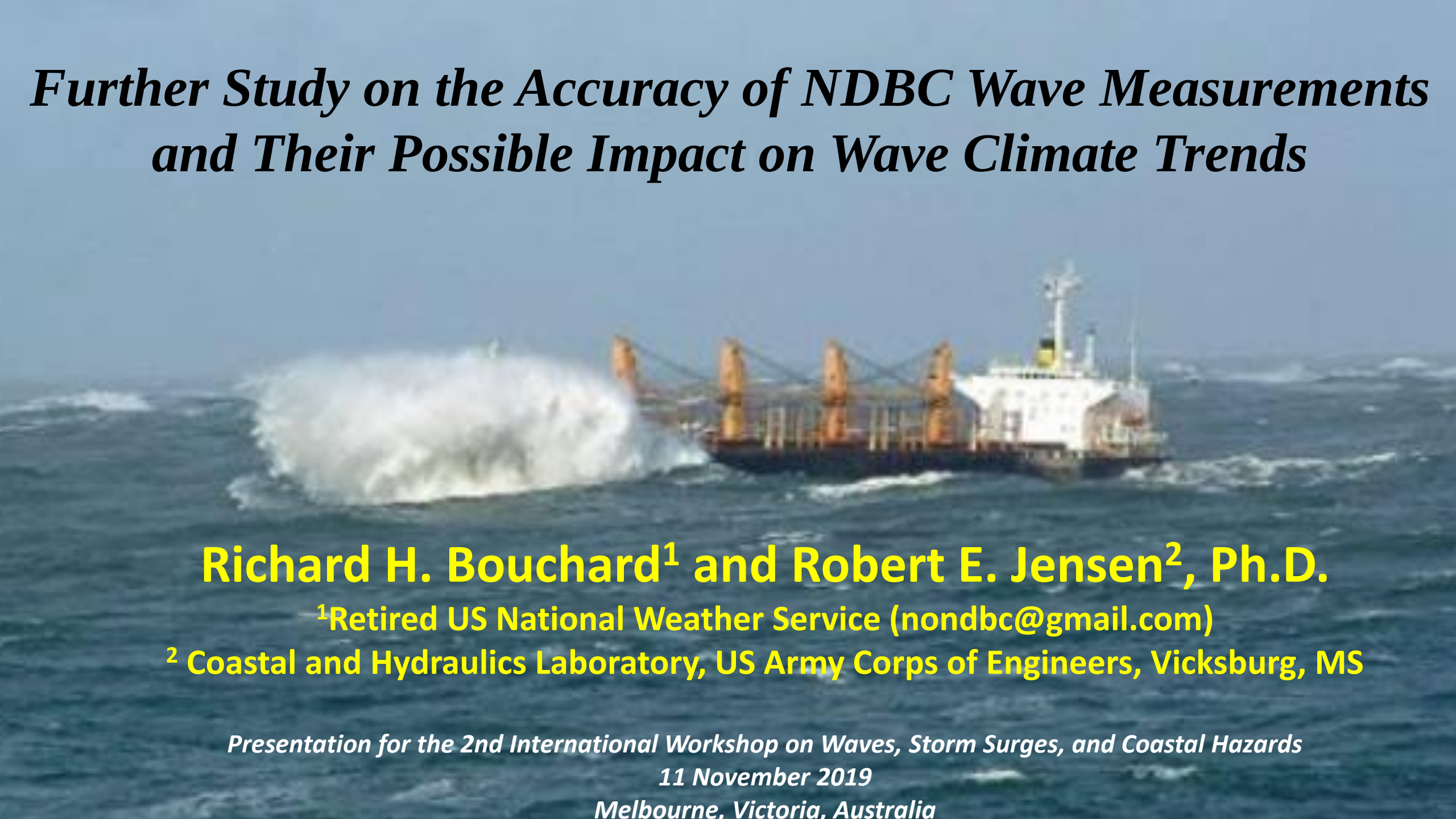
Further Study on the Accuracy of NDBC Wave Measurements and Their Possible Impact on Wave Climate Trends



