Wave Observing Changes and Trends in NE Pacific Monthly Mean Hs

By Bridget R. Thomas[1], Richard Bouchard[2], Johannes R. Gemmrich[3]
[1]Environment Canada, Dartmouth, NS, [2]US National Data Buoy Center, Stennis Space Center, MS, [3]University of Victoria, Victoria, BC

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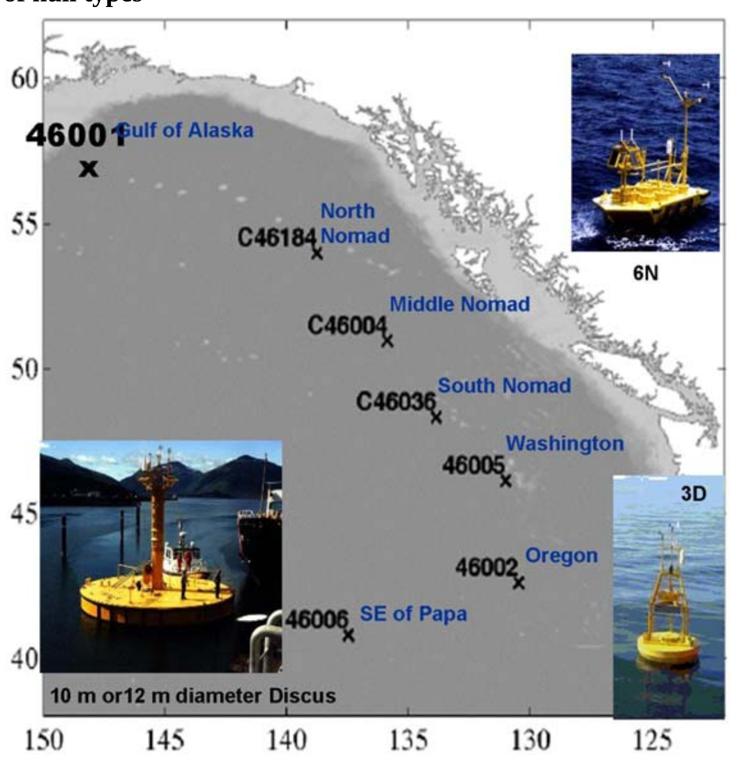
INTRODUCTION

- There is considerable interest in wave climate and trends [e.g.3, 4, 9]
- Homogenous wave time series are important for analysis of wave climate trend and variability, and for coastal planning
- Changes in wave observing programs at US National Data Buoy Center (NDBC) and Environment Canada (EC)'s Meteorological Services Canada (MSC) have resulted in artificial step changes (shifts in the mean) in the long-term record of significant wave height, Hs
- Gemmrich et al. (2011) [1]:
    - assess the changes in the observed time series due to observing changes at 7 offshore moored buoy stations in the NE North Pacific
    - use the results to adjust the hourly data using the step size relative to the mean - a percentage-based adjustment factor
    - calculate trends in daily means and in estimates of extremes.
- This poster:
    - provides more detail on the assessment of the observing changes presented in Gemmrich et al. (2011)
    - shows the impact of adjustments on trends in monthly mean Hs

Figure 1 Locations, WMO ID, and station names of buoys operated by EC (indicated by C) and NDBC; Examples of hull types



DATA and METADATA

- source for NDBC buoy data: NDBC and NODC (National Oceanographic Data Center) archives
- source for MSC buoy data: ISDM (Fisheries and Oceans Canada's Integrated Science Data Management Division) archives, with additional QC
- Information about the observations: NODC archived data, NDBC web pages, internal NDBC technical reports and records, and for the MSC buoys, status reports and email from buoy technicians.
- payload (onboard processor) type for each NDBC buoy was readily available, but the wave processor type (in the first decade or so) was not
- in some cases wave processor type was deduced from information such as spectral band details

METHOD

- calculated monthly mean Hs; used months with ≥ 60% data coverage
- used statistical software **RHTestsV3** [5-8] to detect shifts, make adjustments, and calculate trends
- used reference series of Hs from GROW2000 Wind and Wave Reanalysis, 1970-2009 (Oceanweather 2007) [2] (Use of good reference series increases sensitivity, less chance shifts are related to interannual climate variations)
- detected Type 1 (most significant) shifts in mean in the difference (buoy – ref.) and in de-seasonalized (monthly anomalies) series
- matched steps with metadata when possible, to refine date of shift
- adjusted means using step changes before recalculation of trend

Table 1. Hull and Wave Sensor Types

	Hull Sizes/Types
10D	10-m Discus (10-m diameter hull)
12D	12-m Discus (12-m diameter hull)
6N or NOMAD	Navy Oceanographic Meteorological Automatic Device (6-m boat-shaped hull)
3D	3-m Discus (3-m diameter hull)
	Wave Sensor Types (Acc = accelerometer)
SD	Strapped-down acc. (Columbia or Schaevitz)
DW	vertically-stabilized (gimballed) acc. (Datawell)

Table 2 Payload Types (* = discontinued) [wave processors used with this payload]

	NDBC
EEP*	Engineering Experimental Phase (1st wave measuring weather buoy, deployed at 3 stations, 1 in NE Pacific) [EEP]
PEB*	Prototype Environmental Buoy [WSA]
PEB UDACS*	PEB (General Dynamics) UHF Data Acquisition and Control System [WSA]
UDACS (A)*	UDACS (modification A) [WDA]
MXVII (MOD)*	Magnavox Phase II (modified) [WDA]
GSBP*	(Magnavox) Generalized Service Buoy Payload [WDA]
DACT	Data Acquisition and Control Telemetry [WA]
VEEP	Value Engineered Environmental Payload [WA, WPM]
ARES 4.4	Acquisition and Reporting Environmental System [WA, WPM]
AMPS	Advanced Modular Payload System [WA, WPM]
	EC
Zeno*	(AXYS Environmental Ltd) Zeno [Zeno]
WM	(AXYS Environmental Ltd) Watchman [WM]

Table 3 Wave Processor Types (* = discontinued)

	NDBC
EEP*	Internal to EEP payload (used Blackman-Tukey)
WSA*	Wave Spectrum Analyzer (internal to PEB - analog input only, 12-channel (band) starting at 0.05 Hz)
WDA*	Wave Data Analyzer (used Blackman-Tukey)
WA	Wave Analyzer (uses Fast Fourier Transform (FFT))
WPM	Wave Processing Module (uses FFT; doubling of frequency bands for freq < 0.1 Hz, compared to WDA or WA)
	EC
Zeno*	Internal to Zeno payload, used FFT
WM	Watchman, uses FFT, same freq. bands as Zeno (module within WM payload)

RESULTS: OBSERVING CHANGES & SHIFTS IN MONTHLY MEAN SIG. WAVE HT

Figure 2. 46001 Gulf of Alaska Buoy (NDBC).

