Long Term Wave Measurements and Trend at Canadian Coastal Locations

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1.Introduction

Long term homogeneous wave measurements are important for climate trend and variability studies and for validation of other sources of wave data, such as hindcast datasets. Relatively long term wave measurements from moored wave buoys in Canadian coastal waters began in 1970, but are limited to only 3 locations, in British Columbia (BC), Nova Scotia (NS), and Newfoundland and Labrador (NL). With one exception, long term wave measurements from moored weather buoys in Canadian deep water locations began later, with most first deployed around 1988 (One offshore buoy, ID 46004, was first deployed in 1975.). These long term coastal wave datasets have not been systematically analyzed. The wave climate from offshore weather buoys has been analyzed at US locations, and in Canadian waters in the Pacific (e.g. Gower 2002), but assessment and adjustment for any inhomogeneties has been limited. Before reliable results from climate trend analysis are possible, it is important to first adjust the data series for any changes in location or observing methods that could cause shifts in the long term record. Not all of the changes that could cause such shifts have been documented, and the effects of some changes, such as changes in hull type or wave processing methods, are not well understood.

In this study, we assembled wave datasets (joining Waverider and weather buoy stations where necessary) and any available metadata at 3 long term coastal sites, near Tofino BC, Halifax NS, and Torbay, northeast of St. John's NL, beginning in early 1970s. For many years the reporting frequency of the Waverider varied depending on the wave height, which had the potential to cause a high bias in the monthly means. We calculated monthly means using weighting factors to account for reporting frequency variations. We used a newly developed statistical homogeneity test to detect artificial step changes in the time series, homogenize the data sets, and assess long term trends. This method has been recently applied to long term Canadian wind data (Wan et al. 2009).

Section 2 describes the wave data and metadata used in this study. Section 3 describes the method to weight the data for reporting frequency and the statistical methods used to detect and adjust for shifts in the monthly mean significant wave heights, and to analyze trend. Section 4 presents the results of inhomogeneity detection and adjustment, and climate trends at each location. Discussion follows in Section 5 with a summary in Section 6.

2. Data

a) Measurements

In this study we assembled long-term time series of coastal wave data in 40 to 80 m water depth, from wave buoys and weather buoys at three locations: near Tofino, British Columbia (BC), on the west coast of Vancouver Island; in the harbour approaches at Halifax, Nova Scotia (NS); and near Torbay, northeast of St. John's, Newfoundland and Labrador

(NL). Data from Canada's Department of Fisheries and Oceans (DFO) wave buoys and the Environment Canada weather buoys are archived by the Integrated Science Data Management Division (ISDM) of DFO (formerly the Marine Environmental Data Service (MEDS)). The archived data are available online at http://www.meds-sdmm.dfo-mpo.gc.ca/MEDS/Databases/Wave/WAVE_e.htm. Near Tofino and Halifax, the time series of wave buoy measurements from the early 1970's to the late 1990's were extended to the present by joining the record to weather buoy wave time series. With the exception of one year of directional Waverider (DWR) data near Tofino, the wave buoy data comes from non-directional Datawell Waveriders. Historical locations of the Waveriders and nearby weather buoys at each site are plotted in Figure 1. The year and month of position changes are indicated in the legend for the location markers. Historical metadata for each of these sites is given in Tables 1-3.

The Waverider near Tofino was deployed in June 1970 and operated nearly continuously until May 1999. For the last year of its operation it was a directional WR. The ISDM ID for the non-directional Tofino WR data is MEDS103; for the directional WR it is MEDS303. We extend the time series to the present by joining the Waverider data record to wave data from an Environment Canada 3D weather buoy 25 km away, at La Perouse Bank (WMO ID 46206), beginning in May 1999. Buoy 46206 had been in operation since 1988. During the 10 year overlapping period, we found that the data correlates well, with hourly significant wave heights from buoy 46206 reading about 11 % higher than hourly means of the Waverider Hs (Figure 2), as would be expected for a location further from shore in somewhat deeper water.

A Waverider was deployed in the approaches to Halifax Harbour in December 1970. Over the years the name used for the station included Hartlen Point, Osborne Head, Shearwater, Halifax Harbour, and Halifax Approaches; in the ISDM archive the station is referred to as Osborne Head, with ID MEDS037. Environment Canada took over operation of the WR in 1998, and it was discontinued in September 2001. In March 2000, EC deployed a 3 m Discus (3D) weather buoy within a few km of the wave buoy. The weather buoy, named the Halifax Approaches Buoy (WMO ID 44258) continues to the present (during some periods a 6 m NOMAD (6N) buoy was used instead of the 3D). Unfortunately although the deployment of the WR and the 3D overlapped by more than a year, both had frequent data gaps at different times, for various reasons including vandalism, so the number of paired observations is lower that would be expected. A comparison of overlapping hourly 3D and WR Hs shows good agreement, to within 1% for most of the range, except for a handful of points above 5 m when the 3D was a little higher than the Waverider (Figure 3).

The seasonal Torbay Waverider (MEDS016), northeast of St. John's NL, operated from 1972 to 1997. It was typically deployed in June, and recovered in January or February to avoid pack ice.

We used the ISDM quality control flag determined by ISDM and included in each report. We also used additional quality control flags as needed to screen erroneous data. Close examination of the Waverider data showed that, in general, the ISDM flag was quite reliable at flagging suspect or bad data. One possible cause of intermittent bad data was icing. Juszko (1988) reported that the Datawell Waverider is susceptible to icing causing intermittent data gaps. If the antenna ices up the buoy may tip over until the ice has melted, with no transmissions during that interval. There was a longer term unexplained problem at the Halifax Waverider in the early years of its deployment. For about two years in the early

1970s the monthly means were abnormally low (when compared to monthly means from all years), but the ISDM flags indicated the data was acceptable. We do not know a reason for the low values, but we excluded the data during this interval. The ISDM flags did not always catch problems with the weather buoy wave data so additional steps were used to exclude bad data. The most frequent source of erroneous wave data from the weather buoys, not always caught by the ISDM flags, was when the buoy was transmitting data before it was fully deployed or after it had been recovered. Typically in these cases the wave heights were near zero. We also excluded cases when the buoy was known to be adrift due to mooring failure.

For the Waverider data we used the ISDM archived value VCAR for the significant wave height. For the weather buoy data, the ISDM archives include two fields for the significant wave height, VCAR and VWH$. VCAR is Hs calculated by ISDM from the transmitted spectral data (band-averaged at the high frequency end of the range). VWH$ is calculated by the wave processor onboard the buoy, from the full spectrum. See the reports by Axys (1996 and 2000) for further details. Generally VCAR and VWH$ agreed fairly well, although VCAR was erroneous for unknown reasons from the summer of 2005 to the next. The low frequency end of the range used to calculate Hs on coastal weather buoys has varied at ISDM and onboard the buoy and has not always been the same. Mercer and Thomas (2009) showed that an overly restrictive low frequency cutoff can reduce the calculated value of Hs, in extreme storms or in long period swell. At buoy 46206, we used whichever of the two valid fields, VCAR or VWH$, corresponded to the lowest low frequency cut-off (details in Table 1).