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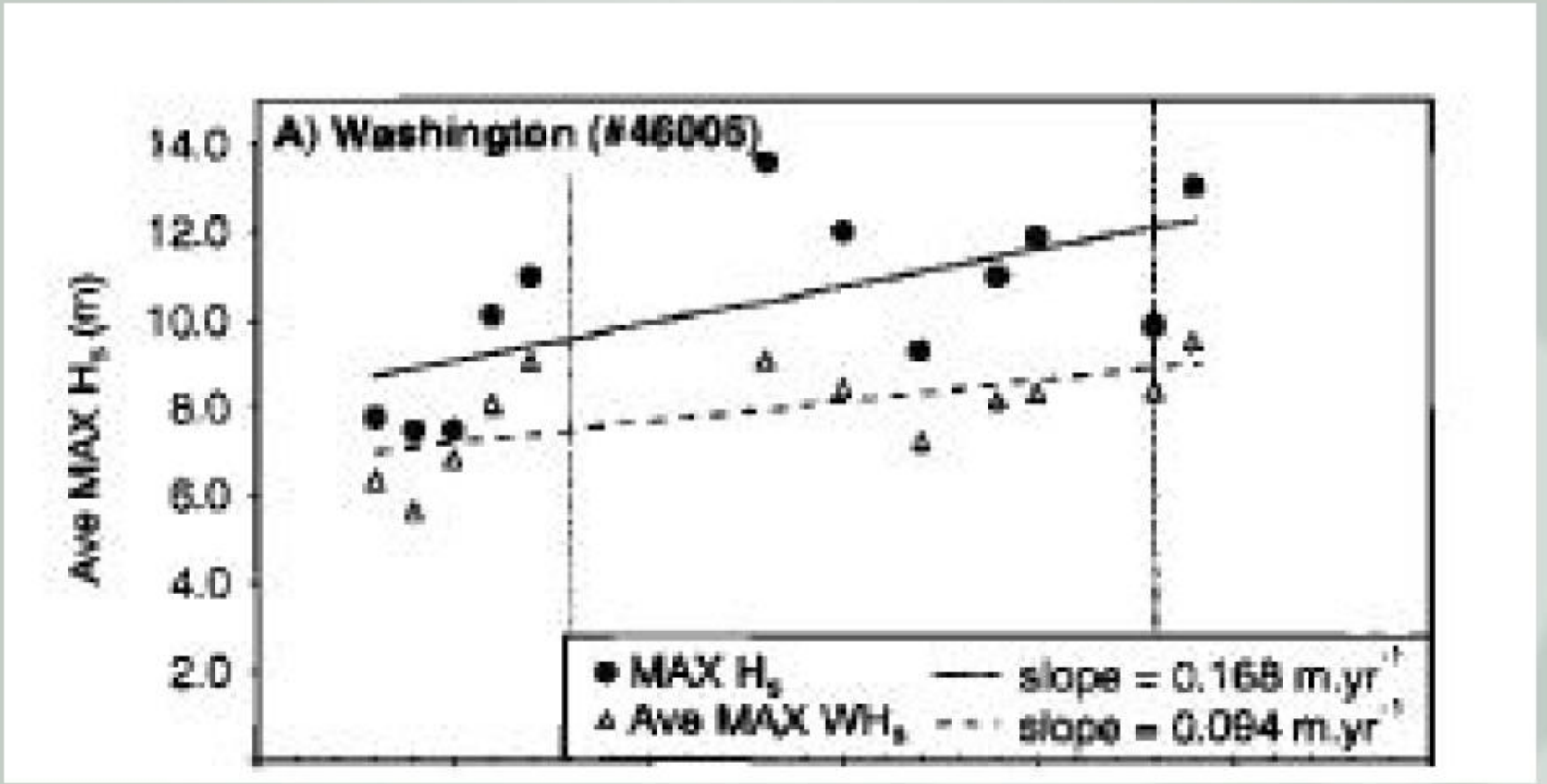
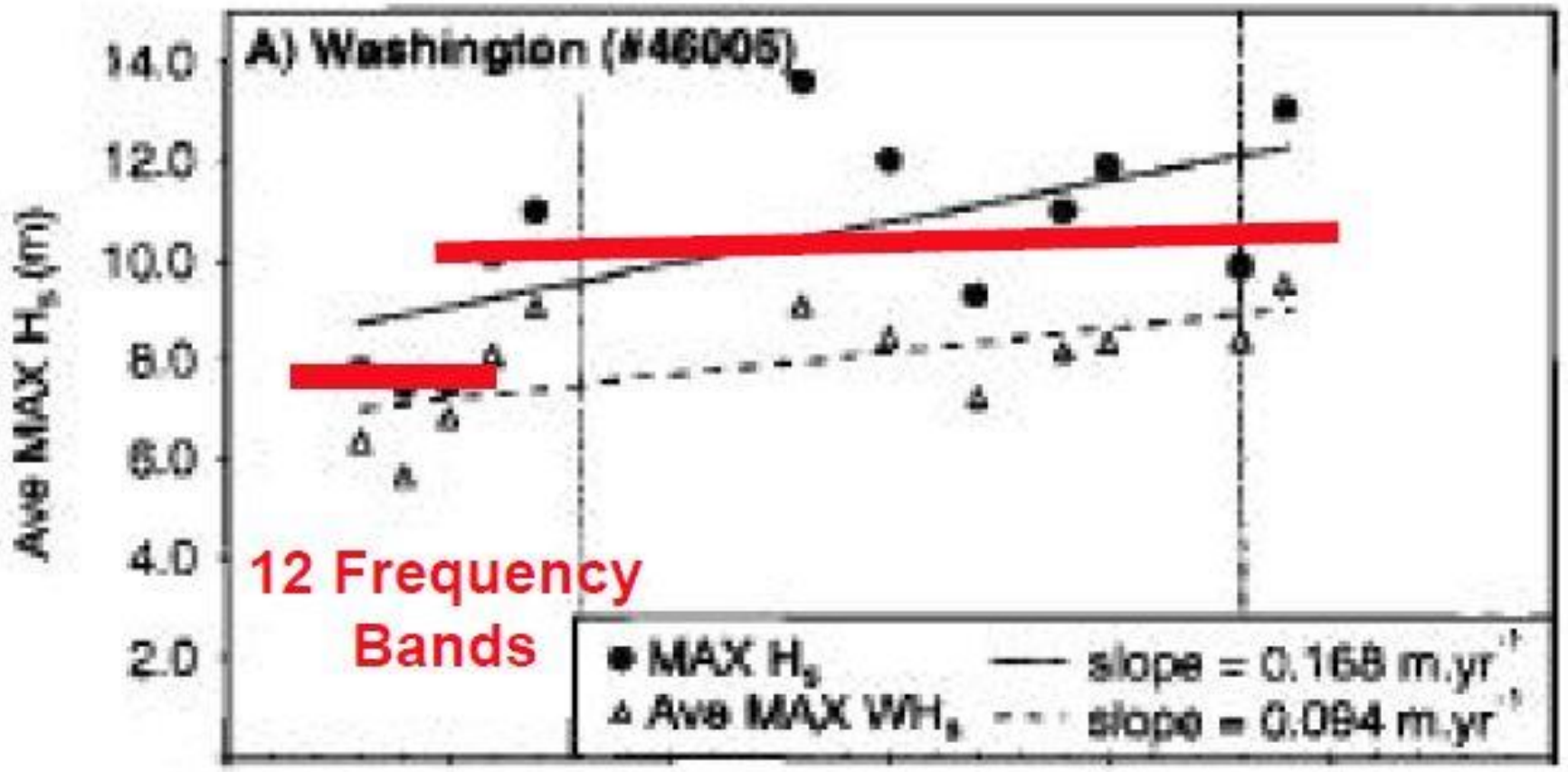
Motivation

Are Ocean Wave Heights Increasing in the Eastern North Pacific? **- Allan and Komar, *Eos*, Vol. 81, No. 47, November 21, 2000**



The authors were not aware of system changes



Gemmrich, Thomas, and Bouchard (2011): ***Several recent studies reported long-term trends extracted from these records. However, significant modifications of the wave measurement hardware as well as the analysis procedures since the start of the observations result in inhomogeneities of the records.*** Also Livermont *et al*. (2015) and (2017).

