Storm Surges[1]

- or -

Is that an Ocean in my Basement?

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Abstract: The strong winds and the low atmospheric pressures of storms can cause coastal waters to flood inland regions. The result is called a "storm surge." These surges can cause massive damage, and may do so increasingly as the climate changes. In this article, I outline the Physics of storm surges (touching on more general issues in Fluid Mechanics and Mathematics), as well as listing some important storm-surge events. I end with a few words on predicting storm surges, a topic of much research at Dalhousie University and elsewhere.

1. What is a Storm Surge?

I was lucky enough to grow up near the Bay of Fundy, where variations in sea level are taken as a part of life. But since the Bay is so cold, and the currents so intense, few locals swim there. Instead, they go to the Northumberland Strait, where the waters are warm and the sandbars are inviting.

But nobody would go to the beach without knowing the phase of the tide. Low tides are great for playing on sandbars, but you can get tired walking until you get to water deep enough for swimming. High tides give you water to swim in, but not much of a beach for sun-bathing. So, everybody tumbling into the family car knows whether the tide will be high or low. (The best time to go? In the afternoon, on a rising tide. That gives the best of both worlds.)

Luckily, the tides are easy to predict. Look in the paper, listen to the radio, or infer it from the previous day[2]. Sometimes, though, you can be quite wrong on this prediction of sea-level. Sometimes the high tide is much higher than it "should" be ... sometimes the high tide swamps your cottage! Worse, in some low-lying regions, such as Bangladesh, these too-high tides can

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2 Students should be able to tell you a rule for this prediction, for local tides. They may also be able to infer this rule, based on knowing the length of a day and the length of a month.

kill thousands. What causes this?

The answer is that these strange tides are not tides after all. They are "storm surges," caused by the winds and low pressures of atmospheric storms. Although the name calls to mind surging waters, i.e. increases in sea-level, we use the same phrase for anomalously low waters as well. Although surges may occur at any time, the public is most interested in high-water surges occurring at high tide, and low-water surges occurring at low tide, since these cause the most problems. Thus, predicting the timing of storm surges relative to tides is a major goal.

The next section outlines the Physics of storm surges. After that, I'll mention a few particularly important storm-surge events through history, as well as issues in the Maritimes. At the end of the essay, I'll sketch some of the ongoing work at Dalhousie University, which has as a goal the prediction of storm surges along the lines of weather prediction. Much of what I say has wider relevance, I think; for example, understanding the fluid dynamics of storm-surges will help a student to understand other types of Physics.

2. Storm-Surge Physics

Everybody knows that winds are intense during storms. That follows almost by definition. What is less well-known is that storms involve anomalously low atmospheric pressure. The pressure changes are tied up with the Coriolis effect, which causes air to swirl around regions of low pressure[3] instead of flowing inwards toward the centre of the low.

These two things – the wind and the low pressure – act together to cause storm surges.

The wind can sweep waters onshore like a broom sweeping dust into a corner. If the dust is thick enough, it will tend to slump back into the room, as the water will tend to slump back to the sea, if the wind ceases. As for the low pressure, it's also simple: the water is simply sucked upwards at regions of low pressure. The latter is so simple that there is a simple rule for prediction. The former is more complicated, and requires Calculus for true understanding ... but I'll try to explain it more simply for the present purpose, in the next subsection.

2.1 The wind effect

Wind itself is irrelevant to the ocean; all that matters is the wind stress. (A stress is a force per unit mass. In this case, we're talking about a tangential stress, i.e. the drag the wind exerts in a horizontal direction, divided by the area of the sea surface on which the force is applied.) The stress is related to the wind in ways you might expect, e.g. stronger winds make larger stresses, and in ways you might not expect, e.g. a given wind produces a varying stress as time goes on, because the stress is partly related to the waves and the waves evolve over time. We boil these details down into an apparently simple rule, which states that the wind stress, represented by the

