SCIENTIFIC WAVE PREDICTIONS

The Great Lakes Cruising Club has been given permission to use this excellent article, "Of Rogue Waves and Little Ripples" published in the March, 1977 issue of "Motor Boating & Sailing" authored by Dr. William L. Donn. Dr. Donn is a faculty member of the City College of New York and the Lamont-Doherty Geological Observatory of Columbia University, and is also the author of numerous college textbooks, including Meterology. He is one of the world's foremost authorities on marine weather, and often testifies in admiralty cases.

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Your Log Book Committee feels the material contained herein is more than just interesting or fascinating and should be regularly considered by every boating member who is using the open waters of The Great Lakes. By use of the charts and graphs worked up with the kind help of Dr. Donn, we feel that safer and more pleasant passages can be possible for each of us.

Excerpts of Dr. William L. Donn's article as follows:

Seat-Pant Forecasting is Fine, But Scientific Wave Predicting is Best

The sea has many moods. When Balboa first sighted the western ocean, it was so serene and calm he named it "Pacific," meaning "peaceful." Had he chanced to sail across it in winter, or during the times of frequent summer and autumn tropical storms, he might well have given it a different name. The greatest wave ever recorded was observed aboard the U.S. Navy tanker *Ramapo* enroute from Manila to San Diego. On that day of Feb. 7, 1933 winds were measured at 68 knots, and the resulting sea waves dwarfed the 478-foot tanker. Although all of the waves were gigantic, one seemed monstrous in comparison. It was observed by Lieut. F. C. Margraff, the watch officer on the bridge. From geometric relationship of the wave crest to the height of the superstructure and the pitch angle of the vessel, Lieut. Margraff calculated conservatively that this rogue wave was *at least 112 feet high.*

The Atlantic Ocean can also whip up a raging sea. For example, on April 12, 1966 the 43,000-ton luxury liner *Michaelangelo* of the Italian Lines was heading westward toward New York City through a whole gale. While 1,500 miles east of the city, the ship was buffeted by waves estimated to be 25 to 30 feet high when a mountainous wave suddenly towered above the others. This monster crashed into the ship, inundating the forward half, crushing steel superstructure and smashing bridge windows 81 feet above the waterline. The bulkhead below the bridge was bent in at least 10 feet, and steel flaring on the bow was torn off. Needless to say, loose gear was sent flying. The human toll included three killed and at least 12 injured. About 900 miles farther westward the *Indian Trader* met the same storm. This time the pounding by the high waves resulted in death to one crewman and injury to three others.

Monster waves like these are fortunately rare. But 30- to 50-foot waves often are sighted by merchant vessels and by the ocean weather ships that maintain fixed locations at sea. In January 1976, for instance, a gigantic and intense low-pressure system spread over much of the north Atlantic Ocean. On Jan. 29, Ocean Weather Station Romeo reported 46-foot waves, while the *Polyarny Krug* battled 55-knot winds and 36-foot waves. By the 30th, *Romeo* was still fighting 50-knot winds and 49-foot waves. Other vessels all over the Atlantic rolled and pitched in the stormy seas blown up by this fierce gale.

Lest this talk scare the mariner from putting to sea again, let's take a harder look at the average sea surface. To begin with, huge storms and waves (with the exeption of summer hurricanes) are features of the cold months of the year — usually November through April. Even then, the kinds of waves described are not everyday features of the sea. If one looks at the daily marine weather map, reports are shown from 50 or more vessels in both the Atlantic and Pacific Oceans. The accumulated reports for the past 100 years show that 80 percent of the time ocean waves are below 12 feet in height, and 45 percent of the time they are less than four feet. In fact, the highest waves met by the sailing vessel *Venus* during her circumnavigation of the globe from 1836 to 1839 were only 25 feet, and this was in the Southern Ocean off Cape Horn.

