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Atmospheric Turbulence and Storm Surge Due to Hurricane Belle (1976)

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ABSTRACT

Mean and fluctuating winds were measured within the atmospheric surface layer at three locations across Long Island during the landfall of Hurricane Belle on 9 August 1976. An order of magnitude increase in wind shear was observed. A maximum friction velocity of ~133 cm s^{-1} and a maximum energy dissipation rate of ~130 cm^2 s^{-3} were estimated. Mean wind speeds at the beach were found to be 3–5 times the corresponding wind speeds inland. A periodicity in rainfall associated with bands of thundershowers was observed. A storm surge of ~125 cm was estimated from water level records near Shinnecock Inlet. The records indicated the three successive stages, forerunner, hurricane surge and resurgence, associated with the hurricane.

1. Introduction

Hurricane Belle started as a tropical depression and became organized on 6 August 1976 about 400 mi east of Palm Beach, Florida. The disturbance deepened through the tropical storm phase to become a hurricane by 8 August. It then moved northward and made landfall on Long Island near Jones Beach around 2200 EST 9 August (0300 GMT 10 August). The storm track of Hurricane Belle is shown in Fig. 1 which indicates a near-northerly movement at a rate of about 20 mi h^{-1}. A series of satellite pictures taken on 9 and 10 August is shown on Fig. 2. The storm was weakening rapidly as it approached land (Lawrence, 1977). An understanding of the microstructure of severe storms like hurricanes in the surface layer is important for a variety of applications—design of buildings and structures, prediction of damages, evacuation of people, etc. The study of the structure of hurricanes within the first 100 m over water becomes logistically difficult due to the rough seas and lack of stable platforms. The environmental data buoys operated by NOAA (National Oceanic and Atmospheric Administration) monitor the mean quantities of the storm as it passes by, and the National Hurricane Research Laboratory of NOAA studies hurricanes at higher altitudes with aircraft (Miller, 1962; Riehl and Malkus, 1961; Merceret, 1976). This paper examines the structure of the variation of wind across Long Island as the hurricane approached and then moved over the Island. Analysis of the storm surge associated with the hurricane is also presented.

2. Measurements

Wind speed and direction were measured at a height of about 10 m at three locations across the island—Smith's Point, Brookhaven Airport and Brookhaven National Laboratory. The relative location of these three stations is shown in Fig. 3. The storm made landfall near Jones Beach ~90 km west of Shinnecock Inlet. In addition, wind speed, direc-

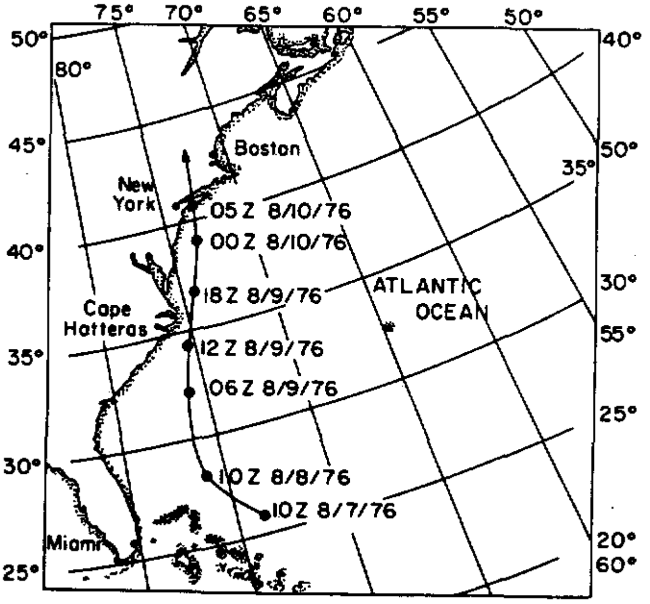

FIG. 1. Hurricane Belle storm track.

