A CASE OF PERSISTENT BREAKING OF INTERNAL GRAVITY WAVES IN THE ATMOSPHERIC SURFACE LAYER OVER THE OCEAN

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Abstract. Formation and breaking of internal gravity waves contributing to a very significant increase in turbulence in the atmospheric surface layer over the Atlantic Ocean off Long Island, New York are reported. Contrary to the bursts that are characteristically of short duration, this increase in turbulence lasted for more than one hour and was typical of what one would observe during unstable atmospheric conditions. However, mean temperature profiles indicated strong stable conditions.

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1. Introduction

Internal gravity waves are known to co-exist with turbulence close to the earth's surface during nocturnal stable atmospheric conditions (Caughey and Readings, 1975) over land. Internal waves have also been observed in the marine surface layer during daytime conditions with stably stratified atmospheric surface layer (SethuRaman, 1977). These waves tend to break because of instability caused by various atmospheric processes and may reform again if conditions are conducive. Theoretical studies (Gossard and Hooke, 1975) and field observations (Ludlam, 1967; Woods, 1969, etc.) have shown that internal waves in the atmosphere and oceans become unstable as the local Richardson number becomes less than about 0.25. Layers with Richardson numbers greater than 0.25 tend to have stable propagating waves.

Strong surface-based inversions off Tiana Beach (Figure 1) are common due to warm air advection with southwesterly winds over the cold ocean, particularly during spring and summer seasons. Formation of the internal gravity waves and their intermittent breaking have been observed at Tiana Beach for several years. The purpose of this paper is to present a set of observations showing the formation of internal gravity waves in the marine surface layer and their breaking, increasing the turbulence to levels far higher than the values that one would expect over water during stable conditions. The breaking and the resulting turbulence lasted for more than one hour as compared with periods typically less than five minutes for intermittent bursts. The wave-breaking could have been due to shear instability, resonance with surface gravity waves, etc.

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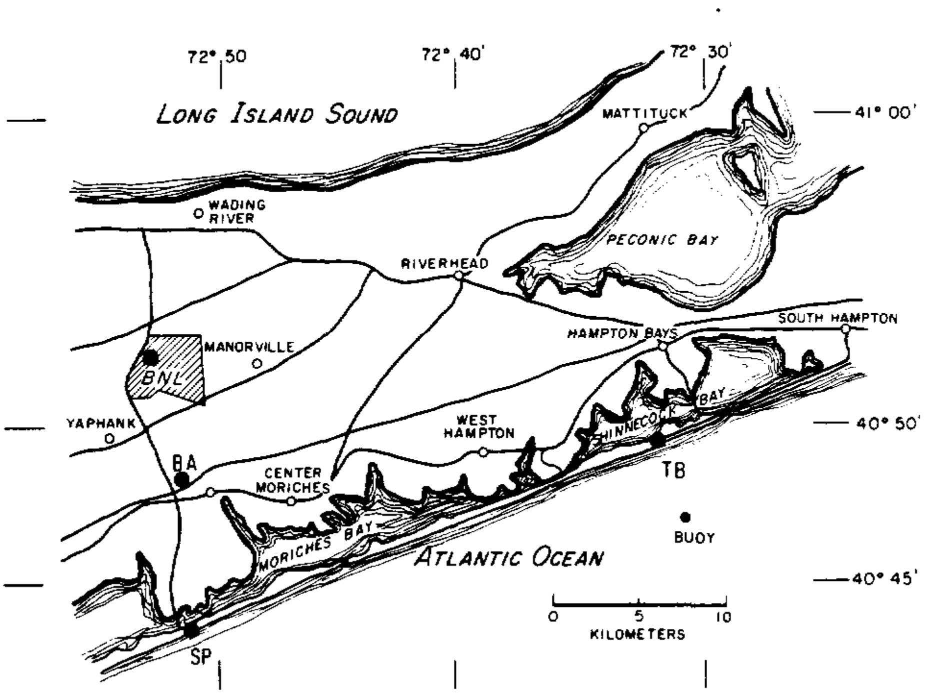

Fig. 1. Map of a portion of Long Island showing the location of the experimental site, Tiana Beach.

2. Measurements

Observations reported here were obtained on June 10, 1976 as part of the coastal meteorological studies conducted by Brookhaven National Laboratory (Raynor *et al.*, 1975, 1978). Observations were made at a 24-m high meteorological tower located at a distance of about 40 m from the ocean and at a 10-m mast on the beach very close to the land-sea interface. Mean wind speeds were measured at heights of 3.4, 10.7, 14.3, 18.0 and 23.5 m on the tower and at heights of 1, 2, 4, 6, 8, and 10 m on the mast. Other measurements at the tower consisted of mean wind direction; longitudinal, lateral and vertical components of turbulence; air temperature; and relative humidity at 23.5 m and air temperatures at 10.7 and 18 m levels. Turbulence was measured with a MRI vector vane, air temperature with thermistors and relative humidity by a Vaisala probe. Pilot balloon soundings were made at the beach to obtain wind speeds and directions at higher elevations. A single engine aircraft was used to make mean temperature and turbulence measurements over the ocean at heights up to 1000 m. A Universal Indicated Turbulence System, manufactured by MRI, was used to measure energy dissipation rate ε, an indicator of turbulence. Analog data were digitized at 8 per second and processed with a digital computer.