Sea, Swell and Chop

Nearly all of the waves visible on the surface of water, whether lakes, rivers or oceans, are wind waves — or waves generated by the wind blowing on the water. *Sea* is the term used to include waves that are still under the influence of the wind. When the waves travel away from the region of generation they become more regular in appearance and are called *swell.*

Sea consists of a very irregular pattern of crests and troughs. Some waves grow very rapidly in height, others more slowly. The length of a wave (distance from crest to crest) is also variable. In a growing sea, the aspect that really disturbs mariners is the wave steepness, or ratio of wave height to length. In fact, low, steep waves of short length may be more of a problem to small boats than high ones. For example, a wave that is four feet high and 20 to 30 feet in length will give a very rough ride to a boat of similar size because the stern may be high on a crest while the bow is in the trough, plunging into the next crest. In the open sea, a 30-foot-high wave about 200 feet or so in length will provide a series of gently sloping hills and valleys for the small boat to ascend and descend.

To some extent, waves tend to regulate their own steepness. When the height-to-length ratio exceeds 1/7, a wave becomes too steep to maintain its form and the crest spills over in a cascade of white water forming the well-known "whitecaps." As a result of this breaking process in windy weather, waves that are growing too fast in height break continuously, thus preventing oversteepening and even rougher conditions. Those waves that are short in wavelength as well as in crest length are called *chop.* Chop is characteristic of bays, lakes and rivers, where waves do not have the room to develop lengths reached in the open sea.

How Waves Grow

At some threshold speed between one to three knots, calm water surfaces develop slight ripple-like disturbances. Their crest-to-crest length is about a half-inch or so. As these corrugations (or capillary waves) grow, they provide a rough surface that helps transfer energy from the wind to the water. Even large water waves are covered with these capillary waves that aid in their continued growth.

The three factors of prime importance in the growth of waves are the wind speed, the fetch or distance over which the wind blows in a uniform direction, and the duration of the wind having a uniform direction. The first is obvious: The higher the wind speed, the higher the waves.

But even a high wind blowing across a narrow body of water will never raise very high waves, no matter how long the shore before it has a chance to grow very large. As the water body becomes wider, the wind can continue to build the waves over a greater distance or fetch. For a given wind speed, the longer the fetch, the higher will be the waves — up to a certain point. Beyond this point, waves of a maximum height and length will be developed for a particular wind speed. Once this wave size is reached, the waves will stop growing and will maintain a uniform maximum height and length will be developed for a particular wind speed. Once this wave size is reached, the waves will stop growing and will maintain a uniform maximum height and length known as the *fully arisen sea.* For each wind speed there is a particular fully arisen sea state.

The duration of the high wind is also a factor. Even if the fetch is long enough to provide room for the maximum wave development for a given wind speed, the wind may not blow for a long enough time to push the growing waves from one end of the fetch to the other. Hence, fetch and wind duration may impose limits to the growth of waves regardless of wind speed. Oceanographers have developed charts giving the height and length of waves for different speed, fetch and duration of the wind.

Theoretically, the huge waves described earlier would be commonplace over the ocean when 50-knot winds or higher prevail. Mariners are saved from such storm-tossed seas by the fact that most of the time neither the fetch nor the duration is long enough for the development of fully arisen seas from such winds. When the necessary fetch and duration are present, the mariner has his hands full.

Oceanographers have learned that the most useful picture of the sea state for given wind conditions is given by the significant wave height. This is the average of the highest third of all the waves present — or the average of the highest 33 out of every 100 waves. The significant wave height for a fully arisen sea at different wind speeds can be readily determined from charts or tables. Wave heights, prior to their becoming fully arisen, can also be determined for limited fetch or duration. The probability of occurrence of waves with heights greater than the significant wave height can also be determined.

Each fetch (distance) shown is the *minimum* for a fully arisen sea (FAS) at that particular wind speed.

Wind speed in knots	20	25	30	35	40	45	50	55
Fetch for FAS (nautical miles)	285	395	525	650	800	960	1,100	1,300
Significant wave height (ft.)	7	12	17	23	30	38	46	56
Average of highest one-tenth waves (ft.)	9	15	21	29	38	48	59	71
Maximum wave (ft.)	14	21	31	42	55	70	86	104

The table above gives the significant wave height (average of highest one-third), the average of the highest one-tenth of all of the waves, and the maximum wave height for fully arisen seas (FAS) developed by winds from 20 to 55 knots. It also gives the fetch necessary at each wind speed. The maximum wave height refers to the highest in a thousand.

