

## NOTES

### Seasonal Variations in the Formation of Internal Gravity Waves at a Coastal Site

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#### ABSTRACT

Atmospheric internal gravity waves that formed over a coastal and an inland site were identified from analog records of wind speed and direction. Internal gravity waves occurred at all hours at the coastal site but only during nights inland. More waves formed during the spring and summer at the coastal site as compared to other seasons. The frequency distribution of internal gravity waves inland showed no preference in seasons.

#### 1. Introduction

Formation of stable atmospheric layers often leads to the generation and propagation of internal gravity waves. Instability of these waves causes breaking and enhanced turbulence. Wavebreaking in upper layers of the atmosphere leads to clear air turbulence (CAT), a phenomenon extensively investigated. Internal waves also occur near the earth's surface within the atmospheric boundary layer when stable atmospheric conditions prevail (SethuRaman, 1977; Caughey and Readings, 1975; Metcalf, 1975, etc.). In such cases, internal waves coexist with turbulence caused by mechanical roughness. Enhancement of turbulence occurs when the waves break (SethuRaman, 1980). Occurrence of the waves in the boundary layer significantly modifies the diffusion characteristics of the atmosphere. This is due to the reason that diffusion is minimum when the waves occur with a sharp increase in turbulence and diffusion when the waves break (SethuRaman, 1977).

Restricting ourselves to the atmospheric-surface layer, about 100 m above the surface, waves occur over land mostly with nocturnal inversions. Over coastal waters, stable atmospheric conditions conducive to the formation of internal waves can occur at any time of the day due to the thermal inertia of large bodies of water. The purpose of this note is to discuss the climatological variations of the occurrence of internal gravity wave events at a coastal site as compared with an inland site, and possible reasons for the difference.

#### 2. Data

Mean wind speed and direction at a height of 24 m have been recorded continuously at Tiana Beach,

Long Island, New York, since June 1975 as part of a coastal meteorological study (Raynor *et al.*, 1975). A directional vane with a propeller (Aerovane) is used for the measurements. An Easterline-Angus recorder is used for recording the observations on a chart.

Data for this study were obtained from wind speed and direction charts. Internal waves were easier to identify from wind direction than from wind speed charts due to better sensitivity in the chart records. Data were obtained as "gravity wave events" (Fig. 1), an event consisting of a number of internal gravity waves that occurred consecutively. Thus, an event may last for several tens of minutes depending on the number of gravity waves. A definition of this kind had the advantage of characterizing the meteorological conditions for a set of waves. From the number of waves and the beginning and ending times of an event, the average apparent period of the waves was estimated.

Observations at Tiana Beach over a three-year period 1976-78 were used for the analysis. The height of measurement at Tiana Beach was 24 m. Similar data were obtained from wind speed and direction measurements made at a height of 106 m at Brookhaven National Laboratory (BNL), 15 km inland, to compare with the observations made at the coastal site. The main purpose of this study is to discuss the meteorological conditions conducive to the occurrence of internal waves at a coastal site. Comparison with an inland site is made to present the results in contrast to inland conditions. Observations at 106 m had to be used inland due to lack of measurements at 24 m. Moreover, it is believed that a height of 24 m may be well within the aerodynamic boundary layer due to the presence of a

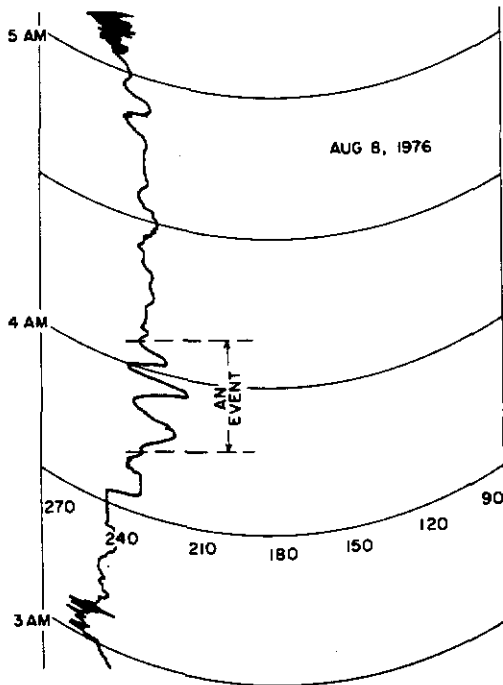


FIG. 1. A typical internal gravity wave event at Tiana Beach. Three waves from 0345 to 0405 with an average amplitude of  $\sim 21^\circ$  can be seen. The wind speed was  $5 \text{ m s}^{-1}$  and the direction southwesterly.

rough terrain making it difficult to identify internal waves.

