Status of Storm-Tide Research

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Because of the importance of the problem of forecasting high water levels that accompany hurricanes at coastal stations, I feel that some general remarks about the status of storm-tide research would be of value in stimulating further research. The aim of this paper (*1*) is not to give a comprehensive résumé of all work done to date on the subject of storm tides but to attempt to define the general problem and to point out some specific questions that require answers if an adequate prediction of storm tides is to be achieved.

General Problem

The quantitative investigation of any natural phenomenon demands an adequate definition. In the storm-tide problem, we require a statement of scope because water-level variations in general are characterized by a diffuse power spectrum that covers an extremely broad range of periods—from fractions of a second to many years. Of the entire spectrum, the astronomical tides and seiches (*2*) are evidently the only phenomena in which the power is concentrated in a finite number of discrete periods. Ordinary surface waves and swell cover a rather broad range in which the power is evidently continuous but does possess blurred peaks that characterize the particular generating factors. We know less about the intermediate range of periods between those of swell and astronomical tides, but we do know that such phenomena as surf beat, edge waves, tsunamis, and storm tides occur in a diffuse and overlapping manner within this range. Storm tides no doubt overlap the periods of ordinary astronomical tides as well.

As a working definition, one might define storm tides as those disturbances of water level exclusive of (i) ordinary surface waves, ripples, and swell; (ii) tsunamis and other anomalies of water level associated with molar disturbances of the earth; (iii) surf beat associated with the irregularity of the net shoreward transport of water by ordinary surface waves and swell in the surf zone; (iv) astronomical tides; (v) variations in water level resulting from water density changes by thermal processes or from redistribution of mass associated with modifications in the quasigeostrophic circulation of the oceans (owing to changes in the vorticity of the zonal wind field of oceanic scale); and (vi) ultralong-term variations in apparent water level of geological nature such as may result from subsidence and other causes. Seiches, on the other hand, are considered as part of the storm-tide problem and represent merely the natural mode or free forms associated with the dynamic aspect of the problem for a particular basin.

In short, this implies that storm tides represent those nonastronomical anomalies of water level that result from the winds, from abnormal atmospheric pressure, and from excessive precipitation caused by local storms, excluding ordinary wind wave "noise" and phenomena directly associated with such waves.

This definition is very useful in the formulation of the problem from a mathematical standpoint. From the standpoint of comparison of theory with observation, it is necessary that the appropriate unwanted vibrations be filtered out of the total water-level variation that occurs. By and large, an ordinary float in a still-well type of water-level recorder with a suitable orifice will filter out all ordinary waves and swell and perhaps much of the surf beat, which is probably of low power anyway. There is no formal difficulty in extracting the astronomical tides, and for East Coast and Gulf of Mexico stations, the occurrence of tsunamis seems improbable. This leaves items (v) and (vi) superimposed on the storm-tide data. The first of these is probably of negligible magnitude but can be evaluated, if the question arises, through oceanographic measurements in the deep water offshore. The second can certainly be regarded as negligible for the time that it takes a storm to pass a particular site.

Storm tides, like swell and astronomical tides, are basically gravity wave phenomena and therefore must involve some consideration of the dynamic effects associated with the movement of water (*3*), as well as consideration of the driving forces. Unlike swell, the storm tides can be considered as of long wave length compared with depth, and they are not entirely free waves. Like astronomical tides, the storm tides are long forced waves, but the driving force occurs at the surface of the water rather than on the entire mass of water itself.

In certain very special circumstances, a condition of (at least) quasisteady state —in the presence of the primary forces (wind stress and atmospheric pressure) —may be achieved and the problem becomes one of computing the "wind set-up" and/or "inverted-barometer" effect. In other special circumstances, the equilibrium may be one of balance between the pressure gradient, which is associated with the slope of the surface, and one or more of the secondary or dynamic forces that are associated with the motion of the water. The latter would be free waves, either standing or progressive, and are damped or not depending on whether or not bottom friction is present. One can visualize many other special cases; however, these two seem to serve as useful limiting cases.

The first of these special cases has been employed almost exclusively in past work pertaining to the problem of relating wind speed to water surface slope in lakes and bays (*4*). Needless to say, one should be cautious in accepting the results of such studies and should make sure that the conditions of quasisteady state were in fact realized. Attention to such matters does not seem to have been stressed until recently (*5*).

In the general problem, the storm-tide phenomenon is neither one of static equilibrium nor one of free gravity wave motion, nor is it a simple linear combination of these two limiting cases. This is one of the basic difficulties in attempting to establish a practical method of storm-tide prediction that will cover all the possible situations that may arise. The reason the forecasting of ordinary waves and swell has succeeded as well as it has is that one deals with the transformation of *free waves,* the initial heights of which are described in statistical terms —that is, on a probability basis—essentially through empirical formulas. The storm tide on the other hand must be considered in more detail than that involved in merely prescribing such quantities as a "significant" height and period. An accurate prediction of the entire time history or at least the maximum height

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to be attained at the site considered, under given storm conditions, is necessary if the method is to be successful.

