UTILIZATION OF WAVE FORECASTING IN THE INVASIONS OF NORMANDY, BURMA, AND JAPAN

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Introduction. War, grim destroyer of society, provided an unusual stimulus to ocean wave research in the years 1942 through 1946. Theory, observation, and prediction of sea, swell, and surf made the greatest strides in their history during this brief five-year period. The time already seems long ago when only the vaguest concept existed of the growth and decay of ocean waves and their ultimate transformation into breakers. Even in the early part of 1942, methods for observing and predicting these phenomena were essentially qualitative. The French had established a forecasting service for the open roadsteads of North Africa in the early 1920's, but results were still crude twenty years later. Naval meteorologists had done no better, and were accustomed to discussing wave conditions according to sea scales in which the terms might well mean different things to the man in a small boat and to the man aboard a battleship.

The groundwork for the quantitative forecasts of sea, swell, and surf required by large-scale amphibious operations was laid in both Great Britain and the United States during 1942. In that year, Instructor Commander C. T. Suthons, R.N., of the British Naval Meteorological Service, correlated a number of wave observations with wind conditions and prepared a memorandum which contained certain "rules of thumb" and crude forecasting graphs. About the same time, Mr. W. H. Munk in the Oceanographic Section, Directorate of Weather, Headquarters, Army Air Forces, was assigned the problem of developing wave generation and decay diagrams which could be used for the invasion of North Africa. For the same invasion, Commander R. Steere, U.S.N., prepared the first quantitative surf observation code. This code, named after its originator, was eventually revised and is now the currently used Combined Surf Code.

During early 1943, Mr. Munk worked with Dr. H. U. Sverdrup, Director of the Scripps Institution of Oceanography, to develop a technique of wave forecasting based on theoretical, as well as empirical, considerations. By July of that year, the necessary relationships had been established and a group of eight Army Air Force meteorologists, including the writer, was already assigned to study and test the embryonic forecasting method. Trial "hindcasts" made for the North African coast from the Northern Hemisphere Weather Map Series by this group indicated that the technique could be used by meteorologists after a relatively small amount of training. In

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† The views expressed in this article are solely those of the author and are not to be construed in any sense as being the official viewpoint of the Navy Department.

fact, the short course in military oceanography built around the technique and taught at the Scripps Institution of Oceanography was cut in duration from the original three months to one month as refinements and organized material became available.

*Wave Forecasting for the Normandy Invasion**

When, in the fall of 1943, Lieutenant J. C. Crowell, A.U.S., member of the initially trained group, arrived in England and was assigned the task of preparing wave forecasts for the operations of the U. S. Assault Training Center at Woolacombe, Devon, many problems were still unsolved. These included such fundamental questions as the type of wave height the generating graphs provided, the manner in which waves were transformed into breakers while passing through shallow water, the effect on wave height when the waves approached the coast at an angle, the effect of opposing and following tidal currents, and the relationship between wave conditions and the efficiency of an amphibious operation. Answers to most of the problems had to be forthcoming within the next few months, for General Dwight Eisenhower, U.S.A., arrived in Great Britain during January, 1944, to organize Operation OVERLORD, the invasion of Normandy.

It was evident to all concerned that the success of Operation OVERLORD hinged upon the efficiency of the flow of troops and supplies across the beachheads. Even with favorable weather, it was estimated fifteen weeks or more would be required to transport as many Allied divisions across the English Channel as the Germans had available in Northern France and Belgium[1]. To provide a satisfactory wave forecasting service for this operation, Captain L. G. Garbett, C.B.E., R.N., Director of the Naval Meteorological Service, collaborated with Colonel T. S. Moorman, Jr., U.S.A., Staff Weather Officer to the 9th Air Force and the 1st U. S. Army, in establishing the Swell Forecast Section, Admiralty. Organized with the approval of Commander R. Steere, U.S.N., aerologist to the Commander of U.S. Naval Task Force 122, the Section finally consisted of one British meteorologist (Instructor Lieutenant H. W. Cauthery, R.N.), two American meteorologists (Crowell and the writer), two American enlisted men (Technical Sergeant E. A. Lochner, A.U.S., and Sergeant E. L. Hynes, A.U.S.), and two WRNS ratings. Housed two floors underground, the Section had direct access to Admiralty's Forecast Section with its wealth of weather data and excellent communication facilities. The name, *Swell* Forecast Section, was not intended as a pun but rather as a security measure to direct thought away from the fact that the invasion might be scheduled for beaches not directly exposed to ocean swell.

* The writer wishes to point out that the results described in this paper were due to the combined efforts of the personnel of each of the wave forecasting groups with which he was associated. It is to be stressed that the paper should not be construed as a complete history of wave forecasting in the war theatres mentioned. There were several hundred meteorologists trained in the technique, and it is beyond the writer's scope to adequately and accurately describe their work in the field.

The objects of the Section were to develop the technique of forecasting sea, swell, and surf, and to provide forecasts on the basis of this technique for the invasion of Europe. The technical problems facing the Section were four in number; (1) to forecast the height and period of ocean swell coming from the Atlantic; (2) to determine the extent to which this swell would penetrate the English Channel; (3) to forecast the height and period of waves caused by local winds in the Channel; and (4) to study the effects of shallow water, tidal currents, and coastal irregularities on waves. The final aim, of course, was to forecast surf heights on specific beaches. The investigations were carried out under two handicaps, security and limited time. Although the date, place, and other details of the impending operation were known to the Section, security measures were so rigid that wave researchers in the States could not be contacted concerning the problems mentioned earlier. As only three months were available, the empirical approach was adopted as the one most likely to provide the necessary information.

The first task undertaken was the organization of a synoptic network which eventually totaled fifty-one wave reporting stations (FIGURE 1), and was probably the largest of its kind ever organized. In the main, the stations were His Majesty's Coast-guard lookouts, manned by retired seamen. Visual observations made at these stations were reported in a seven-figure group, IIHHPPM, where II is the station number, HH the average wave height in feet, PP the average wave period in seconds, and M the difference in feet between the height of the maximum wave observed and the average height. Daily observations were made at 0700, 1300, and 1800 GMT for an interval lasting three minutes and included a wave count and an estimate of the height of each wave breaking during that time. Rocks or other objects of known size occurred in the surf zone at a few of the stations and aided in the estimation of height. As soon as observations were made, the data were phoned to district headquarters and then relayed as a collective by teleprinter direct to the Admiralty. To study the exposure of each location and to provide the necessary instruction, all the stations were visited by one or more members of the Section. Although visual observation is subject to considerable error, the close spacing of stations permitted checks of one against the other, and the large amount of synoptic information supplied was invaluable for verification and research purposes.

Four of the stations (Padstow, Pendeen, Weymouth, and Newhaven) had aneroid pressure-recorders installed in comparatively deep water by the Director of Mine Design. Reports from these stations, made in the same fashion as those from the visual stations, were extremely valuable in checking the visual reports and in providing data on waves in deep water.

A special reporting station was also established at Weston Mouth. This location was chosen because it is protected from Atlantic swell and the maximum fetch available is similar to that of Seine Bay, the site of the assault beaches. The station consisted of seven dan buoys, topped by graduated poles, and laid at equal intervals along a straight line to seaward. Observations were made by sailors five times daily with the aid of a graticuled theodolite and stop watch. However, the unusually calm spring weather prevented the achievement of the purpose of the station, *i.e.*, the acquisition of a large group of reliable observations on the transformation of

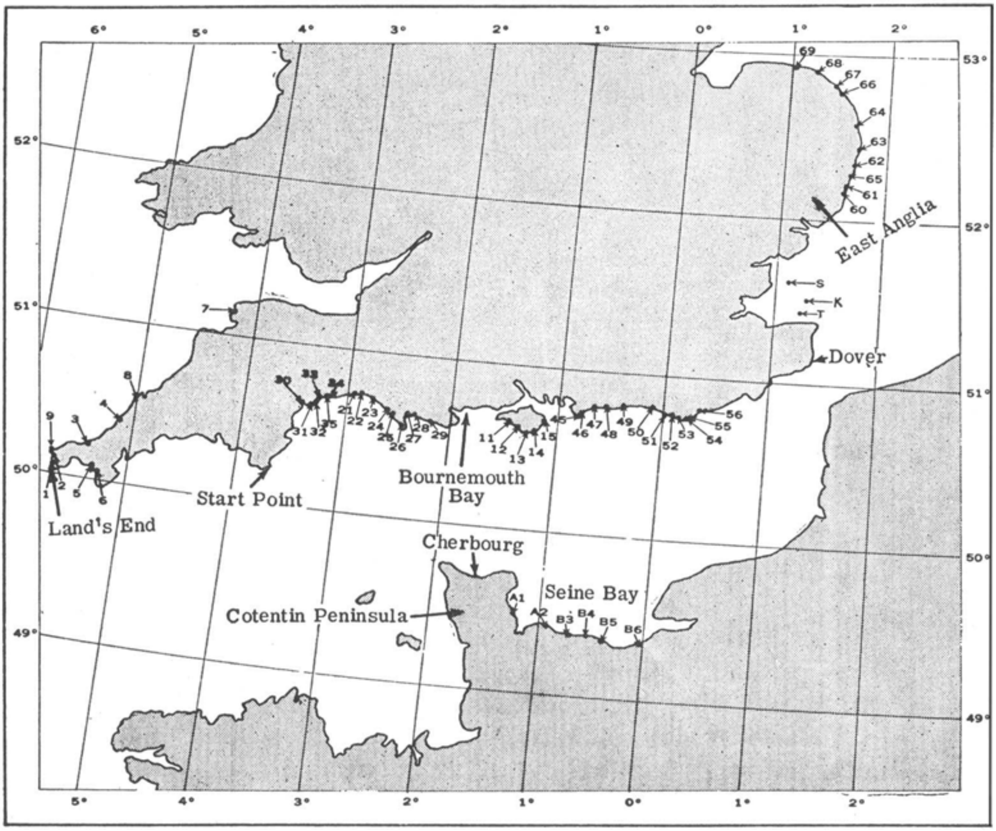

FIGURE 1. Index map showing location of English wave reporting stations and the invasion beaches of Normandy (for names of stations and beaches, see TABLE 1).

waves moving into shallow water. In fact, the station reported waves one and one half feet or higher on only forty-two occasions in four months of operation.