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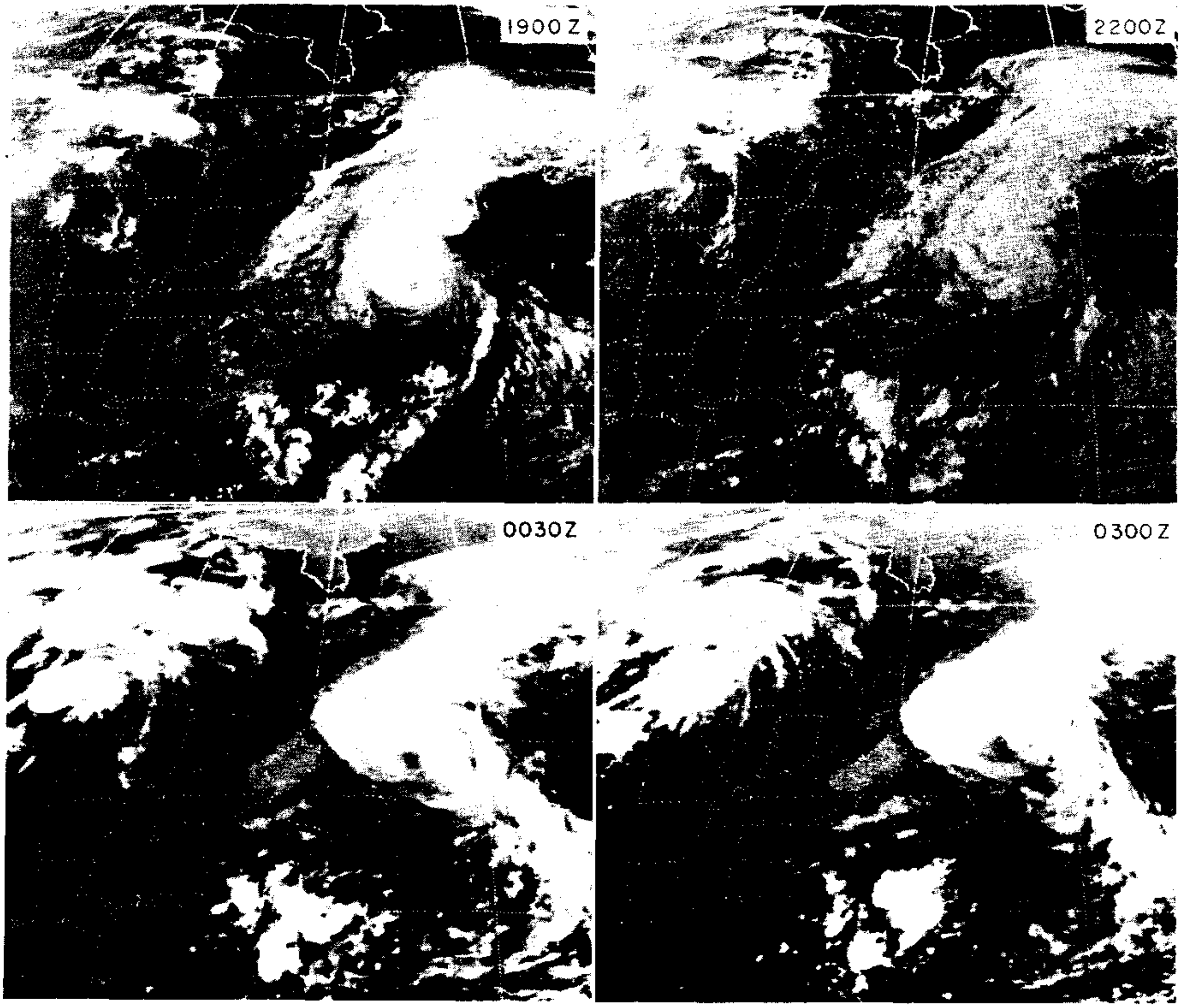

FIG. 2. Satellite pictures of Hurricane Belle. The times noted are GMT. The top two are visible (9 August) and the bottom two are infrared (10 August) views of the hurricane.

tion and turbulence were measured at a height of 109 m on a 126 m high meteorological tower at the Laboratory. Speed and direction of wind at all three locations were observed with a Bendix Aerovane. The wind speed presented here is the longitudinal component along the mean wind direction. The frequency response of the Aerovane is estimated to be better than 1 Hz (SethuRaman and Brown, 1976). Spectral analysis of the data discussed in a later section confirms this assumption. The speed and direction of wind at each location were recorded on strip charts. The wind speed at 109 m at Brookhaven National Laboratory was recorded on magnetic tape in analog form. These were later low-passed through a four-pole RC analog filter (Krohn-hite Model 3323) at 3 Hz and digitized at 8 s^{-1}.

