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The Effects of Changes in Moored Buoy Observational Practices on Long Term Wave Trend

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Motivation

- Need homogeneous long-term marine data for: validation of reanalyses/satellite data, design, trend analysis
- High media interest in recent studies of moored buoy data
  - But these studies did not assess or account for changes in observing methods, which affect the trends
  - **Ruggiero et al. 2010**: NE Pac buoy waves: increasing trends, especially extremes
    - inconsistent with ~ zero trend in Tofino BC monthly mean Hs records, adjusted for location/hull/sensor changes (Thomas & Swail 2010)
  - **Young et al. 2011**: buoy & satellite data: no overall trend in monthly mean waves, but increasing trends in extremes - altimeter)

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The Bigger Kahuna: Are More Frequent and Higher Extreme Ocean Waves a By-Product of Global Warming?

Increasing maximum wave heights off the Pacific Northwest coast may pose a greater threat than rising sea levels

By Lynne Peeples | February 2, 2010 |

HIGHER ROLLERS: Waves pound a beach and structure between Depoe Bay and Boiler Bay on the Oregon Coast.
Image: Erica Harris, Oregon State University

http://www.scientificamerican.com/article.cfm?id=big-waves-northwest

West Coast waves getting bigger

Researchers say increases have implications for ocean communities

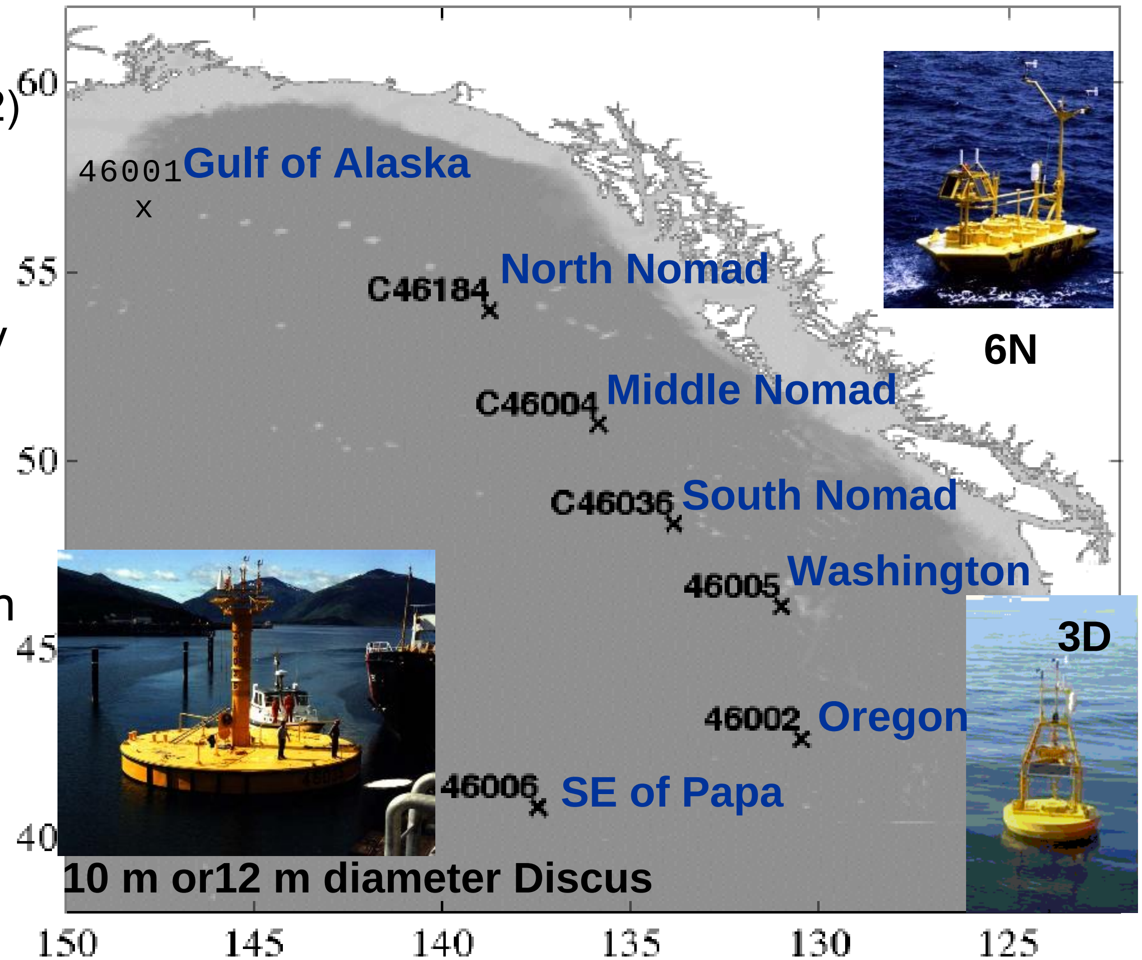
BY JUDITH LAVOIE, TIMES COLONIST FEBRUARY 9, 2010 8:30 AM

Method

- We examine changes in weather buoy wave measurement methods using homogeneity testing software and metadata for individual NDBC and Environment Canada (EC) buoy stations, and calculate trends based on data adjusted for these changes
  - Quality control archived wave measurements
  - Gather metadata for individual buoy stations, such as hull type and size, wave processing method, and wave sensor type over the years
  - Calculate weighted (to account for changes in reporting frequency) monthly means of significant wave height, Hs
  - use months with at least 60% coverage
  - Test for homogeneity using RHTest statistical software, with and without a reference time series
  - Relate detected step changes to metadata to confirm for adjustment
  - Adjust time series for artificial step changes and calculate trends

