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ExWaMar, (2016-2019) "EXtreme wave WArning criteria for MARine structures", Norwegian Research Council project (no 256466).

On concurrency of wave and crest height characteristics at two neighbouring wave buoys

- *using a new flexible and cost effective wave sensor*

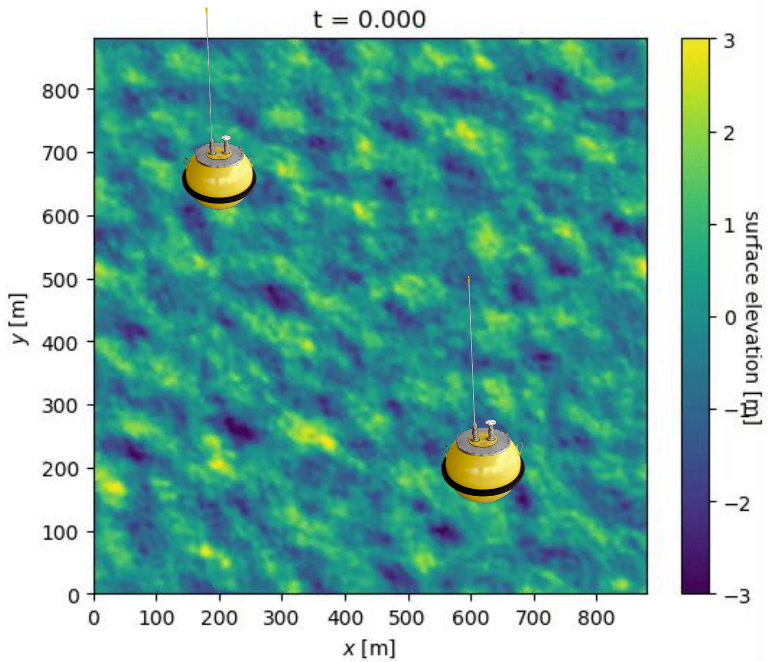
Ole Johan Aarnes, Birgitte Furevik, Anne Karin Magnusson, Odin Gramstad, Elzbieta Bitner-Gregersen and Harald Tholo

11.11.2019 - 2nd International Workshop on Waves, Storm Surges and Coastal Hazards

Motivation

- **Are <u>sea states</u> with higher probability of elevated wave heights/crests verifiable with buoys?**

- **Comparing wave height/crest statistics from two adjacent wave buoys**
  - ✓ Identical sensors
  - ✓ Homogeneous wave conditions (deep water)
  - ✓ Buoys tend to underestimate crests
  - ✓ Short time series (~4 months)

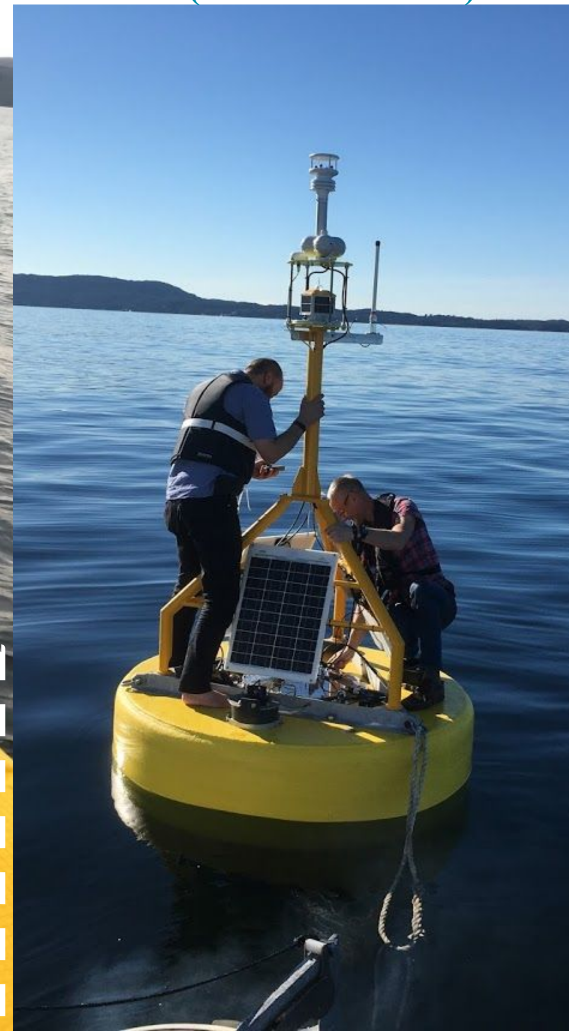


Tideland

Motus (Wave sensor #18)

EMM 2.0

Motus (Wave sensor #17)



Waverider

Reference buoy

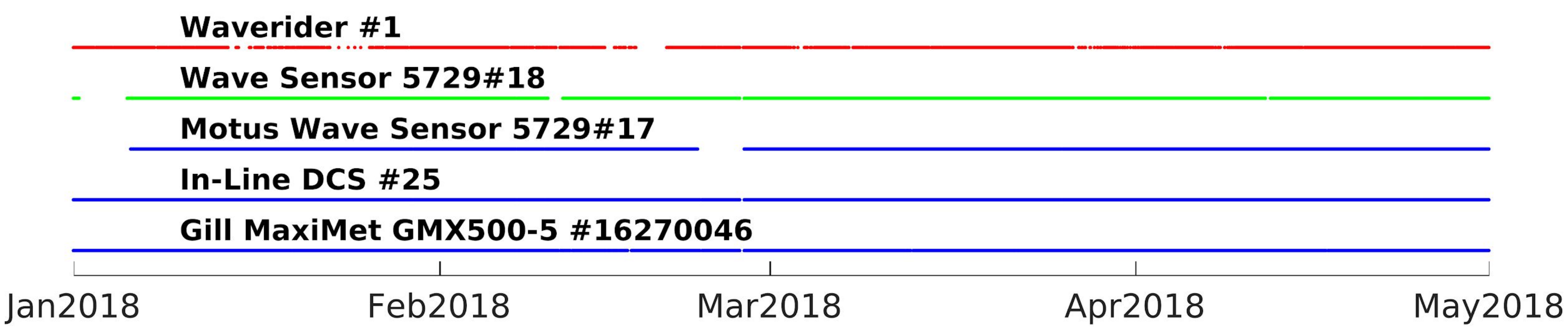
Motus Wave Sensor

- *a new flexible and cost effective wave measuring device*
- *Inertial Measurement Unit (IMU) / Micro Electro-Mechanical Systems (MEMS)*

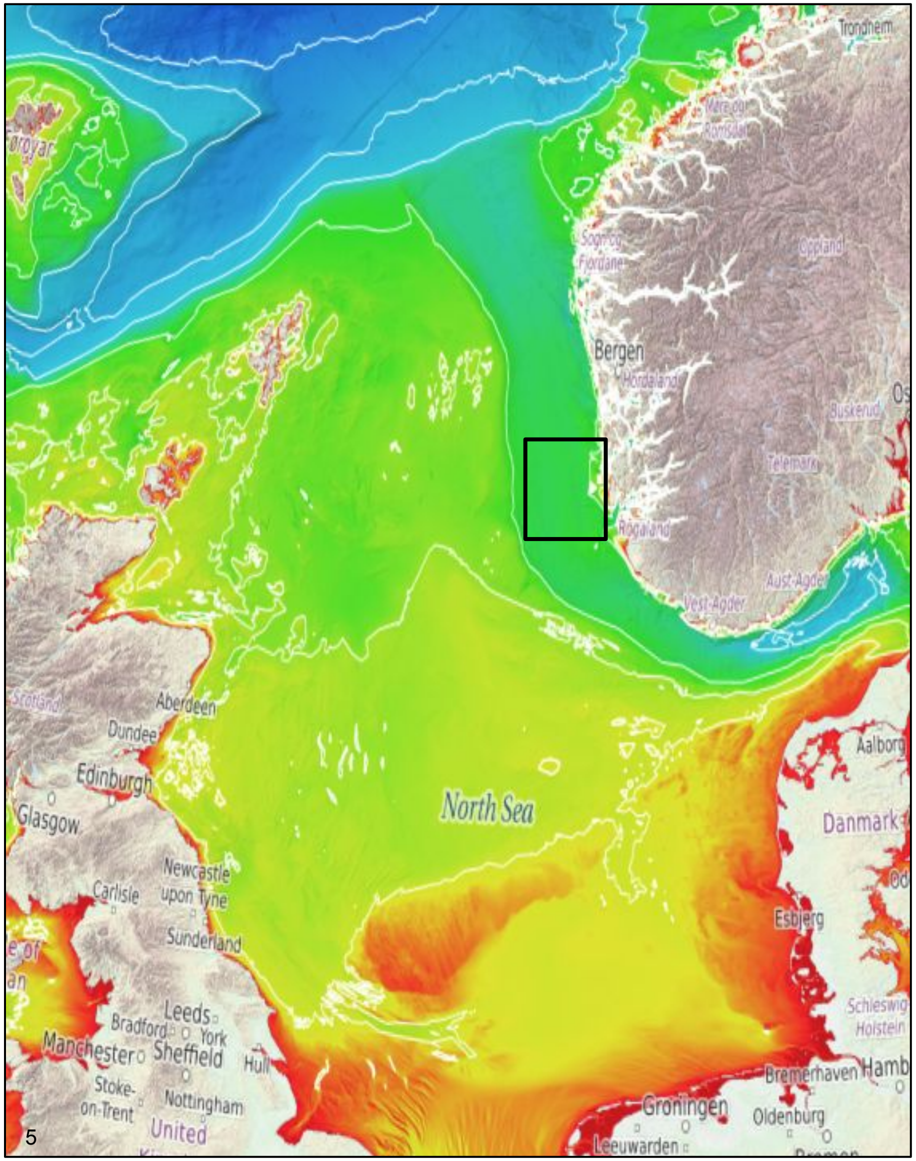
Available data

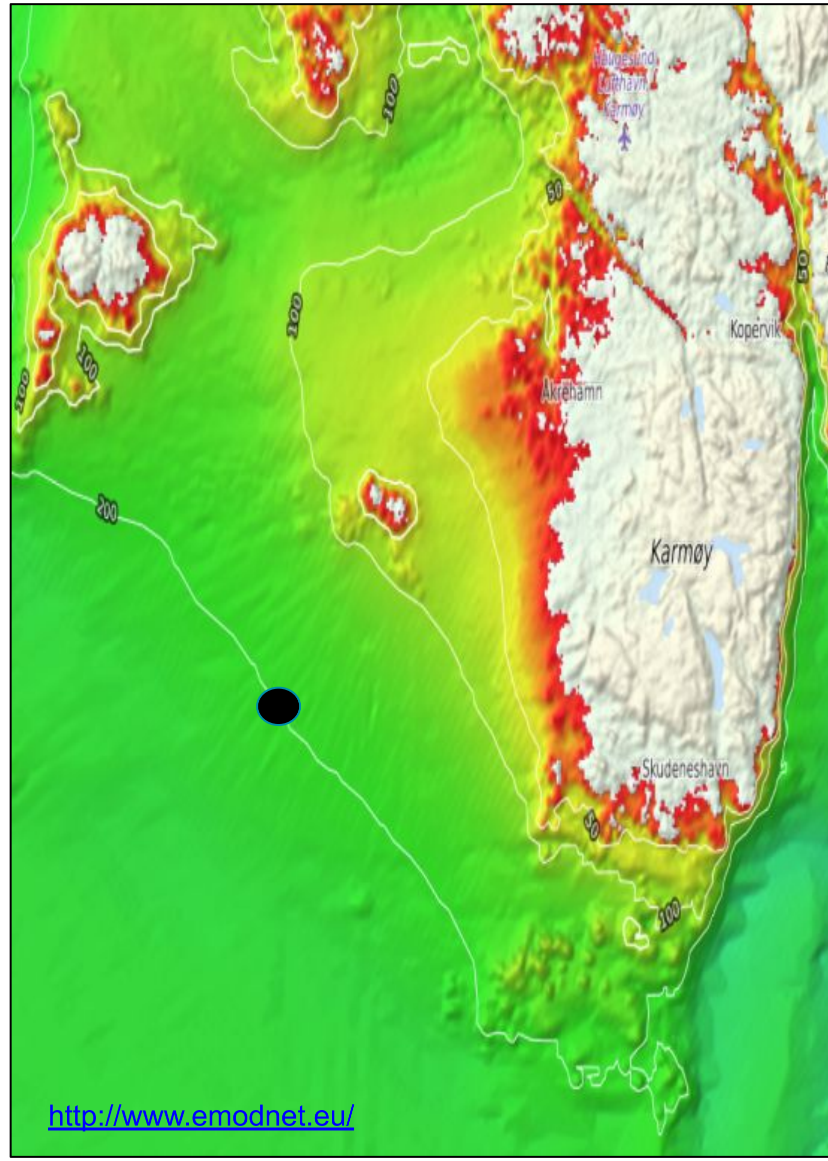
*No filtering applied

Data (30 min data) / Sensor		Waverider / Sensor #1	Tideland / Sensor #18	EMM2.0 / Sensor #17
Wave	Integrated parameters	√	√	√
	Fourier coefficients	√	√	√
	Surface elevation (4Hz)*		√	√
Currents	Speed/direction			√
Winds	Speed/direction (gust)			√