Other measurements at the Laboratory consisted of barometric pressure, air temperature and precipitation. The variation of barometric pressure during the passage of the hurricane is shown in Fig. 4. Minimum pressure was observed around 0100 EST. The air temperature variation shown in Fig. 5 indicates a sharp increase at 2000 with the temperature decreasing to the original value in ~5 h. An increase of 4°C was noticed as the hurricane passed Long Island. Precipitation was continuously measured at the Laboratory with a tipping bucket device and also by a sequential sampler. Samples of precipitation from the sampler were later analyzed for various chemical compositions. The data obtained from the rain gage were averaged to 30 min/values and are plotted in Fig. 6. A periodicity of ~1 h in rainfall is noticeable. Most of the precipitation occurred preceding the hurricane.

Sea surface elevations near Shinnecock Inlet

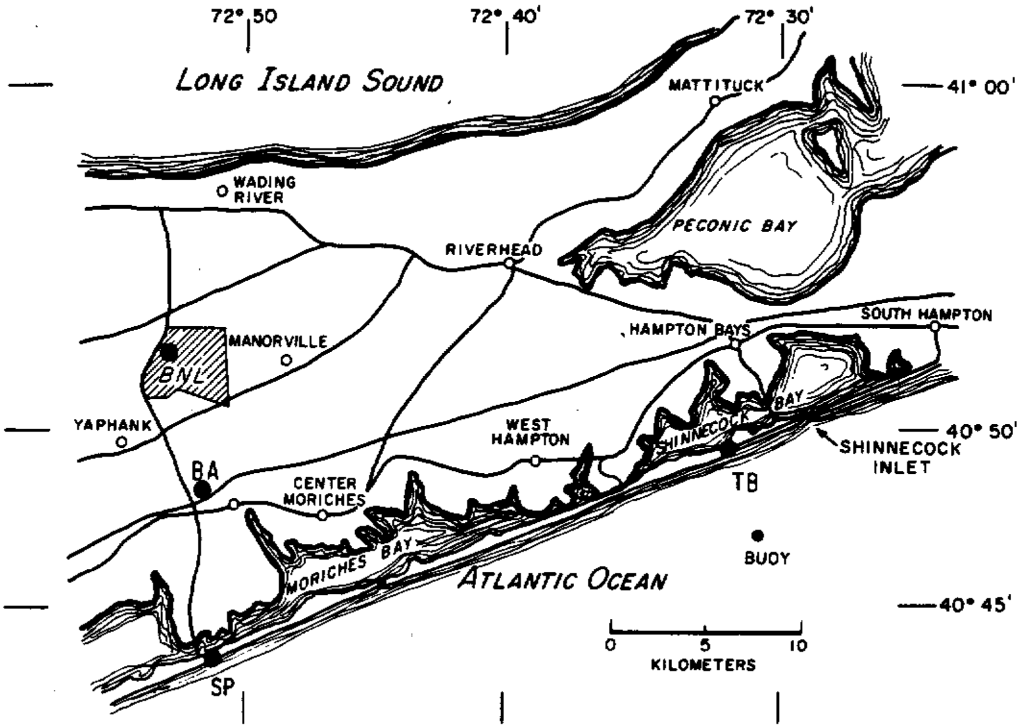

FIG. 3. Map of a portion of eastern Long Island showing Brookhaven National Laboratory (BNL), Brookhaven Airport (BA) and Smith's Point (SP).

near Westhampton Beach, Long Island, were obtained from the Suffolk County Department of Public Works. These observations were analyzed to estimate storm surge due to hurricane Belle.