NDBC & EC Buoys (& hull types) used in study

- Wave Data Starting Dates:
  - 1972 (46001)
  - 1976 (46004, 46005, 46002)
  - 1977 (46006)
  - 1986 (46036)
  - 1987 (46184)
- Now EC, but first operated by NDBC:
  - 46004 (to 1988)
  - 46036 (to 1987)
- NDBC first deployed 10D or 12Ds then replaced them with 6m NOMADs during 1980s, early 1990s
- 46036 & 46184: 6N since 1st deployed
- 6N starting to be replaced by 3D hulls in last few years



Data Sources & QC

- NDBC Moored Buoys
  - NDBC (http://www.ndbc.noaa.gov/hmd.shtml) and NODC (F291) (http://www.nodc.noaa.gov/BUOY/buoy.html) (some metadata such as anemometer height with data records, in NODC archive)
  - QC already done
- EC Moored Buoys
  - ISDM (Format B) (http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/waves-vagues/index-eng.htm) for raw buoy data
  - Checked ISDM Q_FLAG; additional QC needed to flag (& exclude) reports from buoys transmitting before fully deployed or when adrift, or reports from obviously faulty wave sensors

Metadata Sources

- NDBC
  - NDBC Data Inventory– hull type, station name, locations, observed fields, onboard processor of NDBC buoys (http://www.ndbc.noaa.gov/data_availability/data_avail.php)
  - Early NDBC wave processing modules determined from technical reports and data characteristics eg number of spectral bands (wave module inferred, in some cases)
- EC
  - technical reports
  - Internal EC web page maintained by buoy specialists: status reports with information about deployments, hull and payload numbers, active/inactive/faulty sensors
  - Personal communication with buoy specialists
  - Detailed inspection reports (beginning in 2008 - Pacific)

Changes in Onboard/Onshore Wave Processing, NDBC

- Discontinued Payload (Onboard Processor)/ Wave Processors:
  - **EEP** (Experimental Engineering Phase) payload/processor: first buoys deployed at 3 stations measuring waves
  - PEB (Prototype Environmental Buoy) / **WSA** (Wave Spectral Analyzer) – analog, only 12 frequency bands
  - UDACS (UHF Data Acquisition & Control System) / **WDA** (Wave Digital Analyzer)
  - GSBP (General Service Buoy Payload)/WDA
  - DACT (Data Acquisition and Control Telemetry) / **WA** (Wave Analyzer)
- Current Wave Processing Method (used with any payload)
  - **WPM** (Wave Processor Module) – more frequency bands in low frequency range than WDA or WA, longer sampling period
- Changes in low frequency noise filtering methods applied to spectral data (onshore), used to calculate Hs and Tp
  - changes can be applied systematically to all original archived spectral data, beginning in 1984

Do any of these changes cause step changes in historical record?

Changes in Onboard/Onshore Wave Processing, EC Buoys

- wave processor change: from Zeno to Watchman (WM), late 1990s
- Wave spectral band-averaging error in first versions of Watchman, corrected after about a year (reduced ISDM-calculated Hs, not buoy-calculated Hs)
- Change in definition of Hmax (with change in processor) - doesn't affect Hs
- Change in use/value of low frequency cut-off (LFC) (not expected to have much effect on deep water buoys), applied to spectral data to exclude spurious energy in very low frequency bands from calculation of Hs and Tp
  - originally LFC just applied by ISDM for calculation of Hs and Tp from transmitted spectral data, not for buoy-reported values
  - since ~ 2000 also applied LFC onboard buoy for calculation of Hs and Tp (but complete (band-averaged) spectral data is transmitted)

Changes in hull type

- 10 m or 12 m-diameter Discus buoys at all NE Pacific NDBC stations were replaced by 6m boat-shaped NOMAD (6N) buoys (Navy Oceanographic Meteorology Automated Device) in:
  - 1982 (46001)
  - 1983 (46004, 46002)
  - 1986 (46005)
  - 1992 (46006)
- In last few years, NDBC started replacing 6N buoys with 3m-diameter Discus (3D) buoys (46006 in 2008, 46005 in 2010)
- Would expect smaller hulls to be more responsive to waves, better able to pick up smaller waves → do we see a positive step change with the change from the large Discus to the NOMAD buoys?
- Offshore EC buoys have always been NOMAD buoys, while nearshore EC buoys have nearly always been 3Ds

Changes in wave sensor

- NDBC non-directional wave buoys have always used strap-down heave sensors (fixed) (all NDBC offshore buoys in this study)
- EC used Datawell accelerometers in first deployments of 3 offshore Pacific Nomads, 1986 until late 1990s near the time of change of Zeno to Watchman processor, then replaced by strap-down (also called fixed) accelerometers or heave sensors

→ do we see a step change in wave record with change in wave sensor from verticially-suspended to strap-down (at EC buoys)?

