CHAPTER 35

EFFECTS OF THE GULF STREAM ON NEARSHORE WAVE CLIMATE

R.J. Lai and S.L. Bales*

ABSTRACT

Large scale ocean currents, such as the Gulf Stream, Kuroshio, Peru Current, Agulhaus Current, etc., strongly modify the surrounding wave characteristics. As the Gulf Stream moves along the Continental Shelf of the southeast coast of the United States, the local ocean environment is divided into three wave climatic regimes. They are the offshore, the Gulf Stream, and the nearshore regimes. The nearshore zone is bounded by the land to the west and the Gulf Stream to the east. The distance between land and the Gulf Stream varies from 10 to 60 miles. Most of the waves in this regime are generated offshore and cross the Gulf Stream. The correlation of local wind and waves in the nearshore regime is poor except in the presence of a persistent onshore storm.

A semi-empirical approach has been developed to compute the nearshore wave climate. The hindcast/forecast directional waves from the Spectral Ocean Wave Model (SOWM) of the Navy Fleet Numerical Oceanography Center have been used as the source of the initial offshore wave conditions. After crossing the Gulf Stream, which is assumed to be a uniform current with a velocity of 2 m/s, the waves are either refracted to the nearshore regime or reflected to the offshore regime following ray theory. The onshore waves in the nearshore zone are confined to the sector from 30 to 150 degrees. The computed results are then compared with measured data with good agreement.

In summary, the Gulf Stream acts as a barrier to damp long waves and to regroup short waves. The refraction of long waves can be predicted by using ray theory. Further field experiments are needed to quantify the variation of the Gulf Stream and to investigate the interaction with approaching long waves and local wind generated short waves.

1. INTRODUCTION

The development of wave climate of a region provides the general prevailing wave conditions throughout the year. This is considered important to the design of offshore structures and for the planning of ship operations. The rapid development and large increase of population along the coastal zone makes the nearshore wave climate an urgent task for all phases of engineering works. These nearshore activities include safe ship navigation to avoid collision and

*David W. Taylor Naval Ship Research and Development Center, Bethesda, Maryland 20084-5000, U.S.A.

grounding, pollution transport, nearshore structure, beach erosion abatement, etc.

The complexity of the boundary conditions and changing dynamic parameters from the interaction of air-sea-land at the nearshore zone make the generalization of wave dynamics in coastal zones a difficult task. Furthermore, large scale ocean currents moving along major continental shelves strongly modify the approaching waves from the offshore to the nearshore. One of these regions is located at the southeast coast of the United States. The nearshore regime is bounded by the land to the west and the Gulf Stream to the east. The distance between land and the Gulf Stream varies from 10 to 60 miles (see Figure 1). The local ocean environment of this area is divided into three wave climatic regimes. They are the offshore, the Gulf Stream, and the nearshore regimes. Most of the waves in this regime are generated offshore and approach the nearshore regime by crossing the Gulf Stream. The effects of the Gulf Stream play an important role in the formation of nearshore wave climate which will be presented here.

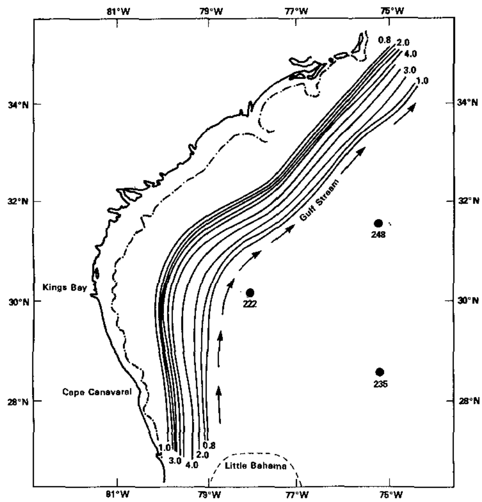


Figure 1. Map showing the Gulf Stream and SOWM grid points used at St. Marys (Kings Bay) and Cape Canaveral