3. Variation of mean wind speeds and gusts across the island

The three stations shown in Fig. 3 are located nearly north–south across the Island with Smith's Point being at the south shore about 100 m from the ocean and Brookhaven Airport and Brookhaven National Laboratory about 10 km and 18 km inland. The 5 min/mean, minimum and peak wind speeds measured at Smith's Point and at Brookhaven National Laboratory are compared in Fig. 7 from 1600 EST 9 August to 0100 EST 10 August. The observations correspond to a height of 10 m at both stations. Unfortunately, the instrument and recorders at Smith's Point stopped functioning at 2300

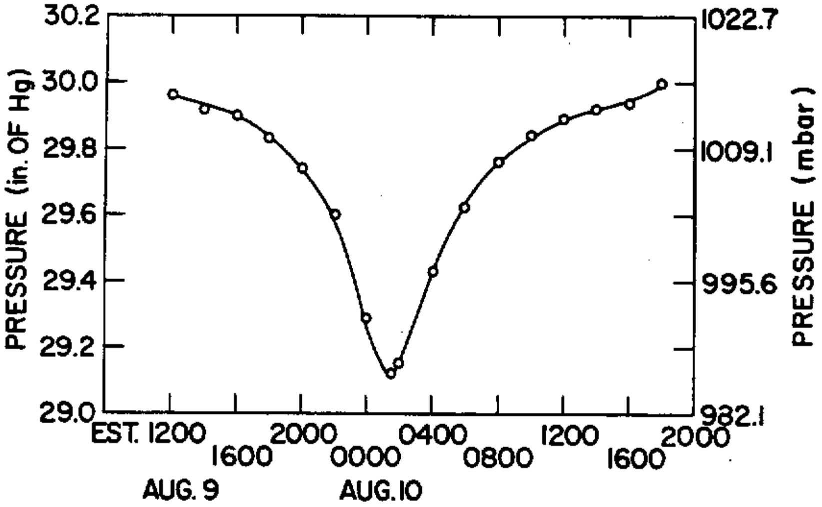

FIG. 4. Variation of the barometric pressure at BNL during the passage of storm.

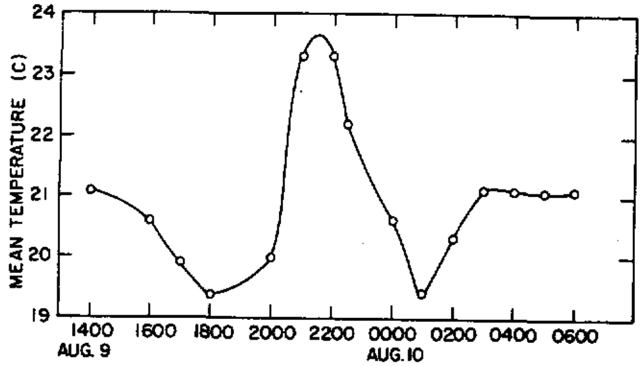

FIG. 5. Air temperature variation at BNL measured at a height of ~2 m. Note the increase when the hurricane made landfall.

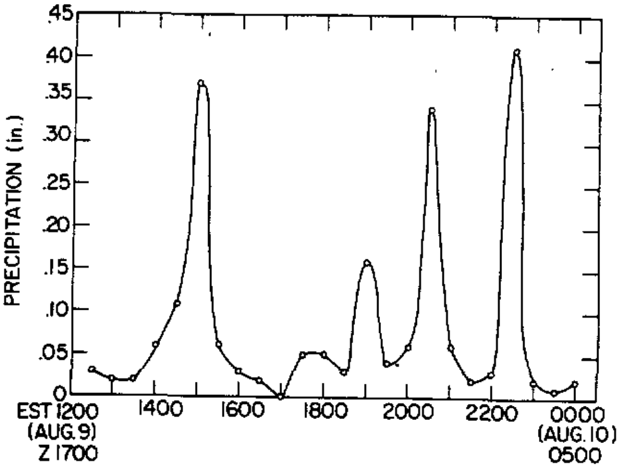

FIG. 6. Thirty-minute mean precipitation at BNL observed with a tipping bucket rain gage. A periodicity of rainfall associated with bands of thundershowers is seen.

