Wind Direction Meander at a Coastal Site during Onshore Flows

GILBERT S. RAYNOR AND JANET V. HAYES

Atmospheric Sciences Division, Department of Applied Science, Brookhaven National Laboratory, Upton, NY 11973

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ABSTRACT

About 700 cases of wind direction meander occurred in a three-year period during onshore flow at a Long Island coastal site. Most appeared to be caused by internal gravity waves but some by roll vortices. Each case was documented with respect to date, time, wind speed, wind direction and stability, and described by duration, number of waves, angular amplitude and period. Hourly wind data for the same years were examined to determine the frequency of onshore flows.

Most meander cases occurred in spring and summer, at low to moderate wind speeds and with stable conditions over the ocean. Duration varied from 4 to 438 min and averaged 94 min. The number of half-waves per case varied from 4 to 63 and averaged 10. Frequency varied from 0.3 to 30 with a mean of 4 waves per hour. Mean angular amplitude ranged from 4 to 68 and averaged 14°. Maximum amplitudes as large as 125° occurred. Results were compared to σ_y data from oil-fog smoke diffusion experiments. Calculations show that horizontal dispersion caused by a combination of meander and turbulent diffusion can be more than 30 times greater than that caused by diffusion alone and averaged 4 times greater. However, meander with angular amplitudes greater than 3° occurred only 15% of the time during onshore flow even though the air over the ocean was stable 59% of the time. Thus, the presence of significant meander cannot be assumed for diffusion calculations, although diffusion measurements indicate that minor meanders are frequent during stable conditions.

1. Introduction

Oscillatory or wave-like motions occur in the atmosphere over a range of scales from the micro to the planetary. Those occurring in the lower atmosphere with periods of minutes or tens of minutes are particularly effective in dispersing airborne gases and particulate matter over short and medium ranges (1–50 km). Such motions are most frequently observed as meander in the horizontal wind direction, although similar fluctuations take place in vertical velocity, temperature and pressure. Only horizontal wind direction fluctuations are analyzed in this study.

Many cases of wind direction meander appear to be caused by gravity waves which occur in stably stratified layers of the atmosphere or at density discontinuities. Meander is also caused by topographic features (Hanna, 1983) but is normally evident only in stable atmospheres. Thus, over land in the middle latitudes, meander is effectively restricted to the nighttime hours, typically to periods with a surface-based temperature inversion. Over large bodies of water, however, a stable layer may persist both day and night for long periods when air of higher temperature flows over the colder surface. Intense surface-based inversions extending to a height of tens or a few hundreds of meters provide an ideal environment for the formation and propagation of gravity waves which typically occur with light to moderate surface wind speeds (SethuRaman, 1977; SethuRaman *et al.*, 1982).

Gravity waves and their characteristics have been studied by many investigators with the aid of wind, temperature and pressure instruments, radar, acoustic sounders and aircraft. In one of the earlier studies, Gossard and Munk (1954) described and analyzed oscillations with periods of 5–15 min recorded by a barograph and an Aerovane at La Jolla, California. Waves illustrated by them appear identical to some observed in this study. Hooke *et al.* (1972, 1973) used an acoustic sounder, a microbarograph array and, in their later study, an instrumented tower in Colorado, to document the characteristics of gravity waves generated by shear instability in the planetary boundary layer (PBL). In a more recent Colorado study, Einaudi and Finnigan (1981) used similar data to investigate the interactions between the PBL and a gravity wave while Finnigan and Einaudi (1981) described the effect of the wave on the turbulence structure. Metcalf (1975) used an instrumented aircraft and a vertically pointing FM-CW radar to investigate the characteristics of gravity waves in the low-level marine inversion on the California coast. He showed that the motions observed were predominantly due to trapped gravity waves propagating horizontally within thin sublayers of the inversion.

Breaking of gravity waves can cause periodic bursts of turbulence within an otherwise stable layer. This phenomenon was discussed theoretically by Chimonas (1972) and observed by Caughey and Readings (1975) and SethuRaman (1980).

A smaller number of meander cases appear to be caused by roll vortices that occur at higher wind speeds and near-neutral lapse rates. An early description of roll vortices was given by Woodcock and Wyman (1947). Their effect on diffusion was reported by Hallanger *et al.* (1962), whose analysis of data from diffusion experiments near the California coast indicated that the greater than expected lateral diffusion was caused by quasi-stationary waves, apparently roll vortices. Angell *et al.* (1968) used constant-level tetroons to demonstrate the presence and characteristics of longitudinal roll vortices at a site in Idaho. LeMone (1973) described the structure and dynamics of roll vortices in a comprehensive study based on tower and aircraft measurements. Faller (1965) used a combination of laboratory and theoretical studies to show that roll vortices should be a general feature of the turbulent PBL wherever the stratification permits their existence. Finally, SethuRaman (1979) attributed increases in the turbulence level over the ocean at wind speeds above 10–12 m s^{-1} to helical roll vortices.

Determining the cause of each meander case is beyond the scope of this study and would not be possible without much more extensive measurements than were obtained. However, based on available information, it is believed that most cases with light to moderate wind speeds under stable conditions are caused by gravity waves and most cases under neutral or unstable conditions with higher wind speeds are caused by roll vortices. It is also considered possible that other mechanisms may cause meander of the wind at this location.

Meander may be a much more effective dispersive mechanism than turbulent diffusion during those periods in which it occurs. A mathematical model of dispersion of a fluctuating plume in which the total plume dispersion was separated into spreading and meandering components was given by Gifford (1959). The model was developed to treat any deviation of plume centerline position from the mean downwind direction, but it is applicable to periodic oscillations such as those described here.

Kristensen *et al.* (1981) described a model to account for the effect of meandering on lateral plume dispersion in a very stable atmosphere. Based on meteorological data from two Danish sites, they concluded that estimates of mean concentration can easily be a factor of 4–6 too high if dispersion by meandering is not taken into account. However, no comprehensive experimental or observational study of meander relative to its importance in diffusion appears to have been made. Thus, information is lacking on how often periods of meander occur, their duration, their diurnal, seasonal and geographic patterns of occurrence, and the coexisting meteorological conditions such as wind speed and stability. Without such information, the importance of meander as a dispersive mechanism cannot be evaluated.

