COMPARISON OF HINDCAST RESULTS AND EXTREME VALUE ESTIMATES FOR WAVE CONDITIONS IN THE HIBERNIA AREA – GRAND BANKS OF NEWFOUNDLAND

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1. INTRODUCTION

Since the mid 1980s, Oceanweather Inc. has performed four separate wind and wave hindcast studies that included the area around the Hibernia offshore oil development on the Grand Banks of Newfoundland. These studies are: 1) the site specific hindcast study for Hibernia prepared for Mobil Research and Development Corporation (1982-86), 2) the "Wind/Wave Hindcast Extremes for the East Coast of Canada," performed around 1992 by Oceanweather and MacLaren Plansearch Limited, for the Atmospheric Environment Service (AES), under funding from the Federal Program of Energy Research and Development (PERD), 3) an 82 storm hindcast covering the years 1957-1995, using the Canadian Spectral Ocean Model (CSOWM), and 4) the so-called AES-40, a 1999-2000 study that hindcasted 40 continuous years of winds and waves, again for the Atmospheric Environment Service (now Meteorological Service of Canada). The four studies covered different years, the wind and wave models used in the four studies were not the same, and the first three studies were storm studies having different populations while the fourth study modelled continuous years. The present report compares the results obtained from these four disparate studies for the Hibernia area, along with the extreme value estimates for wave conditions.

2. OVERVIEW OF THE STUDIES

The Mobil study is comprehensively described in a series of four papers published in the proceedings of the 2nd International Workshop on Wave Hindcasting and Forecasting, held in Vancouver, B.C., on April 25-28, 1989. A total of 29 severe storms occurring between January 1951 and December 1984 were selected from archived meteorological charts, early regional hindcasts, and recorded data. Winds were first calculated from hand-drawn pressure maps based on synoptic measurements that were available in real-time. These were then modified through kinematic analysis and the inclusion of pressure and wind data not reported in real-time. Waves were hindcast using the ODGP 1-G deep model. Different wave model grids were used in the study, beginning with a 2° latitude by 2° longitude spacing for storms 1 to 20, covering an area from 81°W to 6°E, and 26.45°N to 64.63°N. The remaining storms, 21 through 29, used a nested grid with a coarse grid of 1.25° latitude by 2.5° longitude, covering most of the North Atlantic west of 20° W, and a fine grid of spacing half that of the coarse covering 60°W to 45°W, and 41°N to 50°N.

The PERD study was intended to develop a hindcast data base and extreme wave estimates for the Canadian east coast offshore exploration areas: the Grand Banks, the Scotian Shelf, and Georges Bank. The time period covered in the storm selection process was 1957 – 1988. A total of 68 storms covering the three areas were included in the study. The winds were modelled using a blend of surface pressure analysis and kinematic analysis wind fields. Waves were hindcast using a deepwater ODGP wave model. A nested model grid was used with the coarse grid spacing of 1.25° latitude by 2.5° longitude extending from 25°N to 67.5°N and 20°W to 80°W, and a fine grid of half the spacing of the coarse and covering the are between 38.75°N to 53.75°N and 42.5°W to the coast.

The CSOWM study was performed in 1995 and 1996 as an update to the PERD study wherein the time period of the hindcast was extended and the wave model was changed. The CSWOM study used the third generation, shallow water version of the Canadian Spectral Ocean Wave Model and hindcasted 82 storms covering the time period from 1957 to 1995. A nested grid was used having a coarse grid spacing of 1.084° longitude on the assumed equator (at 51°W) and a nested fine grid with spacing of about 0.361° of longitude. The study was done using Oceanweather's 1GDdeep, 3GDdeep, and 3GShallow wave models. The results discussed in this paper are from the 3Gshallow model. This study is thoroughly described in the paper ***"A Revised Extreme Wave Climatology for the East Coast of Canada,"*** by V. R. Swail, M. Parsons, B. T. Callahan, and V. J. Cardone, and presented at the 4th International Workshop on Wave Hindcasting and Forecasting, held in Banff, Alberta, in October 1995.

The AES 40 study modelled the entire 40 year time period from 1958 to 1997, with an update to 1998 and 1999 in progress. The study utilized the results of the NCAR/NCEP (U.S. National Centers for Environmental Prediction) global re-analysis for 1958-97 wind fields as input to a third generation deep water wave model. The winds were modified by adding measured winds from high quality buoys, platforms, and C-MAN stations. Cyclone wind fields were also generated and added to the background winds. Lastly, the wind fields were refined using Oceanweather's Interactive Objective Kinematic Analysis System (IOKA). The wave model grid spacing was 0.625° latitude by 0.833° longitude, which is within 10% of a square grid between 38° and 45° North, over a grid domain from 80°W to 20°E, and the Equator to 76°N.

3. THE STORM POPULATIONS

As discussed previously, the storm populations in the first three studies differed from each other, and the fourth study was continuous, but covered a different time period. The following Table 1 gives the peak significant wave height for the different storm populations. For the AES 40 study, all storms generating peak significant wave heights exceeding 9.5 meters at the grid point nearest Hibernia are included in the present comparison. Interestingly, two of the storms included in the three storm studies, 08 – 13 March 1974 and 16 – 20 March 1976, have no results for the grid point nearest Hibernia (grid point 5622) in the AES 40 study due to the presence of at least 50 percent ice cover. For these storms results from another grid point (5551), just to the southeast of the point previously used to represent Hibernia, have been included.