3. Analysis of Data

The synoptic situation that existed on June 10, 1976 is shown in Figure 2. Weather was mostly clear with less than one-tenth cirrus and altocumulus. A large high-pressure system centered near western Virginia extended over much of the east

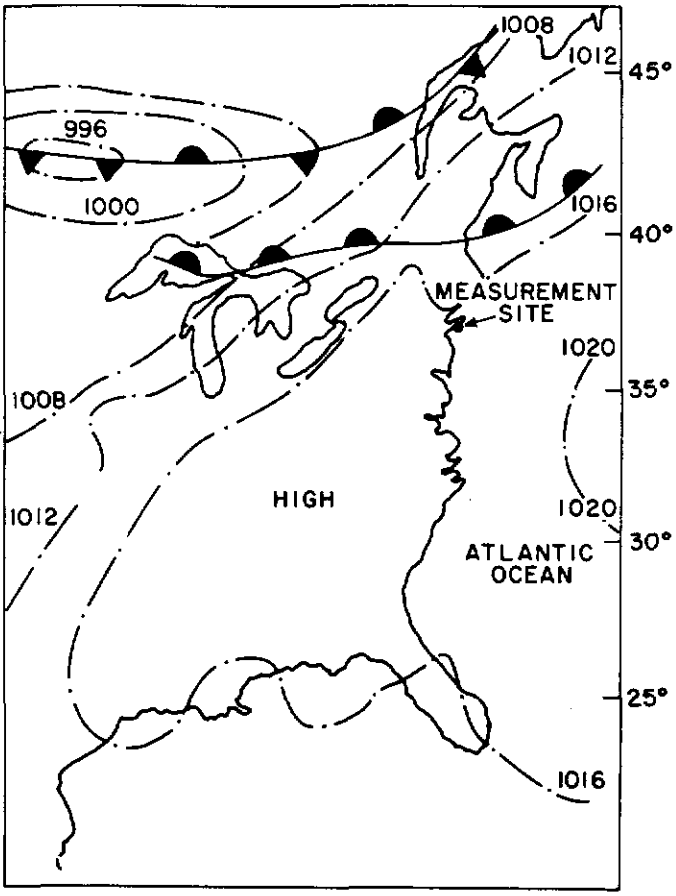

Fig. 2. Surface weather map at 0700 EST, June 10, 1976 showing the synoptic conditions in the vicinity of the experimental site.

coast. A weak east–west front extended from southern Maine westward and a weak trough extended southward along the New England coast to New Jersey. Wind direction was southwesterly at Tiana Beach. The meteorological conditions described above are most conducive to the formation of internal gravity waves in the stably stratified layer immediately above the water surface (SethuRaman, 1976; 1977). Vertical profiles of mean potential temperatures over the ocean at three different time periods during the experiment are shown in Figure 3. Three layers of differing stabilities seem to exist: the first 100 m has the steepest temperature gradient (Slab 1); above 300 m, near-neutral conditions exist (Slab 3); a transition layer (Slab 2) lies in between. The measurements made at 1150 EST pertain to the initial conditions when internal waves were clearly visible in the wind records and the succeeding measurements were taken after wave breaking was observed. An interesting feature in Figure 3 is the maintenance of the stability disparity between Slabs 1 and 2 even after mixing caused by the breaking waves. Surface-based inversions existed for all three time periods.

Mean wind speed and direction were continuously measured at 23 m with a directional vane and recorded on a chart. Speed and direction traces for the time