EST due to power failure. A mean wind speed of ~40 m s^{-1} was observed at Smith's Point before power failed. The mean and peak wind speeds at Smith's Point were three to five times higher than those observed inland. The wind speeds at Brookhaven Airport were in between the values measured at Smith's Point and Brookhaven National Laboratory. The roughness length over ocean for aerodynamically rough flow will be a few millimeters and the corresponding value at Brookhaven is estimated to be ~1 m. The reduction in wind speeds at an inland site for onshore flows has been observed before (Raynor, 1977) and is attributed to increase in roughness. Increases in wind speeds associated with periodic thundershower activity are also seen at both of the stations. A uniform increase in wind speed from 20 m s^{-1} at 2100 EST to ~40 m s^{-1} at 2230 EST was observed at Smith's Point. The rate of increase was smaller at Brookhaven National Laboratory.

4. Wind shear

The hourly mean wind speeds and wind directions observed at 10 m and 109 m on the meteorological tower are compared in Table 1 to get an estimate of the longitudinal and lateral shears. Differences between the 5 min mean wind speeds

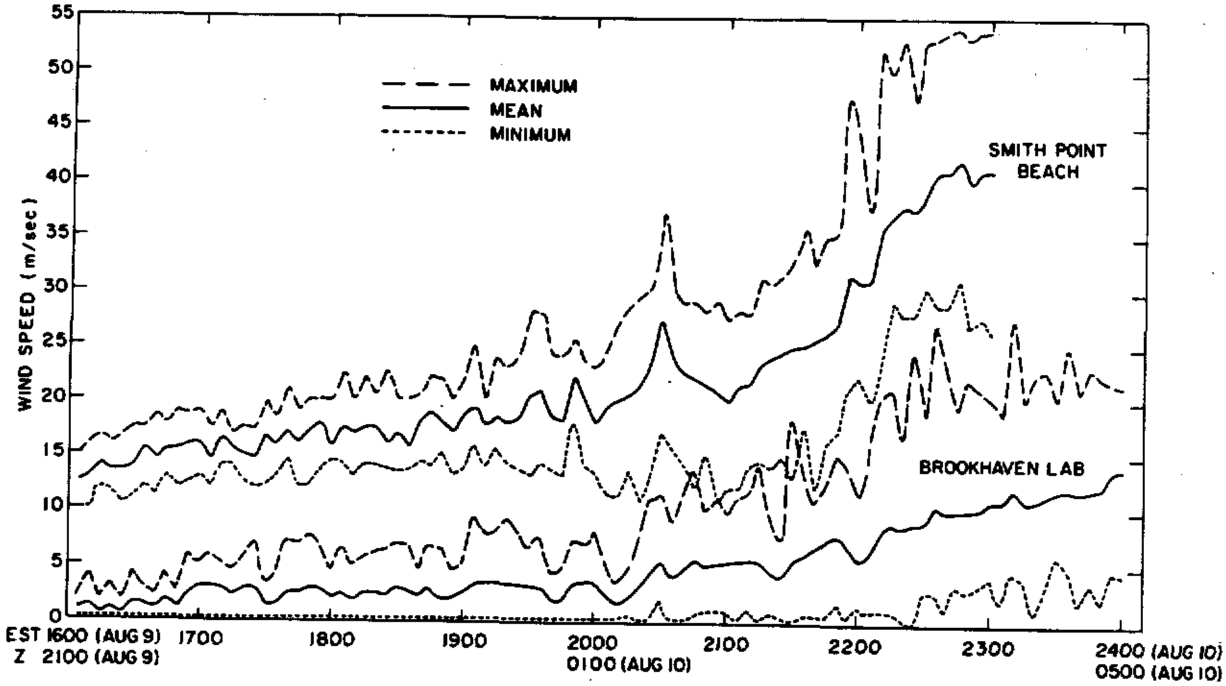

FIG. 7. Variation of the mean, minimum and peak wind speeds at Smith's Point and at BNL. Height of measurement 10 m.

TABLE 1. Time history of mean wind shears.