Wave information of lesser value was received from three anti-aircraft "forts" in the Thames estuary, from high-speed motor launches on night patrol out of Dover, and single-engined aircraft (P-51s) flying weather reconnaissance over the Channel. Checking of wave conditions on the assault beaches proper was carried out by studying aerial photographs of the beaches. This was accomplished by determining the depth of breaking from these photographs by referring to special tidal data and beach profiles prepared for the invasion and then converting depth of breaking into breaker height by assuming breaking occurred in water one and one half times deeper than the height. This method, although crude, indicated no greater error in the forecasting technique being employed.

TABLE 1
WAVE REPORTING STATIONS AND ASSAULT BEACHES

Number	*Station*	*Number*	*Station*
1	Sennen	45	Selsey Bill
2	Cape Cornwall	46	East Beach
3	Godrevy	47	Bognor Regis
4	Fistral Beach	48	Littlehampton
5	Prah Sands	49	Worthing
6	Loe Bar	50	Newhaven
7	Woolacombe	51	Kemp Town
8	Constantine Bay	52	Cuckmere Haven
9	Pendeen	53	Birling Gap
11	Blackwood Point	54	Holywell
12	Atherfield Point	55	Eastbourne
13	St. Catherine's Point	56	Pevensy Bay
14	Woody Point	60	Sizewell
15	Foreland	61	Dunwich
21	Seven Rock Point	62	Benacre
22	Charmouth	63	Lowestoft
23	West Bay	64	Gorleston
24	Abbotsbury	65	Southwold
25	Langton Herring	66	Polling
26	Fortuneswell	67	Mundesley
27	Osmington	68	Cromer
28	Osmington Mills	69	Cley
29	Lulworth Cove		*Assault Beaches*
30	Orcombe Point	a-1	Utah, American
31	Budleigh Salterton	a-2	Omaha, American
32	Ladram Bay	b-3	Gold, British
33	Sidmouth	b-4	Juno, British
34	Beer Head	b-5	Sword, British
35	Weston	b-6	Band, British

Fort Reports: S, Sunk; K, Knock; T, Tongue.

Early forecasting of the Section was directed toward predicting swell conditions at Land's End. A fair degree of success was achieved, although the rigid accuracy desired was not obtained in all cases. Work was also initiated into determining how far swell penetrated the upper reaches of the English Channel. Cornish[2] and various coast guard personnel had mentioned that swell occasionally penetrated at least as far as Bournemouth Bay. After studying the observations of the wave reporting stations, it was found that long-period waves rarely appeared at stations east of Start Point. By analogy, it was to be expected that swell approaching the assault beaches from south of west would be cut off by the Cotentin Peninsula and that swell from a direction close to due west, even though of appreciable height off Cherbourg, would be considerably reduced in height at the beaches. From this and certain theoretical considerations, it was decided that only extremely high swell from the west would need to be taken into account in forecasting surf heights on the beaches in question and that such waves would diminish to less than half their original height. This conclusion was verified on October 14, 1944, when the first really noticeable swell appeared at Omaha Beach with breaker heights of 2 to 3 feet and a period of 9 seconds, although heights of 12 to 15 feet were reported off Cherbourg. During the summer months, such a situation was unlikely and the problem resolved itself into forecasting waves and surf resulting from local winds.

Fetches in the central part of the Channel and at the assault beaches were rarely greater than 120 miles. Verification of forecasts soon indicated the tremendous importance of correct wind forecasts. To provide accurate wave forecasts, *i.e.*, those with an error of one foot or less in height if the heights were less than five feet, and with an error of 2 feet or less if waves were greater than five feet in height, wind forecasts had to be in error less than one Beaufort force and less than two points ($22\frac{1}{2}$ degrees) in direction. Forecasts of wave period were unnecessary because variation in the slope and period of wind waves did not appear to affect small craft operation noticeably.

Before surf heights could be predicted, it was necessary to estimate the effect of shallow water and coastal irregularities upon deep-water wave height As mentioned before, a comprehensive theory of these effects was not available, and it was decided to obtain a direct relationship between observed breaker heights and wave heights computed from generation diagrams. Such a technique would also incorporate correction factors needed to take into account tidal stream effects, influence of land bounding the channel, error in determining wind speed from meteorological charts, possible errors in the generation graphs, and several lesser considerations. If the necessary relationships between computed and observed data could be established for winds blowing onto the English coast, it was hoped that similar relationships would exist for winds blowing onto the French coast.

It was also necessary to determine how the height values extracted from generation graphs might be compared to observations which reported both average and maximum wave heights, particularly since the maximum height reported was often double that of the average height. It appeared that small craft operation was concerned neither with the occasional maximum wave nor with the average value, which is considerably depressed by the many small waves present in a wave train. However, a value half way between the average and maximum height appeared to be highly useful. This value, termed the "Predicted Height," was used for purposes of comparison. The value falls amazingly close to the "Significant Wave Height" defined by Sverdrup and Munk about a year later.[3] (See FIGURE 2).

Although a complicated shoal system existed off part of East Anglia, the ten wave observation stations spaced four to fourteen miles apart along that coast proved particularly valuable in working out the relationship between computed and observed height. FIGURE 3 illustrates the results of a study the writer made of heights observed during nineteen synoptic weather situations in which the wind direction held with 15 degrees of a given direction for eighteen hours or more during the months April-July, 1944. The hatched areas of the illustration are the zones in which weighted values for over two hundred height values occurred, using both Sverdrup-

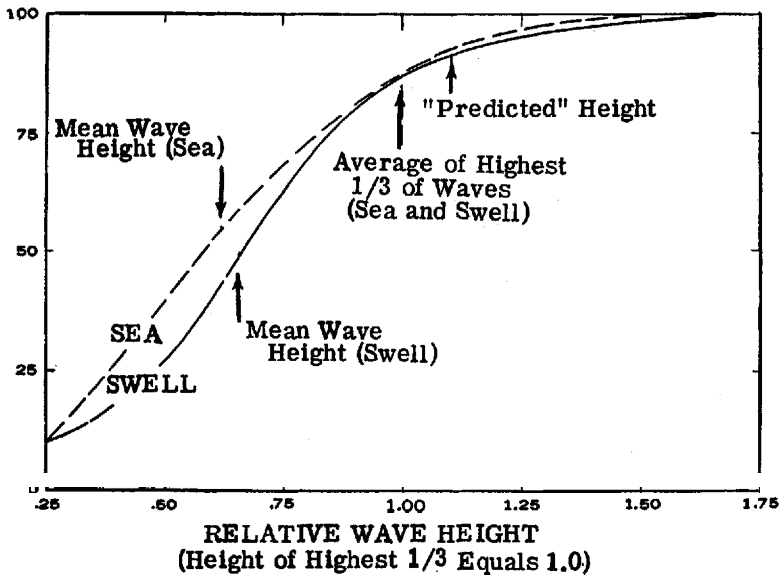

FIGURE 2. Per cent of occurrence of relative wave height for sea and swell (after Scripps Institution of Oceanography's Wave Report No. 68).

Munk[4] and Suthons generation graphs. It is evident that, for waves approaching along the normal to the beach, the Sverdrup-Munk values were a trifle high. This discovery caused the Swell Forecast Section to apply a reduction of 10 per cent to values computed by this method to obtain breaker height. The computed Suthons values were much higher than the observed heights. Because of this, and because the Sverdrup-Munk curves were presented in a much more usable fashion, the latter curves were used in all operational forecasting. Other theoretical and empirical considerations likewise indicated that the increase in height of wind waves at the time of breaking could be neglected, a fact substantiated by later wave research.