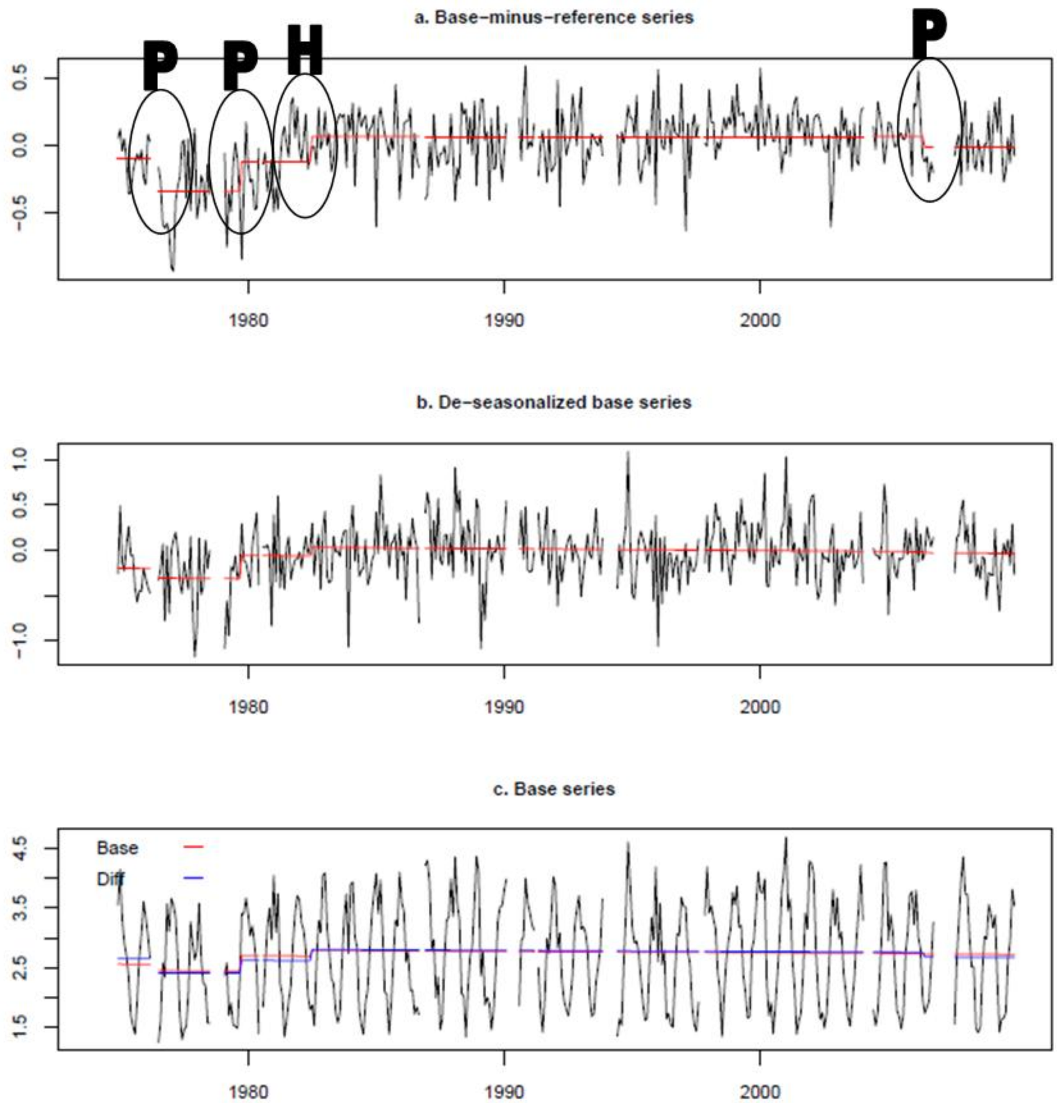


Table 4. 46001 Gulf of Alaska Buoy. Observing changes matched with shifts in monthly mean significant wave height. S = segment, R = possible/probable reason (observing chg) for step (<u>at start</u> of segment): P = wave processor; H = hull type/size; F = faulty sensor; nF = no longer faulty; U = unexplained; A = acc.

S	*Data Start*	*Data End*	*Hull*	*Payload*	*Wave Proc*	*Acc*	*ΔHs (m)*	*R*
1	1974/12	1976/04	12D	EEP	EEP	SD		
2	1976/07	1979/09	10D	PEB	**WSA**	"	**-0.24**	**P**
3	1979/10	1980/06	"	UDACS (A)	**WDA**	"	**0.22**	**P**
"	1980/07	1982/06	"	GSBP	"	"		
4	1982/06	1990/03	**6N**	"	"	"	**0.19**	**H**
"	1990/07	2006/05	"	DACT	WA	"		
5	2006/05	2010/12	"	ARES 4.4	**WPM**	"	**-0.08**	**P**

Figure 3. As in Figure 2 for 46184 North Nomad Buoy (EC).