Time (EST)	Mean wind speed (m s^{-1}) z = 10 m	z = 109 m	Difference	Mean wind direction (deg) z = 10 m	z = 109 m	Absolute difference
9 August						
1600–1700	1.7	5.9	4.2	58	58	0
1700–1800	2.5	7.8	5.3	53	53	0
1800–1900	2.8	8.6	5.8	55	54	1
1900–2000	3.4	10.2	6.8	55	52	3
2000–2100	6.3	10.8	4.5	73	75	2
2100–2200	7.5	11.8	4.3	105	78	27
2200–2300	12.0	18.0	6.0	108	95	13
2300–2400	13.8	20.8	7.0	118	113	5
10 August						
0000–0010	14.8	19.8	5.0	150	144	6
0100–0200	9.5	16.9	7.4	188	190	2
0200–0300	8.0	15.8	7.8	220	222	2
0300–0400	6.8	13.2	6.4	237	234	3

at the two levels were even higher with the maximum observed velocity difference of 9.5 m s^{-1}. As shown in Table 1, the mean directional shear increased appreciably to 27° around 2200 EST and slowly decreased to about 6° in 3 h. The mean wind directions at 109 m given in Table 1 indicate the relative locations of the hurricane as it moved past Long Island.

A rough estimate of the friction velocity u_* can be obtained by using a logarithmic profile relationship of the form

$$\bar{u} = \frac{u_*}{\kappa} \ln \frac{z}{z_0}, \tag{1}$$

where $\bar{u}$ is the mean wind speed at height z, κ is von Kármán's constant (~0.4) and z_0 the roughness length. The atmospheric surface layer tends to be neutrally stratified during high wind conditions due to intense mixing. Hence, using Eq. (1) for the two heights (10 and 109 m) and subtracting one from the other, a relationship of the form

$$u_2 - u_1 = \frac{u_*}{\kappa} \ln \frac{z_2}{z_1} \tag{2}$$

can be obtained where the wind speeds, u_1 and u_2, correspond to heights z_1 and z_2, respectively. The maximum u_* obtained using Eq. (2) was 133 cm s^{-1}. The normal value for neutral conditions for this terrain is ~60 cm s^{-1} for a mean wind speed of 15 m s^{-1}.

5. Turbulence

Mean and the variance of the wind fluctuations measured at 109 m were computed for every 10 min from 1725 to 2335 EST. A moving mean was adopted for both analyses with the trend in the data removed by linear regression. Variation of the in-

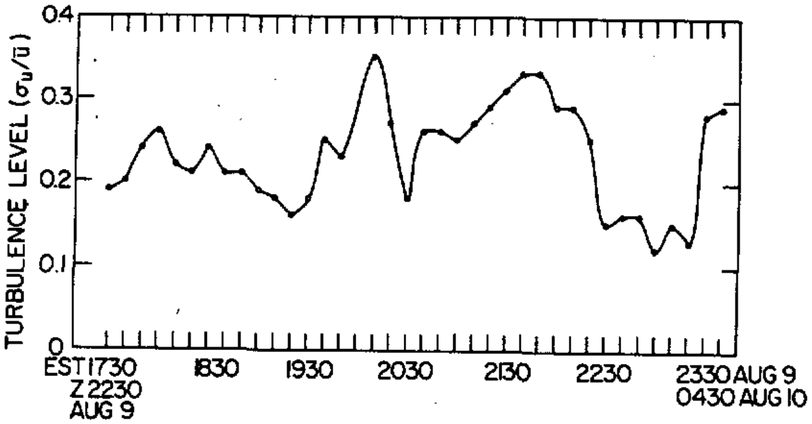

FIG. 8. Variation of turbulence level $\sigma_u/\bar{u}$, based on consecutive 10 min observations of horizontal velocity fluctuations.

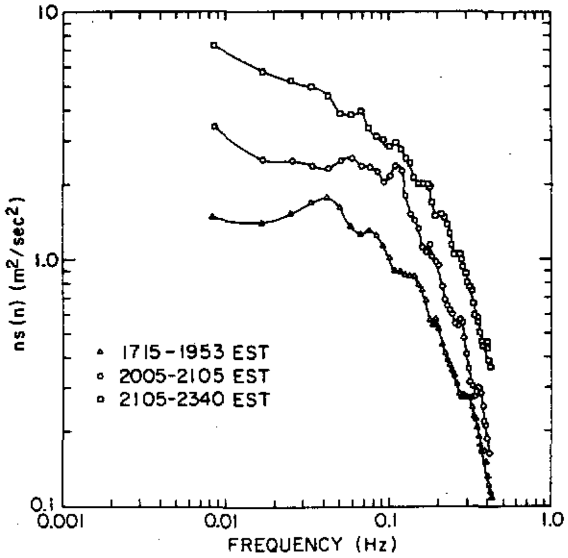

FIG. 9. Variance spectrum of horizontal velocity fluctuations during the approach and landfall of hurricane.