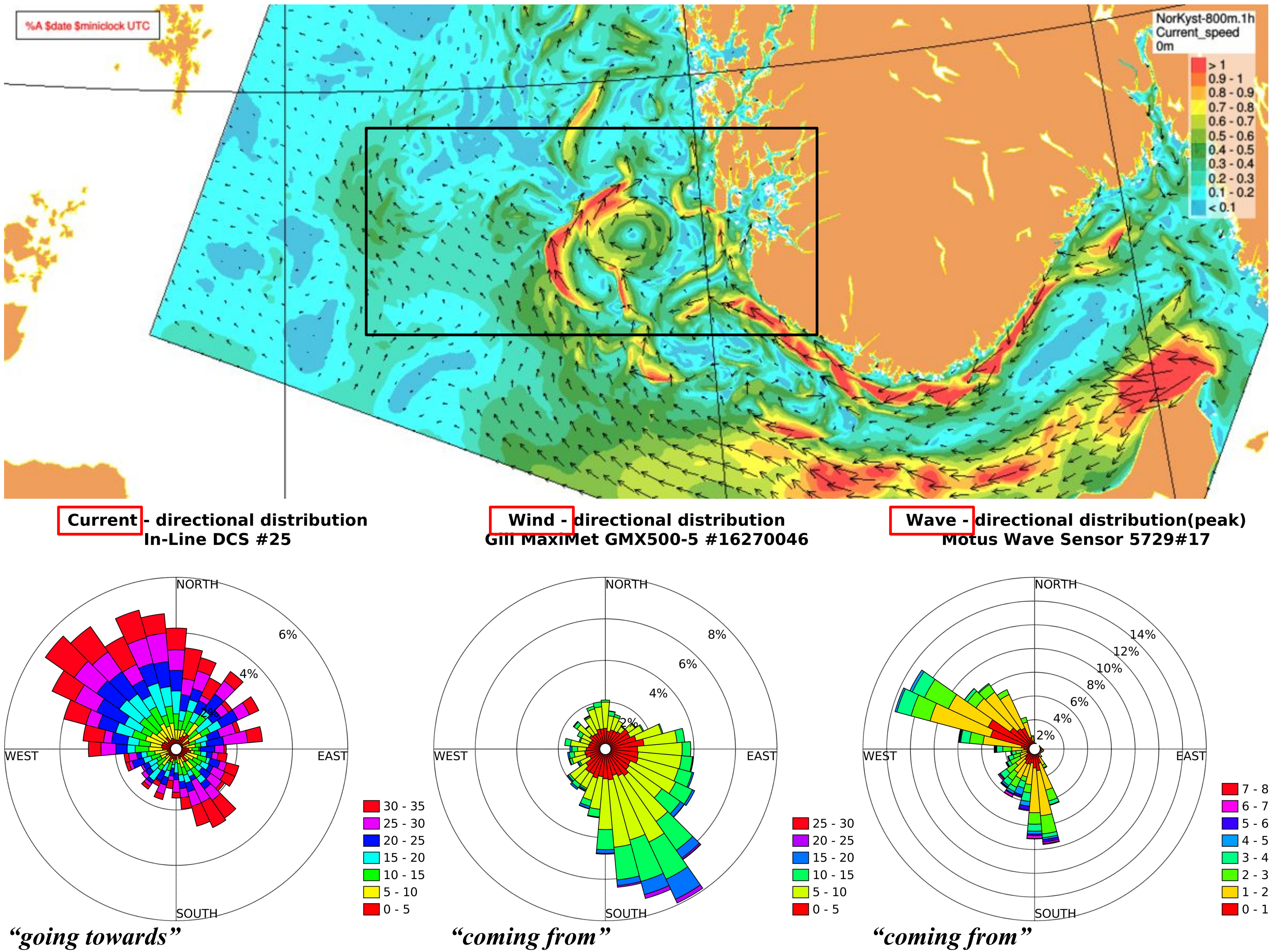


Area of interest / bathymetry

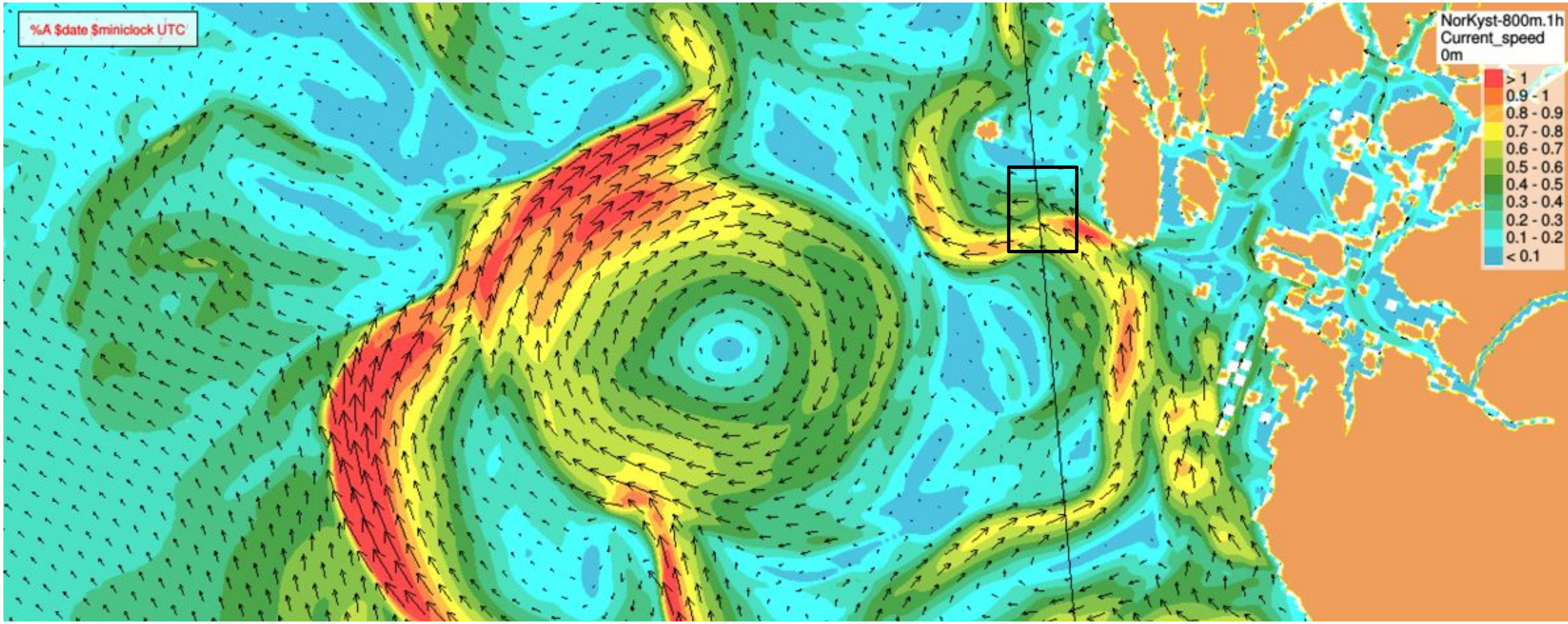




http://www.emodnet.eu/



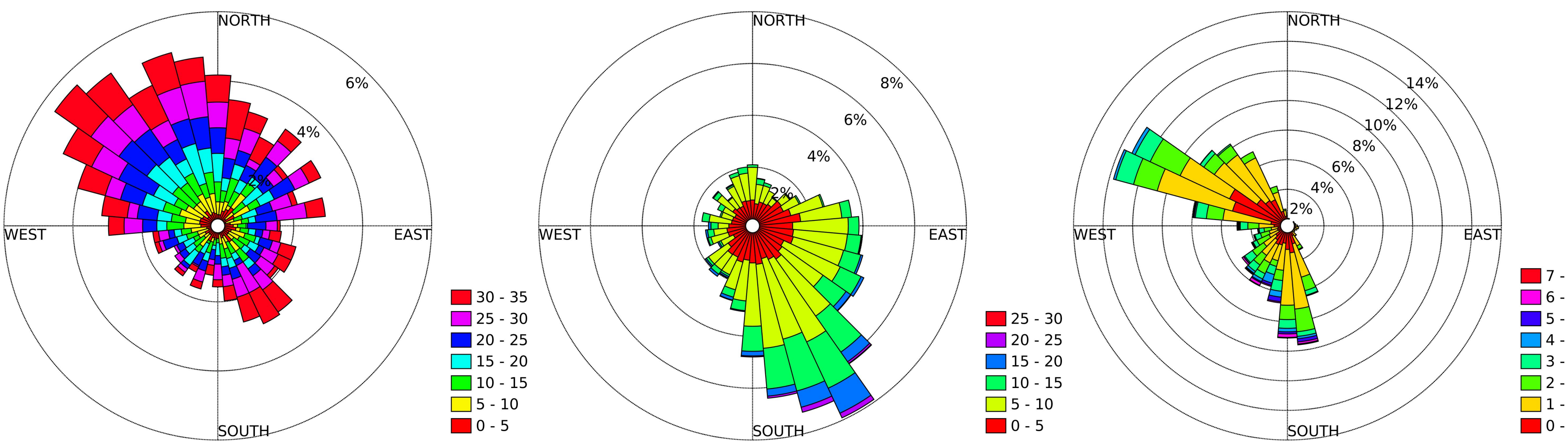
%A $date $miniclock UTC
NorKyst-800m.1h
Current_speed
0m
> 1
0.9 - 1
0.8 - 0.9
0.7 - 0.8
0.6 - 0.7
0.5 - 0.6
0.4 - 0.5
0.3 - 0.4
0.2 - 0.3
0.1 - 0.2
< 0.1
Current - directional distribution
In-Line DCS #25
Wind - directional distribution
Gill MaxiMet GMX500-5 #16270046
Wave - directional distribution(peak)
Motus Wave Sensor 5729#17
NORTH
WEST
EAST
SOUTH
2%
4%
6%
30 - 35
25 - 30
20 - 25
15 - 20
10 - 15
5 - 10
0 - 5
“going towards”
NORTH
WEST
EAST
SOUTH
2%
4%
6%
8%
25 - 30
20 - 25
15 - 20
10 - 15
5 - 10
0 - 5
“coming from”
NORTH
WEST
EAST
SOUTH
2%
4%
6%
8%
10%
12%
14%
7 - 8
6 - 7
5 - 6
4 - 5
3 - 4
2 - 3
1 - 2
0 - 1
“coming from”



Current - directional distribution
In-Line DCS #25

Wind - directional distribution
Gill MaxiMet GMX500-5 #16270046

Wave - directional distribution(peak)
Motus Wave Sensor 5729#17

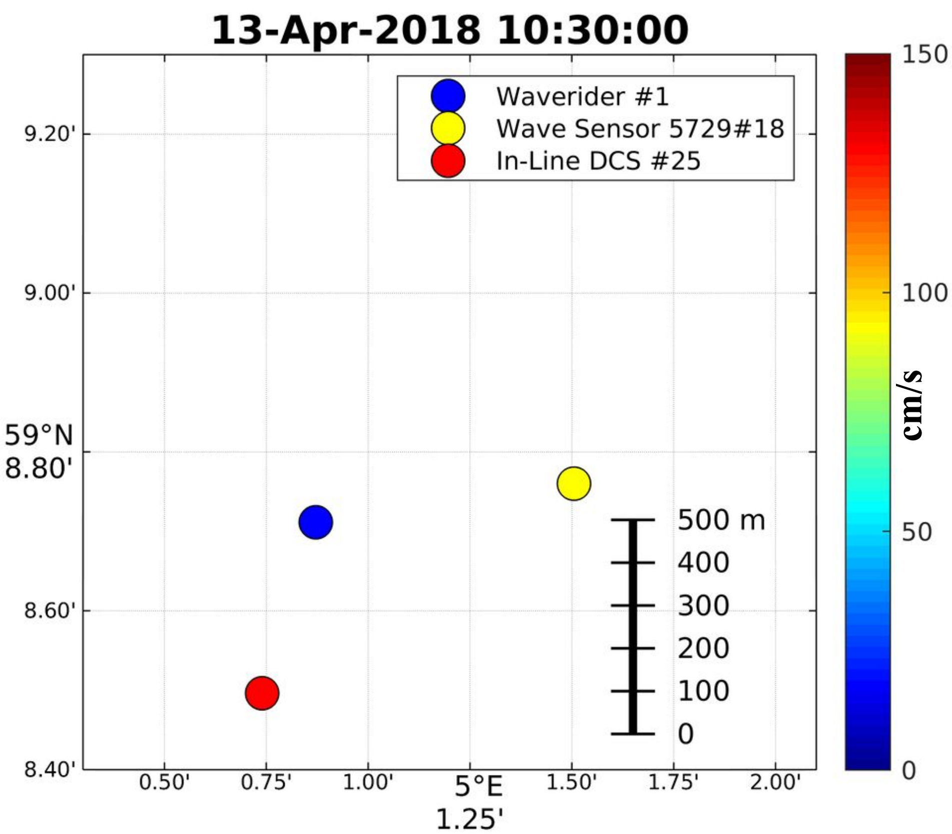


"going towards" *"coming from"* *"coming from"*

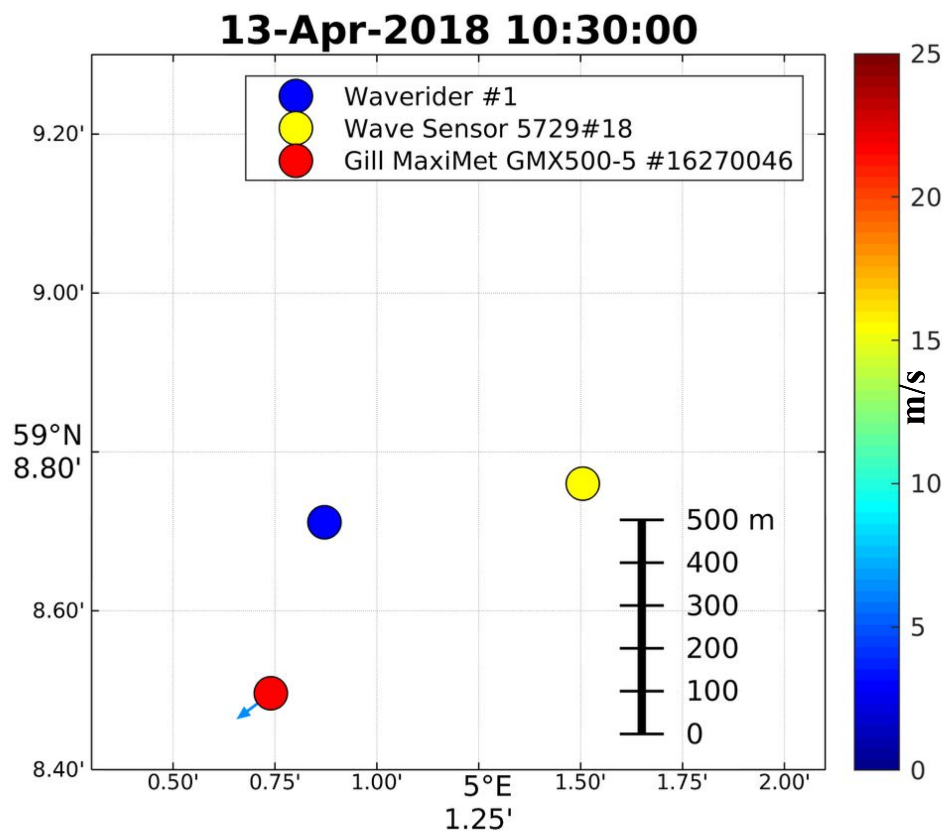
Buoy drift vs winds/currents

- one week of data

Drift relative to **current**



Drift relative to **winds**



- Sensor #17(**red**) and sensor #18(**yellow**) similar behavior
- Waverider #1(**blue**) slightly less affected by winds (windage)

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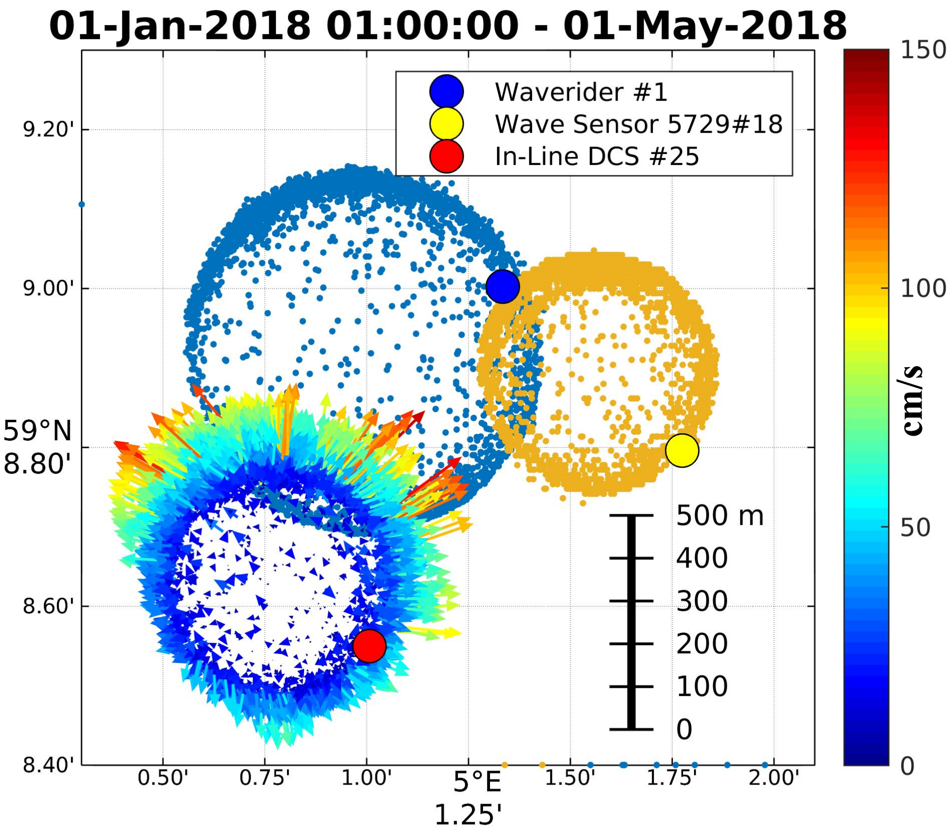
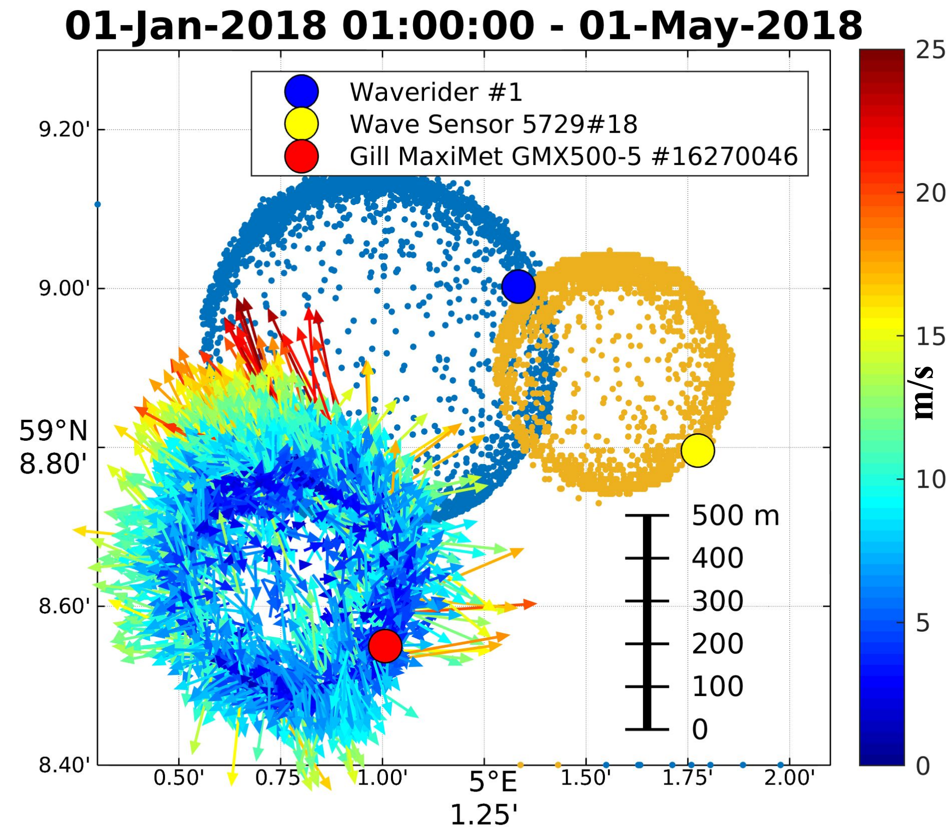
Buoy drift vs winds/currents