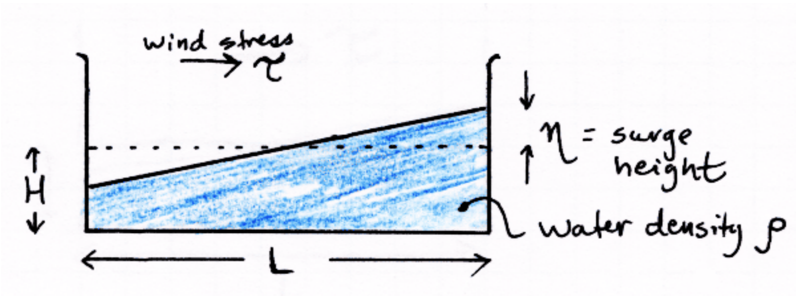
[3] If you've taught about the Coriolis effect, it might be instructive to ask students whether storms in the southern hemisphere have low pressures or high pressures. Another good question is whether the air flows in the same direction around lows in the two hemispheres. They could determine such things by thinking about the Physics, or they could go to weather websites in Australia.

Greek letter τ ("tau"), is related to the wind speed **U** by the formula

$$\tau = \rho_a \; C_D \, U^2 \qquad \text{... equation 1}$$

where ρ_a is the air density, of value 1kg/m^3, and C_D is a "drag coefficient" of value 0.001 to 0.002, depending on conditions. The stress τ is measured in Newtons per m^2, or equivalently in Pascals. (It might be good for students to calculate its value, from the above formula, for what they consider to be typical wind speeds. They should find that wind stresses[4] are of order 0.1Pa to 0.5Pa for strong winds.)

Imagine a box, of length **L**, holding water of depth **H**. (This is meant to represent the ocean, but it helps to think of it as a box, forgetting about details of non-flat bottom, a non-straight coast, etc.) Suppose that a stress of strength τ is applied at the surface, starting at some time **t=0**. Students should be able to tell you what will happen in response to the stress. Over short time intervals, the water will move downwind. Hitting the boundary, it will pile up, and gradually a slope will thus develop in the sea surface. This slope will create a force that opposes the wind stress. Eventually, as water piles up on the coast and the slope increases, the surface-slope and wind-stress forces will come into equilibrium. This much should make sense to students. As to how it works quantitatively, however, we need to start asking them to take things on faith[5]. The "faith" in this instance is that the water feels a force (per unit mass) of $\tau/(\rho_w H)$ from the wind and a force (again, per unit mass) of $2g\eta/L$ where **g** is the gravitational acceleration (of value 10m/s^2), η (the Greek letter "eta") is the sea-surface elevation at the coast and ρ_w is the water density (of value 1000 kg/m^3). If these two forces balance, therefore, we get a prediction for the storm-surge magnitude, i.e. the increase in sea-level at the coast:



$$\eta = [\tau \; / \, (2\, g\, \rho_w)] * (L \, / \, H) \qquad \text{... equation 2}$$

This formula permits the calculation of surge height for any geometry. Students should be invited to explore the formula for various values of the parameters. For illustration, I'll take **L**=10^{5}m and **H**=10m as round numbers, and I'll take 0.5Pa as the wind-stress[6]. The result is a predicted coastal surge of η =0.2m. As a scale value, one should take this to be between 0.1m and 1m. Obviously different geometries[7], and different wind stresses, will give different results.

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4 Hint: the phrase "run like the wind" has lasted for generations, and some of your students will know how fast a person can run a 100m dash, so it should be easy for the class to decide, for themselves, what value of U is appropriate for winds. Also, it would be instructive for them to compare this stress with the tangential stress of a penny glued on a wall, or the normal stress of a penny sitting on a floor. They should find the results of the comparison to be dramatic, and you should be prepared to explain this. Some of the students may be interested in cars, and if so they will know the value of C_D for racing cars ... why are the values so different?