The right-hand columns suggest that the ocean is a dangerous place in a storm. When the right combination of wind speed, fetch and duration occur, the monster waves described in the table can develop, and are predictable features of a storm-tossed sea. What saves the mariner, as noted earlier, is that seas are rarely fully arisen for high wind speeds for lack of an adequate fetch and duration. As a good rule of thumb, it has been estimated that winds above 30 knots rarely have the fetch to develop a fully arisen sea. In fact, as the wind speed increases, the fetch associated with that speed usually decreases, so that in most cases a cutoff wave height develops. This is indicated in the next table, which gives the most probable fetch for wind speeds from 30 to 55 knots, as well as resulting wave heights. Except for 30 knots (FAS), each (distance) shown is for cutoff waves (not fully arisen sea).

Wind speed in knots	30	35	40	45	50	55
Fetch (most probable in nautical miles)	700	600	500	400	300	200
Significant wave height (ft.)	17	22	27	31	33	33
Average height of highest one-tenth (ft.)	21	29	33	38	42	46
Maximum wave height	31	42	49	55	61	68

Note that the height of the waves in the columns to the right hardly changes despite the high velocities because the actual fetch decreases so much at higher wind speeds. We also see why waves above 30 feet are rarely reported for the ocean because the significant wave height, which best describes the sea condition, levels off at about 33 feet.

All of this may be good news for mariners in large commercial vessels, but small boats can have a rough time even with 30-knot winds, which are fairly common at sea. Although the significant wave height for a fully arisen sea is 17 feet — a high, but possibly bearable condition, occasional maximum waves nearly double this, or 31 feet can be expected. *What might not be a great menace for an ocean liner becomes a rogue wave for smaller vessels.*

When cold winds blow over warm water waves can grow to much greater heights than those expected from the forecast theory we described above. Conditions like this exist off the east coast of the United States, where cold air masses from the north or northwest may spread southward or eastward across the warm waters of the Gulf Stream any time from early autumn to late spring. The northwest boundary of the Gulf Stream is often marked by a temperature contrast of 20°F between the warm current and the colder waters beyond.

Three effects generate larger-than-normal waves. First, the cold air becomes warmed as it sweeps out over the warm water. The warmed air rises and is replaced by air from aloft that always blows much faster than the surface-level wind, which is retarded by friction. The resulting surface winds, however, can be 50 percent higher than those observed at coastal stations or expected from weather-map conditions. Hence, much higher waves will be raised.

A second important effect is caused by the turbulent motion acquired by cold air when blowing over a warm surface. The vertical eddies involved in such turbulence generate waves about ten percent higher than warm winds with corresponding speeds.

In the Great Lakes, cold autumn winds from the north frequently cross lake waters that still retain much of their summer warmth compared to the land, which cools rapidly. At such times wind speeds out over the water only ten miles from the coast may be double those of coastal winds. Casualties to ships of all sizes are greatest during autumn months, when waves are much higher than those generated by the same winds at other seasons.

Whether in the Great Lakes, the Gulf Stream or anywhere in the seas, mariners in vessels of all sizes should be familiar with the potential hazards whenever the possibility exists of cold air crossing bodies of warm water. Higher and steeper waves than would otherwise be expected should be anticipated. If opposing currents exist, the hazard is still greater.

Any experienced boatman has certainly encountered waves that have been a problem. Of course, what constitutes difficult waves depends on the relation of boat length and draft to height and length, or steepness, of the waves. The best advice is to always be forewarned and know your vessel. Avoiding high waves is much safer than maneuvering properly in them.

I would like to add to Dr. Donn's article with the following explanations and comments.

The graphs and tables that follow have been simplified and condensed for easy reference. Notice on figure 1 (graph) that we have provided an easy way to obtain the Significant Wave Height by relating the fetch you have as a percent of the Fetch for the Fully Arisen Sea at a particular wind speed. An example is shown that a 30 knot wind speed will give a Significant Wave Height of 13 feet if the fetch limitation is 200 miles.

