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Variability in the surface wind direction at a coastal site of complex terrain

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Abstract. Variability in the standard deviation of surface wind direction (σ_θ), under different Pasquill stability regimes on diurnal, seasonal and interannual scales has been investigated making use of a 10-year data set collected at Visakhapatnam (17°42′ N., 82°18′ E) during January, April, August and October for winter, pre-monsoon, monsoon and post-monsoon seasons respectively. The diurnal scale variability in σ_θ is more pronounced during day time than in night. The seasonal variability in σ_θ is only moderate around noon while relatively large fluctuations are noticed on inter-annual scale only during day time in January and August. The seasonal dispersion in σ_θ decreased from most unstable regime to most stable regime.

Keywords. Inter-annual variability; wind direction fluctuation; gravity waves; meso-scale eddies; Pasquill stability; turbulence.

1. Introduction

Standard deviation of surface wind direction (σ_θ) is drawing the attention of the environmental scientists owing to its significance in dispersion studies, especially over a complex terrain. The standard deviation of the horizontal distribution of concentration (σ_y) may be obtained from σ_θ using the relation

$$\sigma_y = \sigma_\theta \cdot x \cdot f(x),$$

where x is the downwind distance from the source and $f(x)$ is a function of distance which varies between 1·0 and 0·33 from the source to a distance of 10 km (Pasquill 1976). An excellent review of diffusion schemes was presented by Hanna *et al* (1977). The study of σ_θ is also useful to characterize the atmospheric turbulence in terms of Pasquill (A–G) stabilities to give σ_y and σ_z (standard deviation of vertical distribution of concentration) values indirectly (Sedefian and Bennett 1980). Several studies have appeared in the literature showing relations between σ_θ and Pasquill stability classes (Singer and Smith 1953; Slade 1968; McElroy 1969; Shirvaikar 1975; Panchal and Chandrasekharan 1978; Padmanabhamurthy and Gupta 1979; Sadhuram and Vittal Murthy 1983).

σ_θ is known to be influenced by several factors which should be considered while using σ_θ values in diffusion models. Munn (1964) showed the dependence of σ_θ on the sampling interval, wind speed and roughness elements. The influence of meandering air flow, roll vortices and gravity waves on wind direction has been described exhaustively (Metcalf 1975; Sethuraman 1977; Sethuraman *et al* 1982; Hanna 1983; Raynor and Hayes 1984). Sethuraman (1977) demonstrated that during breaking of a gravity wave the turbulent energy would be about 100 times higher than that during the formation of a wave and this leads to enormous mixing and dispersion. Sadhuram (1986) studied the dependance of σ_θ on wind speed, stability and its seasonal variability utilizing a 10-year data set and concluded that a climatological value of σ_θ is not a good choice for diffusion models. From the above discussion it is apparant that σ_σ has to be derived from the measurements for use in diffusion models particularly over a complex terrain. In this context the following questions are relevant; what would be the error of estimation in the pollution concentration if we use climatological (seasonal or annual) values? Do the values of σ_θ considerably vary from year to year? If so, what would be the order of magnitude in the variation of σ_θ? The present study attempts to address these questions and the results are expected to be useful for environmental studies. The temporal variation of σ_θ under different Pasquill stability regimes for typical seasons is discussed.

2. Data and methodology

Verrall and Williams (1982) reviewed some commonly used methods for the computation of σ_θ and proposed a new method based on sines and cosines of direction angles. Here, the computations of σ_θ are made from wind direction range, a method proposed by Slade (1968) which is quite simple and widely used by several workers. The method is as follows:

σ_θ is computed utilizing the continuous wind direction traces. The accuracies in the wind speed and direction are approximately $\pm 0{\cdot}2$ m/sec and $\pm 2{\cdot}0°$ respectively. Depending upon the fluctuations the trace in any hour could be divided into 10, 15 or 20 min periods. If the trace is smooth and uniform, longer averaging periods would suffice. If the fluctuations are large, a shorter averaging period is to be chosen. Here, a 20-min interval for smooth and uniform traces and a 15-min interval for large fluctuations have been selected. The range of wind direction during the sampling period has to be estimated and all such ranges during a one-hour period are averaged and considered as the mean range of wind direction for the hour. Approximate values of σ_θ are obtained by dividing the direction range values by 6·0 as proposed by Slade (1968).