	Mobil	PERD	CSOWM	AES 40 5622
Date				
10 - 14 Nov 52	7.1			
08 - 11 Feb 54	11.6			
20 - 23 Sep 55	9.5			
09 - 13 Dec 55	10.7			
16 Jan 59				9.6
07 - 08 Feb 59		9.3	8.6	10.4
17 Feb 59				9.7
09 - 10 Jan 60		8.8	9.3	10.0
20 - 23 Jan 61	11.7	11.1	9.5	11.1
15 - 18 Dec 61	9.7	10.3	10.9	11.5
05 Jan 62				9.5
26 Feb 62				9.5
02 May 62				10.1
26 Feb 63				10.7
16 Nov 63		10.3	10.0	10.5
20 Dec 63			8.0	8.8
10 - 14 Jan 64	6.3	10.9	10.0	9.8
09 - 10 Feb 64		9.3	8.4	10.8
14 - 18 Mar 64	8.4	9.2	8.7	8.1
24 Jan 65		7.4	7.0	8.4
17 - 20 Feb 65	9.9			9.9
29 Mar 65				10.0
09 - 10 Jan 66		8.8	9.1	10.1
29 Jan 66			9.4	9.7
13 - 17 Feb 66	10.4	12.0	12.6	13.7
21 - 24 Feb 66	8.9			8.7
20 Apr 66				10.8
17 Feb 67				10.8
20 - 24 Feb 67	11.9	12.6	11.4	13.2
05 - 06 Jan 68		10.1	9.4	11.3
26 Dec 69			7.1	5.6
20 - 24 Jan 70	12.1	9.8	9.2	10.1
28 Dec 70			6.2	5.8
06 - 07 Jan 71				10.6
16 - 19 Jan 71	11.8	12.0	11.2	12.8
04 Mar 71			7.4	7.5
06 Dec 71				11.0
04 Jan 72				11.1
21 Feb 72			6.3	6.8
18 Dec 72			7.4	8.6
26 - 29 Oct 73	11.1	10.8	9.2	10.4
03 Nov 73			6.2	7.0
04 Jan 74		9.6	10.1	10.6
07 Feb 74			7.1	7.2
08 - 13 Mar 74	10.4	10.0	8.9	10.0
23 Feb 76				9.9
16 - 20 Mar 76	10.3	12.4	10.3	9.5
19 Oct 76				11.1
07 Nov 76			7.2	6.5
05 Dec 76				9.6
19 - 22 Jan 77	12.1	11.0	10.0	11.5
07 Feb 77		9.8	8.7	7.3
14 Feb 78				9.9
17 Feb 78				10.3
01 - 05 Mar 78	10.2	11.5	11.0	9.7
04 Feb 79			6.1	6.0
02 - 06 Jan 80	8.9			8.8
11 - 12 Feb 80		8.4	8.0	9.5
27 Feb 80				10.5
19 - 20 Nov 80		9.5	9.6	11.2
29 Nov 80				9.8
08 Mar 81			8.1	9.8
07 Dec 81			9.8	4.1
30 - 31 Dec 81		10.2	7.9	11.3
13 - 18 Jan 82	11.7	12.6	11.0	13.0
01 - 04 Feb 82	9.2			8.0
11 - 16 Feb 82	13.4	13.4	13.0	12.1
25 Feb 82				9.8

Date	Mobil	PERD	CSOWM	AES 40 5622
07 - 12 Dec 82	8.6			6.5
12 Feb 83			11.9	9.1
16 - 17 Feb 83		10.3	8.4	12.1
05 - 11 Mar 83	9.2			10.1
25 - 30 Nov 83	8.8	10.2	10.2	11.3
18 - 23 Dec 83	11.2	13.3	12.6	13.4
24 - 27 Dec 83	8.8			9.0
27 Jan 84				9.6
29 Mar 84			6.3	6.6
06 - 07 Jan 85		9.0	8.0	9.9
28 - 29 Jan 85		11.4	11.3	12.7
16 Dec 85		9.9		9.6
19 Dec 85			9.4	10.5
05 Jan 86		9.2	7.5	8.7
15 Nov 86				10.8
09 Dec 86				11.2
15 Feb 87				10.6
26 Feb 87				9.6
18 Feb 88				10.6
09 Mar 88			7.7	8.5
05 Jan 89			8.0	10.0
22 Jan 89				10.3
09 Dec 89			7.3	7.3
22 Dec 89				9.6
30 Dec 89				10.0
03 Jan 90				9.9
20 Jan 90				11.3
29 Oct 91			6.3	7.5
04 Dec 91				10.0
02 Mar 92			9.3	10.1
03 Nov 92				11.6
05 Dec 92			9.9	11.8
26 Dec 92			6.3	8.0
18 Jan 93			6.8	7.5
15 Mar 93			6.7	8.2
28 Dec 93			10.6	10.6
31 Dec 93			9.6	12.5
07 Jan 94				10.6
10 Dec 94			7.1	8.1
14 Feb 95			10.3	11.7
05 Apr 95			6.0	6.8
03 Nov 95				9.7
25 Sep 96				10.1
22 Nov 97				9.7
16 Dec 97				10.9
25 Sep 96				10.1
22 Nov 97				9.7
16 Dec 97				10.9

