Coupling between a moving air-pressure disturbance and the sea surface

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ABSTRACT

On 23 November 1953 an atmospheric pressure disturbance travelled eastward across Long Island Sound (east of New York City) at an average speed of 42 ft/sec. Simultaneously, abnormal water level heights were recorded with increasing amplitude in Long Island Sound eastward from New York City. This is explained as a disturbance produced by near resonant coupling between the atmospheric pressure disturbance and the free wave traveling in the region of appropriate depth in the Sound.

Introduction

Coupling between a squall-line and a high wave in the English Channel has been discussed by Proudman (1952). Resonant coupling between atmospheric pressure-jump lines and the waters of Lake Michigan (U.S.A.) have been shown for cases of surface gravity waves and edge waves, respectively by Ewing, Press & Donn (1954) and Donn & Ewing (1956). Donn & McGuinness (1960) showed a case of coupling between atmospheric gravity waves and low amplitude (20 mm) long period (10 min) ocean waves recorded off New York City at Texas Tower No. 4 (before its collapse in a storm). Redfield & Miller (1957) suggested that hurricane storm surges affecting Long Island may at times be explained by resonant coupling between the ocean wave and the storm traveling northward over the shallow continental shelf off eastern United States.

This report deals with a case in which a relatively strong coastal sea level disturbance is related to a travelling atmospheric pressure disturbance. Cases of this type are of importance in the understanding of air–sea energy coupling. They are also of value because of the catastrophic effects of storm surges that have been generated in the past by resonant coupling to hurricanes, squall lines and related phenomena. In view of the difficulty of developing exact mathematical solutions of this problem because of the complex configuration of natural water bodies, more case studies, as noted by Harris (1957) are of particular value. In this report we will consider a case of an anomalous sea wave associated with a moving air-pressure disturbance.

Tide Gauge Data

During the early evening of 23 November 1953 an unusual increase in water level occurred at Woods Hole, Massachusetts. This disturbance was recorded with increasing amplitude at tide stations in Long Island Sound eastward from New York City. The locations of the tide stations whose records are illustrated in Fig. 1 are shown in the bathymetric chart of Fig. 2. At Montauk, the wave height is 0.42 feet; at Newport 0.55, and at Woods Hole, 0.93 feet. At Montauk and Woods Hole the effect occurs with one wave being especially prominent and with wave periods of about 20 min. At Newport a high amplitude train of waves with a period of about 10 min occurs for about three hours. Unfortunately, no other tide station existed in Long Island Sound east of New York City.

In Table 1, the arrival times of the main peak of the sea level disturbance is given together with a summary of the wave heights.