Most diffusion models in operational use do not consider meander explicitly, although it may be included with turbulence as an increase in σ_y. The U.S. Nuclear Regulatory Commission (NRC) permits the reduction of calculated plume concentrations to account for meander under certain conditions when wind speeds are less than 6 m s^{-1} and stability is Pasquill class D through G (Nuclear Regulatory Commission, 1982). However, this procedure is based on a single set of 23 diffusion experiments designed to study wake effects at an inland nuclear reactor site (Start *et al.*, 1977) and the routine application of the method at all sites including coastal ones has been questioned (Raynor *et al.*, 1980).

This study was designed to document the occurrence and characteristics of wind direction meander at a coastal site during onshore flows and to evaluate the importance of meander in diffusion calculations. It is part of a long-term investigation of coastal meteorology and diffusion (Raynor *et al.*, 1975, 1979) conducted by Brookhaven National Laboratory.

2. Methods

Wind direction and speed measurements from a Bendix-Frieze Aerovane mounted at 23 m above the ground on a tower near the ocean at Tiana Beach, Long Island, were recorded on strip charts at a speed of 3 inches per hour and used in this study. Data were available from three nonconsecutive yearly periods (14 July 1975–13 July 1976, 15 November 1976–14 November 1977 and 1 May 1978–30 April 1979). During these periods, data were missing for 58 days or 5% of the time due to instrument or chart problems, storm damage and power failures. Missing periods occurred in all seasons and are not believed to affect the findings of the study except to decrease the total number of cases.

Cases of meander were identified by the periodic wave-like nature of the direction trace. Only cases with a mean wind direction between 100 and 220° or ±60° from a direction normal to the coast were used. Meander also occurs with other wind directions, but it is less frequent and coexisting turbulence levels are usually higher. Meander was easily separated visually from higher frequency turbulence, wind direction shifts, and the random motions that occur during light and variable winds. Only cases with two or more full waves were included. Six hundred and seventy-five cases were found in the 1037 days examined, an average of 237 cases per year.

The following data (Fig. 1) were recorded for each case: date and time of beginning and end and time of the peak of each oscillation or half-wave to the nearest minute, number of half-waves, direction of each peak to the nearest degree measured at the center of the trace, mean wind direction during the meander period,

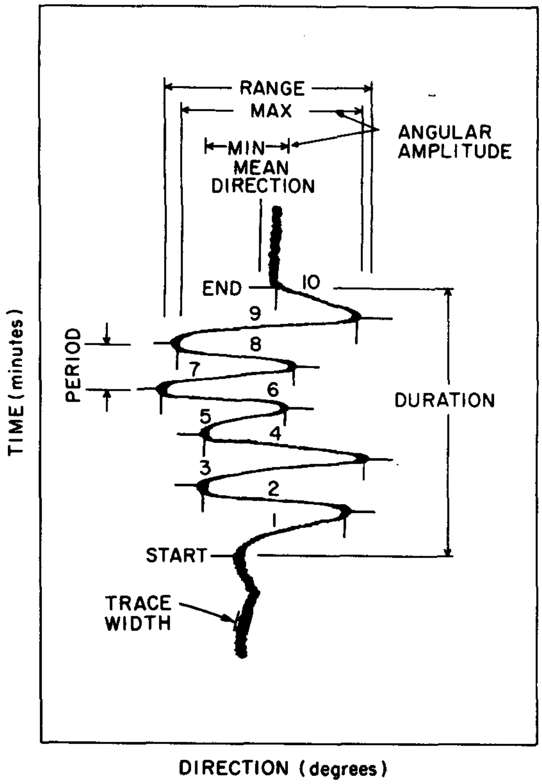

FIG. 1. Diagram of a representative meander case illustrating the measurements taken as described in the text. Each half-wave is numbered. Tick marks indicate the locations at which direction and time are read.

maximum trace width without the meander, and a modified version of the Brookhaven gustiness classification (Singer and Smith, 1953). The mean wind speed during the case was determined from the wind speed chart. All cases were assigned a sequence number and all data entered into a computer database for subsequent analysis.

For each case, the following parameters were calculated: mean, standard deviation, maximum and minimum of the direction ranges or angular amplitudes of the swings or half-waves, and total direction range over which swings occurred (Fig. 1). Similar parameters were calculated for the time differences or periods between alternate peaks and troughs and the speed or rate of change in direction of each swing (degrees per minute). The mean period and frequency were also calculated for each case. Wavelengths could not be calculated since the direction of propagation was unknown, and it could not be assumed that the waves were traveling at the speed of the wind. Gossard and Munk (1954) described a method for computing the mean and orbital wind vectors from direction and speed measurements at successive intervals during wind oscillations. However, the method has a ±180° ambiguity, and it was not considered either useful or feasible to apply it to our data. Because the primary purpose of this study was to evaluate the effects of meander on diffusion, angular amplitude statistics were compared to the width of the trace to give a meander diffusion factor.

With the use of hourly climatological data from the same instrument for the same time periods, the percentage of hours with onshore flow and the percentage of hours with both onshore flow and meander were computed. Frequency distributions of the measured and derived parameters were calculated and data were classified by season, time of day, wind speed and stability.

Measurements of plume standard deviations (σ_y) taken over shorter and longer time intervals during diffusion experiments at Tiana Beach using oil-fog smoke as a tracer (Raynor *et al.*, 1975) were examined to document the amount of variability in σ_y as a function of averaging period. Previous studies have shown that the difference between near-instantaneous σ_y and time-averaged σ_y is caused largely by shifts in plume centerline position even though experimental periods were selected for relatively steady wind directions, and oscillations of the type studied here did not normally occur during smoke releases. Thus, the diffusion data give a lower limit to the increase in σ_y with time due to slight meander or minor wind direction changes under nominally steady directions.

3. Results

a. *Examples of meander*

Representative cases of meander are shown in Figs. 2–4. Fig. 2 illustrates six cases of varying duration, angular amplitude and frequency under stable or near-stable conditions with wind speeds from 4.0 to 7.1 m s^{-1}. All are believed caused by gravity waves which usually occur under these conditions. Trace A is a typical nonturbulent case under very stable conditions. Traces B, C, and D indicate stable periods during the meander period but less stable conditions before and after. Trace E is also preceded and followed by more unstable conditions but periods of increased turbulence at the ends of several swings suggest incipient breaking of the waves. Trace F has about the smallest amplitude of any case found and a fairly high frequency.