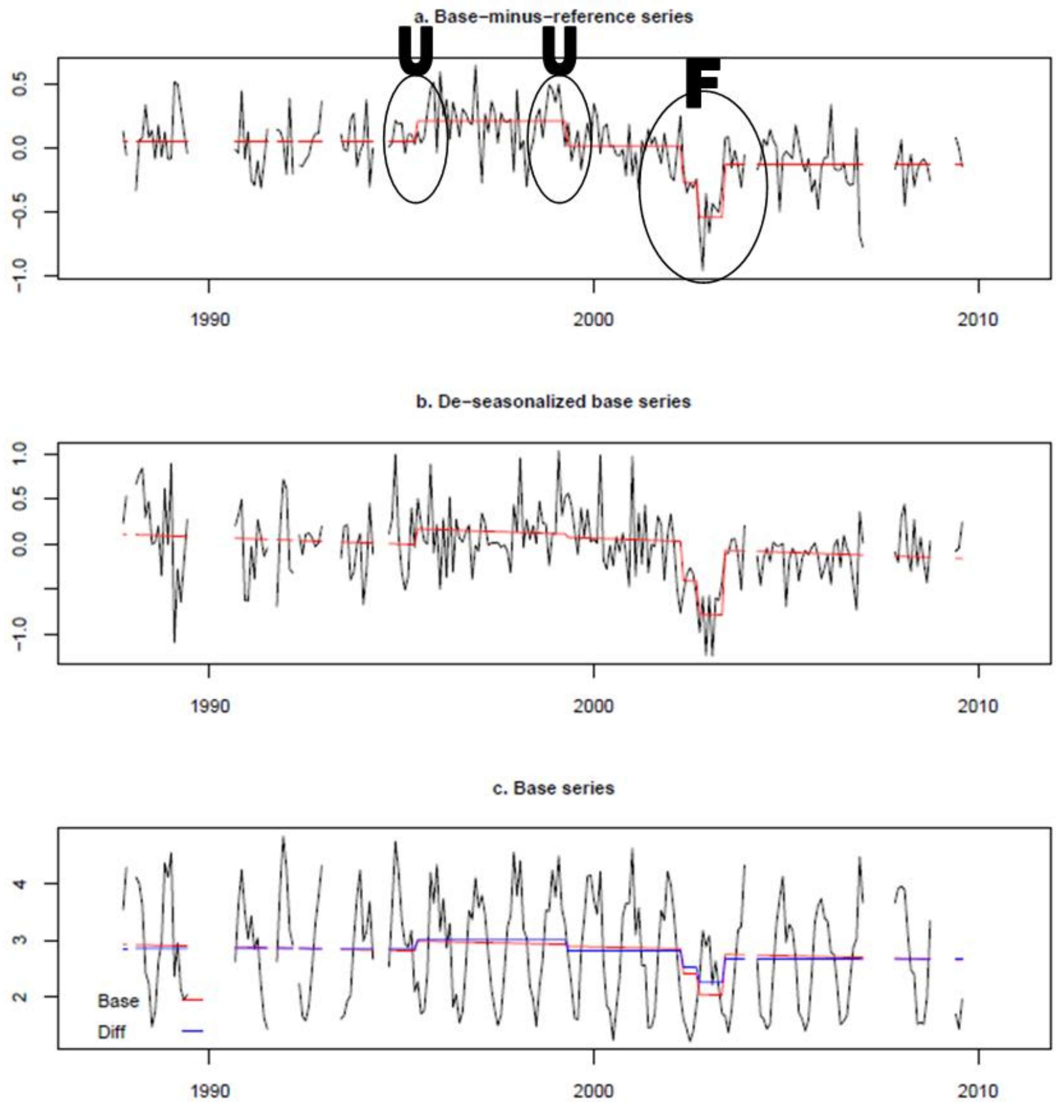


Table 5. As in Table 4 for 46184 North Nomad Buoy.

S	*Data Start*	*Data End*	*Hull*	*Pay*	*Wave Proc*	*Acc*	*ΔHs (m)*	*R*
1	1987/09	1995/06	6N	Zeno	Zeno	DW		
2	1995/06	1999/05	"	"	"	"	0.16	U
3	1999/05	2000/04	"	"	"	"	-0.20	U
"	2000/04	2002/05	"	WM	WM	SD		
4	2002/05	2002/09	"			?	-0.29	F
5	2002/10	2003/05	"	"	"	?	-0.27	F
6	2003/05	2009/12	"	"	"	SD	0.41	nF

Figure 4. As in Figure 2 for 46004 Middle Nomad (EC except operated by NDBC 1976 – 1988).