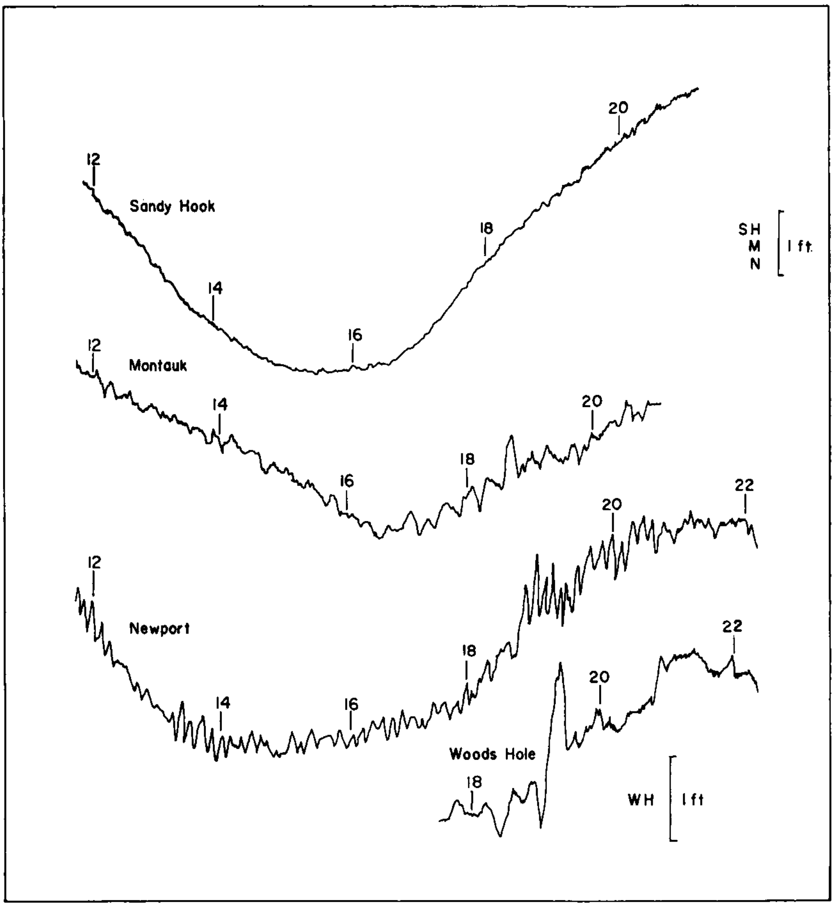

Fig. 1

Air Pressure Data

During the afternoon of 23 November a cold front crossed the region shown in Fig. 2 from west to east. The front was preceded by pressure irregularities for several hours as illustrated in the microbarograms in Fig. 3. The pressure fluctuations are more prominent on the New York and New Haven records which have been recorded on a compressed time scale—one clock rotation per week, compared to one rotation per day at other stations.

The pressure irregularities at New York and New Haven begin with a sharp increase in pressure (pressure-jump) at 0500 and 0600 respectively, and culminate with a stronger pressure drop with the trough arriving at 1345 and 1445 respectively. At Hartford, Providence and Woods Hole, the initial jump is very weak (not evident on these extended records) but the terminating drop is present with diminishing amplitude. Travelling air pressure disturbances of this nature apparently result from internal gravity waves in the atmosphere (e.g. Tepper, 1952; Balanchandran & Donn, 1964).

It is this last strong pressure trough propagating over the entire critical area (Fig. 2) that correlates well with the sea level disturbance. The microbarogram from Nantucket, about 90 km to the southeast of Woods Hole, has no indication of the air pressure fluctuations. The data of arrival times and magnitudes of the culminating pressure trough are given in Table 2. Arrival times refer to the negative peak point. Although data for Boston are included to show the extent of the disturbance, they are not involved in further discussion because the station is somewhat outside the critical area.

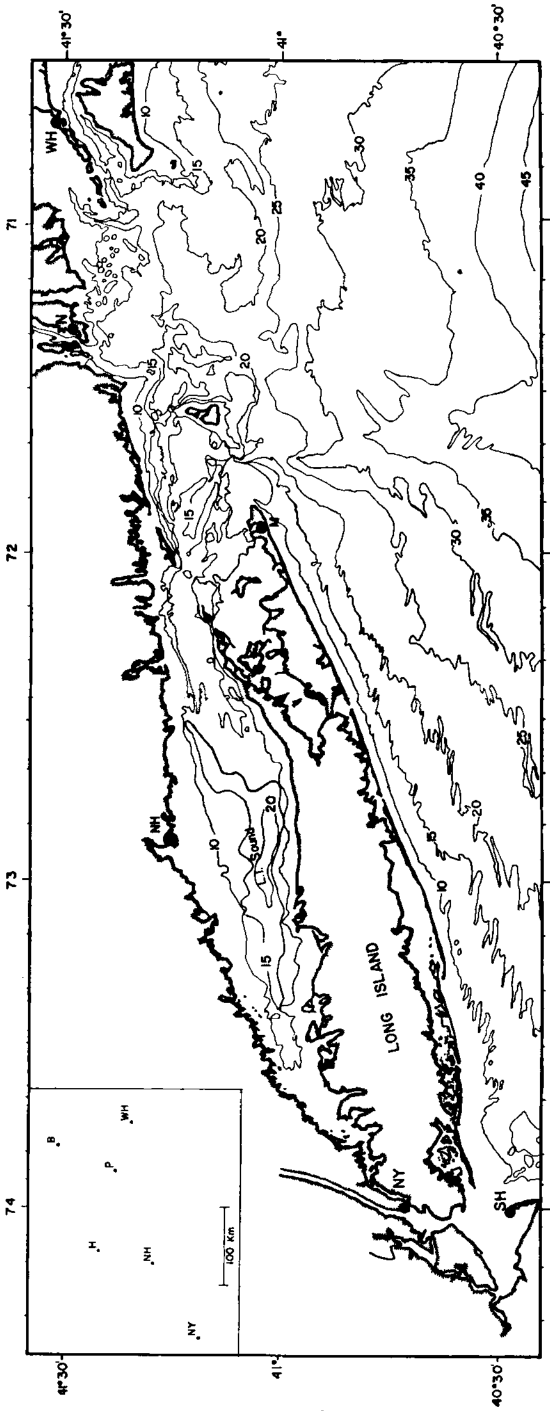
LONG ISLAND
L.I. Sound
WH
NH
NY
SH
B
P
H
100 Km
41°30'
41°
40°30'
71
72
73
74