Figure 3 illustrates a classic case of breaking gravity waves following five of the swings to the left. This case occurred with a mean wind speed of 3.0 m s^{-1}. The breaking phenomenon was discussed by SethuRaman (1977, 1980). Similar bursts of turbulence also occurred from time to time during stable conditions with little or no evidence of meander in the horizontal wind direction. These cases may indicate gravity waves propagating vertically.

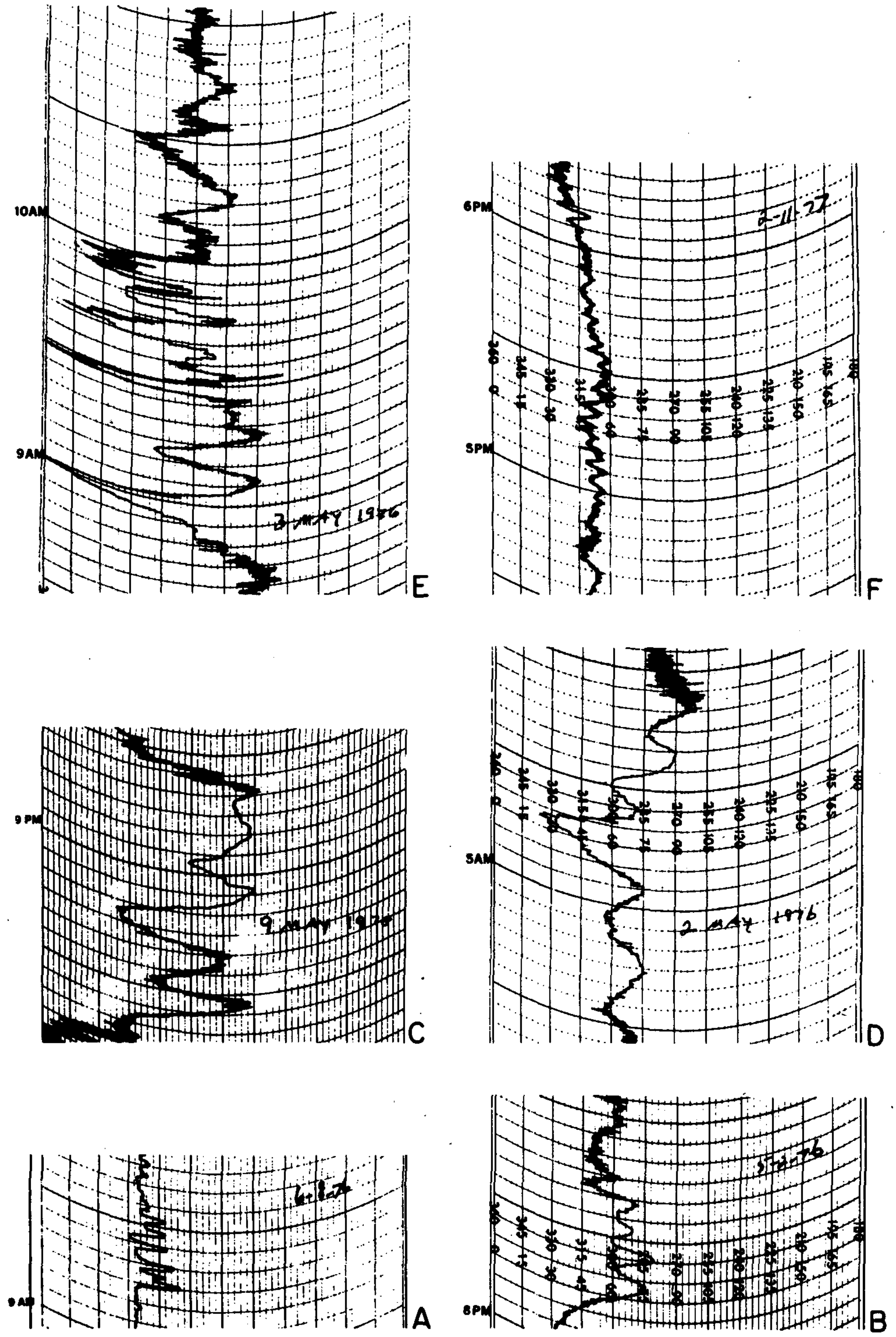

FIG. 2. Sections of wind direction charts showing representative cases of meander during stable or near-stable conditions. The direction in which the vane was oriented was displaced 90° from the directions printed on the chart. This was done so that 180° would be located in the center of the chart rather than on the edge, roughly centering traces during onshore flows and permitting greater accuracy in reading directions.

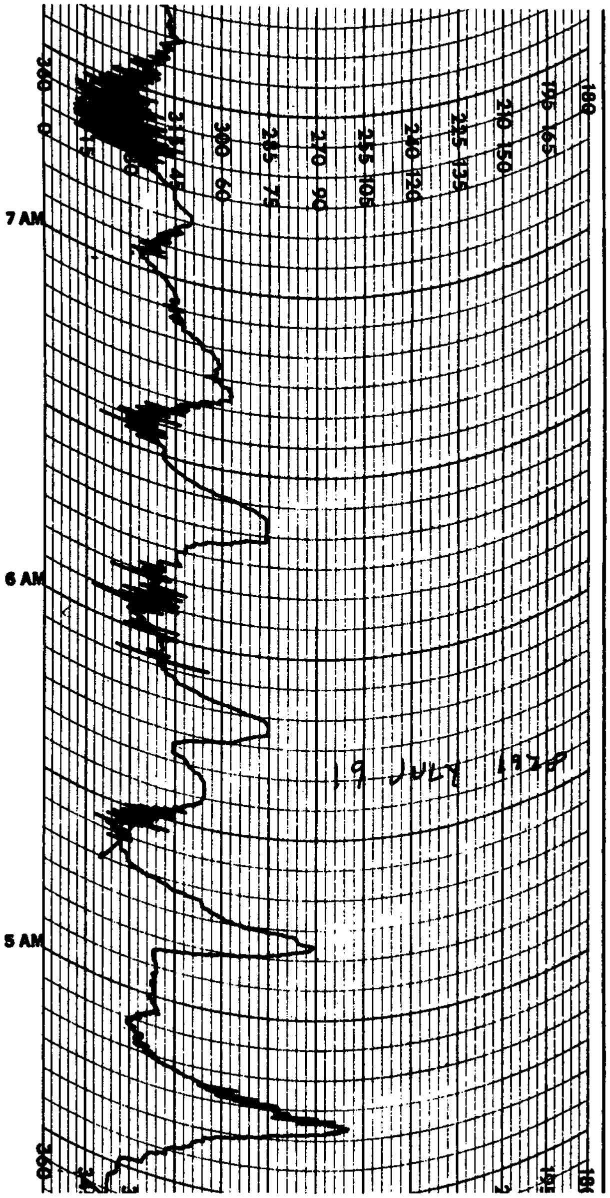

FIG. 3. A section of a wind direction chart showing a meander case with breaking of internal gravity waves.