- *4 months of data*

Current relative to position



Winds relative to position



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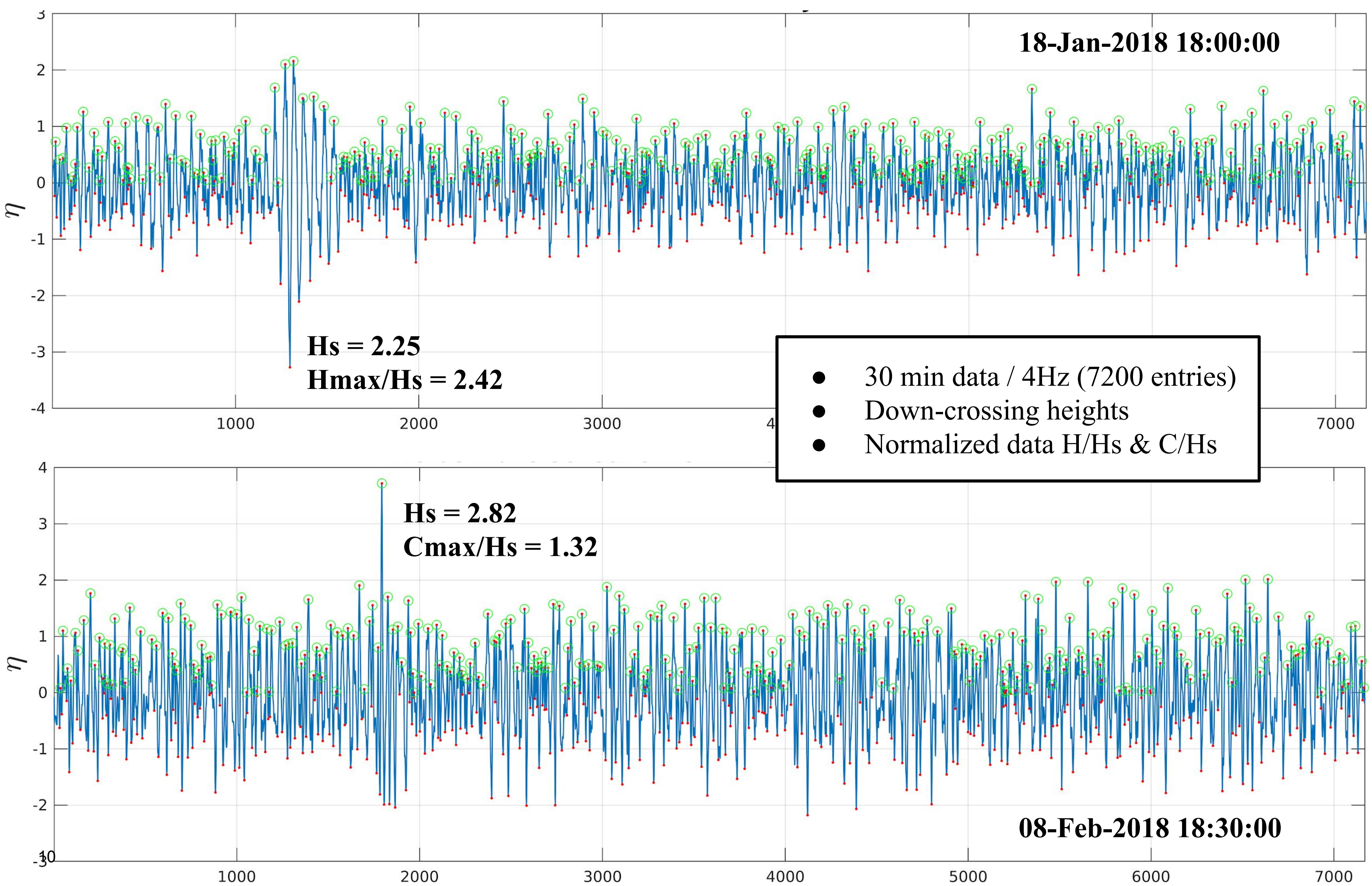
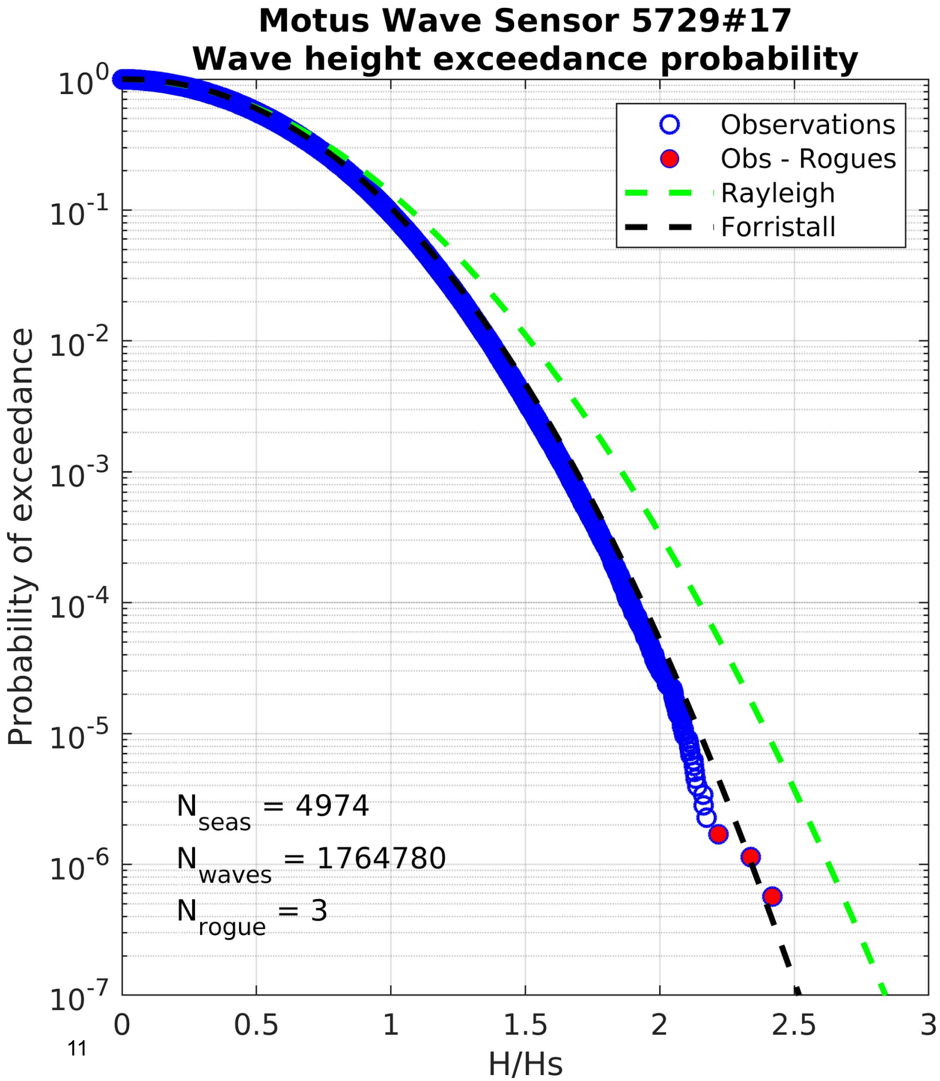
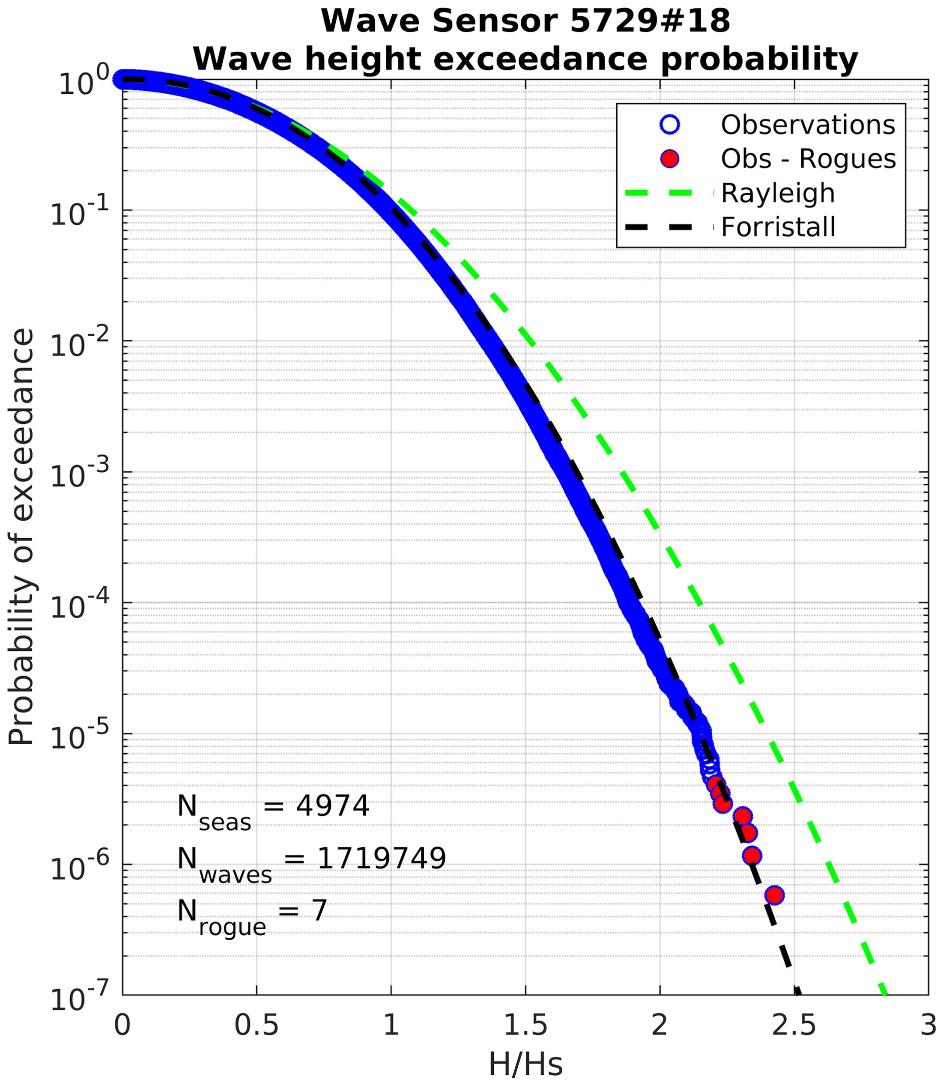
Surface elevation data