2. LOCAL WAVE CHARACTERISTICS

A field measuring program has been ongoing to investigate the wave characteristics of this region since 1984. The results have been used to calibrate the Shallow Water Wave Model (Lai and Silver, 1986a) and to develop the local wave climate. The measured results of 1984 and 1985 have been published recently (Lai and Foley, 1986b). In short, submersible field stations measured directional waves four times a day at Cape Canaveral, Florida and St. Marys Inlet, Georgia. Although the data recovery rate is about 60 percent during the measuring period, the measured data reveal many interesting local wave characteristics. These can be briefly summarized as follows:

a. Correlation of Local Wind and Wave

Strong winds imply high seas in deep water. In the nearshore zone, however, winds come from all directions and waves are limited to onshore directions; therefore, the correlation of local wind and waves becomes a difficult task. Measurements at St. Marys Inlet, Georgia provide both amplitudes and directions of wind and waves. Based on these data, wind and wave roses for the winter season of 1984 have been developed and are given in Figures 2a and 2b. Although most of the winds of the nearby shore station at the Mayport Air Station are from west, north, and northeast directions, the approaching wave directions are confined by geography to northeast, east, and southeast directions. Similar data for the summer are shown in Figures 3a and 3b for 1984. There is some correlation between the wind and wave data; however, a precise local correlation is almost impossible to establish. This has been illustrated in Figure 4 in which both daily variations of offshore and nearshore wind are compared with measured directional waves. It is clearly shown that offshore wind has better correlation with nearshore waves. This points out the fact that the wave climate in the nearshore zone is dominated by the storm and wind patterns offshore and propagates to the shore with some local wind input unless the onshore storm persists for more than 24 hours. At that time, the local wind and wave direction coincide.

b. Directional Wave Spectra

A series of measured directional wave spectra have been evaluated. The direction of long waves tends to be from the 50 to 120 degrees band while the directions of short waves are scattered. Although the same offshore storms pass through the southeast coast of Florida, the measured directional wave data at Cape Canaveral and St. Marys Inlet show different characteristics (see Figures 5 and 6). The major differences of these nearshore zones are the local topography and the heading of the Gulf Stream north (Cape Canaveral) versus northeast (St. Marys Inlet). Some of these characteristics at these two sites resulted from the effects of the Gulf Stream, which will be discussed further in the following section. While the data of Figures 5 and 6 were collected for different storms, their general characteristics are representative of each site.

3. APPROACH

The measured field data reveal the characteristics of the local waves and the poor correlation of local wind and waves. However, the data can only provide short-term wave statistics which are not enough to establish nearshore wave climatology. Therefore, hindcasting techniques have been applied here to develop the nearshore wave climate.

The U.S. Navy Fleet Numerical Oceanography Center (FNOC) has operated a Northern Hemispheric wave forecast/hindcast model, called the Spectral Ocean Wave Model (SOWM) (Lazanoff and Stevenson, 1975)