Four cases under neutral or slightly unstable lapse rates are shown in Fig. 4. Here, high-frequency turbulence is superimposed on the meandering motions and also occurs before and after the periods of meander. These cases occurred with wind speeds of 5.0 m s^{-1} (C), 8.0 m s^{-1} (A,B), and 18.0 m s^{-1} (D) and are believed due to roll vortices.

b. *Periods of occurrence*

Thirty-two percent of the meander cases occurred in the spring and 47% in the summer when the ocean is normally colder than the land and the air stable. Only 14% occurred in the fall and 7% in the winter. Twenty-six percent of the hours with onshore flow occurred in the spring, 38% in summer, 23% in the fall, and 13% in winter. Thus, the frequency of meander periods in the spring and summer is greater than expected based on the frequency of onshore hours and appears related to the more stable conditions prevailing during these seasons.

Omitting transition hours near sunrise and sunset, we note that 65% of meander cases occurred during the day and 35% at night. However, daytime hours occur about 59% of the time during the spring and summer period and onshore hours are increased during the day by sea breezes. Thus, the number of meander cases is approximately proportional to the number of hours with onshore flow during the day and night and no diurnal preference for occurrence is evident from the data.

A variety of synoptic situations cause onshore flow on the south shore of Long Island but the most common is the southwesterly circulation in the westerly portion of an anticyclone. Numerous cases occur with sea breeze circulations which mostly develop when an anticyclone is centered over the region and gradient winds are light. Other cases occur in the warm sector of a frontal system. Periods of meander were observed during all of these situations but predominantly during fair weather.

Meander of the angular amplitudes studied occurred during only a small percentage of the time even with favorable conditions. Hourly mean wind direction data were available for 92% of the hours during the three-year period. Twenty-eight percent of the hours had mean wind directions in the onshore sector, 100–220°. The total length of all meander periods was about 15% of the total number of hours with onshore winds.

c. *Conditions of occurrence*

Most meander cases occurred with light to moderate wind speeds, nearly 64% in the 3–6 m s^{-1} range and less than 2% at speeds of 12 m s^{-1} or greater (Fig. 5A). This distribution is quite different from that of all onshore hours (Fig. 5B) which has a greater percentage of both lower and higher wind speeds. The mean wind speed during all onshore hours was 6.6 m s^{-1} compared to 5.2 m s^{-1} during meander periods (Table 1). Thus, meander occurred in a higher than expected percentage of hours with wind speeds from 3–6 m s^{-1}.

The distributions of wind direction during meander periods and all hours with onshore flow is shown in Fig. 6. Meander occurs more frequently with south to southwest winds than with southeast to south. Air over the ocean is more frequently stable with a southwest flow due to the shorter fetch of continental air over the ocean (Raynor *et al.*, 1975).