Because the East Anglian stations had an accumulative exposure of about

268 degrees, the observations provided a clue as to the extent heights were reduced when waves approached the shore at an appreciable angle. The spread of values for different angles of refraction is shown in FIGURE 3,

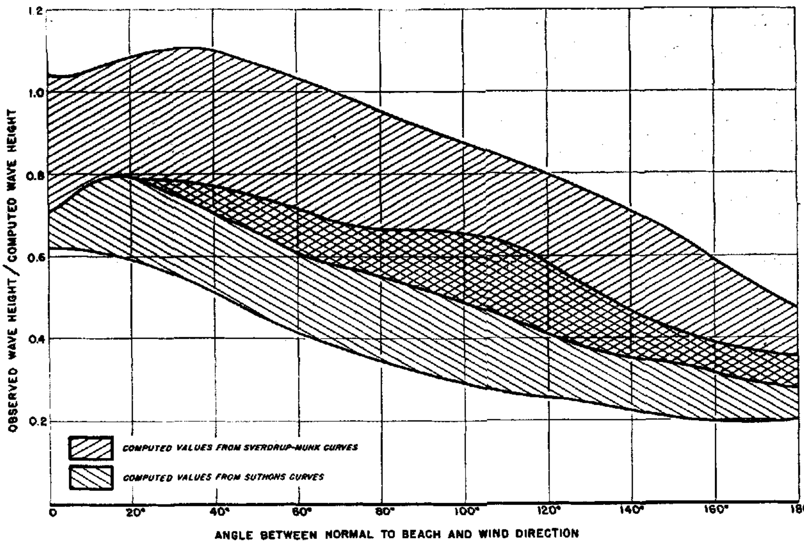

FIGURE 3. Variation of wave height with angle of approach to shore, according to observations made along the East Anglian coast.

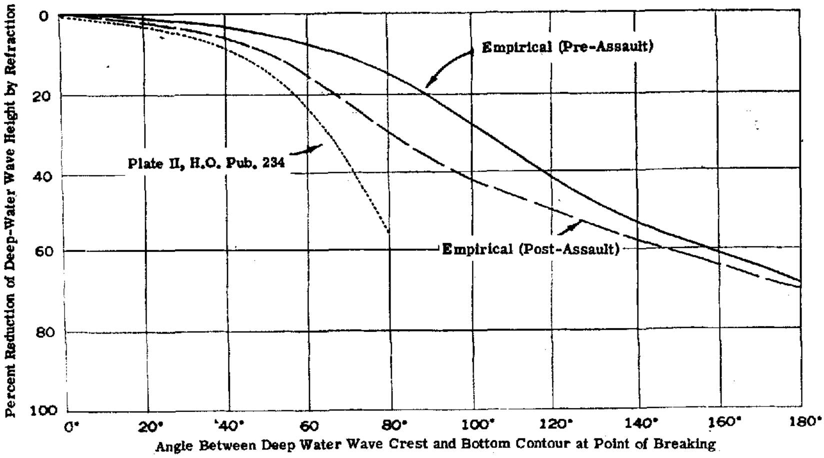

FIGURE 4. Values for reduction of wave height by refraction according to theory and two sets of empirical data.

while the values used in the Swell Forecast Section are given in FIGURE 4. It will be seen that the values used are in good agreement with the theoretical values given for a simple beach in the subsequently published "Breakers and

Surf, Principles in Forecasting"[5] for refraction angles less than forty degrees, but that considerable discrepancy occurs for greater angles.

The empirical values obtained for angles of refraction between ninety and one hundred and eighty degrees were particularly valuable because the technique of preparing wave refraction diagrams as developed by O'Brien and associates[6] was unknown to the Section at that time.

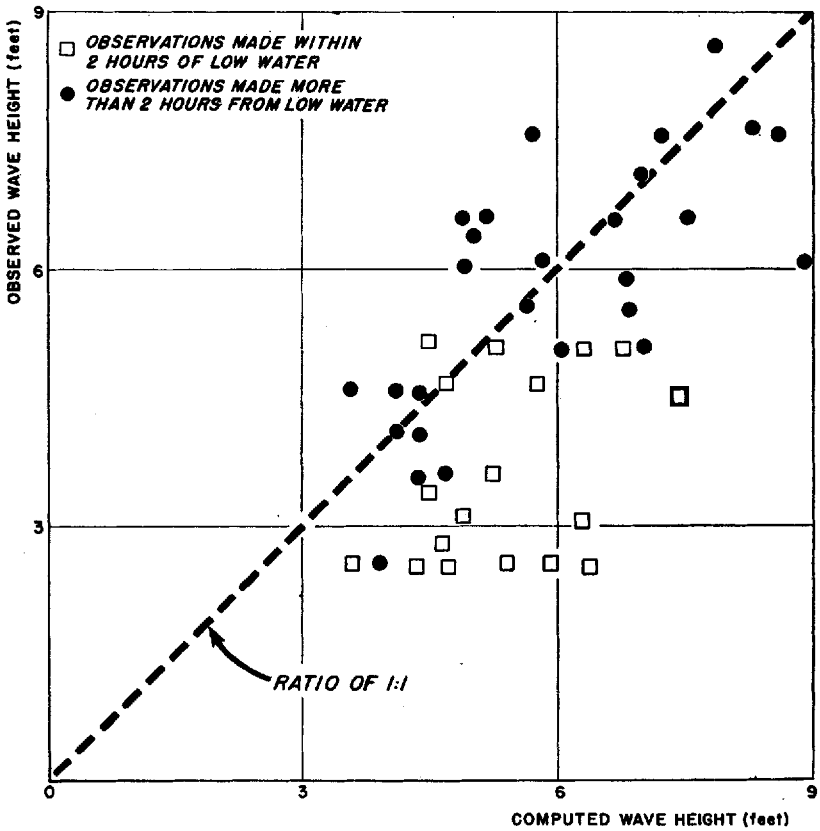

FIGURE 5. Computed versus observed wave heights for different tidal stages at Cley, Norfolk.

A third interesting feature found in the East Anglian data was that heights observed at certain stations within two hours of low water were inexplicably lower than the computed heights. This reduction, which averaged about twenty per cent, was particularly well evidenced in the distribution of height values for Cley, Norfolk, where the observations made more than two hours from low tide center about the ratio of 1:1 for observed versus computed heights, but the observations within two hours of low tide have only one value with a ratio greater than 1:1. (See FIGURE 5). Investigation indicated that there should be no appreciable error in observing at low tide, because the water line retreated only one hundred and fifty feet or so in most cases. The irregular offshore bottom topography likewise appeared to be incapable of causing the unusual decrease. In fact, one of the stations with a relatively smooth offshore profile had a greater height reduction than stations with irregular profiles. A third possibility was that strong tidal streams opposed the forward motion of the waves and caused a pronounced loss of wave energy offshore through partial breaking. This effect is believed to be the cause, inasmuch as this is a region in which the time of low water coincides roughly with the time of the strongest northerly-flowing tidal streams. Since these tidal streams range from 1.0 to 1.5 knots at neaps and from 2.0 to 2.5 knots at springs, and most of the situations studied were for waves approaching from the north, it is highly probable that the tidal streams acted as a partial breakwater. This phenomenon of opposing tidal streams acting like a breakwater has long been mentioned in the literature, one of the more remarkable examples being reported in the Shetlands by Stevenson[7] during the last century.

The tidal current effect on wave height was given additional scrutiny because one of the basic publications on English Channel weather maintained that the sea conditions raised by winds in the Channel depended largely upon the tidal streams. However, the wave observations along the Channel coast did not show any undue fluctuations in height, as were observed in East Anglia and as one might be led to expect from this statement. Although several stations did report suspicious heights, investigation indicated that the water line receded a considerable distance at these stations and reliability of observations made during low tide was open to considerable question. It was decided that tidal streams never raised the breaker heights if tidal streams opposed wave motion offshore. Tidal streams off the assult beaches generally paralleled the shore such that the effect could be ignored in forecasting surf conditions there. However, it was recognized that strong tidal streams, such as those found off the northeast tip of the Cotentin Peninsula, would cause marked changes in deep-water wave characteristics. Before D-Day, the Section believed that only the wave steepness would be markedly changed, the height increase being of the order of a foot or less. Subsequent work at Scripps proved this assumption to be in error as it was found that the height increase could be two or three times the original deep water height if the opposing current were strong enough and breaking did not occur.

When in early April, 1944, the Supreme Headquarters, Allied Expeditionary Forces (SHAEF), required 5-day wave forecasts for the English Channel and adjoining sea areas, the Swell Forecast Section had acquired a considerable backlog of experience in handling the problems outlined here. Preparation of the OVERLORD weather forecasts was the result of frequent conferences held *via* private secure telephone between three weather centrals (Air Ministry, U. S. Strategic Air Forces, and Admiralty), and the three staff meteorologists representing SHAEF, Allied Air Headquarters, and the Allied Naval Commander, Expeditionary Forces. After the general synoptic picture for the next five days had been decided upon in each of the weather conferences, the conferees agreed on the wind forecast to which one of the wave forecasters had been listening at Admiralty. Then, either alone or in consultation with another wave forecaster, the wind-wave forecast was prepared and incorporated with the swell forecast made just prior to the conference, in order that the complete wave forecast could be given at the close of the conference.

From June 15 onward, forecasts for SHAEF were made daily for three-day periods, while Allied Naval Commander, Expeditionary Forces, received forecasts twice daily for a two-day period. Forecasts were also sent *via* radio to USAAF mobile weather stations in Normandy to aid in preparation of forecasts used in unloading operations, and to the Office of the Chief Engineer, European Theatre of Operations, for inclusion in the Daily Hydrographic Bulletin issued by that activity to the U. S. Ground Force Commands.