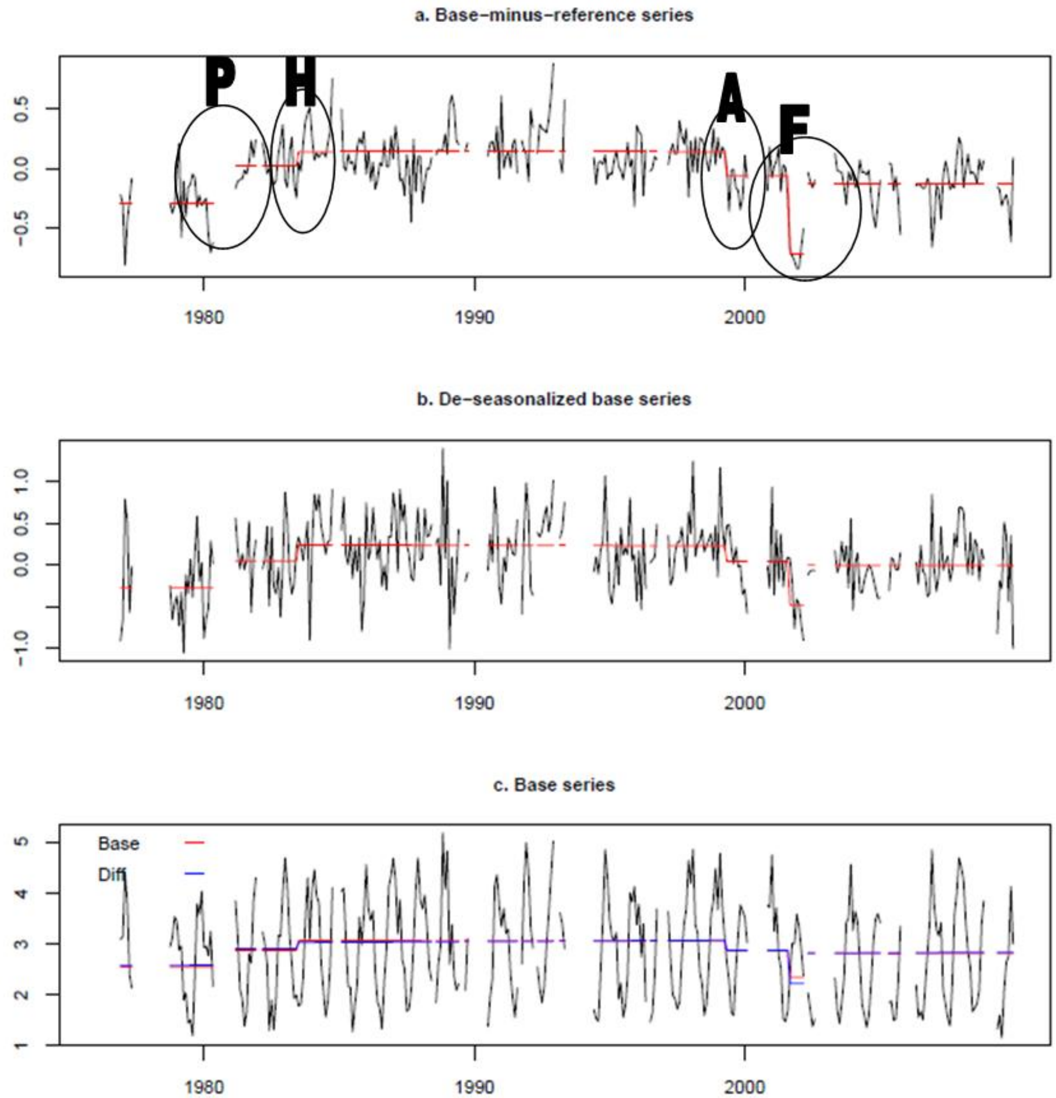


Table 6. As in Table 4 for 46004 Middle Nomad Buoy.

S	*Data Start*	*Data End*	*Hull*	*Payload*	*Wave Proc*	*Acc*	*ΔHs (m)*	*R*
1	1976/10	1977/05	10D	PEB	WSA	SD		
"	1978/09	1980/05	12D	PEB UDACS	"	"		
2	1981/02	1983/06	"	UDACS (A)	**WDA**	"	**0.32**	**P**
3	1983/06	1988/06	**6N**	GSBP	"	"	**0.12**	**H**
"	1988/06	1999/05	"	Zeno	Zeno	DW		
4	1999/05	2000/02	"	WM	WM	**SD**	**-0.20**	**A**
"	2000/04	2000/05	"	"	"	DW		
"	2000/10	2001/05	"	"	"	SD		
5	2001/05	2002/04				**?**	**-0.66**	**F**
6	2002/05	2010/12	"	"	"	**SD**	**0.59**	**nF**

Figure 5. As in Figure 2 for 46036 South Nomad Buoy (EC except operated by NDBC 1986 – 1987).

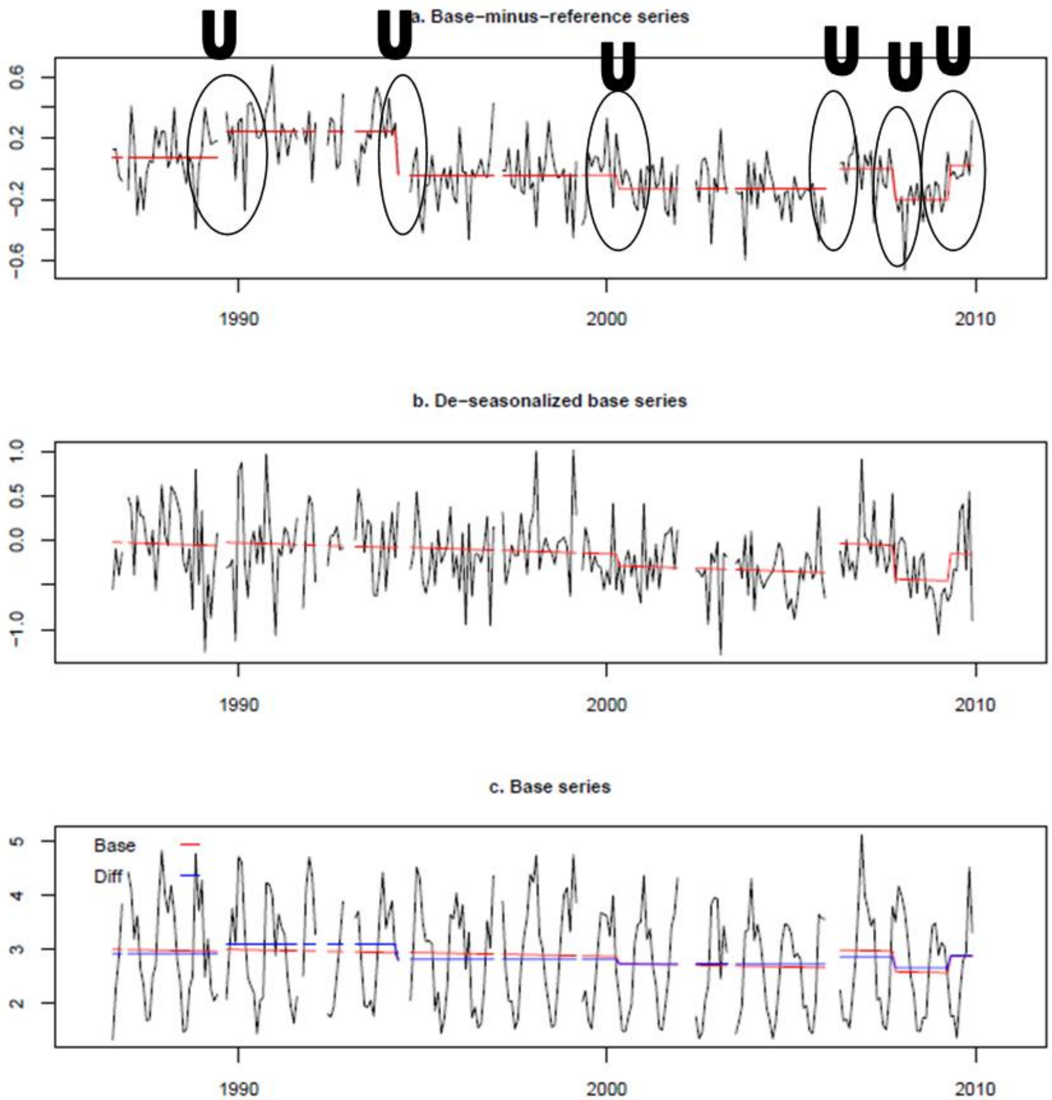


Table 7. As in Table 4 for 46036 South Nomad Buoy.