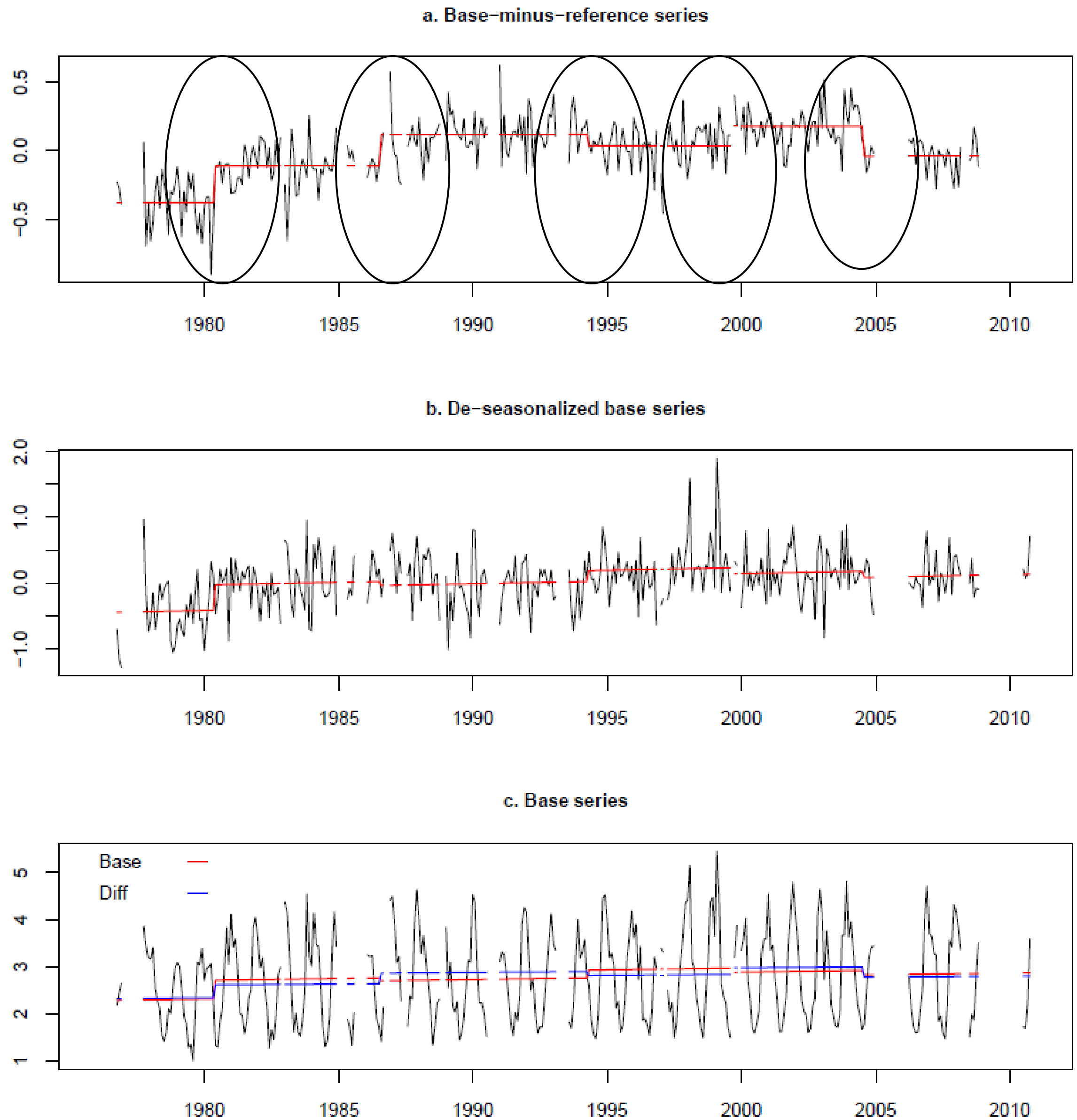
Use of RHTest to Detect Step Changes/Calculate Trend

- Use RHTest (Wang & Feng 2010) to look for shifts in the mean, and estimate magnitude, significance, and date/time of each step
  - without a reference series:
    - test the de-seasonalized monthly mean series (monthly anomalies), assuming same trend in the segments between steps as the overall trend
  - with a reference series (reduces chance that real climatic steps would be attributed to observing method change):
    - test the difference (buoy – reference) series, assuming zero trend in segments
    - then test the de-seasonalized series for the magnitude of steps at the same date/time as the difference series, assuming same trend in the segments as the overall trend
- Run RHTest iteratively to search
  - for **Type 1 steps (p 0.95),** don't need metadata to accept) **[first run – results not modified]**
  - Check for metadata that support the detected change points (and refine date/time, if needed)
  - then either search for **Type 0 steps (less statistically significant**, which the user can accept if supported by metadata) or calculate the magnitude of Type 0 steps added based on metadata **[user modified results]**
- Use RHTest to calculate trends while accounting for seasonal cycle and lag:
  - ignoring the mean steps,
  - after adjusting for difference-estimated change points
  - after adjusting using de-seasonalized-estimated change points

Reference Time Series

- the reference series needs to be homogeneous & have a similar trend as the data series
- For reference series, use GROW hindcast wave data (references), using the grid point nearest each buoy location
  - GROW2000 (1970-2009) or
  - GROW Fine NE Pacific (1980-2009)
- Mainly use GROW2000, as the GROW Fine starts after the data at some stations
- RHTest (run without a reference series) on the chosen GROW2000 grid points finds the series to be homogeneous