The rapidity with which the wave forecasts had to be prepared and the control exercised on fetch and refraction values by the complex coastal outline caused the Swell Forecast Section to develop "Surf Prediction Diagrams" for beaches with different characteristics, namely the British group, Omaha, and Utah. The diagram for Omaha Beach is shown in FIGURE 6. The polar section of the diagram delineates the maximum effective duration for various wind speeds from any direction, with the dashed parts of the curves indicating indirect fetches where waves were likely to appear because of refraction and diffraction processes even though headlands intervened. A comparison was made between the maximum effective duration determined from the diagram and the actual duration. The lesser value was then entered along with the proper wind speed in the generation graph based on the Sverdurp-Munk curves. The wave height so determined was reduced by the appropriate correction factor given in the rim of the diagram, with the resulting value being considered the predicted surf height.

The accuracy of operational forecasts made in the above manner is of interest. Using the definitions given earlier for accuracy of wind and wave forecasts and excluding all cases in which wind forecasts were in error, it was found that wave forecasts were correct eighty-eight per cent of the time for the assault beaches in the period June 6–30. If all bases are excluded in which winds were light or directly offshore, because no forecasting skill is involved, the forecasts were correct eighty-three per cent of the time for the same period.

In addition to information provided by the Swell Forecast Section, "on-the-spot" climatological studies and forecasts of wave conditions were supplied field commanders during the pre-assault and assault phases by staff meteorologists such as Steere with Task Force 122 and Lieutenant D. W. Pritchard, AUS, with Headquarters, 1st U. S. Army. These meteorologists had been supplied with special "Notes on the Sea, Swell, and Surf in the English Channel" and pertinent surf prediction diagrams prepared just before D-Day which incorporated most of the "know-how" acquired during the four months of the Swell Forecast Section's existence.

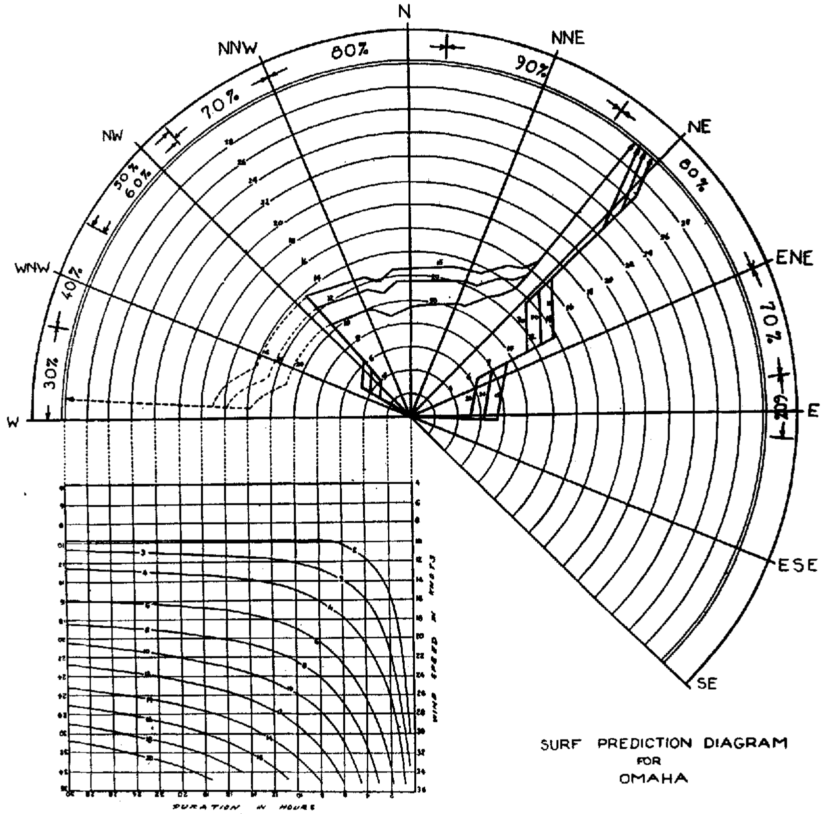

FIGURE 6. Surf prediction diagram as prepared for Omaha Beach a month before the Normandy invasion.

Although the invasion was originally scheduled for June 5th, the passage of a cold front caused a 24-hour postponement of D-Day. During the early part of the 6th (D-Day), wind waves offshore still averaged three to four feet in height with occasional heights from interference as high as six feet. All the beaches with the exception of Utah were directly exposed to winds of 12 to 18 knots, which raised three to four foot surf throughout the day. On sheltered Utah, surf heights were two feet and less. This condition remained until the afternoon of June 7th, when the northwest winds dropped to 5 to

10 knots and permitted waves to be but 1 to 2 feet high on all beaches by evening.

For the next eleven days, wave conditions did not markedly hinder invasion operations. On June 19th, however, a steep pressure gradient between a large anticyclone, centered northwest of the British Isles, and a comparatively weak cyclone, spreading across France and Spain, caused strong northeasterly winds in the Dover Strait and the English Channel. Although the naval command ships, USS AUGUSTA and HMS SCYLLA, only

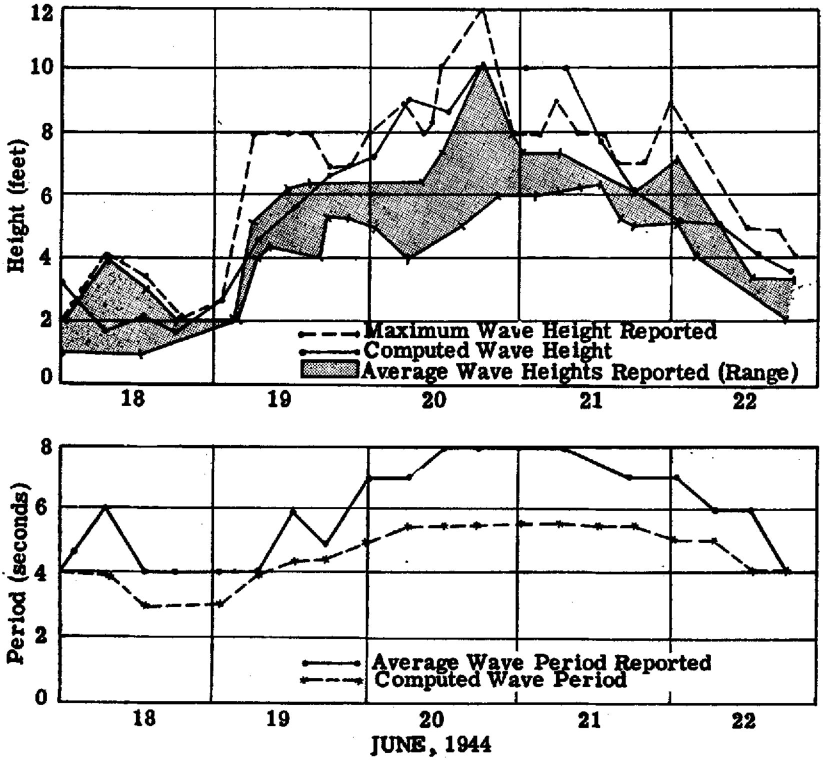

FIGURE 7. Waves observed and computed ("hindcast") for the area immediately off the Normandy Beaches (49° 26'N-49° 30'N; 00° 30' W-00° 50'W).

reported average wind speeds of about twenty knots and maximum wave heights of ten to twelve feet off the beaches, this episode was called the "Big Storm," for seven hundred landing craft were damaged or lost and the floating Loebnitz piers on Omaha Beach wrecked beyond repair[8] (See FIGURE 7). The twenty-four hour forecast for the 19th called for an increase in wind strength sufficient to raise wave heights to four feet, but heights of six to eight feet actually existed by that evening. A revision prepared a few hours after the routine forecast, however, provided sufficient warning, if a storm plan had been placed in effect. Forecasting for the remainder of the storm was particularly accurate, the drop in wave heights to operational values being forecast within two hours of the actual time of occurrence.

It is interesting to speculate on what might have occurred if D-Day had been postponed to the next favorable tidal period which happened to fall just before the "Big Storm". With the large high-pressure cell centered just west of Great Britain, the temptation was to forecast light winds instead of the packing of the isobars and resulting strong northeasterly winds which actually occurred over the Channel. If such had occurred, the story of the buildup phase on the beachhead, by coming just at the time of the "Big Storm," would have been much different than it actually was. This particular meteorological type was troublesome throughout the summer, for it re-appeared several times, though in a less pronounced fashion. Even if the northeasterly winds were light during night and morning hours and wave heights correspondingly low, reinforcement by the afternoon sea-breeze quickly raised heights to four feet or above, a value sufficient to shutdown DUKWs transporting cargo to shore from the freighters anchored outside the artificial breakwaters. As winds reported by weather stations just a few miles inland were generally light and variable on such occasions, forecasting from the beachhead itself was the only practical solution to the problem.