The initial reporting frequency of the Waverider in the early 1970s was 3-hourly; it increased over the years. For many years, the reporting frequency was dependent on the wave height. Beginning in 1976 (Tofino) and in 1982 (Osborne Head and Torbay), reports were 3-hourly except every 20 minutes while waves were over 5 m, then beginning in 1987 wave buoys normally reported hourly, increasing to twice hourly in high waves, and decreasing to only once every 3 hours in very low waves. Beginning in 1997 until the Waveriders were discontinued there were two reports per hour. The weather buoys reported hourly.

The mooring locations have changed slightly over the years; the positions are part of the archived reports. The spectral data files from the weather buoys also include the actual GPS positions. As these stations are close to the coast, relatively small changes could put the wave buoys into slightly different local wave climates.

Datawell Waveriders have small (1 m diameter) spherical hulls, and they use a vertically stabilized accelerometer, with a displacement range of ±20 m. The weather buoys near Tofino and Halifax were 3 m Discus buoys (except for a 6 m NOMAD buoy with a boat-shaped hull for a few years near Halifax). These report non-directional wave data. They use strapped-down accelerometers, with a displacement range of ±15 m. The numbers of frequency bands, band resolution, sampling rate, and sampling period at the Waverider have increased over the years (as determined from the wave spectral files archived by ISDM), and these are different that those used by the accelerometer and wave processor on the weather buoys.

b) Hindcast Wave Data used for Reference Time Series

The statistical method used to detect inhomogeneities in the time series is most reliable when used with a homogeneous reference time series. For the reference time series, we used the deep water GROW2000 (Global Reanalysis of Ocean Waves) hindcast wave data

(Cardone et al 2000, Cox and Swail 2001). GROW2000 has a fine grid spacing over Canadian waters of 0.625° latitude by 1.25° longitude; we used the nearest model grid point to each buoy location (details in captions of Tables 1-3). In GROW2000, the NCEP (US National Center for Environmental Prediction) reanalysis wind speeds (NRA), used as input to the wave model, were corrected using spatially varying regressions developed from global evaluation of NRA wind against adjusted in-situ data and corrected satellite scatterometer winds. Tropical systems were added to the base GROW2000 wind fields to better predict the swells generated by tropical systems including western Pacific typhoons (Cox and Cardone 2000). The GROW2000 hindcast period begins in January 1970 and was recently updated to December 2008

3. Method

a) Monthly means: weighting the individual wave heights for variations in the reporting frequency

Marine datasets often have gaps, due to the harsh operating environment which damages instruments and transmitters, or occasionally interrupts transmission. For this reason, it is important to assess the number of observations in a month, compared to the total possible, so that only monthly means with a sufficiently high coverage of reports are used. We used monthly means with at least 65% coverage. There were many years when the reporting frequency of the Waverider depended on the wave height, with more frequent reports in high waves, as described in Section 2. If the reports were all used with equal weight, this would introduce a high bias in the monthly means. We weighted individual reports depending on the interval of time between preceding and following reports. The standard reporting intervals over the years included 180, 60, 30, and 20 minutes. The weight was calculated from the reporting interval in minutes, divided by 60 minutes, so that 3-hourly (synoptic) reports were weighted 3, hourly reports were weighted 1, reports 3 times an hour were weighted 0.333, etc. Intervals between reports could also increase intermittently due to occasional missing reports. The weight for any given report was calculated as the average of the weights calculated from the preceding and following interval lengths. If either the preceding or following interval exceeded 4.5 hours, the weight was based only on the other interval. If both exceeded that limit, the report was not used. This value of 4.5 was chosen to accommodate changes in reporting from the synoptic hours (0, 3, 6, 9, 12, 15, 18, and 21) to either the hour before or the hour after the synoptic hours. This could change from one deployment phase to the next. Months with at least 65% coverage were included in the time series analysis. We used the sum of the weights rather than the number of reports, out of the total possible, to determine the coverage.

Figure 4 for monthly mean Hs at Torbay, NL, shows means calculated with and without weights to compensate for differences in reporting frequency as a function of wave height. Difference in monthly means are most pronounced between 1982 to 1987, when the normal reporting frequency was every 3 hours except every 20 minutes in waves over about 5 m, i.e. 9 times more often in high waves. The largest difference in monthly means is nearly 1.5 m. From 1987 to 1998 the normal reporting frequency was hourly, going to twice hourly in high waves, and only every 3 hours in very low waves. Differences are less pronounced. This figure also shows the seasonal nature of the Waverider, deployed in summer and recovered in winter.

b) Detecting and adjusting for non-climatic systematic shifts in monthly means, and trend analysis

We used the penalized maximal T (PMT) test (Wang et al. 2007, Wang 2008a) in the statistical package RHTestV3 (Wang and Feng 2009), to detect shifts in monthly mean measured Hs, using the GROW2000 hindcast data at the nearest grid point for a reference series. The method accounts for lag-1 autocorrelation and the seasonal cycle.

Use of a reference series minimizes the effect of climate periodicity or background trend in the data, to the extent that these are similar in each series. The difference between the base data series and the reference series is assessed for mean shifts. The de-seasonalized (monthly anomaly) data series is also assessed for mean shifts, as a check on the results from using the difference series. The data is de-seasonalized by subtracting the overall monthly mean from each monthly mean. The penalized maximal F (PMF) test (Wang 2008a and 2008b), that is also part of RHTestV3 and does not require use of a reference time series, was used to test for artificial shifts in the hindcast series. The GROW2000 monthly mean Hs at the three locations of interest were found to be homogeneous.

The PMT and PMF tests could not run with the monthly mean Hs from the Torbay Waverider with its long gaps every year. However it was possible to run the PMT test with annual means of the July to December monthly means.

We assessed available metadata to determine whether to keep the change points detected in the measurement series (for use in the adjustment process), or whether to adjust the timing of the shift which is identified to the nearest year and month. We looked at various possible causes of systematic shifts, focussing on changes occurring near the time of the identified change point. The relevant metadata for each station is presented with the results.

The software calculates 3 sets of trends: 1) for the original data (ignoring all detected shifts), 2) for the data adjusted using the detected step changes estimated from the difference series, and 3) for the data adjusted using the step changes estimated from the de-seasonalized series.

4. Results

a) Tofino, BC (Tofino Waverider Joined with La Perouse Bank Buoy Data)

The reference time series used for the Tofino location is the nearest GROW2000 hindcast grid point, G41855, from January 1970 to December 2008. A comparison of monthly means from the Tofino location and GROW shows very good correlation, with the GROW waves a little higher, which would be expected for a slightly more offshore location and the use of deep water wave physics only. The homogeneity of the reference point was assessed with the PMF test; no change points were found. Results of the PMF test on the GROW hindcast data are shown in Figure 5.