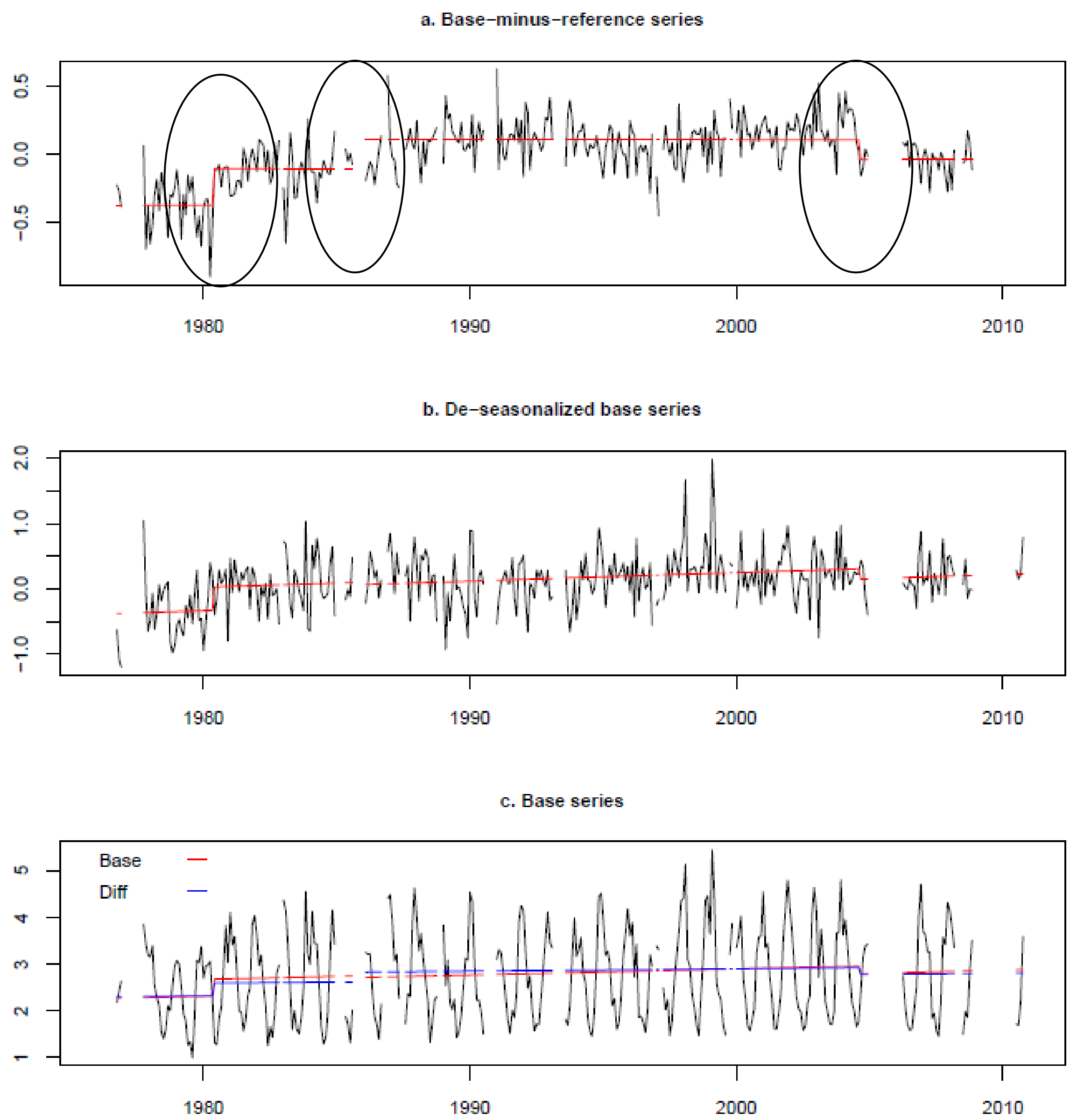
Results 46005 Washington - 1) without user modification