tensity of turbulence or turbulence level, $\sigma_u/\bar{u}$, where σ_u is the standard deviation of the longitudinal velocity fluctuations and $\bar{u}$ the mean velocity is shown in Fig. 8. The turbulence level averaged around 0.20 up to 1930 EST after which there was an abrupt increase to ~0.35. This period corresponded to intense thundershower activity. There was a decrease in turbulence level followed by a persistent increase which again corresponded to another band of thundershowers. A periodicity of rainfall and gusts is known to occur with the approach of hurricanes. The turbulence level over land with neutral atmospheric stability will usually be ~0.15.

Variance spectra using a conventional analysis (Blackman and Tukey, 1958) were computed for three periods as given below to determine the variations in amplitudes and dominant frequencies as the hurricane approached. The data were pre-averaged to 1 s before spectral analysis. It is equivalent to a low-pass filter with the cutoff frequency at 0.5 Hz.

1) 1715–1953 EST— storm located a few kilometers south of Long Island.
2) 2005–2105 EST— the first band of thundershowers associated with the hurricane.
3) 2105–2340 EST— the landfall.

All three variance spectra are shown in Fig. 9. The amplitudes at all frequencies analyzed increased successively for the three time periods. The dominant peaks shifted to higher frequencies as the hurricane approached. The energy-containing eddies were in the range of frequencies 0.1–0.01 Hz and lower. This corresponded roughly to scales of the order of 200 to 2000 m and higher, with a mean wind speed of 20 m s^{-1}.

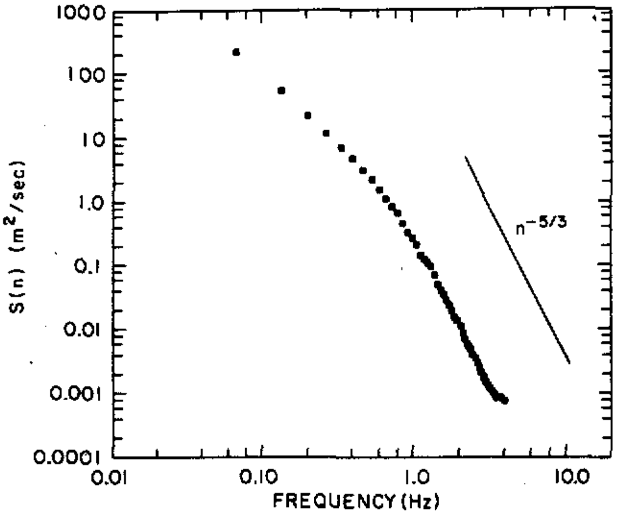

FIG. 10. A typical variance density spectrum for high frequencies.

Using Kolmogoroff's inertial subrange relationship,

$$S(k) = K\epsilon^{2/3}k^{-5/3}, \tag{3}$$

where k is the wavenumber, $S(k)$ the spectral density, ϵ the energy dissipation rate and K Kolmogoroff's constant (~0.5), energy dissipation rates were estimated from variance spectra. Data sampled at 0.125 s were used for this analysis. A typical spectrum of $S(n)$ versus n is shown in Fig. 10. A line with −5/3 slope is also indicated in the figure. Values of σ_u and ϵ were computed for ten 15 min time periods starting from 2105 EST as listed in Table 2.

There is a fivefold increase in ϵ as hurricane Belle moved over Long Island with the maximum value corresponding to peak σ_u value. Merceret (1976) obtained ϵ values ranging from 3 to 3000 cm^2 s^{-3} with most values between 10 and 1000 over Hurricane

TABLE 2. Energy dissipation rates.