5 Better still, we need to tell them to learn Calculus quickly, so they can stop taking things on faith.

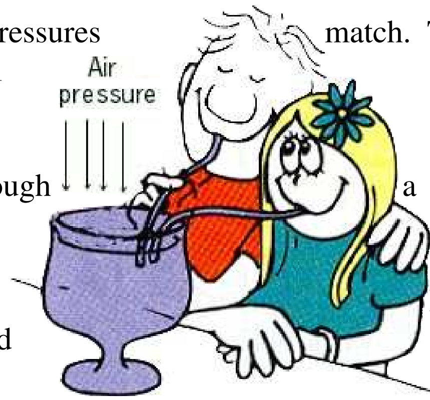
6 Note that the stress goes as the square of the wind speed, so tripling the speed increases the stress by approximately an order of magnitude.

7 Note that **L** and **H** do not contribute separately to the stress; only their ratio does.

2.2 The Air-pressure Effect

The effect of air pressure is simpler than that of wind stress, because the geometry doesn't come into play. The basic principle is that water tends to flow from regions of high pressure to regions of lower pressure. Therefore, if the air imposes a smaller pressure at some site *A*, compared with another site *B*, the water will move from *B* to *A*. Gradually, the water will start piling up at B, and this increases the pressure at *A*.

After a time, an equilibrium will be established, when the pressures match. This will happen when the the ocean water at *A* has piled up by 1 centimetre for each millibar[8] of lowered air pressure.



The effect is exactly like the upwelling of a milk-shake through a straw. Since this is much like the function of a barometer, oceanographers and atmospheric scientists have taken to calling this sucking effect the "inverted barometer" effect. It is simply described by the "centimetre per millibar" rule stated above.

So, to estimate the size of the effect, one needs merely to have a value for the decrease of atmospheric pressure in a storm. This is typically of order 10 to 20 millibars, i.e. yielding 0.1 to 0.2m in sea-level elevation.

2.3 Wave effects

Students will almost certainly ask whether storms cause big waves, and of course they do. These waves are part and parcel of the damage of storm surges. For example, a 1938 hurricane hit New England with a surge of 2-5m and waves of 10-15m. To make things worse, the event occurred at a high tide. Estimates put the number of dead at 600 or higher.

2.4 Combined Effects

Well, guess what? Waves, wind-stress, and low atmospheric pressures go together like birds of a feather! For this reason, we have to worry about a sort of triple whammy effect, in assessing the likelihood of storm-surge damage. From a mathematical point of view, though, these aspects of the phenomenon of storm surges are treated with the same tools, and this helps a lot. Indeed, if this essay were designed for undergraduates, right about now I'd be writing down the dynamical equations for these effects, and it would become clear that we use different words for things that are, physically, the same. The "waves" of common language are, technically, high-frequency surface waves, and the storm surges are low-frequency surface waves; one is a special case of the other, and this enables an integrative understanding.

3 Experiments and Demonstrations

[8] A millibar is a non-metric unit roughly equivalent to 10^2 Pa. Normal atmospheric pressure is roughly 10^5 Pa, or 1000 millibar, i.e. a "bar" is 1 atmosphere.

If a barometer is available for demonstration, it would be informative for students to take daily readings, noting both the magnitude of variations and their frequency. (If a computer is available, these data could be subjected to Fourier Analysis, which should reveal the so-called "storm band" of variability at periods of 3 to 5 days.) As for the stress and pressure effects discussed above, students could be asked to invent their own demonstrations, for use in a class project or perhaps a science fair ... but first they should do some calculations, with the formulas given above, to see whether the effect would be measurable with the equipment at hand.