The base time series is composed of the monthly means from the Tofino waverider data combined with the La Perouse Bank 3D buoy data beginning May 1999. There were only two significant position changes during the deployment period of the Tofino Waverider, the first in May 1983 and the second in January 1987, each of about 5 km (see Figure 1a). The reporting frequency, number of wave frequency bands, and resolution increased in 1987.

The PMT test found two Type 1 change points in the base minus reference series (the difference series), in August 1979 and June 1999 (Table 4). There is no particular metadata to suggest what may have caused the small negative shift in the difference series in August 1979. However it is statistically significant and there is a corresponding (although smaller) step in the de-seasonalized base series, so this change point is kept. The second change coincides with joining the record from the 3D further out in deeper water in May 1999. This step change of about 0.2 m, for annual mean wave heights of about 2 m, is consistent with the approximately 11% difference in wave heights at La Perouse Bank (46206) and the Tofino Waverider during the decade long overlapping period. We reran the PMT test with the month of the 1999 change point corrected to be May rather than June. Results are shown in Figure 6 and in Tables 4 and 5.

Despite the proximity to shore, changes in position (1983 and 1987) do not appear to cause any Type1 systematic shifts in the monthly mean Hs from the Waverider. The dominant nearshore wave climate would be from the open ocean, to which the three locations appear to be equally exposed. The water depth is 40 m at all three locations.

The trend in annual monthly mean wave heights is positive before adjustments, 0.3 cm yr^{-1}, but adjusting for the two shift points changes the annual trend to slightly negative, -0.09 or -0.37 cm yr^{-1}, depending on whether the series is adjusted using the difference-estimated or the de-seasonalized estimated step changes (Table 5).

b) Halifax, NS (Osborne Head Waverider Joined with Halifax Approaches Buoy Data)

Table 2 shows relevant historical metadata on location and reporting frequency for the wave buoy in the approaches to the Halifax Harbour, including location changes of 1 km or more. The biggest relocation occurred in September 1976, when the buoy was redeployed about 8 km further from shore. The wave buoy used one system of variable reporting frequency from October 1982 to September 1986; the frequency varies from 3-hourly to 3 times per hour in high waves (over about 5 m). It used a different system of variable reporting frequency from October 1987 until September 1997; the wave frequency increased from hourly to 2 times per hour in high waves, and decreased to 3-hourly in low waves.

The PMT test detected 2 change points in both the difference series and the de-seasonalized series, in August 1976 and Sept 2000. Another change point was detected in 1998 in the difference series only, during a period with data gaps; it was not used to adjust the series. Results are shown in Figure 7 and Tables 4 and 5 for the two change points.

The August 1976 positive shift, of 0.25 m, or about 18% of the average of the monthly means, seems to coincide with a repositioning of the mooring to a location about 8 km further from shore. The earlier location, besides having a shorter fetch in offshore winds, may also have been partially sheltered by the Chebucto Peninsula from waves arriving from the southwest. No other metadata changes seem to explain this shift.

There is no definitive cause of the step change identified at September 2000, of about -0.10 m (-8% of the average), however there were a number of observing changes that may have contributed to a shift. There was a 2 km change in location in the summer of 2000. In November 2001, the data from the 3D buoy is used, and the position changed 4 km from the 2000 location. However, beginning in August 2002 the buoy was returned to the same location as the 1976 to 2000 interval. The change in buoy type from the Waverider to the larger 3D hull may contribute to somewhat lower monthly mean Hs, however there was no strong indication of this in the hourly comparison of data (Figure 3). Despite no definitive explanation for the step, it is statistically significant and it is detected in both the difference series and the de-seasonalized series, so it is kept.

The trend prior to adjustments is 0.16 cm yr^{-1}, corresponding roughly to +0.1% per year of the annual mean of 1.4 m. While still positive, the trends are reduced after adjustment for step changes, to 0.02 or 0.10 cm yr^{-1} (depending on whether the difference or de-seasonalized estimated step changes are used) (Table 5).

c) Torbay, northeast of St. John's, NL (Waverider Data)

Table 3 gives metadata for the seasonal Torbay Waverider, located northeast of St. John's NL. Position changes are small relative to the distance from shore and would not likely have caused any apparent climate shifts. As noted earlier, the reporting frequency increased in higher wave heights, beginning in 1982. The Waverider was deployed each summer and recovered in the winter to avoid pack ice. For this reason, the monthly mean time series is interrupted every year for several months. This poses a problem for statistical test for autocorrelation so our results are more limited than at Tofino and Halifax. We analyzed monthly means with at least 65% coverage. With that restriction the analysis period reduces to 25 years, from August 1972 to December 1996. Each of the months from July to December was well represented with 18 to 23 years with at least 65% coverage. The coverage for the months from February to June was less than 25% and for January it was no more than 56%. With so many gaps each year the PMT would not run with all available data, but it did run for each month separately, for the months from July to December. It also ran as an annual series using the average of the monthly means from July to December. We show results for this annual mean (July to December) value.

Monthly means over all years of the hindcast Hs, which correlates very well with the Waverider data, shows a smooth seasonal transition from a minimum in July to a maximum in December, so the month with the highest mean Hs is well represented by the Waverider data.

The PMT test of the annual mean of the September to December monthly mean Hs did not detect any change points. The series is found to be homogeneous, so no adjustments are needed. The time series shows a positive trend of +0.37 cm yr^{-1}.

5. Discussion

The numbers of frequency bands, band resolution, sampling rate, and sampling period at the Waverider have increased over the years (as determined from the wave spectral files archived by ISDM), and these are different from those used by the accelerometer and wave processor on the weather buoys (described by Axys 1996 and 2000). The potential for wave processing changes to cause a mean shift in the time series is not known. This analysis suggests that changes in wave processing during 1970 to 1999 at 3 Canadian Waveriders did not introduce inhomogeneities in the Waverider time series of Hs.

The effect of different low frequency cutoffs (used in calculation of Hs) on wave climate statistics for weather buoys needs to be quantified and accounted for.

The small (1 m diameter) spherical Waveriders may have different wave following characteristics than the larger hulls of the 3 m Discus or 6 m NOMAD (boat-shaped) weather buoys. There could also be differences related to use of a vertically-suspended accelerometer in the Waverider and a strapped-down accelerometer in the 3D weather buoys. However the magnitude or even sign of effects from these differences has not been determined and is still the subject of research. A limited comparison of Waverider and 3 m Discus buoy significant wave height near Halifax suggests that there is good agreement, at least up to 5m.

In some cases there was no clear metadata to explain the statistically significant step changes. Accepting or deleting (using or not using) these step changes in the adjustment of the time series can make slight differences in the resulting trends. There were also slight differences in the trends depending on whether difference-estimated or de-seasonalized estimated step changes were used. These variations contribute to some uncertainty in the resulting trends of the adjusted series.

