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On nowcasting wind shear induced turbulence over Chennai air field

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सार – अक्तूबर 2001 में चेन्नै के चक्रवात संसूचन रेडार केन्द्र में लगाए गए नए डाप्लर मौसम रेडार के माध्यम से, हवाई जहाजों के उतरने और उड़ान भरने के समय हवाई पट्टी के उपमार्ग में पायलटों द्वारा अनुभव की गई पवन अपरूपण से उत्पन्न प्रक्षोभ के लिए मौसम विज्ञान की प्रेरक परिस्थितियों का विश्लेषण करना संभव हो पाया है। यह रेडार 21 फरवरी 2002 से कार्य कर रहा है। इस अध्ययन में फरवरी से अक्तूबर 2002 के दौरान के पवन अपरूपण का समीक्षात्मक विश्लेषण किया गया है। त्रिज्य, दिगंशीय और उच्चता अपरूपण के संयोजन वाले त्रिविमीय अपरूपण (3 डी.एस.), सामान्य प्रक्षोभ अपरूपण की घटना जब इस का मान 16 एम.पी.एस. / कि.मी. से अधिक हो जाता है, इससे कम से कम आधा घंटा पूर्व सीधी सूचना देते हैं। 20 एम.पी.एस. / कि.मी. से अधिक के 3 डी.एस. प्रायः पायलटों द्वारा अनुभव किए गए प्रक्षोभों से संबद्ध होते हैं। अत्याधुनिक और व्यापक परिकलन क्षमता की उपलब्धता से अब सतह का वर्णन करना संभव हो सका है जिस पर अपरूपण तीव्रता से परिकलित उच्चता / उर्ध्वाधर / त्रिज्य / दिगंशीय आदि से रेडार से मापे गए आँकड़ों की मात्रा के प्राप्त होने से 3–5 मिनट में सक्रिया हो जाता है। तथापि पवन अपरूपण प्रेरक प्रक्षोभ के लिए सहायक अपरूपणों के थ्रेश होल्ड मानों के सार्थक निष्कर्ष पर पहुँचने के लिए और पायलटों को सचेत करने के लिए इस सूचना के उपयोग हेतु विस्तृत डाटा बेस बनाने के लिए पायलटों से सूचना प्राप्त करना अत्यंत अनिवार्य है। पवन अपरूपण चेतावनियाँ जारी करने के लिए समुद्री हवा के रूख का मानीटरन करना भी उपयोगी हो सकता है। हवाई अड्डे के आसपास अपरूपण से उत्पन्न होने वाले प्रक्षोभ की संभावित प्रागुक्ति के लिए समय परीक्षित रिचर्डसन संख्या की भी जाँच की गई है जबकि प्रक्षोभ के सक्रिय होने के निश्चित स्थान और समय को सही–सही बताया नहीं जा सकता है। यह आशा की जाती है कि पायलटों द्वारा अनुभव किए गए पवन अपरूपण के संबंध में संक्षिप्त, सही और समयानुसार उड़ान की रिपोर्ट और ऐसी प्राप्त की गई सूचना के विश्लेषण के दौरान हुए अनुभव के आधार पर निकट भविष्य में संभावित पवन अपरूपण के बारे में सतर्क / चेतावनी जारी करना संभव होगा।

ABSTRACT. With the newly installed Doppler Weather Radar at Cyclone Detection Radar station, Chennai during October 2001, it has been made possible to analyse the meteorological conditions conducive for the wind shear induced turbulence experienced by the pilots in the approach runway at the time of landing and take-off. The radar has been put into operation *w.e.f.* 21 February, 2002. Wind shears reported during February – October 2002, have been critically analysed in this study. The three dimensional shear (3DS), a combination of radial, azimuthal and elevation shears, gives a first hand information atleast half an hour before the occurrence of shear induced moderate turbulence when its value exceeds 16mps/km. The 3DS of more than 20mps/km is normally associated with turbulence experienced by the pilots. With the availability of sophisticated and vast computing power, it is now possible to delineate the layer at which the shear is active within 3-5 minutes from the receipt of the radar measured volume data by quickly computing elevation / vertical / radial / azimuthal shear etc. However, to arrive at a meaningful conclusion on the threshold values of shears that are conducive for wind shear induced turbulence and to make use of this information to alert the pilots, feed back from the pilots to build a detailed data base is absolutely inevitable. Monitoring of passage of sea breeze front may also be useful to issue wind shear warnings. The time tested Richardson number has also been verified for its 'outlook predictability' of the shear induced turbulence around the airport, though it can not pinpoint the exact location and the time at which turbulence is active. It is hoped that with precise, accurate and timely in-flight report about the wind shear experienced by the pilots and based on the experience gained in analyzing such information, it will be possible to issue probable 'wind shear alert / warning' in the near future.

Key words – Doppler Weather Radar, Wind shear, Turbulence, Richardson number, Aviation, Three dimensional shear, Elevation shear, Vertical shear, Radial shear, Sea breeze.

1. Introduction

The World war II, despite its political and sociological impacts, contributed two important technological advancements to the mankind, one, in the fields of the aviation industry and two, the utility of radar for weather observations. Since most of the aviation hazards have been related to the thunderstorm, the first advanced field experiment called the "Thunderstorm Project" was conducted in the year 1946 in Florida with the help of radars that were capable of observing thunderstorms. The discovery of downdraft was one of the major findings of the thunderstorm project (Fujita, 1990). Since the aviation hazards due to bad weather could be observed by the radar at a space and time resolution very much desirable to avert the aircraft incidents and accidents, the radar observation is considered as prophylactic and assumes the greatest significance in aviation industry for the safe aircraft operations.

Lee and Beckwith (1981) has excellently documented the aviation hazards such as wind shear, thunderstorm, precipitation, line squall, turbulence, gust front and microburst etc. Information relating to these weather hazards besides the wind and shear information at different levels make the radar usage both in operational and in research mode during the past four decades, specifically after the late 1970s. Fujita and Caracena (1977) and Fujita (1980) have documented that wind shear at the time of take-off or landing was the main cause for a number of aircraft accidents. In most of the cases they studied, the wind shear was associated with strong down drafts from thunderstorms. The wind shear can be found out in the downdraft on all sides of a thunderstorm cell and the gust front may precede the actual storm by even 15 nautical miles or so [Federal Aviation Administration (FAA), 1979]. For aviation purposes, wind shear is described as an abrupt change in wind direction and/or speed in very small spatial scale in the atmosphere. According to International Civil Aviation Organisation (ICAO, 1983), wind shear of magnitude as high as $417 \times 10^{-3}\ s^{-1}$ (25mps in the first 60m a.g.l) have been observed and the atmosphere is capable of producing such a very strong vertical shear very close to the ground. These strong shears are often associated with gust front from thunderstorms. Airplanes may not be capable of safely penetrating all intensities of low level wind shear and hence the pilot should know to detect, predict and to avoid the severe wind shear conditions. In view of availability of ample space and time, an aircraft can recover from the loss of altitude due to strong shears encountered at higher altitudes. However similar magnitude of wind shear when encountered in the lower atmosphere results in considerable loss of altitude leading to aircraft incidents/ accidents. Hence a pilot accords much importance to low level wind shear rather than the wind shear at higher levels albeit he avoids it at all levels for a safe and smooth air navigation.

The life time of the shear is very minimum (say a maximum of few minutes) but its catastrophic effect is very high. Such a short lived shear can be deducted by a Doppler Weather Radar (DWR) probing the atmosphere continuously. In the absence of a DWR, a study on wind shear aspects around Chennai airport was not made possible till late 2001. The technical details of newly installed DWR, in replacement of outlived analogue S-band radar at Cyclone Detection Radar (CDR) station, Chennai during October 2001 is given in Annexure I. The CDR (labeled as MDS in Figures) is located at 16 km northeast of the Chennai airport (labeled as MO in Figures). The DWR was operated continuously from 31 October, 2001 to understand the functionalities of the state-of-the art DWR (such as velocity unfolding upto four times, frequency agility and second trip recovery) in different scan strategies. Typical 250 km scan strategies with single pulse repetition frequency (PRF) and dual PRF mode adopted during the period 1 November 2001 – July 2002, to gain an insight of DWR concept – as a first time experience, are given in Annexure II. The abbreviation/ contracted forms of the various scan parameters that are used in the legend of the product displays have been mentioned in the Annexure II. In this paper, a diagnostic study has been made on a few wind shear observations reported by the airline operators during February – October 2002 with a view to nowcast [nowcasting is described by Browning (1982) as the description of current weather and extrapolation upto 2hours] the shear induced turbulence over Chennai airport.