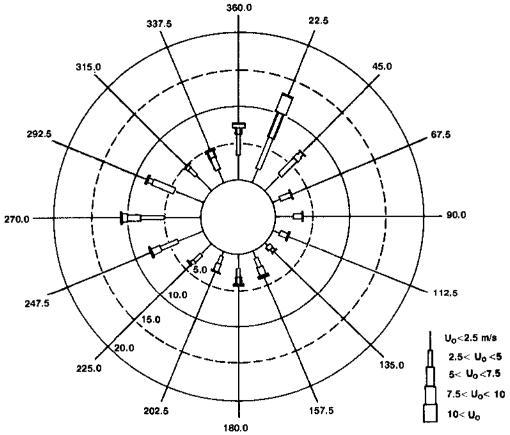


Figure 2a. Wind rose for Mayport Naval Air Base near St. Marys for winter 1984

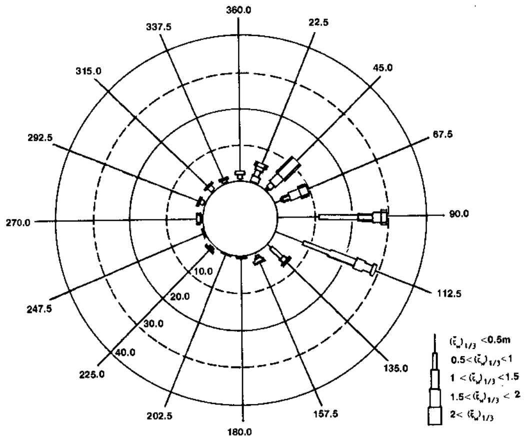


Figure 2b. Wave rose for St. Mary entrance Station 5 offshore for winter 1984

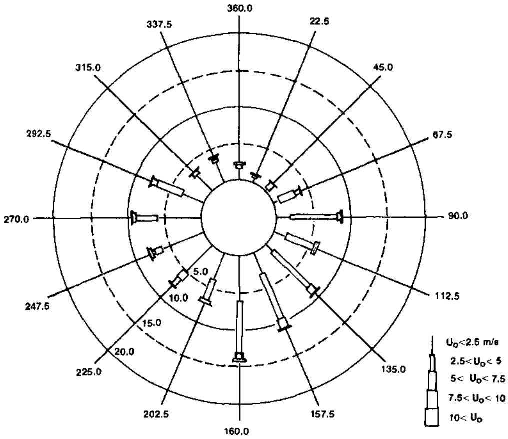


Figure 3a. Wind rose for Mayport Naval Air Base near St. Marys for summer 1984

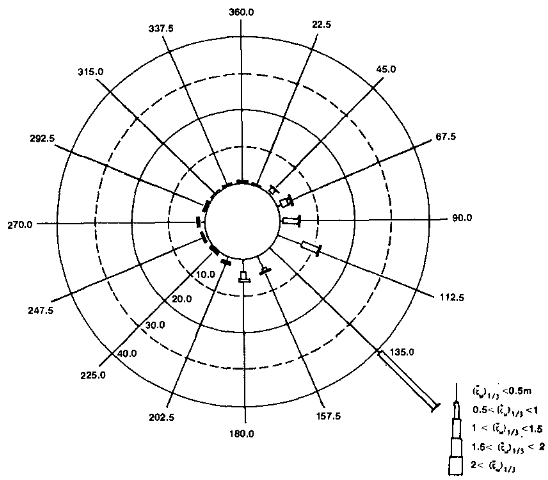


Figure 3b. Wave rose for St. Mary entrance Station 5 (offshore) for summer 1984

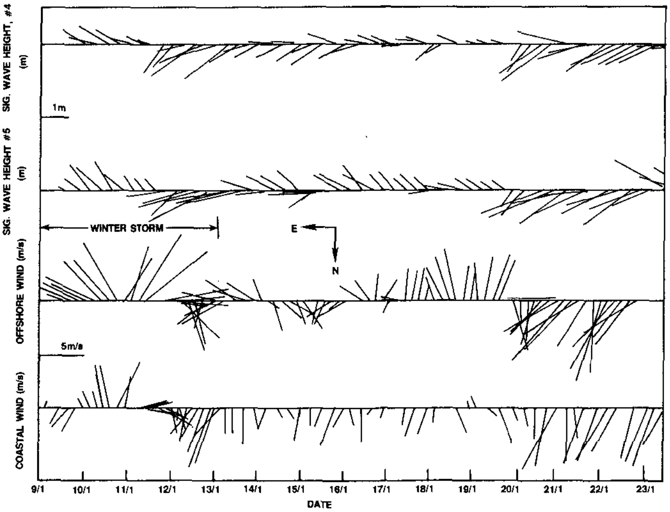


Figure 4. Measured waves at Stations 4 and 5 and winds at offshore buoy (Uo) and coastal station (Un)

from 1975 to 1985.* The deep water wave statistics derived from SOWM have been widely used at the David Taylor Naval Ship Research and Development Center (DTNSRDC), other Navy and government centers, NATO countries, and in the private sector (Bales, et al., 1982). The approach here was to transform the corresponding offshore data from the SOWM hindcast climatology to the nearshore zone to establish wave statistics over a period of 15 years.

