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An account of low level wind shear over Chennai airport - Part II : Turbulence and eddy dissipation

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सार – अंर्तराष्ट्रीय नागरिक विमानन संगठन (आई.सी.ए.ओ.) के निर्धारित दिशानिर्देशों के अनुसार सभी उतरने वाले वायुयान के लिए पवन अपरूपण चौकसी को जारी करने के लिए उड़ान के दौरान वायुयान से प्राप्त की गई निम्न स्तरीय पवन अपरूपण रिपोर्टों (एल.एल.डब्ल्यू.एस.) का उपयोग किया गया है। इस शोध–पत्र में, मानक एलगोरिथ्म का प्रयोग करते हुए डी.डब्ल्यू.आर. से रिकार्ड किए गए अरीय पवन आँकड़ों से पवन गति की पुष्टि करने के लिए, 1000 एवं 1800 फीट की ऊँचाई पर उड़ान भर रहे वायुयानों से प्राप्त किए गए आँकड़ों का उपयोग किया गया है। पहले से प्रयोग में लाए जा रहे (रेडियो सौंदे/रेडियो पवन) उपरितन वायु आँकड़ों, वायुयान से प्राप्त किए गए पवन आँकड़ों तथा डी.डब्ल्यू. आर. आकलित पवन आँकड़ों का स्वतंत्र रूप से उपयोग करते हुए विक्षोभ सूचकांक और प्राचल निर्धारित किए गए हैं और वायुयान चालक दल से प्राप्त पवन अपरूपण से प्रभावित विक्षोभ की रिपोर्टों के साथ से इनकी तुलना की गई है। परिसीमा स्तर में मीन पॉवर लॉ (पवन एस्कैलेशन नियम) प्रौफाइलों में स्थिर और अस्थिर वायुमंडलीय स्थितियाँ पाई गई है।

डी.डब्ल्यू.आर. से प्राप्त हुए अरीय वेग आंकडों के आधार पर धरातल से 600 मीटर की ऊँचाई तक के त्रिआयामी अपरूपण (3 डी.एस.) प्राप्त किया गया है। इनकी तुलना रेडियो सौंदे/रेडियो पवन से आकलित पवन अपरूपण वेग एवं डी.डब्ल्यू.आर. से आकलित पवन से की गई है। त्रिआयामी अपरूपण के $16 * 10^{-3}$ प्रति सेकेण्ड मान अधिक होने पर मध्यम विक्षोभ की घटना के सही पूर्वानुमान का पता चला है। यह आम धारणा है कि पवन अपरूपण एक अल्पावधि प्रक्रिया है जो केवल कुछ मिनटों तक बनी रहती है। यह देखा गया है कि निम्न स्तरीय पवन अपरूपण तथा प्रेरित मध्य विक्षोभ की घटनाओं का 10 घंटे से अधिक अवधि तक बने रहना चैन्ने के ऊपर उड़ान भर रहे वायुयान के लिए अप्रत्याशित नही हैं।

ABSTRACT. In-flight reports on Low Level Wind Shear (LLWS) received from aircrafts are used to issue wind shear alerts for all subsequent landing aircrafts as per standing guidelines of International Civil Aviation Organisation (ICAO). In this paper, winds reported by aircrafts at 1000 and 1800 ft. are used to validate the wind estimated from DWR measured radial wind data employing standard algorithms. Turbulence indices and parameters have been computed independently using conventional (RS/RW) upper air data, aircraft measured winds and DWR estimated winds and compared these with wind shear induced turbulence reported by aircrews. Mean power law (wind escalation law) profiles in the boundary layer have been arrived at for unstable and stable atmospheric conditions.

Three dimensional shear (3DS) upto 600 m a.g.l. has been worked out from DWR measured radial velocity data and compared with wind shear computed from RS/RW and aircraft measured winds and DWR estimated winds. It is found that 3DS values of more than $16 * 10^{-3}$ s^{-1} predict well the occurrence of moderate turbulence. Contrary to the general belief that wind shear is a short lived phenomenon which may last for a few minutes only, it has been observed that incidences of LLWS and induced moderate turbulence lasting more than 10 hrs are not at all uncommon over Chennai aircraft.

Key words – Chennai airport, Low level wind shear, Richardson number, Three dimensional shear, Eddy dissipation rate, Turbulence index, Doppler weather radar, METAR.

1. Introduction

Low level wind shear (LLWS) is a severe aviation hazard. Since the vectorial change in wind often create eddies, the touch-down, landing and take-off phases of aircraft operations are affected by the LLWS as the swirls of air cause turbulence (Fujita & Caracena, 1977 and Fujita, 1980). It is a well known fact that abrupt change in wind direction combined with significant change in wind speed exceed the performance capabilities of many sophisticated aircraft and a number of aircraft accidents and severe incidents have been well documented in literature [Fujita and Caracena, 1977; Federal Aviation Administration (FAA), 1979; DiMarzio *et al*., 1979 and International Civil Aviation Organisation (ICAO), 1983]. Wind shear is mostly associated with convective currents and thunderstorms and it is also observed at the boundary of temperature inversions [Her Majesty Stationery Office (HMSO), 1994]. In an aircraft accident investigation by ICAO, change of wind speed as high as 25 m s^{-1} in the first 60 m a.g.l. has been observed (ICAO, 1983). When this sort of shear occurs at higher altitudes, say well above 6000 m a.g.l., loss of altitude and/or turbulence may result in but an alert pilot may however effectively overcome any possible incident or accident as sufficient headway clearance is available. On the other hand, when this magnitude of shear occurs during approach or take-off phase, say below 1000 m, it may be quite impossible for the pilot to avert the accidents/incidents as the height available is not sufficient to overcome the effect of shear. Hence, a pilot accords much importance to LLWS and he is expected to detect, predict and avoid severe wind shear conditions as the airplanes may not be capable of safely penetrating through all intensities of LLWS (Lee and Beckwith, 1981).

In the absence of low level wind shear alert system, ICAO (2004) envisages the reporting of LLWS encountered by an aircraft to the local air traffic services as in-flight report so that subsequent flights can be warned. Though literature survey reveals that the active lifespan of the shear is to a maximum of few minutes, active LLWS cases have been probed continuously for more than twelve hours by Doppler Weather Radar (DWR) over Chennai airport and documented (Suresh, 2008, personal communication). In the absence of 24 hrs wind shear surveillance by remote sensing (DWR, Wind profilers, LIDAR/SODARs/Sonic anemometer arrays etc), the in-flight report on aircraft measured winds at a few levels and wind shear information, besides serving as the basic input for the meteorologists to issue trend forecast for the next few hours, is quite useful to devise and validate algorithm(s) to estimate the horizontal winds from the radial wind measurements of DWR. In this connection, it may be mentioned that algorithms proposed by Lhermitte and Atlas (1961), Browning and Wexler (1968) and Waldteufel and Corbin (1979) are being used to estimate the horizontal wind at various heights from radial wind measurements under certain assumptions. Hence, in order to serve the aviation community still better, the aircrews operating from Chennai airport have been impressed upon to record and intimate aircraft observed winds at different heights at approach phase regardless of their experiencing of LLWS or otherwise. Despite repeated reminders on this aspect at various operational forums with airline agencies, the response was not appreciable (Suresh, 2004). However, whatever in-flight reports received through Air Traffic Controllers (ATC) at Chennai airport during 2006-2007 have been used in this paper to validate the DWR based algorithms, to derive power law profile (wind escalation law) and to devise suitable method to issue low level wind shear alert and TREND forecast over Chennai airfield.

2. Winds and turbulence measurements by Doppler Weather Radar

The primary measurement and products of a DWR are the radar reflectivity, radial velocity and velocity spectrum width. While radar reflectivity is a measure of precipitation intensity and atmospheric moisture contents, the radial velocity is the component of wind acting either towards or away from the radar and the velocity spectrum width is a measure of turbulence. The utility of Doppler Weather Radar (DWR) to issue wind shear alert has been well documented in literature (Browning, 1982; Wilson *et al*., 1984; Eilts, 1987; Doviak and Zrnic, 1993, Fujita, 1990; Sauvageot, 1992; Lau *et al*., 2002; Cheng, 2002 and Raghavan, 2003). A state-of-the art DWR supplied by M/s Gematronik GmbH, Germany has been put into operation use w.e.f. 20th February 2002 at Cyclone Detection Radar station of IMD, Chennai and its capability and merits have been described in Bhatnagar *et al*. (2003); Rao *et al.* (2004); Suresh (2004, 2006, 2007) and Suresh *et al.* (2005). This DWR located about 16 km away from Chennai airport can be used as a Terminal Doppler Weather Radar (TDWR) as the shear products are quite valid and applicable for the aviation weather surveillance (Suresh, 2004).