2. Data and methodology

Information about wind shear is known to the aviation industry and to the airport meteorological office only when it is reported by the pilot either as an in-flight report to the Air Traffic Controller (ATC) or by way of de-briefing the Meteorological Office (MO). In the absence of such a report, it may not be possible to know about the wind shear that was prevailing at any height above ground. Since the turbulence is the manifestation of static stability and kinetic energy in the atmosphere and the kinetic energy is governed by the velocity gradient, wind shear assumes importance as it induces turbulence. Turbulence in association with cloud or clear air is unsafe for the air navigation. Hence, to attempt a diagnostic study about the meteorological conditions that are favourable for causing the wind shear with an end view to device a method to alert the aircrews, pilot's precise and prompt report about the wind shear condition is absolutely inevitable. In this paper, four such incidences

TABLE 1

Comparison of mean horizontal winds (dddff, ff in mps) measured by Pilot balloon and RS/RW and that derived from DWR, Chennai during February – March 2002

Height (m)	Data	0000 UTC		0600 UTC		1200 UTC		1800 UTC	
		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Surface	RS/RW	31701	21402	08502	20903	09407	19804	11202	22303
	DWR	27905	23106	01004	23703	04801	22406	06002	21507
300m	RS/RW	10101	21705	07106	23002	09008	20305	08609	20606
	DWR	15603	21206	06505	20501	09007	20206	09105	21006
600m	RS/RW	10204	22004	07405	20303	08606	20905	08510	22905
	DWR	14806	21105	07006	22603	09206	21106	09206	22805
900m	RS/RW	10607	23505	08607	2203	08406	21506	08810	23406
	DWR	13406	23405	10105	22905	09904	22705	09704	22406
1500m	RS/RW	09411	23106	09213	22003	08108	21806	09011	22509
	DWR	10606	21804	11004	19602	08404	21005	08103	21707
2100m	RS/RW	07912	22608	09512	22605	07610	22307	08812	23109
	DWR	09405	21406	09808	24708	08405	22507	12604	22407
3100m	RS/RW	06711	23311	09207	21706	05309	22609	07109	23010
	DWR	07305	23807	12402	21105	06005	22407	08405	22206

reported by the pilots through ATC, Meenambakkam airport, Chennai (located at 16km in 233° azimuth from the DWR) during May – October 2002 have been studied. Radial velocity data obtained from DWR, Chennai and temperature and wind data in the lower atmosphere from Radio Sonde/Radio Wind observatory, Chennai (located very close to the airport) have been used to analyse the meteorological conditions that were conducive for shear induced turbulence and also to find out pre-cursors, if any, available so that such pre-cursors can be used to alert the air crews in future. Climatological Tables of Radio Sonde published by India Meteorological Department (IMD) for the period 1971-80 have been consulted to have an overall idea about the atmospheric stability that would normally prevail in the lower atmosphere and also for comparing the results obtained from the current RS/RW data to identify significant changes, if any.

2.1. *Velocity variance*

When a pulse radar samples a volume, if there is a difference (which normally happens in an unstable atmosphere) in velocity between bottom and top of the volume being sampled, there will be a velocity variance in the volume sampled. The wind shear estimated from a DWR is the spatial gradient of wind velocity between a pair of points within the same sample volume. In other words, the wind shear can be computed in radial, azimuthal and vertical directions. Hence the sum of variances in radial, azimuthal and vertical directions contributes to the shear induced velocity variance of the sample volume considered. Gust fronts arise out of velocity variance. Variance of the radial velocity (V) is predominantly a measure of wind shear and turbulence (Rinehart, 1999). Doppler velocity spectral width (W) is often considered as an indicator of turbulence. According to Wilson and Wilk (1982) when the spectrum width exceeds 4mps, there is 95% chance for turbulence. However, it has been well documented by Rinehart (1999) that the wind shear between layers may produce strong spectrum width, yet turbulence may not be present. Hence, it is desirable to estimate various shears from the radial velocity measured by the DWR to correlate with the shear reported by the pilots rather than concentrating on the spectrum width.

Since a DWR can measure only the radial velocity (*i.e.*, the velocity component of the prevailing wind, either moving towards or away from the radar), the prevailing wind at different levels can be deduced by using standard algorithms proposed by Lhermitte and Atlas (1961), Browning and Wexler (1968) and Waldteufel and Corbin (1979). However, these algorithms assume that the wind field as uniform and estimate the prevailing wind from a single DWR data. Table 1 summarises the mean horizontal wind measured by Pilot Balloon and RS/RW ascents released by Meteorological Observatory (MO), Chennai and that estimated by DWR, Chennai during February – March 2002. The bias in the direction of the prevailing wind was within ± 30°, and the speed within ± 3mps, when the atmospheric condition was almost stable. Nevertheless, since it is expected that the variability between the prevailing wind and radial wind will be uniformly seen at all levels, the difference between the shear computed from prevailing wind and that derived from DWR may be quite negligible. More over, as the upper wind observations are taken only at a few stations and that too with six hourly periodicity for Pilot Balloon and twelve hourly periodicity for RS/RW, shears derived from DWR data have been used by the aviation community throughout the world in view of its high spatio-temporal resolution and frequent and timely availability.

2.2. *Shear products from Doppler weather radar*

The various types of shear products that can be derived from volume scan of a DWR are briefly outlined here. By shear we mean the change in wind velocity in radial or azimuthal or elevation directions or in a combination of some of these directions. The following are the shear products available with the DWR, Chennai.

Radial Shear (RDS) : Derivative of wind in the radial direction.

Azimuthal Shear (AZS) : Derivative of wind in azimuthal direction.

Elevation Shear (ELS) : Absolute change of wind in elevation direction is calculated by considering data of one elevation above and one elevation below the selected elevation. If the selected elevation exactly matches with one of the volume scan elevations, then the elevation just above the selected elevation is considered for computing shear.

Radial Azimuthal Shear (RAS) : The RDS and AZS are computed for each bin. The resultant shear is worked out by taking square root of the squared radial and squared azimuthal shear values.

(*i.e*) $\text{RAS} = (\text{Radial shear}^2 + \text{Azimuthal shear}^2)^{0.5}$

Radial Elevation Shear (RES) : By considering one elevation above and one elevation below the selected elevation, RDS and ELS are computed and the RES is computed as done for RAS.

$\text{RES} = (\text{Radial shear}^2 + \text{Elevation shear}^2)^{0.5}$

Three Dimensional Shear (3DS) : Radial, azimuthal and elevation shears are computed for each bin and 3DS is calculated by the formula,

$\text{3DS} = (\text{Radial shear}^2 + \text{Azimuthal shear}^2 + \text{Elevation shear}^2)^{0.5}$.

Starting from 125 m, with a vertical layer spacing of 250 m, the polar data set is converted into Cartesian data set. Thus each vertical column of Cartesian grid has a number of layers with 250 m spacing. The maximum value in each vertical column is identified and displayed in a top projection image. Since most pilots are concerned about the impact of wind shear in the lowest layer of the atmosphere (*i.e*, while taking off or landing), the highest layer was set to 1.5 km initially. However, based on the user requirements, the height of the highest layer has been brought down to 0.8 km with effect from August 2002. This display helps one to quickly identify the maximum shear value over a region of interest from 0.125 to 1.5 km a.g.l (or 0.8 km, as the case may be) and further identification of azimuthal / elevation / radial shear which contributed to this shear need to be done based on computation of all other shears or through any other available information.