S	*Data Start*	*Data End*	*Hull*	*Pay*	*Wave Proc*	*Acc*	*ΔHs (m)*	*R*
1	1986/08	1987/09	6N	GSBP	WDA	SD		
"	1987/09	1989/07	"	Zeno	Zeno	DW		
2	1989/07	1994/06	"	"	"	"	0.17	U
3	1994/09	1998/07	"	"	"	"	-0.28	U
"	1998/07	2000/04	"	WM	WM	DW		
4	2000/04	2001/05	"	"	"	"	-0.09	U
"	2001/05	2006/01	"	"	"	SD		
5	2006/05	2007/11	"	"	"	"	0.13	U
6	2007/11	2009/05	"	"	"	"	-0.20	U
7	2009/05	2010/12	"	"	"	"	0.22	U

Figure 6. As in Figure 2 for 46005 Washington Buoy (NDBC).

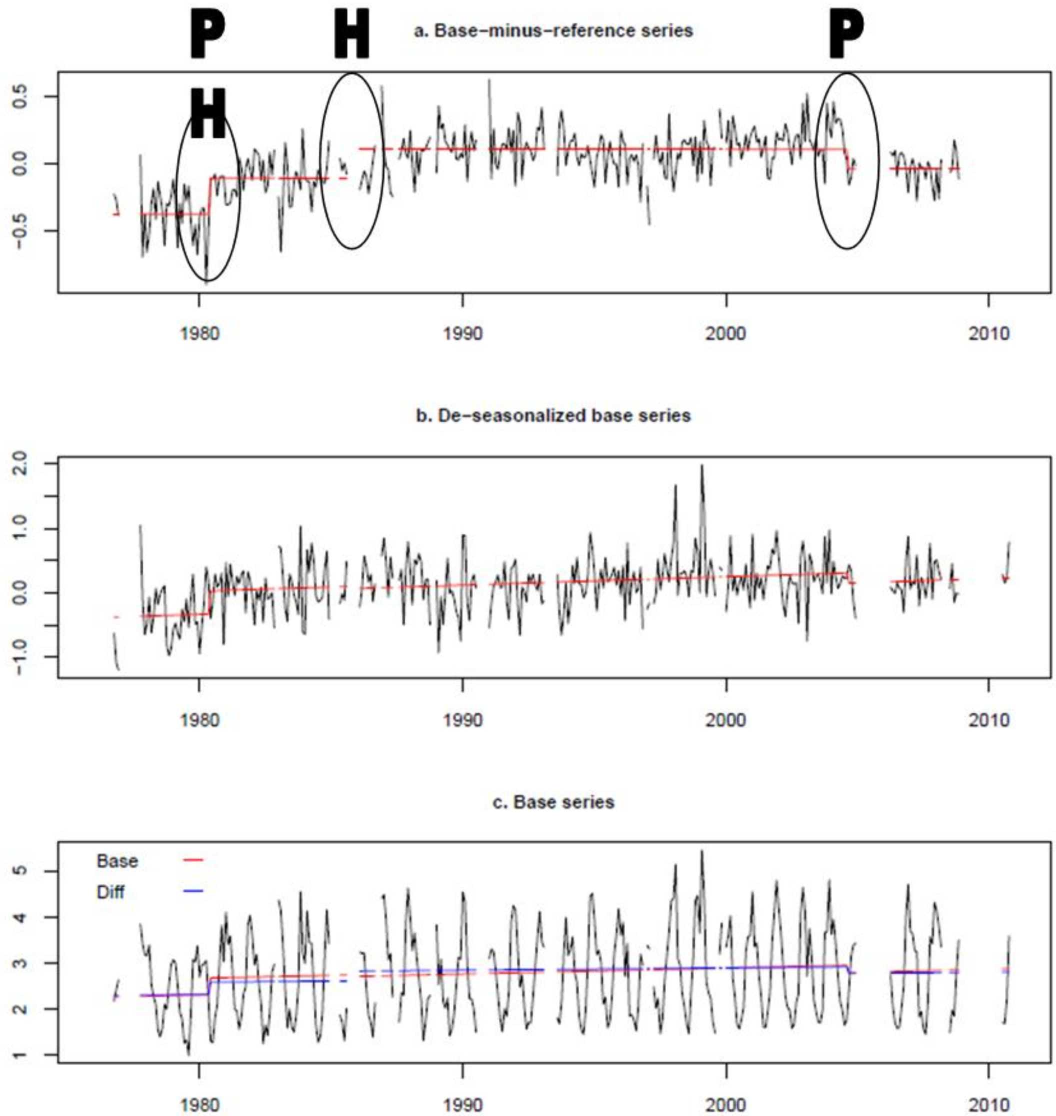


Table 8. As in Table 4 for 46005 Washington Buoy.

S	*Data Start*	*Data End*	*Hull*	*Payload*	*Wave Proc*	*Acc*	*∆Hs (m)*	*R*
1	1976/10	1978/08	10D	PEB	WSA	SD		
"	1978/08	1980/06	12D	"	"	"		
2	1980/06	1981/11	**6N**	MXVII (MOD)	**WDA**	"	**0.27**	**PH**
"	1981/11	1985/10	12D	UDACS (A)	"	"		
3	1986/02	1990/08	**6N**	GSBP	"	"	**0.21**	**H**
"	1991/01	2004/09	"	DACT	WA	"		
4	2004/09	2008/12	"	ARES	**WPM**	"	**-0.14**	**P**
"	2010/06	2010/11	3D	AMPS	"	"		

Figure 7. As in Figure 2 for 46002 Oregon Buoy (NDBC).