- *Motus Wave Sensor 5729#17: Maximum wave/crest height*



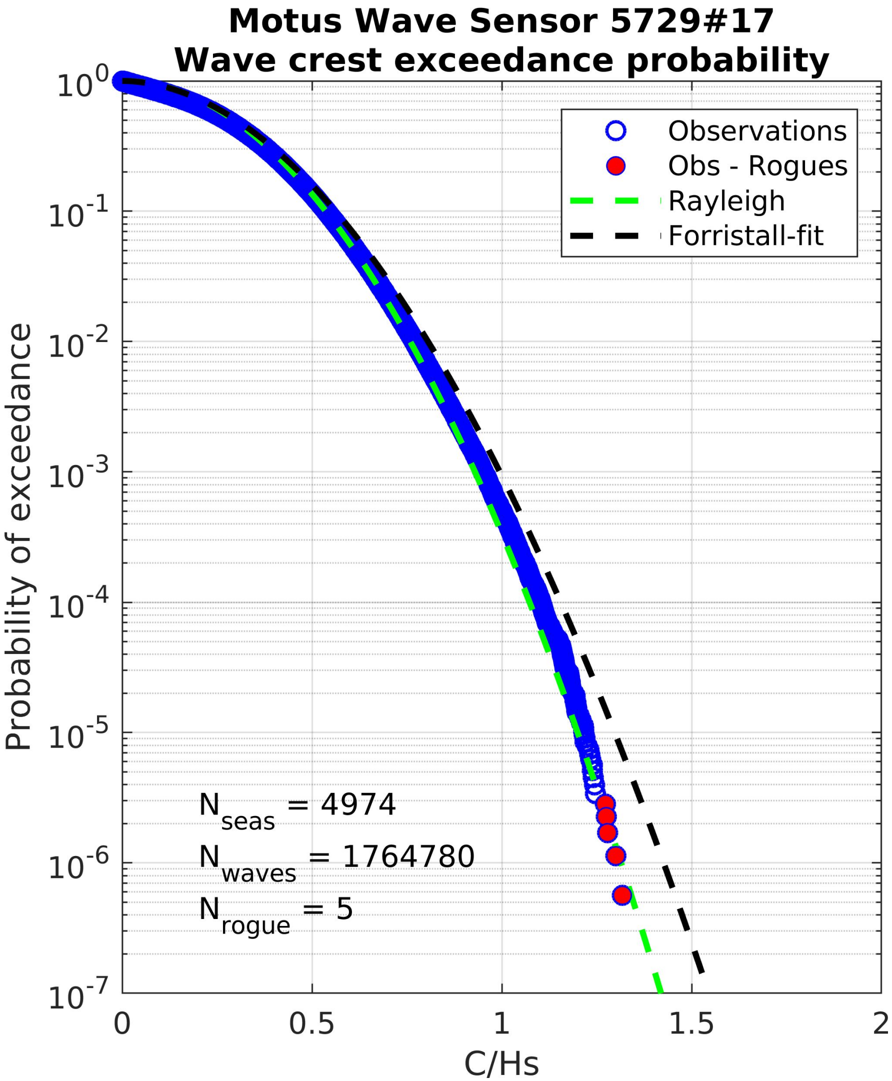
Normalized Wave Height Distribution

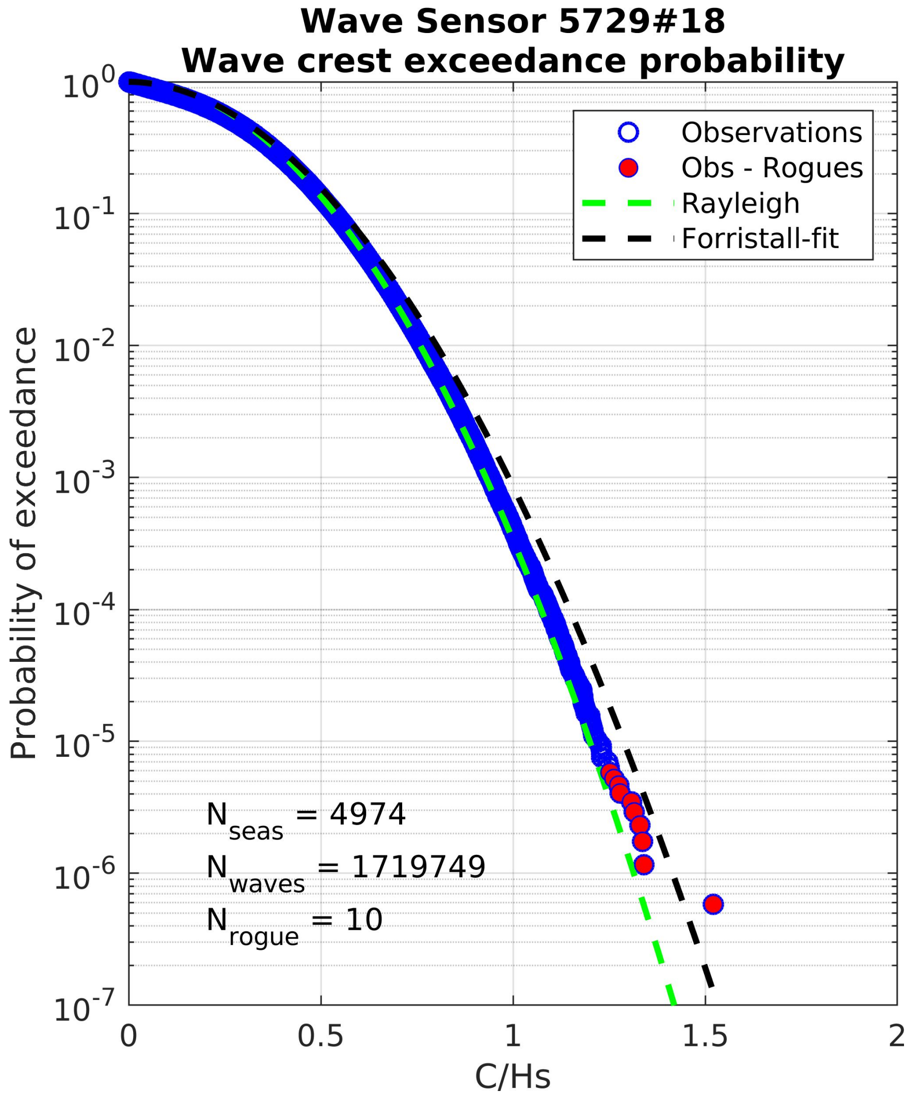




Hmax/Hs > 2.2
Cmax/Hs > 1.25

Normalized Crest Height Distribution

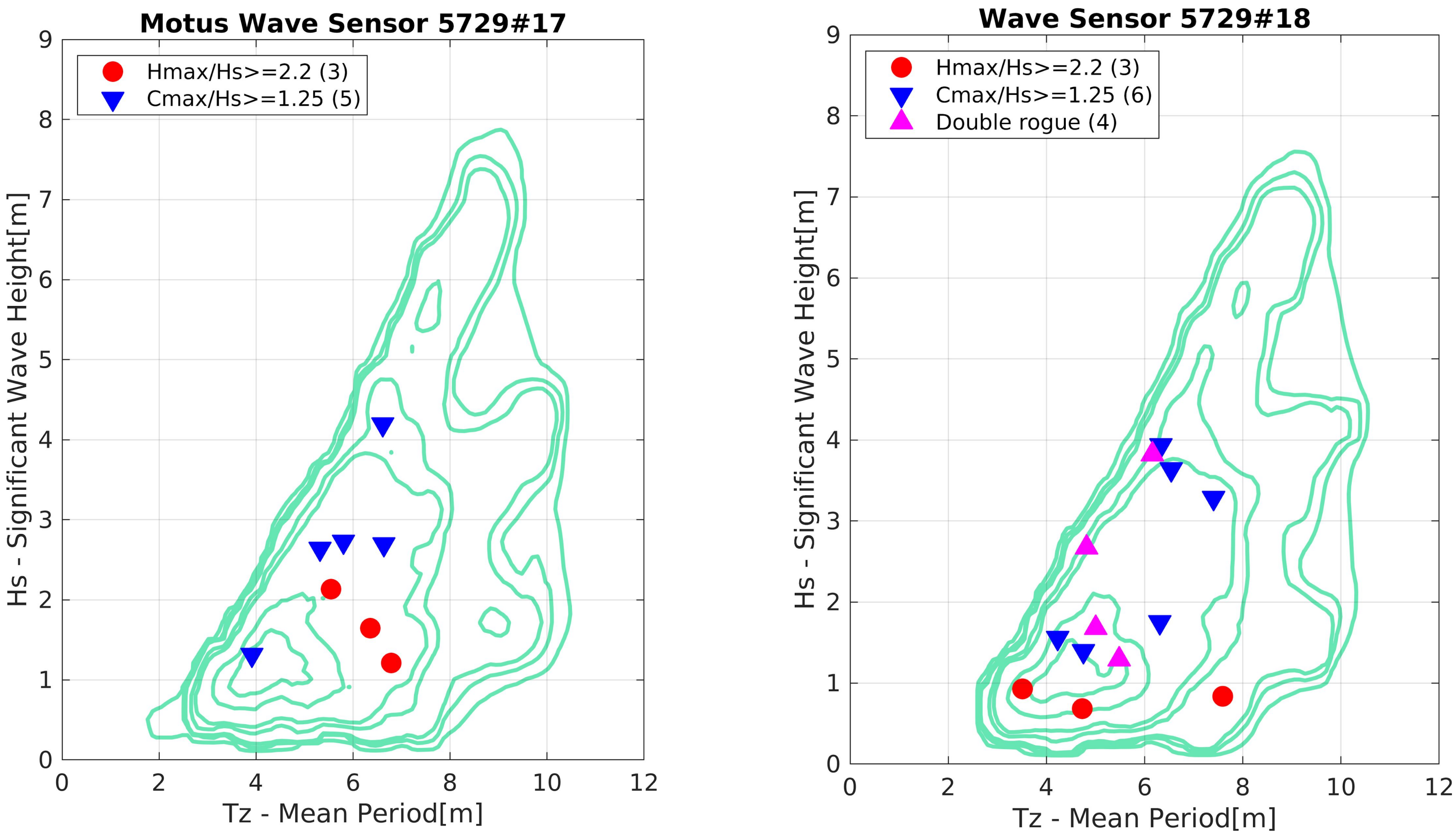




Rogue wave occurrences

- *Statistics and type of sea states (Hs/Tz)*

Hmax/Hs > 2.2
Cmax/Hs > 1.25



	n_{seas}	n_{waves}	Max (H/Hs)	Max (C/Hs)	Rogues H>2.2Hs	Rogues C>1.25Hs	Double rogues
Sensor #17	**4974**	**1764780**	**2.42**	**1.32**	**3**	**5**	**0**
Sensor #18	**4974**	**1719749**	**2.42**	**1.52**	**7**	**10**	**4**

Hmax/Hs > 2.2
Cmax/Hs > 1.25

Rogue waves

- *mechanisms and predictability*

- In the absence of shoals (deep water) the main mechanisms for rogues are
  - linear superpositioning
  - current effects (refraction)
  - **modulational instability**
    - steep sea states
    - narrow wave spectrum (bandwidth), both in frequency and direction

- **Benjamin-Feir index** (BFI) - a predictor of rogue waves?
  - ratio between wave **steepness** and **spectral bandwidth**
  - high BFI may represent increased probability of rogues
  - demonstrated numerically and in wave tanks - not well documented in the open ocean

---

Steepness

$$\epsilon = k_p H_s / 2$$

Spectral bandwidth

"Half width half maximum" → $BFI_f = \epsilon f_p / \delta_f$

$$\delta_\theta = \sqrt{2\left(1 - \frac{\left|\sum_{j=1}^{36} D(\theta_j) e^{i\theta_j}\right|}{m_0}\right)}$$ → $BFI_\theta = \epsilon / \delta_\theta$

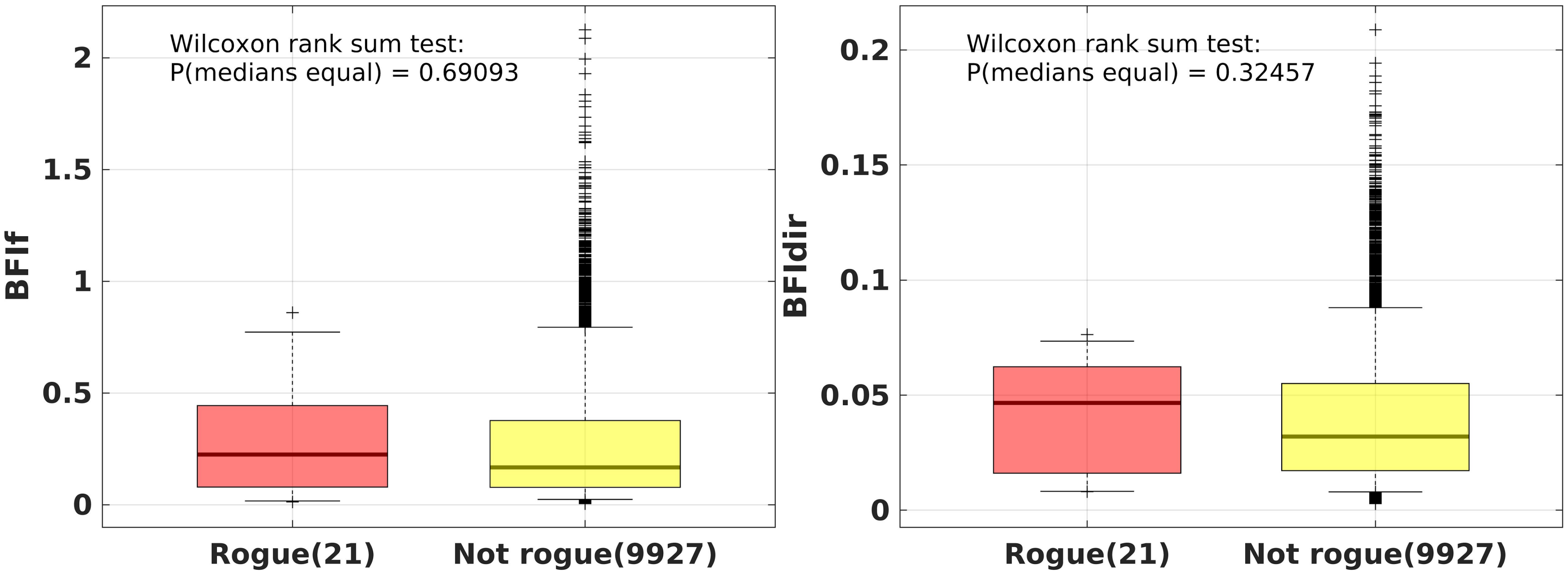
BFI

BFI - Rogue wave predictability

- *combining sensor #17 and #18*

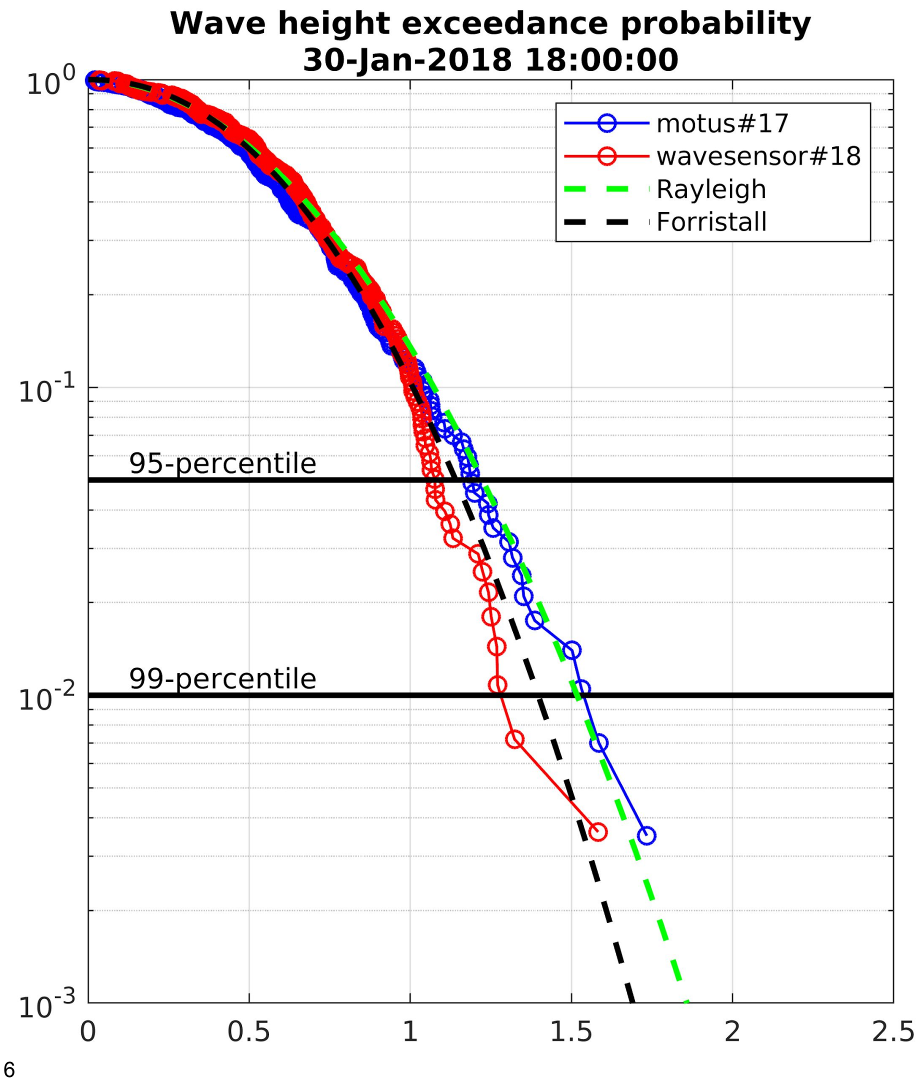
$$BFI_f = \epsilon f_p / \delta_f$$

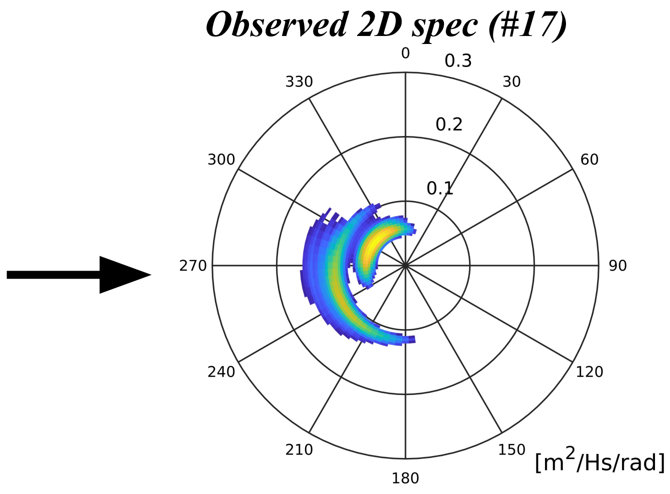
$$BFI_\theta = \epsilon / \delta_\theta$$