Another example might be that you may observe a Significant Wave Height of 20 feet along with a wind of 40 knots. Using the graph we can see that about 21% represents the percentage of your fetch compared to that fetch of the Fully Arisen Sea. Referring to listing of minimum fetch for Fully Arisen Sea alongside of the graph, we can see that 21% of the fetch for this Fully

Arisen Sea at 40 knots is .21 times 806 miles or about 169 miles, the fetch you are observing.

Notice that the highest 1/10 waves are found by multiplying Significant Wave Height by 1.28 while Maximum Wave Height (Rogue Wave) is found by multiplying by 1.86.

Table 1 and Table 2 are shown together to make it possible to approximately determine the various wave heights at increasing distances or fetch at different wind speeds, along with the same information as they relate to the length of time in hours that the wind blows at different wind speeds.

Looking at the two tables together it can be seen for example that 100 miles of fetch and 30 knots of wind will give wave heights, A, B, & C, of 11 feet, 14 feet, and 20 feet, respectively, but to know how long this will take we look at the other table and see that it takes about 14 hours at 30 knots. Another example would be that 250 miles of fetch and 50-knot winds would give A, B, & C, wave heights of 31 feet, 40 feet, and 58 feet, respectively, while Table I tells us that we should need about 18 hours of time for this to happen at 50 knots. Obviously we would extrapolate for times or fetch in between those printed.

Table 3 can be used for a quick approximation of relations between fetch, Significant Wave Height, and time each as a percentage of that for Fully Arisen Seas. It's easy to see that only 10% of full fetch gives 49½% of Significant Wave Height while using only 20½% of the time for a Fully Arisen Sea!

Graph 2 (Conversation Diagram) simply relates the fetch for Partially Arisen Seas to Fully Arisen Sea (percentage) to the corresponding Partially Arisen Sea time to Fully Arisen Sea time (percentage).

Obviously, all of the above is theoretical in that the wind direction is likely to change by 10, 20, or even 30 degrees during a period of ten to twenty hours. Certainly, then, the wave heights would be modified somewhat, probably only slightly for 10 degrees and much more for 30 degree wind direction shift.

The other variable is wind speed itself which might be 20 knots at 10:00 A.M., 25 knots at 1:00 P.M., 30 knots at 3:00 P.M., and back down to 20 knots by 5:00 P.M. We can easily see that it becomes a judgement matter and compromises must be figured. Remember, all of the above have been laid out in knots and nautical miles (approximately a 6,000-foot mile compared with a statute mile of 5,280 feet.).

Good Luck!!

Report by Dave Dalquist,
Rear Commodore,
Lake Superior

TABLE I TIME NEEDED FOR VARIOUS WAVE HEIGHTS (PARTIALLY ARISEN SEA)

