CHAPTER 9

A PRELIMINARY STUDY OF STORM SURGES IN HUDSON BAY by K.B. Yuen and T.S. Murty Oceanography Branch, Marine Sciences Directorate, Department of the Environment, Ottawa, Ontario.

Abstract

In view of resource exploration, hydro-electric power development and other activities, there is a clear need for a better understanding of the hydrodynamics of Hudson Bay. One particular area that has received little attention in the past is storm surges. It is likely that a storm surge prediction will be very useful in the future and towards this goal a two-dimensional homogenous model has been constructed. A hindcast of the storm of October 15, 1969 is presented here. The calculated surge for Churchill, Manitoba compares favourably with observed residues. The overall response of the basin and the types of oscillations that are produced are also described here. In addition, the differences in behavior between James Bay and Hudson Bay proper are demonstrated. Finally the results also indicate the steady circulation which the storm has produced.

INTRODUCTION

Hudson Bay is one of the most complex and least known large water bodies in Canada. For its vast size it is extremely shallow and the topography is complicated by islands. Storm surges in most Canadian waters are not nearly as large or as devastating as those found in more tropical areas, nevertheless the prediction of storm surges is of great importance in the planning of human activity and resource management. As an initial step, a numerical model of Hudson Bay. was constructed for the purpose of studying the behaviour of storm surges in the Bay.

THE MODEL

In Figure 1 is shown the grid that was used to approximate Hudson Bay. It is 74 x 80 in dimension and is in polar coordinates. The actual configuration is a staggered grid and the black dots represent the Z or water level points, which are spaced two grid lengths apart. The components of the velocity are calculated at points midway between the Z points. This particular configuration facilitates the application of central difference operators. Figure 2 shows the depth configuration of Hudson Bay with a contour interval of 100 metres.

Figure 2 shows the depth configuration of Hudson Bay with a contour intervals at 100 metres. The Bay is guite shallow, except for several deep areas which reach 300 metres. James Bay is much shallower, with maximum depths of about 60 metres. The average depth in the model of Hudson Bay is about 111 metres and James Bay about 38 metres.

The linearized equations used by Heaps (1969) in his work on storm surges in the North Sea are given by:

 $\frac{\partial M}{\partial t} = 2 \Omega N \sin \phi - \frac{gh}{a \cos \phi} \frac{\partial R}{\partial \chi} - \frac{h}{\beta a \cos \phi} \frac{\partial Pa}{\partial \chi} + \frac{1}{\beta} \left[T_{s_{\chi}} - T_{B_{\chi}} \right]$

 $\frac{\partial N}{\partial t} = -2 \Delta M \sin \phi - \frac{\partial h}{\partial \phi} \frac{\partial n}{\partial \phi} - \frac{h}{\beta a} \frac{\partial P a}{\partial \phi} + \frac{1}{\beta} \begin{bmatrix} T_{s} & -T_{s} \end{bmatrix}$

$$\frac{\partial n}{\partial t} = -\frac{1}{a\cos\phi} \left[\frac{\partial M}{\partial \chi} + \frac{\partial}{\partial \phi} \left(N\cos\phi \right) \right]$$

where χ is East longitude, ϕ is North Latitude, M and N are the χ and ϕ components of the flow, \uparrow_{S} is the surface wind stress, \uparrow_{G} is the bottom stress, and P_{A} is the atmospheric pressure. For the calculations, a quadratic wind stress law and a linear bottom stress law were used. The grid spacing was 10 min. of latitude and 15 min. of longitude. For the solution of the equations all the derivatives are approximated by central finite differences both in time and space; the calculations leapfrog in time, with water levels calculated at even time steps and flow components at odd time steps. The stability criterion was calculated to be 157 seconds, but a value of 60 seconds was used.

THE METEOROLOGICAL DATA

In Figure 3 is displayed four typical storm tracks. The present study concerns the storm of October 15, 1969 which is depicted by the dotted line. The centre of this storm was located to the north of Hudson Bay and sat there for about the first three days of our calculations, but then moved south over the Bay during the next two days. The calculations commenced at 1800 hrs, Greenwich Mean Time, October 15, 1969 and covered approximately five days.

In earlier studies of the circulation in Hudson Bay (Murty and Yuen, 1972) the method of introducing the pressure data was to extract such information from sixhourly weather charts onto a coarse grid and then polynomials were fitted to interpolate the data onto the finer grid of the hydraulic model. However, this procedure is time comsuming and such fine interpolation of the pressure may not be justified by the accurracy of the data. Instead we divided the Hudson Bay area into a number of regions, (See Figure 4) for each of which we approximated the pressure gradient from the weather maps. Surface winds were then calculated from the geostrophic approximation, with a modification of .6 in amplitude and a 20 degree rotation. Time wise, values of the pressure gradient and wind stresses were interpolated linearly between the six hourly intervals. The points shown in Figure 5 are sample points at which time series plots are shown below and these are numbered for easy reference.