4. Prominent Local Storm-Surge Examples

4.1 Storm Surge Damage Statistics

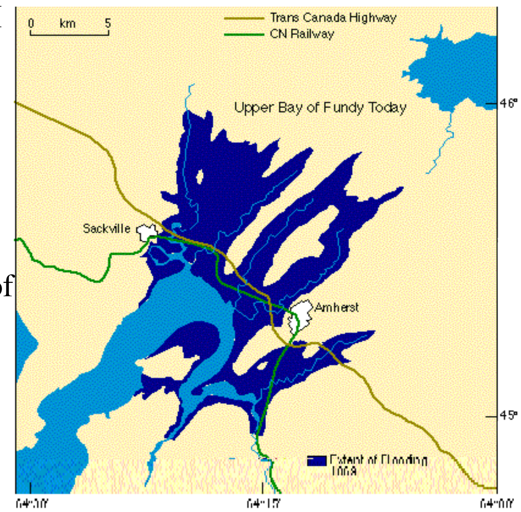
Some major historical storm surges			
Date	Shelf region	Estimated maximum surge height	Estimate of lives lost
November 1218	Zuider Zee (Dutch North Sea)	unknown	100,000
October 1737	India and Bangladesh	12 m	300,000
1864	Bangladesh	unknown	100,000
October 1876	Bangladesh	15 m	100,000
1897	Bangladesh	unknown	175,000
September 1900	Galveston, Texas (Gulf of Mexico)	4.5 m	6000
Jan/Febr 1953	Southern North Sea	3.0 m	2000
March 1962	Atlantic coast, USA	2.0 m	32
November 1970	Bangladesh	9.0 m	500,000

The table, taken from a web source, shows some especially damaging storm surges through history. There is much that could be discussed about such a table. For example, it would be worth asking students what factors might explain the relationship between the surge height and the number of lives lost. Some issues that come to mind include topography and poverty. Bangladesh, for example, is in a region prone to strong storm surges, because of its weather and the ocean shape, and it is also a low-lying country, with many poor people living within a metre or two of sea-level. Those are poor people without SUVs to take them to high land, if in fact there were any high land to find.

4.2 The "Saxby Gale" event of 1869

In the 19th century, a British Naval instructor named Stephen Saxby made a prediction that seemed, quite literally, "lunatic." He suggested that the weather was controlled (as the tides are) by the gravitational forces of the moon and sun, so that lunar cycles could be used to predict the weather. (We now know that the weather is more random than the tides, but after all, he was making his prediction long before computers, and in the early days of the theory of Fluid Mechanics, so he can be excused for his ideas. Also, it's worth noting that the astronomical conditions of which Saxby spoke occur on a 18.6 year interval, and indeed we can measure tidal variations on that time-scale, with modern tools.)

In late 1868 (when Canada was still a baby), he predicted that there would be a terrible storm, on the 5th of October of the next year[9]. For reasons of which I am not aware, his prediction was taken up in many newspapers. And, as it turned out, he was right! There was a strong storm on the east coast of North America. This came to be called the "Saxby Gale", and it caused wide-spread flooding in the Maritimes. A web search on the term will show students many resources, e.g. old newspaper articles and modern-day post-hoc simulations of the event.



The diagrams illustrate the amount of flooding near Amherst and near Truro. Students need only look at the highways on these figures, to get a dramatic insight into the flooding. Perhaps students interested in geography or geology could help others, by group projects involving mapping out the extent of flooding, in various regions, for various sea-level increases. I imagine that students with an interest in economics could assess the costs associated, as various buildings and facilities were damaged. Indeed, it seems to me that a good collaborative science/arts project could be put together around storm surges in local regions, with students strong in Physics helping those strong in History, and vice versa.

Returning to Saxby's communication, though, I'd like to quote what he said. The source is the *The Standard; London, England; Friday, December 25,1868; Issue No. 13,851 Page 5*. This is available on the web, at various places. He wrote

> *TO THE EDITOR*
> *... threatens, not only us in Great Britain, but all parts of the earth as about to happen in the coming year. Some of your readers may probably be incredulous as to weather warnings given so long an interval before an expected danger: allow me, therefore, first to give at least one authentic instance ...*

This leads him to a discussion of a previous prediction along similar lines. Students might benefit from thinking about whether his technique is "scientific" in the modern sense.