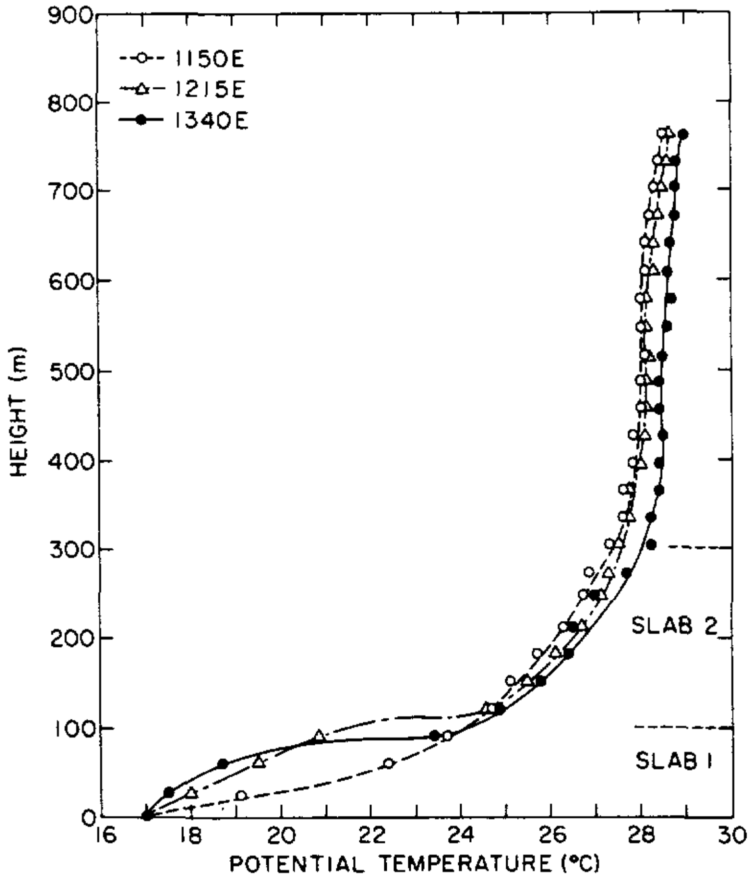

Fig. 3. Mean potential temperatures measured by the aircraft 2 km offshore at different times. Surface temperature was measured with an infrared detector.

interval 1130 to 1430 EST are shown in Figure 4. The direction trace shows clearly the occurrence of internal waves from about 1155 to about 1220 EST and intermittent breaking of waves to about 1300 EST. This phenomenon has been observed before (SethuRaman, 1977). It generally occurs due to shear instability causing pockets of turbulence. Waves usually reform again if the flow remains sufficiently stable. Persistent breaking causing increased turbulence from 1300 EST to 1430 EST is a feature that was not observed before during diffusion experiments conducted at Tiana Beach with onshore stable flows (Raynor, *et al.*, 1975) or in a climatological analysis of the wind records at Tiana Beach for three years. Wind direction of 250 deg pertains to alongshore flow (Figure 1). The continuous chart recording of speed and direction was helpful in planning and obtaining subsequent observations made from the aircraft to determine the aerial extent of wave-breaking. Measurements from the aircraft supplemented simultaneous observations made from the beach.

Wind speed and direction at higher elevations obtained from pilot balloon soundings are shown in Figure 5. Although these are instantaneous observations, they still define to some extent the structure of the boundary layer. Pilot balloon

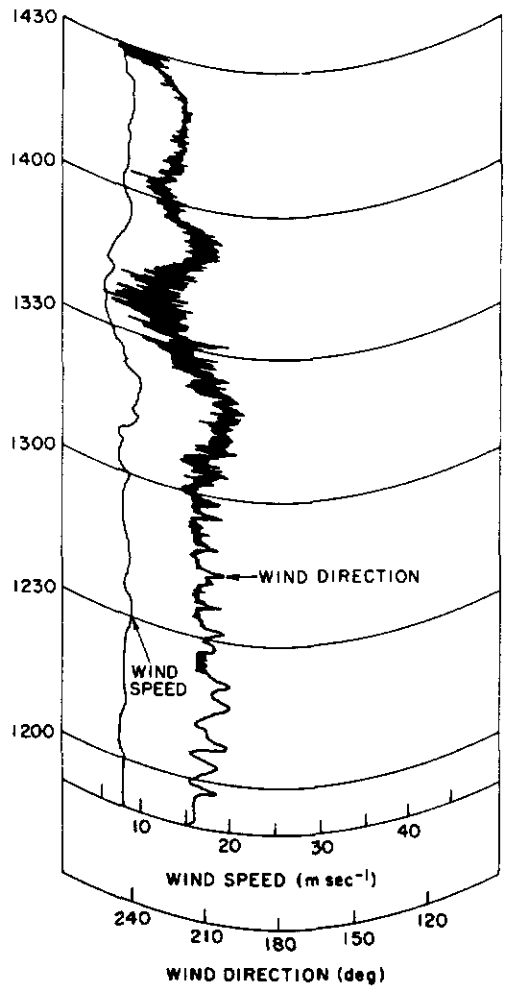

Fig. 4. Wind speed and direction at 24 m for the duration of the experiment measured by a directional sensor (Aerovane) located at the beach. Formation of internal waves and their breaking can be seen.

ascents were made at three different time periods corresponding to different events in the experiment. Referring to Figure 4, Ascent 1 was made when the gravity waves were dominant in the flow and Ascent 2 was made when persistent breaking of the waves occurred. Variation of wind speed with height indicates the existence of two layers – a low-level jet-like flow up to about 200 m and a fairly-well-mixed layer above. These two layers are roughly the same as noted from the potential temperature structure in Figure 3. Flow in the first 200 m is similar to the 'nocturnal jet' commonly observed over land with strong surface-based inversions.

Time histories of fluctuations of speed, horizontal direction and elevation angles are shown in Figure 6. Internal gravity waves are clearly seen in the horizontal directions and elevation angles. Amplitudes in horizontal direction angles were between 12 and 15 deg. Formation and breaking correspond to the same time periods mentioned with reference to Figure 4. Wavelike features are apparent even after the onset of breaking. Instantaneous vertical velocities reached values up to 100 cm s^{-1}, which is typical of strong convective flows.