If, because of lack of information on surf conditions, work was suspended even one hour earlier than necessary, it resulted in the loss of hundreds of tons being off-loaded. In a similar fashion, any delay in resumption of operations after a siege of high waves cost valuable operational hours. To reduce this loss, British and American beachhead commands utilized both the forecasts from Admiralty and special forecasts prepared locally, the latter being more up-to-date because of slow communications between England and Normandy. The Flag Officer, British Assault Forces, had his own mobile weather station under Lieutenant J. H. C. Fulford, R.N.V.R.; Chief Warrant Officer White, U.S.N., at Cherbourg provided U. S. naval beach activities with necessary information; and Lieutenants D. W. Pritchard, AUS, and R. O. Reid, AUS, issued wave predictions required by the U. S. Army Commands. After the breakout, it was evident that the American beaches required a weather station of their own and could no longer rely on weather units at air fields. Under the command of Pritchard, Detachment YK of the 21st Weather Squadron, 9th Air Force, issued its first forecast on this new basis during September 12, 1944. As operations over the beaches did not cease until mid-November, the beach commands became increasingly weather conscious. Work initiated by the writer, after a visit to the beachhead in July, indicated a relationship so pronounced between wave height and the amount of tonnage discharged that wave forecasts actually became quantitative estimates of the scale of the next day's activities (FIGURES 8 and 9). This work was then developed by

Pritchard and Reid at Detachment YK on Omaha Beach. Seiwell's recent paper in the *Military Engineer* discusses in detail the work of this detachment;[9] therefore, further discussion of this phase is omitted here.

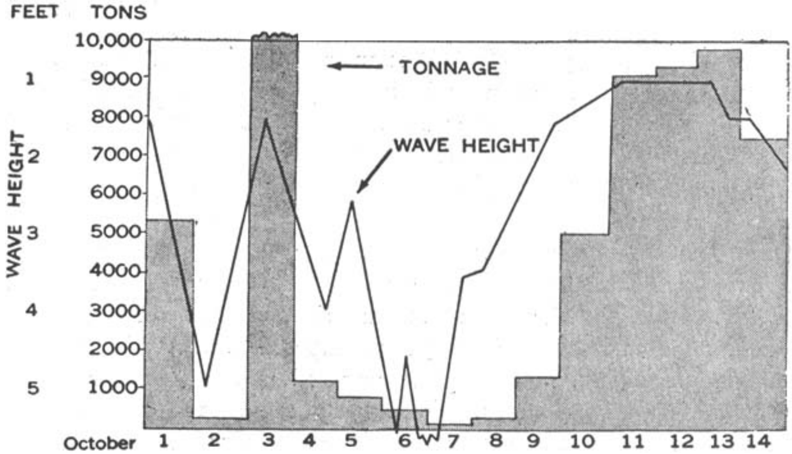

FIGURE 8. Effect of wave height upon amount of tonnage unloaded daily at Omaha Beach, Normandy during the first two weeks of October, 1944.

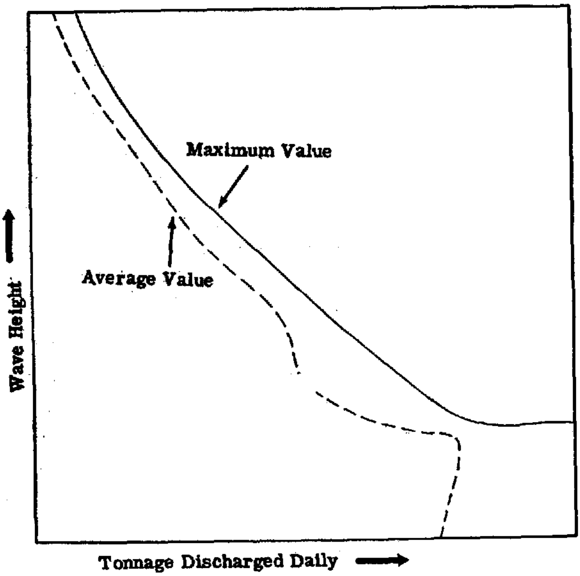

FIGURE 9. Relation between rate of unloading and the wave height at Omaha Beach, Normandy.

Forecasting for Amphibious Operations in the Bay of Bengal

Faced with the necessity of taking landing craft across the Bay of Bengal during the southwest monsoon, the Royal Navy transferred the Swell

Forecast Section, Admiralty, to the Joint Meteorological Centre, Colombo, Ceylon, in late 1944, to supply wave forecasts for the Southeast Asia Command and the British East Indies Fleet. Through the courtesy of the American Army's weather service, the key American personnel (Crowell, Lochner, and the writer) remained with the unit.

The problems facing the Swell Section, as it was called following the transfer, were as fully numerous and intriguing as those which had faced the group before OVERLORD. Tropical meteorology did not possess methods of determining wind speed and direction with the accuracy desired in wave forecasting. The strong southwesterly winds of the monsoon were predominantly offshore for the area in which synoptic weather reports were available, but onshore in the assault areas, where there was little synoptic weather information. Fetches were now of the order of hundreds and thousands of miles, rather than the tens of miles found in the English Channel. The entire Bay of Bengal was exposed to southerly swell that could originate anywhere in a vaguely observed oceanic expanse stretching southwards as far as Antarctica. Forecasting the amount of height increase resulting from interference between different swell trains was also considered an outstanding problem after it was observed that breakers averaging three to four feet in height at Colombo were sometimes accompanied by maximum heights of fourteen feet.

As in England, the first work accomplished was the organization of a wave reporting network. This time the synoptic net composed of twenty stations was over three thousand miles in length (FIGURE 10 and TABLE 2). Two reports were made daily of average and maximum breaker height, average period, and the angle which the breakers made with the beach. During the organization of this network in February and March, 1945, each of the stations, with the exception of Cocos and Diego Garcia Islands, was visited by a member of the Swell Section for instructional purposes. Because of the nature of travel in Asia, these visits were often extremely interesting. For example, when Crowell visited Saugor Island, in the delta of the Ganges, he found himself the center of attraction for the entire populace, since he was the first white man to enter those parts in many years. The Admiralty Research Laboratory, Teddington, England, also cooperated in the observation program by sending two technicians, Mr. Alexander and Lt. Ogilvie, RNVR, to install and maintain two pressure-type wave recorders. In order to determine whether there was a suitable installation site along the Arakan coast, Crowell flew behind the Japanese lines in a light airplane. He decided that shallow offshore profiles and living problems eliminated this possibility, even though British troops were advancing rapidly enough to secure any site selected. Plans were then made for installing the instruments at Colombo and Addu Atoll, and this was accomplished during the summer of 1945.

Although the Swell Section knew that the initial landing for which fore-

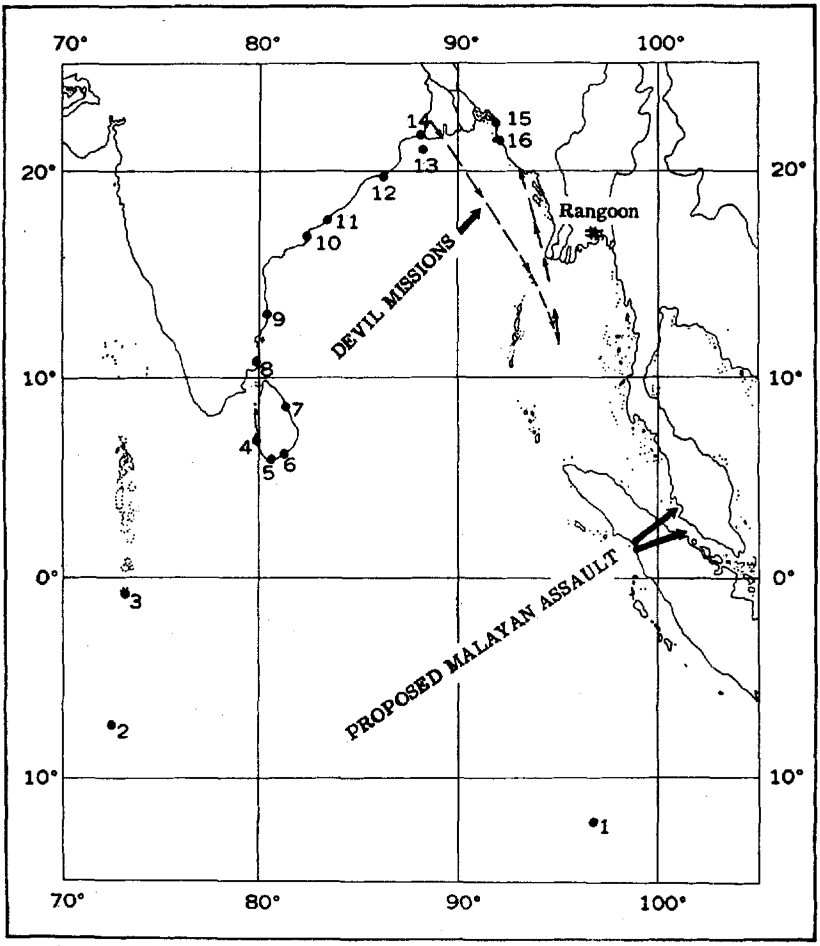

FIGURE 10. Index map showing location of wave reporting stations established to aid wave forecasting for the Bay of Bengal (for names of stations, see TABLE 2).