### 3. Discussion of results

One of our objectives is to examine the directional, diurnal and seasonal dependence of the occurrence of internal waves at Tiana Beach and to compare the results with those obtained at an inland site. The main differences between a coastal and an inland site

are the presence of a large body of water for onshore wind directions at the coastal site and greater aerodynamic roughness inland.

The percent of gravity wave events that occurred at Tiana Beach during the years 1976 and 1977 are shown by sectors of  $22.5^\circ$  each in Figs. 2 and 3, respectively. It can be seen that for both years, the maximum percentage of internal wave events occurred with a southwesterly wind direction. The actual number of wave events varied significantly between the two years. The total number of internal wave events was 40 in 1976 and 88 in 1977. Data for three months, from August to October, were missing in 1976; but it is believed that this may not have altered the total number of events appreciably. Thus onshore flow with a southwesterly wind direction seems to account for most of the internal wave events that occur at the coastal site. This is believed to be due to warm continental air flowing over the cooler ocean causing surface-based inversions. Southerly and southeasterly wind directions were usually found to be associated with near-neutral thermal stabilities due to long fetch over water. Frequencies of occurrence of internal gravity waves at Tiana and BNL were compared with those of wind directions. The results are shown in Table 1 (calms were not counted as a separate category). Percentage of occurrence of wind directions for different sectors were computed from hourly mean winds observed at both the sites. The maximum number of internal waves seems to occur for a southwesterly wind direction even at BNL which is  $\sim 15 \text{ km}$  inland. This might be due to the advection of relatively warmer air over a radiatively cooled land surface. Marine air has less diurnal variation in temperature as compared to air over land.

For a typical inland location, stable atmospheric conditions occur at night due to radiational cooling

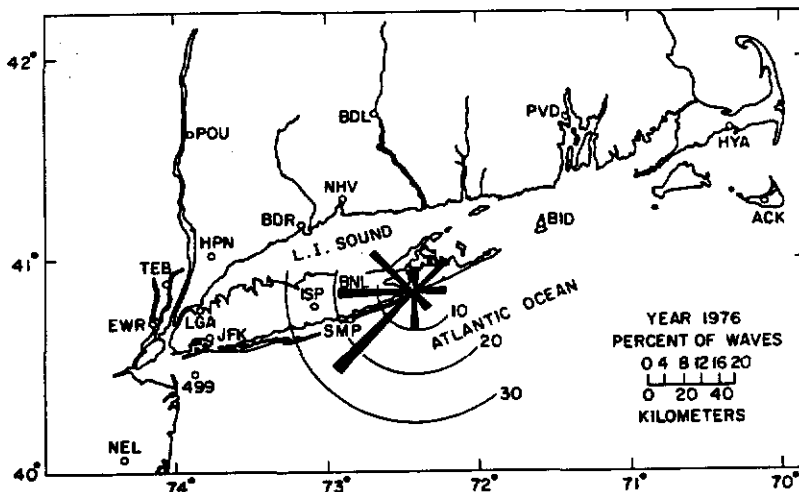


FIG. 2. Occurrence of internal gravity-wave events as a function of wind direction for the year 1976. Total number of events was 40.