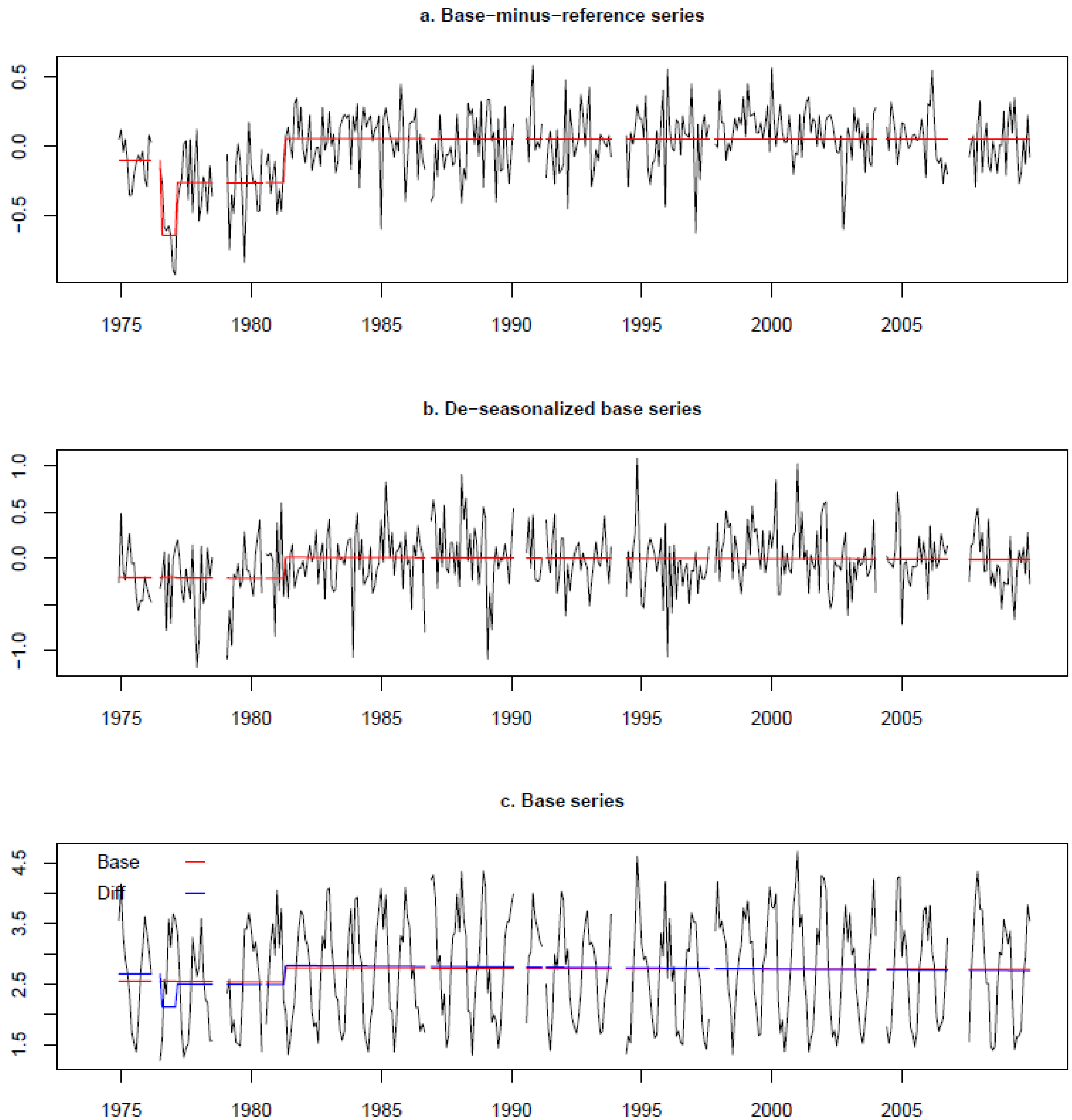
46005 Payload/Wave Processor Changes

Data Start	Data End	Hull Type	Payload	Wave Module
1976/10	1978/08	10D	PEB	WSA
1978/08	1980/06	12D	"	"
1980/06/13	1981/11	6N	MXVII (MOD)	WDA +
1981/11	1985/10	12D	UDACS (A)	"
1986/02	1990/08	6N +	GSBP	"
1991/01	2004/09	"	DACT	WA
2004/09/09	2010/06	"	ARES	WPM -
2010/06	2010/11	3D	AMPS	"

Results 46005 Washington - 2) after user modification



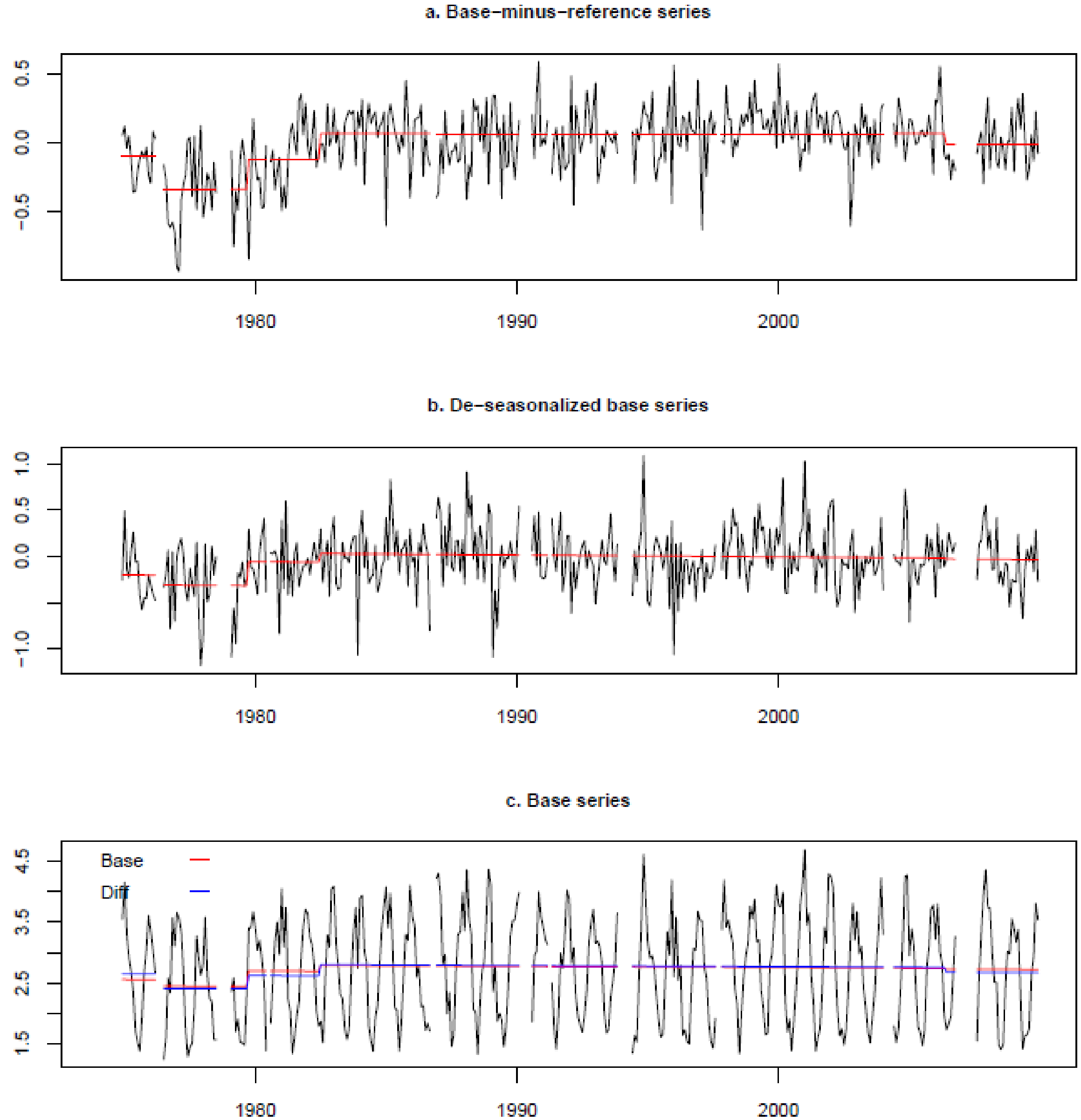
Results 46001 Gulf of Alaska - 1) without user modification



