2	0.49	1.25	1.47E-05
	9,231	1.60E-05	1.60E-03	1.30E-04	2.60E-03	100.0	8.1	0.08	1.63	2.26E-05
	8,932	1.25E-06	7.00E-05	1.70E-05	5.80E-05	56.0	13.6	0.24	0.83	2.07E-07
	7,694	1.50E-05	3.00E-04	1.60E-04	1.30E-03	20.0	10.7	0.53	4.33	1.84E-06
13-Feb-99	12,537	0.23E-04	9.00E-05	2.30E-05	1.40E-04	3.9	1	0.26	1.56	3.02E-07
	11,580	0.28E-04	5.60E-03	9.30E-04	4.50E-03	200.0	33.2	0.17	0.80	1.48E-04
	10,595	3.30E-04	4.20E-03	2.40E-03	4.60E-03	12.7	7.3	0.57	1.10	9.62E-05
	9,325	**7.20E-04**	3.60E-03	1.76E-03	5.30E-03	5.0	2.4	0.49	1.47	7.64E-05
	7,898	1.00E-04	**1.00E-02**	1.10E-03	1.30E-02	100.0	11	0.11	1.30	**3.54E-04**
22-Feb-99	12,343	1.40E-05	3.90E-03	4.10E-04	4.80E-03	278.6	29.3	0.11	1.23	8.61E-05
	12,362	1.70E-05	5.00E-04	2.70E-04	5.00E-04	29.4	15.9	0.54	1.00	3.95E-06
	11,751	2.50E-04	4.00E-03	2.70E-03	5.10E-03	16.0	10.8	0.67	1.27	8.94E-05
	9,850	1.60E-05	?	7.40E-05	?	?	4.6	?	?	?
	9,242	0.750E-05	1.20E-04	2.75E-05	7.50E-05	16.0	3.7	0.23	0.63	4.65E-07
23-Feb-99	12,282	2.70E-05	1.70E-04	6.60E-05	2.20E-04	6.3	2.4	0.39	1.29	7.84E-07
	11,662	0.90E-05	2.10E-03	1.00E-03	3.80E-03	233.3	111	0.48	1.81	3.40E-05
	10,243	7.00E-05	**1.20E-02**	5.50E-03	1.15E-02	171.4	78.6	0.46	0.96	**4.65E-04**
	9,969	3.30E-05	2.60E-04	7.20E-05	3.30E-04	7.9	2.2	0.28	1.27	1.48E-06
	9,536	5.70E-05	1.40E-03	5.70E-04	1.80E-03	24.6	10.8	0.41	1.29	1.85E-05
Australia										
6-Aug-99	12,200	2.00E-06	5.30E-05	2.05E-05	5.33E-05	26	10	0.38	1	1.36E-07
	11,400	5.26E-06	1.68E-04	3.94E-05	5.20E-04	319	7.5	0.23	1.26	7.70E-07
	9,980	7.27E-04	1.79E-02	1.03E-02	2.30E-02	24.6	14	0.58	1.3	8.45E-04
	A 9,650	3.66E-04	1.34E-02	5.75E-03	1.48E-02	36.6	16	0.43	1.1	5.48E-04
	B 9,650	**5.57E-03**	**1.20E-01**	**1.00E-01**	**1.31E-01**	21.5	18	0.83	1.1	**1.47E-02**
	9,320	1.08E-03	3.42E-02	1.80E-02	3.43E-02	31.5	17	0.52	1	2.24E-03
	9,000	3.67E-04	1.90E-02	1.16E-02	2.66E-02	51.8	32	0.61	1.4	9.26E-04

Table 2 Summary of turbulence measurements for 6 August 1999.

Altitude	"L" = $(C_T^2/(\partial\Theta/\partial z)^2)^{3/4}$	$g/\Theta\ w\theta/\varepsilon$	θ^2 / w^2	$(L_E / L_B)^2$	Flux Ri	Gradient Ri number	K_H / K_M Inverse Turb Prandtl No.	$L_I = q^3/\varepsilon$ meters
9000	4.4	0.124	0.465	1.9	.03	.07	.41	632
9320	10	0.06	0.682	2.7	.04	.07	.55	202
B 9650	34	0.27	0.418	1.7	.37	.33	1.1	500
9980	33	0.40	0.668	4.0	.40	.32	1.2	456
11400	0.6	125	2.26	10	24.8	42	.6	6.4 km
12200	0.3	139	0.8	6.9	6.4	5.5	1.1	82 km