Over all months and years at the longer term locations of Halifax and Tofino, the absolute values of the trends are small, less than 0.4 cm yr^{-1}. However it would be worth exploring the data by month or by season, as the patterns may be different. The largest positive trend was at Torbay, however this was over a relatively short period, 1972 to 1996, for half of the months of the year, so it would be affected more affected by interannual variability than at the two longer term sites.

The consistency in results for the hindcast and the wave measurements provides some indirect confirmation that the GROW2000 hindcasts are homogeneous at these locations.

6. Summary

There are nearly 40 years of wave measurements from two coastal locations in Canada, near Tofino BC and Halifax NS, beginning in 1970 and extending to the present. These long term records result from joining nearly 30 years of Datawell Waverider measurements at those locations to about 10 years of weather buoy wave measurements. There are about 27 years of Waverider data at Torbay, northeast of St. John’s, NL. The Waverider stations were discontinued around 1999 but weather buoys had already been deployed nearby (for Halifax) and 25 km offshore at La Perouse Bank (for Tofino) which continue to the present. The Torbay Waverider was not replaced when it was discontinued, and it was a seasonal buoy. However the months of July to December (the month with the highest monthly means) are well represented, from 1972 to 1996.

Our results show that variable reporting frequency, dependent on wave height, can cause a high bias in monthly means, and thus potentially cause artificial shifts in the long time series (when not correctly weighted). The largest bias in monthly means occurs when the normal reporting interval of 3 hours (synoptic reports) increases to 3 times per hour in waves over 5 m. The monthly mean series could be adjusted for this error, but it is not necessary if the original reports are weighted properly to compensate for this.

The largest step change in the monthly mean Hs record, in the approaches to Halifax Harbour, appears to be due to a station relocation of about 8 km (to further offshore), in 1976. The largest step change in the monthly mean Hs record, near Tofino, was due to the joining of the Tofino Waverider near shore data to the 25 km further offshore 3D La Perouse Bank data, in 1999.

An increase in number, range, and resolution of wave spectral bands and wave sampling frequency around 1987 did not appear to cause any significant step changes in the Waverider record. It is not clear if the change from a Datawell Waverider to a 3m Discus near Halifax in October 2001 contributed to a significant step change. Comparison results of overlapping data show fairly good agreement between the Waverider and 3D buoy Hs. There was a shift detected near September 2000 but other factors (that may have contributed to an apparent shift) also changed in the years from 2000 to 2002.

Both of the original long-term wave records, from joined Waverider and weather buoy data, near Tofino and Halifax, show small positive trends of 0.2 to 0.3 cm yr^{-1}. Near Tofino, the adjustments for artificial shifts (including joining records from two stations) result in a small negative trend, of -0.1 to -0.3 cm yr^{-1}. Near Halifax the adjustments for artificial shifts (including a station relocation) reduce the trend to a smaller but still positive value, of 0.02 to 0.1 cm yr^{-1}. The Waverider record near Torbay northeast of St. John's NL appears to be homogeneous; it shows a slight positive trend of 0.4 cm yr^{-1}over the years 1972 – 1996.

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Table 1 Historical metadata to June 2009 for Tofino (MEDS103, MEDS303) / La Perouse Bank (46206) buoy: ID, date of change, location, distance from previous location, water depth, buoy type [Waverider (WR), directional Waverider (DWR), 3 m Discus buoy (3D)], reporting intervals, wave period corresponding to lowest frequency band used in calculation of Hs by ISDM [or onboard 46206]. Reference data series GROW2000 GP 41855, 48.75° N 126.25° W.

Station ID	***Date***	***Lat (°N)***	***Long (°W)***	***Chg (km)***	***Water Depth (m)***	***Type***	***Reporting Interval [Alternate (s)] (min)***	***Long wave period limit***
MEDS103	1970/06	48.991	125.744		40	WR	180	19.5
“	1976/08	48.99	125.740	0	“	“	180 [20]	27.3
“	1983/05	49.04	125.740	6	“	“	“	“
“	1987/01	49.037	125.800	4	“	“	60 [30, 180] or 30	28.6
MEDS303	1998/09	49.037	125.800	0	“	DWR	30	25.0
“	1998/12	49.03	125.8	1.0	“	“	30	“
46206	1999/05	48.83	126.00	28	73	3D	60	16 [36.6]
“	2002/05	“	“	4.6	“	“	“	16 [17.1]
“	2004/01	“	“		“	“	“	28.4 [17.1]
“	2004/04	“	“		“	“	“	28.4 [18.3]
“	2005/05	“	“		72	“	“	- [18.3]
“	2006/05	48.835	125.998			“	“	28.4 [17.1]

Table 2 As in Table 1, for the Halifax buoy. Buoy type includes the 6 m NOMAD buoy (6N). Reference data series GROW2000 GP 40849, 43.75° N 60.00°W.

Station ID	*Date*	*Lat (°N)*	*Long (°W)*	*Chg (km)*	*Water Depth (m)*	*Type*	*Reporting Interval [Alternate(s)] (min)*
MEDS037	1970/12	44.544	63.464		50	WR	180
"	1976/09	44.490	63.404	7.7	57	"	"
"	1982/10	44.490	63.403	0	"	"	180 [20]
"	1987/10	44.490	63.403	0	"	"	60 [30, 180] or 30
"	1997/10	44.490	63.403	0	"	"	30
"	1998/12	44.489	63.416	1.0	"	"	"
"	1999/10	44.490	63.403	1.0	"	"	"
"	2000/07	44.507	63.405	2.0	"	"	"
44258	2001/10	44.543	63.374	4.0	50	3D	60
"	2002/08	44.502	63.403	5.0	58	6N	"
"	2005/06	44.502	63.403	0	"	3D	"

Table 3 As in Table 1, for the Torbay buoy, northeast of St. John's NL, 1972 - 1998. Reference data series GROW2000 GP 41505, 46.875° N 52.50° W.

Station ID	*Date*	*Lat (°N)*	*Long (°W)*	*Chg (km)*	*Water Depth (m)*	*Type*	*Reporting Interval [Alternate(s)] (min)*
MEDS016	1972/06	47.64	52.47		168	WR	180
"	1976/06	47.60	52.44	5.0	167	"	"
"	1978/06	47.62	52.42	2.7	165	"	"
"	1979/06	47.60	52.44	2.7	166	"	"
"	1981/01	47.63	52.50	5.6	162	"	"
"	1982/06	47.63	52.50	0	162	"	180 [20]
"	1987/10	47.63	52.50	0	165	"	60 [30, 180] or 30

Table 4 Type 1 step change statistics for monthly means of Hs near Tofino and Halifax [The wave data near St. John's NL was found to be homogeneous]: date (year/month), step-sizes estimated from the difference series and from the de-seasonalized series, and their significance. Step-size percentages are relative to the mean of all monthly means used: 2.05 m (Tofino), and 1.39 m (Halifax).