Table 1. The Storm Populations

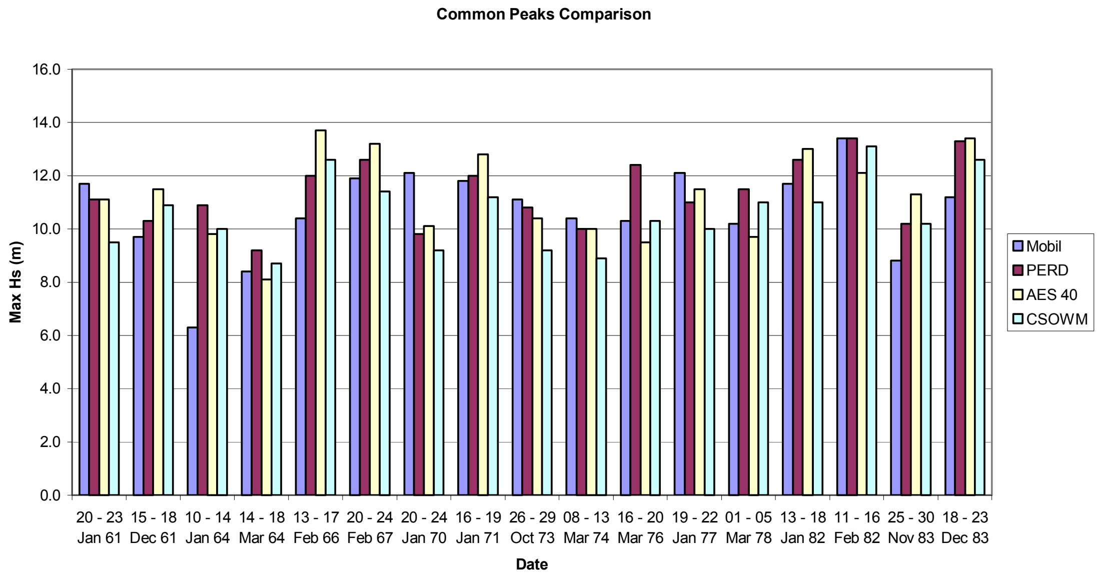
A total of 17 storms are found in all four hindcast studies. These are summarized in Table 2 below:

Date	Mobil	PERD	CSOWM	AES 40	Mean	Variation	Variation /Mean
20 - 23 Jan 61	11.7	11.1	9.5	11.1	10.9	1.6	0.15
15 - 18 Dec 61	9.7	10.3	10.9	11.5	10.6	1.8	0.17
10 - 14 Jan 64	6.3	10.9	10.0	9.8	9.3	4.6	0.50
14 - 18 Mar 64	8.4	9.2	8.7	8.1	8.6	1.1	0.13
13 - 17 Feb 66	10.4	12.0	12.6	13.7	12.2	3.3	0.27
20 - 24 Feb 67	11.9	12.6	11.4	13.2	12.3	1.8	0.15
20 - 24 Jan 70	12.1	9.8	9.2	10.1	10.3	2.9	0.28
16 - 19 Jan 71	11.8	12.0	11.2	12.8	12.0	1.6	0.13
26 - 29 Oct 73	11.1	10.8	9.2	10.4	10.4	1.9	0.18
08 - 13 Mar 74	10.4	10.0	8.9	10.0 *	9.8	1.5	0.15
16 - 20 Mar 76	10.3	12.4	10.3	9.5 *	10.6	2.9	0.27
19 - 22 Jan 77	12.1	11.0	10.0	11.5	11.2	1.1	0.10
01 - 05 Mar 78	10.2	11.5	11.0	9.7	10.6	1.8	0.17
13 - 18 Jan 82	11.7	12.6	11.0	13.0	12.1	2.0	0.17
11 - 16 Feb 82	13.4	13.4	13.0	12.1	13.0	1.3	0.10
25 - 30 Nov 83	8.8	10.2	10.2	11.3	10.1	2.5	0.25
18 - 23 Dec 83	11.2	13.3	12.6	13.4	12.6	2.2	0.17
Mean						2.11	0.20

* "ice" storms – data from Point 5551

Table 2. Peak Hs in the 17 Storms Included in All Four Populations

The following figure shows the peak significant wave height values for these 17 storms in each of the four studies:



4. COMPARISON OF RESULTS

Generally, the comparison of the peak results for these 17 storms is quite good. Defining the "variation" as the difference between the highest and the lowest (standard deviation is not particularly meaningful for a sample set of four values), the mean variation is 2.11 meters. Another measure of variation might be the "variation" defined above divided by the mean value of the results for a given storm in all four studies. By this measure, the mean value of "variation over mean" is 0.20 or 20%. Remembering that this variation is defined as the difference between the lowest and highest hindcast values for a storm, this 20% value for variation over mean is similar to a variation of plus and minus 10% from the mean value.