TABLE 2

WAVE REPORTING STATIONS ESTABLISHED TO AID WAVE FORECASTING FOR BAY OF BENGAL

Number	*Station*	*Number*	*Station*
1	Cocos Island	9	Madras (two)
2	Diego Garcia	10	Cocanada
3	Addu Atoll (two)	11	Vizagapatam
4	Colombo	12	Puri
5	Kogalla	13	Sandheads Lightship
6	Hambantota (two)	14	Saugor Island
7	Trincomalee (two)	15	Chittagong
8	Negapatam	16	Cox's Bazaar

casts were required was on the Burmese coast, the exact location for the first operation was made known only two weeks in advance. This operation, termed DRACULA, was the invasion of Rangoon in the delta of the Irrawaddy. The shortage of time prohibited detailed study of hydrographic data and aerial photographs, as desired. It was evident that forecasting for this region would be particularly difficult because tidal streams reached velocities as high as 7 knots, and shallow water extended miles to sea (FIGURE 11). Fortunately, a Scripps report on the effect of tidal streams on waves was available.[10] Detailed study soon indicated that the problem was not solved by any means, for the Scripps study assumed deep water, and did not treat with the loss of energy waves experience in passing through tens of miles of currents continually increasing in speed.

Wave forecasts were particularly desired in the assembly area offshore, where there was approximately a three knot current and the mean depth of water was about thirty-eight feet. The correction technique suggested by the Scripps report on tidal currents, when augmented by the correction for change in height due to shallow water, appears to give values for wave height that compare favorably with those actually experienced at the site. Sample values obtained by this method are given in Table 3.

Considering the vastness of the area, the meteorological and wave observation network for DRACULA was unusually good. A submarine, HMS STRONGBOW, was stationed just west of the northern tip of Sumatra, and the Second Weather Reconnaissance Squadron, U.S.A.A.F., arranged a special series of flights, termed the DEVIL missions, to the Andaman Sea (FIGURE 10). To insure high caliber wave observations, Lochner accompanied each of these flights as a wave observer and spent over one hundred hours in the air during the ten-day period. Hourly wave observations were radioed with the hourly in-flight weather reports to Calcutta and thence to Colombo. Although made from fast medium bombers (B-25s), the wave observations were generally of high caliber. Wind wave and swell heights were estimated while flying from 50 to 100 feet above the water, and wave period and direction of travel in deep water were generally obtained between altitudes of 1,000 to 4,000 feet. Along coastlines, period and direction were obtained through close scrutiny of breaker zones at lower altitudes. To make certain that undetected, low, long-period swell was not entering the area, the flights swung over Preparis Island, where surf on variously oriented beaches could be readily studied.

At the time of the operation, very low southwesterly swell from a broad, shallow low pressure area in the region of the Andaman Islands was present in the assembly area and combined with waves 2 to 4 feet high, formed by local winds. Low southerly swell from a tropical storm at about 10 degrees, south latitude, also arrived during the operation but was of little operational significance. The official wave forecast for the assembly area, as prepared by the Section, stressed that waves about 4 feet in height would be decreased

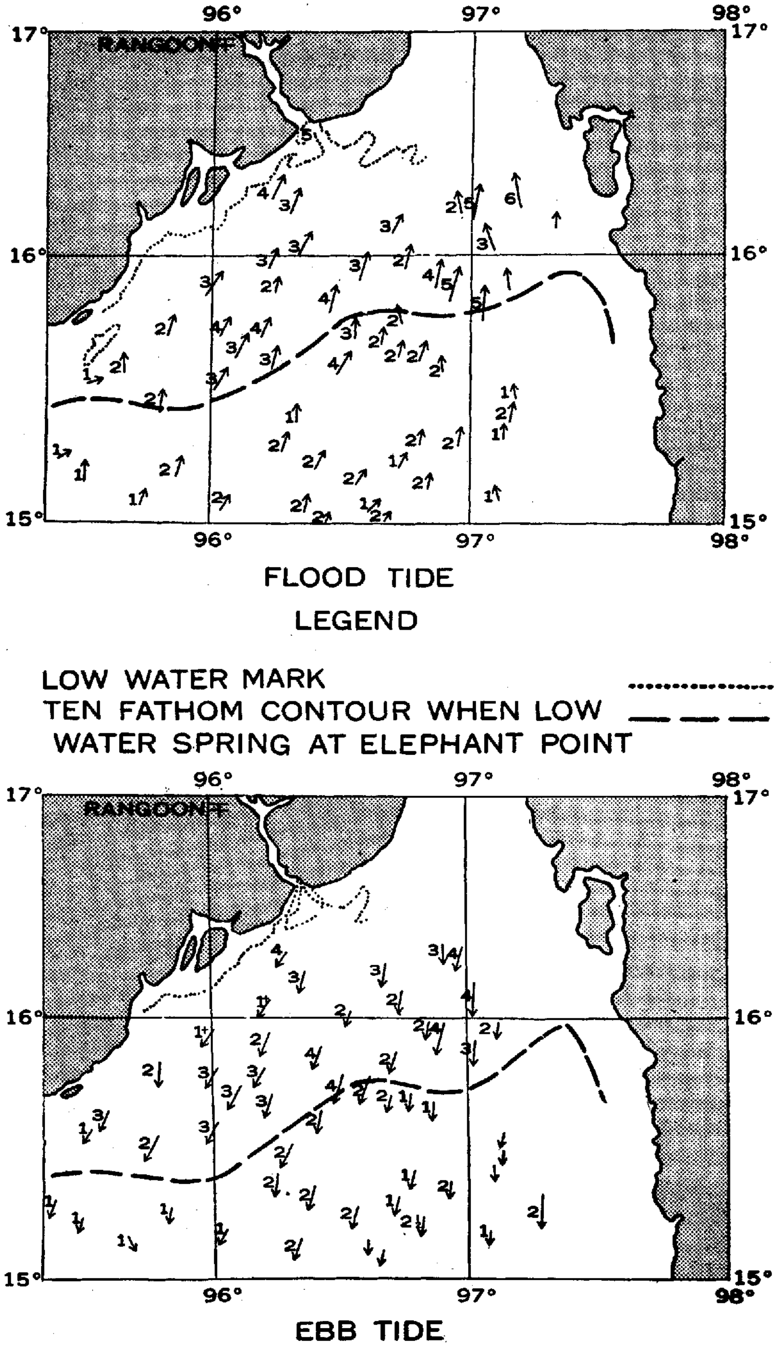

FIGURE 11. Sketch map showing tidal currents in the Gulf of Martaban during ebb and flood tide.

by half a foot on flood tide and increased by 1 to 2 feet on ebb tide. On-the-spot wave forecasts were supplied the invasion fleet by Cauthery, embarked aboard the HMS BLACKMORE, one of the participating destroyers. In keeping with the rule, unusually severe weather conditions occurred just at the time a major operation was scheduled, as in the case of the landings on Sicily, Japan, Leyte, and Normandy. The tropical low in the Andaman area threatened to develop into a storm just at the time of the operation. Luckily, the storm formed only a small but very intense center, about 50 miles in radius, which passed west of the Rangoon area and eventually turned inland near Ramree Island without damaging naval craft.

While the forecasts of the Swell Section had been very satisfactory during the operation, there was no post-assault requirement for such work. The group was free to turn full attention to the problems raised by the projected invasion of Malaya scheduled for September 9, 1945. Timing of this

TABLE 3
PROPOSED WAVE HEIGHTS FOR ASSEMBLY AREA OF DRACULA

Deep water wave height (feet)	*Flood tide (3 knot following current)*		*Ebb tide (2.5 knot opposing current)*	
	Period of 6 seconds	*Period of 8 seconds*	*Period of 6 seconds*	*Period of 8 seconds*
2	1.5 feet	1.5 feet	2.5 feet	2.5 feet
4	3	3	5	5
6	4.5	4.5	8	7.5
8	6	6	10.5	10
10	7.5	7.5	13	12.5
12	8.5	9	15.5	15
14	10	10.5	18	17.5

operation was particularly critical since, it would have used both parachute and air-borne troops, as well as troops transported by landing craft. Because of this, Southeast Asia Command was particularly interested in the odds of occurrence when conditions were favorable for landing craft to cross the Bay of Bengal during the monsoon. Because the "hindcasting" technique of establishing sea and swell conditions from past weather maps is not readily applicable to this region, it was decided to establish operational conditions in terms which could be defined by data available in wind, sea, and swell roses for five-degree squares. The problem was far from simple, as sea and swell observations are not highly reliable, being predominantly descriptive in nature, rather than quantitative. In addition, climatologists have usually over-simplified the roses. In so doing, they have often chosen climatic breakdowns that included the entire range from favorable to unfavorable in one category as in the case of wind forces 4 to 7. Determination of operational limits of the landing craft in terms of the natural environment was also difficult, but values were eventually assigned that did not arouse a storm of criticism. By averaging favorable wind conditions with favorable sea conditions, a fairly reliable value was obtained. This was then corrected for unfavorable swell conditions which occurred when the first two conditions were satisfactory. Computations of this type provided a value for operational conditions for each five-degree square by months, so that one was able to quantitatively compare locations or months, even though individual values by themselves contain appreciable error because of crudeness of