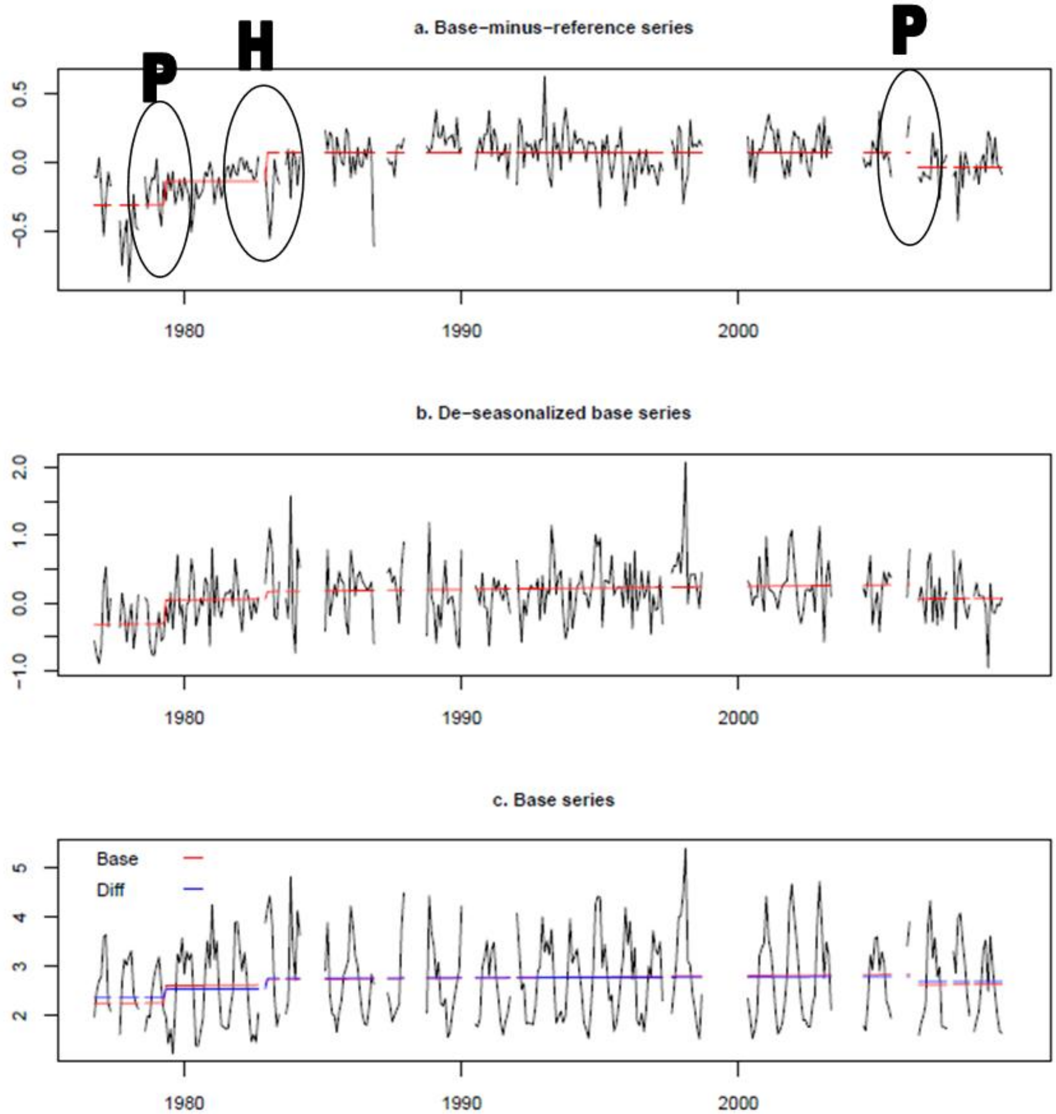


Table 9. As in Table 4 for 46002 Oregon Buoy.

S	*Data Start*	*Data End*	*Hull*	*Payload*	*Wave Proc*	*Acc*	*ΔHs (m)*	*R*
1	1976/10	1979/04	10D	PEB	WSA	SD		
2	1979/05	1980/09	“	UDACS (A)	**WDA**	“	**0.17**	**P**
“	1980/09	1982/12	“	GSBP	“	“		
3	1983/01	1990/02	**6N**	“	WA	“	**0.21**	**H**
“	1990/06	2006/04	“	DACT	“	“		
4	2006/06	2009/07	“	ARES 4.4	**WPM**	“	**-0.11**	**P**

Figure 8. As in Figure 2 for 46006 SE of Papa Buoy (NDBC).