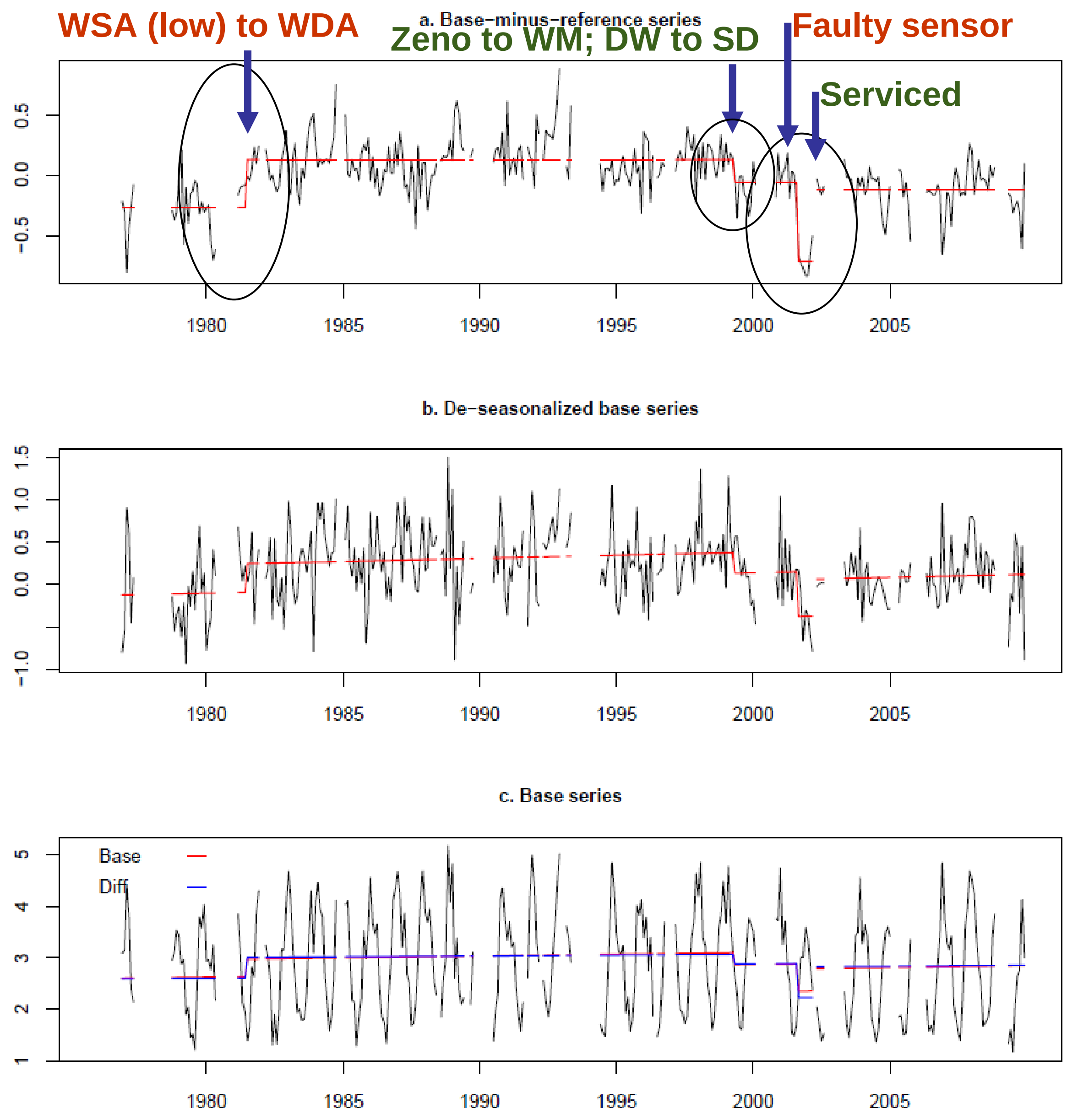
46001 (Gulf of Alaska) Payload/Wave Processor/Hull Changes