Horizontal Shear (HZS) : The change of wind velocity in north-south (NS) and east-west (EW) directions have been calculated and the resultant is worked out using the formula

$\text{HZS} = (\text{NS shear}^2 + \text{EW shear}^2)^{0.5}$.

Vertical Shear (VCS) : The absolute difference between velocities of two user defined layers is computed and displayed in a constant altitude type PPI.

The radial velocity and the spectrum width data have been analysed critically based on the earlier works done elsewhere with DWR data. All the shear products have been computed to find out the threshold values which can act as a pre-cursor to nowcast such a short lived meteorological phenomenon.

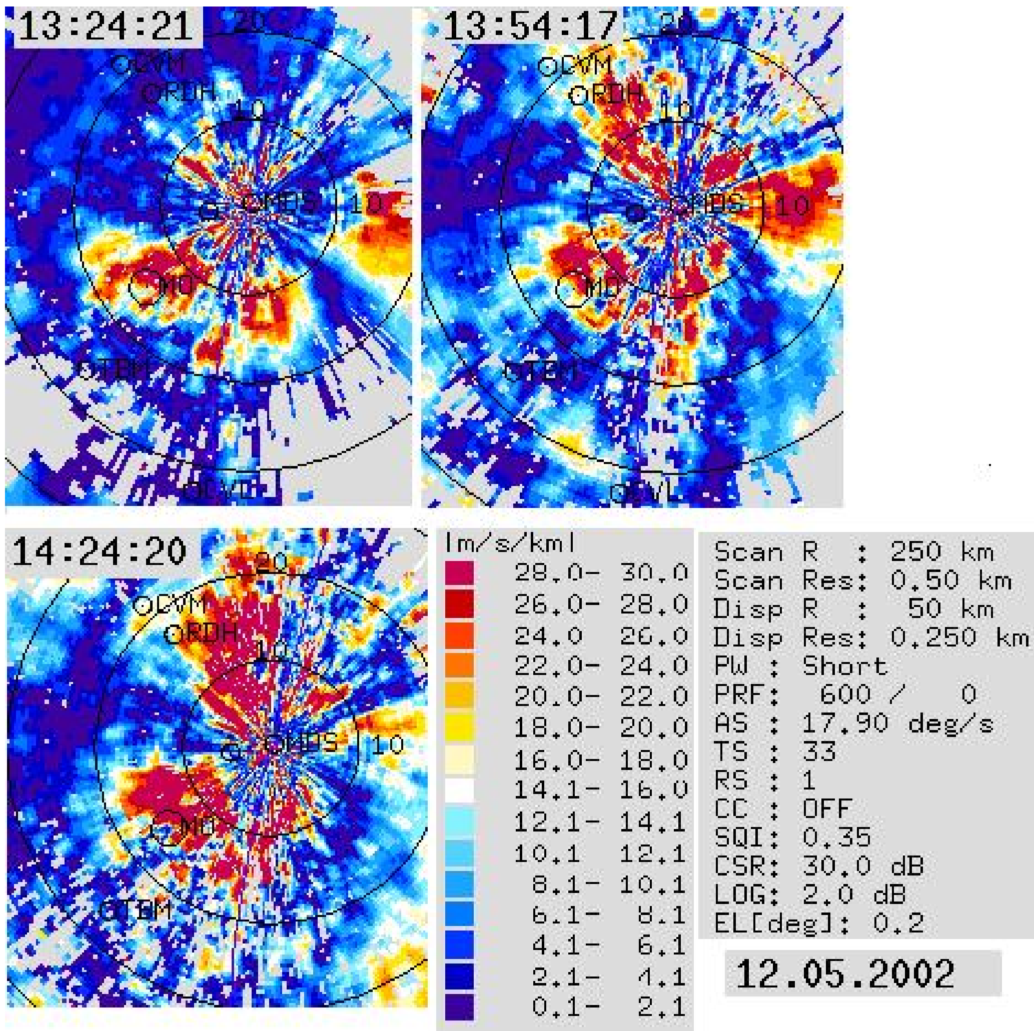

Fig. 1. Plan Position Indicator (PPI) display of elevation shear at 0.2° elevation from 1324 to 1424 UTC on 12 May 2002. Range rings are placed at 10 km interval

3. Wind shear case studies from DWR, Chennai

The term 'wind shear' has been ascribed by aviation community to describe the effect of three dimensional wind variation changing the airspeed of the aircraft which poses problem to the aircrews in handling the aircraft at lower levels. For the meteorological community, the structure of wind variations that causes the shear induced turbulence, though a very short lived phenomenon, is of more concern. Hence, throughout this study by wind shear we mean the shear induced turbulence experienced by the pilot. Though the radar was continuously operated from 31 October, 2001 in test mode – during installation and commissioning phase, the radar was put into operational use *w.e.f.* 21 February 2002. During this period all the airline offices have been informed about this new facility through the aviation meteorological office, Meenambakkam airport, Chennai with a request to pass on the information about the wind shear, if any, experienced by the pilots immediately to facilitate analysis of the dynamical parameters conducive for causing such a shear. However, only six cases were reported from February to October 2002. Out of six cases, on two occasions radar data was not available for analysis due to the fact that the radar was under maintenance during the said period. Hence, only four wind shear cases are considered in this study for analysis. Two more cases have been reported from January 2003 to May 2003 and the results of these cases are presented in this paper in section 5 as recent wind shear cases.

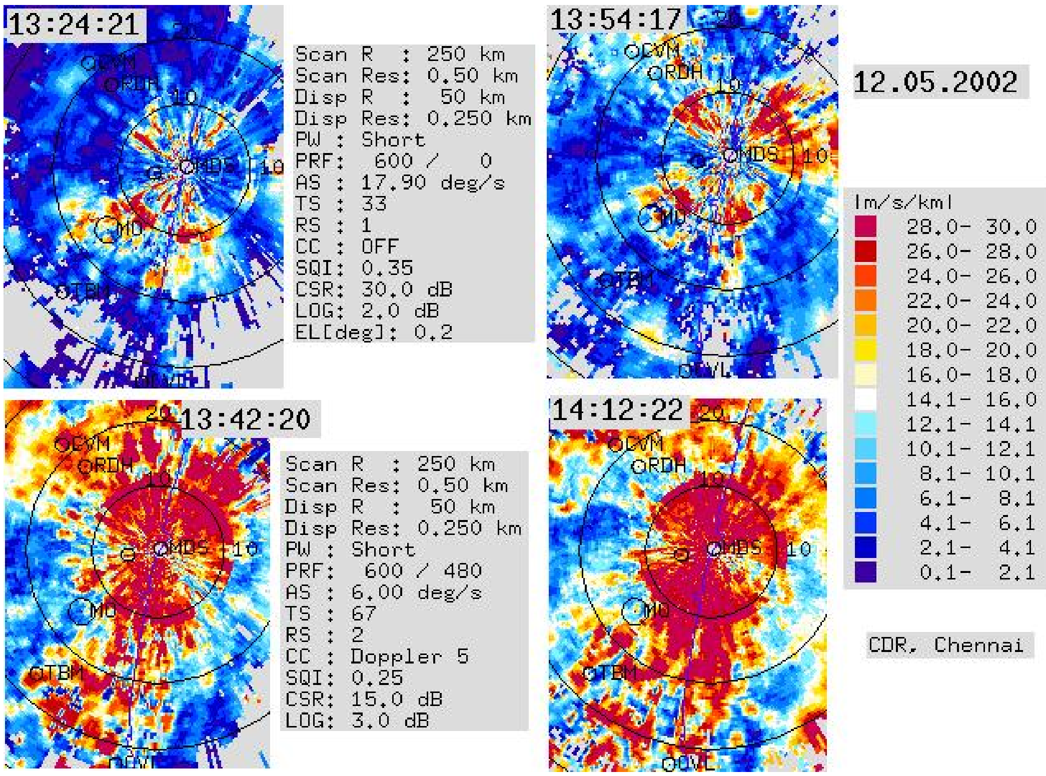

Fig. 2. Three dimensional shear display during 1324 – 1412 UTC on 12 May 2002. Range markers are 10 km apart. Scan parameters of the top and bottom displays are placed in between the displays derived from the same type scans