The most obvious exception to the generally favorable comparisons is the 10 – 14 January 1964 storm. The peak of this storm appears to be substantially underestimated in the Mobil study compared to the other two studies: a peak Hs of 6.3 meters for the Mobil study compared to 10.9 in the PERD study, 10.0 in the CSOWM, and 9.8 in the AES 40 study. The variation between the Mobil and PERD results is more than 4 meters, or about 50% of the mean value from the four studies. Ignoring the Mobil study, the variation is only 0.9 meters, and the mean value is 10.2. It seems likely that the Mobil result is erroneous.

Four other storms show "variation over mean" values in excess of 20%. These are:

13 – 17 February 1966
20 – 24 January 1970
16 – 20 March 1976
25 – 30 November 1983.

In two of these (February 1966 and November 1983) the Mobil study results are lowest and the AES 40 results are highest, with the PERD and CSOWM results agreeing very well with each other and falling approximately mid-way between the Mobil and AES 40 results. For the January 1970 storm, the Mobil results are the highest, the CSOWM is the lowest, and the AES 40 and PERD results are in excellent agreement with each other. In the last case (March 1976), the PERD result is much higher than the other three results, with these agreeing reasonably well with each other.

The Mobil, PERD, and CSOWM studies are all storm hindcasts, thereby involving a storm selection process. It is interesting to compare the storm populations in these three studies during the overlapping years, 1957 to 1984. During this time it appears that the Mobil storm selection process did not include a total of four events that had peak significant wave heights in excess of 10 meters in the PERD results. These were the following storms:

16 November 1963
5 - 6 January 1968
30 – 31 December 1981
16 – 17 February 1983.

With regard to the reverse of this, the PERD study included all the Mobil storms where the hindcast Hs exceeded 10 meters during the overlap period. In each of the four 10 meter events found in the PERD study but not the Mobil study, the AES 40 results for these storms all exceed the PERD results, but the CSOWM results are all lower than the PERD results. In three of the four events the AES 40 results exceed the PERD results by more than one meter in peak Hs. Considering that the Mobil study had only 15 events where Hs exceeded in 10 meters, this storm comparison would probably lead to an expectation that the AES 40 extreme wave estimates are likely be larger than the Mobil study results.

Looking at the annual occurrence rates of storms producing significant wave heights in excess of varying thresholds is also interesting. This is summarized in the following table 3:

	Mobil (34 years)		PERD (30 years)		CSOWM (37 years)		AES 40 (40 years)	
Threshold Hs (m)	N	λ	N	λ	N	λ	N	λ
10	15	0.44	20	0.67	19	0.51	58	1.45
11	10	0.29	11	0.37	10	0.27	25	0.60
12	3	0.088	7	0.23	4	0.11	10	0.25
12.5	1	0.029	4	0.13	3	0.081	7	0.18
13	1	0.029	2	0.067	1	0.027	4	0.10

Table 3. Exceedances of Threshold Significant Wave Heights at Hibernia in the Four Studies

The trend is very apparent: the Mobil study appears to indicate a substantially lower rate of exceeding the various thresholds, than the PERD and AES 40 studies, i.e., these large storms are less frequent than we see in either of the other studies. With the exception of the 12.5 m threshold, the CSOWM threshold exceedances are very similar to those seen in the Mobil study. Generally the AES 40 study indicates that the thresholds are exceeded about three times more often than what was indicated in the Mobil results. This may or may not affect the extreme value estimates (return periods for various rare events) but it undoubtedly has an influence on operations planning.

For example, suppose that a storm with Hs greater than 10 meters causes the cessation of a certain operation on the Hibernia platform. The Mobil study indicated that this would occur, on average, once every 2.3 years, while the AES 40 study indicates that it would occur, on average, 1.45 times each year. Over a 25 year platform life this translates into an expected 11 exceedances in the Mobil study versus 36 exceedances in the AES 40 study. It is possible that this could have an effect when considering project life cycle economics, which is often important both for development scenario selection as well as estimating the expected economic value of a project.

5. EXTREME VALUE ESTIMATES OF HS FROM THE FOUR STUDIES

Estimates of extreme significant wave heights using the results of the four studies have been made using the Gumbel and Borgman (Gumbel on H_s^2) extreme value distributions. The distributions were fit using the method of moments as defined by Oceanweather.

The following data sets were analyzed:

1) The 26 Mobil hindcast storms used by Mobil in estimating extremes. The two storms that produced the lowest peak Hs values (6.3 and 7.1 m) are excluded, following the procedure outlined in Mobil's series of published papers.

2) The Mobil hindcast storms producing Hs values exceeding 9.5 meters. There are 18 such events.

3) The 30 storms designated as Grand Banks storms hindcast in the PERD study having hindcast Hs values of 9.0 meters or higher.

4) All PERD storms in which the maximum Hs exceeded 9.5 meters. The total number of such storms was 25.

5) All CSOWM storms where the peak Hs value is greater than or equal to one half

of the maximum Hs in the study. The number of such storms is 58.

6) All CSOWM storms where the peak Hs value is equal to greater than 9.5 meters. This is a sample size of 24 storms.

7) All AES 40 storms having maximum Hs values exceeding 9.5 meters. This totaled 81 events.

8) All storms found in the PERD study that had hindcast maximum Hs values greater than 9.5 meters in the AES 40 study. There were 28 such events.