What are we going to do?

- Previously, Bouchard *et al.* (2018) showed a simulated change in systems at an NDBC station would result in a change in the trend of the significant wave height.
- Using measurements from Project FLOSSIE (**F**ield **L**aboratory for **O**cean **S**ea **S**tate **I**nvestigation and **E**xperimentation) platforms[1,2], concatenate the significant wave height time series of a newer wave system to an older wave system
- New system: 3-m aluminum discus using NDBC Digital Directional Wave Module (DDWM)
- Older System: 6-m NOMAD using Wave Analyzer (WA))
- Datawell Waverider Mk III as ground truth
- Change point is midway in time period (08 Jul 2017), not 50% of obs
  - First period has 14,687 obs while the second period has 14,030
- This study goes further:
  - 18 months more data
  - Greater scrutiny of the data
  - Attempt to correct the NDBC data to see if it improves the simulation data trend

[1] Other FLOSSIE systems include (but not used for this study) are: AXYS®-provided Triaxys Next Wave II DNS/WM and ECCC-provided Strapped Down Accelerometer / AXYS-Watchman

[2] In association with the Data Buoy Collaboration Panel's Task Team on Wave Measurements, https://www.jcomm.info/index.php?option=com_oe&task=viewGroupRecord&groupID=420

The Systems

- NOMAD, ID 46FLO: Funded by US Army Corps of Engineers, Coastal and Hydraulics Lab (CHL)
  - 6-m boat-shaped of 6300 kg; hull points the bow into the currents
  - First wave measurements in May 1977 in use in 2019
  - 51 hulls built
  - Recorded highest NDBC wave measurement of 16.9 m in January 1991 (6N WA)
  - Mast extends 5 m above the water line
  - Built and operated by NDBC – contains five wave systems
- 3-meter Discus (3D), NDBC 46042 Monterey CA, funded by US National Weather Service
  - Circular aluminum hull of 1720 kg; with wind fin, bow points into the wind
  - Used since the mid 1980s
  - 70+ hulls built
  - Tied highest wave measurement, 16.9 m, in August 2005 (Hurricane Katrina); did not use DDWM.
  - Mast extends 5 m above the waterline
  - Contains 2 wave systems
- Datawell Waverider MkIII (DWR), 46114 (Coastal Data Information Program (CDIP) West Monterey CA #185), funded by CHL, deployed and operated by CDIP Scripps
  - 0.9 m spherical hull of 220 kg

Wave System Characteristics

	DWR	NOMAD WA	3D DDWM
Sampling Frequency (Hz)	1.28	2.00 (subsampled 1.00)	1.7066
Sampling Duration (seconds)	1600	1200	1200/600[1]
Samples	2048	1200	2048/1024[1]
# Frequency Bands	63	48	46
Minimum Frequency (Hz)	0.0250	0.0300	0.0325
Maximum Frequency (Hz)	0.5800	0.5000	0.4850
Equivalent Degrees of Freedom		33	24

- **WA and DDWM use strapped-down accelerometers; DWR vertical stabilization**
- WA used since 1984
- This version of DDWM used since 2012 has tilt correction to mitigate *Bender Effect* (Bender *et al.* (2010))
- See: NDBC (1996) and Datawell (2019) for more details

[1] For frequencies 0.365 to 0.485 Hz

Sampling

Start DWR	End DWR	DWR Sample Start Time (minutes after the hour)	WA NOMAD Sample Start Time	WA NOMAD Overlap with DWR (minutes)	DDWM 3D Sample Start Time	DDWM 3D Overlap with DWR
16 Oct 2015	03 Aug 2016	24	30	20	20	16
03 Aug 2016	24 Sep 2017	33	30	17	20	7
24 Sep 2017	12 Jun 2018	33	30	17	20	7
14 Jul 2018	31 Mar 2019	33	30	17	20	7

- DWR & DDWM do two measurements per hour
- WA does one measurement per hour
- Study uses only one of each of the DWR & DDWM measurements every hour

Deployments

Start DWR	End DWR	Water Depth	NOMAD Start	NOMAD End	Water Depth	Start 3D DDWM	End 3D DDWM	Water Depth
16 Oct 2015	03 Aug 2016	1463	16 Oct 2015	31 Mar 2019	2377	16 Oct 2015	16 Aug 2017	2098
03 Aug 2016	24 Sep 2017	1463						
24 Sep 2017	12 Jun 2018	1463				16 Aug 2017	31 Mar 2019	1646
14 Jul 2018	31 Mar 2019	1510						

DWR ~ 40 km northwest of Monterey, CA USA (Northeast Pacific)

NOMAD ~ 20 km west-southwest of DWR (avoid marine sanctuary)