3.1. *Wind shear on 12 May 2002*

Jet airways reported moderate wind shear at 1000 ft a.g.l. over approach runway RWY07 of the Chennai airport at 1411 UTC/ 12 May 2002. Maximum AZS value, from 1154 to 1354 UTC, was just 5×10^{-3} s^{-1} which is too low a value to cause wind shear based on the literature we surveyed. The ELS at 0.2° elevation was more than 16×10^{-3} s^{-1} from 1154 UTC and the value exceeded 20×10^{-3} s^{-1} from 1324 UTC over the area in which shear was reported at 1411 UTC. Fig. 1 displays a plot of ELS at 0.2° elevation. Though the ELS was more than 16×10^{-3} s^{-1} in south to west quadrant of the radar site as well as to the airport (labeled as MO in the figure) from 1124 UTC onwards, there was no report about the wind shear during this period presumably due to any of the following reasons — (*i*) There could have been aircraft operations in the airfield under study but the effect of which could have been neither felt nor considered worthy by the pilots for reporting to ATC while passing through the shear region or (*ii*) no in-flight report was passed on to the ATC by the pilots despite the fact that they might have experienced wind shear or (*iii*) the airplanes might not have taken-off or landed through this region at all. Other types of shears such as RDS, RAS, RES, HZS etc were computed and the results were not showing any advance information / clue about the shear experienced at 1411 UTC by the pilot. However, besides the ELS, the 3DS between 0.125 and 1.5 km a.g.l was also giving an advance information about the probable area of wind shear. The 3DS in excess of 18×10^{-3} s^{-1} could be seen from 1112 UTC itself around Chennai. Fig. 2 shows the display of 3DS from 1242 UTC.

As expected, the scan with signal quality index (SQI) of 0.25 [placed at the bottom of (Fig. 2)] shows relatively a little higher shear value (and over a wider area) than that is shown by the scan with SQI of 0.35 (placed at the top of Fig. 2). Nevertheless the magnitude of the shear has been consistent over the region under study. Combining both 3DS and ELS at 0.2° elevation, one may infer that wind shear was active around Chennai airport from 1154 UTC itself though there were no in-flight report about the shear upto 1411 UTC. Vertical

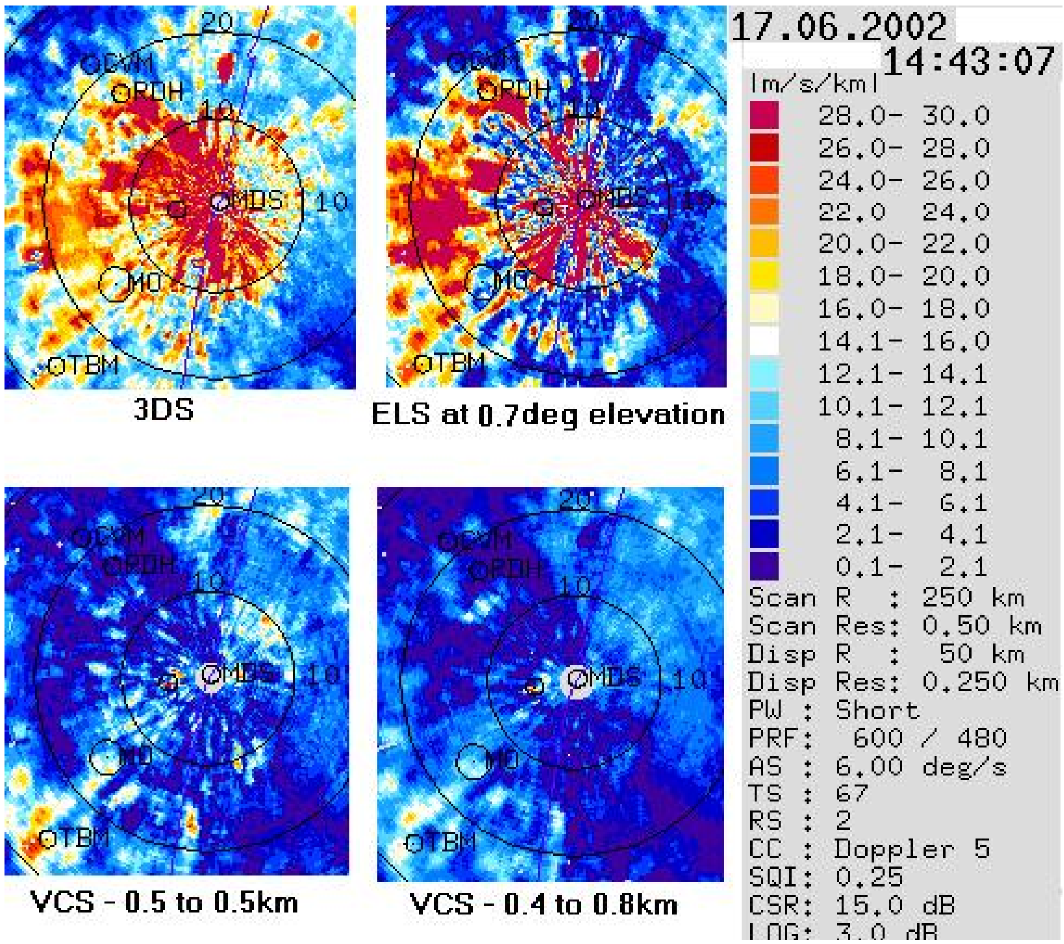

Fig. 3. Display of three dimensional shear (3DS), elevation shear (ELS) at 0.7 elevation and Vertical shear (VCS) in the layers 0.5 - 0.7 km and 0.4 - 0.8 km at 1443 UTC/ 17 June 2002. Range rings are 10 km apart

shear between 0.2 and 0.4 km was giving the same information as derived from ELS and 3DS.

It can be inferred from the above that when the computed shear (3DS / ELS / VCS) exceeds $16 \times 10^{-3}\ s^{-1}$, moderate wind shear is most probable. ICAO (1995) prescribes 0.5 km as the minimum height upto which the wind shear warning to be issued and this height may be increased to suite to local topography which may favour wind shears at greater heights. In regard to Chennai air field, as the pilots are more concerned about the low level wind shear at the time of landing and take-off (precisely from 0.8 km to 1.5 km), the 3DS should be computed immediately after each volume scan as we do not know any information, beforehand, about the exact layer / level in which wind shear is active. If the 3DS is found favourable for causing wind shear induced turbulence to aircrafts, then the ELS at the lowest two/three elevations and thence VCS at various layers upto 0.8 km may be computed quickly (each shear computation may not take more than a minute) to delineate the layer in which the shear is active. This information, if conveyed immediately to the pilot, would help the aircrew to avert the shear region and hence has a good use / economic value.

3.2. *Wind shear on 17 June 2002*

Wind shear at 1458 UTC/17th June 2002 was reported at 2000 ft while approaching the RWY07 by an aircraft. AZS values were less than 4 mps/km and did not throw any light on the wind shear. The 3DS around Chennai airport was more than 16mps / km from

TABLE 2

Lower atmospheric upper air data obtained from RS/RW ascents, Chennai - 1200 UTC/ 17 June 2002 and 0000UTC / 18 June 2002

Level (m)	Wind (dddff) speed in kt	Temp (°C)	Dew Pt (°C)
	1200 UTC / 17 June 2002		
015	22506	31.6	23.9
150	23406		
300	24710		
303		28.7	18.4
550		25.4	14.7
600	26915		
700	27417		
726		24.1	14.4
900	27719		
	0000 UTC / 18 June 2002		
015	27010	28.0	22.9
150	27112		
228		27.9	21.8
300	27913		
505		25.2	18.8
600	28419		
700	28621		
732		23.0	16.9
900	28823		

1113 UTC. It got dropped to lower values (less than 12 mps/km) between 1243 and 1413 UTC. The highest value of 3DS was 28mps/km at 1443 UTC. The 3DS of more than 20 mps/km continued upto 1543 UTC. Since the 3DS has been worked out between 0.125 and 1.5 km, to identify the layer that has high wind shear and in turn contributed to high 3DS value, ELS at 0.7, 1.3, 2.0, 2.7 and 4.0° have been computed to find out the elevation at which the shear value was high. The ELS at all elevations (except at 4.0° elevation whose values are somewhat lower than those obtained from other elevations) at 1213 UTC exceeded 16×10^{-3} s^{-1}. However, the ELS at 0.7° elevation (32×10^{-3} s^{-1}) at 1443 UTC was the highest of all the ELS computed. It may be appropriate to mention here that the ELS at 0.7° elevation (*i.e.*, the shear between 0.7° and the immediate next higher elevation 1.3°) pertains to the altitude varying between 0.32 and 0.65 km in the range 20-25 km from DWR.