9) All storms found in the PERD study that had hindcast maximum Hs values greater than 9.5 meters in the AES 40 study, including Hs values from an adjacent grid point for the two PERD storms that occurred with greater than 50% ice coverage in the AES 40 study. There were 30 such events.

10) All storms in the AES-40 study with maximum Hs greater than 9.5 meters, occurring during the years covered by the PERD study (1957 – 1988). This totaled 62 events. Comparison of this data set to the PERD storm set qualitatively assesses the effect of storm selection. The comparison is not perfect however, since the wind and wave modeling changed between PERD and AES 40.

	Gumbel Distribution, Method of Moments Hs (m)									
Return Period										
2	9.7	9.6	10.5	10.5	9.8	9.9	11.3	10.9	10.9	11.3
5	11.2	11.3	11.8	11.8	11.2	11.2	12.1	12.2	12.2	12.2
10	12.1	12.1	12.6	12.6	12.2	12.0	12.7	13.0	13.0	12.8
20	13.0	12.8	13.4	13.4	13.2	12.7	13.3	13.8	13.8	13.5
25	13.3	13.0	13.7	13.6	13.5	12.9	13.5	14.1	14.1	13.7
50	14.2	13.7	14.5	14.4	14.5	13.5	14.1	14.9	14.9	14.3
100	15.0	14.4	15.3	15.1	15.5	14.2	14.7	15.7	15.7	14.9
	Mobil	Mobil	PERD	PERD	CSOWM	CSOWM	AES 40	AES 40	AES 40	AES
								PERD storms	PERD storms *	PERD years *
		Hs > 9.5		All Hs > 9.5	All Hs > 0.5 * max Hs	All Hs > 9.5	All Hs > 9.5	Hs > 9.5	Hs > 9.5	Hs > 9.5
	N = 26	N = 18	N = 30	N = 25	N = 58	N = 24	N = 81	N = 28	N = 30	N = 62

	Borgman Distribution, Method of Moments Hs (m)									
Return Period										
2	9.7	9.5	10.6	10.5	9.8	9.7	11.3	11.0	11.0	11.4
5	11.3	11.4	11.8	11.9	11.1	11.2	12.1	12.2	12.2	12.4
10	12.1	12.1	12.6	12.6	12.0	11.9	12.7	13.0	13.0	13.0
20	12.9	12.7	13.3	13.3	12.7	12.5	13.2	13.7	13.7	13.6
25	13.1	12.9	13.5	13.5	13.0	12.7	13.4	13.9	13.9	13.8
50	13.8	13.5	14.2	14.1	13.7	13.3	13.8	14.5	14.5	14.4
100	14.4	14.1	14.8	14.7	14.3	13.9	14.3	14.7	15.1	14.9
	Mobil	Mobil	PERD	PERD	CSOWM	CSOWM	AES 40	AES 40	AES 40	AES
								PERD storms	PERD storms *	PERD years *
		Hs > 9.5		All Hs > 9.5	All Hs > 0.5 * max Hs	All Hs > 9.5	All Hs > 9.5	Hs > 9.5	Hs > 9.5	Hs > 9.5
	N = 26	N = 18	N = 30	N = 25	N = 58	N = 24	N = 81	N = 28	N = 30	N = 62

* "ice" storms included

Table 4. Extreme Value Estimates of Hs

The results for extreme value estimates of significant wave height from these ten data sets, for both the Gumbel and Borgman distributions, are summarized in Table 4.

Comparing first the AES 40 PERD storms, with and without the two "ice" storms, clearly shows that the addition of these two storms, both having peak Hs values near the middle of the storms used in the analyses, did not effect the extreme value estimates at all.

Perhaps the most remarkable observation based on review of table 4 is the high degree of consistency among the results for the ten data sets. This is summarized in table 5 below:

	Gumbel			Borgman		
Return Period (years)	Mean	Std. Dev.	COV	Mean	Std. Dev.	COV
2	10.4	0.66	0.063	10.5	0.72	0.069
5	11.7	0.45	0.039	11.8	0.47	0.040
10	12.5	0.38	0.031	12.5	0.44	0.035
20	13.3	0.38	0.028	13.2	0.44	0.033
25	13.5	0.40	0.030	13.4	0.43	0.032
50	14.3	0.45	0.032	14.0	0.42	0.030
100	15.1	0.52	0.034	14.5	0.38	0.026

Std. Dev. – standard deviation
COV – coefficient of variation

Table 5. Statistical Summary of Hs Estimates from the Ten Data Sets.

In the earlier discussion regarding the storm selection process, a foundation was laid for the expectation that the results from the Mobil hindcast study might yield low estimates for extreme wave heights. Comparing first the Gumbel distribution, it is seen that this is only marginally true. For all 26 Mobil storms the 100-year Hs value is 15.0 meters, actually 0.3 meters higher than the AES 40 value for all peaks above 9.5 meters. Compared to the AES 40 results for all PERD storms where Hs exceeded 9.5 m, the Mobil value is only 0.7 meters, or about 5%, lower than the largest 100-year Hs determined for the eight data sets. The estimate obtained using the subset of Mobil results where Hs exceeded 9.5 meters resulted in an even lower 100-year Hs value, 14.4 meters, but this is still only 9% less than the largest 100-year Hs. Essentially the same results are found from comparisons of the Borgman distribution results.