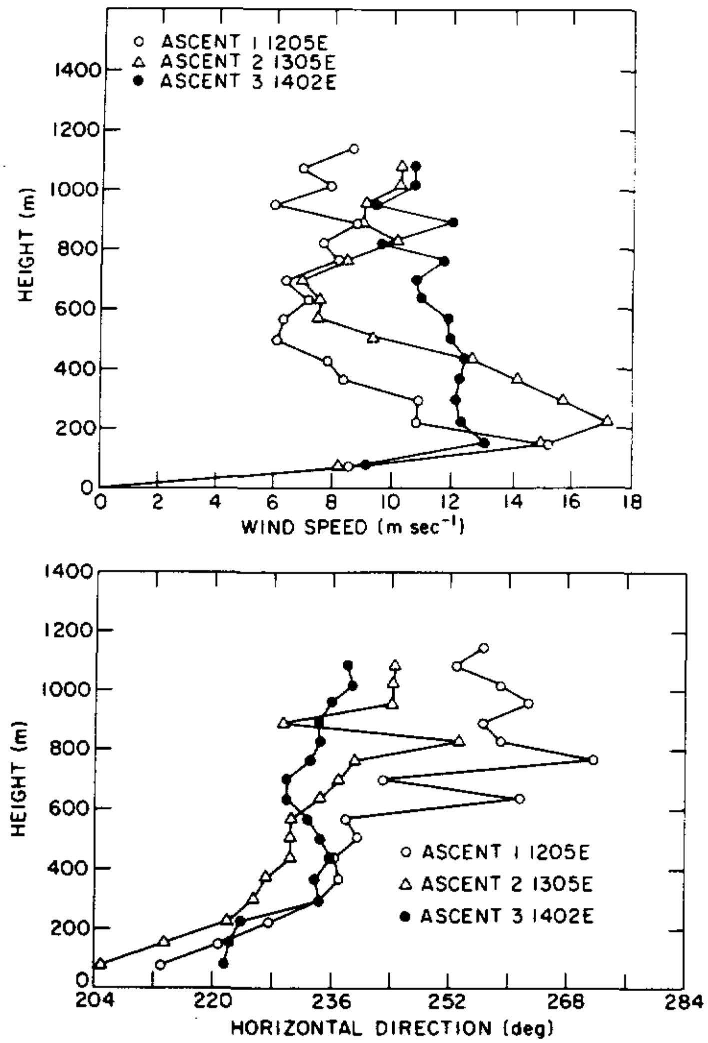

Fig. 5. Wind speed and direction up to a height of 1000 m obtained by pilot balloon soundings at the beach.

Time history of the energy dissipation rate ε measured at different times at various elevations over the ocean during the experiment are shown in Figures 7, 8 and 9. These flights were made parallel to the beach about 2 km offshore. Figure 7 shows the ε measured at a height of 40 m at 1230 EST during intermittent breaking of waves (see Figure 4) and at 1406 EST during continuous, persistent breaking. Values usually observed over water at this height for stable atmospheric conditions are about 1 $cm^2 s^{-3}$ (Raynor *et al.*, 1979). An increase by about two orders of magnitude (Figure 7) was rather surprising. A relation of the form

$$\varepsilon = \frac{u_*^3}{kz} \tag{1}$$

where u_* is the friction velocity, k is Von Kármán's constant (≈ 0.4) and z the height is appropriate for ε during near-neutral conditions. With $u_* = 20\ cm\ s^{-1}$, ε for a

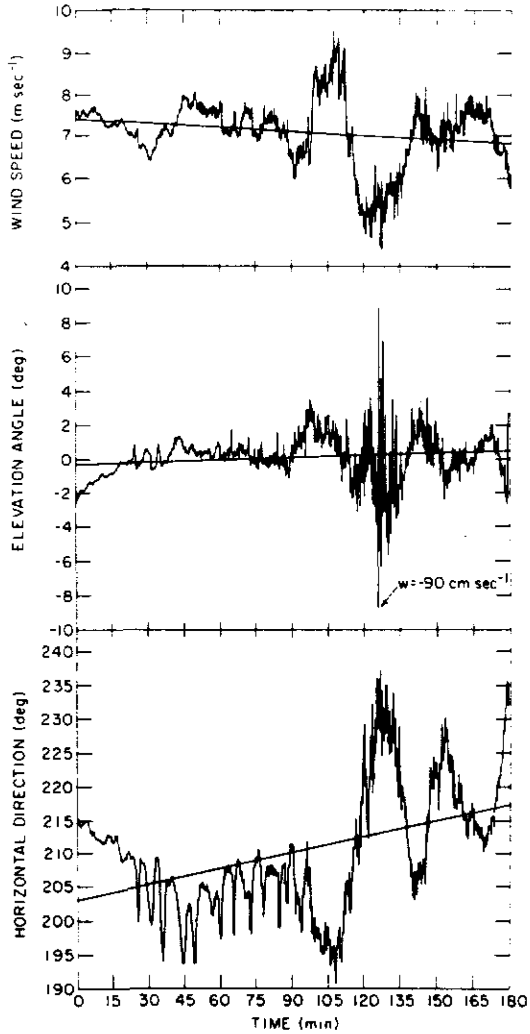

Fig. 6. Time history of vector wind speed, elevation angle and horizontal direction fluctuations at 23.5 m. Solid line through the data is a linear regression line. Starting time was 1135 EST.