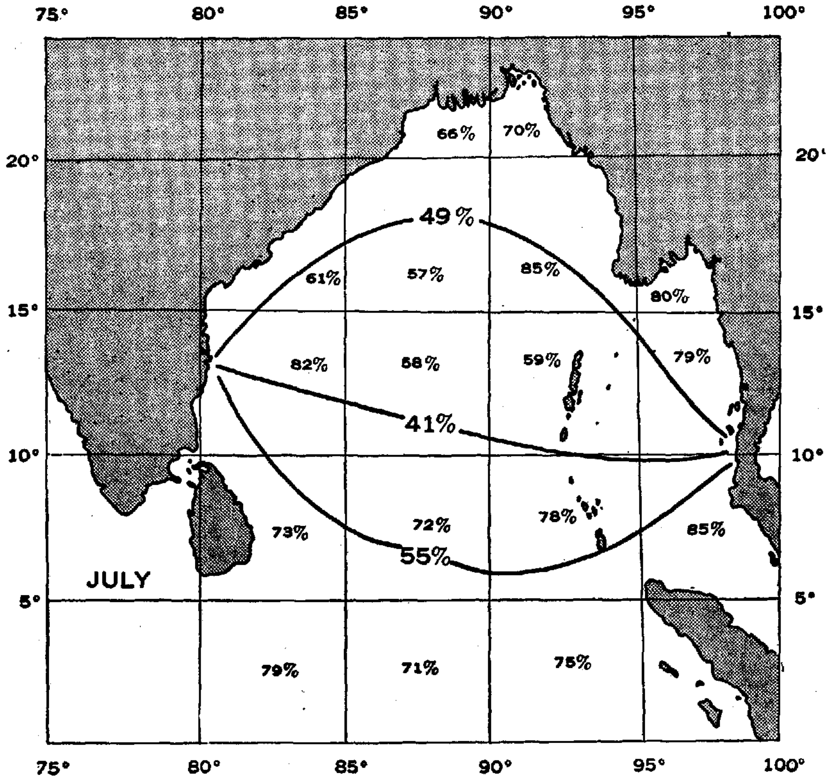

FIGURE 12. Probable frequency of suitable conditions for crossing the Bay of Bengal during the southwest monsoon, as well as suitable conditions for each 5° "square" (month of July).

basic data (see FIGURE 12). Routes could be compared by determining the lowest and highest values of possible occurrence of acceptable conditions along each route and assuming that the true value of acceptable conditions in each case lies at some unknown point between the two extremes. The best estimate is found by taking the mean of the extremes and comparing the values obtained. A technique similar to the one just described for routes was also developed to determine probable frequency of various surf heights along a long strip of simplified coastline.[11]

Wave Forecasting for the Projected Invasion of Japan

During May, 1945, it became evident that large scale amphibious operations involving Army troops in the western Pacific would require an oceanographic service. To meet this requirement, American personnel of the Swell Section were transferred to China and thence to the Philippines to form the nucleus of the Oceanographic Section of the Far East Air Forces (FEAF) Weather Central at Manila. Once chains of command became clarified, it was determined that the Manila weather group held final responsibility for over-all planning of the Army's invasion weather service. The Oceanographic Section was then instructed to proceed with planning and implementation of a wave forecasting service for operation OLYMPIC, the invasion of Kyushu.

Inasmuch as this, the largest amphibious assault in history, would be undertaken during winter months over three open beaches with varying orientations, wave conditions were bound to be an important factor (see FIGURE 13). To reduce this factor, there were available a back-log of experience in the subject, experienced forecasters in both Navy and Army, and perhaps most important, a realization by the field forces that oceanographic forecasts, if properly used, were of definite value in combating this factor. Since the Navy had primary responsibility for "staging" and "initial assault" phases and the Army primary responsibility during "build-up" and "supply" phases, it was only logical to pool the efforts of meteorologists from both services to make certain that there would be continuity and confidence in the weather service offered to the assault forces. The coordination was relatively easy in the Manila area because FEAF and 7th Fleet Weather Centrals shared the same building and because aerologists to Commander, Amphibious Forces, U. S. Pacific Fleet and to the 3rd and 7th Amphibious Forces were aboard flagships anchored in Manila Bay. Visual wave observations scheduled to begin during September would also have been a joint affair. Weather observers at various points on Okinawa, Iwo Jima, Ie Shima, Guam, Saipan, Samar, and Luzon and aboard four weather ships stationed east and northeast of the Philippines would have reported daily at 0700, 1200, and 1600 hours local time in the Combined Surf Code. As sea conditions could be inferred from wind data, the weather ships would have reported only swell height and direction according to the code, swell taking the place of surf in this instance. Observations would then have been radioed to Manila for inclusion in the routine synoptic broadcast. Installation of wave measuring instruments was not planned, because of shortage of time and equipment.

Meanwhile, as plans for OLYMPIC developed, forecasts were prepared for the Transportation Section of Philippine Base Section, operators of inter-island shipping. The frequent hurricanes of the summer of 1945 soon tested the forecasting techniques developed by Commander W. J. Francis, U.S.N.,[12] and it became distressingly evident that wind forecasts being made in conjunction with these storms were inadequate to serve as the basis for accurate sea, swell, and surf forecasting. One example of this was the wave forecasts prepared when typhoon "Queenie" crossed northern Luzon from east to west as a weak low during the night of August 5th and reached maximum intensity while about 300 miles west of the island on August 7th.

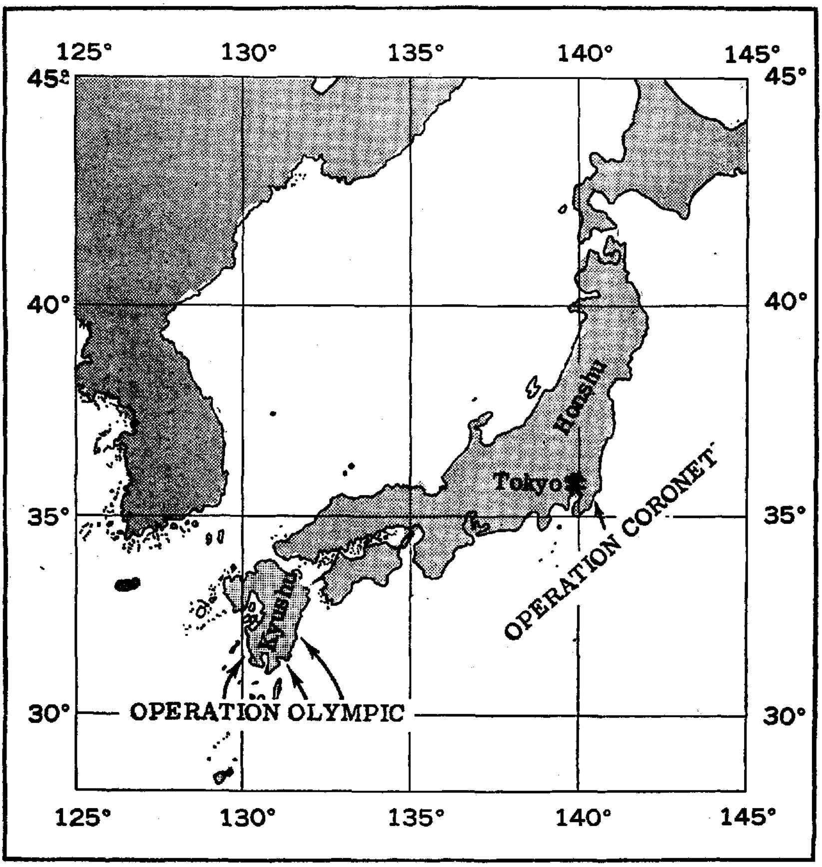

FIGURE 13. Index map showing proposed amphibious assaults against Japan.

A flight by a Navy hurricane reconnaissance plane indicated waves to be about 40 feet high and surface winds in excess of 80 knots in the southern quadrant, the sector from which swell would be generated for the north-western coast of Luzon.[13] Both Army and Navy forecasts called for breakers to be twelve to eighteen feet high along this coast during the 8th, yet when Lochner flew north during the morning hours, he found breakers to be but two to three feet high! Surface wave observations made just south of the mouth of the Laoag River during early afternoon gave an average height of three to four feet and a maximum of six feet or a trifle higher. The wave period, if determined from the number of waves in a five minute interval, was six seconds; if determined from a series of sharply defined waves, seven seconds. The storm continued westward to the coast of French Indo-China and wave conditions in the Luzon area soon returned to normal. The sharp discrepancy between forecast and observed wave heights east of this storm can only be explained by a wind distribution entirely different than that expected from the circular isobaric pattern customarily drawn for typhoons. Winds observed by the reconnaissance flight and by surface ships in the southern quadrant within 150 miles of the storm's center bear out this assumption. Of thirteen reports available, only one indicates a westerly wind, while the others range from south-southeast to southwest, directions which would provide a generating area so oriented that swell would pass to the north of the Philippines. Unfortunately, this anomalous situation was not evident at the time, and the rule that wave forecasts are no better than the wind analyses on which they are based was verified with a vengeance.

By the time hostilities ended in mid-August, 1945, the wave forecasting service for OLYMPIC had become well defined. The basic sea, swell, and surf forecasts required by General MacArthur's headquarters and the forces afloat would be supplied by a joint oceanographic section in the weather central building at Manila. This group would also act as the central collecting and disseminating agency for surface and aerial wave observations. An Army oceanographic meteorologist would have been aboard each of the task force flagships to assist the force aerologist and to provide wave forecasts required by the staff Army meteorologist. Once beachheads had been secured, mobile weather stations staffed by oceanographic meteorologists would be established at each beach command to provide weather and wave information in a manner similar to that finally developed in France.