The process of transforming waves from deep water to shallow water requires three wave parameters deirved from SOWM: significant wave height, $(\tilde{\zeta}_W)_{1/3}$; primary incident wave direction, θ_O; and incident modal wave period, T_O. Since the distance between deep and shallow water in this case is less than 120 kilometers and the uncertainty of predicting wave frequency, the shift of wave period for long waves (with $T_O \geq 6$ sec) has not been considered. Therefore, the shallow water wave periods are assumed to be the same as the hindcast ones from SOWM. The other two parameters are interrelated and are treated separately.

The correlations of significant wave height between deep (hindcast/forecast) and shallow water (measured) were developed using the given forecast wave direction and normalized by the significant wave height of the SOWM at the deep water grid points. The average of three grid points located along the central Florida east coast are used to provide the hindcast/forecast wave spectrum for both Cape Canaveral and St. Marys Inlet. These are grid points 221, 222, and

*The SOWM has now been replaced by a global model called GSOWM.

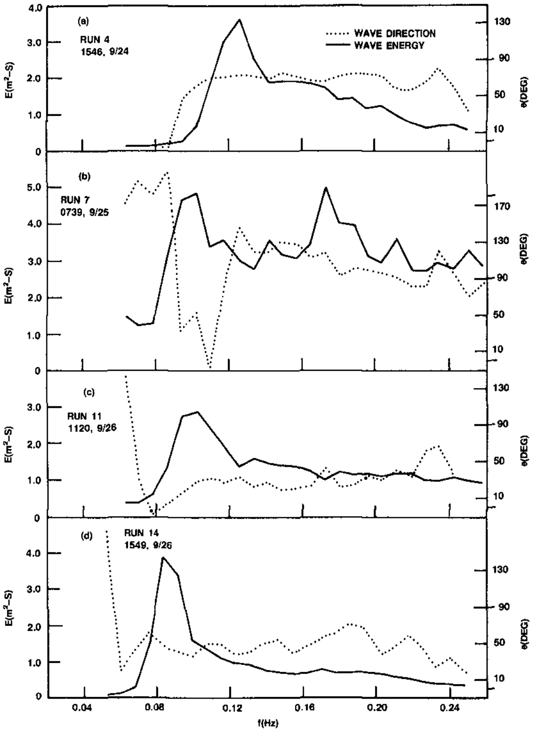


Figure 5. Measured wave spectra with mean directions at Station 2 of Cape Canaveral during the passage of the storm of 1983

235 which are located at (31.8° N, 75.1° W), (30.4° N, 77.9° W), and (28.8° N, 75.2° W), respectively, see Figure 1. The averaged spectral values of these grid points provides the overall wave forecast by the SOWM at the offshore region (Lai, et al., 1984).

The changes of approaching wave direction from deep to shallow water are complex on the Florida east coast due to the existence of the Gulf Stream, see Figure 1. Therefore, the process of transforming the forecast wave direction of SOWM into shallow water has been divided into two steps. The first step was to calculate the change in SOWM wave direction from deep water into intermediate depth by crossing the Gulf Stream. Then, by using the Shallow Water Wave Model (SWWM), the waves at the intermediate depths were transformed to the shallow water zone.

A simplified analytical solution and numerical model have been used to transform the offshore wave direction to the nearshore zone. The Gulf Stream along the Florida east coast heads northward running almost parallel to the coast line and turns to northeast direction