height of 40 m over water will be approximately 5 $cm^2 s^{-3}$. Values of ε during stable conditions will be far less than 5. Spatial separation of pockets of turbulence is seen for the time period 1230–1240 EST and complete turbulence for the period 1406–1422 EST. It is interesting to note that the observations in Figure 7 were taken within Slab 1 (see Figure 3) where a strong surface based inversion existed during the experimental period. Figure 8 shows the time histories of ε at 183 and 335 m during persistent breaking of waves. An elevation of 183 m is within Slab 2 where moderately stable conditions existed during the experiment (see Figure 3). An abrupt change in turbulence above 100 m is shown in Figure 9. The aircraft ascended from 90 to 140 m during the 8-min flight offshore. Values of ε decreased abruptly above 100 m. Another factor worth noting is that ε increased with height (Figures 6 and 8) in Slab 1. This is contradictory to the generally observed decrease of ε with height.

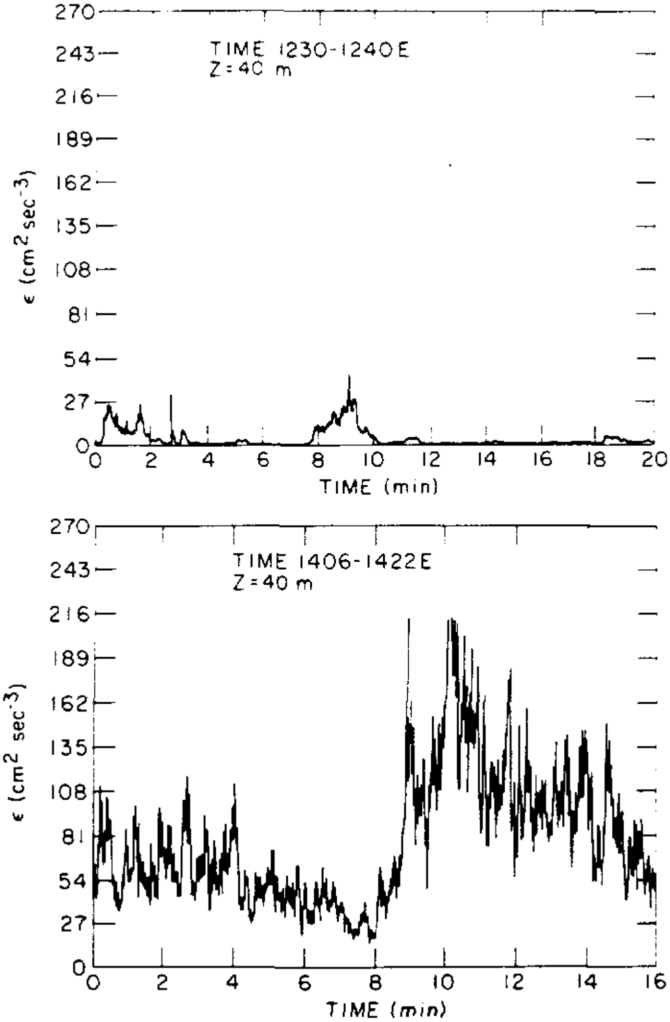

Fig. 7. Energy dissipation rate ε measured at a height of about 40 m (Slab 1 in Figuare 3) above the ocean 2 km offshore during the partial breaking (1230–1240 EST) and during the continuous breaking (1406–1422 EST) of internal waves. Increase in mean might be due to variations in altitude.

Typical energy spectra for the v-component for different time intervals are shown in Figure 10. Data were preaveraged over 10 intervals before computing the spectra. For the time interval 1135–1220 EST, when the waves were present but not breaking, the peak of the v-spectrum occurred at a frequency of 0.003 Hz or a time period of about 6 min corresponding to the periodicity of the waves inferred from Figure 4 or from Figure 6. Harmonics of this dominant wave can be seen at higher frequencies in the spectrum. The time interval 1220–1305 EST represented a period of partial wave-breaking. The peak of the spectrum occurred at about the same frequency with somewhat less energy and with increased energies at higher frequencies. Harmonics of the dominant wave were still present. For the remaining two time intervals that were representative of the continuous wave-breaking event, energy decreased at the dominant frequency, but increased at lower and higher frequencies.