Turning now to his actual prediction, I quote

[9] He predicted the storm would occur somewhere in the world. In fact, the world is a big place, so there was some possibility of his prediction being correct just by chance. Some students might be able to offer insight on this, from their statistics courses.

> *...1869, that at seven a.m., on October 5, the moon will be at that part of her orbit which is nearest to the earth ... the moon will be on the earth's equator... and nothing more threatening can, I say, occur without miracle. ... In the meantime there will be time for the repair of unsafe sea walls, and for the circulation of this notice by means of your far-reaching voice, throughout the wide world.*

which is enough to tell you that he had, indeed, been thinking of tidal forcing in a quite thorough way.

As for the effect of the storm surge, we also have local records, and students interested in history may find it useful to look them up on the web. Here is a quote from the Moncton Times (1869 Oct 8):

> *... were awakened in the night to find there dwelling partly filled with water and all means of reaching dry land apparently cut off ... only chance of escape seemed to be by means of a raft ... he and his family got upon it and committed themselves to the mercy of the waves ... the raft parted ... The bodies of three of the children were found on Tuesday but the other has not yet been recovered.*

This illustrates the very human consequences of storm surges. Multiply four children by several tens of thousands, and you have the story of Bangladesh, revealed by the table above.

4.3 Prince Edward Island

A glance at a topographic map will tell you that much of Prince Edward Island is low-lying, and populated. For this reason, several studies have been undertaken of the expected effects of storm surges. Detailed reports are available on this from the Geological Survey of Canada (I imagine you can get them from their website, but I've not checked, since I have the reports from personal communication).

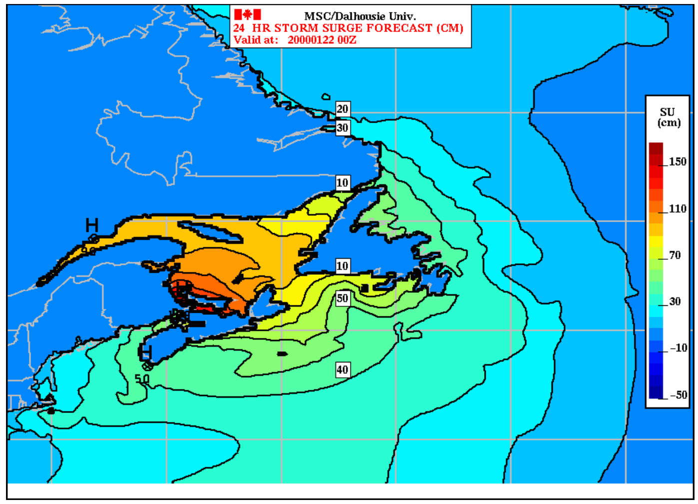
For storm surges of feasible size, it has been calculated that the City of Charlottetown has the potential to lose $46 Million due to property damage. That's not peanuts[10]. Furthermore, this is a problem that is not going to go away just by ignoring it. As the mean sea level increases -- as it is predicted to do owing to both climate change and subsidence of the land -- and as more people build houses near the coast, storm surges will probably cause increasing problems. We can't prevent storm surges (although dykes are of great help, and have been used near the Bay of Fundy for 10 generations, which is a remarkable history lesson in itself), but damage can be reduced if adequate warning is available. As it happens, storm-surge prediction is one of the research interests at Dalhousie University, my institute, and so I'll say a few words about that in the next section.

[10] How many teachers could be paid for a year with that? How many researchers to try to aid predictions, so that damage could be minimized? (Most research is done by students working on their PhD degrees; they are paid about 1/5th the salary of teachers, so a little money goes a long way!) These are questions that might interest students with an interest in economics and in social policy.