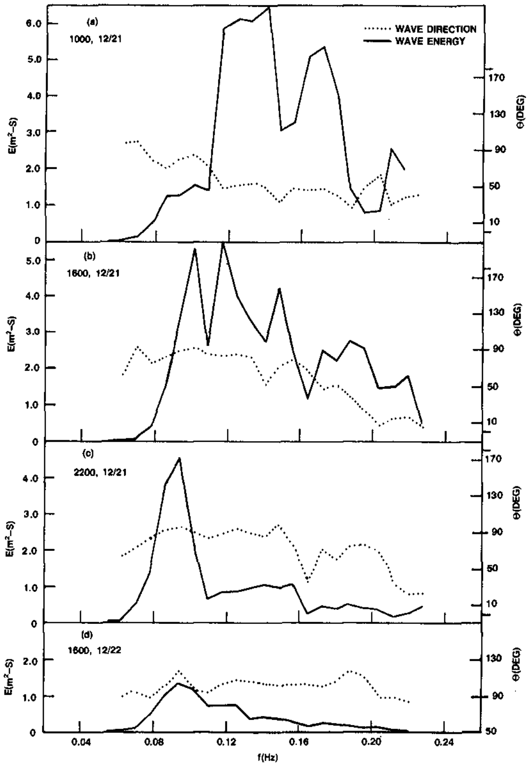


Figure 6. Measured wave spectra with mean directions at Station 5 of St. Marys during the passage of the storm of 1984

near Jacksonville, Florida. Here, it is assumed that the Gulf Stream is a uniform current, with a mean velocity of 2.0 m/s. The changes of wave direction are calculated from the following analytical solution

$$\cos\,\theta_1 = \cos\,\theta_0/\left[1 - \frac{U_1 - U_0}{C_0}\cos\,\theta_0\right]^2 \tag{1}$$

where θ_0 and θ_1 are the primary incident and refracted wave directions before and after crossing the Gulf Stream, respectively (Kenyon, 1971; Phillips, 1981). U_0 and U_1 are the mean currents of the deep water offshore section and the Gulf Stream, and C_0 is the original wave phase velocity. The value of U_0 was assumed to be zero in this computation.

The relationship between the parameters defined in Equation (1) are shown in Figure 7. The wave direction after refraction by the Gulf Stream is a function of the incident modal wave period, T_0, and incident direction, θ_0. The relationship between θ_0, θ_1, and T_0, with

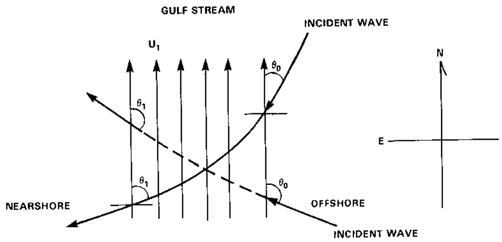


Figure 7. Change of Wave direction by the Gulf Stream where θ_0 is incident wave direction and θ_1 is predicted wave direction after crossing

assumed values of U_0 and U_1, are shown in Figures 8 and 9. In the Cape Canaveral area, as shown in Figure 8, when the waves approach from the southeast with large wave periods, the waves may reflect back to the deep water zone as shown in the upper section of the figure. This phenomenon has been discussed by Hayes (1980) and others (Chao, 1970). Furthermore, the incident waves from the north and northeast are refracted to the wave direction greater than 30 degrees. This implies that the direction of most waves (except the local wind waves in the intermediate water zone) are refracted and arrive in the nearshore zone range from the northeast, the east, and the southeast directions after crossing the Gulf Stream. In the St. Marys Inlet area, due to the change of flow direction of the Gulf Stream and the bottom bathymetry, the results are different from those of the Cape, as shown in Figure 9. Here the shoreline turns to the northeast direction near the St. Marys area, as does the Gulf Stream. The incident wave directions of the offshore zone are then confined to the 40 to 180-degree range. The changes of wave directions after crossing the Gulf Stream around St. Marys are shown in Figure 9. The offshore wave directions are limited from 40 to 160 degrees range. The nearshore wave directions range then from 70 to 165 degrees according to Equation (1).

The changes of wave directions after crossing the Gulf Stream have been computed using SWWM (Lai, et al., 1984), and will not be discussed in detail here.