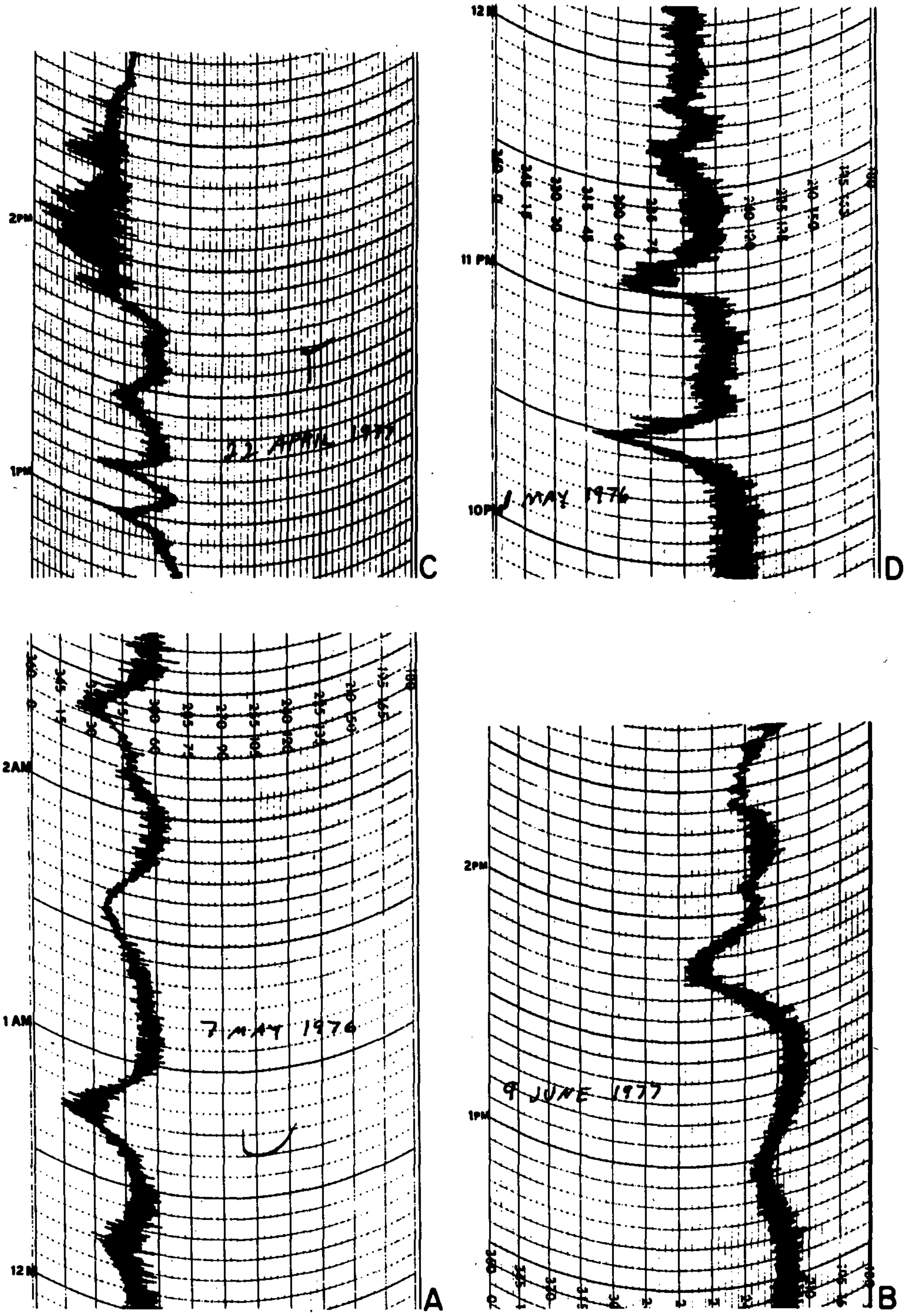

FIG. 4. Sections of wind direction charts showing representative cases of meander during neutral or unstable conditions.

Using a modification of the Brookhaven gustiness class as a measure of stability (Singer and Smith, 1953) 27.3% of all onshore hours were unstable (class B), 13.8% were neutral (class C) and 58.7% stable (class D). During meander periods, 19.0% of the cases were unstable, 8.7% neutral, and 72.3% stable. Thus, meander occurs preferentially during stable conditions.

Similar results were found by using the width of the

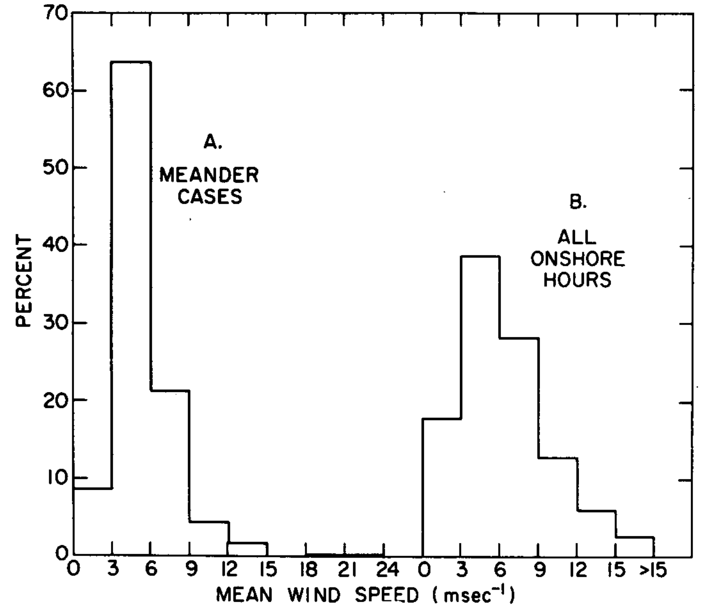

FIG. 5. Frequency distributions of wind speeds during meander cases (A) and all onshore hours (B).

direction trace as a measure of stability (Fig. 7). Seventy-one percent were less than 10°, indicating rather stable conditions and 27% less than 3°, very stable conditions. Ninety-six percent were less than 15° and only 4% greater.

Although temperature profiles over the ocean were not available during the periods of meander included in this study, profiles were measured from aircraft during numerous diffusion experiments (Raynor *et al.*, 1975) and coastal internal boundary layer investigations (Raynor *et al.*, 1979) when conditions were similar. These measurements showed that surface-based inversions of several degrees Celsius or more typically extended to a height of a few hundred meters during stable periods with southwesterly onshore winds. With southeast winds when fetches over the ocean were greater, inversions were usually only a degree or so. During periods of higher wind speeds in which roll vortices appeared to occur, lapse rates were near neutral.

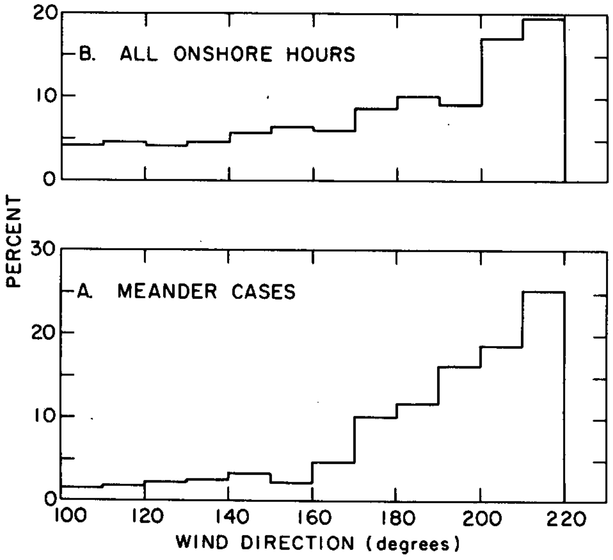

FIG. 6. Frequency distributions of wind directions during meander cases (A) and all onshore hours (B). The direction perpendicular to the shore line is 160°.

Periods of meander quite often followed a shift in mean wind direction or were terminated by a shift. In a few cases, a marked trend in direction occurred during the meander period but, in most cases, the mean direction remained relatively constant. Mean wind speeds were usually quite steady but occasionally increased or decreased significantly during meander periods. Oscillations in speed similar to those in direction were not normally apparent but occurred in a few cases. Other observations from the same site (SethuRaman, 1977) and elsewhere (e.g., Gossard and Munk, 1954; Hooke *et al.*, 1972, 1973; Caughey and Readings, 1975) have documented oscillations in wind speed as well as in elevation angle, vertical velocity, temperature and pressure.