Boxes show Q1 and Q3 while whiskers represent the 5- and 95-percentiles

Higher order spectral model (HOSM) vs observations





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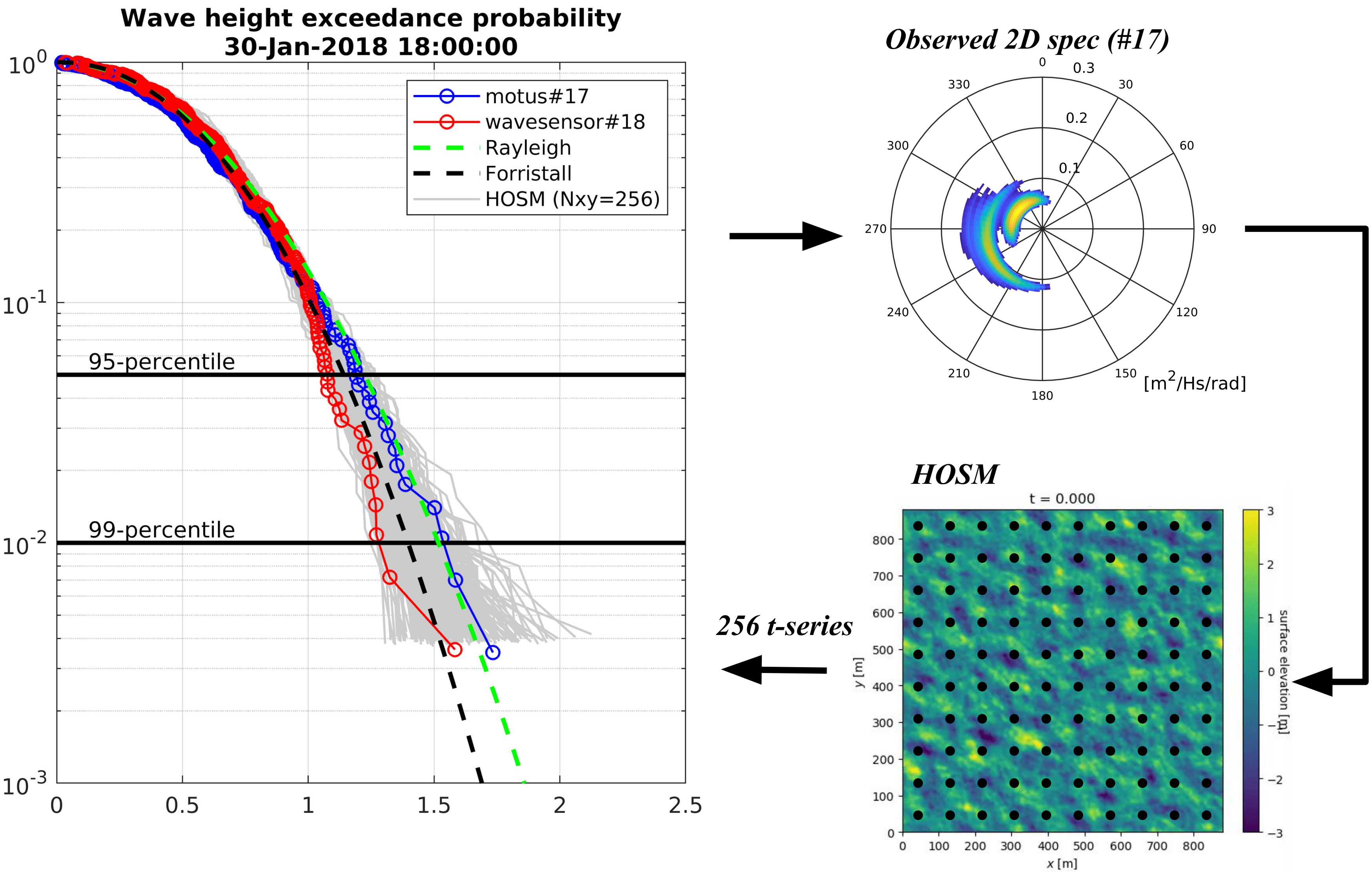
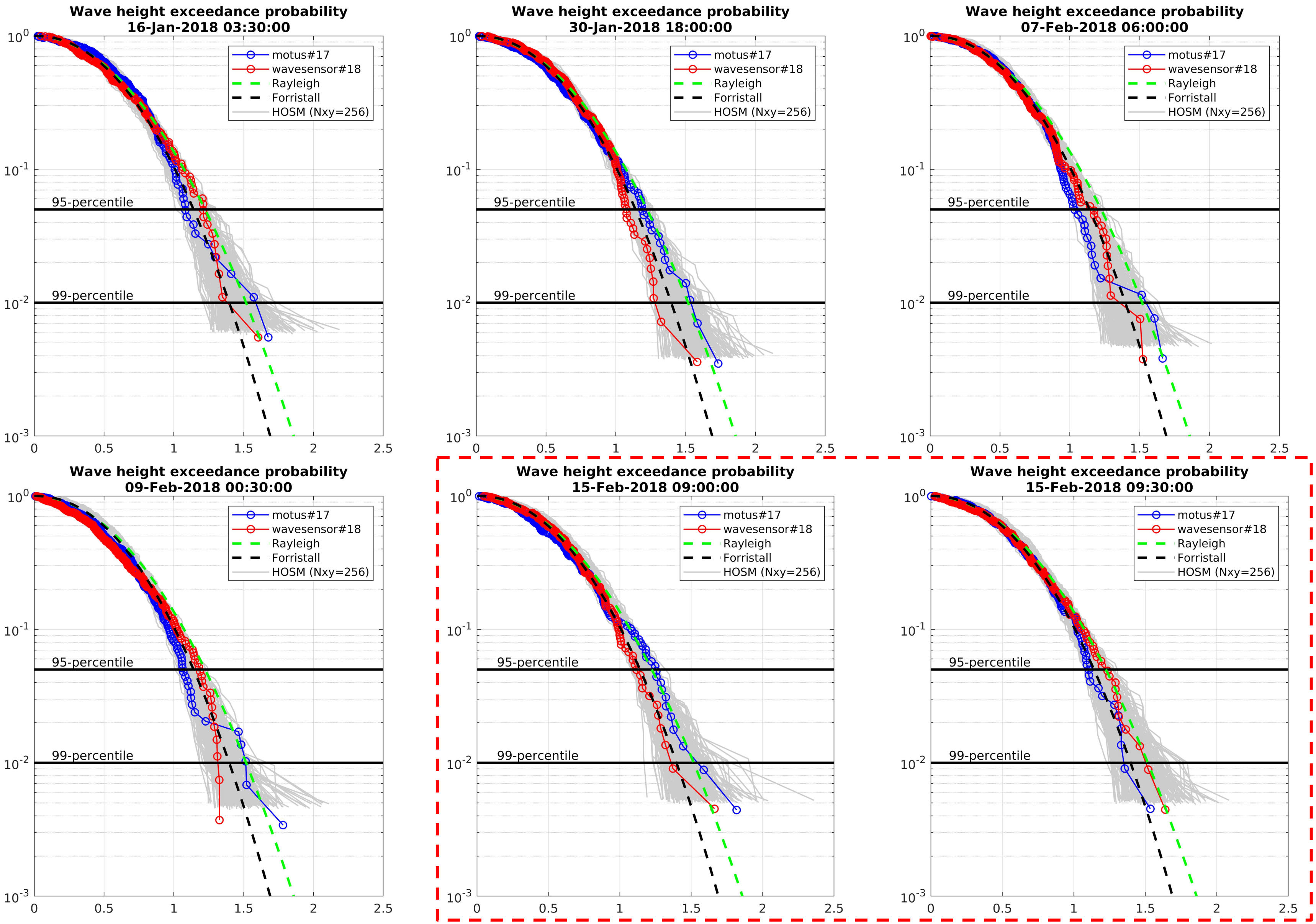
Higher order spectral model (HOSM) vs observations



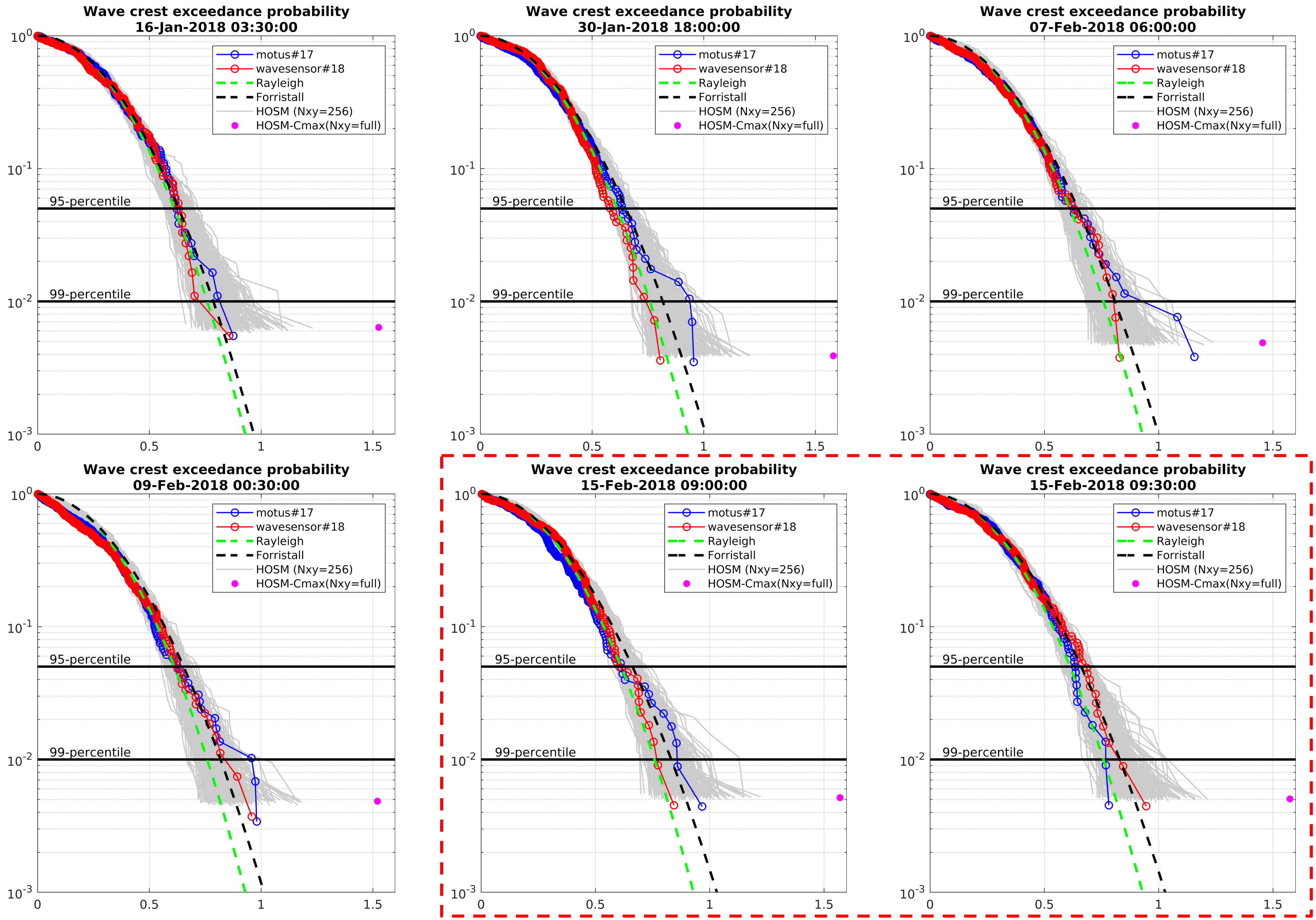
Higher order spectral model (HOSM) vs observations

- *Wave <u>height</u> distribution: Six case studies*



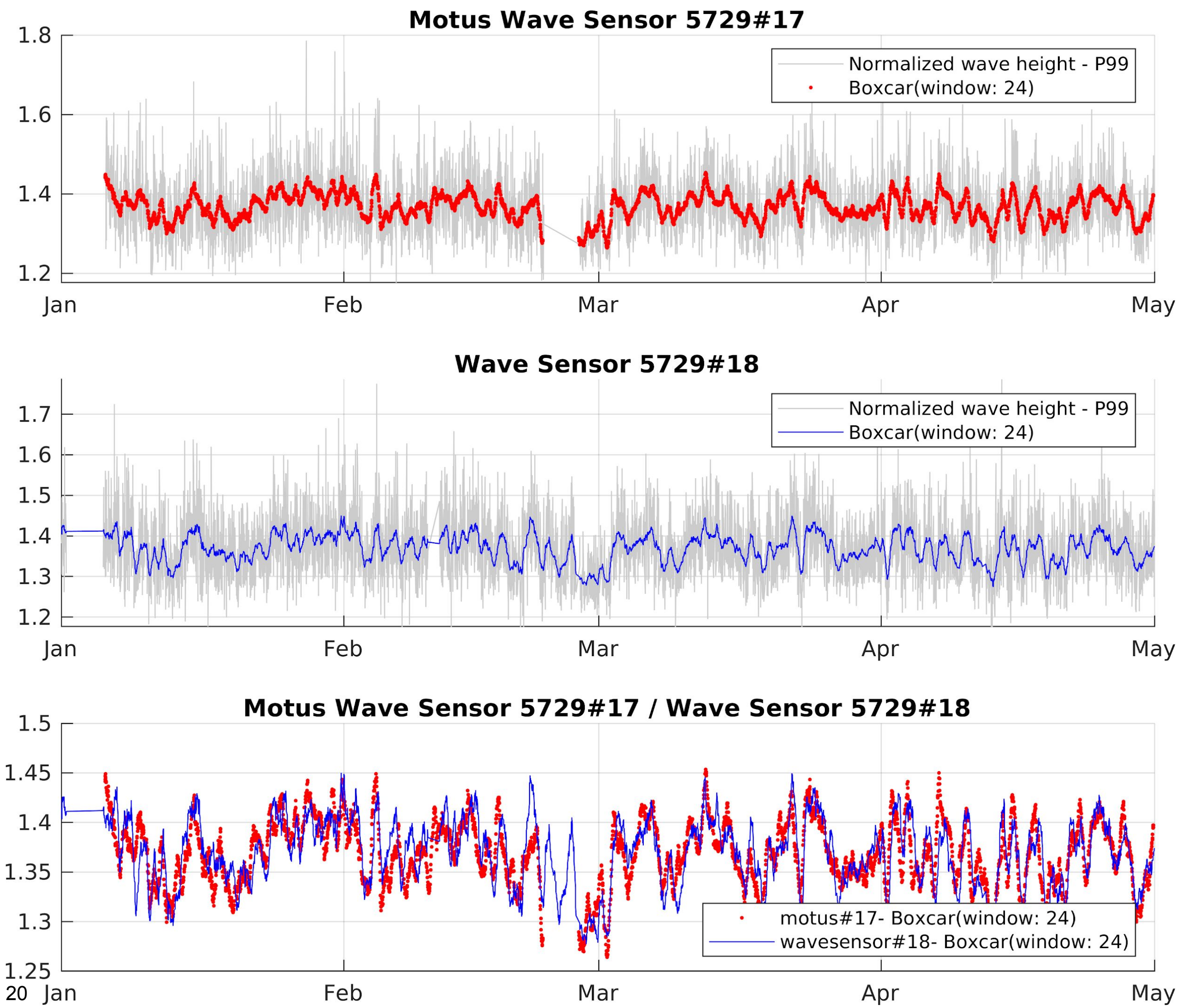
Higher order spectral model (HOSM) vs observations

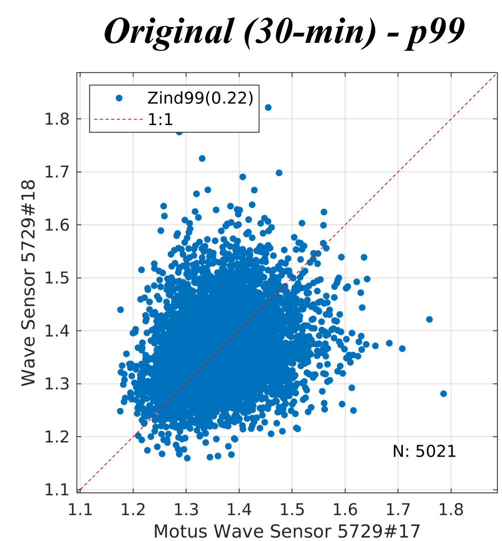
- ***Wave crest distribution: Six case studies***