4. RESULTS AND DISCUSSIONS

The wave statistics from the transformed SOWM data over a period of 15 years have been developed and published in other reports (Lai, Silver and Bales, 1984). In general, the characteristics of these wave statistics are dependent on the site chosen around the nearshore zone. Two of them are located near the field measuring sites. Thus, the measuring wave data can be used to develop short term statistics and to verify the transformation method. Two sets of short terms wave

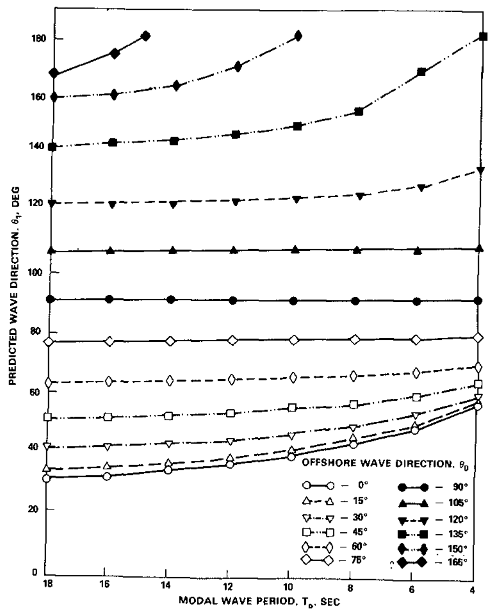


Figure 8. Predicted wave direction (θ_1) after crossing the Gulf Stream at Cape Canaveral

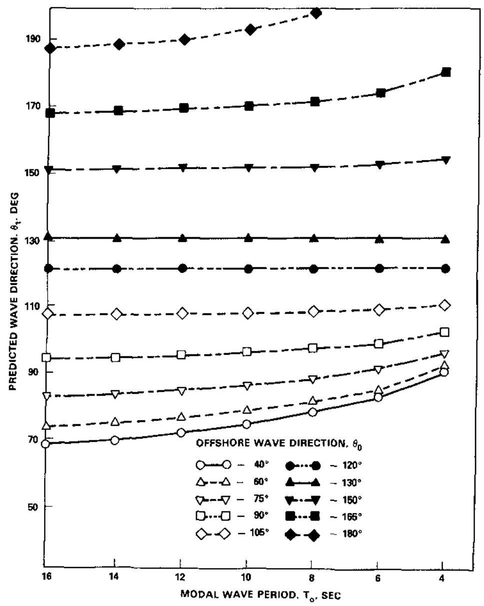


Figure 9. Predicted wave direction (θ_1) after crossing the Gulf Stream at St. Marys

statistics are presented. One is from measured field data, and the other is from the corresponding transformed SOWM data. Comparisons are made to evaluate the transformation method and to discuss the effects of the Gulf Stream on wave climate.

The wave statistics are grouped according to seasons, i.e., Winter (December to February), Spring (March to May), Summer (June to August), and Fall (September to November). Since the recovery rate of field data is around 60 percent during 1984 and 1985, it is difficult to compute wave statistics for all four seasons. The available measured and hindcast data of the rougher seasons (i.e., Winter and Fall) were chosen for comparison.

Comparison of measured and hindcast wave direction statistics are shown in Figures 10, 11, and 12. The solid lines represent the offshore hindcast data from SOWM. The dashed lines represent the nearshore transformed hindcast data, and the dotted lines represent the measured field data at the same period of time. Each figure is divided into parts (a) and (b). The data in part (b) consist of all waves. The results of part (b) show that the transformation method which takes into account the effects of the Gulf Stream and the local shoaling zone is credible. The waves from north, northeast, and east directions refract to east, normal to the shore, as predicted from the ray theory. However, the waves from south and southeast directions reflect to the offshore which is difficult to assess in the transformation process. Furthermore, when offshore waves cross the Gulf Stream, longer waves tend to follow the ray theory, and short waves are affected by the currents and local wind force. These local energy inputs interact dynamically with short waves and cause the waves to break or reorganize. This has been clearly indicated from the measured data. The analyzed results of long waves without confused sea of short waves are shown in part (a). Overall improvement for the long waves is evident especially for the waves from the north, northeast, and east directions. Here, the long waves are defined as waves with periods larger than 6.7 sec (or frequencies less than 0.15 Hz). There is only a moderate improvement on the waves from the south and southeast directions due to the complex phenomenon of wave reflection and due to less accuracy for predicting waves generated from the south near Little Bahama Basin by the SOWM (see also Figure 1).