Year/Mo	*Step-size, difference series (m)*	*Step-size, de-seasonalized series (m)*	*PFmax*	*CV95 (upper and lower)*	*Nseg*
Tofino+La Perouse Bank					
1979/08	-0.098 (-4.8 %)	-0.022 (-1.1 %)	3.90	3.55 (3.21-3.92)	287
1999/05	0.194 (9.5 %)	0.221 (11 %)	9.27	3.55 (3.22-3.92)	319
Halifax					
1976/08	0.245 (18 %)	0.250 (18 %)	7.00	3.25 (2.93-3.60)	290
2000/09	-0.092 (-6.6 %)	-0.123 (-8.9 %)	3.52	3.26 (2.94-3.61)	327

Table 5 Trend Statistics near Tofino and Halifax (all monthly mean Hs, 1972 - 2009), and Torbay (means of Jul to Dec monthly mean Hs, 1972 - 1996): 1) original series, 2) series adjusted using difference-estimated steps, and 3) series adjusted using de-seasonalized-estimated steps. Means of all monthly means used: 2.05 m (Tofino), 1.39 m (Halifax), and 2.17 m (Torbay).

Step Adjustments to Original Date Series	***Trend (m mo^{-1})***	***Trend (cm yr^{-1})***	***p***	***Cor***
Near Tofino BC, 1972 - 2009				
None	0.000265	0.32	0.96	0.128
difference-estimated steps	-8.2e-05	-0.09	0.72	0.095
de-seasonalized-estimated steps	-0.000305	-0.37	0.99	0.094
Near Halifax NS, 1972 - 2009				
None	0.000131	0.16	0.88	0.205
difference-estimated steps	1.5e-05	0.02	0.57	0.077
de-seasonalized-estimated steps	8.4e-05	0.10	0.83	0.076
Near Torbay NL, 1972 – 1996 (mean of monthly means Jul – Dec)				
Adjustment to Original Date Series	***Trend (m yr^{-1})***	***Trend (cm yr^{-1})***	***p***	***Cor***
None	0.003663	0.37	0.79	-0.056

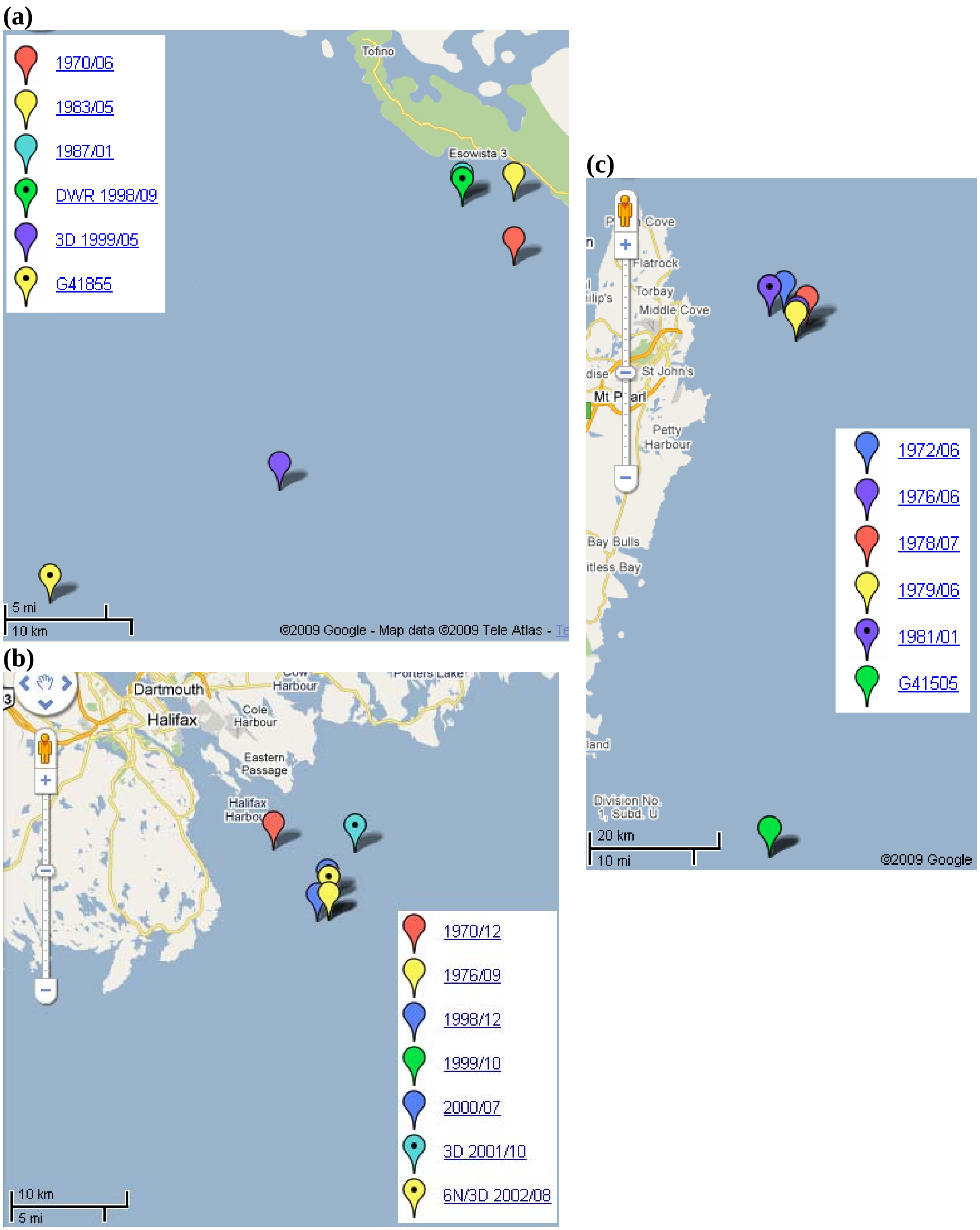

Figure 1 Historical locations of (a) Tofino Waverider (MEDS103 and MEDS303) and La Perouse Bank 3D Buoy (46206) (to 2009), with nearest GROW2000 grid point 41855, (b) Osborne Head Waverider (MEDS037) and Halifax Approaches Buoy (44258) (to 2009), and (c) Torbay Waverider (MEDS016) (to 1999), with nearest GROW2000 grid point 41505.