This method is simple and it would be possible to compare these results with those reported for other sites. The details of data, description of the roughness elements near the experimental site, climate of the city had been reported earlier (Sadhuram and Vittal Murthy 1983, 1984a; Sadhuram 1986).

Here, the interannual variability of σ_θ, σ_θ vs Pasquill stability regimes and diurnal variation of σ_θ during different seasons have been presented diagrammatically for the period 1958–67.

3. Results and discussion

3.1 *Climatology of* σ_θ

The mean values of σ_θ for different Pasquill stability regimes were compared with the values reported for a flat terrain and for a coastal station (Sadhuram and Vittal

Murthy 1983). Here, the percentage frequency of stability categories, mean wind speeds and σ_θ values have been included (table 1). In general the standard deviation values in σ_θ are higher in unstable regimes (A,B&C) and lower in stable regimes (E&F). Mean wind speeds are lower in stable and unstable regimes and higher in neutral regimes which is quite obvious. Weaker winds and strong insolation at noon favours free convection and with the strengthening of the wind speed the mechanical turbulence dominates the thermal turbulence. Similarly during night weaker winds discourage vertical diffusion and turbulence. However, the horizontal eddies are not totally suppressed by vertical stability processes but could be produced by gravity waves, terrain interactions with the flow or surface inhomogenities etc (Hanna 1983).

The diurnal variation in σ_θ, wind speed and Pasquill stability frequencies is shown in figure 1. The value of σ_θ showed a progressive increase from dawn reaching the maximum at local noon (= 1200 hr) and a decrease thereafter during all the seasons. The wind speed also showed a similar trend but the maximum occurring during afternoon (= 1500 hr). In general, the speeds are weaker during night in all the seasons. The winds are stronger during afternoon in January and April compared with those in August and October which could be due to the influence of land sea breeze circulation. But in August and October which are typical months for thè SW and NE monsoon seasons respectively conditions may not favour the generation of local circulation. The dominance of unstable conditions during day and stable conditions during night is quite obvious. Neutral conditions (D) predominent at 0700 hr and 1700 hr (Sadhuram 1982) are not discernible due to coarse time interval considered here. More details on Pasquill stability classes and their percentage frequencies are presented elsewhere (Sadhuram and Vittal Murthy 1986).

3.2 *Day-to-day variation*

The mean σ_θ values also show day-to-day variation and the variability is significant around noon than in night (figure 2a). The values of σ_θ are higher in January at

Table 1. Mean wind speed and σ_θ values with Pasquill stability regimes.

Month/stability		A	B	C	D	E	F
Jan	I	5·2	17·6	10·7	5·0	12·0	49·5
	II	1·9	2·5	3·8	4·4	3·2	1·0
	III	16·0±2·7	12·0±2·2	8·0±3·2	6·0±2·3	6·0±0·9	4·0±0·8
Apr	I	1·0	10·0	16·3	14·0	20·3	38·4
	II	2·1	3·5	4·7	5·5	3·5	1·7
	III	17·0±1·2	13·0±2·1	9·0±1·2	8·0±0·8	6·0±1·3	6·0±0·5
Aug	I	3·6	13·6	13·3	12·0	23·5	34·0
	II	2·2	2·4	3·6	3·4	3·4	1·4
	III	12·0±2·2	10·0±2·0	7·0±1·3	7·0±1·3	5·0±1·3	4·0±0·6
Oct	I	7·1	20·8	8·7	4·1	11·7	48·4
	II	2·2	2·4	2·8	2·7	3·3	1·2
	III	14·0±2·3	10·0±1·5	8·0±1·6	7·0±1·9	6·0±1·4	4·0±0·8

I-percentage frequency of stability; II-wind speed (m/sec); III-σ_θ (Deg)