Time (EST)	$\bar{u}$ (m s^{-1})	ϵ (cm^2 s^{-3})	σ_u (m s^{-1})
2105–2120	14.52	23	3.92
2120–2135	12.62	43	4.09
2135–2150	13.04	54	4.48
2150–2205	14.16	72	4.55
2205–2220	17.56	130	5.56
2220–2235	21.17	46	3.68
2235–2250	23.55	20	3.85
2250–2305	23.36	32	3.32
2305–2320	24.78	33	3.67
2320–2335	21.70	43	3.49

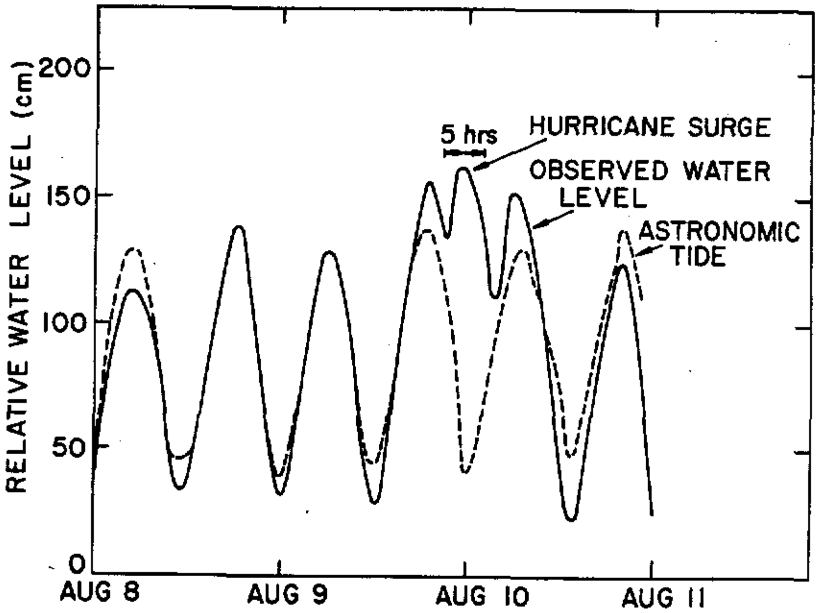

FIG. 11. Sea level observations and predicted astronomical tides near Shinnecock Inlet, Long Island.

Caroline of 1975 from aircraft measurements. No correlation was found between the mean square shear and the energy dissipation rate for the observations in Tables 1 and 2. This might be due to lack of stationarity. Maximum ϵ was observed just before the passage of a band of thundershowers (Fig. 6).

6. Storm surge

Water levels measured at Shinnecock Inlet (Fig. 3) and predicted astronomical tides from 8 to 11 August are shown in Fig. 11. Hurricane Belle moved parallel to the coast (Fig. 1) and made landfall ~70 km west of Shinnecock Inlet. Three distinct peaks can be seen in the water-level records. This feature has been observed by Redfield and Miller (1957). They refer to these three successive stages as forerunner, hurricane surge and resurgence. The hurricane surge coincides roughly with the time of landfall, around 2200 EST. From Fig. 11, the maximum hurricane surge is estimated as 125 cm and the duration at 6 h. This is in agreement with the value reported for New York City (Lawrence, 1977). Fortunately, this surge occurred close to low tide thus causing minimal flooding. The forerunner occurred ~4 h before landfall increasing the water level by ~20 cm. The water level reached a transient minimum before the hurricane surge approached Lond Island. The third peak in the record, often called resurgence, occurred ~7 h after the hurricane made landfall. These oscillations are attributed to a "wake" of waves in the trail of the hurricane (Munk *et al.*, 1956). Only one oscillation of 25 cm amplitude was observed. This may be due to the orientation of Long Island in a direction approximately normal to the continental United States thus damping the oscillations. Rise in water level caused by the drop in atmospheric pressure is 1 cm mb^{-1}. A rise of 30 cm at the eye of the hurricane is estimated for Belle. The remaining surge of 95 cm was obviously caused by the wind.

7. Summary

Meteorological observations were made in the atmospheric surface layer during the approach and passage of Hurricane Belle at three stations across Long Island. Analysis of these observations reveals the following characteristics of hurricane Belle:

- Increase in turbulence level by a factor of 2–3 as compared to values before landfall.
- Increase in energy dissipation rate by a factor of 5 during the passage of bands of thundershowers.
- Presence of bands of thundershower activity.

There was a decrease in mean wind speed inland by a factor of about 4 as compared with the corresponding values at the beach. A hurricane-induced surge of 125 cm was estimated from water-level observations.

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