3D ~ 14 km northwest of DWR, then 10 km north-northwest of DWR

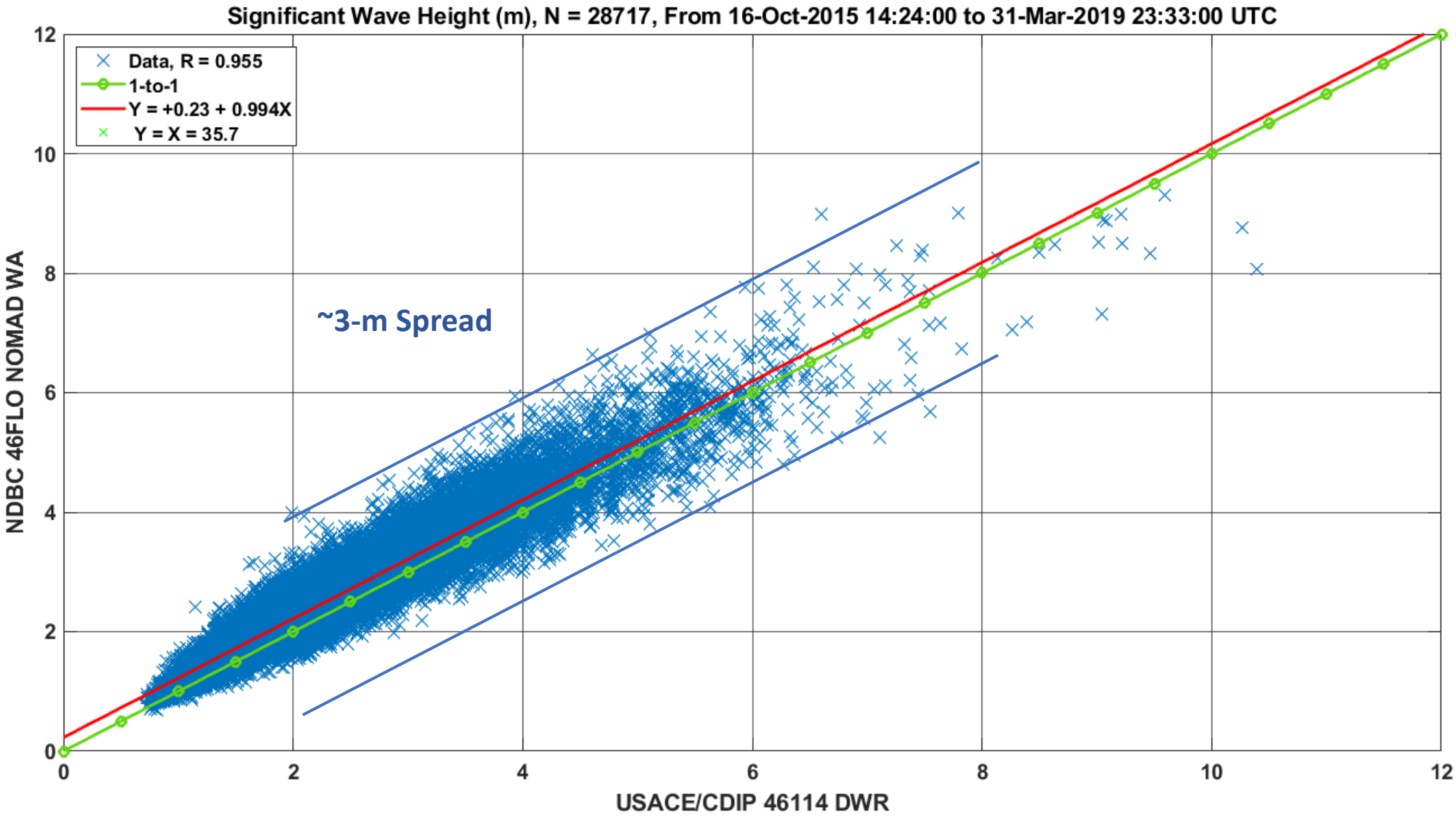
FLOSSIE Dataset: Significant Wave Heights (meters)
16-Oct-2015 14:24:00 to 31-Mar-2019 23:33:00 UTC
Spans: 30,298 Hours or ~1263 Days
After Removing Missing or Failed Quality Control
28,717 Hours of Triplet Reports

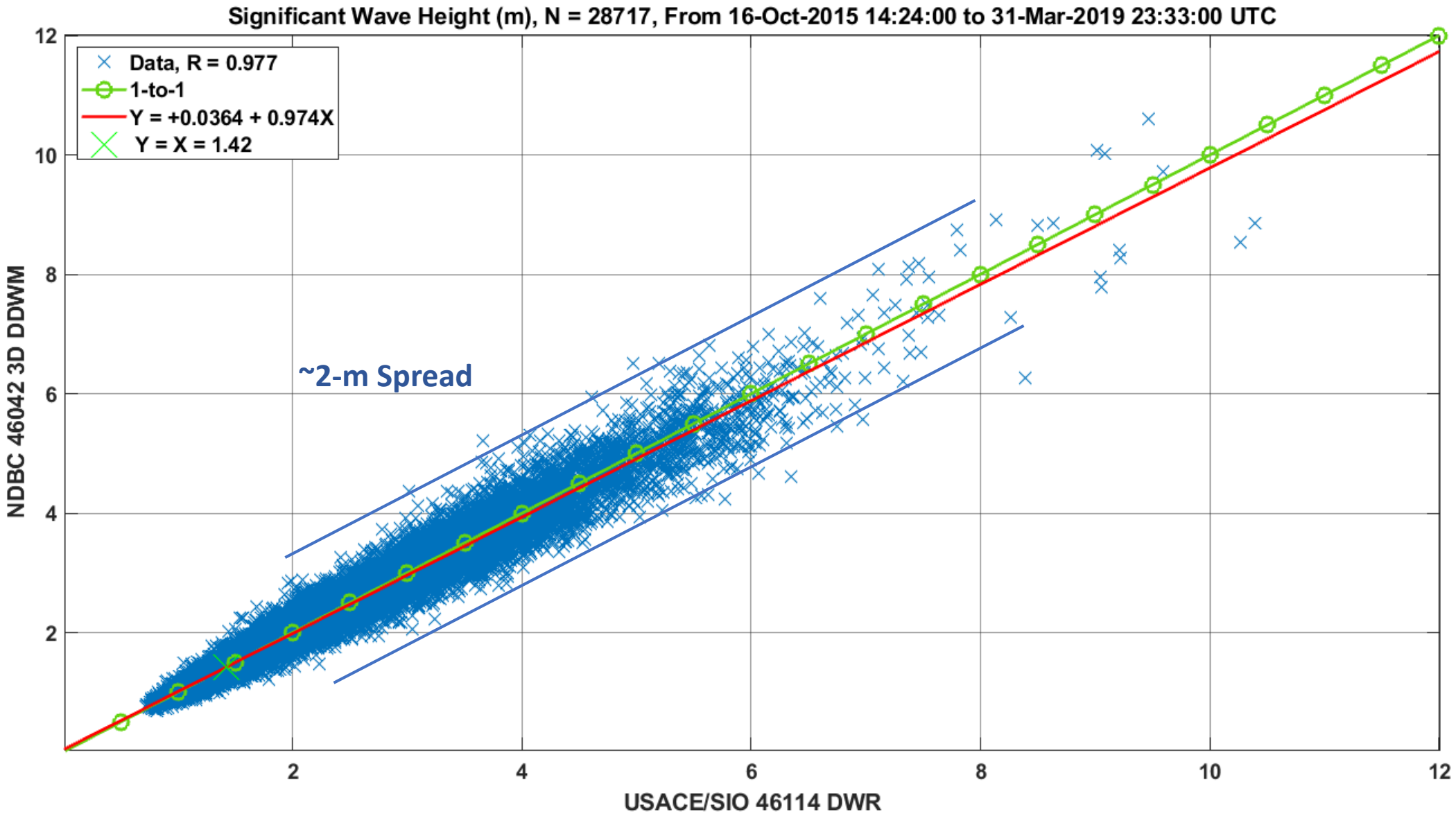
	DWR	NDBC NOMAD WA	NDBC 3D DDWM
Mean	2.31	**2.52**	**2.28**
Median	2.08	**2.31**	**2.07**
Standard Deviation	0.99	**1.03**	**0.99**
Maximum	10.39	**9.31**	**10.61**
Minimum	0.72	0.69	0.68
Range	9.67	**8.62**	**9.93**