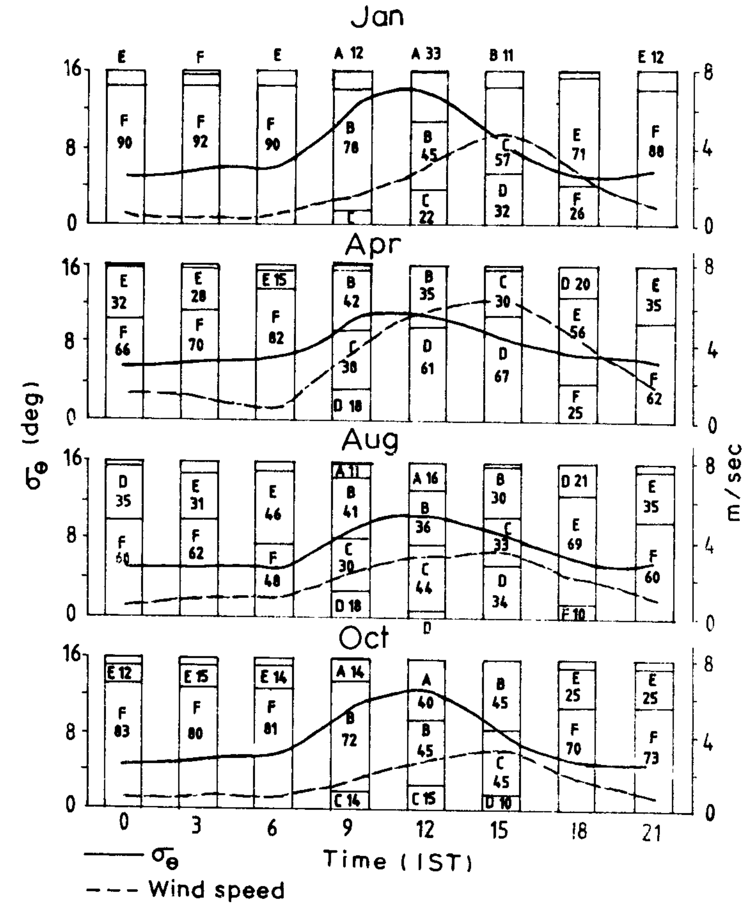

Figure 1. Diurnal variation of mean wind speed, σ_θ, Pasquill stability and their percentage frequency during typical months of the respective seasons.

0900 and 1200 hr and lower at 1800 hr compared with those in April. Similarly at 1500 and 1800 hr the values of σ_θ are found to be higher in August whereas lower at 1200 hr compared with those in October. Observing figures 2a, b carefully it can be inferred that the trends in σ_θ in January and October as well as April and August are similar because the city (Visakhapatnam) is under the influence of SW winds during April and August and NE winds in January and October (Sadhuram and Vittal Murthy 1984a). The higher values in January and October are due to the lower wind speeds. At 1800 hr the mean values of σ_θ are higher in April compared with those in August although the wind direction and the roughness elements are the same (see figures 2a, b). The mean wind speed in April and August at 1800 hr are about 4·0 and 2·0 m/sec respectively whereas the values of σ_θ are 8·0 and 6·0. Normally one would expect a decrease of σ_θ with the increase of wind speed which is not seen here. Therefore, obviously there must be some other mechanism responsible for the enhancement of σ_θ such as meandering, roll vortices and gravity waves. It is already mentioned that the stronger wind during afternoons in April is

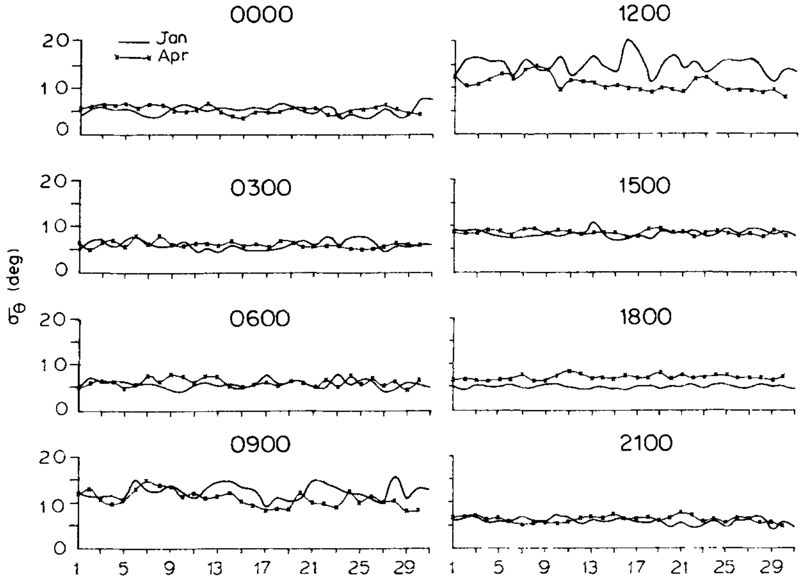

Figure 2a. Daily variation of mean σ_θ during January and April (10 year means).