[An important point to note is that the Hibernia platform was designed to a 100-year Hs value of 15.9 meters, based on the 90% control level value obtained using the Borgman distribution fit. The AES 40 results for all storms exceeding 9.5 meters, fit with the Gumbel distribution using the method of moments, would define this Hs as having a return interval of 125 years. For the other data sets, the return period would be longer.]

Examination of the other return periods shows that, at 2 years for example, the Mobil hindcast is much lower than the PERD and AES40. This difference indicates that the mean value of the extreme storms is much lower in the Mobil study (as seen in the earlier discussion), but that the standard deviation of the storm peaks is much higher. This creates a larger slope to the return period line. Another result is that the confidence intervals will also be much larger.

6. EXTREME VALUE ESTIMATES OF HMAX FROM THE FOUR STUDIES

Estimates of extreme significant and maximum wave heights using the results of the three studies have been made using the Gumbel and Borgman (Gumbel on H_m^2) extreme value distributions. The distributions were fit using the method of moments as defined by Oceanweather.

The following data sets were analyzed:

1) The 26 Mobil hindcast storms used by Mobil in estimating extremes. The two storms that produced the lowest peak Hs values (6.3 and 7.1 m) are excluded, following the procedure outlined in Mobil's series of published papers..

2) The Mobil hindcast storms producing Hmax values exceeding 17.5 meters. There are 18 such events.

3) The 30 storms designated as Grand Banks storms hindcast in the PERD study having hindcast Hs values of 9.0 meters or higher.

4) All PERD storms in which Hmax exceeded 17.5 meters. The total number of such storms was 25.

5) All CSOWM storms where the Hmax value is greater than or equal to one-half of the maximum Hmax in the study. The number of such storms is 60.

6) All CSOWM storms where the Hmax value is equal to greater than 17.5 meters. This is a sample size of 22 storms.

7) All AES 40 storms having Hmax values exceeding 17.5 meters. This totaled 93 events.

8) All storms found in the PERD study that had hindcast maximum Hmax values greater than 17.5 meters in the AES 40 study. There were 28 such events.

9) All storms found in the PERD study that had hindcast maximum Hmax values greater than 17.5 meters in the AES 40 study, including Hmax values from an adjacent grid point for the two PERD storms that occurred with greater than 50% ice coverage in the AES 40 study. There were 30 such events.

10) All storms in the AES study with Hmax values greater than 17.5 meters, occurring during the years covered by the PERD study (1957 – 1988). This totaled 68 events. Comparison of this data set to the PERD storm set qualitatively assesses the effective of storm selection. The comparison is not perfect however, since the wind and wave modeling changed between PERD and AES 40.

Table 6 summarizes the Hmax results from the four studies. Immediately after Table 6, the results for extreme value estimates of maximum wave height from these ten data sets, for both the Gumbel and Borgman distributions, are summarized in table 7.

The most remarkable observation based on review of table 7 is again the high degree of consistency among the results for the eight data sets. This is summarized in table 8.

Again the presence of the two PERD "ice" storms in the AES 40 results for the PERD storms, both having Hmax values near the middle of the storms used in the analyses, did not affect the extreme value estimates at all.

In the earlier discussion regarding the storm selection process, a foundation was laid for the expectation that the results from the Mobil hindcast study would yield low estimates for extreme wave heights. Comparing first the Gumbel distribution, it is again seen that the Mobil study yields only slightly lower values. For all 26 Mobil storms the 100 year Hmax value is 27.4 meters, actually 0.3 meters lower than the AES 40 value for all storms where Hmax is above 17.5 meters. Compared to the AES 40 results for all PERD storms where Hmax exceeded 17.5 m, the Mobil value is 1.9 meters, or about 7%, lower than this largest 100 Hmax determined for the ten data sets. The estimate obtained using the subset of Mobil results where Hs exceeded 17.5 meters resulted in an even lower 100 year Hmax value, 26.4 meters, nearly 10% less than the largest 100-year Hmax. Essentially the same results are found from comparisons of the Borgman distribution results.

[An important point to note is that the Hibernia platform was designed to a 100 year Hs value of 29.3 meters, based on the 90% control level value obtained using the Borgman distribution fit. This turns out to exactly equal the highest Hmax estimate in the present comparisons, that derived from the AES 40 results for all the PERD storms with an Hmax exceeding 17.5 meters fit with the Gumbel distribution using the method of moments.]

The variation in the estimates obtained for the 2-year return period is significantly greater than what is seen for the 100-year return period. For example, for the Gumbel distribution the variation is 1.7 meters, or equivalently, about 16%. At first consideration this is a counterintuitive result. Since the time period covered with each data set is on the order of 30 to 40 years, the estimate of the values corresponding to return periods well within this time period would be expected to be consistent among the data sets. More careful review of the results reveals that the high estimates of 2-year return period come from the continuous study (AES 40) as opposed to the storm studies. This occurs because the continuous study by default includes many more storm events that produce moderately high waves than are found in storm studies since, by definition, the storm studies focus on the most extreme events.