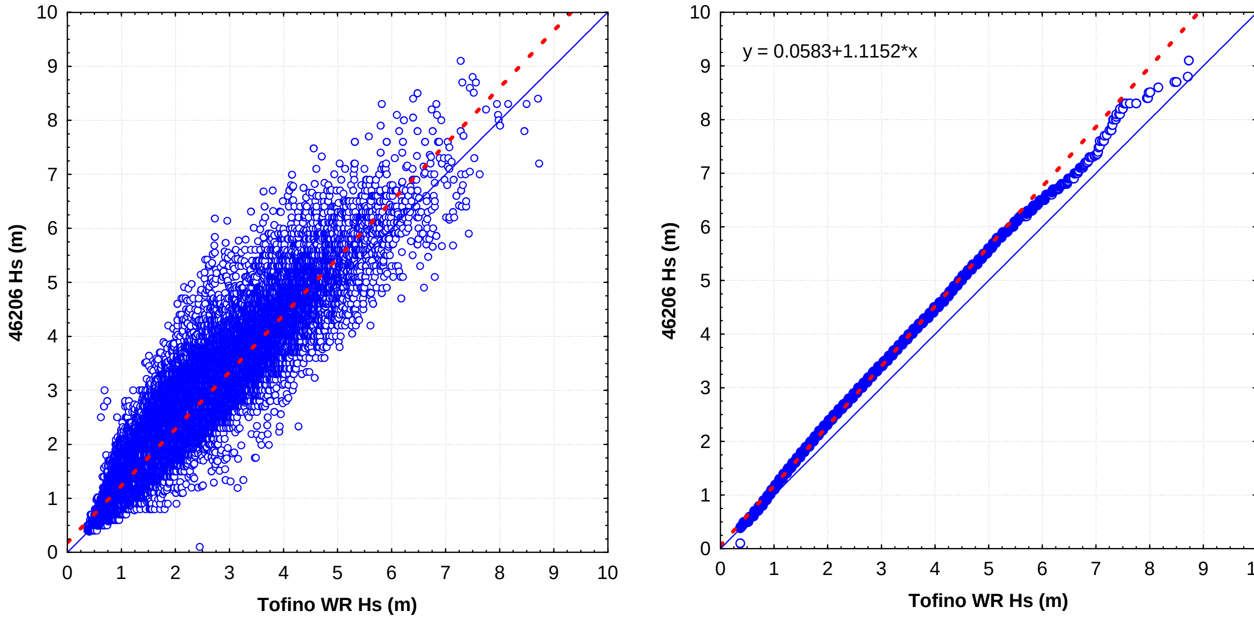

Figure 2 Tofino Waverider and 3D La Perouse Bank comparison of measured wave height: (a) frequency scatterplot and (b) quantile-quantile scatterplot of hourly significant wave height (Hs) from 3D La Perouse Bank buoy (46206) plotted against hourly mean Hs from the Tofino Datawell Waverider (MEDS103 and MEDS303), for overlapping period Nov 1988 to May 1999.

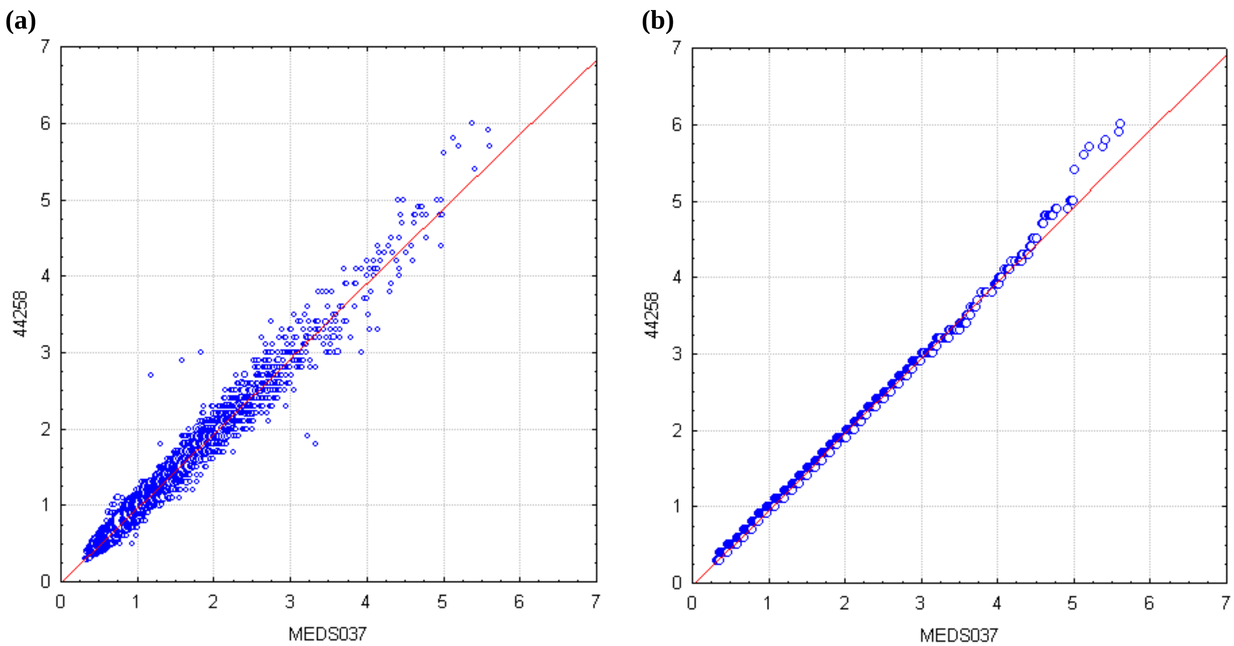

Figure 3 Halifax (Waverider and 3D) comparison of measured wave height: (a) frequency scatterplot and (b) quantile-quantile scatterplot of hourly significant wave height (Hs) from 3D Halifax Approaches buoy (44258) plotted against hourly mean Hs from the Osborne Head Datawell Waverider MEDS037, for overlapping period Mar 2000 to Sept 2001.

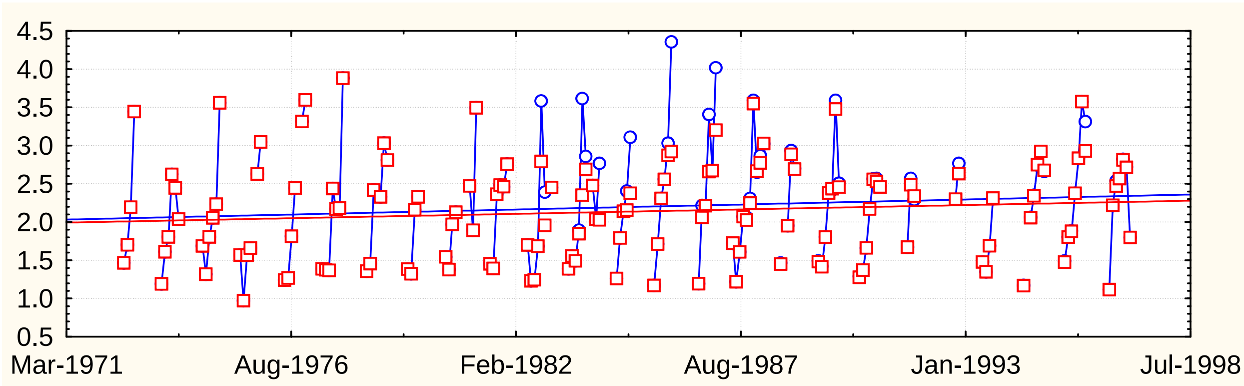

Figure 4 Monthly mean Hs at the Torbay Waverider (MEDS016), calculated with and without weights to account for changes in reporting frequency as a function of wave height, 1982 – 1998.