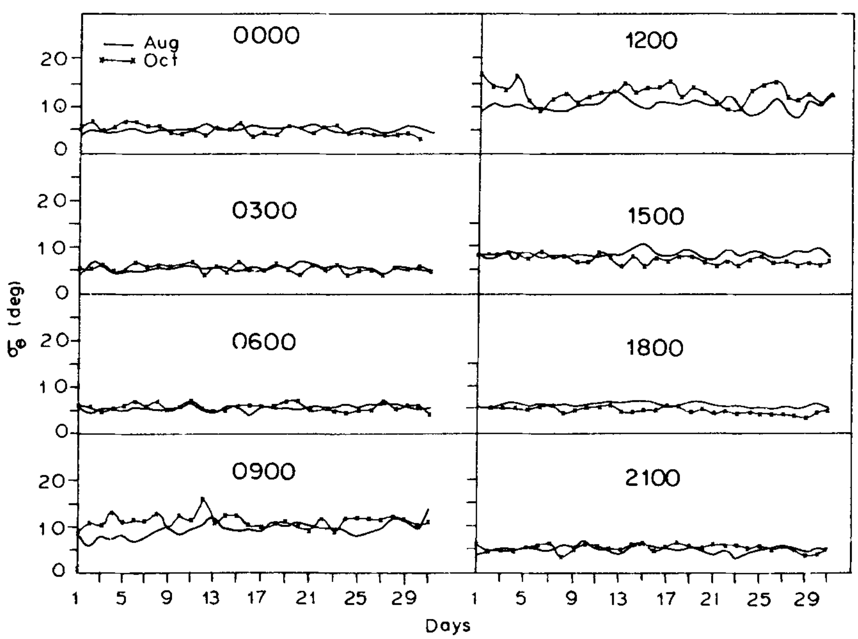

Figure 2b. Same as figure 2a but for August and October.

due to the superposition of the local land-sea breeze circulation on general synoptic flow. It is also observed that the percentage frequency of stable layers is maximum in April and almost nil in August during afternoon hours (Sadhuram and Vittal Murthy 1984b). Formation of stable layers often leads to the generation and propagation of gravity waves (Sethuraman *et al* 1982). The stability wind roses also show a considerable SSW and S directions during April and August in D&E Pasquill stability regimes and the wind speed classes 3–6 and > 6 m/sec are present in those directions (Sadhuram and Vittal Murthy 1986). Sethuraman *et al* (1982) found that the frequency of occurrence of gravity waves is more pronounced in the wind speed range 3–8 m/sec during spring and summer at a coastal site. The above points suggest that the enhancement of σ_θ in April may be due to the generation and propagation of gravity waves towards the observational site while in August the conditions are not favourable for the generation of gravity waves. Unfortunately studies on gravity waves are not available for Indian conditions to confirm the above view.

3.3 *Interannual variability*

Figures 3a, b show the year-to-year variations of σ_θ and wind speed with time 1800–0600 hr (night time) 0600–1800 hr (day time) corresponding to typical seasons. For the sake of clarity, the variability is shown for four years viz 1958, 1960, 1964 and 1967 instead of all the 10 years starting from 1958 to 1967. It is clearly seen from the figures that both σ_θ and wind speed gradually increase from 0000 to 1200 hr and decrease further in all the years. Figure 3a shows that in January σ_θ varies significantly from year to year during day time whereas such a trend is not significant in wind speed. Year-to-year fluctuations are also higher around 0300 hr which could be attributed to the variability in the frequency and intensity of ground inversions. In general, the variability in σ_θ is less in April and October compared with January and August. But in the case of wind speed the scatter is larger in April and August compared with January and October. It is interesting to see that in August the entire curve of σ_θ deviates from year to year. The highest values are seen in 1958 and the lowest in 1967. The deviation is mainly due to the activity of the monsoon which shows fluctuation from year to year. Therefore, during August the synoptic scale circulation seems to be the dominating factor. But the fluctuations in σ_θ in January may not be due to the above mechanism since the wind speeds are more or less uniform in all the years. The higher fluctuations in σ_θ during 0900 to 1500 hr are mainly due to the variability in thermal turbulence. The winds are very weak in January during early hours which favours the formation of strong ground inversions. From the selected years the general variability in σ_θ and wind speed at 1200 hr is as follows: The σ_θ value varied from 12–18, 10–12, 8–14 and 12–15 during January, April, August and October respectively. The corresponding ranges in the wind speed are $\approx$ 4, 6–7, 3–6 and 3–4 m/sec respectively. From this it could be pointed out that the variability in σ_θ is higher than that of wind speed. This suggests that wind speed alone cannot control the behaviour of σ_θ.