The generation of a storm tide by the action of the wind depends rather critically on depth. This suggests a further inherent difficulty in the storm-tide prediction. The scale or effective wave length of the storm tide will be comparable to that of the storm fetch; thus an extreme range of depths may exist over the length of the wave. Consequently, even if the waves were regarded as free, the conventional methods of shoaling and refraction as employed in ordinary swell would not be applicable.

The 11 factors that must surely play a role in the determination of water level are as follows. (i) The depth of water, including the normal tide and the storm tide itself. Mean depth is in general a function of both of the horizontal coordinates, and the total depth is dependent on time in addition. (ii) The nature of the basin of water—whether it is enclosed or is in open communication with the deep sea. (iii) The scale of the storm relative to the scale of the basin of water. (iv) The wind velocity (both speed and direction) and its variation with space and time. (v) The atmospheric pressure and its variation with space and time. (vi) The velocity of propagation of the storm. (vii) The relationship between the wind stress and the wind speed and the stability of the air. (viii) The bottom friction associated with the flow of water; the nature of the bottom material. (ix) The inertial force associated with the acceleration of the water. (x) The deflecting force associated with the rotation of the earth (this may be of importance for large-scale disturbances on an open continental shelf). (xi) Rainfall (probably minor except over land areas).

Present Status of Research

There are two natural avenues of attack on the problem of storm-tide prediction that have been pursued in the past. These are (i) numerical analysis of existing measurements of storm tides and storms for a given site in the attempt to devise an empirical prediction technique that is statistically significant and (ii) mathematical analysis of assumed physical models where the formulation of the problem involves simple conditions on a number of the variables in order that a solution can be achieved. Some such special cases can be checked against existing data in those cases in which the conditions of the theoretical model are satisfied to a certain degree.

Many of the theoretical cases treated to date deal with conditions that are so restrictive that they are of virtually no value in prediction. A great deal of the literature on the subject, for example, deals with forced and/or free waves in a canal of constant depth and infinite length. Such one-dimensional problems yield interesting results, but they are applicable to real problems only in a qualitative sense if at all. In those few cases in which two-dimensional problems have been considered, certain important features of the behavior of the fluid are revealed that do not have any counterpart in the one-dimensional problem. This is particularly true of certain resonance phenomena.

The problem of the forced surge in a long canal of constant depth, which was investigated by J. Proudman (*6*), is one of the more elegant of the existing theories because of its simplicity. However, the criterion of resonance that is predicted by the theory, that the Froude number

$$V/\sqrt{gh}$$

be unity is hardly of any use when the depth h varies in the direction of the velocity of the storm V.

Among the more sophisticated mathematical theories on the subject, we find two dimensions considered with traveling storms, but again the depth is held constant right up to the shore, which is a vertical sea wall. Most of the more practical theories treat the problem by numerical solution; in so doing they are capable of considering such complications as actual bottom topography, but they are not capable of treating some of the important features involved in resonance phenomena. The theoretical work thus far completed has merely scratched the surface so far as our basic understanding of the real storm-tide problem is concerned.

From both the mathematical and physical standpoints, the general storm-tide problem falls into one of the following two broad categories: (i) Storm tide rise small compared with the normal depth, and (ii) storm tide rise represents a significant fraction or even exceeds the normal depth (such as near a sloping beach).

In the first case, the mathematical problem can be linearized and the general problem of the forced water level disturbance is formally capable of solution by the standard procedure of normal modes provided that the boundary conditions and forcing functions are specified. This involves first solving for the two-dimensional natural modes (or "seiche" modes) of the basin and then expressing the space variation of the forcing functions in terms of these natural modes and solving for a set of time-dependent coefficients. This leads to a solution in series form from which numerical values may be quite difficult to achieve. Only in certain special cases can a closed-form solution in terms of tabulated functions be achieved. However, a number of such special cases are important with respect to the variety of the results thereby achieved.

In the second case, the mathematical problem is nonlinear, and no general method for analytic solution exists. Certain special cases in this group are susceptible to treatment by the method of characteristics as used in gas dynamics and shock-wave theory, but this procedure has definite limitations. The only general procedure is that of some numerical method of solution employing finite difference equations. Here one must be guided by certain criteria concerning the stability of the numerical process in order to assure that the level of error involved does not exceed prescribed bounds. The numerical procedure indicates the use of high-speed computers for obvious reasons and suffers from the inability of achieving a compact analytic solution that indicates the role played by each of the independent variables considered (unless a considerable amount of computation is carried out).

Storm-Tide Behavior

In a lake the principal dynamic action manifests itself in the formation of a seiche superimposed on the forced wind set-up. The latter will have a value that depends on the rate at which the wind is varying. If the effective period of the variation of the mean wind is of the order of the natural frequency of the lake or bay, then a resonance can exist and the amplitude of the wind set-up can build up to a value many times the steady-state value under a sustained wind of the same magnitude. However, this requires several repetitions or cycles in the forcing agent. For the case of the passage of a single storm, where only one cycle is accomplished, the forced dynamic set-up may be of the same order as the steady wind set-up under conditions of the peak wind in the storm. Perhaps a more effective dynamic effect in a small lake would occur when the wind increases over the whole lake very suddenly and is thereafter sustained for many hours (such as may occur with a rapidly moving large hurricane). In this case the water level will rise at one end to a value that is about twice the steady-state value corresponding to the same wind, provided that the wind is sustained long enough. This is the result of the joint action of the forced and free seiches induced by the wind.