Fig. 2

Table 1. *Water disturbance data*

Station	Arrival time (EST)	Height of disturbance (ft)
Sandy Hook	—	0.00
Montauk	1842	0.84
Newport	1842	1.10
Woods Hole	1924	1.86

We calculated the speed and direction of propagation of the air pressure trough with the assumption that it extended as a straight line perpendicular to the travel direction. This is justifiable in view of the well known behavior of pressure-jump lines and the presence of a squall line on the U.S. Weather Bureau map just preceding the critical time.

The speed and direction of travel of the air disturbance can be found from any triangluar array of stations. In view of the inaccuracy involved in determining arrival times from microbarograms of the type used, the changing appearance of the records and the nature of the station network, the results have limited accuracy. We used the two triangles formed by New York, New Haven, Hartford and New Haven, Hartford, Providence. Providence was used in place of Woods Hole because of its expanded barogram time scale. Wave vector computations give for the western triangle a speed of 54 ft/sec from 277°; for the eastern triangle, a speed of 30 ft/sec from 280°. The average speed over the network is 42 ft/sec.

Table 2. *Air pressure data*

Station	Arrival time (EST)	Pressure change (millibars)
New York City	1330	3.4
New Haven	1500	2.7
Hartford	1507	2.7
Boston	1750	0.7
Providence	1815	2.0
Woods Hole	1825	1.8

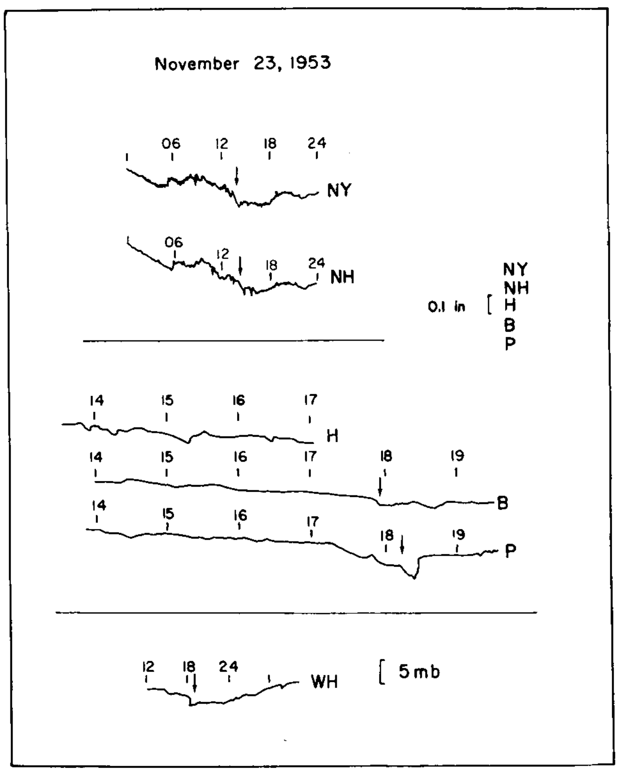

Fig. 3

Discussion

The similarity in occurrence of the air and sea waves suggests an air-sea coupling effect particularly since no seismic disturbances had occurred which might have generated a seismic sea wave (which are practically unknown in this region). Although no pressure data is available from Montauk and Newport, the arrival time of the air wave should have been about the same as at Providence. Some uncertainty exists because the exact orientation of the pressure trough line cannot be determined.