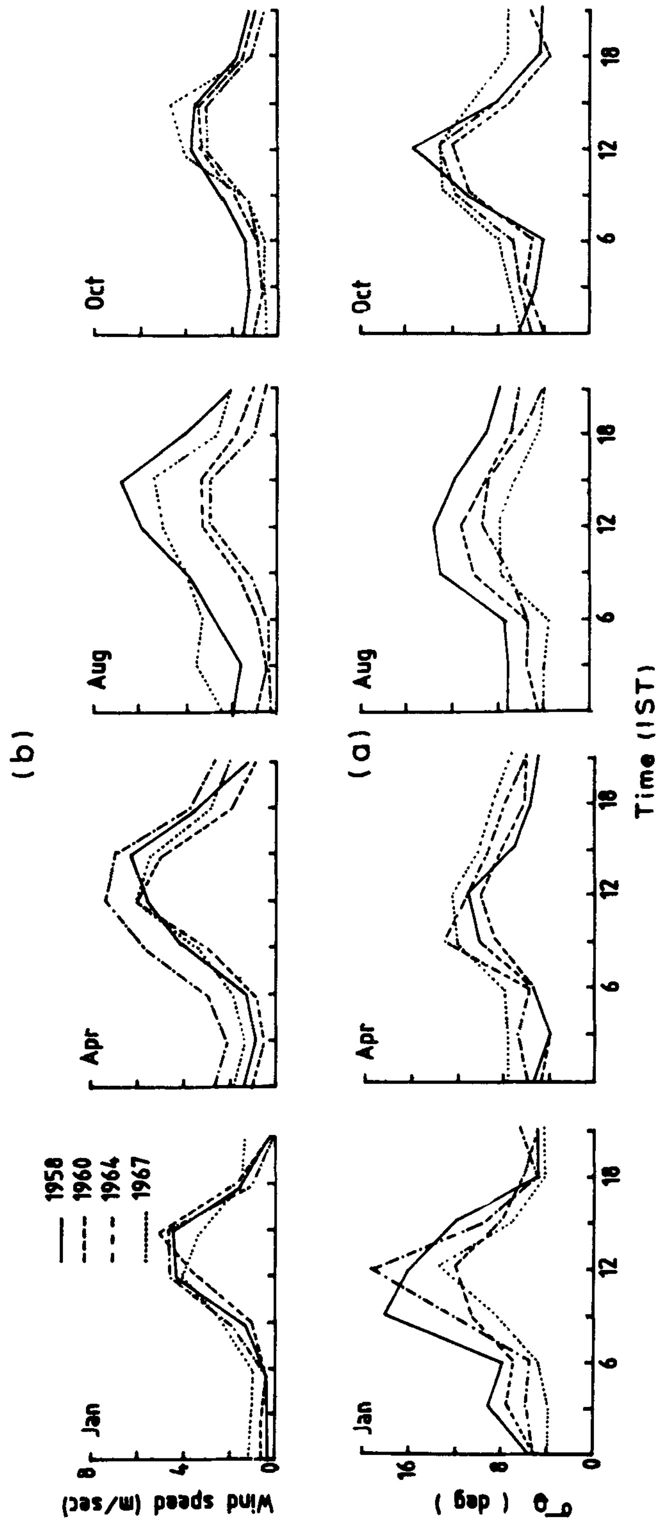

Figure 3. Inter-annual variability of (a) σ_θ and (b) wind speed with time during representative months of the respective seasons.

4. Conclusions

The present study reveals that day-to-day variability in mean σ_θ is significant during the day as compared to night. Seasonal variability in σ_θ could be attributed to the variability in the predominant wind direction and insolation. Year-to-year fluctuations are noticed in σ_θ which are greater pronounced during day in January and August. It appears that in August the synoptic scale circulation is more important than the local factors. In general, the scatter in σ_θ is higher in unstable conditions and lower in stable conditions. In April at 1800 hr the climatological values of σ_θ are higher compared to those in August although the roughness elements and the wind direction are the same. This is not seen in the individual years.

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