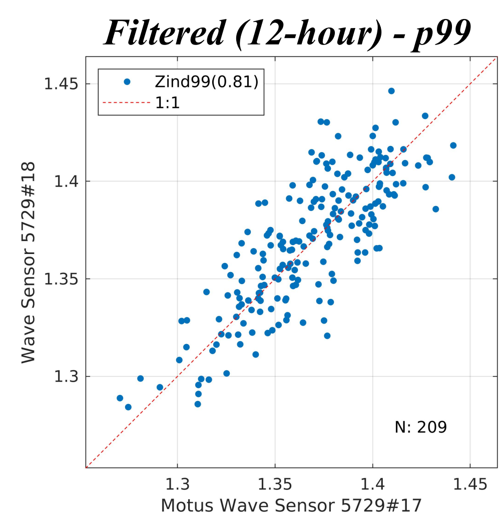


Wave heights - 99 percentile

- *30-min data vs filtered (boxcar: 12 hours / 24 time steps)*

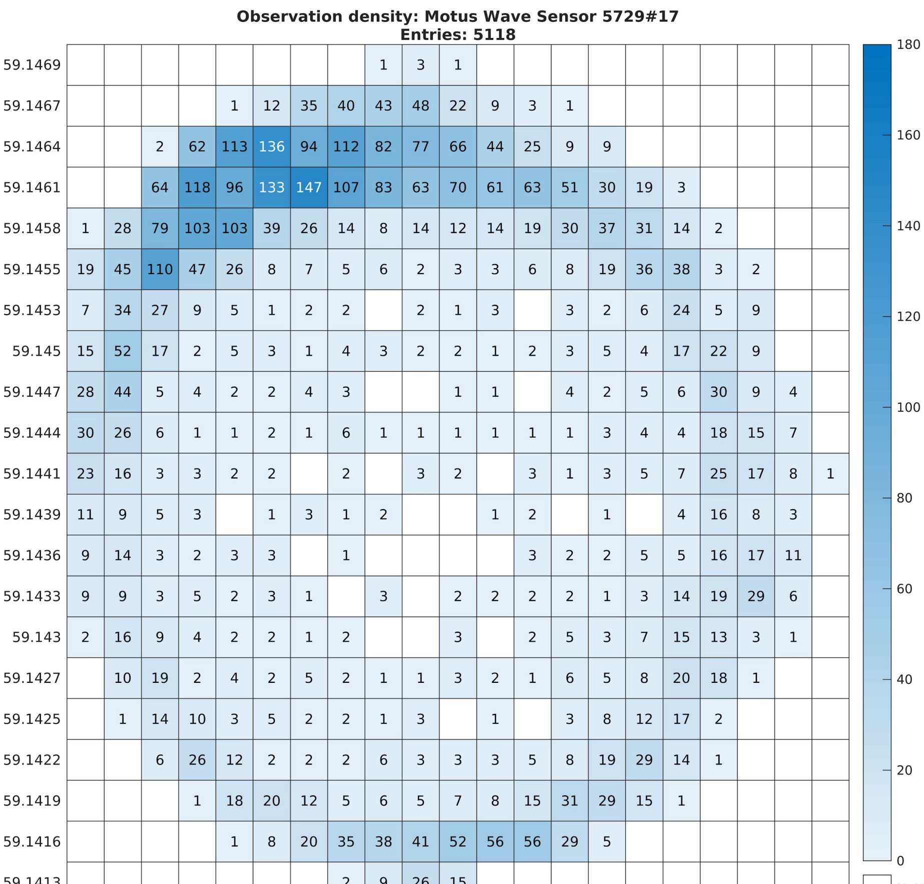


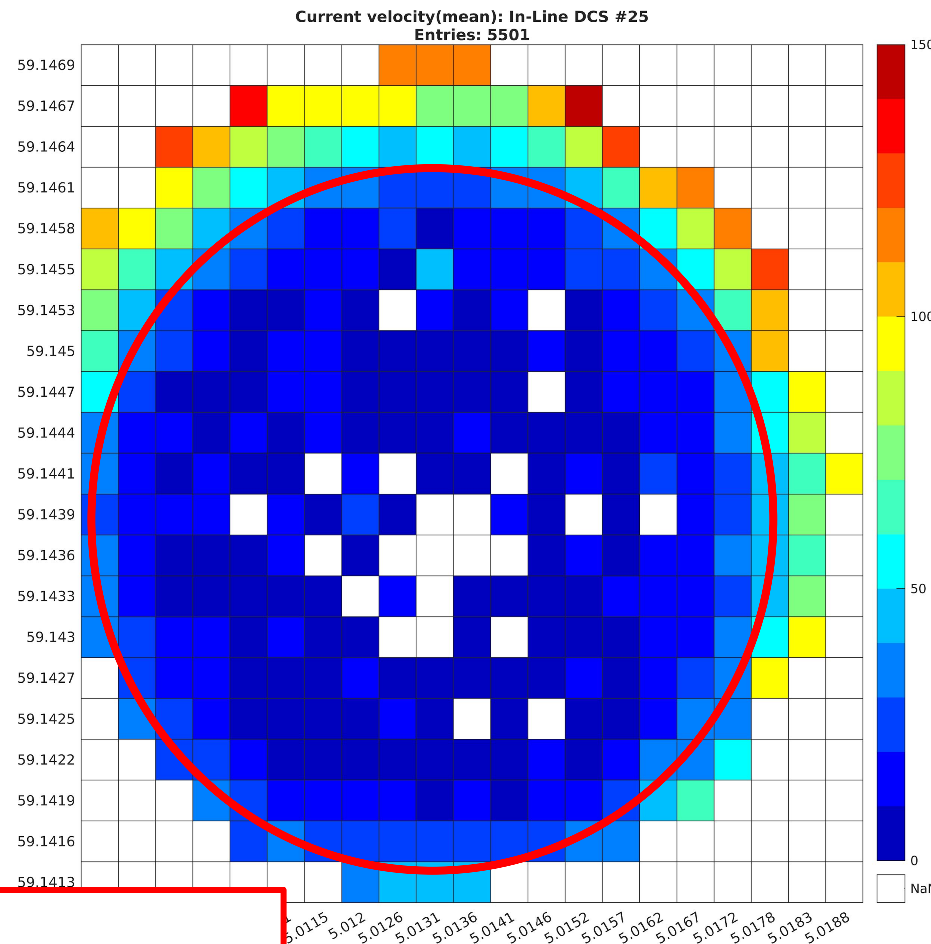




Buoy position density/mean current velocity

- *binned by equally sized lat/lon-bins*





Are wave/crest statistics affected by:

- radial position (current velocity) due to line tension?
- current heading relative to waves?

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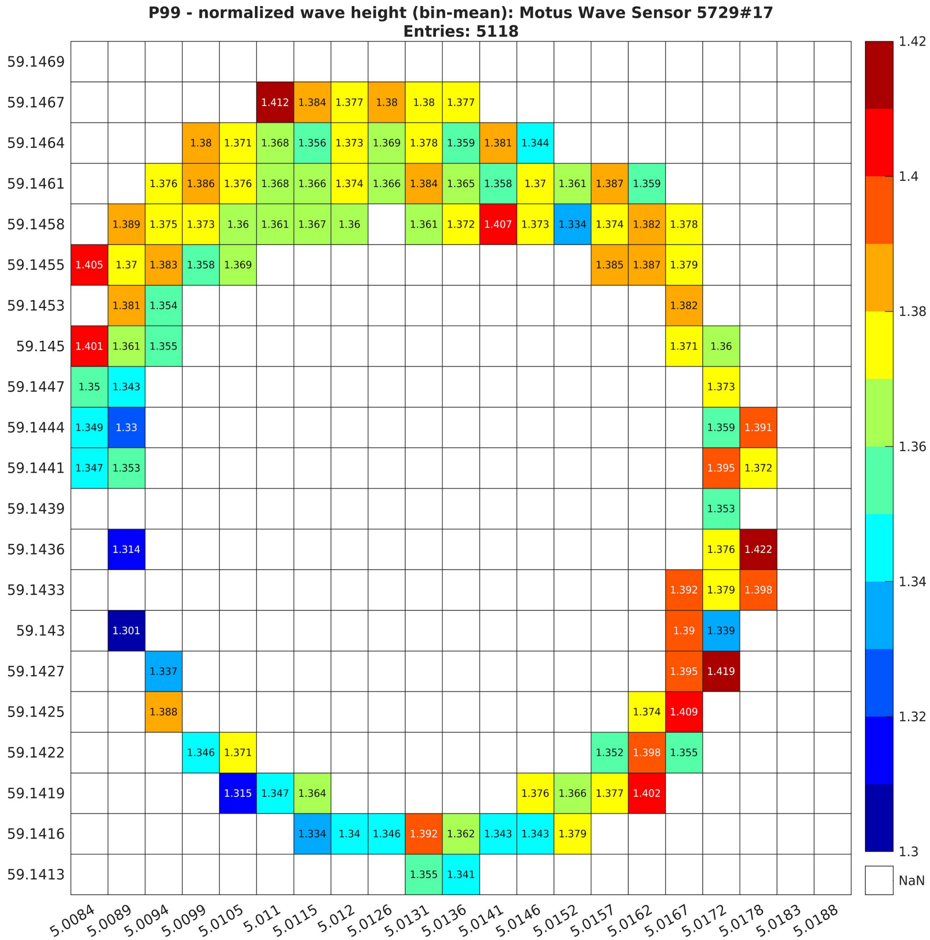
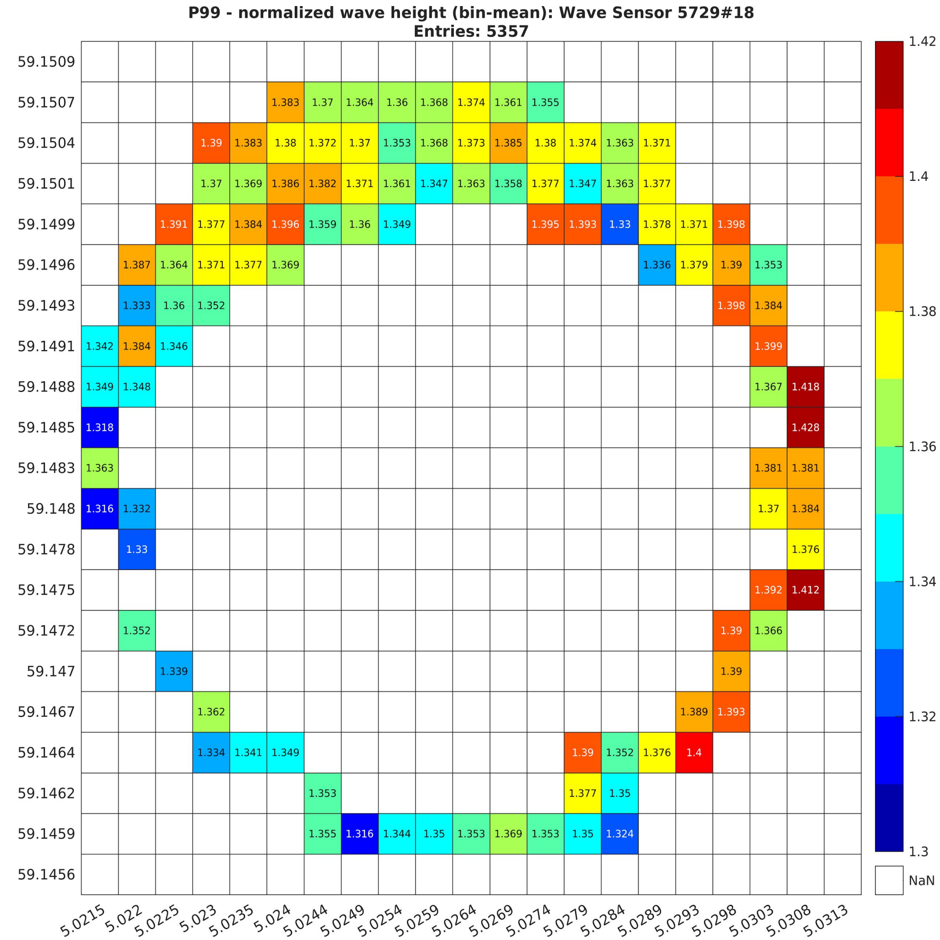
P99 - normalized wave height

- *mean value per lat/lon-bin (bins N<12 censored)*





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Summary / conclusions

Based on 4 months of wave data from two adjacent MOTUS buoys, we find that:

- Long-term wave height/crest statistics correspond to 2nd order wave theory

- Short-term variability in upper tail behavior (rogues) is significant
  - temporally and spatially
  - supported by higher order spectral model (HOSM) simulations
  - challenging to verify sea states (para) representing elevated probability of rogues using buoys
  - higher percentiles may provide a more robust metric for rogue wave warning (validation)

- Wave height/crest statistics
  - seem unaffected by line tension (due to currents)
  - could be affected by current heading (relative to wave direction)

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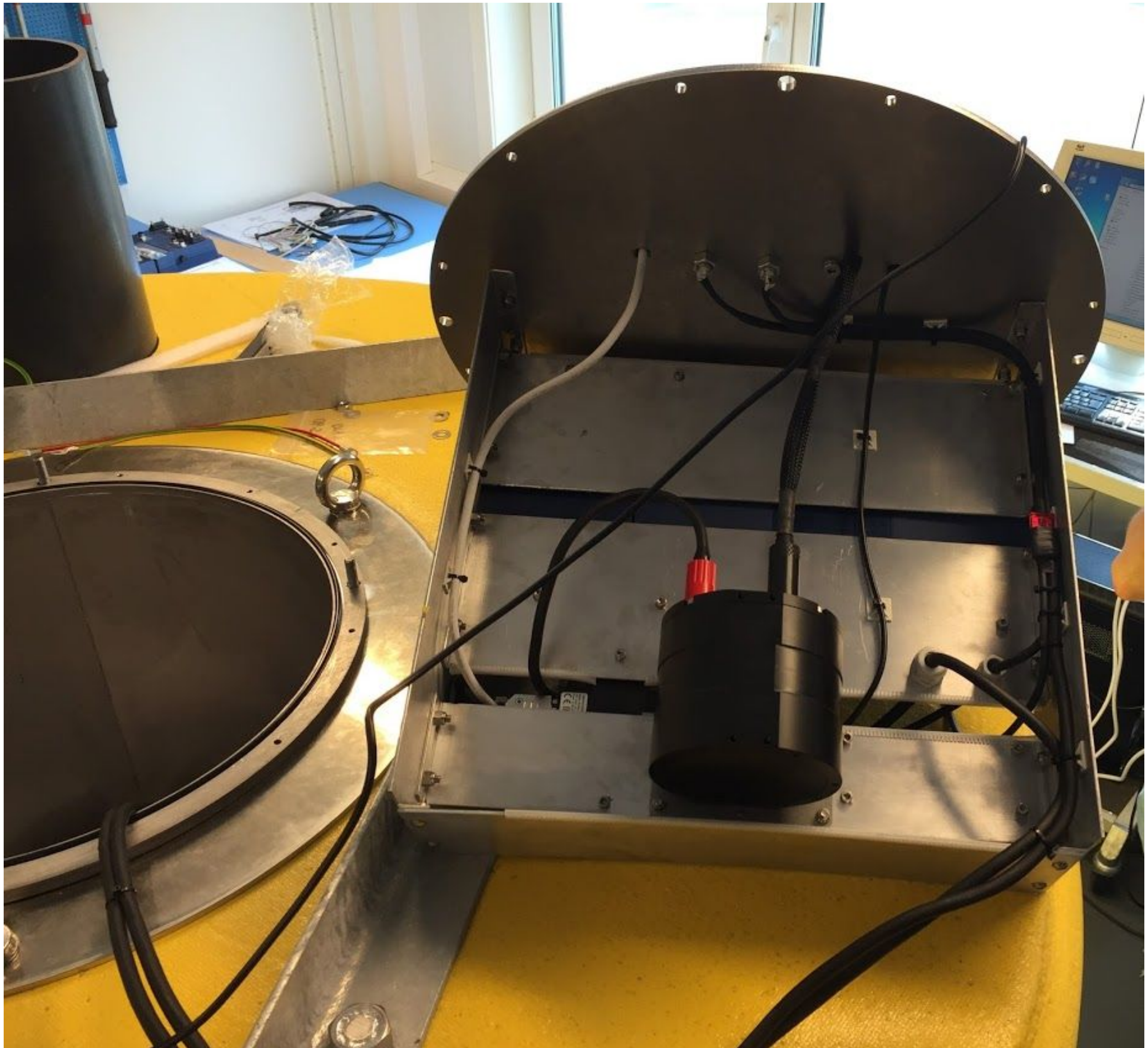
Extras