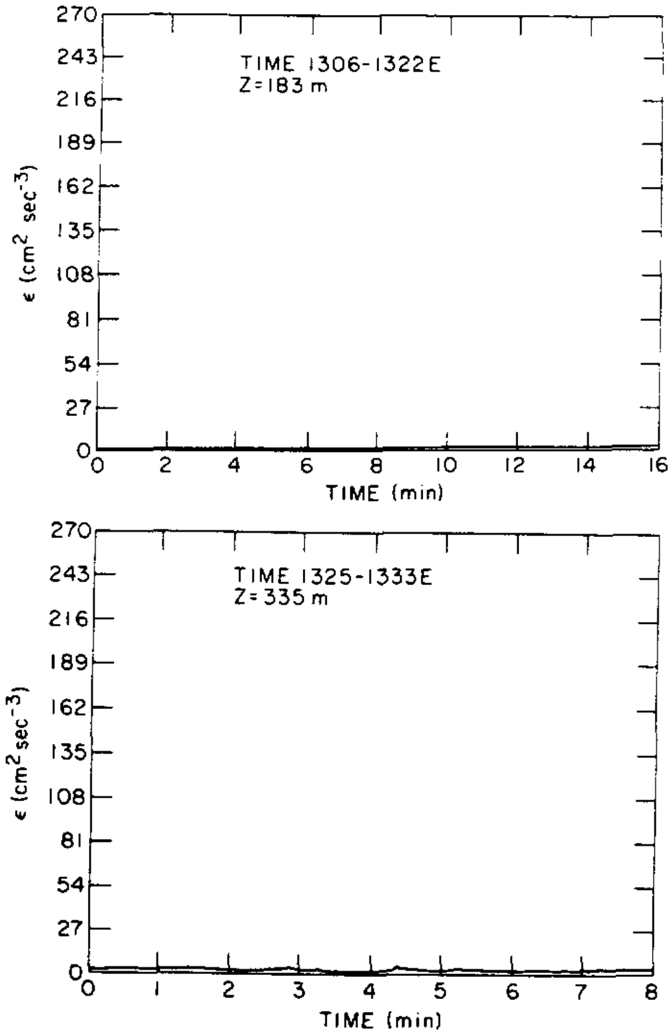

Fig. 8. Energy dissipation rate ε measured at 183 m (Slab 2) and at 335 m above the ocean 2 km offshore. Notice the low turbulence values as compared to Figure 7.

Increase in energy at higher frequencies might be due to the process of wave breaking that enhances turbulence.

Mean wind speeds, standard deviations and covariances of velocity fluctuations, and other turbulence statistics at Tiana Beach during the experiment are given in Table I. Mean wind speeds did not vary much during the 3-hr time period; but the turbulence varied significantly. Time periods in Table I have been selected to correspond to the various events during the experiment such as wave propagation, bursts, and continuous breaking. Standard deviations of longitudinal, lateral and vertical velocity fluctuations, σ_u, σ_v and σ_w, respectively, increased to maximum values during the initial stages of continuous breaking (1305–1350 EST). The longitudinal axis was chosen along the mean wind direction. σ_v was observed to be greater than σ_u for all time periods. This is probably due to the propagation of waves in the lateral direction. Intensity of turbulence, $\sigma_u/\bar{u}$ increased by a factor of five