2.1. *Velocity Azimuth Display (VAD)*

VAD as defined originally by Lhermitte and Atlas (1961) was to record the radial velocities when the antenna is rotated in a circle at constant elevation angle at a fixed slant range close to the radar site to obtain wind velocity profiles in widespread precipitation. However with the modern DWRs, this technique can be used in non-precipitation conditions as well since the modern receivers are quite sensitive to detect clear air returns. Later this technique was modified by Browning and Wexler (1968) to estimate the kinematics of wind fields such as horizontal wind, divergence and deformation by employing harmonic analysis. A typical plot of radial velocity against azimuth will look like a sinusoidal curve if wind is linear and there is no variation in its speed and direction around the area of probing. The horizontal wind vector can be estimated under these assumptions, which may be prevailing only in fair weather and in stable atmospheric conditions.

Mathematically, the radial velocity (V) can be expressed as

$$V = V_h \cos\alpha \;\cos(\beta - \beta_o) - V_f \;\sin\alpha \qquad (1)$$

where V_h and β_o are the horizontal wind speed and direction respectively, V_f is the fall velocity of the particles, α is the antenna elevation angle and β is the azimuth angle. A quick interpretation of the above equation would lead to $V = V_h$ when α is very small and when $\beta = \beta_o$ or $\beta = \beta_o + \pi$ and if the fall velocity is quite small and negligible. It should be remembered that VAD may not be valid if the horizontal wind blowing at the time of observation is not perfectly linear and if asymmetry is present in both direction and speed (which normally happens in tropical atmosphere). Also, the VAD technique is valid only for low elevation angles either in precipitation or in clear air mode. Hence the interpretation requires adequate experience and its utility may be made with a word of caution. Further treatment of VAD is beyond the scope of this paper and interested readers are encouraged to refer to standard books on DWR.

2.2. *Volume Velocity Processing (VVP)*

The horizontal wind vector and the kinematics of wind field can be derived by adopting suitable algorithms and the display can be in the form of a vertical time section of horizontal wind. An extension of VAD into multiple VAD and by making certain assumptions, Waldteufel and Corbin (1979) has proposed VVP algorithm. The algorithm is briefly described below. The radial velocity V_r as observed by radar can be written as

$$V_r = u \cos\theta \cos\varphi \;+\; v \sin\theta \;\cos\varphi \;+\; w \sin\varphi \qquad (2)$$

where θ and φ are the azimuth and elevation angles. In this algorithm the wind $V = V(u, v, w)$ is assumed to vary linearly in space around its value (u_o , v_o , w_o) at a point, usually the radar centre, (x_o , y_o , z_o). (*i.e.*)

$$u = u_o + u_x^{/} (x - x_o) \;+ u_y^{/} (y - y_o) \;+ u_z^{/} (z - z_o)$$

$$v = v_o \;+ v_x^{/} (x - x_o) \;+ v_y^{/} (y - y_o) \;+ v_z^{/} (z - z_o)$$

$$w = w_o + w_x^{/} (x - x_o) + w_y^{/} (y - y_o) + w_z^{/} (z - z_o)$$

By transforming into polar coordinates (R, θ, φ) where R is the radius (slant range in our case) and regrouping we obtain

$$\begin{aligned} V_r = \; & \cos\theta \cos\varphi \,(u_o - u_x^{/} x_o \;-\; u_y^{/} y_o \;-\; u_z^{/} z_o) \\ & + \sin\theta \cos\varphi \,(v_o - v_x^{/} x_o \;-\; v_y^{/} y_o - v_z^{/} z_o) \\ & + \sin\varphi \,(w_o - w_x^{/} x_o \;-\; w_y^{/} y_o \;-\; w_z^{/} z_o) \\ & + \mathrm{R} \cos^2\theta \cos^2\varphi \; u_x^{/} + \mathrm{R} \sin^2\theta \cos^2\varphi \; v_y^{/} \\ & + \mathrm{R} \cos\theta \sin\theta \;\cos^2\varphi \,(u_y^{/} + v_x^{/}) + \mathrm{R} \sin^2\varphi \; w_z^{/} \\ & + \mathrm{R} \;\cos\theta \sin\varphi \cos\varphi \,(u_z^{/} + w_x^{/}) \\ & + \mathrm{R} \sin\theta \sin\varphi \cos\varphi \,(v_z^{/} + w_y^{/}) \end{aligned} \qquad (3)$$

The vorticity derivatives $v_x^{/}$ and $u_y^{/}$ cannot be extracted as they are either summed up with the other unknown quantities such as u_o and v_o or summed up together. Thus in order to retrieve u_o and v_o in the absence of any additional information, the only possibility is to choose radar as the centre, *i.e.*, $x_o = 0$ and $y_o = 0$. When we assume linear approximation (in locally stratiform conditions), $w_y^{/}$ and $w_x^{/}$ are far far less than $u_z^{/}$ and $v_z^{/}$ and hence $w_y^{/}$, $w_x^{/}$ can be neglected. With these assumptions Waldteufel and Corbin (1979) modified the radial velocity term so that the components of radial velocity terms can be retrieved without any contamination by other components. The modified term V_r is

$$\begin{aligned} V_r = \; & \cos\theta \cos\varphi \;\; u_o + \sin\theta \cos\varphi \; v_o + \sin\varphi \;\; w_o \\ & + \mathrm{R} \cos^2\theta \cos^2\varphi \; u_x^{/} + \mathrm{R} \sin^2\theta \cos^2\varphi \; v_y^{/} \\ & + \mathrm{R} \cos\theta \sin\theta \;\cos^2\varphi \,(u_y^{/} + v_x^{/}) \\ & + \sin\varphi \,(\mathrm{R} \sin\varphi - z_o) \, w_z^{/} \\ & + \cos\theta \cos\varphi \,(\mathrm{R} \sin\varphi - z_o) \, u_z^{/} \\ & + \sin\theta \cos\varphi \,(\mathrm{R} \sin\varphi - z_o) \, v_z^{/} \end{aligned} \qquad (4)$$

Since R and φ are constant and there is no z term in VAD and $w_y^{/}$, $w_x^{/}$ are very small, the radial velocity term for VAD can now be re-written as

$$\begin{aligned} V_r = \; & \cos\theta \cos\varphi \;\; u_o + \sin\theta \cos\varphi \; v_o \\ & + \cos^2\theta \,(\mathrm{R} \cos^2\varphi \; u_x^{/} + \sin\varphi \; w_o) \\ & + \sin^2\theta \;\,(\mathrm{R} \cos^2\varphi \; v_y^{/} + \sin\varphi \; w_o) \\ & + \sin\theta \;\cos\theta \; \mathrm{R} \cos^2\varphi \,(u_y^{/} + v_x^{/}) \end{aligned} \qquad (5)$$

The computation of horizontal divergence poses a serious problem because of the contamination of $u_x^{/}$ and $v_y^{/}$ by the appearance of vertical velocity term w_o. This again re-confirms the applicability of VAD to simply low elevation angles only. Solving of the above equation is by means of theories on matrix algebra and require large volume of data points. The range bin data up to 30 km from the radar, barring the first few kilometers data which are normally contaminated with ground clutters and sidelobes, have been used to estimate the vertical profile of wind. In other words, the horizontal wind estimated through this method is applicable for a range circle up to 30 km. Preliminary validation of this algorithm over Chennai was made by Suresh (2004) and he documented that the estimation was quite satisfactory and encouraging. In this paper, horizontal winds at 300 and 600 m altitude over Chennai has been estimated using VVP algorithm and compared with those reported by aircrews.

2.3. *Shears computed from radial velocity*

Various types of shear products can be derived through derivatives of radial winds in radial direction, azimuthal, elevation angles and combination of these. Radial, azimuthal and elevation shears can be combined into a single product, *viz*., three dimensional shear (3DS) using the formula,

$$\text{3DS} = \sqrt{\left(\textit{Radial shear}^2 + \textit{Azimuthal shear}^2 + \textit{Elevation shear}^2\right)} \tag{6}$$

Since very fine vertical resolution is quite possible close to the radar site (with 1° beam width), combining the three shears will be truly representing the atmosphere in comparison to other shears. The 3DS in excess of $16 * 10^{-3}\ \text{s}^{-1}$ (*i.e*., $16\ \text{m s}^{-1}\ \text{km}^{-1}$) has been associated with moderate wind shear (Suresh, 2004).

In this paper, the radial, azimuthal and elevation shears are calculated from a volume scan data set whose scan parameters have been described latter in this paper. A fit window of nine bins is considered for computing azimuthal and radial shear values through the method of least squares. Two adjacent elevation data are considered for computing elevation shear. Then the 3DS is obtained using the above formula for each range bin. The polar shear volume data set thus computed is converted into a Cartesian volume (with vertical layer spacing of 150 m) and the maximum 3DS value of each bin has been identified for plotting. Based on ICAO guidelines and procedures (ICAO, 2004) and considering the aviation user requirement through the Airports Authority of India, Chennai, wind shear acting up to 600 m a.g.l. is very crucial for aviators. For alerting low level wind shear up to 600 m, we restricted the 3DS product generation to 600 m only. Hence, the displayed value may be thought of as the maximum 3DS value from surface to 600 m over the range bin concerned and the precise height corresponding to this value is not readily known to the user. The advantage of this product is that shear is computed from the radial velocity itself without making any assumption to estimate the horizontal wind and then to compute the shear from these estimated horizontal winds in a conventional manner.