Date	Mobil	PERD	CSOWM	AES 40 5622
10 - 14 Nov 52	13.2			
08 - 11 Feb 54	20.6			
20 - 23 Sep 55	17.6			
09 - 13 Dec 55	19.8			
16 Jan 59				18.2
07 - 08 Feb 59		17.1	16.4	19.6
17 Feb 59				17.6
09 - 10 Jan 60		16.2	17.3	19.2
20 - 23 Jan 61	21.6	20.4	17.3	20.8
15 - 18 Dec 61	18.4	19.0	20.6	22.3
05 Jan 62				17.7
26 Feb 62				17.7
02 May 62				18.7
26 Feb 63				20.1
16 Nov 63		19.0	18.6	19.6
27 Dec 63			8.0	17.9
10– 14 Jan 64	12.4	20.1	18.7	18.2
09 - 10 Feb 64		17.1	15.5	19.6
14 - 18 Mar 64	15.8	16.9	16.7	15.3
24 Jan 65		13.6	13.7	15.8
17 - 20 Feb 65	18.0			18.7
29 Mar 65				18.7
03 Jan 66				17.5
09 - 10 Jan 66		16.2	17.0	19.2
29 Jan 66			17.1	18.2
13 - 17 Feb 66	19.8	22.1	23.5	25.5
21 - 24 Feb 66	16.6			16.5
20 Apr 66				20.3
17 Feb 67				20.0
20 - 24 Feb 67	21.4	23.2	20.8	24.3
05 - 06 Jan 68		18.6	17.4	21.1
26 Dec 69			12.6	10.7
20 - 24 Jan 70	22.3	18.0	17.1	19.4
28 Dec 70			11.4	11.0
06 - 07 Jan 71				20.1
16 - 19 Jan 71	21.6	22.1	22.1	24.2
04 Mar 71			13.8	13.9
06 Dec 71				20.6
02 Jan 72				20.2
04 Jan 72				20.7
21 Feb 72			11.7	12.7
03 Dec 72				17.5
18 Dec 72			13.6	15.6
26 - 29 Oct 73	20.2	19.9	17.4	19.4
03 Nov 73			11.6	13.2
04 Jan 74		17.7	19.1	20.2
07 Feb 74			13.0	13.2
08 - 13 Mar 74	18.7	18.4	16.8	18.7
23 Feb 76				18.1
16 - 20 Mar 76	18.2	22.8	18.6	17.9
19 Oct 76				20.5
07 Nov 76			13.1	13.3
05 Dec 76				18.0
19 - 22 Jan 77	22.5	20.2	19.2	21.6
07 Feb 77		18.0	16.5	13.8
14 Feb 78				18.8
17 Feb 78				19.9
01 - 05 Mar 78	18.7	21.2	20.1	17.7
05 Oct 78				17.5
04 Feb 79			11.7	11.9
10 Dec 79				17.6

Date	Mobil	PERD	CSOWM	AES 40 5622
02 – 06 Jan 80	16.3			17.1
11 - 12 Feb 80		15.5	14.6	17.7
27 Feb 80				19.6
19 - 20 Nov 80		17.5	18.2	21.2
29 Nov 80				18.4
08 Mar 81			15.9	18.9
07 Dec 81			18.2	13.8
30 - 31 Dec 81		18.8	18.2	21.2
13 - 18 Jan 82	21.5	23.2	20.4	23.9
01 - 04 Feb 82	16.9			14.9
11 - 16 Feb 82	24.7	24.7	23.0	23.1
25 Feb 82				17.8
07 - 12 Dec 82	15.8			12.4
16 - 17 Feb 83		19.0	22.2	23.1
05 - 11 Mar 83	16.9			19.0
25 - 30 Nov 83	16.2	18.8	18.7	21.0
14 Dec 83				17.2
18 - 23 Dec 83	20.6	24.5	22.8	25.1
24 - 27 Dec 83	16.2			16.6
27 Jan 84				17.9
29 Mar 84			11.9	12.2
06 - 07 Jan 85		16.6	15.4	19.3
28 - 29 Jan 85		21.0	20.8	23.9
16 Dec 85		18.2	17.3	17.8
19 Dec 85				19.7
05 Jan 86		16.9	13.7	16.0
15 Nov 86				19.8
09 Dec 86				20.7
15 Feb 87				19.7
26 Feb 87				17.9
18 Feb 88				19.3
09 Mar 88			13.9	15.6
30 Dec 88				17.5
05 Jan 89			14.5	18.3
22 Jan 89				19.2
09 Dec 89			13.7	13.9
22 Dec 89				18.0
30 Dec 89				18.5
03 Jan 90				18.4
20 Jan 90				21.3
28 Jan 90				18.7
28 Nov 90				19.7
12 Jan 91			21.9	23.1
29 Oct 91			11.6	14.2
04 Dec 91				18.6
02 Mar 92			16.9	19.0
03 Nov 92				21.7
05 Dec 92			17.9	21.5
26 Dec 92			11.7	14.6
18 Jan 93			12.2	13.9
15 Mar 93			12.6	15.3
28 Dec 93			18.8	19.5
31 Dec 93			17.2	22.6
07 Jan 94				20.0
10 Dec 94			13.0	14.8
04 Jan 95				17.5
14 Feb 95			18.4	21.3
05 Apr 95			11.0	12.7
03 Nov 95				17.9
25 Sep 96				18.8
22 Nov 97				17.8
16 Dec 97				19.9