Periods of meander sometimes followed a change in mean wind speed usually corresponding to a change in direction and were sometimes ended with a change in speed. However, the majority of cases took place with relatively steady mean speeds and directions, light

TABLE 1. Characteristics of meander cases

Parameter	Mean	Standard deviation	Minimum	Maximum	n
Duration (min)	93.5	65.1	4.0	438.0	675
Mean wind speed (m s^{-1})	5.2	2.3	0.8	21.9	639
Mean wind direction (deg)	191.5	26.9	100.0	220.0	675
Trace width (deg)	7.9	5.1	1.0	30.0	675
Half-waves, number of	10.1	6.5	4.0	63.0	675
Half-wave angular amplitude (deg)					
Case mean	14.3	8.4	3.8	67.5	675
Case standard deviation	6.8	5.1	0.6	44.7	675
Case minimum	6.3	5.2	1.0	53.0	675
Case maximum	26.2	16.8	5.0	125.0	675
Maximum range (deg)	32.9	20.8	5.0	180.0	675
Half-wave period (min)					
Case mean	10.5	7.2	1.0	93.8	675
Case standard deviation	5.1	4.0	0.0	37.9	675
Case minimum	4.9	3.9	1.0	40.0	675
Case maximum	19.5	12.8	1.0	125.0	675
Frequency (waves per hour)	4.2	3.2	0.3	30.0	675
Rate of direction change (deg min^{-1})					
Case mean	2.1	1.9	0.3	13.4	675
Case standard deviation	1.2	1.5	0.0	19.4	675
Case minimum	0.8	0.7	0.1	5.7	675
Case maximum	4.6	5.4	0.4	60.0	675
Meander diffusion factor					
From mean angular amplitude	3.8	3.1	1.5	33.8	675
From maximum angular amplitude	6.2	5.7	1.5	50.5	675
From maximum range	7.6	7.7	1.7	91.0	675

to moderate speeds, southwesterly directions and stable conditions.

d. Characteristics of meander

Duration of meander periods ranged from 4 to 438 and averaged 94 min (Table 1). The distribution of durations by 30 min intervals is shown in Fig. 8 which shows that 66% of the cases lasted from 30 to 120 min. Duration did not differ significantly with season or time of day. Durations were somewhat shorter with low (<3 m s^{-1}) and high (≥12 m s^{-1}) than with moderate wind speeds. During stable conditions (trace width 1–6°) 30–60 min durations were most frequent. During

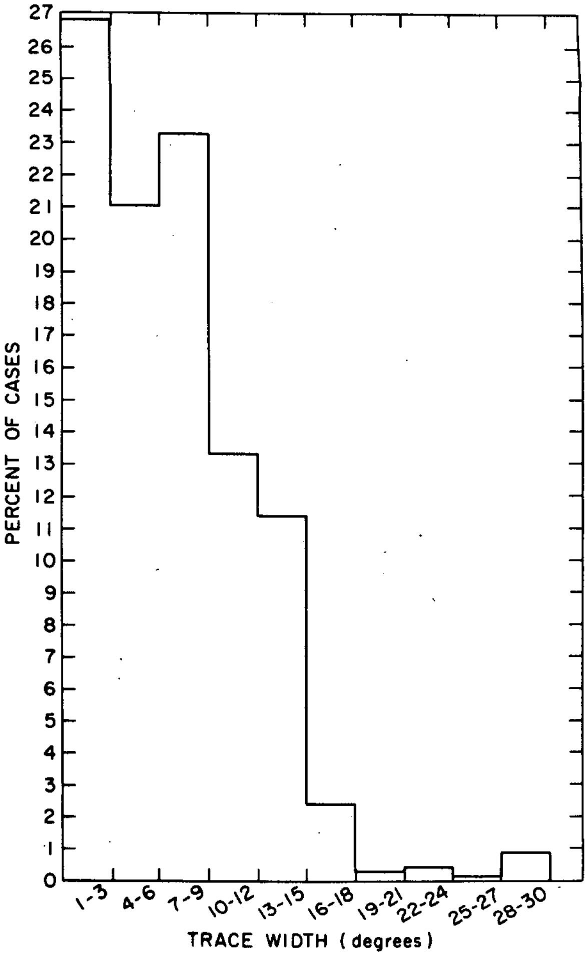

FIG. 7. Frequency distribution of trace width during meander cases.

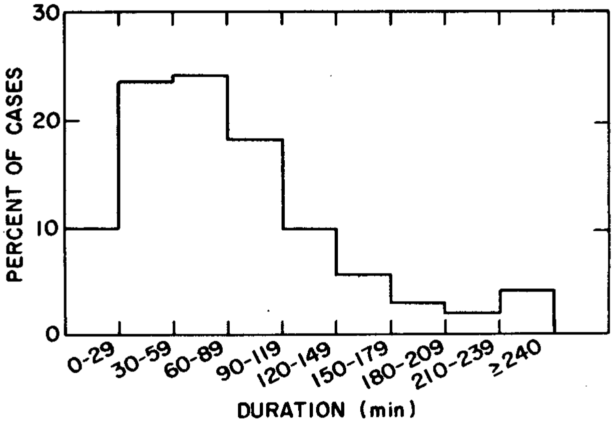

FIG. 8. Frequency distribution of duration of meander cases.

less stable conditions (trace width > 6°) 60–90 min durations were most common.

The number of half-waves varied from 4 to 63 and averaged 10.1 (Table 1). The number decreased almost continuously from a maximum at 4 (Fig. 9). A typical case consisted of only a few swings but a small percentage had over 20 half-waves. No seasonal, day-night or wind speed differences were found. The number averaged somewhat greater during the most stable conditions (trace width ⩽ 3°) but did not vary otherwise with stability. The mean half-wave period varied from 1 to 94 min and averaged 10.5 min (Table 1). It has the distribution shown in Fig. 10. Table 1 also includes statistics on maximum and minimum half-wave periods per case.

Frequency ranged from 0.3 to 30 and averaged 4.2 waves per hour (Table 1). The distribution is sharply peaked at 1–4 waves per hour (Fig. 11) and did not differ with season, time of day or wind speed but showed a decreasing trend with trace width. Very stable cases peaked at 3–4 waves h^{-1} and unstable cases at 1–2 waves h^{-1}.

Mean angular amplitude varied from 3.8 to 67.5° and averaged 14.3° (Table 1). Statistics for maximum and minimum angular amplitudes per case are also given in Table 1. Few cases had mean swings less than 5 or greater than 30° (Fig. 12). No significant differences were found with season, time of day or wind speed. A small trend for greater angular amplitude with decreasing stability was evident.

Maximum angular ranges over which swings occurred varied from 5 to 180° and averaged 33° (Table 1). The distribution (Fig. 13) is similar to that of mean angular amplitude (Fig. 12) but with greater magnitudes.