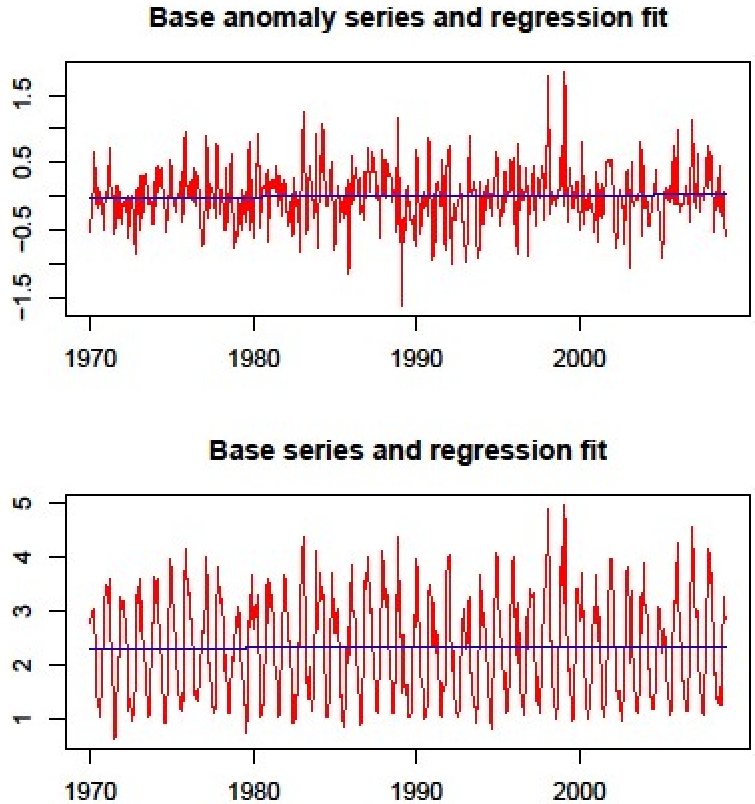

Figure 5 Time series of monthly anomalies (de-seasonalized series) and monthly mean GROW2000 hindcast Hs at GP 41855, near Tofino BC.

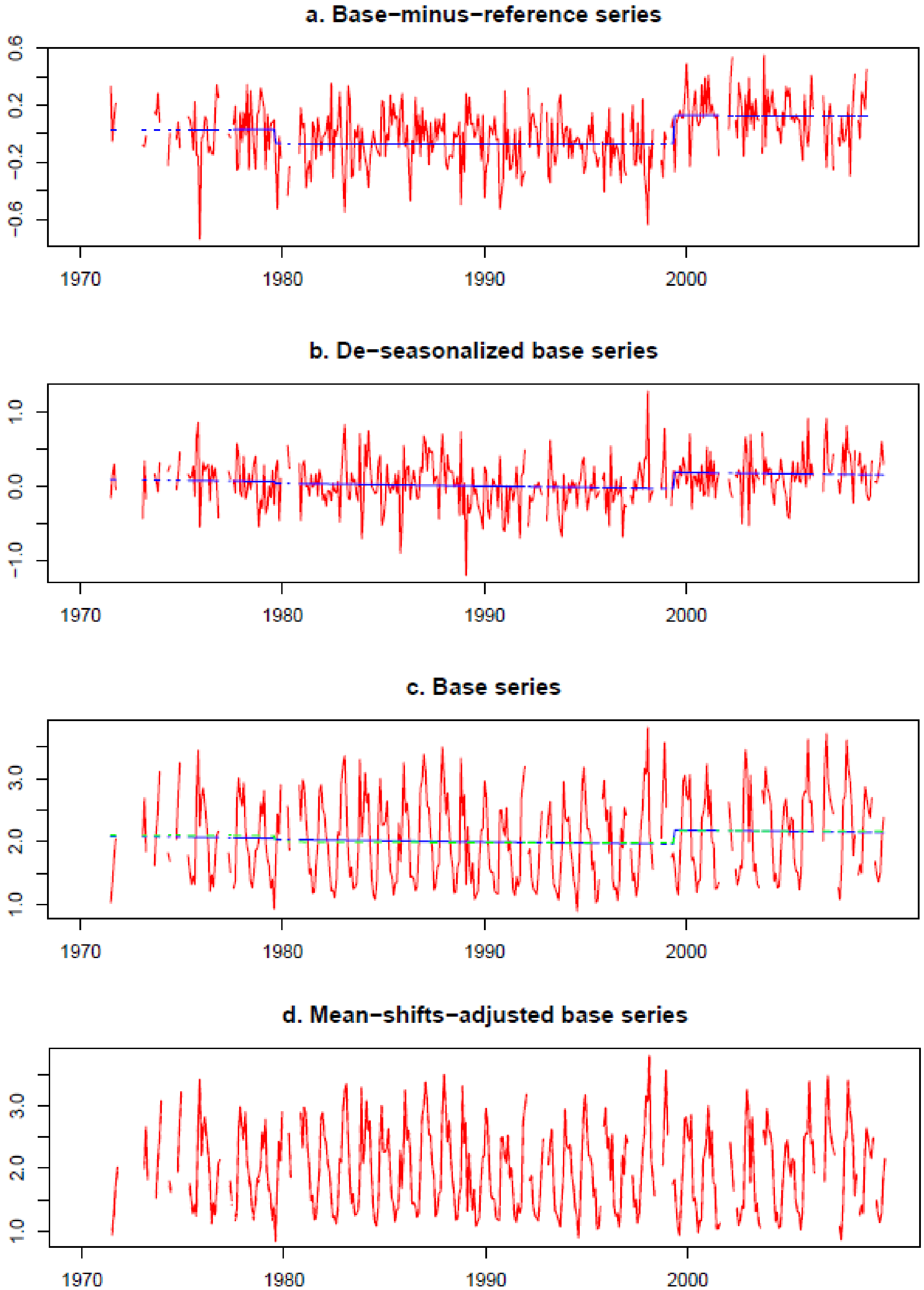

Figure 6 Time series of monthly mean Hs (m) at Tofino (1972 – May 1999) + La Perouse Bank (May 1999 – October 2009) (the base series) referenced to the GROW2000 grid point 41855 (January 1970 – December 2008): a) the base minus reference series, showing Type 1 difference-estimated shifts (change points) at August 1979 and May 1999 (corrected from June 1999), b) the de-seasonalized base series, showing the de-seasonalized-estimated shifts, c) the base series, and d) the base series adjusted using difference estimated shifts.