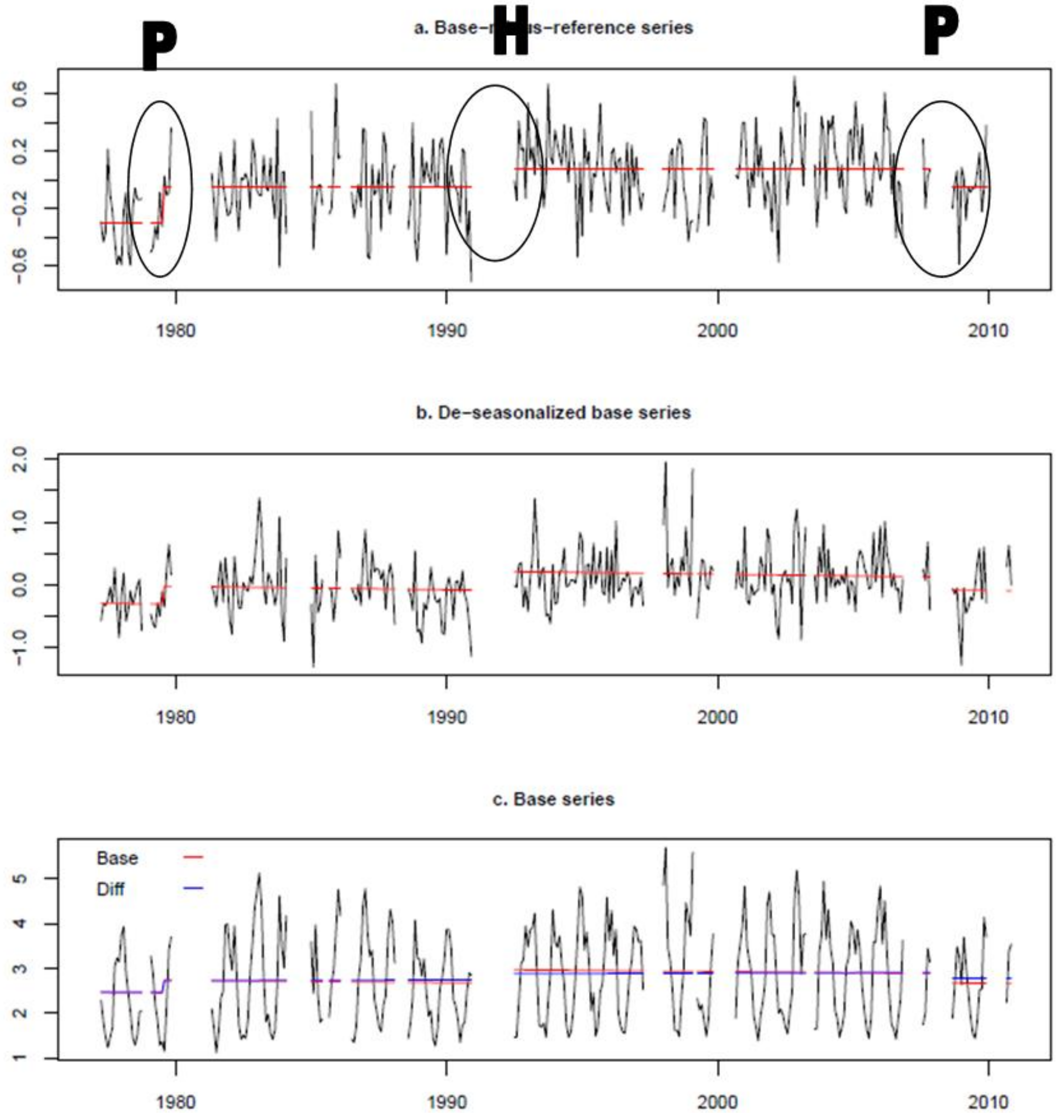


Table 10. As in Table 4 for 46006 SE of Papa Buoy.

S	*Data Start*	*Data End*	*Hull*	*Payload*	*Wave Proc*	*Acc*	*ΔHs (m)*	*R*
1	1977/04	1979/08	10D	PEB	WSA	SD		
2	1979/08	1985/06	12D	UDACS (A)	**WDA**	"	**0.25**	**P**
"	1985/08	1986/02	6N	GSBP	"	"		
"	1986/06	1988/03	12D	"	"	"		
"	1988/08	1991/01	"	DACT	WA	"		
3	1992/06	1999/12	**6N**	"	"	"	**0.13**	**H**
"	2000/08	2006/12	"	VEEP	"	"		
"	2007/08	2007/12	"	DACT	"	"		
4	2008/08	2010/01	3D	ARES 4.4	**WPM**	"	**-0.13**	**P**

SUMMARY OF OBSERVING CHANGES & SHIFTS IN MONTHLY MEAN Hs

Table 11. Summary of observing changes related to shifts in monthly mean Hs

Observing Change	*Avg Step Size (m, %)*	*Org*	*Buoys*
EEP to WSA	-0.24 (-8.9%)	NDBC	46001
WSA to WDA	+0.26 (+9.4%)	"	46001, 46004, 46002, 46005, 46006
10/12D to 6N	+0.17 (+6.3%)	"	46001, 46002, 46005, 46006
WA to WPM	-0.12 (-4.1%)	"	46002, 46005
Unexplained, Zeno	± 0.28 (±9%)	EC	46036, 46184
Datawell Acc. to SD	-0.17 (-5.9%)	"	46036, 46004, 46184
Faulty Sensor	-0.61 (-21%)	"	46004, 46184
Unexplained, WM	± 0.25 (±8%)	"	46036

NDBC

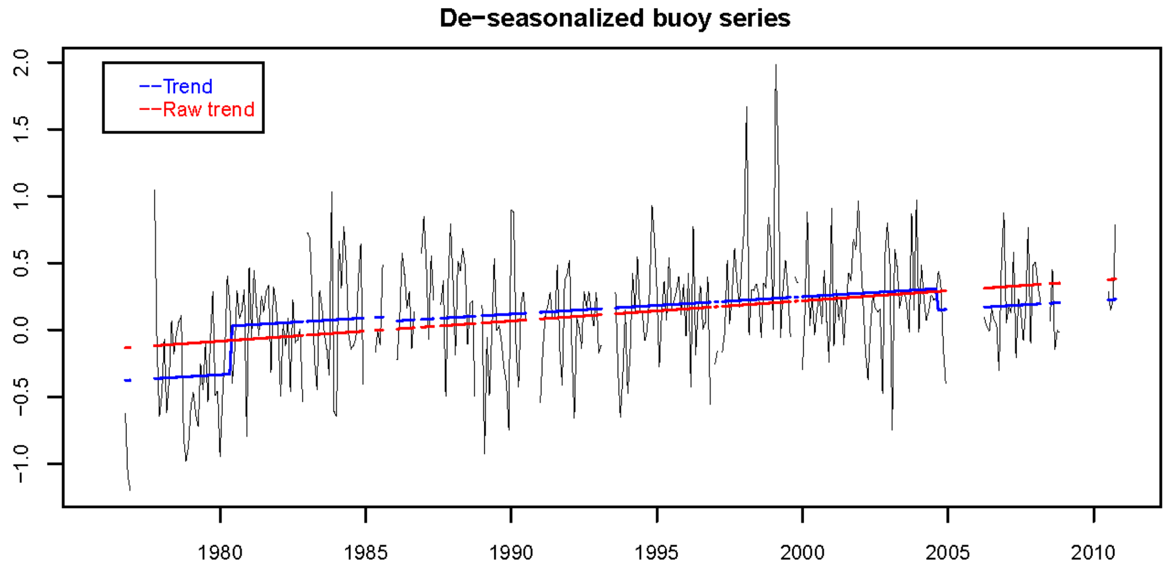
- one of earliest NDBC payload/wave module types, PEB/WSA: mean Hs ~ **9% low** - causing a significant positive step when replaced by the WDA system (deployed with various payloads)
  - also biased low compared to the first type of weather buoy to calculate Hs from spectral wave data, EEP
- some uncertainty in timing/attribution of shifts in early years at some stations
- records from the early 1980s to early 2000's relatively homogeneous, no apparent step change from WDA to WA
- present NDBC wave module, WPM: mean Hs ~ **4% lower** than previous modules (WA, WDA)
- 6N buoys: mean Hs ~ **6% higher** than at the large Discus buoys they replaced