Comparison of measured and hindcast wave period statistics is shown in Figure 13. The solid lines are from the hindcast data of SOWM and the dashed lines are from the field measured data. The wave periods from SOWM are taken from offshore region and applied to nearshore region directly. The assumption of this direct application has been discussed in a previous publication (Lai et al., 1984). The results show the direct comparison of three sets of data as referred to (a), (b), and (c) in Figure 13. The data of Figure 13(a), (b) and (c) are identical to the data of Figures 10, 11, and 12. The agreement is encouraging if one separates the long and short waves again. The overall wave period of long waves between two data sets agrees well although the distribution is not very consistent. Further research is needed to take into account the local wind force on wave evolution during the process of crossing the Gulf Stream.

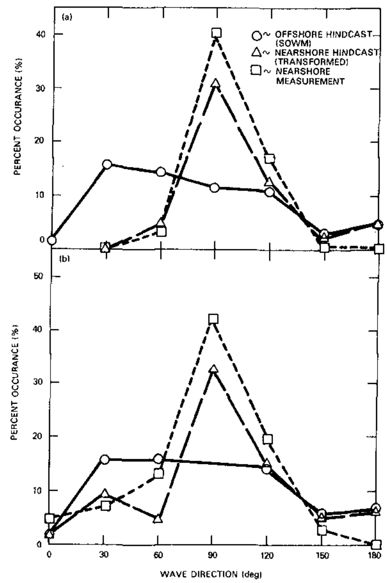


Figure 10. Comparison of measured and hindcast wave direction statistics of winter 1984 at St. Marys, where (a) for long waves, (b) all waves

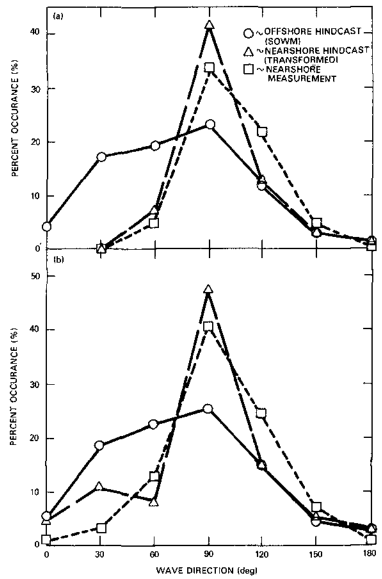


Figure 11. Comparison of measured and hindcast wave direction statistics of fall 1984 at St. Marys, where (a) long waves only, (b) all waves

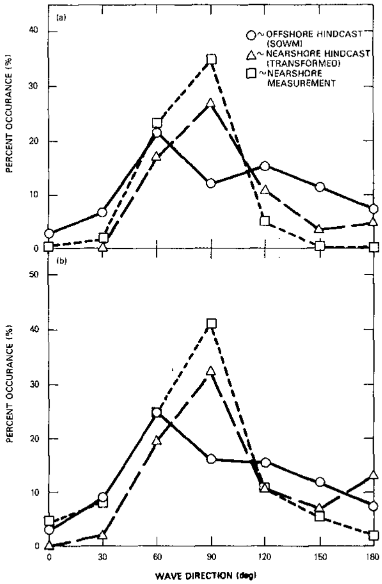
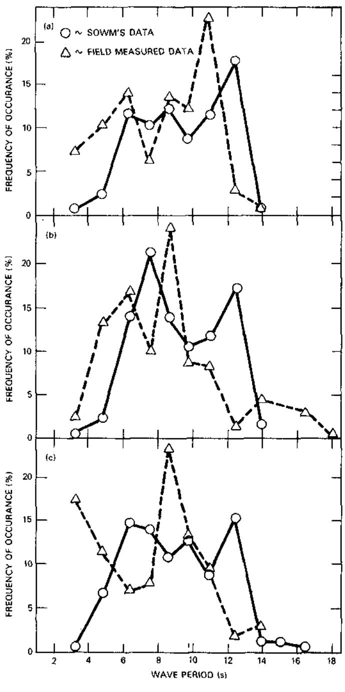


Figure 12. Comparison of measured and hindcast wave direction statistics of winter 1985 at Cape Canaveral, (a) long waves only, (b) all waves