Hence to further narrow down the layer in which the shear was maximum, we computed VCS from 1300 to 1600UTC in the layers 0.2 - 0.8, 0.4 - 0.8, 0.4 - 0.6 and 0.5 - 0.7 km. The VCS was more than 16mps/km in the layers 0.4 - 0.8 and 0.5 - 0.7 km from 1330 UTC. Maximum value in these layers at 1443 UTC shows an advance information about the moderate shear reported by the pilot at 1458 UTC at 0.6 km a.g.l. The combined effect of ELS at 0.7, 2.0 and 2.7° elevation and VCS caused the 3DS to have maximum value during 1413 and 1448 UTC. Fig. 3 shows 3DS, ELS at 0.7° elevation and VCS between 0.5 - 0.7 km and 0.4 - 0.8 km at 1443 UTC on 17 June. Hence 3DS exceeding 16 mps/km may be considered as a pre-cursor for the presence and / or to nowcast moderate shear induced turbulence in the lower levels upto say 1.5 km. In view of the vast computing power available now-a-days, based on first hand information from 3DS, delineating the specific layer and region in which the shear is active (based on VCS, ELS computation) can be done very quickly say within three to five minutes.

The time tested Richardson number (R_i), which is a measure of ratio of stability to the kinetic energy available in the shear flow, also may be used as a tool to identify the onset (when the R_i is less than 0.25) and cessation of turbulence (when the R_i is more than 1.0) caused by wind shear (Wallace and Hobbs, 1977; Atkinson, 1981; Pielke, 1984; Ellrod and Knapp, 1992). Table 2 lists the temperature, dew point temperature and wind data obtained by the RS/RW ascent at 1200 UTC of 17th in the boundary layer. The prevailing wind in the lower atmosphere upto 600m was southwesterly to westerly. Based on 1200 UTC (upper air) RS/RW data of Chennai, the R_i was worked out between surface and 600m. The R_i was –0.467 in view of the steep lapse rate (unstable stratification) between surface and 550 m and strong wind shear between surface and 600 m.

The negative value of R_i (due to absolutely unstable stratification) is a good indicator of onset of shear induced turbulence in the southwest to west sector of airport. This shows that at 1200 UTC the wind shear was active in southwest to west sector of airport and indicates that an aircraft approaching the runway RWY07 through this sector may experience turbulence –which of course had been confirmed by a reported wind shear at 1458 UTC. In order to understand the normal atmospheric stability that

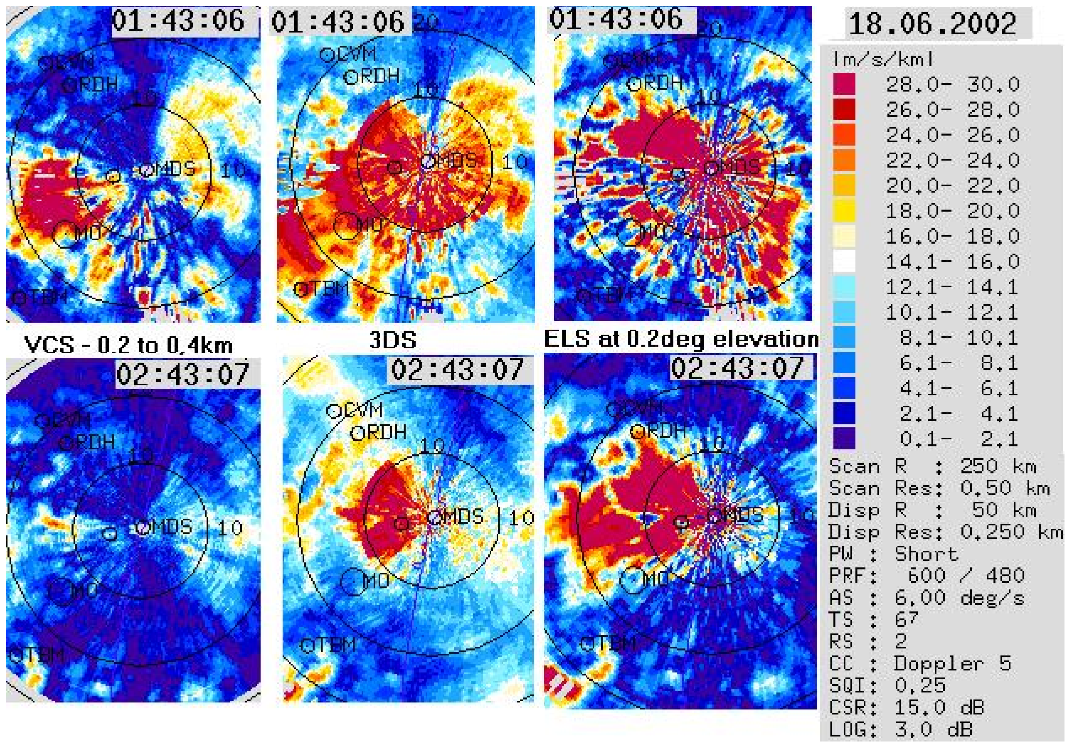

Fig. 4. Three dimensional shear (3DS), elevation shear (ELS) at 0.2° elevation and vertical shear (VCS) between 0.2 and 0.4 km a.g.l at 0143 and 0243 UTC on 18 June 2002 around DWR, Chennai. Range markers are placed at 10 km interval

may prevail at 1200 UTC during May, we computed R_i between surface and 473 m based on climatology (IMD, 1999) and found that it is 3.04. This indicates that the atmosphere in this boundary layer is normally stable. Hence, a quick look at 0000 and 1200 UTC RS/RW data may help the forecaster to have 'a general outlook' of possible wind shear if the computed R_i falls/approaches the threshold value, albeit the exact time and sector (in case the wind drifts over a wider range in the boundary layer) in which the turbulence is active may not be pinpointed from this data.

3.3. *Wind shear on 18 June 2002*

Jet airways reported moderate wind shear at 1000 ft over the approach runway RWY07 at 0245 UTC on 18 June, 2002. The wind observation by the pilot at 1000 ft was 280/35 kt. Lower atmospheric RS/RW data at 0000 UTC on 18th has been tabulated in Table 2. Since the temperature and wind data together were not available at some of the levels, R_i was computed for layers just adjacent to the levels at which temperature and wind are available. Thus R_i was 0.067 between 150 and 600 m and it was 0.0339 in the layer 300-600 m. In either case, R_i was very much less than (*i.e.* less by an order) the threshold value (0.25) and hence in this case also, the R_i was indicating the possibility of wind shear induced turbulence towards west of the Chennai airport. Climatologically the layer from surface to 486 m is stable at 0000 UTC during May since R_i in this layer is 1.49 based on IMD (1999). Hence it is desirable to have a quick look at the low level RS/RW data to identify the unstable layer and based on this information probable wind shear alert (warning) may be issued. The 3DS was more than 20mps/km from 0043 to 0213 UTC and ELS at 0.2^{o} and 0.7^{o} was favourable from 0043 UTC while the ELS at 2.0 was indicating the chances of wind shear from 0143 UTC. The VCS between 0.2 and 0.4 km was more than 20 mps/km prior to 0142 UTC and it was between 12 and 16 mps/km at 0243 UTC when the moderate wind shear was noticed. Fig. 4 displays the 3DS, ELS at 0.2^{o} elevation and VCS between 0.2 and 0.4km a.g.l at 0143 and 0243 UTC/18th. On a critical analysis of the shear values, we infer that since VCS of 12-16 mps/km at 0243 UTC was associated with moderate wind shear as reported by the pilot at 0245 UTC, there could have been severe shear induced turbulence prior to 0143 UTC since VCS