Motus Wave Sensor

- *a new flexible and cost effective wave measuring device*
- *based on Inertial Measurement Unit (IMU) / Micro Electro-Mechanical Systems (MEMS)*



Tideland

Motus (Wave sensor #18)

EMM 2.0

Motus (Wave sensor #17)

Waverider

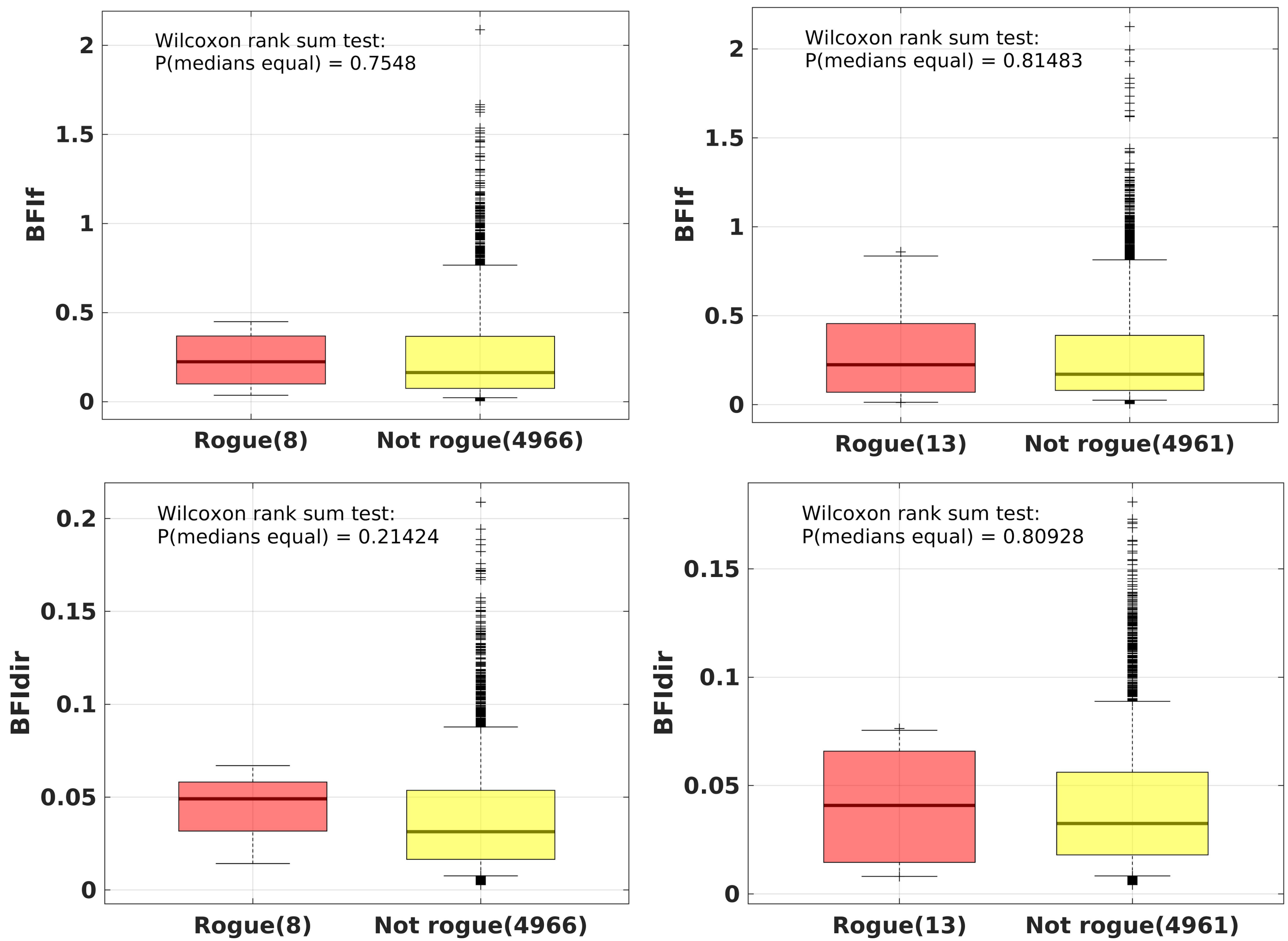
Reference buoy

BFI - Rogue wave predictability

Wave sensor #17 | **Wave sensor #18**

BFI_f

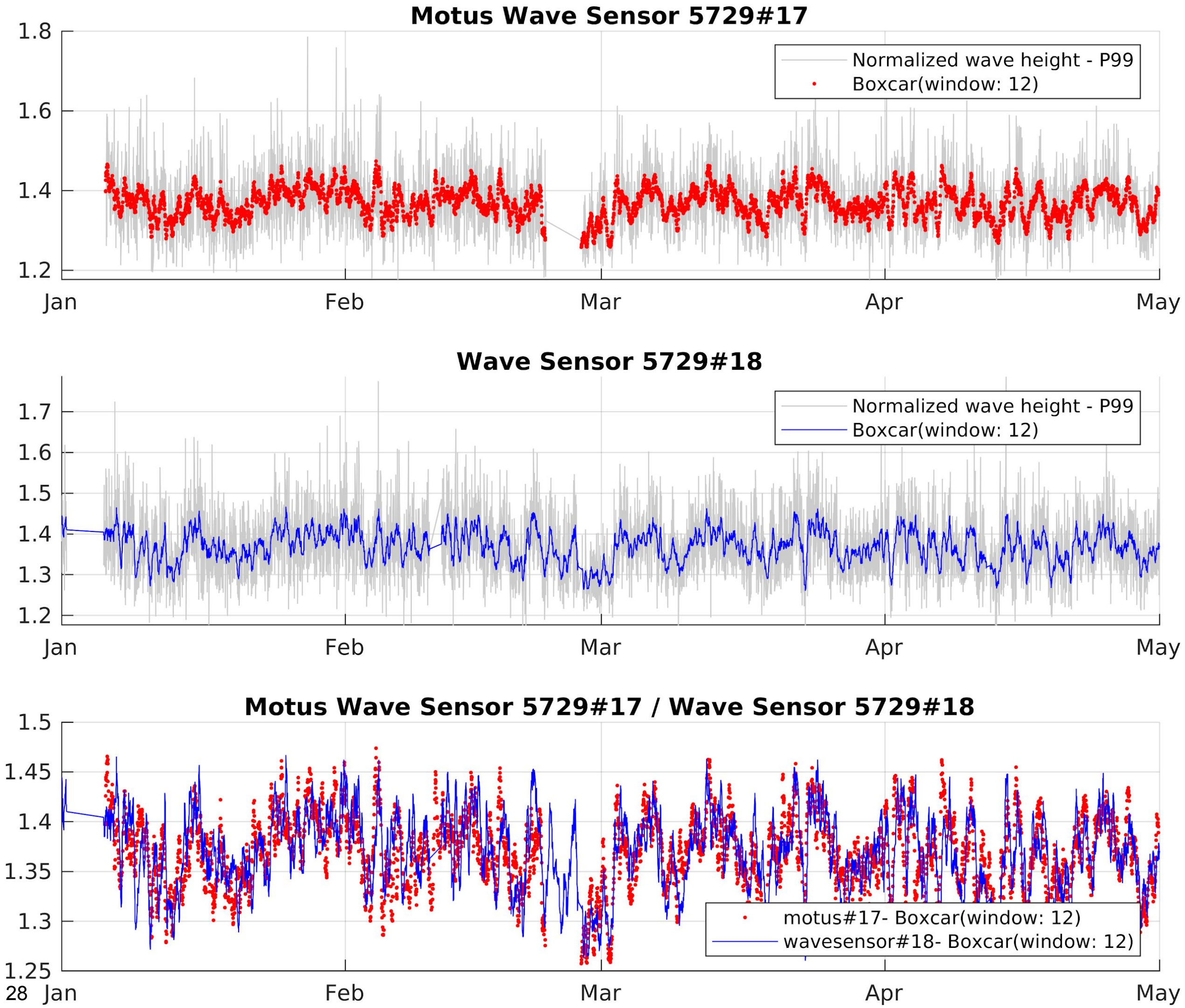
BFI_θ

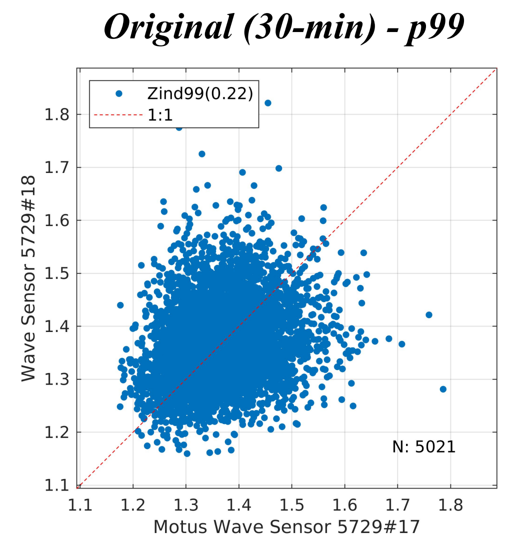


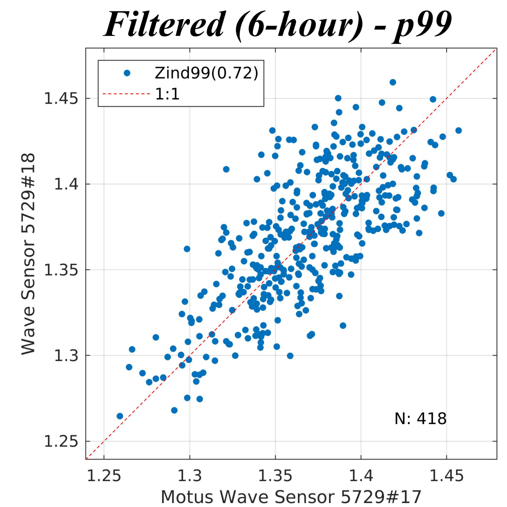
Boxes show Q1 and Q3 while whiskers represent the 5- and 95-percentiles

Wave heights - 99 percentile

- *30-min data vs filtered (boxcar: 6 hours / 12 time steps)*

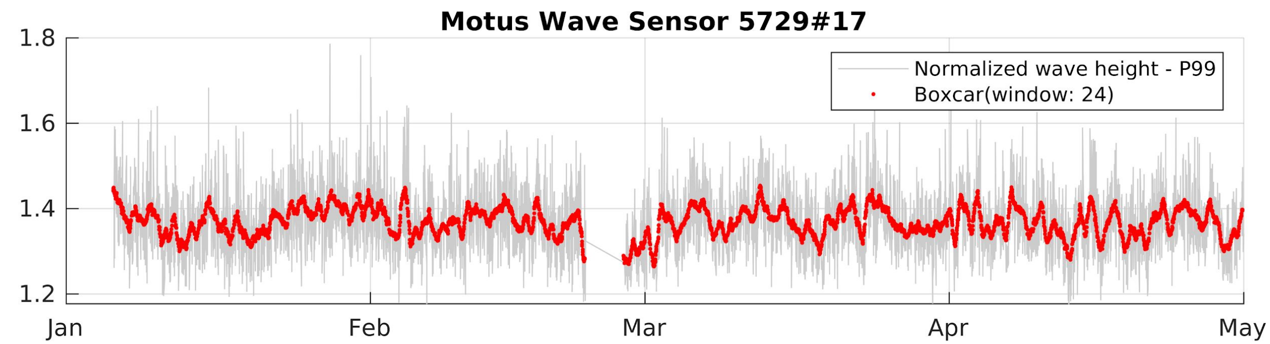


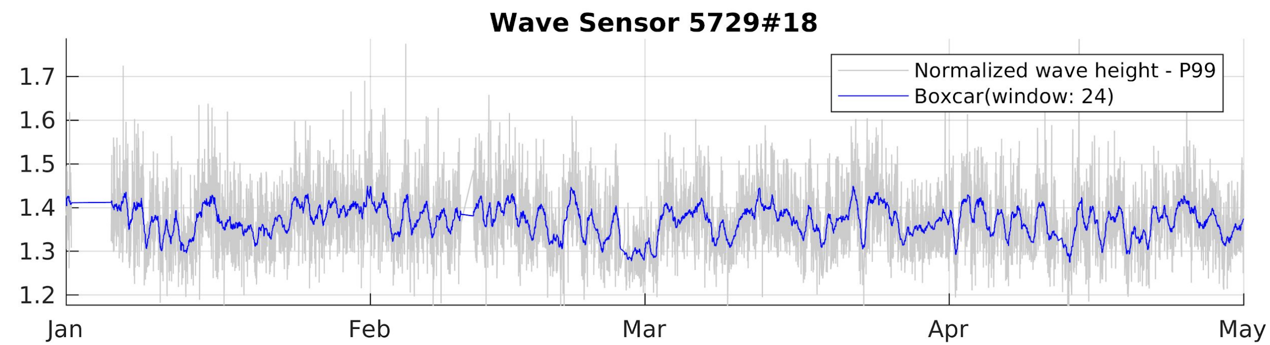


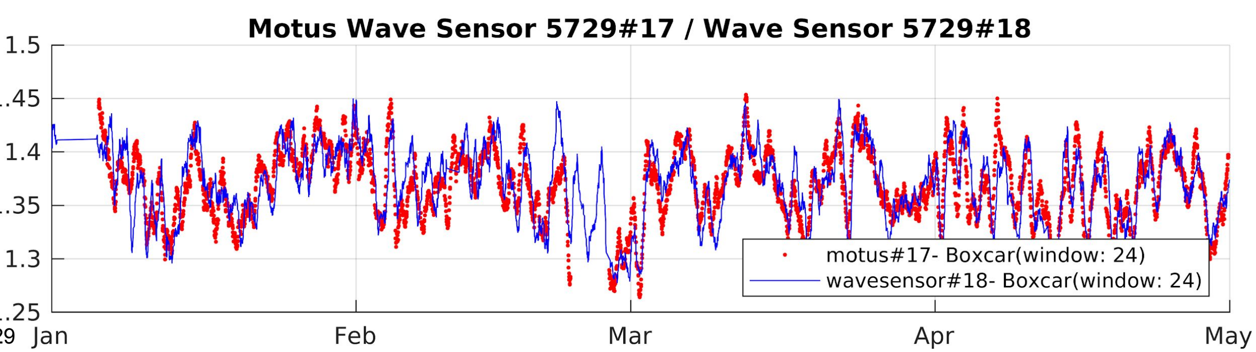


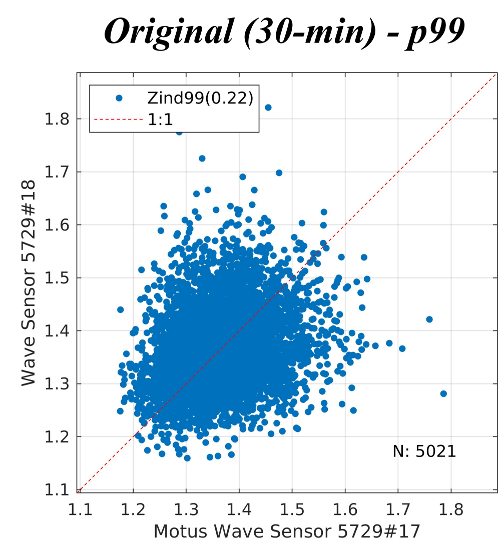
Wave heights - 99 percentile

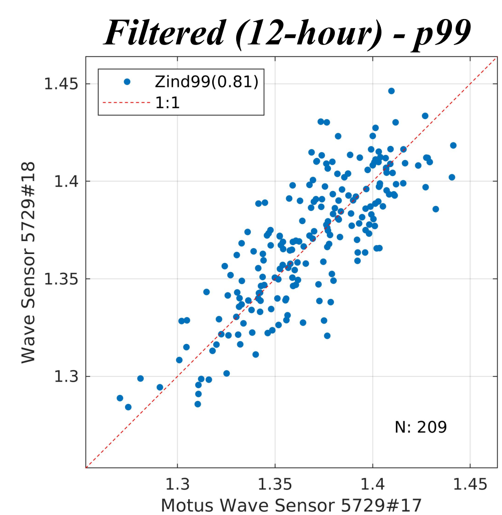
- *30-min data vs filtered (boxcar: 12 hours / 24 time steps)*