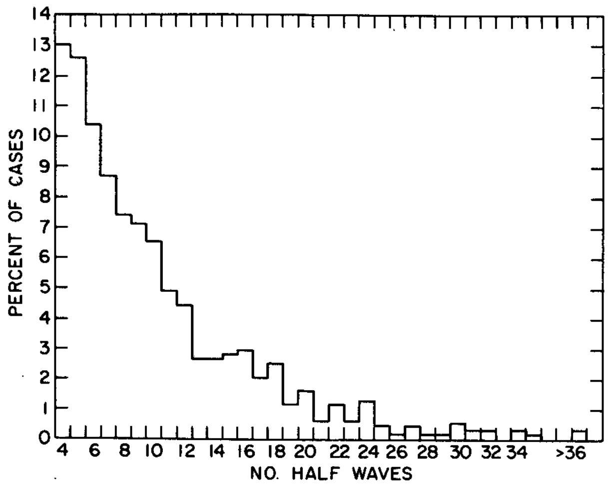

FIG. 9. Frequency distribution of the number of half-waves.

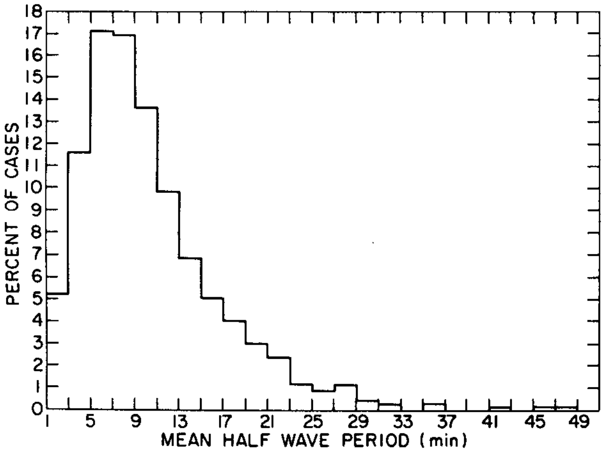

FIG. 10. Frequency distribution of mean half-wave period.

A significant feature of meander is the rate at which wind direction changes, the mean angular amplitude divided by the mean half-wave period. This parameter varies from 0.3 to 13.4 and averages 2.1° min^{-1} (Table 1). The statistics of the maximum and minimum rates per case are also given in Table 1. The distribution is peaked at low rates (Fig. 14). No significant difference was found with any of the parameters investigated.

e. Effects on diffusion

A meander diffusion factor was defined as the ratio of the angular amplitude of the wind direction swings

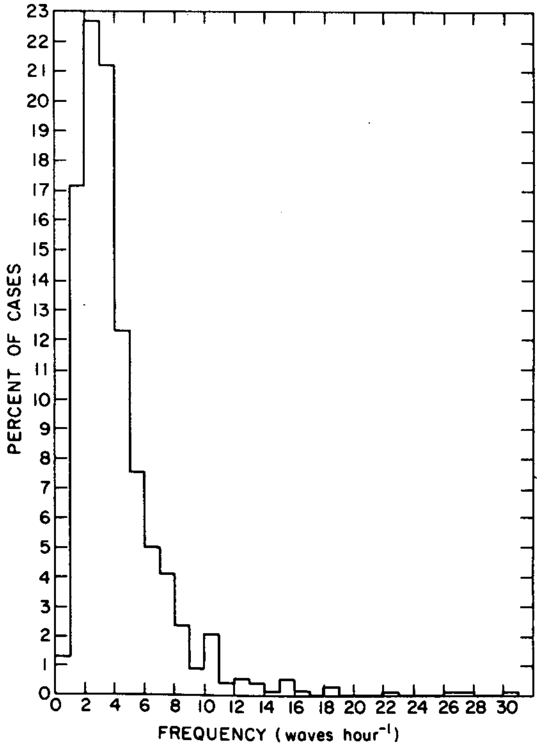

FIG. 11. Frequency distribution of meander frequency.

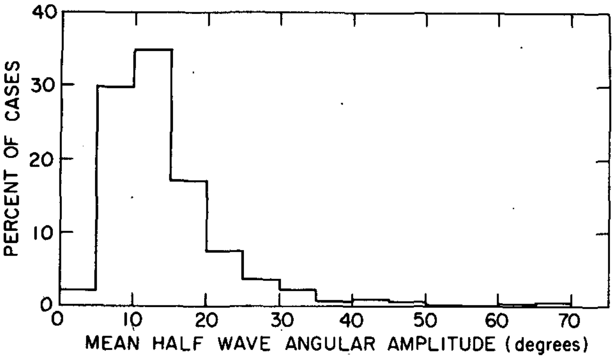

FIG. 12. Frequency distribution of mean half-wave angular amplitude.

to the angular amplitude of the higher frequency wind direction fluctuations or trace width (Fig. 1). Meander diffusion factors were calculated using the mean angular amplitude, the maximum angular amplitude and the maximum range. The statistics of the three meander diffusion factors are listed in Table 1 and their distributions shown in Fig. 15. The factor computed from the mean angular amplitude has a mean of 3.8, a standard deviation of 3.1 and a maximum of 33.8. The factor computed from the maximum angular amplitude has a mean of 6.2, a standard deviation of 5.7 and a maximum of 50.5. The factor computed from the maximum range has a mean of 7.6, a standard deviation of 7.7 and a maximum of 91.

Thirty-six cases characterized by winds of 9 m s^{-1} or greater and trace widths of 9° or more were judged caused by roll vortices. Mean meander diffusion factors for these cases were smaller than those of all cases primarily due to the wider trace widths. Mean values for the three factors were 2.2, 3.0 and 3.3, respectively, showing that meander is less important, although still significant, during high-wind periods with neutral or unstable lapse rates.

These results are similar to the model results derived by Kristensen *et al.* (1981) who found that meander can decrease concentrations by factors of 4–6. Our findings are also compatible with actual concentration data from 44 oil-fog smoke diffusion experiments which involved releases from a boat off the south shore of Long Island and plume sampling along a coastal road (Raynor *et al.*, 1975). The mean time-averaged σ_y during a series of traverses across the plume averaged 2.2 times greater than the mean of σ_y measurements taken during individual traverses. The series of traverses ranged from 8 to 87 min in duration but were mostly in the 20–40 min range. The experimental periods were chosen for a relatively steady wind direction but minor meander was evident in almost all cases and moderate meander in a few. The reasons for the minor meanders were not known, but the cases of moderate meander were believed caused by gravity waves.