EC

- EC Pacific NOMADs used gimballed Datawells (vertically-stabilized) wave sensors until 1999 - 2001 when replaced by strap-downs – related to ~ **6% decrease** in mean Hs (some uncertainty in date of change)
- Change from NDBC operation (GSPB/WDA/strap-down) to EC (Zeno/Datawell-gimballed) not associated with a step (multiple changes cancelling out?)
- unexplained step changes **(~ ± 8%)**, coinciding w/ deployment/ servicing of individual buoys, both in early and recent records
- a faulty wave sensor resulted in mean Hs **~ 20% low**

TRENDS IN MONTHLY MEAN Hs,
before and after adjustment for observing changes

Figure 9. De-seasonalized monthly mean Hs at 46005 Washington, before adjustment



- De-seasonalized means (monthly anomalies) before adjustment
- Red: Trend line before adjustment
- Blue: Trend line after adjustment (superimposed on original segments)

Table 12. Trends in monthly mean Hs, before and after adjustment for observing changes

		Original (Trend: mm/yr)					*Adjusted (Trend: mm/yr)*				
Buoy	***N yrs***	***Trend***	***P***	***Lwr***	***Upr***	***±***	***Trend***	***P***	***Lwr***	***Upr***	***±***
46001	36	**4.7**	**0.99**	0.9	8.5	3.8	-2.0	0.86	-5.5	1.6	3.6
46184	22	**-14.1**	**0.99**	-25.0	-3.2	10.9	-0.7	0.57	-9.3	7.8	8.6
46004	34	-0.2	0.64	-6.5	6.0	6.3	2.7	0.85	-2.4	7.9	5.1
46036	24	**-14.3**	**1.00**	-21.8	-6.8	7.5	0.4	0.55	-6.9	7.8	7.4
46005	34	**15.1**	**1.00**	9.2	21.0	5.9	**5.0**	**0.96**	-0.5	10.5	5.5
46002	33	**8.5**	**1.00**	2.6	14.4	5.9	1.7	0.74	-3.6	6.9	5.2
46006	32	**10.1**	**1.00**	3.1	17.1	7.0	2.0	0.73	-4.5	8.4	6.5

- V. different trends in NDBC & EC, before adjustments, more consistent after
- Trends of either sign are closer to 0 after adjustments
- Trends in monthly mean Hs, adjusted data, are negative in the Gulf of Alaska, becoming positive ~ 51°N, with the strongest trend at 47°N (Washington Buoy): 0.5 cm/yr, 1976-2010 (compared to 1.5 cm/yr, no adjustments, this study and [4])

SUMMARY/CONCLUSIONS

WAVE PROCESSOR CHANGES:

- Mean Hs from the prototype PEB/WSA (early 1970s) **low by ~ 9%**
- NO shift in mean Hs: change from WDA to WA (NDBC); or Zeno to WM (EC)
- introduction of WPM -> **4% drop** in monthly mean Hs

HULL SIZE/TYPE CHANGES:

- change in hull size/type from the large 10m or 12m Discus buoys to the 6m NOMAD's (in the 1990s) related to a **6% increase** in monthly mean Hs
- *Note: should test for a shift in mean Hs with the change from 6N to 3D, last few years*

WAVE ACCELEROMETER CHANGES:

- NDBC wave sensors were strapped-down throughout (at these stations)
- EC 6N,strap-down: mean Hs ~ **6% lower** than Datawell (vertically-stabilized)

UNEXPLAINED CHANGES:

- Some statistically significant (Type 1) shifts **(± 6%)** remain unexplained in both early and recent EC buoy record

TRENDS

- Trends in monthly mean Hs, adjusted data, were negative in the Gulf of Alaska, becoming positive toward the south, with the strongest trend near 47°N **(Washington), +0.5 cm/yr (reduced from 1.5 cm/yr, not adjusted)**
- It is important to do side-by-side comparisons or compare to a common reference (see www.jcomm.info/WET) when changing observing systems, and to document changes (for adjustment & removal of artificial shifts in the record)
- It is important for the ongoing analysis of wave climate trends and variability and coastal planning, etc, that adjusted wave data be available in the historical wave data archives in NOAA and ISDM, as well as in the International Comprehensive Ocean Atmosphere Data Set (ICOADS).

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REFERENCES

1. Gemmrich, J., B. R. Thomas, R. Bouchard. 2011. Observing changes and trends in NE Pacific wave records. *Geophyical Research Letters* (in production).
2. Oceanweather. (2007). *Global reanalysis of Ocean Waves (GROW2000): Project description,* revised 2 Oct. 2007, Tech. rep. Oceanweather Inc., Cos Cob, CT, USA.
3. Peeples, L. (2010). The Bigger Kahuna: Are More Frequent and Higher Extreme Ocean Waves a By-Product of Global Warming? *Scientific American*, 2 Feb 2010. [http://www.scientificamerican.com/article.cfm?id=big-waves-northwest]
4. Ruggiero, P., Komar, P., and Allan, J.C. (2010). Increasing wave heights and extreme value projections: The wave climate of the US Pacific Northwest, *Coastal Engineering*. **57**, 539-552. [http://www.sciencedirect.com/science/article/pii/S0378383909002142]
5. Wang, X.L, and Y. Feng. 2010. *RHtestV3 User Manual*. Climate Research Division, Science and Technology Branch, Environment Canada, Toronto, ON, 23 p. [http://cccma.seos.uvic.ca/ETCCDMI/software.shtml].
6. Wang, X. L., Q. H. Wen, and Y. Wu, 2007: Penalized maximal *t* test for detecting undocumented mean change in climate data series. *J. Appl. Meteor. Climatol.,* **46,** 916–931.
7. Wang, X. L., 2008a: Penalized maximal *F* test for detecting undocumented mean shift without trend change. *J. Atmos. Oceanic Technol.,* **25,** 368–384.
8. Wang, X. L, 2008b: Accounting for autocorrelation in detecting mean shifts in climate data series using the penalized maximal t or F Test. *J. Appl. Meteo.Climatol.,* **47,** 2423-2444.
9. Young, I.R., S. Zieger and A.V. Babanin (2011). Global Trends in Wind Speed and Wave Height. *Science*. **332**, 22 April 2011, p. 451–455.