TIME IN HOURS	A.B.C. MEASURE IN FEET	KNOTS WIND SPEED 10	20	30	40	50
2 Hrs.	A. Significant Wave Height**	.6 Ft.	1.2 Ft.	1.8 Ft	2.6 Ft.	4. Ft
	B. Ave. 1/10 Highest Waves	.8 Ft.	1.5 Ft.	2.3 Ft	3.3 Ft.	5 Ft
	C. Maximum Wave Height	1.1 Ft.	2.2 Ft.	3.3 Ft	4.9 Ft.	8 Ft
4 Hrs.	A. Significant Wave Height**	1.3	2.2	3.8	6	8
	B. Ave. 1/10 Highest Wave	1.7	2.8	4.9	7	10
	C. Maximum Wave Height	2.4	4.1	7	11	15
6 Hrs.	A. Significant Wave Height**	1.7	3.3	6	8	12
	B. Ave. 1/10 Highest Wave	2.2	4.2	7	11	16
	C. Maximum Wave Height	3.2	6	10	16	23
10 Hrs.	A. Significant Wave Height**	2.3	5	9	13	19
	B. Ave. 1/10 Highest Wave	2.9	6	11	17	25
	C. Maximum Wave Height	4.2	9	16	25	36
14 Hrs.	A. Significant Wave Height**	2.6	6	11	18	26
	B. Ave. 1/10 Highest Wave	3.3	8	14	23	34
	C. Maximum Wave Height	4.8	11	20	33	49
18 Hrs.	A. Significant Wave Height**	2.8	7	12	21	31
	B. Ave. 1/10 Highest Wave	3.6	8	15	26	39
	C. Maximum Wave Height	5	12	22	38	57
22 Hrs.	A. Significant Wave Height**	2.9	7	13	22	34
	B. Ave. 1/10 Highest Wave	3.8	9	17	29	43
	C. Maximum Wave Height	6	13	24	42	62
26 Hrs.	A. Significant Wave Height**	3 *	7	14	24	36
	B. Ave. 1/10 Highest Wave	3.8 *	9	18	31	47
	C. Maximum Wave Height	6 *	14	26	45	68
30 Hrs.	A. Significant Wave Height**	3 *	8	15	25	38
	B. Ave. 1/10 Highest Wave	3.8 *	10	19	32	49
	C. Maximum Wave Height	6 *	14	27	47	71
40 Hrs.	A. Significant Wave Height**	3 *	8 *	16	28	42
	B. Ave. 1/10 Highest Wave	3.8 *	10 *	20	35	54
	C. Maximum Wave Height	6 *	15 *	29	51	79

* Fully Arisen Sea

** Significant Wave Height is average of highest 1/3 waves.

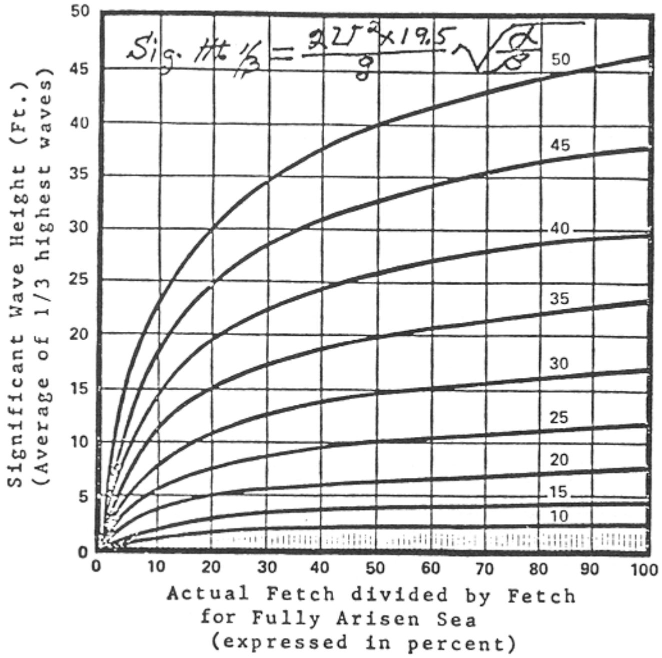
TABLE II FETCH (DISTANCE) NEEDED FOR VARIOUS WAVE HEIGHTS (PARTIALLY ARISEN SEA)