3. Turbulence *vis-a-vis* wind shear

Turbulence is an aviation hazard. Turbulence is one of the hardest elements that can be modeled through classical physics and it is an open problem that is yet to be solved (Mandlebrot, 1982). Turbulence may arise due to thermal and/or dynamic instability. While the thermal turbulence is arisen out of thermal instability (*i.e*., when the environmental lapse rate is higher than dry adiabatic lapse rate), that arisen out of high value of the shear is known as shear induced turbulence. Turbulence Index (TI) has been proposed by various authors to predict the turbulence using the upper air temperature and wind data.

Most widely accepted tool to identify atmospheric turbulence is known as Richardson Number. Richardson number (R_i) which is a concatenation of thermal and shear induced turbulence can be re-written as follows.

$$\text{R}_i = \frac{\dfrac{\text{g}}{\theta}\left(\dfrac{\partial\theta}{\partial z}\right)}{\left(\dfrac{\partial u}{\partial z}\right)^2} = \frac{\dfrac{\text{g}}{\overline{T}}(\Gamma - \gamma)}{\left(\dfrac{\partial u}{\partial z}\right)^2}$$

$$= \frac{\text{Static stability}}{\text{Square of vertical shear of horizontal wind}} \tag{7}$$

where $\overline{T}$ is the layer mean temperature, Γ is the dry adiabatic lapse rate, γ is the environmental lapse rate, u is the zonal component of the wind as per meteorological convention and θ is the potential temperature. From the above, one can infer that the negative static stability explains the thermally induced turbulence and higher magnitude of vertical shear of horizontal wind explains the shear induced turbulence. Change of wind speed of 6 kt and more in a layer of 1000 ft (300 m) is associated with moderate turbulence and 12 kts and more is associated with severe turbulence in aviation parlance (Endlich, 1964 and Ellrod and Knapp, 1992), *i.e*., wind shear threshold of $0.00967\ \text{s}^{-1}$ ($0.019\ \text{s}^{-1}$) is associated with moderate (severe) turbulence. For this purpose, wind shear in this paper is derived from both zonal (u) and meridional (v) components of the wind using the formula $\sqrt{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2}$.

Another form of TI has been proposed by Endlich and Mancuso (1965). They defined TI as $\text{TI} = \left| V\left(\frac{\partial\alpha}{\partial z}\right)\left(\frac{\partial^2 T}{\partial z^2}\right)\right|$ where α is the wind direction (in radians), V the wind speed, z is the height and T the temperature. It can be seen that this index also takes into account the wind speed, change in wind direction with height but considers the second derivative of temperature change with height in contrast to the Richardson Number which considers only the first derivative of temperature with height. It has been documented in their study that $\left| V \frac{\partial \alpha}{\partial z} \right|$ had maximum magnitude in the turbulent regions and $\left| \frac{\partial^2 T}{\partial z^2} \right|$ had the largest values over frontal boundaries and in tropopause.

Ellrod and Knapp (1992) used two types of TI based on numerical weather prediction (NWP) model outputs for forecasting CAT over upper troposphere and stratosphere over the United States. Stretching deformation (DST) and shearing deformation (DSH) were computed to get the resultant deformation (DEF) which is the square root of sum of squares of DST and DSH. The vertical wind shear (VWS) and convergence (CVG) were computed and the turbulent indices were then calculated using the following formulae.

$$TI1 = VWS * DEF$$

$$TI2 = VWS * (DEF + CVG).$$

In the above formulation, only wind components have been used to estimate the turbulence and thermally induced turbulent component has not been considered explicitly. Though many other turbulence indices are in vogue throughout the world, in almost all the indices the wind shear component is finding a place.

In a recent study, Suresh (2008, personal communication) analysed wind shear reports received from aircrafts during the period 1987-2007 employing all the above said indices and observed that 61.5% efficiency could be achieved by jointly using Endlich and Mancuso's TI (TI > $3*10^{-6}$ rad s^{-1} °K m^{-2}) and Richardson Number (R_i < 0.6) in predicting LLWS cases reported over Chennai. It has also been observed by him that in contrast to the general belief that windshear is a short lived phenomenon, there were cases at which LLWS were active for more than 10 hrs over Chennai airport.

International Civil Aviation Organisation (ICAO, 2004), the governing body of international air navigation services, has made recommendations to the effect that a pilot-in-command has to advise the appropriate air traffic services unit as soon as practicable about the wind shear encountered by him so that such an information may be used by the air traffic services to alert other aircraft operations in that air field to ensure safety of aircraft operations. According to ICAO (2004), turbulence and to a large extent the wind shear are the elements which, for the time being, cannot be satisfactorily observed from the ground and for which in most cases aircraft observations represent the only available evidence. Though wind profilers, TDWRs, Doppler LIDARs, Sonic anemometers etc. are installed in some of the major airports in the world either on research or in operational mode, aircraft report on wind shear is the only source for all airports in India. Hence, in this study, aircraft observations of winds and windshear over Chennai airport have been considered for validating with the Chennai DWR data.

4. Data used

The air line agencies, based on the deliberations of various Regional Operations Committee (ROC) meetings conducted by Airports Authority of India, Southern Region, Chennai, have instructed their air crews to report winds at 1000ft and 1800 ft at approach phase to Air Traffic Controllers (ATC) Chennai for validating the winds estimated through DWR Chennai data by aerodrome meteorological office, Chennai. However, quoting high concentration and excessive pressure of work at the time of landing, the air crews have not fully complied with the instructions. Nonetheless, in all, 149 reports were received between 5th January 2006 and 26th April 2007. While some of these reports were associated with LLWS, some of them were not associated with LLWS and these reports were reported just for the purpose of validating the DWR algorithm only. The low level 0000 and 1200 UTC upper air data have been collected from Chennai RS/RW station for 22 cases during the study period when the timings of aircraft reported winds were close to that observed by the RS/RW observations for the purpose of validating both the aircraft and DWR derived winds.

5. Methodology

The aircraft reported winds at 1000 ft (300 m) and 1800 ft (600 m) have been systematically tabulated for the purpose of comparison with the winds estimated through VVP algorithm (Waldteufel and Corbin, 1979) and as measured by RS/RW observations taken at Chennai at 0000 and 1200 UTC. It may be remembered that while the DWR wind estimation is a single value representing 30 km radius circle around the radar, the aircraft

TABLE 1

Comparison of winds reported by the aircrafts over Chennai airport with that estimated using Doppler Weather Radar, Chennai during January 2006 - April 2007 (Total no. of observations =149)

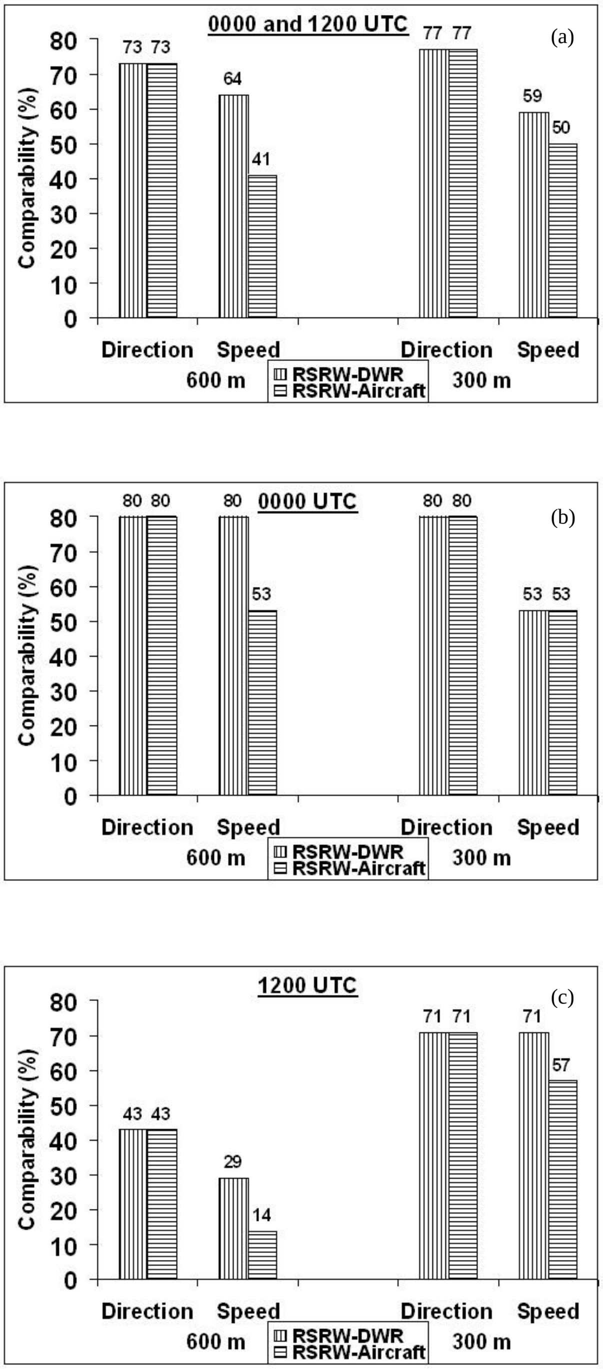
Item	1000 ft (300 m)	1800 ft (600 m)
Difference in wind direction up to 30^{o}	129 (86 %)	129 (86 %)
Difference in wind speed up to 3 kts	116 (78 %)	110 (74 %)
Mean difference for wind direction	21^{o}	20^{o}
Mean difference for wind speed	3.1 kts	3.6 kts

observation is a momentary information at the time of landing over Chennai airport which is 16 km southwest of the Radar. Nonetheless, the 30 km representation is better than the existing RS/RW or pilot balloon network coverage throughout the Globe. Hence, as pointed out earlier the comparability exercise has been made.