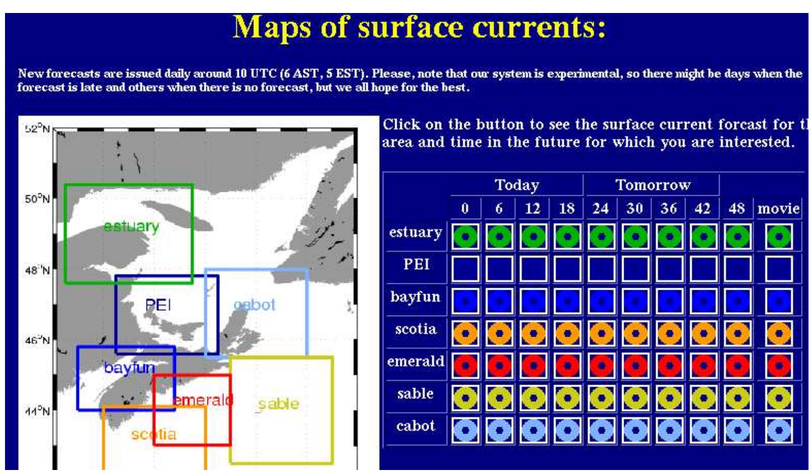
5. Prediction of Storm Surges

Physicists like myself have available long-established general laws governing the motion of fluids. These are called the "Navier Stokes" equations, and they are basically a formulation of Newton's laws for fluids.

Since these equations involve Calculus, I presume they are a bit beyond K12 school levels, and so I won't discuss them here. But, suffice it to say that the equations contain terms for wind-stress in a form analogous to that given above, etc. These equations are field equations, with forces at any given location depending on the flow at nearby locations, and since the geometry and the forcing are complicated, the equations cannot be solved in a closed-form mathematical way. Instead, we use numerical-modelling techniques to solve the equations approximately. Here again, I am stepping outside the skill-level of K12 students, so I need to tread lightly. Suffice it to say that we need large computers to do detailed predictions. The computer coding is done in a highly detailed way, normally in the FORTRAN programming language. There are no microsoft products to help with this sort of work. There is no point/click program that is of any use. Programming is required, and this takes several person-years to accomplish results, which is why this is PhD-thesis work.



The cutting edge of this work is to combine predictions with incoming data, to yield continuously-updated predictions. This technique is called "data assimilation" and it is something that Dalhousie University excels at. The diagram illustrates one of the "products" of this research work. It is a snapshot from one of our web-pages, which shows predictions of storm surges. This web-site is available 24 hours a day, 7 days a week. I have illustrated here the interface at the time of writing; a simple mouse click gives predictions for a given region at a given time.



The predictions are continuously updated, without human intervention, as the atmospheric predictions come in from the weather service. The research is in collaboration with the Meteorological Service of Canada, and the work has been so successful that surge forecasts are now entering the standard predictions of local regions. The hope is that giving the public a warning of oncoming surges will give them a chance to take action, such as moving valuables from the basement to the second floor of their houses[11].

One great challenge in predicting the impact of storm surges is to get their timing correct. A surge occurring at high tide may cause tremendous damage, but if it is delayed by just a few hours until the tides are lower, the damage will be slight. In other words, we need to predict surge timing to within a fraction of a day. This is difficult since surges are caused by storms, and storms are difficult to predict to that resolution. Dalhousie has several researchers working on this problem at the moment. In addition to the local prediction problem, there is also great interest in whether storm surges would be worse, or better, in a changed climate ... but that's a story for another day.

6. Suggestions for Further Reading

A web-search will turn up many good references on storm surges in general, and of particular events, such as the Saxby Gale, and particular regions, such as Bangladesh. For more on prediction strategies, visit the web-site of my department at Dalhousie University, http://www.dal.ca/~wwwocean/index.html. Following links on this site also will take you to my own web-page, which holds a copy of my powerpoint presentation to the AST meeting, on which the present article is based. I hope the presentation will also be stored on the AST web-page.

Acknowledgements: The author would like to thank Jackie Hurst and Doug Mercer for helpful comments and suggestions on the manuscript.

[11] A recent storm surge on PEI actually moved a cottage. The insurance company didn't want to pay out any damages, since they said the cottage was still all right, and moving was not covered by the policy!