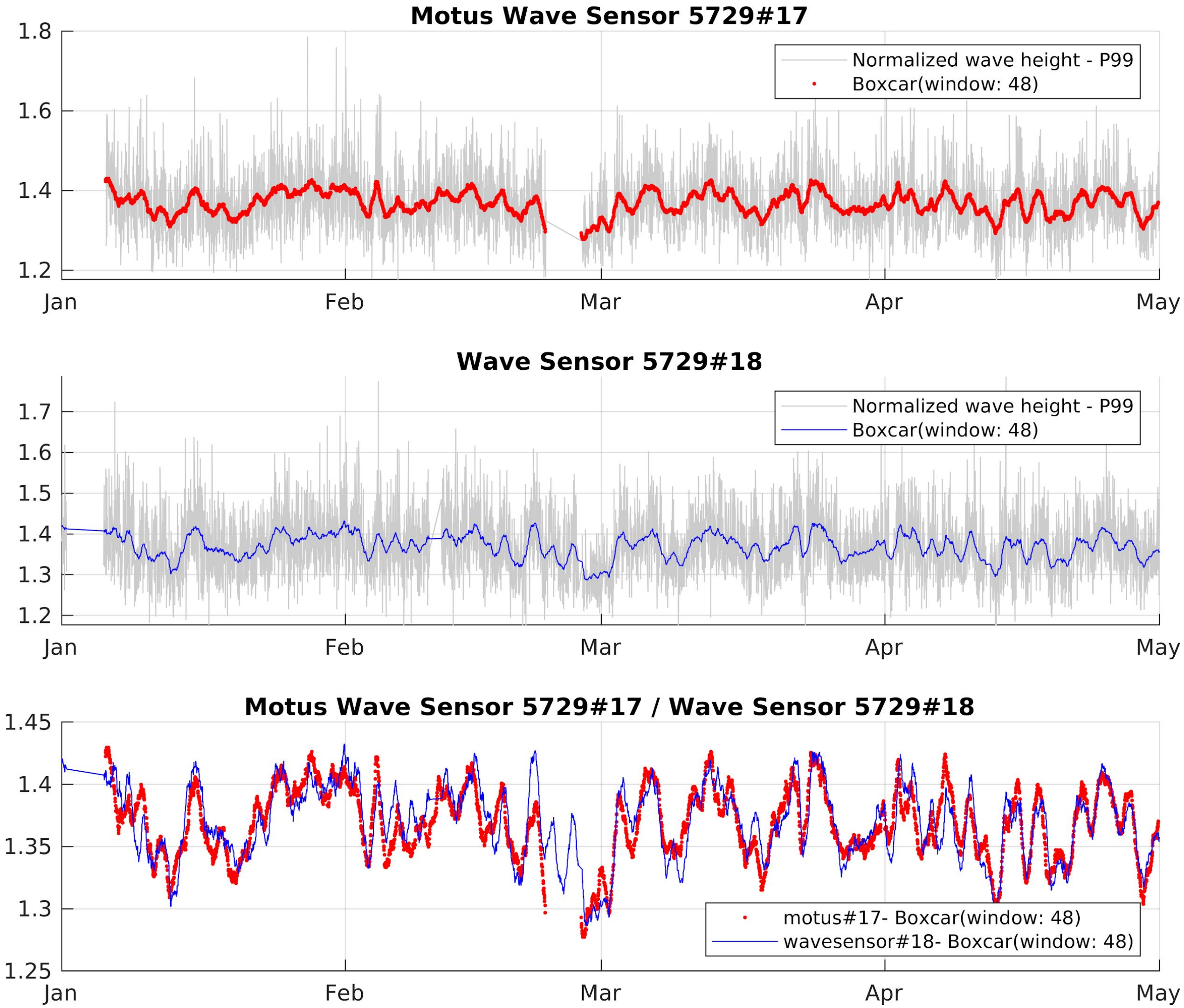


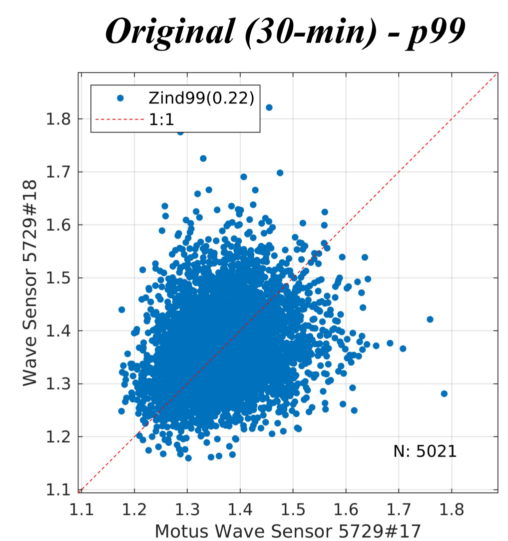


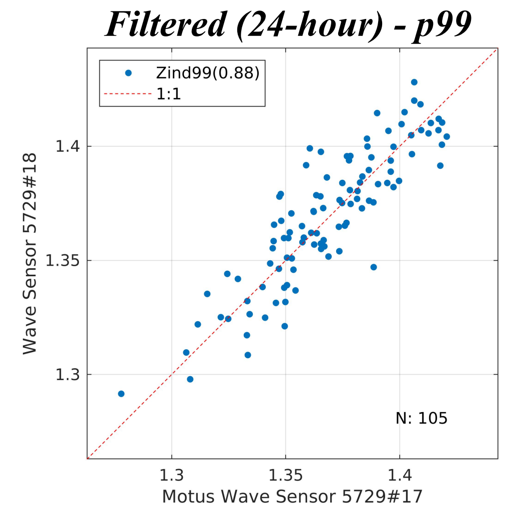


Wave heights - 99 percentile

- *30-min data vs filtered (boxcar: 24 hours / 48 time steps)*







Buoy position density

- *binned by equally sized lat/lon-bins*

Observation density: Motus Wave Sensor 5729#17
Entries: 5118

	5.0084	5.0089	5.0094	5.0099	5.0105	5.011	5.0115	5.012	5.0126	5.0131	5.0136	5.0141	5.0146	5.0152	5.0157	5.0162	5.0167	5.0172	5.0178	5.0183	5.0188
59.1469									1	3	1										
59.1467					1	12	35	40	43	48	22	9	3	1							
59.1464			2	62	113	136	94	112	82	77	66	44	25	9	9						
59.1461			64	118	96	133	147	107	83	63	70	61	63	51	30	19	3				
59.1458	1	28	79	103	103	39	26	14	8	14	12	14	19	30	37	31	14	2			
59.1455	19	45	110	47	26	8	7	5	6	2	3	3	6	8	19	36	38	3	2		
59.1453	7	34	27	9	5	1	2	2		2	1	3		3	2	6	24	5	9		
59.145	15	52	17	2	5	3	1	4	3	2	2	1	2	3	5	4	17	22	9		
59.1447	28	44	5	4	2	2	4	3			1	1		4	2	5	6	30	9	4	
59.1444	30	26	6	1	1	2	1	6	1	1	1	1	1	1	3	4	4	18	15	7	
59.1441	23	16	3	3	2	2		2		3	2		3	1	3	5	7	25	17	8	1
59.1439	11	9	5	3		1	3	1	2			1	2		1		4	16	8	3	
59.1436	9	14	3	2	3	3		1					3	2	2	5	5	16	17	11	
59.1433	9	9	3	5	2	3	1		3		2	2	2	2	1	3	14	19	29	6	
59.143	2	16	9	4	2	2	1	2			3		2	5	3	7	15	13	3	1	
59.1427		10	19	2	4	2	5	2	1	1	3	2	1	6	5	8	20	18	1		
59.1425		1	14	10	3	5	2	2	1	3		1		3	8	12	17	2			
59.1422			6	26	12	2	2	2	6	3	3	3	5	8	19	29	14	1			
59.1419				1	18	20	12	5	6	5	7	8	15	31	29	15	1				
59.1416					1	8	20	35	38	41	52	56	56	29	5						
59.1413								2	9	26	15										

0 20 40 60 80 100 120 140 160 180
NaN

Observation density: Wave Sensor 5729#18
Entries: 5357

	5.0215	5.022	5.0225	5.023	5.0235	5.024	5.0244	5.0249	5.0254	5.0259	5.0264	5.0269	5.0274	5.0279	5.0284	5.0289	5.0293	5.0298	5.0303	5.0308	5.0313
59.1509									5	11	5										
59.1507					1	13	109	192	147	137	124	63	36	9							
59.1504				25	245	275	219	102	43	54	48	42	67	68	51	15					
59.1501			6	156	69	34	21	23	42	76	61	29	21	19	21	41	10				
59.1499		5	148	73	24	53	32	26	14	7	4	4	12	17	17	17	56	17			
59.1496		55	48	15	42	15	1		5	2			2	4	7	12	17	31	12		
59.1493	7	27	20	18	7	2		4	1				1		4	8	7	26	15		
59.1491	21	32	15	8	2	2	3	1	1	1	2	1	1	3	5	5	7	11	26	6	
59.1488	26	37	3	4	4		1		2	2		2	1		1	3	6	7	19	12	
59.1485	16	6	2	3				1	1		1		1	1	2	2	4	5	8	19	
59.1483	26	7	4		2	4		1		1	1	1		1	1	4	3	3	21	28	1
59.148	14	13	4	4	1		2		1	2	1	1	1		1	2	5	9	19	27	
59.1478	8	14	2	4	3	1	1		1	2	1		2	1	1	1	2	4	7	20	
59.1475	5	5	6	4			3	1		1	1	1	4	1	2	3	8	6	22	16	
59.1472		17	7	8	4	1	3	2	1		1	3	3	2	1	2	6	21	19	1	
59.147		4	12	3	5	3	3	2	2	1		2	3	3	4	5	9	19			
59.1467			11	17	7	2		3	5	4	1	2	3	8	4	11	38	17	2		
59.1464				12	17	12	9	4	4	6	4	5	7	16	28	15	23	1			
59.1462					3	10	15	6	6	5	5	7	8	24	30	4					
59.1459					3	7	14	25	31	31	43	63	51	41	13						
59.1456								1	4	11	3	2									

0 20 40 60 80 100 120 140 160 180
NaN

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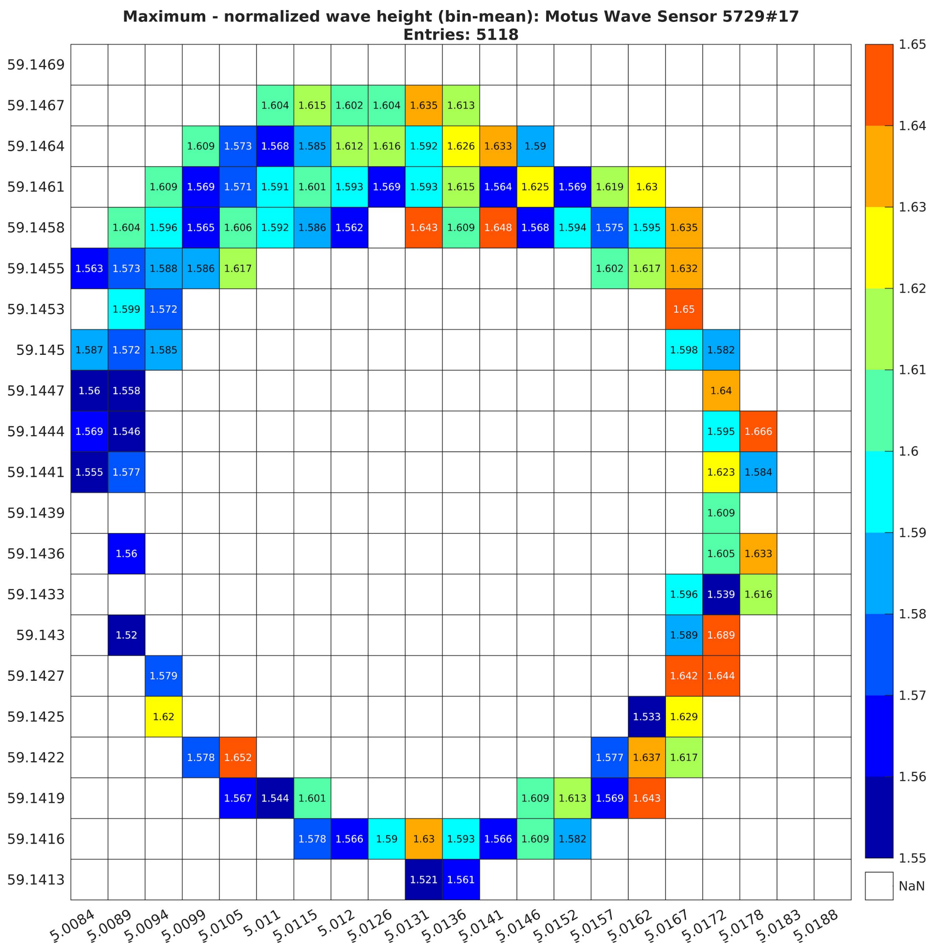
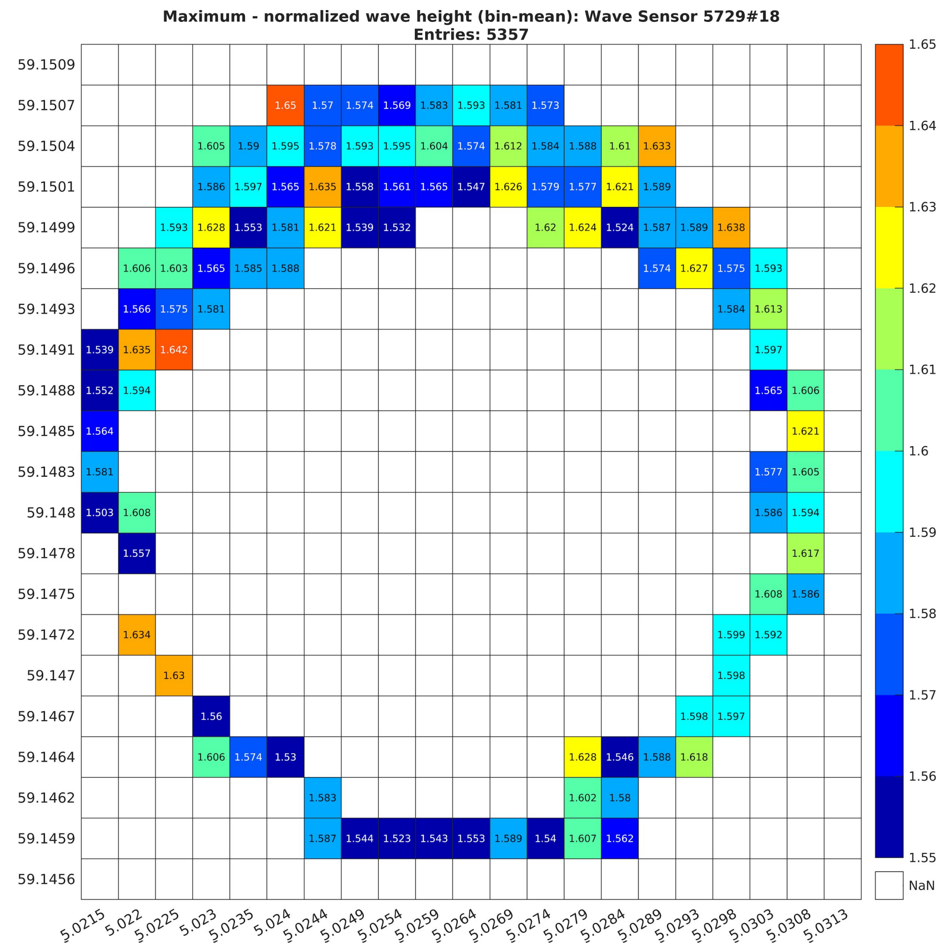
Maximum normalized wave height

- *mean value per lat/lon-bin (bins N<12 sensored)*





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P95 - normalized wave height

- *mean value per lat/lon-bin (bins N<12 sensored)*