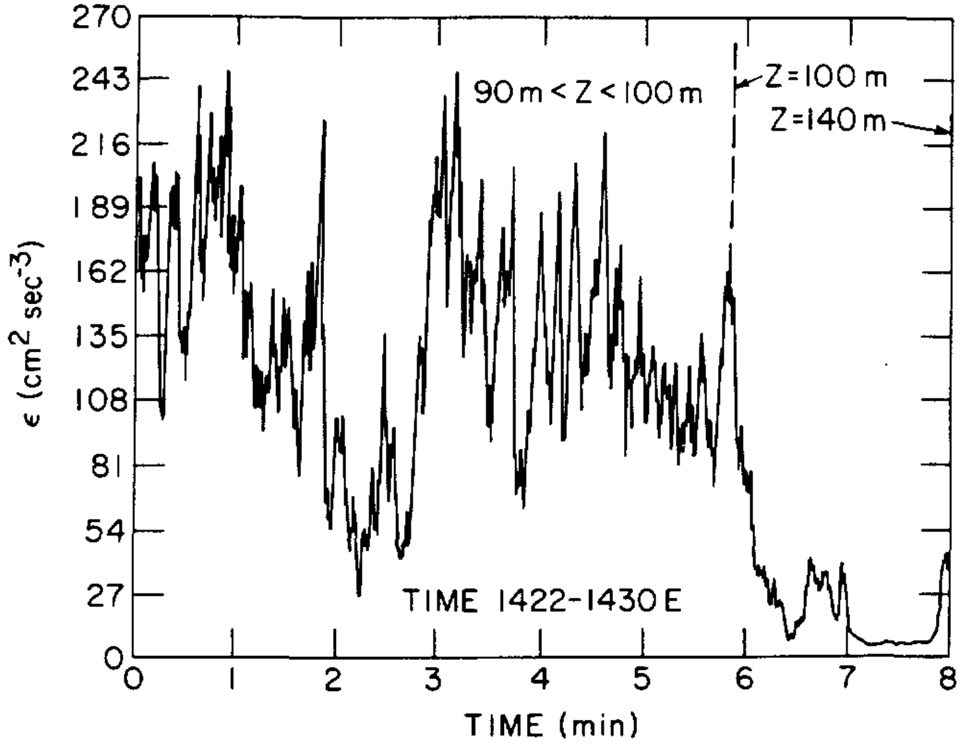

Fig. 9. Energy dissipation rate ε measured near the interface between Slabs 1 and 2 (Figure 3). The aircraft slowly ascended from 90 to 140 m. An abrupt decrease in turbulence can be seen at 100 m.

from about 4% in the beginning to about 20% when the waves started breaking continuously. Assuming a u_* of 20 cm s^{-1} for near-neutral conditions, with $\sigma_u \simeq 2.6u_*$ (SethuRaman *et al.*, 1978), $\sigma_u/\bar{u}$ can be estimated as 7%. Thus the intensity of turbulence increased by a factor of three over the neutral values when waves started breaking continuously although stable atmospheric conditions existed during this period (Figure 3). Turbulent flux $\overline{uw}$ was close to zero during the first two periods (1135–1305 EST). This is typical of conditions when internal wave propagation happens to be a dominant factor. As the wave breaking occurred continuously, turbulent flux $\overline{uw}$ became positive, indicating an upward transfer of momentum. An increase in turbulence and downward transfer of momentum are generally observed with wave breaking (SethuRaman, 1977). As can be seen from Table I, an increase in turbulence was observed but no significant downward flux of momentum; in fact, an upward momentum flux was noticed during the time interval 1305–1350 EST. Turbulent energy given by $\sigma_u^2 + \sigma_v^2 + \sigma_w^2$ is also given in Table I.

A relationship of the form

$$q = fE/\varepsilon \tag{2}$$

when q represents the number of cycles it takes to change the kinetic energy of the motion E by an amount comparable with E, and f is a characteristic frequency associated with a given motion, usually the Brunt–Väisälä frequency N if available, is

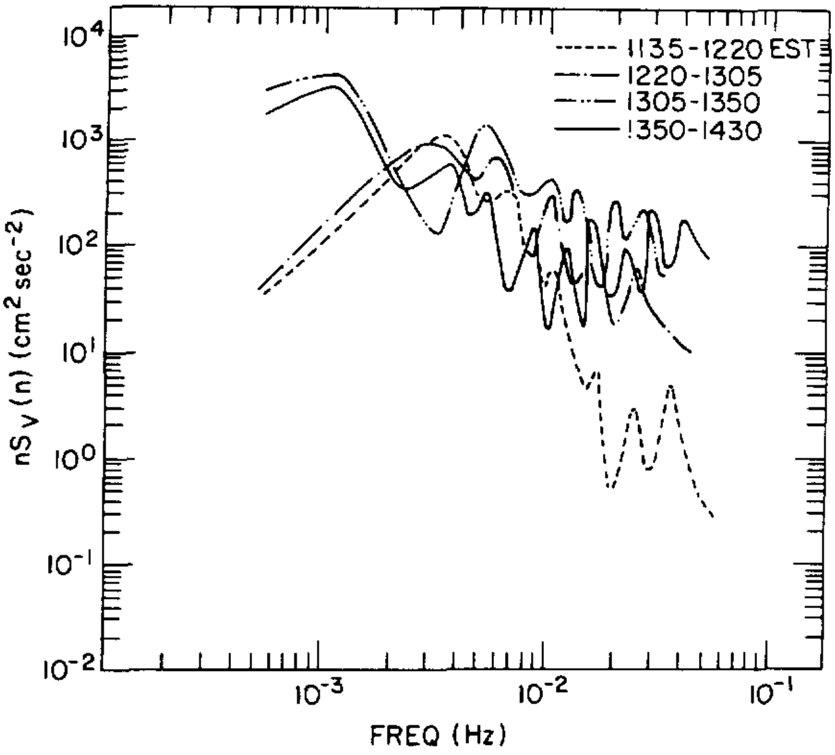

Fig. 10. Variance spectra of lateral velocity fluctuations for different time intervals representing internal wave propagation (1135–1220 EST), intermittent breaking (1220–1305 EST), and continuous breaking (1305–1350 and 1350–1430 EST).

useful in distinguishing internal waves from turbulence (Busch, 1969). For a turbulent motion, q is close to 1. Using appropriate values for f, E and ε, values of q have been listed in Table I. The time period 1135–1220 EST had a value of q two orders of magnitude greater than 1 indicating flow dominated by internal waves. Values of q for other time periods were not much different from 1 indicating the increase in turbulence due to wave breaking. Longitudinal turbulence measured at the beach mast at different levels is given in Table II. For the first time period when the waves were present, intensity of turbulence decreased with height. As the wave breaking occurred, turbulence increased at all levels but remained roughly invariant with height.