Data Start	*Data End*	*Hull Type*	*Payload*	*Wave Module*
1974/12	1976/04	12D	EEP	EEP
1976/07	1979/09	10D	PEB	WSA -
1979/10	1980/07	"	UDACS (A)	WDA +
1980/07	1982/06/23	"	GSBP	"
1982/06/23	1990/03	6N +	"	"
1990/07	2006/05	"	DACT	WA
2006/05	2010/12	"	ARES 4.4	WPM -

Results 46001 Gulf of Alaska - 2) with user modification



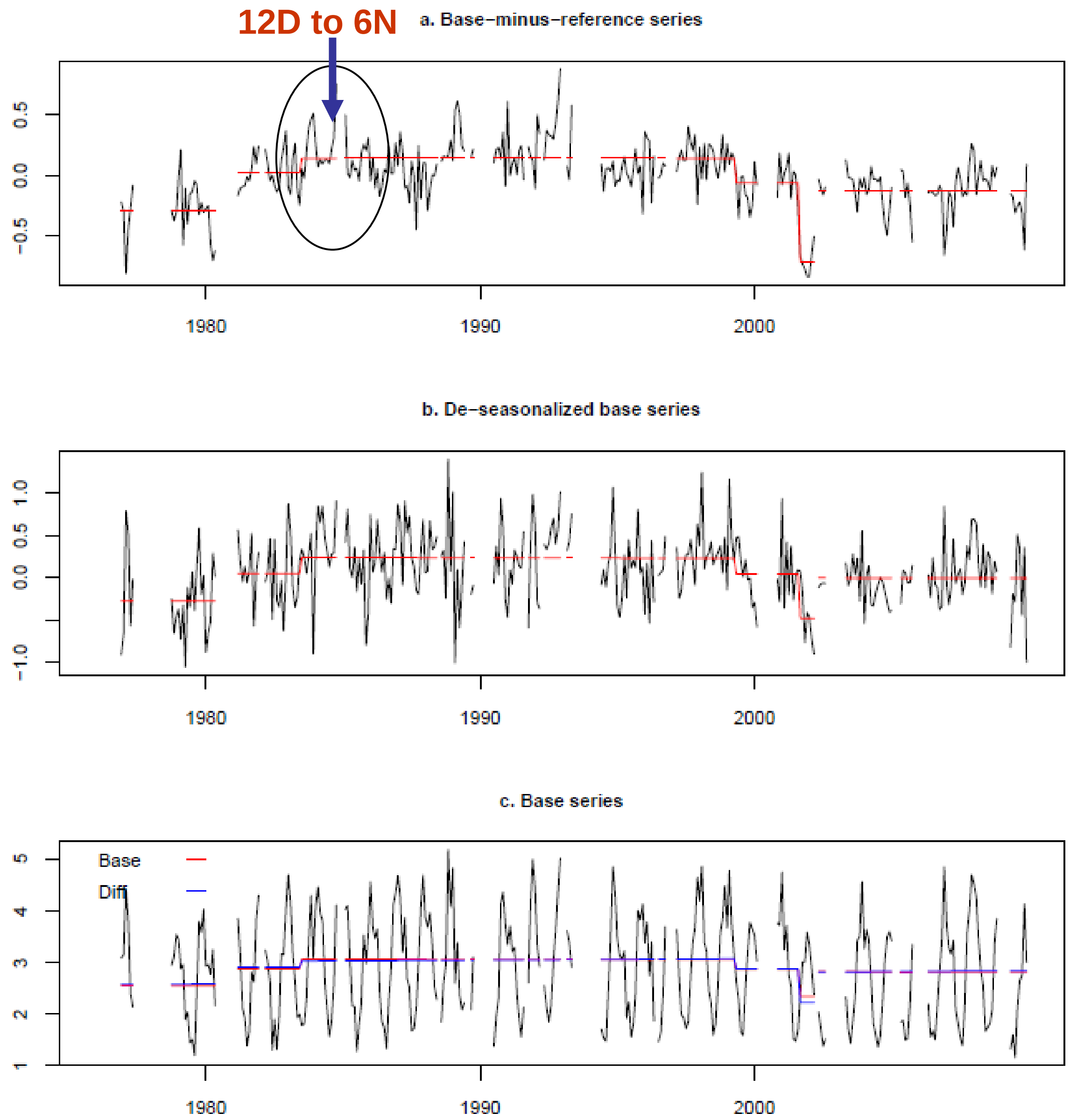
Results 46004 Middle Nomad - 1) without user modification



46004 (Middle Nomad) (2): Payload/Wave Processor Changes, matched with RHTest detected step changes

Data Start	*Data End*	*Hull Type*	*Payload*	*Wave Module*	*Sensor*
1976/10	1977/10	10D	PEB	WSA	FA
1978/09	1980/05	12D	PEB UDACS	"	"
1981/02/23	1983/06	"	UDACS (A)	WDA +	"
1983/06	1988/06	6N	GSBP	"	"
1988/06	1999/05/09	"	Zeno	Zeno	VS
1999/05/09	2000/02/21	"	WM	WM	- FA
2000/04/26	2000/05/28	"	"	"	VS -
2000/10/24	2001/05/09	"	"	"	FA +
2001/05/09	2010/12/14	"	"	"	"