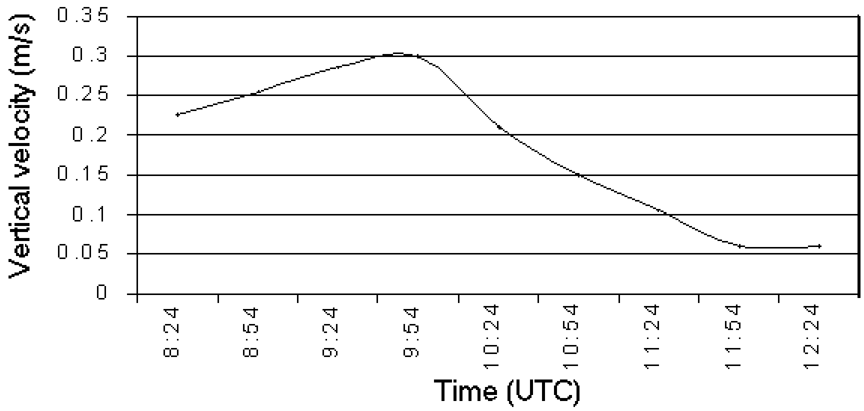

Fig. 5. Plot of vertical velocity from 0824 to 1224 UTC on 1 July 2002, within 30 km radius from DWR, Chennai

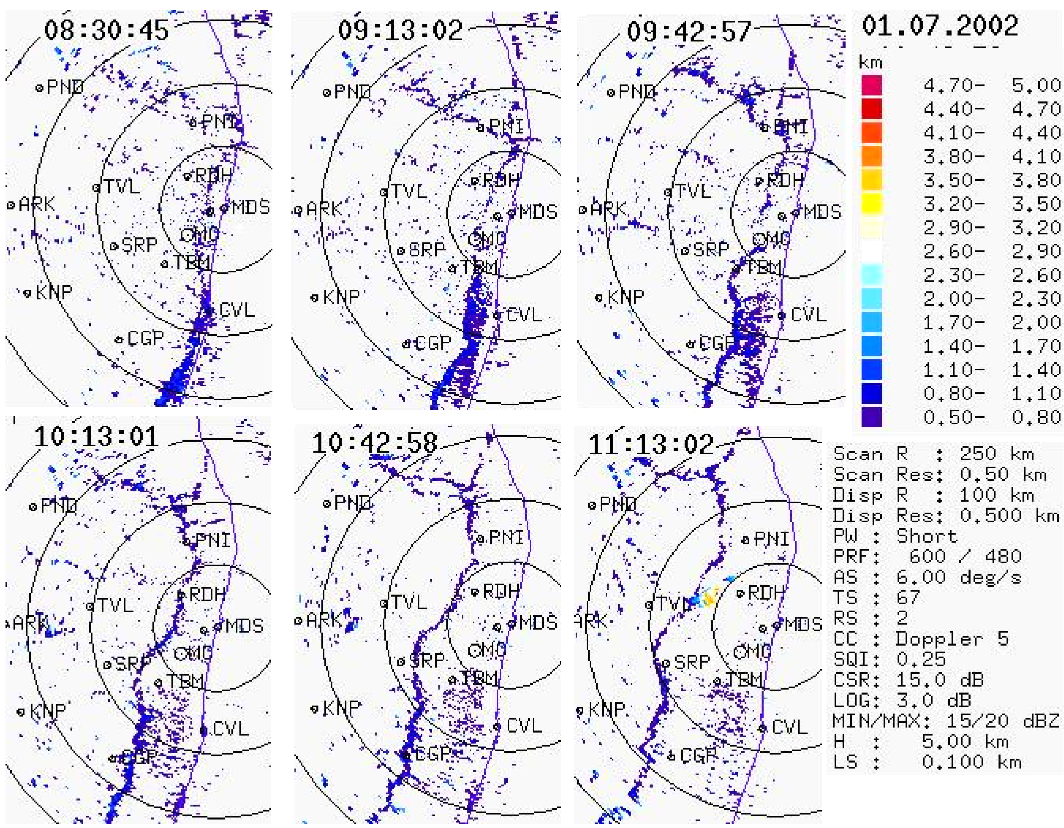

Fig. 6. Penetration of sea breeze front on 1 July 2002. The height of the sea breeze front corresponds to reflectivity factor of 15-20 dBZ. Range rings are 20 km apart

was more than 28mps/km during that period. But in the absence of in-flight information from the air crews, we are unable to validate the shear at 0143 UTC which could have caused severe turbulence. Nonetheless, based on the 3DS in excess of 16 mps/km one may infer that moderate wind shear prevails in those areas upto 1.5 km height and by quickly identifying the levels or elevation at which shear values are more than 16mps/km, it is possible to alert the air crews for cautious air navigation in a specific layer during the next couple of hours.

3.4 *Wind shear on 01 July 2002*

Jet airways reported moderate wind shear over approach runway RWY07 at 800 ft a.g.l at 1000 UTC/ 01 July 2002. The 3DS around airport was more than 18mps/km at 0813 and 0824 UTC and was a bit reduced with a spot value of the order 16-18 mps/km at 0913 UTC. Again at 0943 UTC, it was more than 20mps/km and then dropped to 12-20 mps/km between 1013 and 1100 UTC. Further examination with ELS at 0.2^{o} elevation did not reveal any signal about the moderate shear experienced at 1000 UTC. The maximum vertical shear was in the range 13.4-14.7 mps/km between 0.2 and 0.5 km at 0913 UTC. Since we could not get any clue other than the 3DS, we computed the radial elevation shear (RES) at 0.2^{o} elevation to see that whether any additional information could be derived.

The RES was more than 17.3mps/km at 0954 UTC in the area under study and it was more than 16 mps/km at 0924 and 1024 UTC (Fig. not shown) in the vicinity of the Chennai airport. The contribution of shear between 0800 and 1200 UTC was further analysed by computing vergence (convergence / divergence) within 30 km radius from DWR based on the method proposed by Waldteufel and Corbin (1979). The vertical velocity was computed using continuity equation. A plot of vertical velocity with time is shown in Fig. 5. It may be seen that the vertical velocity was gradually reaching a maximum of 0.3 mps at 0954 UTC and decreased sharply, thereafter. The possibility of vertical movement of thermals / plume could have caused the maximum vertical velocity since the maximum surface temperature on that day was 39^{o} C.