Over a continental shelf or bay that is in open communication to the sea, a greater steady-state water level can result than that in a lake or other small enclosed body because of the additional water transported into the area in question from the virtually unlimited supply of the open sea. That is, in a lake (of constant depth, for example) a uniform steady wind will produce a set-up of S feet at the downwind end and a lowering of water of S feet at the upwind end. On the other hand, in a bay of the *same length and same constant depth* subject to the same steady wind, the water level can be twice the value at the head of the bay (assuming that the wind is directed toward the head of the bay). Furthermore, on a very expansive continental shelf, the greater fetch of water under the action of the wind can lead to greater water level.

Important Questions

Some of the important questions that must be answered before an adequate prediction scheme is developed follow. (i) Under what conditions of the scale and intensity factors is it possible for the dynamic aspects of the water-level problem to become a significant part of the total storm tide? (ii) Under conditions where quasistatic conditions are nearly realized, how important are the two-dimensional aspects of the circulation of water (considering bottom friction) in governing the longitudinal and transverse gradients of water level? (iii) In the case of large scale storms on an open coast or over a moderately large basin such as the Gulf of Mexico, how important is the influence of Coriolis force in balancing the gradients of water level induced by the wind and atmospheric pressure anomalies? (iv) In determining the water level rise on a beach, what are the principal forces involved? (v) How important are the nonlinear aspects of the problem? Under what conditions can an abrupt free surge develop? (vi) Of greatest importance is the question of the appropriate boundary conditions to be imposed at the coast for a gradually varying bottom slope terminating in a beach with no cliffs or sea wall at the shore.

References and Notes

1. Contribution from the department of Oceanography of the Agricultural and Mechanical College of Texas, Oceanography and Meteorology Series No. 56. This paper is based on investigations conducted for the Texas A and M Research Foundation through the sponsorship of the Office of Naval Research.
2. Seiches are free standing waves in an enclosed or partially enclosed basin having a discrete spectrum.
3. The dynamic effects envisaged here include those associated with inertial force, Coriolis force, and frictional force. All of these are directly related to the motion (velocity and/or acceleration) of the water.
4. Actually this is one mode of attack on the problem of evaluation of the surface-resistance coefficient for wind stress.
5. B. Hauriwitz, *Beach Erosion Board Tech. Memo.* No. 25 (1951).
6. J. Proudman, *Dynamical Oceanography* (Wiley, New York, 1953), pp. 295–301.

Amendments to the AAAS Constitution

Dael Wolfle

At the 1953 meeting of the Association, the Council authorized appointment of a Committee on Constitution, Bylaws, and General Operations to review the Association's constitution and bylaws and to recommend appropriate changes. The committee consists of Wallace R. Brode, chairman, Roger Adams, Meredith F. Burrill, Clarence E. Davies, and Milton O Lee. Howard A. Meyerhoff and Dael Wolfle serve as advisers to the committee.

Amendments recommended by the committee were considered by the Board of Directors during their meeting 29–30 October. The board approved the committee's recommendations, with a few changes and additions, and authorized their submission to the Council at the annual meeting of 1955.

The constitution requires that proposed amendments be published in substance in *Science* and *The Scientific Monthly* at least a month before the Council meeting at which they are to be considered. Accordingly, the more important of the proposed amendments to the constitution are described in the following section. The next section lists several additional changes that are being recommended to clarify intent, remove ambiguities, or improve current practices.

Constitutional Changes

Article IV. A quorum now consists of 20 members and the signatures of 20 members are required to call a special meeting of the Council. In both cases it is recommended that the number be increased to 30.

Ordinarily each Council member has one vote, but in a few cases a member represents two or more affiliated societies and the number of votes to which such members are entitled has not been clear. It is recommended that each member have only one vote.

The president presides over Council meetings. If the president is absent, the constitution provides for the election of a chairman by the Council. It is recommended that the president elect serve in the absence of the president.

Article VI. A section committee now includes representatives from societies affiliated with that section and other Council members whose own scientific interests lie in the field of the section. Thus, some affiliated societies, such as state academies of science, may one year be represented in one section committee and the next year in another. It is recommended that representatives of societies that are not affiliated with a section that has a section committee not be made members of a section committee. If adopted, this change will mean that a society may be affiliated with one or more AAAS sections, that its representatives will serve as members of the section committees of such sections, but that the representatives will not be assigned to other section committees. To provide greater flexibility and to permit overlap of membership on section committees, it is recommended that the prohibition against serving on more than one such committee be abolished.

Article VIII. Affiliated societies have one or two representatives in the Council, depending upon the number of their members who are fellows of the AAAS. State academies of science have for some years been an exception to this rule, for regardless of size they have only one Council representative. It is recommended that this arrangement be continued and that it be specified in the constitution.

In order to make formal provision within the Association structure for such