5.1. *Aircraft wind observations vs DWR wind estimation*

We adopted a criterion, *viz*., deviation in wind direction up to 30° between these observation/ estimation/measurements is considered as correct for comparing the point observation of winds by the aircraft at the time of landing with DWR estimated wind. The above limit is based on the operationally desirable accuracy of upper air meteorological information as envisaged in ICAO (2004). Although ICAO (2007) prescribes wind difference up to 5 kts for the actual winds up to 25 kts is operationally desirable, we considered a very stringent limit, *viz*., up to 3 kts difference only, since the speed has more profound effect at the time of landing and take-off operations (Lee and Beckwith, 1981). Table 1 summarises the results of our comparison.

It may be noted that there is a good agreement between the aircraft observations and winds estimated using DWR data, despite limitations already highlighted. In more than 70% of the cases, the differences were practically nil for both wind direction and speed. However, appreciably large differences have been noticed concurrently at both 300 and 600 m observations - 8 occasions in respect of wind directions and 13 occasions in respect of wind speed. These large differences contributed significantly to increase the mean difference values in regard to wind direction and speed.



Figs. 1 (a-c). Percentage number of cases wherein the difference between the RS/RW measured (a) (both 0000 and 1200 UTC) and DWR estimated/aircraft measured wind direction is within 30° and the wind speed within 3 kts over Chennai airport, (b) (0000 UTC) and DWR estimated/aircraft measured wind direction is within 30^{o} and the wind speed within 3 kts over Chennai airport and (c) (1200 UTC) and DWR estimated/aircraft measured wind direction is within 30^{o} and the wind speed within 3 kts over Chennai airport during January 2006 – April 2007

5.2. *Aircraft wind observations vs RS/RW wind measurements*

Since timings of some of the aircraft observations were just close to the regular 0000 and 1200 UTC RS/RW observations, we compared the aircraft reported winds at 1000 and 1800 ft with RS/RW observations by adopting the same criteria mentioned in section 5.1. For this, aircraft reports that fell between 2300 and 0200 UTC have been considered for comparing with 0000 UTC RS/RW observation and those between 1100 and 1300 UTC have been used for 1200 UTC RS/RW observation comparison. We could pick out only 22 aircraft reports close to the RS/RW timings (15 for 0000 UTC and 7 for 1200 UTC RS/RW) for comparison. The sample size is very meager. Nonetheless, being the first non-conventional observation from Chennai airfield, the comparison has been attempted in this paper.

Figs. 1(a-c) show the comparability of winds reported by aircrafts and winds estimated from DWR data with that measured by RS/RW observations. Though the wind direction as observed by aircraft and as estimated by DWR are matching with that measured by 0000 and 1200 UTC RS/RW observations in 73% cases at 600 m and 77% at 300 m, aircraft observations on wind speed just marginally only tallied with RS/RW observations at 41% and 50 % respectively at these heights. Further analysis revealed that the differences between these observations are high during 1200 UTC in comparison to 0000 UTC. The reason for poor comparability of the non-conventional wind observation/estimation with RS/RW observations at 600 m is not readily understood. Hence, we looked into the comparability of wind estimation through DWR data with that observed and reported by the aircrafts just around 0000 and 1200 UTC. The results have been tabulated in Table 2. While, the comparison is quite good at 300 m height for both 0000 and 1200 UTC and it is quite satisfactory for both the levels around 0000 UTC, the deviations are vast at 600 m around 1200 UTC. There was not even a single case at which wind speed difference was within 3 kts out of the seven cases compared for 540 m altitude aircraft observation. As the aircraft data pertains to 540 m (1800 ft) and DWR data pertains to 600 m, it is not clear as to whether there is vast difference in wind speed between these heights due to afternoon convection around 1200 UTC. Hence, it is felt that further analysis with huge database may alone throw some light on the poor comparability of aircraft observed winds at 600 m altitude around 1200 UTC.

TABLE 2

Percentage frequencies of comparability of aircraft reported winds with DWR estimated winds (direction within 30^o and speed within 3 kts) over Chennai airport around 0000 and 1200 UTC

Time (UTC)	Frequency	1800 ft (540 m)		1000 ft (300 m)	
		Direction	Speed	Direction	Speed
0000 & 1200	22	77.3	59.0	86.4	77.3
0000	15	86.7	73.0	86.7	86.7
1200	7	71.4	0	85.7	57.1

5.3. *Wind escalation law in the boundary layer*

On a number of occasions, in addition to 149 cases analysed in this paper, wind was reported by the aircrews at only one level and such reports have not been analysed in the current study. Since shear computation requires winds at two levels, it is necessary to estimate the wind at the other level. We utilized the data set to estimate power law coefficient of the Deacon’s power law wind profile over boundary layer, *viz*.,

$$\frac{V_H}{V_L} = \left(\frac{Z_H}{Z_L}\right)^p \tag{8}$$

where V_H and V_L are the wind velocity at heights Z_H and Z_L (a.g.l.) respectively (Haltiner and Martin, 1957). The power law coefficient (p) was computed from the aircraft measured wind and DWR estimated wind data set independently in order to assess as to whether one can use this coefficient to estimate the wind at a particular height given wind velocity at a reference height. The value of p was +ve (–ve) according as the speed was increasing (decreasing) with height. The mean value of p for aircraft measured wind data was 0.6736 and for DWR estimated wind data it was 0.5582 when the wind speed increases with height. Similarly, when the wind speed decreases with height the mean value of p was – 0.5127 for aircraft data and for DWR estimated data it was – 0.5166. As expected, the mean coefficients as estimated from both the data sets reasonably agree well. For operational use, wind at a particular level can be estimated from the wind at another level in the boundary layer using

$$\frac{V_H}{V_L} = \left(\frac{Z_H}{Z_L}\right)^{0.6} \quad \text{for unstable atmospheric conditions}$$

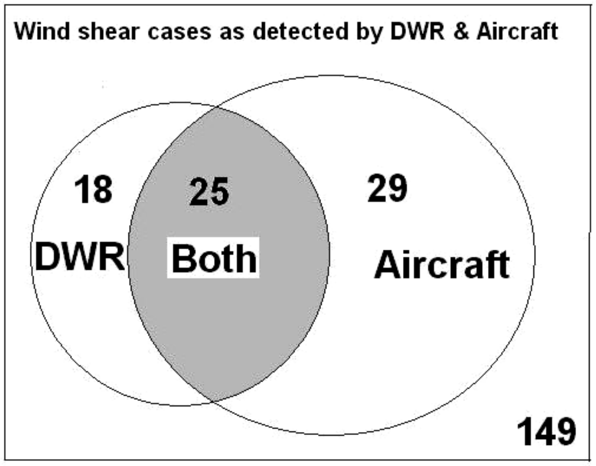


Fig. 2. Venn diagram of moderate wind shear cases detected by aircraft wind observations at 1000 and 1800 ft, DWR estimated wind data at 300 m and 600 m a.g.l. n(DWR) = 43; n(Aircraft) = 54; n(DWR ∩ Aircraft) = 25; n(DWR ∪ Aircraft) = n(DWR) + n(Aircraft) - n(DWR ∩ Aircraft) = 72

$$\frac{V_H}{V_L} = \left(\frac{Z_H}{Z_L}\right)^{-0.5} \quad \text{for stable atmospheric conditions.}$$

Nonetheless, it is concluded that the power law profile can not be straightaway used, in view of its change in sign according as wind speed increases or decreases with height, unless one is reasonably sure of atmospheric instability/stability conditions.