CALCULATIONS AND RESULTS

As a gross measure of the storm itself, the vector mean pressure gradients are shown in Figure 6 as a function of time. The direction of the mean pressure gradient lies in a narrow range from about 25 to 55 degrees but after about 90 hours or so it drops rapidly down towards zero. This is when the centre of the storm started to move southward along the east shore of Hudson Bay. At the bottom of Figure 6 are plotted the water levels at two sample points along the shore that are approximately diametrically opposite to each other at an angle of about 30 degrees. Superimposed upon these two curves is the amplitude of the pressure gradient. In the first case, the pressure curve is reversed because the point represents the point for the west shore. If the higher frequency oscillations are ignored, one can see some sort of correlation between the mean atmospheric pressure gradient and the low frequency variations in the two water levels, the so-called inverse barometric effect.

In Figure 7 is a comparison of the observed surge at Churchill, which is the only permanent station for the area, and the calculated surge at the closest 2 point to it. The two curves are very similar but differ somewhat in exact detail. One major difference is the existence of a large spike at about time 104 hrs. which is not found in the observed. It is about this time that the centre of the storm started to move south over the Bay. The wind direction has shifted around from a northwesterly wind to one coming from the northeast thus causing this surge at the southwest corner of the model.

The calculated surge also shows a number of higher frequency oscillations which are found throughout most of Hudson Bay. These can be seen more clearly in Figure 8 where the water levels at a number of sample points around the shore of the main part of Hudson Bay have been plotted. The order of points begins along the north shore and progresses anti-clockwise around the Bay. One can easily detect two predominant periodicities in the high frequency oscillations, one of period 6.1 hrs. and the other of period 9.2 hrs. In some earlier preliminary calculations we had applied wind impulses and then the basin was permitted to oscillate on its own. In those calculations, one predominant period was found to be 9.2 hrs. Our suspicion therefore was that these two periodicities were related to the two lowest modes. The topography and shape of Hudson Bay are somewhat irregular but the Bay is very roughly a square. The average depth

of the basin, excluding James Bay, was found to be 111 metres. Very roughly, by using Merian's formula, it was estimated that the period of the lowest non-rotating mode would be somewhere between 14 to 15 hrs. From these estimates we referred to Rao's (1966) paper on the free gravitational oscillations in rotating retangular basins. Assuming an average inertial period of 17 hrs. for Hudson Bay, we then interpolated from Tables 1 and 2 of Rao's work to find the periods with rotation. For the 14 to 15 hour periods, the first rotating period would correspond to between 8.7 to 9.5 hrs. and the second period 5.8 to 6.3 hrs. The two figures of 9.2 and 6.1 from the calculations are very consistent, corresponding to a nonrotating period of 14.6 hrs.

In Figure 8 one can follow some of the disturbances around the edge of the basin, since it is basically a rotating system. For example, at the top of the Figure there are several large surges early in the calculations and these progress down anti-clockwise along the western shore. In the vicinity of the south shore, it becomes more difficult to identify them. Another feature is that the higher frequency oscillations are much smaller along the east half of the basin and this is partly due to the fact that that particular side of the Bay is sprinkled with a number of islands so that although the water is shallow there, surges never have a chance to propagate too far. In contrast, the western shore is virtually clear from the north end all the way down to the mouth of James Bay. Indeed, for this storm we found that most of the surges seemed to be generated along the north shore. For point number 10, spikes at 10 hrs., 20 hrs., 68 hrs., 86 hrs., and 96 hrs. correspond to surges at point 27 along the north shore. Generally, not only is the west shore the area of the largest oscillations but the southwest corner seems to be a very sensitive area.

The identity of the disturbances tend to become lost as they progress towards James Bay. Taking a closer look, one actually finds that these high frequency oscillations are damped out in James Bay. In Figure 9, the curves for points 15, 16, 17, 18, 4 and 5 represent a progression from the western side of the mouth of James Bay down to the head, while 6 and 7 progress along the eastern shore. Quite clearly the lower frequency response is propagated into the Bay and this response is found to correspond to the barometric pressure. The higher frequency oscillations are damped out and for point 5 there is barely an indication of their existence. The sequence at the bottom of the Figure, 20, 21, 22 are along a line down the centre of James Bay, and here again is displayed the propogation of the low frequency response and the damping of the higher frequency oscillations.

In Figure 10 is shown another aspect of the behaviour of the surge in James Bay. For the low frequency response to the barometric pressure, James Bay behaves in a very predictable fashion in that it rotates anticlockwise. The contours here are shown at times which correspond to the zero levels and highs and lows for Point 5 which is at the head of the basin. The surface is more or less flat at 22 hrs., the down hill slope of the surface is southward at 28 hrs., eastward at 33 hrs., northward at 40 hrs, approximately westward at 55, south at 68, slightly southeast at 76 and approximately northerly at 86 hrs. Very roughly then, the major part of the disturbance in James Bay is the response to the barometric pressure and in addition the system rotates so that one could probably develop a very simple model by which the water levels throughout James Bay could be estimated quite quickly. Some caution must be taken here of course because it is quite likely that in certain circumstances some of the surges in the main part of the Bay could very well be propagated into James Bay and be amplified quite greatly there because of the shallow depths.