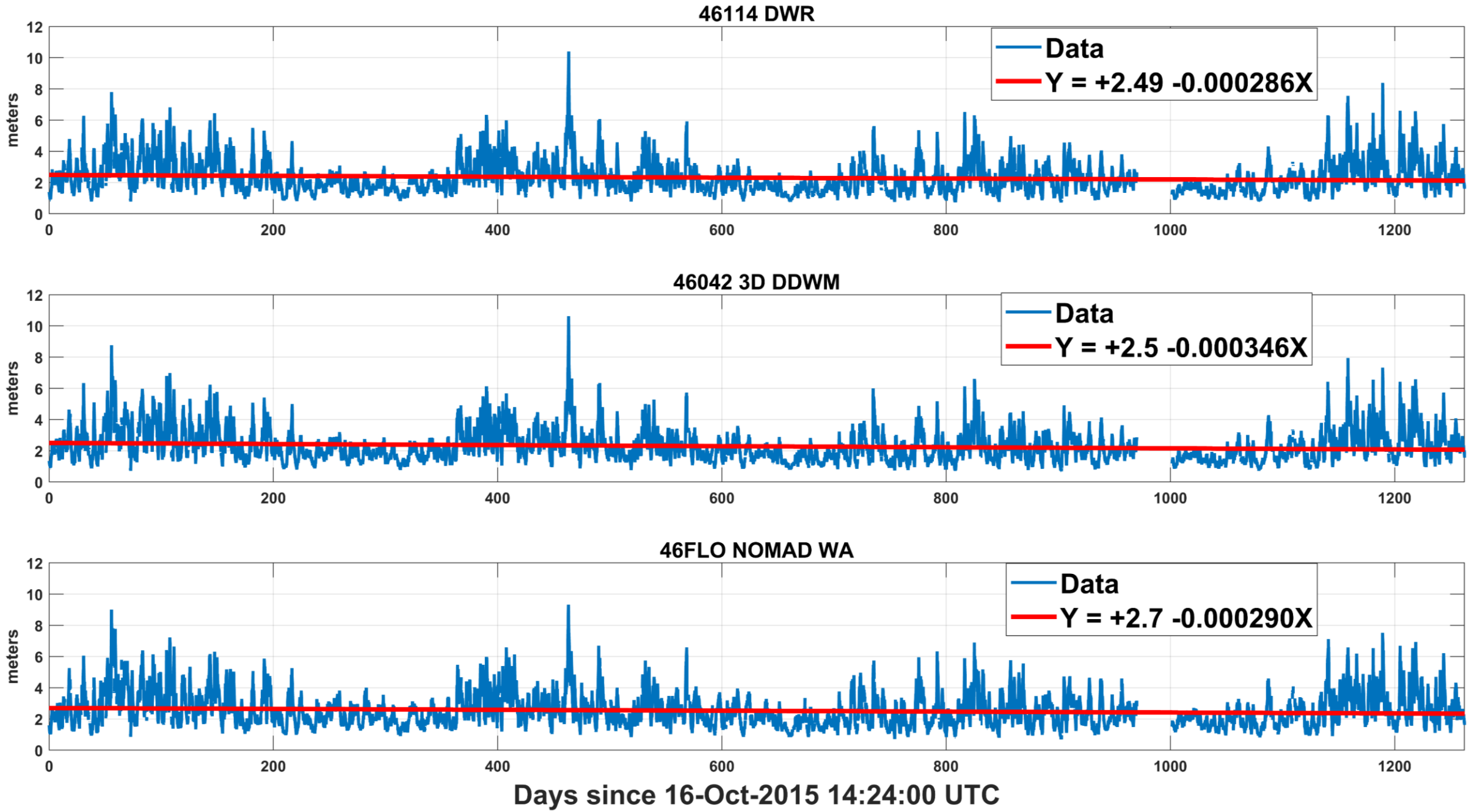
Error Statistics: NDBC Accuracy Claim is 0.2 meters or 5%[2]