As soon as the beachhead stations were functioning, the army meteorologists aboard the flagships would have been withdrawn to serve as the planning unit for the service needed in operation CORONET, the invasion of the Kanto plain in eastern Honshu. This, the last scheduled large scale landing of the war, would also have been particularly susceptible to wave action, for the beach was directly exposed to oceanic conditions and a shallow bar offshore would frequently have caused an additional surf zone certain to have made difficult the ship-to-shore movement of cargo.

Conclusion

Forecasting of sea, swell, and surf conditions in quantitative terms developed during the early part of World War II and reached maturity within three short years. The techniques were basically correct and could be modified by meteorologists trained in the methods to provide reliable forecasts for amphibious operations wherever they might be held. The value of the information is well expressed in one of the citations given for wave forecasting in the Normandy invasion. The citation reads, in part, "The work has aided materially in the success of the assault operation and in operations on the beach after the assault. The efforts . . . have been a real contribution to the success of the present campaign."

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Discussion of the Paper

WARREN C. THOMPSON (*Scripps Institution of Oceanography, La Jolla, California*): An unpublicized phase of sea, swell, and surf forecasting was developed during the war by the Navy Amphibious Forces in the Pacific. This work centered around the Staff Aerological Officer and a team of flying aerologists trained in both forecasting and observing wave and beach conditions on enemy beaches. The team was formed with the object of avoiding needless losses of men and equipment that might be caused by adverse hydrographic conditions in the landing phase of an invasion, such as occurred at Tarawa. The hydrographic information obtained over enemy beaches was used by amphibious commanders in making decisions as to the desirability of utilizing the designated landing beaches. It also served as a guide for boat captains in the initial landing through the surf.

The three members of this unique reconnaissance team were Lieutenant W. M. Johnson, U.S.N.R., Lieutenant D. B. Murphy, U.S.N.R., and Lieutenant W. C. Thompson, U.S.N.R. They began their careers as observers when they enrolled in the Navy course in sea and swell forecasting which was set up under the guidance of Captain H. T. Orville, U.S.N., at Scripps Institution of Oceanography. The course was organized by Dr. H. U. Sverdrup, Director of the Institution, who, with the cooperation of Mr. W. H. Munk, developed the practical technique of wave forecasting which was later to be used by the observers in predicting wave conditions for invasions.

In August, 1944, the three officers were assigned to the staff of the Third Amphibious Force, commanded by Vice Admiral T. S. Wilkinson, U.S.N. The Hydrographic and Special Beach Observers, as they were unofficially designated, were under the immediate supervision of Commander O. D. Finnigan, U.S.N., Staff Aerologist, and were extensively trained by him. Their job was essentially to make pre-invasion aerial observations of weather, sea, and surf conditions at a given beach, extent and type of obstacles in the approaches to the beach, gradient and width of the beach, and any other pertinent data. In order to discharge these duties the observers were required to become proficient in aerial observation, beach hydrography and intelligence, photo interpretation, and aircraft communications. In addition, they were required to have a broad knowledge of amphibious operations, and a detailed knowledge of swell and surf conditions and their effect on amphibious craft and vehicles.

Trial aerial observations were made on the beaches of Oahu and it was found after a little practice that the breaker heights that were observed up to 6–8 feet could be estimated quite consistently within a foot of the actual height when flying at altitudes of 1000 to 2000 feet. The estimated heights were verified by observers on shore. This accuracy of visual estimation fixed confidence in the plan of making surf observations from the air.

The first operation assigned to the Third Amphibious Force, after succeeding the Fifth Amphibious Force in the Pacific offensive, involved the seizure of the southern Palau Islands in order to provide airfields for the forthcoming Philippine invasion. Thompson was chosen to make the first beach reconnaissance and joined the advance force at Guadalcanal. He was necessarily billeted aboard an aircraft carrier and became a member of the flight crew as a Technical Observer. Upon arrival at Peleliu, he made frequent pre-D-day familiarization flights in TBM-type aircraft over the landing beaches.

While aboard the carrier off Peleliu, a continuous forecast of sea and swell was maintained to determine the wave conditions that should be expected in deep water adjacent to the barrier reef which fringed the landing beaches. Since no method of forecasting wave heights and breakers over a submerged reef had been devised, the swell forecasts were valuable only to give an idea of the magnitude of the surf activity. The forecasting procedure used was that which was developed by Sverdrup and Munk, and it proved to be quite accurate and adequate for its purpose.

Lieutenant Commander G. H. Heyen of the Royal Australian Naval

Reserve, on special duty with the U. S. Navy, also acted as a hydrographic observer of the Peleliu beaches. Heyen was engaged because of his extensive knowledge of tropical weather and sea conditions acquired through many years of living and sailing among the coral islands. Before dawn on D-day, 15 September 1944, the two observers flew over the Peleliu landing beaches until it became light enough to see. Comprehensive observations of the surf conditions were then made as quickly as possible, because time as well as accuracy was essential, and the information was relayed by radio to the flagship of the operation. Three or more passes over a beach were required to collect the necessary information, which consisted of breaker heights and periods, type of breaker, width of the surf zone, direction of sea and swell, and so forth. Flights were usually made at altitudes of 1000 to 2000 feet, but at Peleliu they were made as low as 20 to 50 feet. The Palau landing began about three hours after the hydrographic observations were completed. The surf conditions for landing were very good and breaker heights did not exceed two feet. After the landing the main job of the observers was completed. Subsequent observations for invasions were obtained by a similar procedure.

Preliminary invasion plans called for an assault on Yap Island, and Johnson and Murphy were assigned to cover the beaches. However, with stiff opposition encountered at Peleliu and a weaker enemy air strength than anticipated in the Philippines, the Yap operation was canceled. The Yap expedition was diverted to the Philippines and was augmented for a landing on Leyte, which involved both the Third and Seventh Amphibious Forces under the overall command of Vice Admiral Kinkaid, U.S.N., Commander Seventh Fleet. Aerial observations of beach and surf conditions were made at Leyte by Johnson and Murphy several days prior to and during landing operations on 20 October 1944.

Johnson and Murphy next made observations for the landings in Lingayen Gulf. In connection with their sea and swell forecasts, they prepared refraction diagrams for the Gulf, and, on the basis of the diagrams, they made recommendations for landing men and supplies on stretches of beach which displayed the greatest divergence of wave orthogonals. Their advice was well borne out by adverse sea conditions in the Gulf following the operation, and for this timely piece of work Johnson and Murphy were awarded the Commendation Ribbon.

Following the Philippine landings, the Third Amphibious Force retired and the Fifth Amphibious Force resumed the offensive. It opened with a landing on Iwo Jima on 19 February 1945. Prior to and including D-day, Johnson and Murphy reconnoitered the assault beaches on the west side of the island and Thompson covered the alternate beaches on the east side. Whenever it was possible, alternate beaches were chosen for landings so that, if weather and sea conditions on the main assault beaches made landing inadvisable, the alternate beaches might be available for attack. The aerial observations at Iwo Jima were somewhat hampered by cloudy weather, but the sea conditions were found to be very good for the landing on D-day. Several days after, however, high surf conditions which were forecasted temporarily suspended the landing of vitally needed supplies on the assault beach.

The final set of beach and surf observations were made by the three observers at Okinawa. On D−7 day Thompson began making observations of the Karama Retto, a group of small islands a few miles to the west of southern Okinawa. The Retto was occupied because it forms for ships a natural shelter from adverse sea and weather conditions. A few days prior to D-day, Johnson and Murphy began their reconnaissance of the main landing beaches on the west coast of Okinawa and Thompson covered the alternate beaches on the southern coast. On D-day, 1 April 1945, conditions for landing were again quite favorable.

The job of aerial beach observer was not without its hazardous moments, aboard ship as well as in the air. Johnson experienced his first real action aboard the USS FANSHAW BAY when she was heavily shelled by enemy surface craft in the Philippine Sea. Also in the Philippines, Murphy was aboard the USS KITKUN BAY when it was badly damaged by a suicide plane. Later, Thompson was aboard the USS WAKE ISLAND off Okinawa when she also was damaged by a suicide plane. Thus, for obvious reasons the three observers were not generally together aboard the same ship during an operation. However, on D + 2 day off Iwo Jima, they gathered aboard the USS BISMARCK SEA to take part in a fast carrier strike at Okinawa. As fate would have it, two suicide planes attacked the ship at dusk, and a short time later she slipped beneath the waves. It was fortunate that all three observers were rescued, because there were no trained personnel to replace them at that time.

Toward the end of the Pacific hostilities, three additional aerial observers were being trained, but with the Japanese capitulation on 14 August 1945 the landing beach studies were terminated. As a result of their flight activities, the three observers were presented with the Air Medal with Gold Star by Vice Admiral Wilkinson, U.S.N., in a Navy Day ceremony (1945) in Yokohama. At a later date, each was presented separately with the Bronze Star Medal for "heroic and meritorious achievements in the carrying out of their assignments as Hydrographic and Special Beach Observers."