Movement of sea breeze together with convective instability and strong vertical velocity favours development of low/medium clouds (Her Majesty Stationery Office (HMSO), 1960). Between 0900 and 0913UTC sea breeze has advanced upto the airport. The height of the sea breeze front was about 0.6 km a.g.l.. Plan position indicator (PPI) product of reflectivity factor (Z) at 0.2^{o} elevation was generated and found that the sea breeze front was associated with reflectivity of 15 to 20dBZ, with the maximum at the bottom level and decreasing aloft. This reflectivity was caused by in-homogeneities in the refractive index (Bragg scattering), due to the wind discontinuity at the intersection of two air masses of opposite types and lifting of small insects at the points of convergence (Atlas, 1990; Doviak and Zrnic, 1993; and Rinehart, 1999). Hence the height of the sea breeze circulation has been chosen arbitrarily with the echo tops of 15-20dBZ. Fig. 6 depicts the march of sea breeze front as identified by 'thin line' echoes having echo top reflectivity (ETZ) of 15-20 dBZ. The inland penetration of the front is clearly distinguishable from this figure. The height of the sea breeze front close to the airport was of the order 0.3 - 0.5 km between 0913 and 1042 UTC. As the wind shear may be associated with movement or passage of sea breeze front (ICAO, 1995), the turbulence experienced by the aircraft at 1000 UTC could have been due to the passage of sea breeze front as well. The abundance moisture supply from sea breeze front to the unstable layer upto 600 m has caused the development of 4 oktas low and medium clouds at 0900 and 5 oktas low and medium clouds at 1200 UTC. In the absence of RS/RW sounding at 0900 UTC, we analysed the immediately next available RS/RW data (*viz*., 1200 UTC) and found that the lapse rate between surface and 488 m was 8.89^{o} C/km which speculates the possibility of prevalence of convective unstable boundary layer between 0800 and 1000 UTC. The difference in vertical gradient of the horizontal component of wind between surface and 488m was –0.475 m/s. The convective instability prevailed even at 1200 UTC since R_i was 0.0001 between surface and 488m a.g.l. As R_i is based on thermal and/or mechanical components of turbulence, in the present case it has been associated with thermal turbulence rather than mechanical. The rise of thermal plumes due to high insolation, besides causing shear induced turbulence at 1000 UTC, could also have caused development of 3 oktas Sc clouds (600 m base) and one okta Ac cloud (2400m base) at 0900 UTC and the Ac clouds developed further into 2 oktas at 1200 UTC.

4. Discussion

The utility of wind shear products have been assessed, off-line, at DWR, Chennai based on the available in-flight report received from the airline operators. The feedback from the air crews through ATC is some what less informative. Hence all the air line operators have been addressed to pass on the vital shear information immediately to the ATC so that we can get precise and timely information which helps us a develop a data base for understanding the atmospheric conditions favourable for the shear phenomenon. A similar exercise, though with a meager participation from the aircrews initially, was done at Heathrow airport during 1977 which helped the Meteorological Office, Bracknell, UK to adduce wind shear warning strategy in the early 1980s (Roach, 1981). As such it is highly imperative to have information about large number of wind shear incidences with precise level, area and time of observation to devise a method by which one can nowcast its occurrence or otherwise. In this connection it is desirable to have information about the non-turbulent atmosphere also, since 'no wind shear induced turbulence' is also a vital

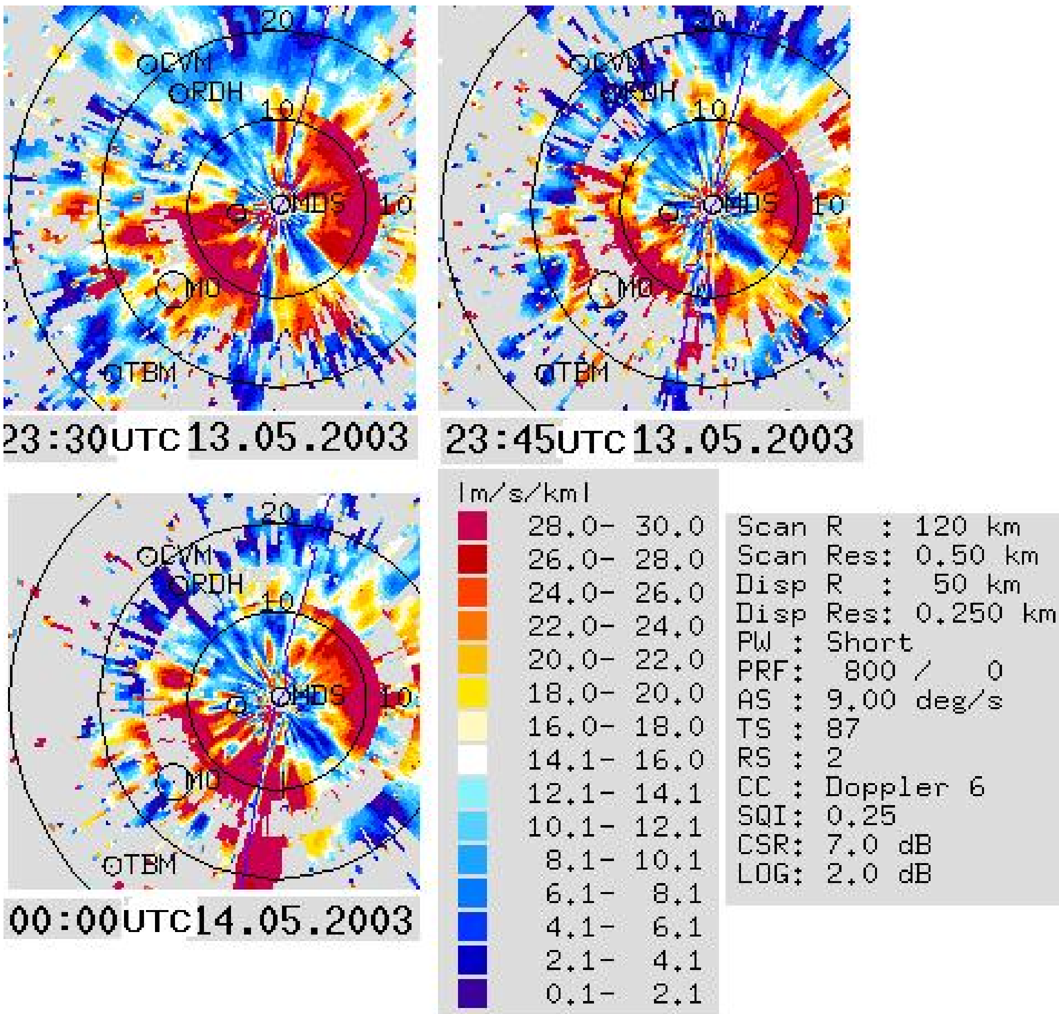

Fig. 7. Three dimensional shear from 2330 UTC / 13 May 2003 to 0000 UTC / 14 May 2003. Range markers are 10 km apart

information to reduce false alarms. Hence before arriving at a meaningful conclusion, it is absolutely essential to have more information about the shear induced turbulence in-flight report from the pilots.

The 3DS has been generated for each scan and made available to the airport meteorological office in real time through file transfer protocol (FTP) server with effect from August 2002 for briefing the pilots about possible wind shear with a request to intimate compliance and feedback. During the year 2002, wind shear was reported only upto 0.6 km. Based on the feed back from the pilots, the maximum height of the 3DS computation has been reduced from 1.5 km to 0.8 km during August 2002 which is in conformity with the general international standards laid down by ICAO (1995). Based on our limited experience, the 3DS exceeding 16mps/km can be used to nowcast the possibility of shear over the area of interest in the layer 0.125 – 0.8 km a.g.l. Since this product displays the maximum value of the shear in each vertical column with a layer spacing of 250 m upto 0.8 km, delineating the exact layer in which the shear is active can be made by computing other shears which is possible only at CDR, Chennai, as of now.

5. Recent wind shear cases (January – May 2003)

Three wind shear incidents have been reported from January to May 2003. Out of three cases, in one case (on

22nd April) the wind shear was reported below 30 m a.g.l which can not be studied by this DWR due to height restriction and nearby obstructions. The other two cases are presented below.

5.1. *Moderate wind shear at 2355 UTC on 13 May 2003*

Jet Airways reported moderate wind shear at 1000 ft (300 m) at approach runway (RWY 25) at 2355 UTC on 13 May, 2003. The 3DS was more than 24mps/km from 2315 UTC. Strong shears of magnitude more than 20 mps/km were seen right from 2300 UTC in the ENE direction of MO, Chennai. The VCS between 0.2 and 0.7 km as well as the 3DS was more than 30 mps/km at 2342 UTC. Wind shear alert warning, based on 2345 UTC DWR product and wind shear report by pilots at 2355 UTC, was issued by MO, Chennai at 0000 UTC of 14th May. The shear was seen upto 0100 UTC of 14th May. Fig. 7 shows the 3DS display from 2330 UTC of 13th May to 0000 UTC of 14th May during which period pilot reported wind shear at 300 m a.g.l in the approach RWY25.

