

Inferring significant wave height from seismic data:

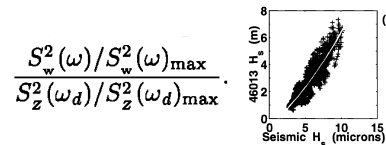
A comparison between methods.

F Bolrão, C Tran, M Lima, S Sherifdeen, D Rodrigues, G Silveira, T Bui-Thanh, S Custodio

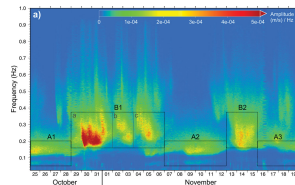


Ocean wave height – Observed at Buoy (blue) vs Predicted from Seismic Data (other colors) [4.5 months]

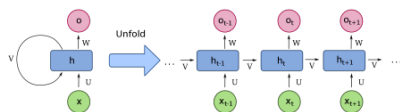
Method 1 (Bromirski et al, 1999)



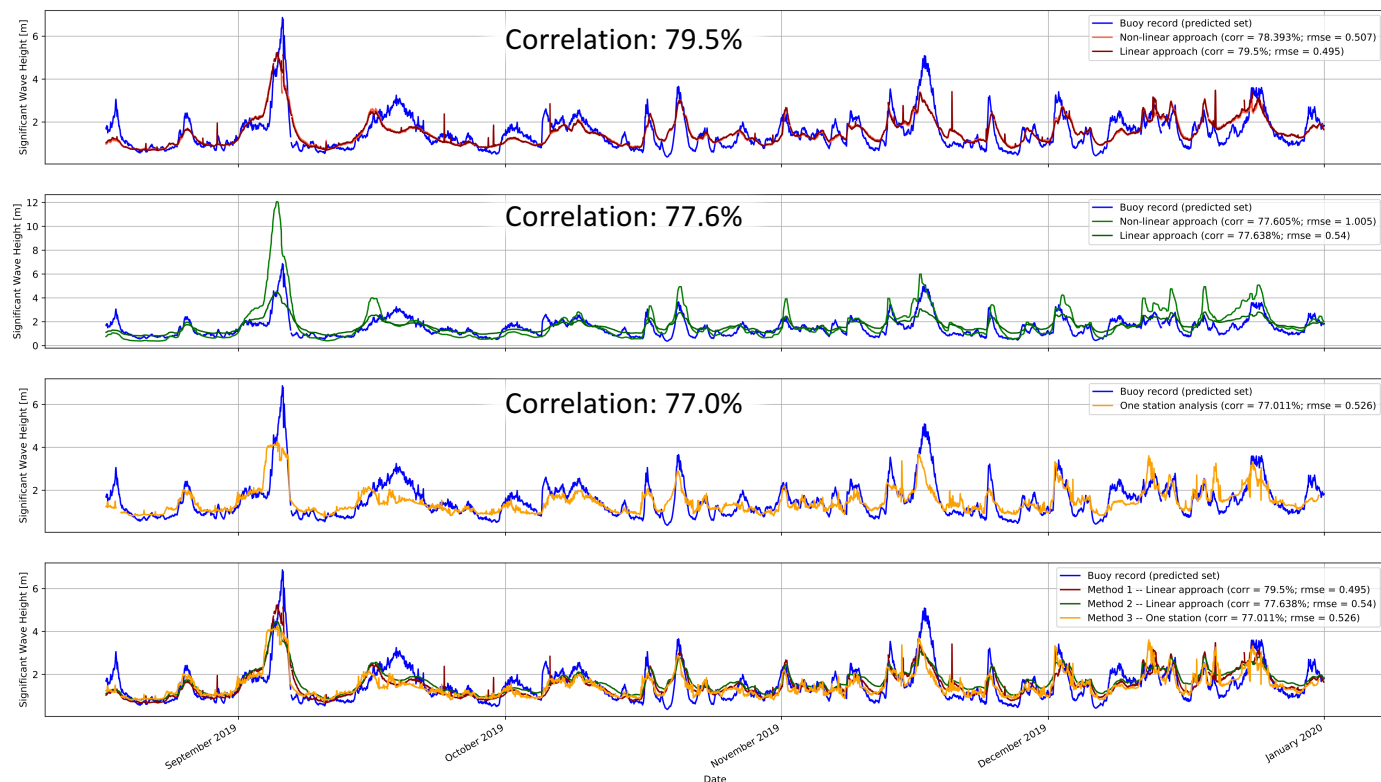
Method 2 (Ferretti et al, 2013)



Method 3 (Recurrent Neural Network)



Methods 1 vs 2 vs 3





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Inferring significant wave height from seismic data: A comparison between methods.