5.4. *Shear induced turbulence*

TABLE 3

Turbulence based on peak value of eddy dissipation rate (ICAO, 2004)

S. No.	Turbulence	Peak value of EDR ($m^2 s^{-3}$)
1	Severe	> 0.5
2	Moderate	0.3 – 0.5
3	Light	0.1 – 0.3
4	No turbulence	< 0.1

While seven cases of moderate turbulence experienced by the aircrews had been passed on to the air traffic control (ATC) tower along with the winds at 1000 and 1800 ft, in the remaining 142 occasions only the winds at these heights were passed on by the aircrews to ATC as in-flight reports. As has been mentioned in section 3, since wind shear threshold of 0.00967 s^{-1} is associated with moderate turbulence, we computed shear between 300 and 600 m a.g.l. from DWR data and between 1000 and 1800 ft from the aircraft reports. Out of 149 aircraft reports analysed in this study, moderate turbulence could have been observed in 25 cases from both DWR and aircraft data. If we consider DWR data alone, moderate turbulence might have occurred in 43 cases and if we consider only the aircraft reported wind data, conditions were favourable for moderate turbulence in 54 cases. But the aircraft had reported only seven cases of moderate turbulence during the period of analysis. Venn diagram of turbulence analysis is shown in Fig. 2. The reasons for the vast difference between actual reporting of turbulence as experienced by the aircrews and as computed manually from the DWR estimated and aircraft measured data have been critically analysed.

In the manual computation of wind shear, we often get a higher value when the wind veers or backs with height by more than 30° and crossing 180° or 360° azimuth and speed in excess of 8 kts at any of the two levels considered. This is so because according to meteorological sign convention, the sign of the zonal wind component between these levels gets reversed when wind crosses 180° or 360° at any one of these levels. This may be one reason as to why we get more number of moderate turbulence in manual computation. At the same time, it must be remembered that winds at any one of level crossing 180° (360°) means the wind at that level is a cross wind for the runway orientation RWY 07/25. Hence, this re-confirms the possibility of turbulence effect due to cross wind component as identified by manual computation method.

It can be seen from Fig. 2 that as many as 72 cases of moderate turbulence at the time of landing were probable during January 2006 – April 2007 whereas only seven cases had been reported by the aircrews. There were as many as 18 cases of moderate turbulence detected by DWR which the aircraft observations could not support. Similarly, 29 cases of aircraft observed moderate turbulence could not be detected by the DWR. Interaction with aircrews revealed that moderate turbulence is quite a common phenomenon over Chennai airport almost throughout the year in view of its topographic and terrain conditions and the pilots are very well aware and well

TABLE 4

Salient technical details of Chennai DWR and scan parameters used in this study

Transmitter	
Type	Klystron amplifier
Peak power	750 kWatts
Frequency	2875 to 2878 MHz
Pulse width	1 μs (short pulse) & 2 μs (long pulse)
Receiver	
Type	Double super heterodyne
Stable (First) local oscillator	2400 MHz
Second local oscillator	465,466,467, 468 MHz
Intermediate frequency	10 MHz
Noise figure	better than 1.5 dB
Minimum digitally detectable signal	–114 dBm in long pulse and –112 dBm in short pulse
Digital part of the receiver	
Band width	1 MHz in reflectivity & 0.5 MHz in velocity mode
A/D conversion	40 MHz, 12 bits
Signal processing	10 DSP chips (120MFLOPS/sec each)
Simultaneous output	Radar reflectivity, radial velocity and spectrum width
Minimum range bin spacing	75 m
Maximum number of range gates	2000
Dynamic range	Better than 95 dB
Beam width	1°
Scan parameters	
Range (km)	300
Resolution (m)	1000
Pulse	Short pulse (1 μs)
PRF 1	500 Hz
PRF 2	333 Hz
Antenna speed (^{o}/sec)	6
Samples processed	46
Clutter to Signal Ratio (CSR)	15 dB
Signal Quality Index (SQI)	0.35
Doppler filter notch width (m s^{-1})	1.2

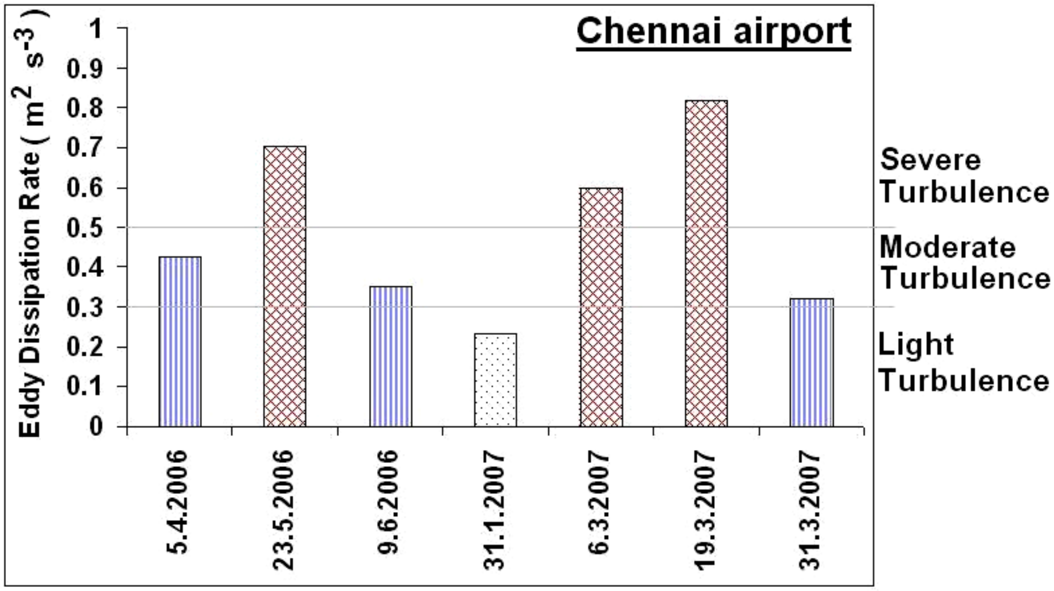


Fig. 3. Eddy dissipation rate as worked from spectrum width data of Doppler weather radar, Chennai for the aircraft reported moderate turbulence cases during January 2006 – April 2007

prepared for the moderate turbulence at the time of landing. Hence, in view of their concentration in safe landing operations information about the low level wind shear are often not passed on to the ATC. This sort of apprehension was earlier made by Suresh (2004). In order to devise a suitable low level wind shear alert/warning strategy, a solid data base of aircraft observed moderate turbulence is absolutely inevitable.

5.5. *Eddy dissipation rate*

ICAO (2007) envisages the observation and reporting of Eddy Dissipation Rate (EDR) by aircrafts (having facility to observed EDR) since the turbulence shall be observed in terms of EDR. Severe/moderate/light turbulence is often associated with EDR and Table 3 summarises the thresholds of EDR for reporting turbulence by the aircrews as suggested by ICAO. However, it may be mentioned that EDR is an aircraft-independent measure of turbulence but actual turbulence depends on factors like aircraft type, and the mass, altitude, configuration and airspeed of the aircraft.

Since turbulence is considered as isotropic, three dimensional turbulence can be deduced from spectrum width which is the fluctuation of radial velocities within the resolution volume (Doviak & Zrnic, 1984 and 1993; Brewster and Zrnic, 1986). According to these authors, error variance and quantization error variance in velocity estimation and the EDR can be calculated using the formulae given below.

Error variance in velocity

$$= \left(\frac{\lambda^2}{32\,\Pi^2 M \rho_e{}^2 T_s{}^2} \right) \left(\frac{(1-\rho_e{}^2)}{2\,\sigma_{vn}\sqrt{\Pi}} \right) \tag{9}$$

where

λ = Wave length of the radar = 0.1 m for Chennai DWR

M = Number of samples processed (46 in the present study).

$\rho_e{}^2$ = $e^{-4\Pi^2}\sigma_{vn}{}^2$ where σ_{vn} is the spectrum width normalized to twice the Nyquist velocity (*i.e.*, 2 $V_{\max}$)

T_s = Sample time spacing.