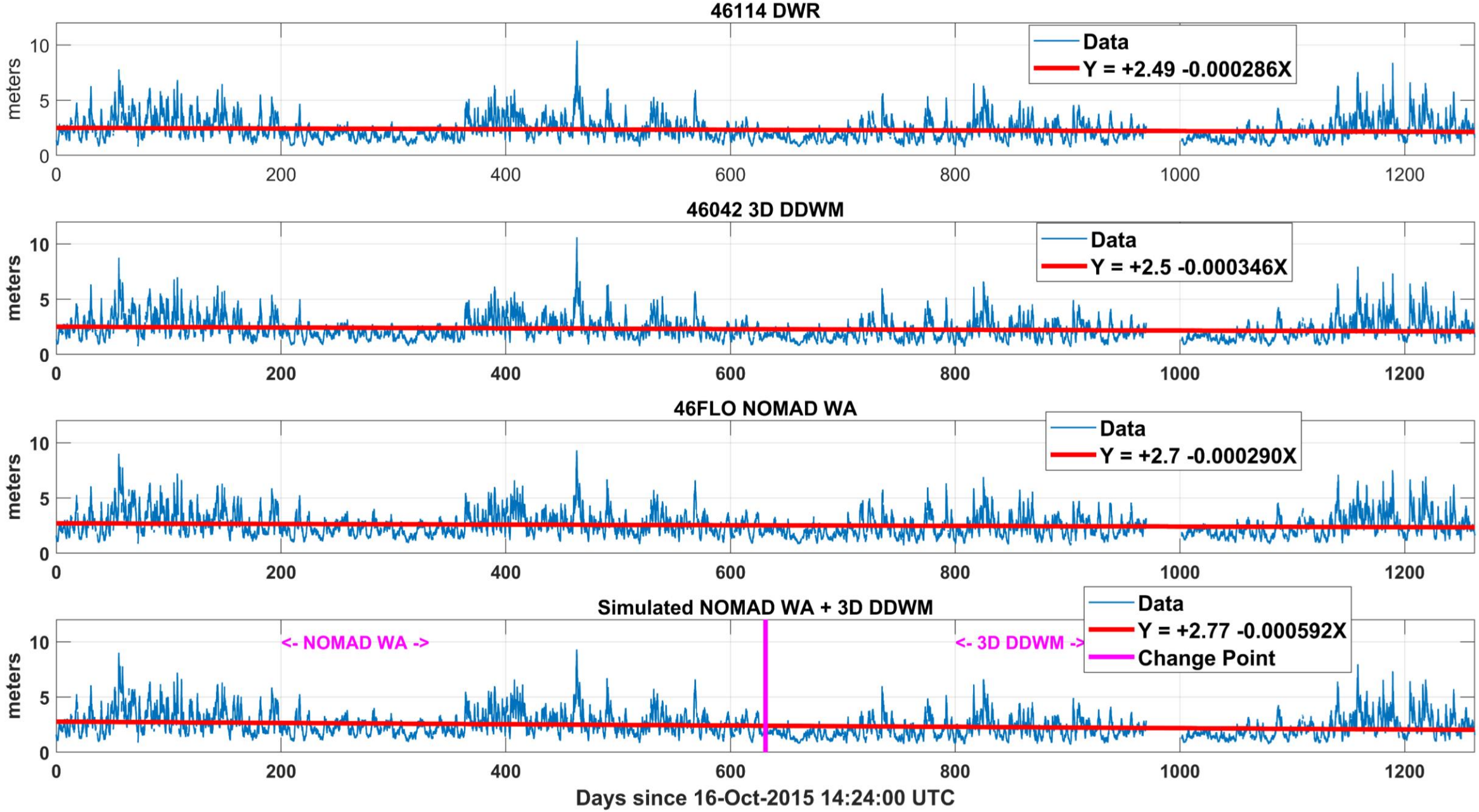
Statistic	6N WA – DWR	3D DDWM – DWR
RMSE	0.37	**0.21**
Mean	+0.21	**-0.02**
Standard Deviation	0.31	**0.21**
Maximum	+2.39	**+1.56**
Minimum	-2.32	**-2.13**
Range	4.71	**3.69**
Scatter Index	0.18	**0.10**
Correlation Coefficient	0.9550	**0.9774**

[2]Meindl and Hamilton (1992)


Significant Wave Height (m), N = 28717, From 16-Oct-2015 14:24:00 to 31-Mar-2019 23:33:00 UTC
Data, R = 0.955
1-to-1
Y = +0.23 + 0.994X
Y = X = 35.7
~3-m Spread
NDBC 46FLO NOMAD WA
USACE/CDIP 46114 DWR
0
2
4
6
8
10
12


Significant Wave Height (m), N = 28717, From 16-Oct-2015 14:24:00 to 31-Mar-2019 23:33:00 UTC
Data, R = 0.977
1-to-1
Y = +0.0364 + 0.974X
Y = X = 1.42
~2-m Spread
NDBC 46042 3D DDWM
USACE/SIO 46114 DWR
2
4
6
8
10
12


46114 DWR
Data
Y = +2.49 -0.000286X
meters
46042 3D DDWM
Data
Y = +2.5 -0.000346X
meters
46FLO NOMAD WA
Data
Y = +2.7 -0.000290X
meters
0
2
4
6
8
10
12
0
200
400
600
800
1000
1200
Days since 16-Oct-2015 14:24:00 UTC