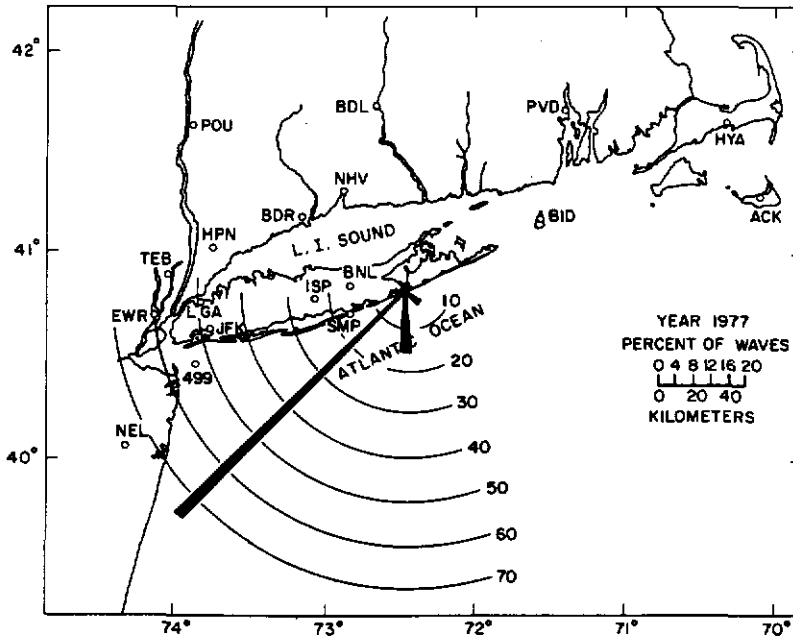


FIG. 3. Occurrence of internal gravity wave events as a function of wind direction for the year 1977. Total number of events was 88.

of the surface. Hence, internal waves generally occur during nights. This was found to be the case for the observations at the Laboratory, as indicated by the frequency diagram in Fig. 4. On the other hand, data at the coastal site (Fig. 5) showed the occurrence of internal waves during both daytime and nighttime hours. This is believed to be due again to the formation of surface-based inversions caused by the cool ocean surface.

Numbers of internal wave events at the coastal site as a function of month are plotted in Fig. 6 for 1976 and 1977 and show significant seasonal effects. For both the years mentioned, the maximum number of wave events occurred in spring and summer. The difference in magnitude and distribution of the internal wave events between the two years could be

due to a relatively more severe winter in 1977 as compared with 1976 causing colder water temperatures during the spring months. The severity of the winter in 1977 could be inferred from radiometric sea temperature measurements made by the U.S. Coast Guard and from monthly mean air temperatures measured at BNL. No significant variations in the occurrence of internal waves between different seasons are noticeable for the inland site at BNL (Fig. 7).

In order to investigate the existence of any critical range of mean wind speeds for the occurrence of internal wave events, the variation with wind speed was investigated. For the coastal site, a range of hourly mean wind speeds, from 3 to 8 m s<sup>-1</sup>, was found to be present when most of the internal waves

TABLE 1. Comparison of the occurrence of internal waves with that of wind direction for the year 1977.

Direction	Percent of occurrence of direction		Percent of occurrence of internal waves	
	Tiana	BNL	Tiana	BNL
N	6.5	8.6	2.3	5.4
NE	8.3	8.9	0.0	8.9
E	6.6	6.8	0.0	3.6
SE	5.0	5.7	2.3	14.3
S	10.2	8.0	14.8	3.6
SW	26.7	22.0	75.0	30.4
W	19.9	19.4	3.4	26.8
NW	16.8	20.6	2.2	7.0

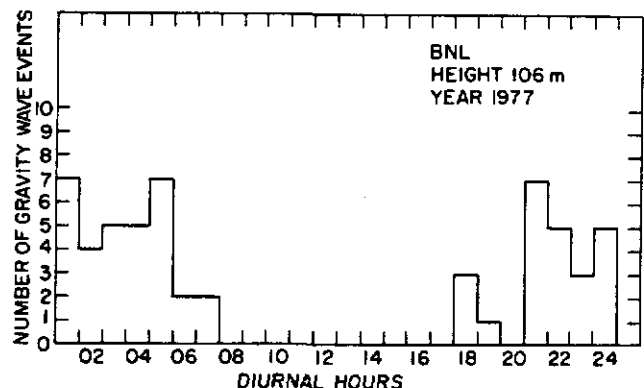


FIG. 4. Diurnal variation of the internal wave events for 1977 at the inland site (BNL). The times are EST.

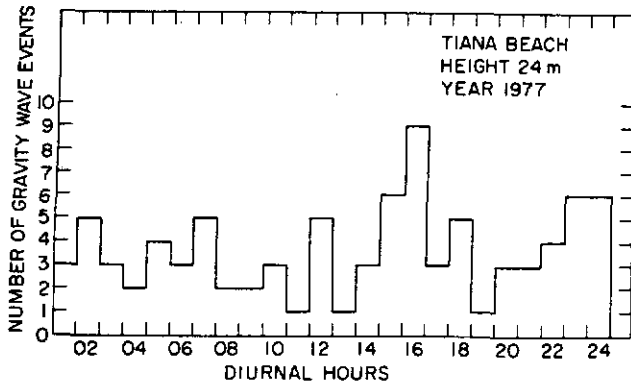


FIG. 5. Diurnal variation of the internal wave events for 1977 at the coastal site (Tiana Beach). The times are EST.