F'gure 13. Comparison of measured a.d hindcast wave period statistics, where (a) winter of 1984 at St. Marys, (b) fall of 1984 at St. Marys, (c) winter of 1985 at Cape Canaveral

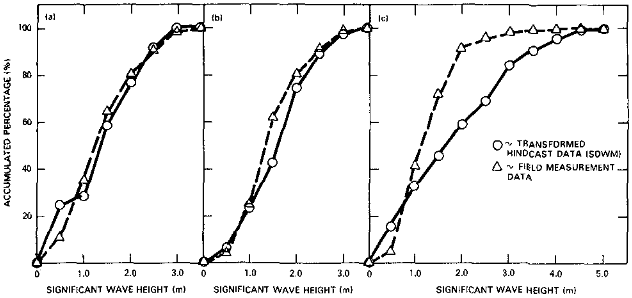


Figure 14. Comparison of measured and hindcast wave height statistics, where (a) winter of 1984 at St. Marys, (b) Fall of 1984 at St. Marys, (c) winter of 1985 at Cape Canaveral

Comparison of measured and hindcast significant wave height statistics is shown in Figure 14. The agreement between transformed hindcast data from SOWM and field measured data in the St. Marys area is very good but not so in the Cape Canaveral area. The reason for this poor agreement is not clear. However, after re-examining the data of Cape Canaveral, it was found that some stormy data during the winter of 1985 are from the south and southeast directions which may be attributed to this poor agreement. The hindcast storm data from the south and southeast directions by SOWM had been hampered by the existence of Bahama Bank to cause such discrepancy, as pointed out previously.

5. CONCLUSION

Developing nearshore wave climates require complex procedures. Shoreline structure, bottom topography, offshore wind and wave conditions and surrounding ocean current must be considered. A wave climate for the southeast coast of the United States has been developed. The offshore hindcast data from SOWM has been transformed to the nearshore zone. The transformation method takes into account the effects of the Gulf Stream and shallow water shoaling. The results have been compared with the field measured data with generally good agreement. The effect of the Gulf Stream on crossing waves should be divided into two categories, i.e., long waves and local wind waves. The refraction of long waves can be predicted by using ray theory. However, to clarify the generation and reflection of waves from the south and southwest directions further research work or field data is needed. Strong currents cause local generated wind waves (i.e., short waves) to stop, break, and reorganize. Further field experiments and research are needed in this area to predict the process of wave evolution in the ocean environment which present strong currents.

REFERENCES

1. Bales, S.L., W.E. Cummins and E.N. Comstock, 1982, "Potential Impact of Twenty Year Hindcast Wind and Wave Climatology on Ship Design," Marine Tech., Vol. 19, No. 2.

2. Chao, Y.Y., 1970, "The Theory of Wave Refraction in Shoaling Water Including the Effects of Caustics and Spherical Earth," Tech. Report 70-7, New York University.

3. Hayes, J.G., 1980, "Ocean Current Wave Interaction Study," J. of Geophys. Res., Vol. 85.

4. Kenyon, K.E., 1971, "Wave Refraction in Ocean Currents," Deep Sea Res., Vol. 18.

5. Lai, R.J., A.L. Silver and S.L. Bales, 1984, "Wave Statistics in Nearshore Zones," Proceedings Ocean Structure Dynamics Symposium '84, Corvallis, Oregon.

6. Lai, R.J. and A.L. Silver, 1986a, "Shallow Water Wave Model at Cape Canaveral, Florida and Kings Bay, Georgia," Tech. Report DTNSRDC/SPD-1190-01.

7. Lai, R.J. and E.W. Foley, 1986b, "Field Measurements of Nearshore Wave Environment at Cape Canaveral, Florida and Kings Bay, Georgia," Tech. Report DTNSRDC/SPD-1190-02.

8. Lazanoff, S.M. and N.M. Stevenson, 1975, "An Evaluation of a Hemispheric Operational Wave Spectral Model," FNWC Tech. Note 75-3.

9. Phillips, O.M., 1981, "Nonlinear Wave Dynamics," IUCEM Symposium Proceedings.