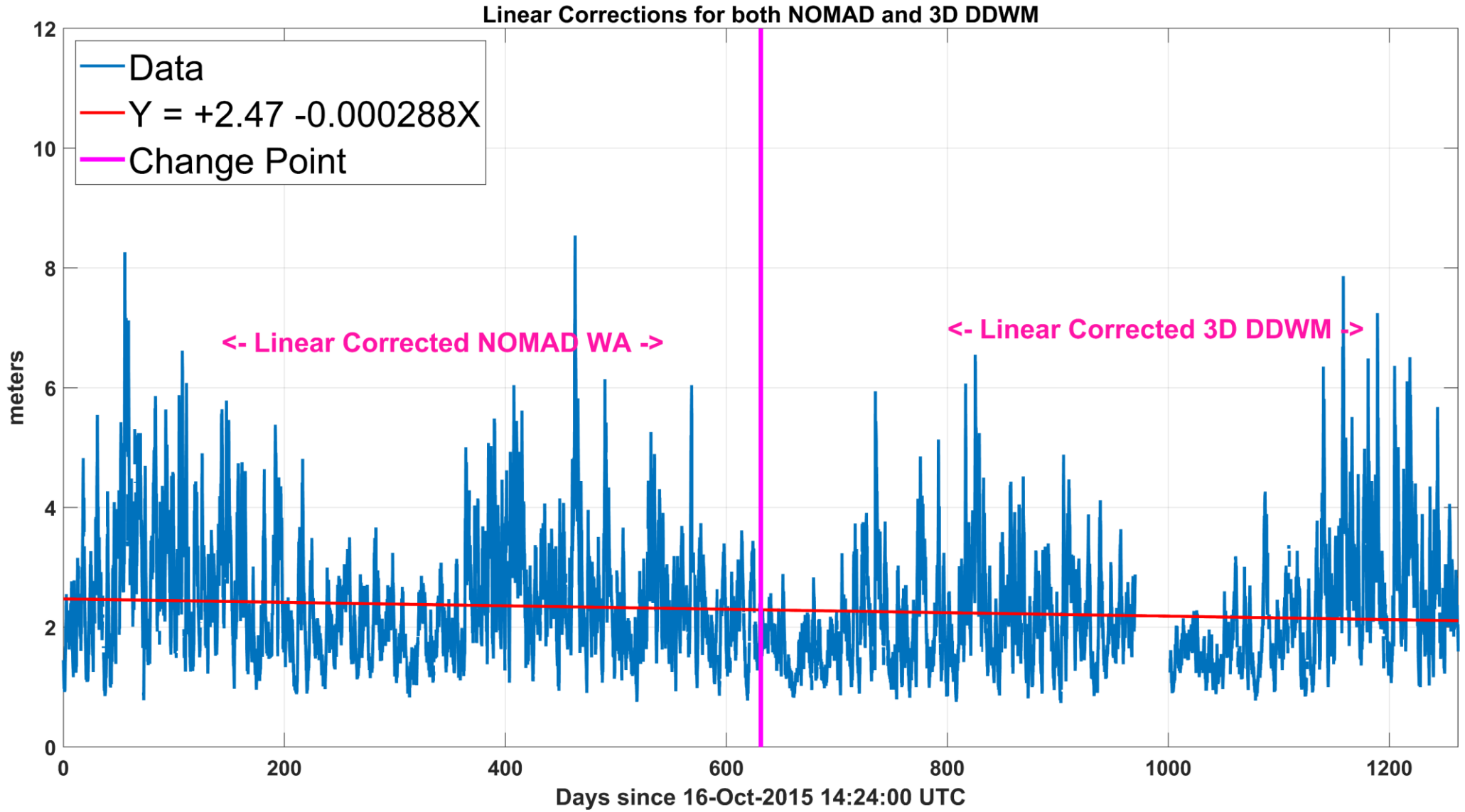

46114 DWR
Data
Y = +2.49 -0.000286X
meters
46042 3D DDWM
Data
Y = +2.5 -0.000346X
meters
46FLO NOMAD WA
Data
Y = +2.7 -0.000290X
meters
Simulated NOMAD WA + 3D DDWM
<- NOMAD WA ->
<- 3D DDWM ->
Data
Y = +2.77 -0.000592X
Change Point
meters
0
5
10
0
200
400
600
800
1000
1200
Days since 16-Oct-2015 14:24:00 UTC

Trend Analyses

	DWR	NOMAD WA	3D DDWM	Simulated
Y-intercept (cm), Day 0	248.6	270.3	**250.1**	276.6
Slope (cm/90 days)	-2.57	**-2.61**	-3.11	-5.33
Change (cm) from April 2019 to April 2022	-31.3	**-31.7**	-37.9	-64.9
Extend Trend to April 2022, resulting prediction(cm)	182.9	203.7	170.6	140.4

Developed Correction Methodology

- Simply develop linear and quadratic least-squares corrections to tune NOMAD WA and 3D DDWM to DWR
- Use entire triplet dataset, not just partitions
- Considered other fits, but ignored because of apparent success of simple methodologies
- Did not consider or account for possible spatial or temporal effects
- Required methodology to not degrade bulk statistics
  - Discarded quadratic correction (See Supplementary Slides)
- Applied corrections to NOMAD WA and 3D DDWM and then re-partitioned and concatenated



Linear corrections applied to each full triplet dataset, not just segments

Linear correction improves trend analysis

	DWR	NOMAD WA	3D DDWM	Simulation	Linearly Corrected Simulation
Y-intercept (cm), Day 0	248.6	270.3	250.1	276.6	247.3
Slope (cm/90 days)	-2.57	-2.61	-3.11	-5.33	-2.59
Change (cm) from April 2019 to April 2022	-31.3	-31.7	-37.9	-64.9	-31.6
Extend trend 3-years to April 2022	182.9	203.7	170.6	140.4	181.0

Linear Correction Improves Error Statistics (meters) Over Simulation But not as good as DDWM by itself

Statistic	6N WA – DWR	3D DDWM – DWR	Simulation	Linearly Corrected Simulation
RMSE	0.37	0.21	**0.31**	**0.27**
Mean	+0.21	-0.02	**+0.09**	**-0.01**
Standard Deviation	0.31	0.21	**0.30**	**0.26**
Maximum	+2.39	+1.56	**+2.39**	**1.67**
Minimum	-2.32	-2.13	**-2.32**	**-2.99**
Range	4.71	3.69	**4.71**	**4.66**
Scatter Index	0.18	0.10	**0.14**	**0.12**
Corr Coefficient	0.9550	0.9774	**0.9565**	**0.9638**

Linear correction improves bulk statistics (meters) over the uncorrected simulation
Except for maximum

	DWR	NDBC NOMAD WA	NDBC 3D DDWM	Simulated	Linearly Corrected Simulation
Mean	**2.31**	2.52	2.28	**2.40**	**2.29**
Standard Deviation	**0.99**	1.03	0.99	**1.03**	**0.95**
Maximum	**10.39**	9.31	10.61	**9.31**	**8.54**
Minimum	**0.72**	0.69	0.68	**0.68**	**0.73**
Range	**9.67**	8.62	9.93	**8.63**	7.81

Observations

- Changes in NDBC systems can cause erroneous trend analysis
- For this example, trends and (most) bulk statistics can be improved with ***A*** correction methodology developed from Project FLOSSIE
  - Transferability?
- However, there remain impediments
  - This approach cannot reliably capture individual waves, e.g., max H_s
  - Poor or nonexistent metadata: much of the archives do not contain hull type or wave system and no motivation to rescue them
  - No quality control of the archive products. Improvement?
  - These are not the only NDBC systems past or present

- FLOSSIE has the potential to improve the understanding of these differences, especially with the spectral and recorded samples that will allow studies to get beneath the processing, obtain a fuller understanding of NDBC wave measurements and lead to more homogeneous and useful datasets
- ~2,500,000 wave observations of NDBC data in archives; 12 buoys > 30 years of observations: https://www.nodc.noaa.gov/BUOY/