In Figure 11 is displayed the surface over the whole Bay which is shown at a contour interval of 20 cm. at times 5, 10, 15, and 20 hours. One can immediately see some of the disturbances travelling along the western shoreline southward. At 5 hrs. there is a -40 cm. depression along the west shore. Its progression down into James Bay is easily followed. The contours in Figure 12 are at a later time and here we find a positive surge at the southwest corner which is propogated around the basin. The speed of this disturbance is generally in the 15 to 30 metre/second range in the main part of the Bay and down to the order of 10 to 15 metre/second or less in James Bay. In relation to the depths, these speeds are well within the correct order of magnitude.

In Figure 13 are seen some surface contours towards the end of the calculation and once again, the same general features are found to persist. There is one significant difference between these contours and the earlier contours however; by this time the atmospheric disturbance has persisted for quite some time and what results is the development of a depression of about 20 cm. in the western half of the basin. Around this depression, the disturbances are generally positive. In order to see this quasi-steady development more clearly, we then attempted to find the mean surface by simple arithmetic averages. The result at time 81 hrs., and at 102 hrs. is shown in Figure 14. The basic pattern of a negative depression of 20 cm. shows up quite clearly. In association with this depression, there is a net circulation which was also obtained by some very rough averages over time. The currents at approximately the same times are shown in the bottom of Figure 14. A very steady coastal jet was found, hugging the shoreline in the anti-clockwise direction. Along the main part of the Bay, particularly along the south shore, there is a large, steady jet of up to 40 cm/second which is also quite wide. Some similar occurrences are found along the eastern shore, but these jets are not found in the northwest corner of the basin. Some of these jets, particularly the ones along the southwest shore, were found to persist throughout the entire calculation, the result of the steady interaction between the wind stress and the shallow depth; but because Hudson Bay is rather flat, this gives rise to a very wide jet.

Summary

A relatively simple two-dimensional model of Hudson Bay has been constructed, which does not include any non-linear terms. Nevertheless, by this simplicity we have managed to gain insight into some of the hydrodynamical characteristics of Hudson Bay. Clearly the inverse barometric pressure effect is very predictable, but much more study is yet required in understanding the excitation of some of the lower free modes. Another aspect that was demostrated was the existence of very wide coastal jets. There is a danger of over generalizing some of these results since they represent but one storm. Nevertheless, they provide the groundwork for a series of calculations of much more complex storms. It is hoped that this programme of study will establish more clearly the necessity and feasibility for storm surge prediction services in Hudson Bay and perhaps indicate the types of empirical methods that may be employed for such prediction services.

References

- Heaps, N.S. 1969. A two-dimensional sea model. Phil. Trans. A 265, 93-137.
- Rao, D.B. 1966. Free gravitational oscillation in rotating rectanglular basins. J. Fluid Mech. 25, 523-555.
- Murty, T.S. and K.B. Yuen. 1972. Geostrophic versus balanced wind stress on Hudson Bay. Submitted to J. Fish. Res. Bd.







Figure 2. The depth configuration for Hudson Bay, with a contouring interval at 100 metres.



Figure 3. Some typical storm tracks over Hudson Bay. The calculation presented here is for the storm of October 16 to 20, 1969.



Figure 4. The grid system for the imput of meteorological data. Pressure gradients and wind stresses are calculated for each grid section.



Figure 5. The numbering system for sample water level points, with reference to the time series shown in the following figures.







Figure 7. A comparison of the calculated versus observed surge at Churchill, Manitoba.







Figure 9. Time series for a number of water level points in James Bay. These curves demostrate the damping of the higher frequency oscillations from the mouth towards the head of James Bay.



CALCULATED HEIGHTS IN JAMES BAY 20 CM. CONTOURS

Figure 10. Surface contours in James Bay at 22, 28, 33, 40, 55, 68, 76, and 86 hours. This series demonstrates the rotation of the water surface in James Bay.



Figure 11. Surface contours in Hudson Bay at 5, 10, 15 and 20 hours. This sequence shows the progression of disturbances in the anti-clockwise direction around the perimeter of the Bay.



Figure 12. Surface contours in Hudson Bay at 25, 30, 35 and 40 hours. The progression of disturbances around the perimeter is again demostrated.



Figure 13. Surface contours in Hudson Bay at 100, 105, 110 and 114 hours. The steady depression in the western half of Hudson Bay has resulted from the persistence of the storm.



Figure 14. Surface contours for the mean water surface at 81 and 102 hours. The vectors in the bottom of the figure show the mean circulation at 80 and 100 hours.

 \mathbf{X}