MILES FETCH	A.B.C. MEASURE IN FEET:	KNOTS WIND SPEED 10	20	30	40	50
12 MILE	A. Significant Wave Height**	1	2.5	3.5	6	7
	B. Ave. 1/10 Highest Wave	1.3	3	4.5	8	9
	C Maximum Wave Height	2	5	7	11	13
25 MILE	A. Significant Wave Height**	1.2	3.5	5.5	8	11
	B. Ave. 1/10 Highest Wave	2.5	4.5	7	10	14
	C. Maximum Wave Height	4	7	10	15	20
50 MILE	A. Significant Wave Height**	2	4	8	11	16
	B. Ave. 1/10 Highest Wave	2.5	5	10	14	20
	C. Maximum Wave Height	4	7	15	20	30
75 MILE	A. Significant Wave Height**	2	5	9	13	20
	B. Ave. 1/10 Highest Wave	2.5	6	11	17	26
	C. Maximum Wave Height	4	9	17	24	37
100 MILE	A. Significant Wave Height**	2	6	11	16	22
	B. Ave. 1/10 Highest Wave	2.5	8	14	20	28
	C. Maximum Wave Height	4	11	20	30	41
150 MILE	A. Significant Wave Height**	3 *	6	12	19	25
	B. Ave. 1/10 Highest Wave	4 *	8	15	24	32
	C. Maximum Wave Height	6 *	11	22	35	47
200 MILE	A. Significant Wave Height**	3 *	7	13	20	29
	B. Ave. 1/10 Highest Wave	4 *	9	17	26	37
	C. Maximum Wave Height	6 *	13	24	37	54
250 MILE	A. Significant Wave Height**	3 *	7	14	22	31
	B. Ave. 1/10 Highest Wave	4 *	9	18	28	40
	C. Maximum Wave Height	6 *	13	26	41	58
300 MILE	A. Significant Wave Height**	3 *	8 *	15	24	33
	B. Ave. 1/10 Highest Wave	4 *	10 *	19	31	42
	C. Maximum Wave Height	6 *	15 *	28	45	61
350 MILE	A. Significant Wave Height**	3 *	8 *	15	25	34
	B. Ave. 1/10 Highest Wave	4 *	10 *	19	32	44
	C. Maximum Wave Height	6 *	15 *	28	47	63

*Fully Arisen Sea

**Significant Wave Height is average of highest 1/3 waves.

Figure 1 (Graph) THE SIGNIFICANT WAVE HEIGHT FOR NON-FULLY ARISEN WAVES CAN BE ESTIMATED FROM THE GRAPH BELOW.



Remember that a minimum fetch is necessary for a fully arisen sea for a particular wind speed. These are as follows:

20 knots	284 nautical miles
25	396
30	526
35	660
40	806
45	956
50	1130
55	1290

For example: a 30 knot wind has a fully arisen fetch of 526 nautical miles. For your 200 Mi fetch table, 200 is 38 percent of 526. Find 38 percent along the bottom of the graph (F/F_{FAS}). Rise vertically to the 30 knot curve then go horizontally to the left side of the graph and find Sig.Ht about 13 feet.

Find the highest 1/10 from the formula

$$H_{1/10} = 1.28 \times \text{Sig. Wave Ht.}$$

For the case above this would be 16.6 ft (1.28x13).

For the maximum wave, multiply the Sig. Wave height by 1.86. For the case above, this would be 24 ft (1.86x13).

As you do this you will see that for high wind speeds and short fetches, e.g. 12NM, there is not much difference in wave heights. A certain amount of fetch is needed before the effect of the high winds is felt.

GRAPH 2 CONVERSION DIAGRAM

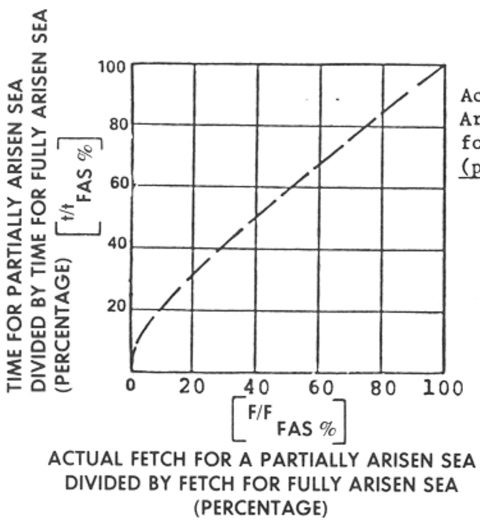


TABLE 3

Actual Fetch for Partially Arisen Sea divided by Fetch for Fully Arisen Sea (percentage)	Significant Wave Height for Partially Arisen Sea divided by Significant Wave Height for Fully Arisen Sea (percentage)	Time needed for Partially Arisen Sea divided by Time for Fully Arisen Sea (percentage)
5	35	14.5
10	49.5	20.5
15	59	26.0
20	65.5	31.5
30	74.5	41
40	81	50
50	86	59
60	90	67.5
70	93	76
80	93.5	84
90	98	92
100	100	100