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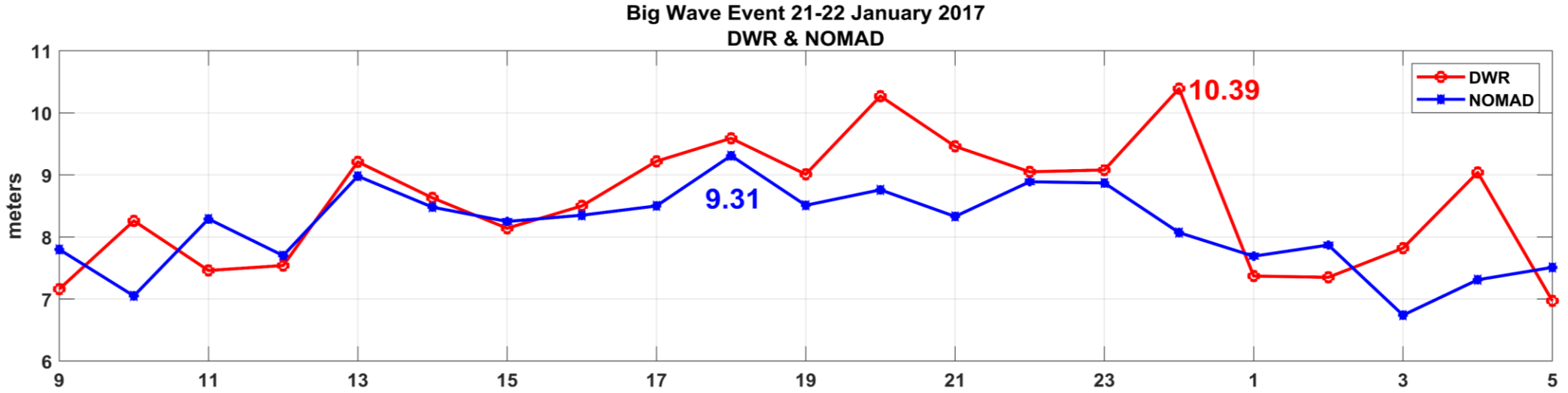
- *Title slide image courtesy of National Weather Service Forecast Office Portland OR USA*
- *Contact Lead Author at: nondbc@gmail.com*

Supplementary Slides

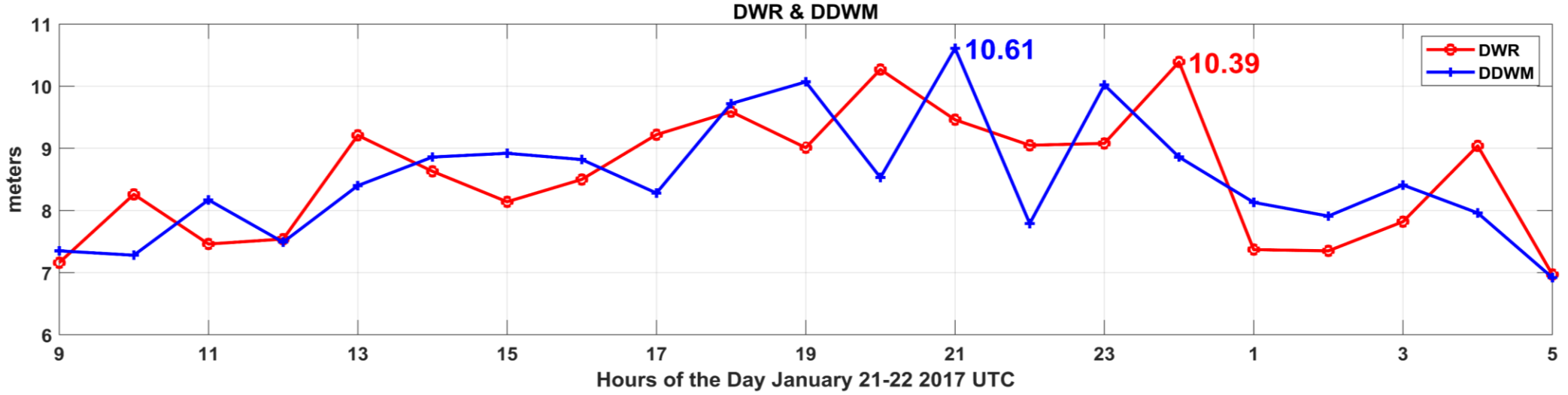
Max Errors due to Separation Distances?

Winds from the South, predominate waves from the WNW

NOMAD SW of DWR
No obvious lag



DDWM NW of DWR
Possible, but inconsistent



Tested Correction Methodologies on Bulk Statistics Discarded Quadratic Correction, Degraded Stats

Statistic	DWR	NDBC NOMAD WA			NDBC 3D DDWM		
		Before	After		Before	After	
			Linear	Quad		Linear	Quad
Mean	**2.31**	2.52	**2.31**	**2.12**	2.28	2.31	2.33
STDEV	**0.99**	1.03	1.03	0.88	0.99	0.97	0.95
Max	**10.39**	9.31	8.54	8.27	10.61	10.47	10.01
Corr Coef	**N/A**	0.9550	0.9550	0.9551	0.9774	0.9774	0.9774
Slope	**-2.57**	-2.61	-2.39	-2.25	-3.11	-3.05	**-2.99**
RMSE	N/A	0.37	0.29	0.35	0.21	0.21	0.21

First and Second Time Period Statistics

	First Period	Second Period
Starts	16 Oct 2015	08 Jul 2017
Ends	08 Jul 2017	31 Mar 2019
#Samples	14,687	14,030
% of Sample Population	51.1	48.9
Mean Height NOMAD WA	2.67	2.37
Mean Height 3D DDWM	2.45	2.11
Mean Height DWR	2.45	2.16
Corr Coeff NOMAD – DWR	0.9500	0.9590
Corr Coeff DDWM – DWR	0.9792	0.9754
Slope NOMAD WA	-6.92	+10.2
Slope 3D DDWM	-6.07	+10.5
Slope DWR	-6.37	+10.5