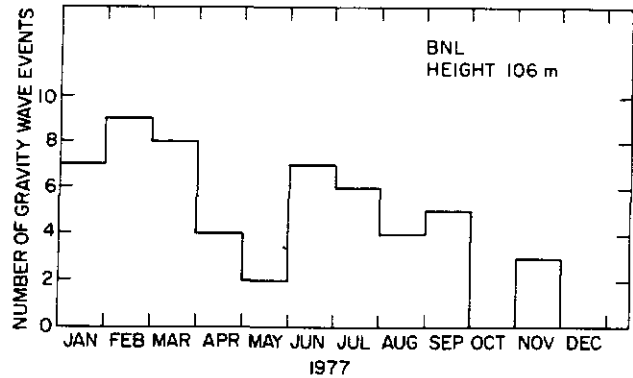


FIG. 7. Internal wave events as a function of the month for 1977 at BNL.

occurred. For the inland site, the range was 2–7  $m s^{-1}$ . The maximum number of wave events occurred with wind speeds between 4 and 5  $m s^{-1}$  at the beach and between 3 and 4  $m s^{-1}$  inland. For wind speeds  $\geq 8 m s^{-1}$ , mechanical turbulence probably becomes important and prevents the formation of temperature inversions.

Mean horizontal amplitudes of the internal waves were computed for each month in 1977 from wind direction charts. This amplitude was read from the chart as the value from crest to trough of the wave. The mean horizontal amplitudes at the beach varied between 10 and 15° throughout the year except for the month of May when they reached a value of about 25°. Corresponding values inland showed the mean to be between 10 and 15° for all months with a maximum of  $\sim 25^\circ$  for June. Time period for the wave was computed from a knowledge of the total length of the event and the number of waves in the event. The number of waves in events studied varied from 2 to 10 with a mean of  $\sim 5$ . Mean monthly time periods of the internal waves varied from 6 to 9 min

for Tiana Beach. Variability from month to month was greater for BNL with values between 4 and 10 min. Individual time periods varied between 3 and 12 min for Tiana beach and 3 to 13 min for BNL. An estimate of wavelengths is difficult to obtain without a knowledge of stabilities and vertical velocity variations. However, previous studies at Tiana Beach have indicated wavelengths of the order of 100–500 m at the height of measurements (SethuRaman, 1977, 1980) for similar time periods.

#### 4. Conclusions

Stable atmospheric conditions that are conducive to the formation of internal gravity waves occur at all hours at the coastal site. At the inland site, internal waves do not appear to occur during daytime due to the surface heating by solar radiation. Thermal inertia of large bodies of water, on the other hand, dampens a diurnal cycle of heating and radiational cooling. During spring and early summer, cooler ocean water causes the formation of stable atmospheric layers near the surface when warmer air masses move in from land. Internal gravity waves tend to form and break in these layers (SethuRaman, 1977; 1980) and affect the transport and diffusive characteristics of the atmosphere. Meandering of plumes of materials released in the atmosphere during stable conditions is one effect. The internal waves seem to form in air masses with moderate wind speeds in the range 3–8  $m s^{-1}$  and have significant amplitudes. Mean periods of the waves were around 6–9 min.

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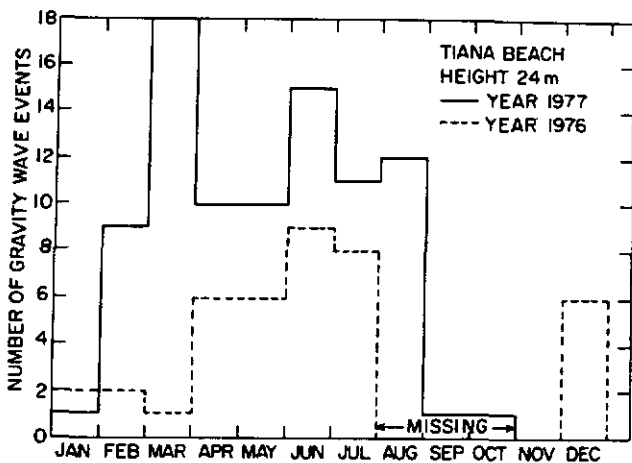


FIG. 6. Internal wave events as a function of the month for 1976 and 1977 at Tiana Beach. MISSING indicates the period for which observations were not available.

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