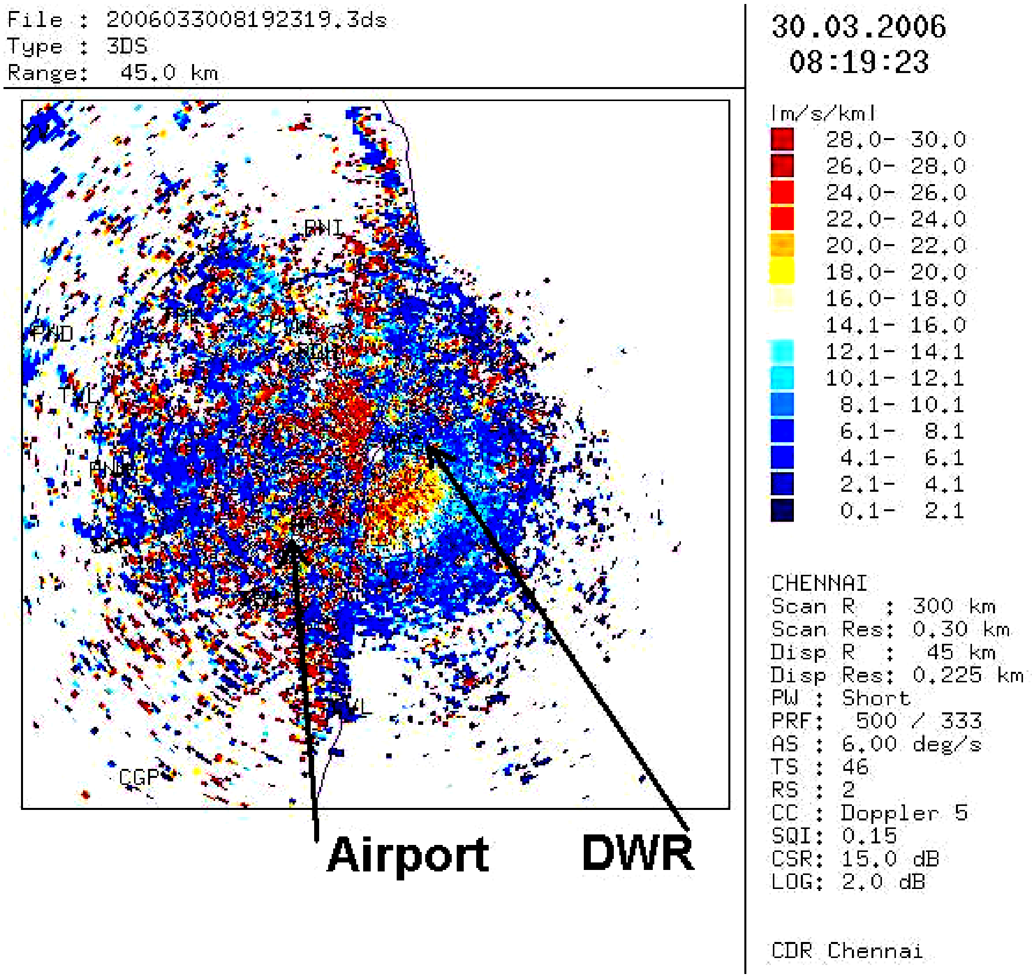


Fig. 4. Three dimensional shear of Chennai DWR at 0819 UTC on 30th March 2006. Chennai airport has been marked as MO and Chennai DWR has been marked as MDS

$$\text{Quantisation error variance} = \left(\frac{1}{12}\right)\left(\frac{2V_n}{2^n}\right)^2 \qquad (10)$$

where V_n is the Nyquist velocity and n is the number of bits used for data storage (in digital signal processing).

$$\text{EDR } (\epsilon) = \frac{0.72\sigma_t^{\,3}}{r\sigma_\theta A^{3/2}} \qquad (11)$$

Where σ_t is the spectrum width which can be obtained from $\sigma_t^{\,2} = \sigma_v^{\,2} - \sigma_s^{\,2}$ where σ_v is the measured spectrum width and σ_s is the contribution due to shear.

r is the range (bin size for the EDR),

A is a non-dimensional constant = 1.6 (Gossard and Strauch, 1983)

$\sigma_\theta^{\,2}$ is the second central moment of two-way radiation pattern and is defined as $\sigma_\theta^{\,2} = \theta^2 / 16 \ln 2$ where θ is the beam width (1° for Chennai DWR).

Error variance in velocity estimation through pulse pair algorithm has been worked out from the spectrum width data obtained from the Chennai DWR (located at about 16 km northeast of Chennai airport) for 30 minutes prior to and 30 minutes later than the reported timings of seven incidences of moderate turbulence. The radar uses hard-wired pulse pair algorithm to estimate radial velocity and spectrum width. Technical details of the scan from which the data has been used for this study has been mentioned in Table 4. The error variance thus computed

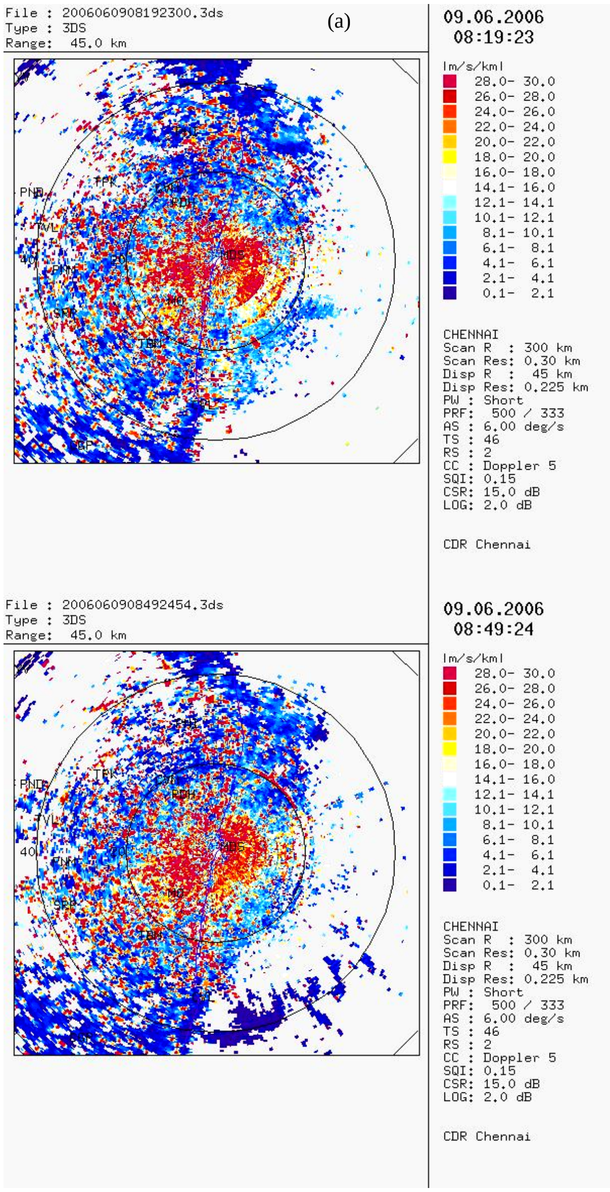


Fig. 5(a). Three dimensional shear product of Chennai DWR at 0819 and 0849 UTC on 9th June 2006. Chennai airport has been marked as MO (about 16 km southwest of Chennai DWR marked as MDS in the above figure)

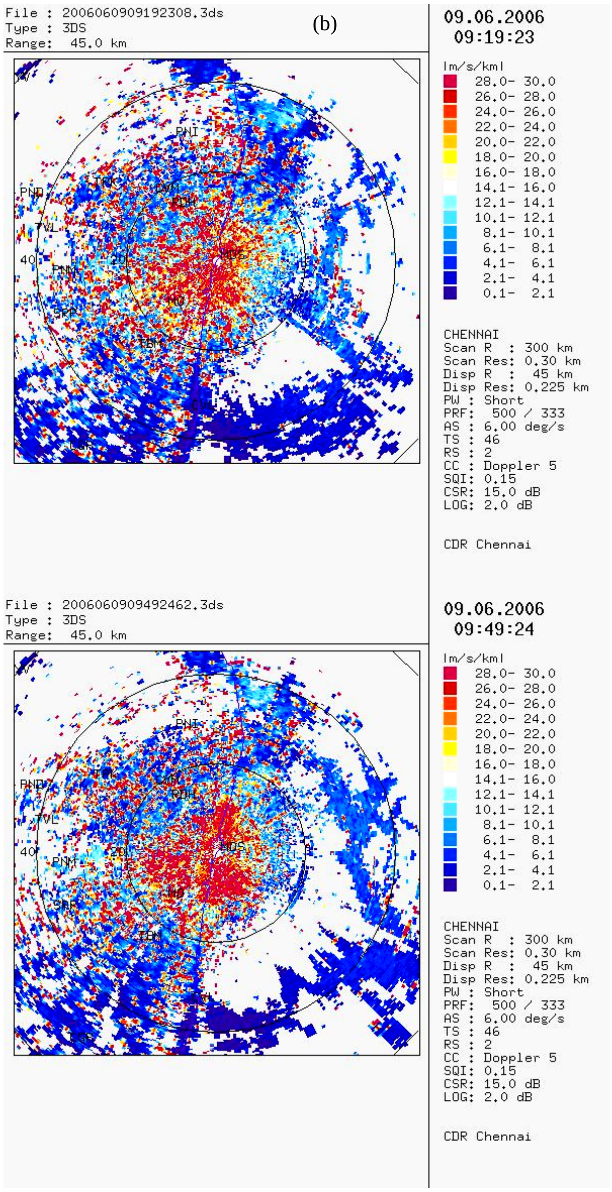


Fig. 5(b). Same as in Fig 5(a) but for the time period 0919 and 0949 UTC

for these seven cases were varying between 0.02 and 0.07 m^2 s^{-2} which is well within the limits computed by Brewster and Zrnic (1986). The quantization error variance with 8 bit data and maximum Nyquist velocity of 30 ms^{-1} (corresponding to 1200 Hz pulse repetition frequency) is very low at 0.0045 m^2 s^{-2} thus certifying the veracity of velocity and spectrum width estimation through the hard-wired pulse pair algorithm.