5.2. *Moderate wind shear on 23 May 2003*

Indian Airlines Corporation (IAC 932) reported moderate wind shear at FL 010 (flight level 010, *i.e.*, 300 m) at 1011 UTC on 23 May 2003 at 3 km before the touch down point of approach runway 07 (RWY 07). At 0945 UTC, the 3DS was in the range of 10 – 12 mps/km and at 1000 UTC it got increased to 12 – 14 mps/km. The 3DS of 18-22 mps/km estimated at 1015 UTC at 7km WSW of MO, Chennai supports the wind shear experienced by the pilot at 1011 UTC at 3 km before the touch down point of RWY07 (which is of length 4 km). The 3DS of this magnitude was seen around the airport upto 1033 UTC. In this case we could not get any advanced information about the possibility of wind shear since 3DS was well below the threshold value of 16mps/km. A severe local storm was observed at 50 km NW of MO, Chennai at 0930 UTC and this was moving south to southwestward. As per the news paper report (*courtesy* : The HINDU, an English daily newspaper, Chennai edition, dated 24 May 2003), hails accompanied by high wind speed were reported between 1055 and 1115 UTC at Thiruninravur (a place 30 km NW of MO, Chennai). Since the gust fronts move ahead of the storm atleast by 30-40 km (Atlas, 1990; Rinehart, 1999), the contributory mechanism for the moderate wind shear experienced by the pilot at 1011 UTC might have originated from the passage of gust front from the severe local storm. However, since the storm was maintaining a distance more than 30 km west of MO, Chennai, the shear experienced near the airport were not of very high order. This wind shear incident suggests that one should have a constant watch on the track of local and severe local storms in addition to monitoring of 3DS product generated at frequent intervals to issue wind shear alert.

5.3. *Lack of feed back from air crews*

Though 3DS threshold value (> 16 mps/km) can be operationally utilised only after studying a number of wind shear occurrences, it is being considered on trial basis for alerting the pilots at the time of take-off and landing operations upto 0.8 km with a view to get feedback from them, similar to the attempts made at Heathrow airport during 1979, to assess the efficacy of the method proposed in this study. The success of issuing the wind shear alert vests with feedback from the air crews. On a number of days, the pilots and flight dispatchers have been briefed about the possibility of wind shear and stressed the need for getting a positive or negative feedback from them. But the response is very bleak. The airline agencies have been frequently and periodically reminded through various channels / modes of communication to accord importance in giving their feedback about the occurrence or non-occurrence of wind shear. It is hoped that the feedback from air crews will be improved in the near future. Till such time a sizeable data base of wind shear cases is built and analysed for the worthiness of the 3DS threshold derived in this study, it is desirable to continue the exercise of briefing the pilots on the possibility of wind shear and to get their feedback positively to assess the efficacy of 3DS.

6. Conclusions

The following conclusions have been arrived at based on the maiden attempt made to study the wind shear using DWR data both in diagnostic mode and in semi-operational mode.

(*i*) Three dimensional shear exceeding 16 mps/km gives a first hand information about the possible occurrence of shear in the layers between 0.1 and 0.8 km a.g.l, in a time frame of 20 minutes to two hours ahead of the actual shear felt and reported by the air crews. This threshold, obtained from a limited number cases, may be used for issuing wind shear alert / warning on trial basis since it has a prophylactic value. The feedback from the air crews about the validity of alert / warning only will help us to fine tune the threshold if needed.

(*ii*) Monitoring of movement of sea breeze front in conjunction with 3DS may be useful to issue wind shear warning.

(*iii*) The upper air RS/RW data (0000 and 1200 UTC) may also have to be fully utilised to compute the Richardson number to ascertain the atmospheric instability condition. This information has is quite vital not only to issue wind shear alert but also to forecast the development of clouds, in particular convective clouds. This information juxtaposed with wind shear information derived from the radar may improve the forecaster's nowcast and short range forecast capabilities.

(*iv*) The forecaster should keep a constant watch on the genesis and movement of local and severe local storms. The possibility of wind shear in association with gust front may have to be kept in mind when 3DS does not throw any light on the chances of wind shear.

Acknowledgements

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ANNEXURE I

System specification of Doppler Weather Radar, Chennai

Transmitter	
Type	Klystron Amplifier
Peak power	750 K Watts
Modulator	Hard switched, switch array, solid state
Frequency	2875 to 2878 MHz
Pulse width	1μs (short pulse) and 2μs (long pulse)
Pulse Repetition Frequency	250-1200 in short pulse & 250-550 in long pulse
Receiver	
Type	Double super heterodyne
Stable Local Oscillator / 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 of 120 MFLOPS/sec each
Simultaneous output	Reflectivity, Velocity and Spectrum width (8bits)
Minimum range bin spacing	75 m
Maximum number of range gates	2000
Dynamic range	Better than 95 dB
Antenna	
Reflector type and diameter	Prime focus feed, 8.5 m
Polarisation	Linear, Horizontal
Scan rate	3 to 36°/s (0.5 – 6 r.p.m)
Beam width	~1°
Gain	44.5 dBi
Height of the focal point of antenna	52 m above mean sea level
Radome	
Panel type	Epoxy-foam sandwich
No. of panels	66 in five layer structure
Shape of panels	Hexagonal and pentagonal
Diameter	11.6 m
Attenuation	Less than 0.7 dB (one way) at 10mm/hr
Sidelobe degradation	Less than 1 dB
Computers and peripherals	
Work station	Two SUN ULTRA10 systems
Monitoring, maintenance and control systems	Five Pentium/AMD PCs
Real time raw data displays	Three 2 k × 2 k flat screen monitors
4mm DAT drive	1
DLT drive	1
Heavy duty Inkjet printers	2
Black and White Laser printer	1
Un-interruptible Power Supply	60 KVA

ANNEXURE II

Scan strategy of 250 km volume scan for Z, V, and W parameters with dual PRF (600/480 Hz)

Scan range (Scan R)	:	250 km
Pulse Repetition Frequency (PRF)	:	600 / 480 Hz
Range resolution (Scan Res)	:	0.5 km
Range Sampling (RS)	:	2
Unambiguous velocity (with velocity unfolding)	:	62.58 mps
Antenna speed (AS)	:	9 deg/sec
Time sampling (TS)	:	66
Clutter to signal ratio(CSR)	:	25.0 dB
Log threshold (LOG)	:	3.0 dB
Signal Quality Index (SQI)	:	0.25
No. of antennal elevation steps	:	12
Elevation angles	:	0.2, 0.7, 1.3, 2.0, 2.7, 3.4, 4.0, 4.8, 5.9, 7.8, 11.2, 19.8°
Total time taken for each volume scan	:	8 minutes

Scan strategy of 250 km volume scan for Z, V, and W parameters with single PRF (600Hz)

Scan range	:	250 km
Pulse Repetition Frequency	:	600 Hz
Range resolution	:	0.5 km
Range Sampling	:	1
Unambiguous velocity (with velocity unfolding)	:	15.645 mps
Antenna speed	:	17.90 deg/sec
Time sampling	:	33
Clutter to signal ratio	:	30.0 dB
Log threshold	:	2.0 dB
Signal Quality Index	:	0.35
No. of antennal elevation steps	:	12
Elevation angles	:	0.2, 0.7, 1.3, 2.0, 2.7, 3.4, 4.0, 4.8, 5.9, 7.8, 11.2, 19.8°
Total time taken for each volume scan	:	4 minutes

Scan strategy of 120 km volume scan for Z, V, and W parameters with single PRF (800 Hz)
(adopted from March 2003)

Scan range	:	120 km
Pulse Repetition Frequency	:	800 Hz
Range resolution	:	0.5 km
Range Sampling	:	2
Unambiguous velocity (with velocity unfolding)	:	20..45 mps
Antenna speed	:	9.0 deg/sec
Time sampling	:	87
Clutter to signal ratio	:	7.0 dB
Log threshold	:	2.0 dB
Signal Quality Index	:	0.25
No. of antennal elevation steps	:	6
Elevation angles	:	0.2, 1.0, 2.0, 3.0, 4.0, 5.5
Total time taken for each volume scan	:	4 minutes