Results 46004 Middle Nomad - 1) with user modification



46004 (4) Payload/Wave Processor Changes, matched w/ modified RHTest-detected steps

Data Start	*Data End*	*Hull Type*	*Payload*	*Wave Module*	*Sensor*
1976/10	1977/10	10D	PEB	WSA	FA
1978/09	1980/05	12D	PEB UDACS	“	“
1981/02/23	1983/06	“	UDACS (A)	WDA +	“
1983/06	1988/06	6N +	GSBP	“	“
1988/06	1999/05/09	“	Zeno	Zeno	VS
1999/05/09	2000/02/21	“	WM	WM	- FA
2000/04/26	2000/05/28	“	“	“	VS -
2000/10/24	2001/05/09	“	“	“	FA +
2001/05/09	2010/12/14	“	“	“	“

NDBC Observing Changes Related to Monthly Mean Shifts in Hs

- Payload/wave module PEB/WSA in late 1970s early 1980s: low Hs compared to the earlier EEP and later payloads/wave modules
- NOMAD buoys: slightly higher Hs than the large Discus buoys
- Newest wave module WPM: slightly lower Hs than previous wave modules WDA, WA

Observing Change	***Step***	***Buoys with Type 1 shift (detected by RHTest)***	***Buoys with Type 0 shift (supported by metadata)***
EEP to WSA	-	46001	
WSA to WDA	+	46001,46004,46004,46006	
10/12D to 6N	+		46001,46004,46004,46006
WA to WPM	-		46001,46004, 46006

[changes in wave module from WDA to WA do not show shifts in Hs]

EC Observing Changes
Related to Monthly Mean Shifts in Hs

- Change from strap-down to vertically-stabilized wave sensor (+)
- Change from VS to strap-down, coincident with chg in processor from Zeno to WM (-)
- Faulty vertically-stabilized wave sensor (biased low)

Observing Change	***Step***	***Buoys with Type 1 shift (detected by RHTest)***	***Buoys with Type 0 shift (added based on metadata)***

Trends before & after adjustment (mm/yr)

		Original					Adjusted				
Buoy	***N yrs***	***Trend***	***P***	***Lwr***	***Upr***	***Uncert***	***Trend***	***P***	***Lwr***	***Upr***	***Uncert***
46001	35	**4.7**	**0.99**	0.9	8.5	3.8	-2.0	0.86	-5.5	1.6	3.6
46184		**-14.1**	**0.99**	-25.0	-3.2	10.9	-0.7	0.57	-9.3	7.8	8.6
46004	33	-0.2	0.64	-6.5	6.0	6.3	2.7	0.85	-2.4	7.9	5.1
46036		**-14.3**	**1.00**	-21.8	-6.8	7.5	0.4	0.55	-6.9	7.8	7.4
46005	33	**15.1**	**1.00**	9.2	21.0	5.9	**5.0**	**0.96**	-0.5	10.5	5.5
46002		**8.5**	**1.00**	2.6	14.4	5.9	1.7	0.74	-3.6	6.9	5.2
46006		**10.1**	**1.00**	3.1	17.1	7.0	2.0	0.73	-4.5	8.4	6.5

Dark shading indicates p>=0.95, lighter shading indicates p>= 0.85

Summary of Observing Changes that Affected Wave Measurements

- Hs from stations with one of earliest NDBC buoy/payloads, PEB/WSA, appear to be biased low, enough to cause a pronounced positive step changes in the climate record when change to the WDA system
- Hs from the very first weather buoy to report spectral wave data, EEP, does not appear to be biased
- the records from the early 1980s to early 2000's appear to be relatively homogeneous, with no apparent step in the change from the WDA to the WA
- The new NDBC wave module WPM appears to report slightly lower Hs than the previous (WA)
- The change from the large Discus buoys to 6N buoys contributed a small positive step to the wave record
- Change in type of wave sensor nearly coincident with change in wave processor at EC stations associated with a slight negative step change
- There are other unexplained step changes in the EC buoy record, perhaps related to water inside the hull (remarks in status reports - water alarms set).

Summary of Results

- Long-term moored buoy wave records contain inhomogeneities due to:
  - Changes in payload processing methods to determine spectral data
  - Changes in hull type
  - Wave sensor errors
  - other unexplained reasons
- Before adjustment for non-climatic step changes, trends in monthly mean significant wave height (Hs) in the NE Pacific for NDBC and EC buoys are inconsistent:
  - Significantly positive (NDBC), up to 0.15 cm/yr, Washington Buoy
  - Zero to significantly negative (EC offshore buoys), to -0.14 cm/yr, S & N Nomad Buoys
- After adjustment, trends for NDBC and EC buoys are consistent (vary from south to north), markedly reduced, and somewhat statistically significant:
  - small and positive in mid-latitudes, up to 0.05 cm/yr at the Washington Buoy
  - Negative values toward the north, to -0.02 cm/yr, Gulf of Alaska Buoy

Conclusions

- Its important to document metadata for each moored buoy station to keep track of observing changes that might introduce artificial trends into the record
- Its important to adjust long term buoy time series for observing changes prior to trend analysis
- A constant offset adjustment for monthly mean values may not apply to extremes or to the hourly reports (a percentage based correction factor may be better)
- Side-by-side installations/deployments of new and older observing systems/platforms are useful, to determine calibration equations that could be used to adjust the entire distribution (of the older system)

Thank you.