Spectrum width due to shear (σ_s) will be at the maximum of 0.5 ms^{-1} if the shear is less than 0.01 s^{-1} and for severe storms with higher shear, it is of the order of 1 to 2 ms^{-1} (Brewster and Zrnic, 1986). Shear value was computed either based on aircraft reported winds or from the latest conventional RS/RW or Pilot Balloon observations. Hence, depending on wind shear, 0.5 to 1 ms^{-1} has been removed from the measured spectrum width in this paper as suggested by (Brewster and Zrnic, 1986) and EDR has been computed for all the seven cases.

Fig. 3 depicts the values of EDR alongwith threshold limits for severe, moderate and light turbulence. Three out of seven cases reported by the aircrews appear to have been of severe turbulence category, three were of moderate turbulence and one in light turbulence category based on ICAO (2007). But, all the seven cases were reported by the aircrews simply as 'wind shear and turbulence'. As none of the aircraft either reported the turbulence index corresponding to EDR or the EDR value itself, it is very difficult to verify the intensity of the turbulence reported by the aircrafts. Nonetheless, it is clear that the DWR measured spectrum width data can be used as a tool to identify the intensity of turbulence as the spectrum width data used for computation of EDR has successfully predicted the aircraft reported turbulence incidences. The lowest spectrum width was 3.2 ms^{-1} on 31st January 2007 and the highest was 4.6 ms^{-1} on 19th March 2007. It may be mentioned here that both these cases were not associated with any convective cloud development. Spectrum width of more than 4 ms^{-1} is associated with severe turbulence and more than 3 ms^{-1} is associated with moderate turbulence (Wilson *et al.*, 1984). These thresholds also confirm the predictability of turbulence through EDR.

6. Turbulence based on 3DS obtained from DWR

In order to verify the utility of 3DS product from the Chennai DWR, in continuation of work done by Suresh (2004), the 3DS product was collected from DWR Chennai almost on real time basis through dial-up connection based file transfer protocol (ftp) utility during the period January 2006 – June 2006. Though the DWR 3DS product was indicating the possibility of turbulence (with 3DS in excess of 24 ms^{-1} km^{-1} on many occasions), not even a single aircraft reported the turbulence experienced by them. As discussed earlier, the pilots might have considered there was no necessity to inform the ATC as the turbulence over Chennai airfield is almost a regular phenomenon and/or in view of their concentration in safe landing they might have forgotten, by oversight, to inform ATC about the turbulence experienced by them. Hence, using the wind observation reported by the aircrafts we computed the wind shear and then correlated the computed wind shear with the 3DS product. In all the cases, we found that 3DS was in excess of the threshold 16 ms^{-1} km^{-1} when the computed wind shear from aircraft reported winds was more than 0.00967 s^{-1} indicating moderate turbulence. A few cases of interest have been discussed in this section.

6.1. *Shear on 30th March 2006*

Based on repeated instructions from ROC (as mentioned in section 4 above), an Indian Airlines aircraft at 0824 UTC/30th March 2006 reported wind at 1000ft (300 m) as 140/11kt and wind at 1800ft (540 m) as 220/06 kt. If we simply take scalar wind shear $\left(\frac{dV}{dz}\right)$, it works out to $10.7 * 10^{-3}$ s^{-1} whereas the vector wind shear we have used in this paper, *viz.*, $\sqrt{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2}$ works

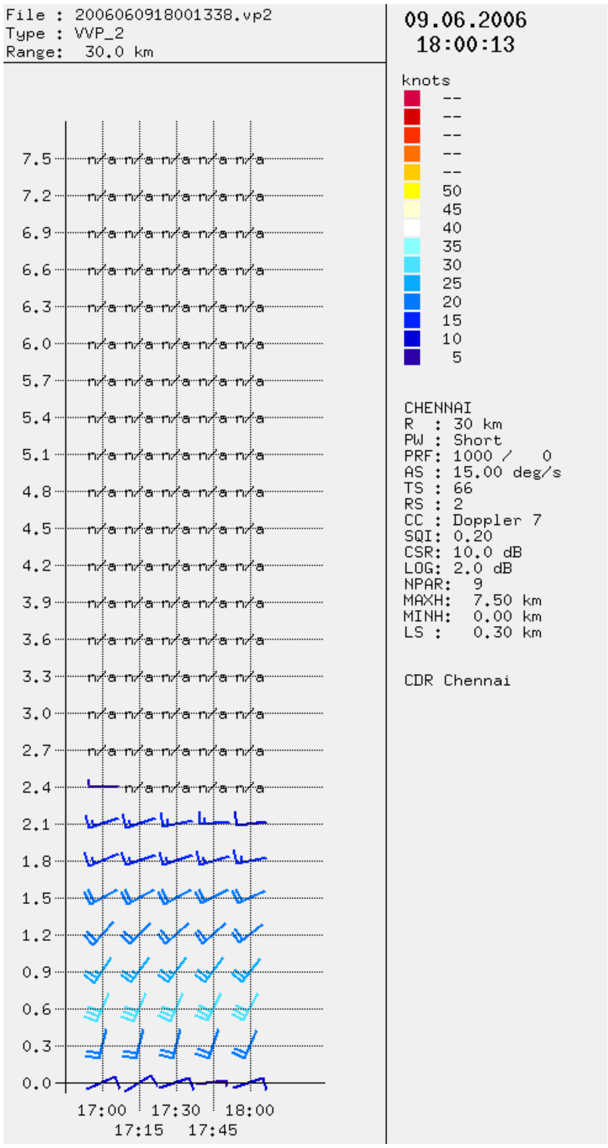


Fig. 6. Vertical time section plot of horizontal estimated from radial winds from 1700 to 1800 UTC on 9th June 2006 through Waldteufel and Corbin (1979)'s volume velocity processing algorithm

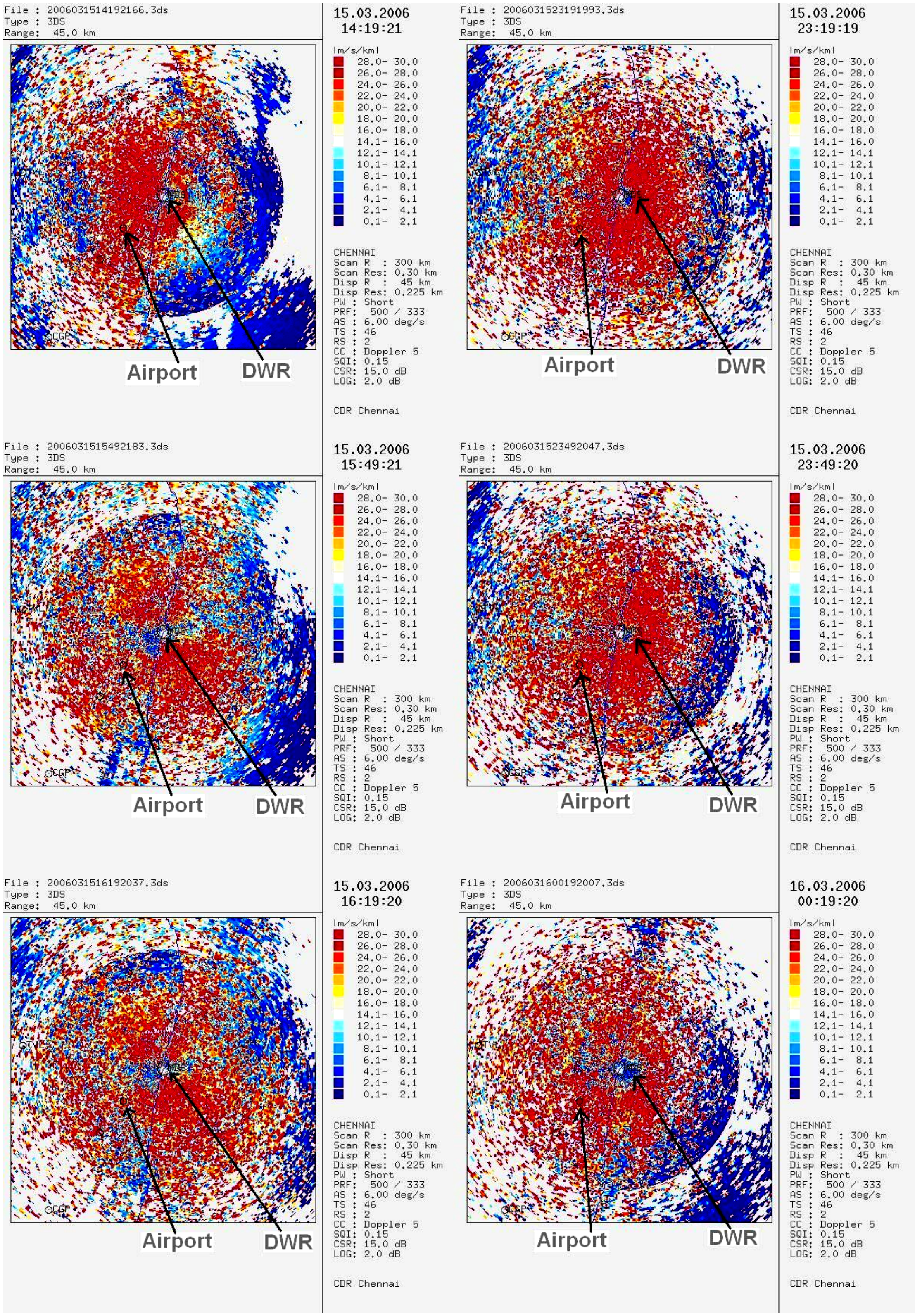


Fig. 7. Panoramic images of 3DS product displays from 1419 UTC/15th March to 0019 UTC/16th March 2006. DWR location has been marked as MDS and the airport location has been encircled in the figure

out 23.7 * 10^{-3} s^{-1}. This high magnitude of shear is because of additive effect of zonal wind components between these levels in view of crossing 180° (cross wind component) as mentioned in section 5.4.