Table 6. The Hmax Populations

Return Period	Gumbel Distribution, Method of Moments Hmax (m)									
2	17.8	17.6	19.3	19.4	18.0	18.3	21.2	20.5	20.5	21.2
5	20.6	20.7	21.7	21.7	20.7	20.7	22.8	22.9	22.9	22.8
10	22.3	22.2	23.2	23.2	22.6	21.9	24.0	24.4	24.4	24.0
20	23.9	23.5	24.7	24.6	24.4	23.1	25.1	25.9	25.9	25.2
25	24.4	23.9	25.2	25.1	25.0	23.5	25.5	26.4	26.4	25.6
50	25.9	25.1	26.7	26.5	26.8	24.6	26.6	27.9	27.9	26.8
100	27.4	26.4	28.1	27.8	28.6	25.7	27.7	29.3	29.3	28.0
	Mobil	Mobil	PERD	PERD	CSOWM	CSOWM	AES 40	AES 40	AES 40	AES
								PERD storms	PERD storms *	PERD years *
		Hmax > 17.5		All Hmax > 17.5	All Hmax > 0.5 * max Hs	All Hmax > 17.5	All Hmax > 17.5	Hmax > 17.5	Hmax > 17.5	Hmax > 17.5
	N = 26	N = 18	N = 30	N = 25	N = 60	N = 22	N = 93	N = 28	N = 30	N = 68

Return Period	Borgman Distribution, Method of Moments Hmax (m)									
2	17.9	17.4	19.5	18.4	18.0	17.7	21.3	20.6	20.6	21.3
5	20.7	20.8	21.8	21.9	20.4	20.6	22.8	22.9	22.9	22.9
10	22.2	22.2	23.2	23.8	22.0	21.8	23.9	24.4	24.4	24.0
20	23.6	23.4	24.5	25.4	23.4	22.9	24.9	25.6	25.6	25.0
25	24.0	23.7	24.9	26.0	23.8	23.2	25.2	26.0	26.0	25.3
50	25.2	24.8	26.0	27.5	25.1	24.2	26.1	27.2	27.2	26.2
100	26.4	25.8	27.2	28.9	26.3	25.1	27.0	28.3	28.3	27.2
	Mobil	Mobil	PERD	PERD	CSOWM	CSOWM	AES 40	AES 40	AES 40	AES
								PERD storms	PERD storms *	PERD years *
		Hmax > 17.5		All Hmax > 17.5	All Hmax > 0.5 * max Hs	All Hmax > 17.5	All Hmax > 17.5	Hmax > 17.5	Hmax > 17.5	Hmax > 17.5
	N = 26	N = 18	N = 30	N = 25	N = 60	N = 22	N = 93	N = 28	N = 30	N = 68

* “ice” storms included

Table 7. Extreme Value Estimates for Hmax

	Gumbel			Borgman		
Return Period (years)	Mean	Standard Deviation	Coefficient of Variation	Mean	Standard Deviation	Coefficient of Variation
2	19.4	1.41	0.073	19.3	1.56	0.081
5	21.8	1.03	0.047	21.8	1.07	0.049
10	23.2	0.94	0.041	23.2	1.04	0.045
20	24.6	0.94	0.038	24.4	1.02	0.042
25	25.1	0.96	0.038	24.8	1.06	0.043
50	26.5	1.06	0.040	26.0	1.12	0.043
100	27.8	1.15	0.041	27.1	1.20	0.044

Table 8. Statistical Summary of Hmax Estimates from the Ten Data Sets.

7. CONCLUSIONS

The comparison study of the extreme value wave height predictions on the Grand Banks near the Hibernia platform described in this paper lead to the following conclusions:

1. The consistency of the 100 year return extremes is remarkable given the differences in the individual storm hindcasts in the various studies, both in terms of the storm populations and the inter-study differences for the same storms. It is postulated that the range and scatter of these estimates is perhaps the intrinsic uncertainty of extremes obtained using the modern hindcasting approach.

2. At shorter return periods the data sets with more storms obviously provide more realistic extremes because they more correctly reflect the frequencies of storms above the thresholds typically adopted in peaks-over-threshold analyses. Consequently, the AES-40 should give the best shorter return values as an entire 40 year time period was hindcast thus modelling many more of the shorter return period storms.

3. The consistency that is present between the different studies for the same storms comes mainly from the consistency of the hindcast methodology for all of the data sets. All the studies were performed using the Oceanweather family of wave models. All the wind fields were developed by kinematic analysis with a consistent treatment of ship and buoy reports. The AES-40 hindcast used the NCEP Reanalysis Project 10-m wind field for background as opposed to the Cardone (1969) PBL model, but the NCEP winds were chosen from several possible options because it provided wave hindcasts with the least bias.

4. Because the AES-40 is a continuous hindcast is provides much better information for operability estimations since it provides the most reliable estimates of the frequency of occurrence of conditions exceeding various thresholds, particularly lower thresholds, which are critical for weather-sensitive operations

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