The average air-pressure change over the critical area was 2.5 mb. The equivalent equilibrium barometric change on the water surface is close to 2.5 cm (1 in.) of water. Because equilibrium would not likely develop in view of the motion of the pressure disturbance, the direct barometric effect would be smaller than one inch of water. In view of the water wave height, which varied from nearly one foot to two feet, a magnification of about 20 times the direct barometric effect, a mechanism of resonant coupling is suggested.

Such a mechanism requires a matching of the phase velocities of the air and water disturbances. According to the phase velocity formula for long ocean surface waves, $C = \sqrt{gh}$, where g is the acceleration of gravity and h is the water depth, the depth of water required to match the average speed of the air wave (42 ft/sec) is nine fathoms. In view of the errors inherent in the air wave computations, an error of ± 2 fathoms is estimated.

As indicated by the position of the 10 fathom contour in Fig. 2, the depth required for resonance is found fairly continuously along the northern border out to the eastern end of Long Island. Also, according to the computed wave direction, a considreable fetch is available along this depth zone. The argument for resonant coupling from air to water is supported by the absence of a detectable water disturbance at Sandy Hook.

In view of the irregular bathymetric and coastal patterns and the possible increase in wave height in the shallow confined waters of the tide gauge sites, it is difficult to estimate quantitatively the magnification due to resonance. Also, it seems clear that the air wavefront oriented roughly north-south, extended across a broad zone of varying depths. The portion travelling over the depth zone of exact resonance would be both limited in breadth and shifting in location.

However, significant increase in water wave height would occur without exact coincidence of air and water wave speed. For a simple rectangular channel Proudman (1952) has derived the water level change that may be caused by atmospheric pressure disturbance, The factor by which the barometric equilibrium water wave height is increased is given by:

$$\frac{v^2}{v^2 - c^2}$$

where C is the speed of the atmospheric disturbance and v is the water wave speed ($\sqrt{gh}$).

For the water wave magnification of approximately twenty-times (refered to earlier) the solution of Proudman's formula applied to the average speed of the air wave yields a depth of 10 fathoms. It thus appears that the tide gauge disturbance in Long Island Sound on 23 November 1953 was generated by near resonant coupling between the atmosphere and the sea surface.

Because the preferred depth for coupling is in the open waters of Long Island Sound, a delay in the arrival of the wave at the tide stations is expected. This can only be checked for Woods Hole where such a delay occurs.

The train of 10 minute waves persisting for about three hours at Newport can be explained as seiche oscillations of the inlet region in which the tide gauge is located. The excitation of seiches by atmospheric pressure disturbances moving at the speed of the free wave velocity in the water has been described by Donn & Ewing (1956), Greco, Calci & Visioli (1957) and Donn (1959).

Acknowledgements

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ВЗАИМОДЕЙСТВИЕ МЕЖДУ ДВИЖУЩИМСЯ ВОЗМУЩЕНИЕМ ДАВЛЕНИЯ В ВОЗДУХЕ И ПОВЕРХНОСТЬЮ МОРЯ

23 ноября 1953 г. возмущение атмосферного давления перемещалось на восток через пролив Лонг-Айлэнд (к востоку от Нью-Йорка) со средней скоростью 13 м/сек. Одновременно аномальные уровни поднятия воды были зафиксированы с нарастающей амплитудой по направлению к востоку в проливе Лонг-Айлэнд. Это объясняется как возмущение, порожденное резонансом между атмосферным возмущением давления и свободной волной, движущейся в области с соответствующей глубиной в проливе.