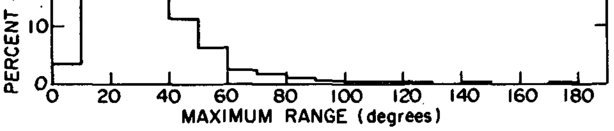

FIG. 13. Frequency distribution of maximum range.

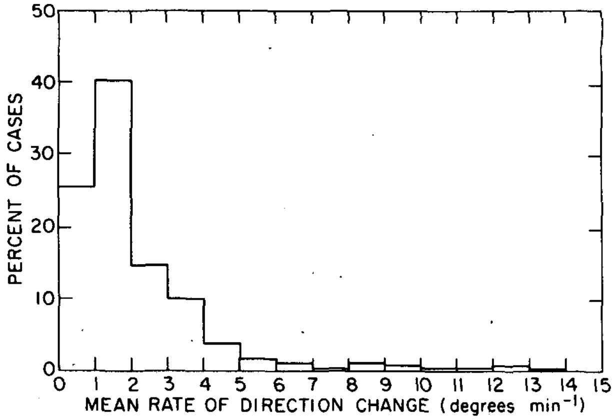

FIG. 14. Frequency distribution of mean rate of direction change.

Thus, in nominally steady winds, meander may double the effective σ_y. In periods of marked meander, σ_y may increase from four to eight times in the mean and many times these values in individual events. Although vertical oscillations were not measured routinely, sporadic bivane measurements at the same site (SethuRaman, 1977) show that σ_w and therefore vertical dispersion is often increased during meander periods.

SethuRaman (1977) also showed that the turbulent energy present during breaking of internal gravity waves was over 100 times greater than during nonbreaking periods and illustrated the dispersion of a smoke plume during one such event. Thus, breaking waves add significantly to the dispersion caused by meanders, but they occur rather rarely and only intermittently.

Because significant meander occurs only about 15% of the time during onshore flow, its presence even with light to moderate wind speeds and stable conditions cannot be assumed for diffusion calculations as is permitted in Regulatory Guide 1.145 (Nuclear Regulatory Commission, 1982). Although the conditions under which meander occurs at one coastal site have been identified by this study, meander does not always occur during these conditions. Thus, for real-time diffusion calculations, the presence or absence of meander should be observed and appropriate diffusion parameters cho-

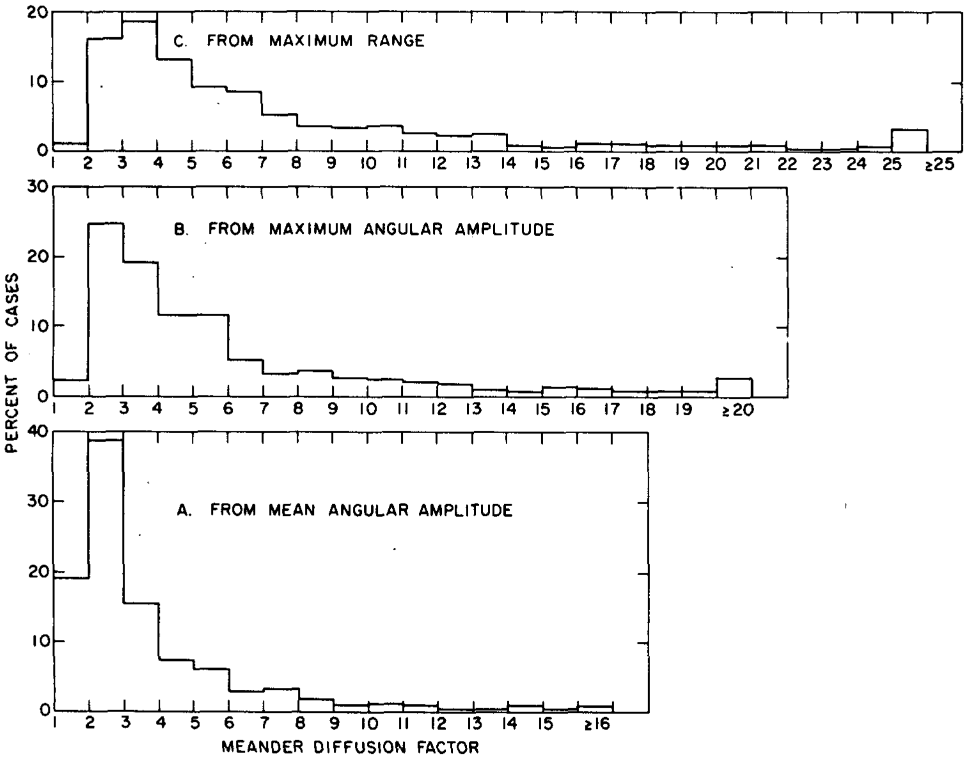

FIG. 15. Frequency distributions of meander diffusion factors calculated from mean angular amplitude (A), maximum angular amplitude (B) and maximum range (C).

sen. For non-real-time diffusion calculations, meander can be simulated using data of the type presented here. However, studies are needed at other coastal locations to determine the representativeness of this site and the generality of these results.

4. Conclusions

Wind direction meander with angular amplitudes greater than 3° occurs about 15% of the time during onshore flow along the south shore of Long Island. Based on conditions of occurrence, most cases appear caused by internal gravity waves and some by roll vortices. Meander occurs most often in the spring and summer due to the combination of stable conditions over the ocean and the prevalence of onshore winds caused by both synoptic systems and seabreezes during these seasons. Cases of meander last from a few minutes to a few hours but 66% are from 30 to 120 min in duration. The number of oscillations varies from 4 to 60 and averages about 10. Angular amplitudes average ~14° but may be as large as 125°. Amplitudes of meandering motions are usually at least several times the amplitudes of higher frequency turbulent oscillations and may be as much as 34 times greater. Horizontal diffusion may be greatly enhanced during periods of meander but meander does not occur often enough to assume its continuous occurrence even during most favorable conditions when performing diffusion calculations.

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