TABLE I

Turbulence Statistics at Tiana ($z = 24$ m)

Time (EST)	$\bar{u}$ (m s^{-1})	σ_u (m s^{-1})	σ_v (m s^{-1})	σ_w (m s^{-1})	$\overline{uw}$ (cm^2 s^{-2})	$\overline{uv}$ (cm^2 s^{-2})	$\overline{vw}$ (cm^2 s^{-2})	$\sigma_u/\bar{u}$	E (cm^2 s^{-2})	q
1135–1220	7.22	0.32	0.67	0.12	3	220	−59	0.044	5657	94
1220–1305	7.35	0.38	0.42	0.06	0	−395	−48	0.052	3244	2.2
1305–1350	6.62	1.33	1.36	0.23	231	−7383	−303	0.201	29429	2.2
1350–1430	7.16	0.51	0.79	0.13	−22	−1859	−500	0.071	9011	0.7

TABLE II

Beach Mast: Turbulence Level, $\sigma_u/\bar{u}$

	z (m)					
Times (EST)	1	2	4	6	8	10
1235–1315	0.125	0.130	0.117	0.108	0.109	0.098
1315–1355	0.178	0.181	0.187	0.185	0.172	0.179

4. Discussion of Results

Observations were presented in the previous sections in the form of raw and analyzed data which gave an insight into this unique phenomenon of 'persistent breaking' of internal gravity waves. The word 'persistent breaking' was chosen to differentiate this process from the usual intermittent breaking or bursts. An attempt will be made in this section to estimate the parameters of the waves and discuss possible causes of the wave-breaking observed in this experiment.

For internal waves, the restoring force is characterized by the Brunt–Väisälä frequency N (rad s^{-1}) given by

$$N=\left\{\frac{g}{\bar{\theta}}\frac{\mathrm{d}\theta}{\mathrm{d}z}\right\}^{\frac{1}{2}} \tag{3}$$

where g is the gravitational acceleration, $\bar{\theta}$ the potential temperature and $\mathrm{d}\theta/\mathrm{d}z$ the potential temperature gradient. Considering the mean temperature profile observed at 1150 EST (Figure 3), it could be divided approximately into three height intervals of differing $\mathrm{d}\theta/\mathrm{d}z$ viz., 0–100 m or Slab 1, where temperatures increase significantly with height, 100–300 m or Slab 2, where temperatures increase slowly with height, and the region above 300 m where temperature remains constant with height. Assuming a linear variation of θ, Brunt–Väisälä frequency N_1 for Slab 1 can be computed as 0.0517 rad s^{-1} or 0.008 23 Hz. Corresponding value of N_2 for Slab 2 will be 0.0222 rad s^{-1}. Since $N_2 < N_1$, the internal waves propagating in Slab 1, will be trapped. From a knowledge of N_1 and the longitudinal and vertical velocity variations, characteristics of the interval waves that existed during the period 1130–1230 EST can be estimated.

Using the method used by Hooke *et al.* (1973), the intrinsic frequency n_w of the wave is related to local N by

$$\left\{\frac{N^2}{n_w^2}-1\right\}^{1/2}=\frac{\Delta U}{\Delta W} \tag{4}$$

where U and W are the amplitudes of the horizontal and vertical velocity perturbations, respectively. From Figure 6, $\Delta U/\Delta W$ can be estimated as 7. Using this value of $\Delta U/\Delta W$ and with N equal to 0.008 23 Hz, $n_w = 0.0116$ Hz. Observed time period of the wave τ_0 is given by

$$\tau_0=\frac{\lambda}{U(z)+C(z)} \tag{5}$$

where λ is the wavelength, $U(z)$ the mean wind speed, and $C(z)$ the velocity of the wave relative to air at height z. With $n_0 = 1/\tau_0$ and $C(z) = \lambda n_w$,

$$\lambda = \frac{U(z)}{n_0 - n_w}. \tag{6}$$

With $n_0 = 0.003$ Hz estimated from Figures 6 and 10, $\lambda \simeq 3800$ m and C (23.5 m) = 4.4 m s^{-1}.

Not much is known about wave breaking. Some of the mechanisms attributed to wave breaking are overturning, shear instability, convective instability, resonant interaction, an instability called 'growing disturbance' (Thorpe, 1975), and wave-turbulence interaction (Chimonas, 1972). The wave breaking observed in this experiment could be due to any one or any combination of the above processes.

5. Conclusions

A case of persistent breaking of internal gravity waves in the atmospheric surface layer over the ocean was observed. Two distinctly different stable layers were present with the internal waves propagating in the lower layer. As waves started breaking, turbulence increased but the momentum flux was upward. Stability of the two layers were significantly different even after the waves started breaking. The reason for this unique persistent breaking is not known at present.

Acknowledgments

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