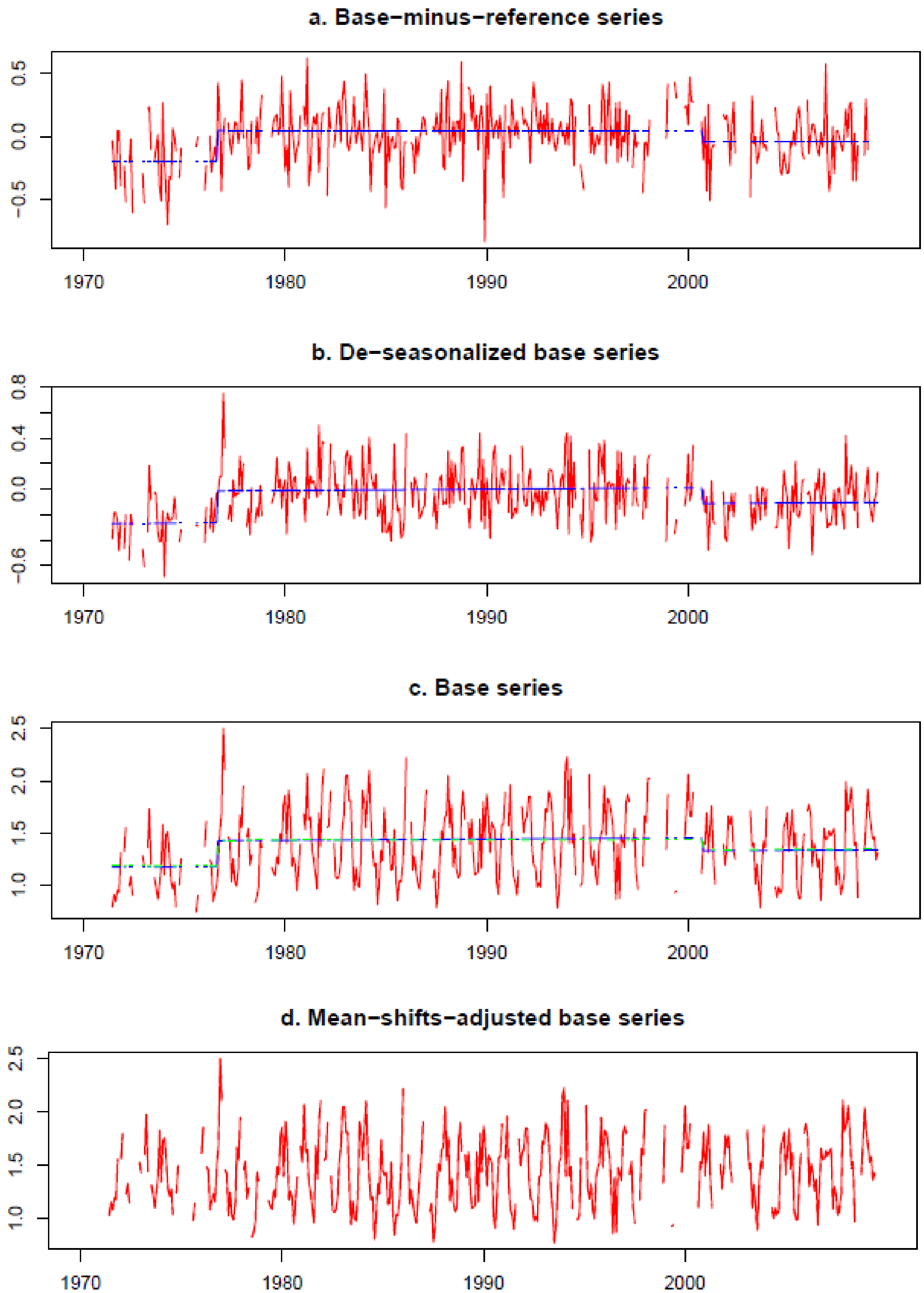

Figure 7 Same as in Figure 6, for Osborne Head Waverider (1972 – September 2001) joined with the Halifax Approaches Buoy (October 2001 to October 2009) (the base series), referenced to GROW2000 grid point 40849 (1970 – 2008), and showing the two Type 1 change points, in August 1976 and September 2000, used to adjust the series.

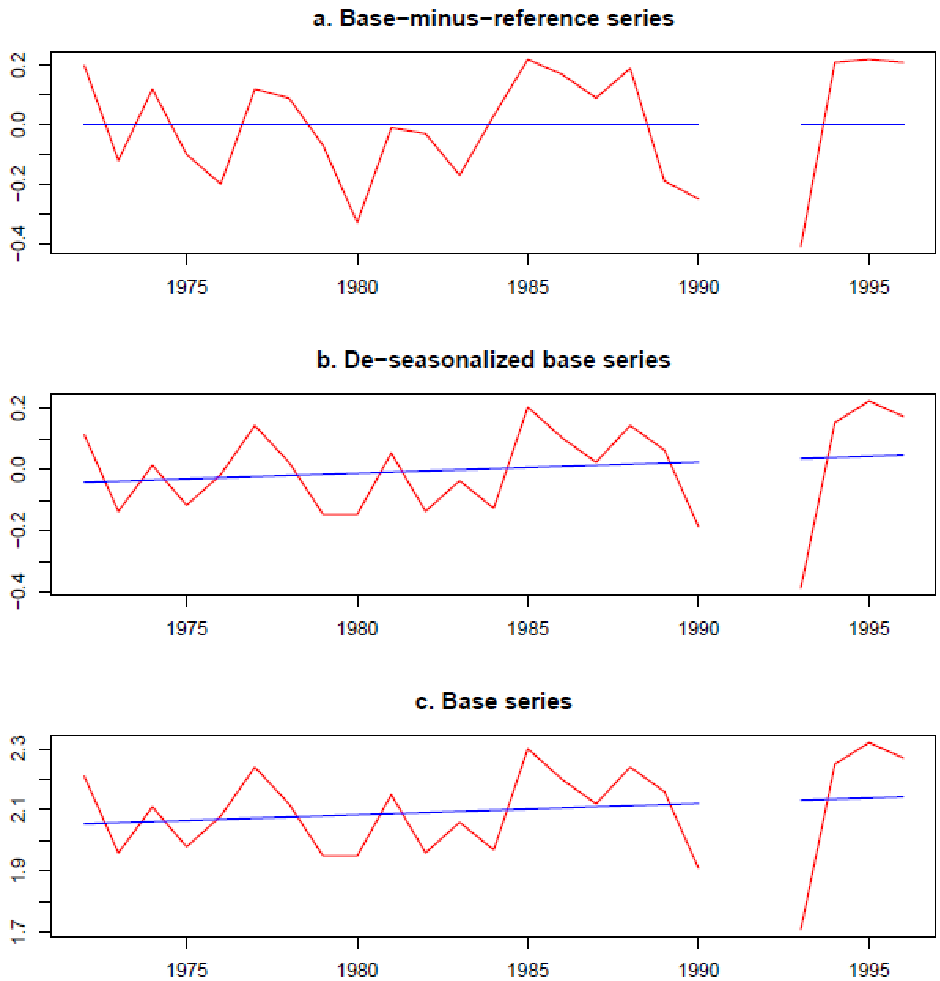

Figure 8 Annual mean of July to December monthly mean Hs at Torbay Waverider (1972 – 1998) (the base series), with GROW2000 grid point 41505 as the reference series: a) the base minus reference series, b) the de-seasonalized base series, and c) the base series. No Type 1 change points were detected.