Horizontal winds at those levels as estimated by DWR at 0819 UTC scan were 160/10 kt and 180/05 kt respectively. The vector wind shear was 7.42 * 10^{-3} s^{-1}. One may observe that though there is no appreciable difference in wind speed, there is a difference of 20° at 300 m and 40° at 600 m in wind direction between aircraft measured and DWR estimated winds. This sort of difference is quite understandable in view of the fact the wind estimated by DWR is based on thousands of range bin samples in a 30 km radius circle whereas the aircraft measured wind is instantaneous. Hence, the wind shear computed from estimated DWR winds, with certain amount of variability within the sample in this particular case, is smaller than that obtained from aircraft measured winds. In this particular case the aircrew reported vaguely as 'wind shear turbulence' and aircraft wind observation supported severe turbulence whereas shear based on horizontal estimation of wind from radial wind did not indicate even moderate turbulence. Hence we looked into the 3DS product which is derived directly from radial wind data. Fig. 4 depicts 3DS at 0819 UTC, five minutes prior to wind reported by the aircraft. Along the RWY orientation (RWY 07/25), 3DS values were in excess of 24 ms^{-1} km^{-1} which suggest that atleast moderate turbulence was very much feasible as this magnitude is much higher than the threshold of 16 m s^{-1} km^{-1} suggested by Suresh (2004). It may also be seen that the computed vector wind shear from aircraft reported winds at two different heights (23.7 * 10^{-3} s^{-1}) and 3DS computed from radial velocity data (24.0 * 10^{-3} s^{-1}) are in perfect agreement with each other.

6.2. *Shear on 9th June 2006*

Moderate wind shear was reported over RWY25 at 0939 UTC by a Lufthansa flight. However, the aircrew had not reported winds at any level. The 3DS was more than 20 * 10^{-3} s^{-1} at 0649 UTC, reduced to little more than 16 * 10^{-3} s^{-1} at 0719 UTC and further dropped to less than 16 * 10^{-3} s^{-1}at 0749 UTC. From 0819 UTC, the 3DS was well above 24 * 10^{-3} s^{-1} indicating moderate to severe wind shear induced turbulence over Chennai airport. Figs. 5(a&b) show the 3DS product display from 0819 to 0949 UTC. Thus, the 3DS product has predicted the turbulence in this case as well. Continuous monitoring of the product on the rest of the day indicated the value of 3DS over Chennai airport was varying between 12 and 26 * 10^{-3} s^{-1}. This indicated that the shear induced turbulence and atmospheric instability (due to convective currents) are not uncommon over Chennai during southwest monsoon season.

Later on this day at late night, at 1804 UTC Thai Airlines had reported wind at 1000 ft as 193/23 kt and at 1800 ft as 210/25 kt. The DWR estimated horizontal winds at 1800 UTC were 200/21 and 210/28 kt respectively. Fig. 6 shows the vertical time section plot of horizontal wind estimated through Waldteufel and Corbin (1979)'s VVP algorithm as mentioned in section 2.2. Both aircraft measured and DWR estimated winds confirm the moderate turbulence identified by the 3DS product.

6.3. *Wind shear on 15th March 2006*

An interesting case of wind shear induced turbulence was from 1419 UTC on 15th March 2006 which continued upto early morning of 16th. Indian Airlines aircrafts at 1038 UTC and 1631 UTC on 15th and 0029 UTC on 16th reported winds at 1000 ft and 1800 ft. Wind shear on these time periods were more than the moderate turbulence threshold described earlier. DWR estimated winds at 1030 and 1630 UTC also confirmed the presence of wind shear. The 3DS product has been displayed as a panoramic view in Fig. 7 from 1419 UTC/15th to 0019 UTC/16th. DWR revealed the presence of moderate turbulence over Chennai airport but none of the aircrafts reported turbulence but for the above three wind reports and that too just for complying with the recommendations of ROC meetings as stated earlier in this paper in section 4. It may be stated here that there were as many as 62 landing operations during the time interval stated above. A later discussion with operations people and with some of the aircrews of different airlines confirmed that there was moderate to severe turbulence but all the pilots were habituated with this sort of turbulence on some days over Chennai and their concentration was to have a safe landing and subsequent take-off operations from Chennai airfield in limited time span and hence there was no time even to de-brief.

A similar long duration wind shear incidence of more than 10 hrs was earlier observed over Chennai airport on 23/24 May 2006 (Suresh, 2008, personal communication) wherein only one aircraft (M/s Air India) reported the observation of turbulence. These cases were brought to the notice of air line operators and the necessity of in-flight/debriefing report on wind shear/turbulence was once again stressed. The necessity of feedback/in-flight report or de-briefing is inevitable to fine tune the 3DS threshold already arrived at by Suresh (2004) based on some eight incidences of reported wind shears and also to validate future incidences. However, aircrews are repeatedly intimating that in view of limited time available to them between two operations (in view of heavy competition in the aviation industry during the present days), they are unable to report to ATC due to their primary concentration on safe landing and take-off operations. Nonetheless, pending the reception of vast data base for fine tuning the 3DS value, the current 3DS threshold (*viz.*, $16 * 10^{-3}$ s^{-1}) may be used by the forecasters to issue low level wind shear alert over Chennai airport as its predictability is quite good.

7. Summary and conclusions

In the absence of full fledged/efficient Low Level Wind Shear (LLWS) alert system, the in-flight reports by aircrews serve as a vital database to issue wind shear alerts. Aircrews have been impressed upon that the in-flight report on LLWS will be quite beneficial for the aviation community and they were periodically requested to pass on this vital information to air traffic controllers at the earliest possible time on observing these phenomenon. They were briefed about similar attempts made at Heathrow airport (Roach, 1981) and subsequent tangible benefits. With the available aircraft measured winds at 1000 and 1800 ft and windshear/turbulence reports, albeit small, the following broad conclusions have been arrived at from this study.

(*i*) There is a good agreement between the aircraft wind observations and winds estimated using DWR data despite the limitation that aircraft measurement is instantaneous and the estimation from DWR measured radial wind is based on certain assumptions and representative of a large number range bin samples.

(*ii*) The wind direction as observed by aircraft and as estimated by DWR are matching well (73% cases at 600 m and 77% at 300 m) with the RS/RW observations. However, wide variation in wind speed could be noticed between aircraft and RS/RW observations, especially close to 1200 UTC.

(*iii*) Aircraft measured winds and DWR measurements indicate a number of wind shear induced turbulence over Chennai airport but the aircrews have not reported the same through air traffic controllers (ATC). Though the aircrews have latter confirmed that wind shear induced turbulence are quite frequent and regular phenomenon over Chennai airport, concentration in safe landing and paucity of time are quoted as reasons for not reporting the wind shear information to ATC.

(*iv*) The DWR measured spectrum width data can be used as a tool to identify the intensity of turbulence. Eddy dissipation rate (EDR) computed from the spectrum width data has successfully predicted the aircraft reported turbulence incidences.

(*v*) There is a good agreement between the computed vector wind shear from aircraft reported winds at two different heights and three dimensional shear computed from radial velocity data.

(*vi*) In contrary to general belief that the wind shear is a short lived phenomenon, wind shear induced moderate turbulence has been found active for more than 10 hrs over Chennai air field.

(*vii*) Three dimensional shear value of more than $16 * 10^{-3}$ s^{-1} may be used by the forecasters to issue low level wind shear alert over Chennai airport as its predictability is quite good.

(*viii*) For operational use, wind at a particular level can be estimated from the wind at another level in the boundary layer over Chennai airport using

$$\frac{V_H}{V_L} = \left(\frac{Z_H}{Z_L}\right)^{0.6} \quad \text{for unstable atmospheric conditions}$$

$$\frac{V_H}{V_L} = \left(\frac{Z_H}{Z_L}\right)^{-0.5} \quad \text{for stable atmospheric conditions.}$$

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