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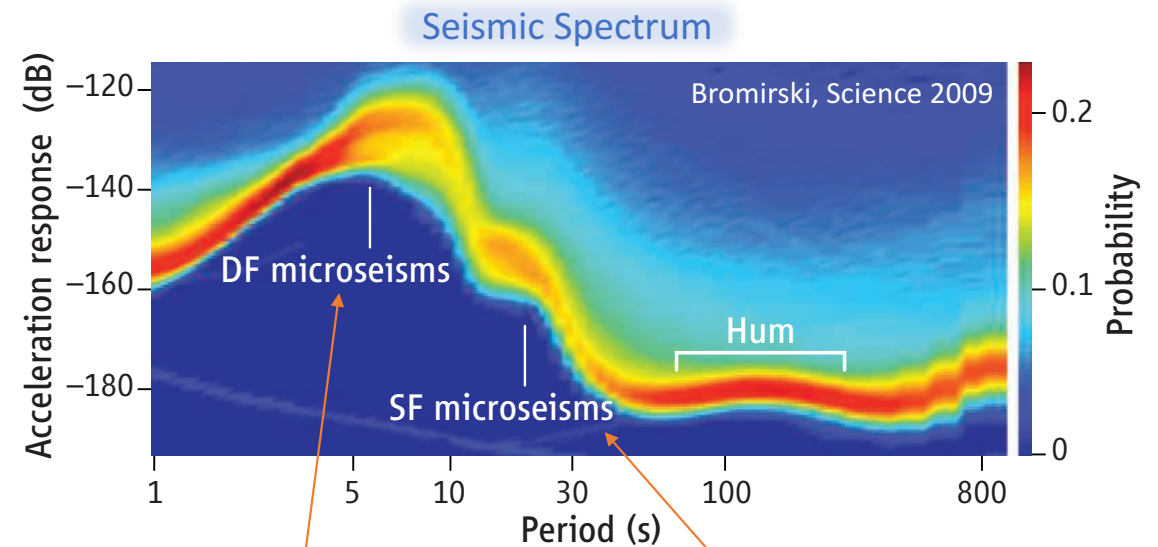
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Background

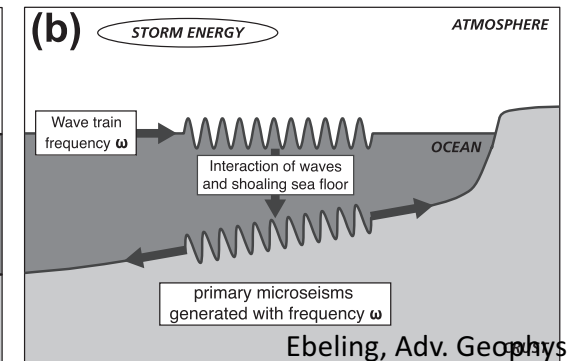
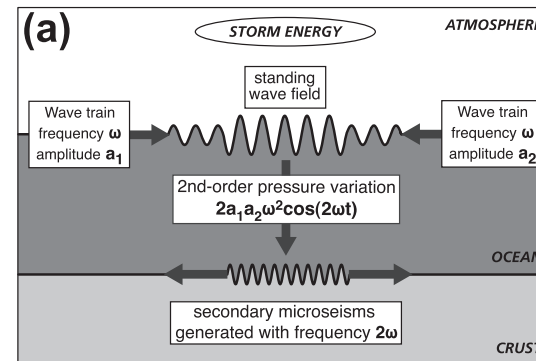
- Under some circumstances, ocean waves couple their energy to the solid Earth, generating peaks in seismic energy that are pervasively observed in seismic stations around the globe.
- The most energetic ocean-generated seismic signal is the double-frequency (DF), or secondary microseisms.



Generation Mechanisms

Double-freq. (secondary) microseisms
Twice the frequency of oceanic swell

Single-freq. (primary) microseisms
Same frequency as that of oceanic swell

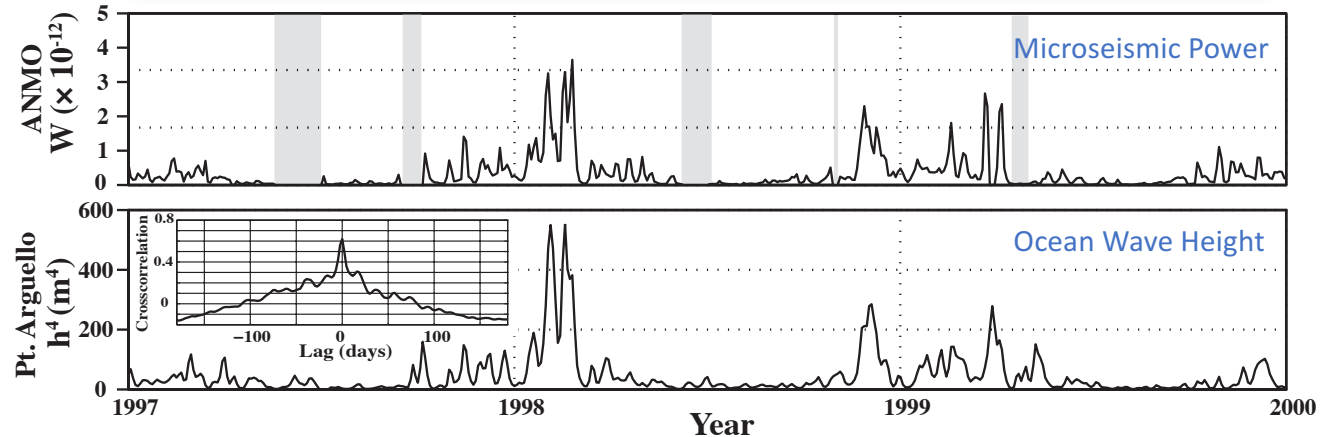


Ebeling, Adv. Geophys. 2012

Motivation

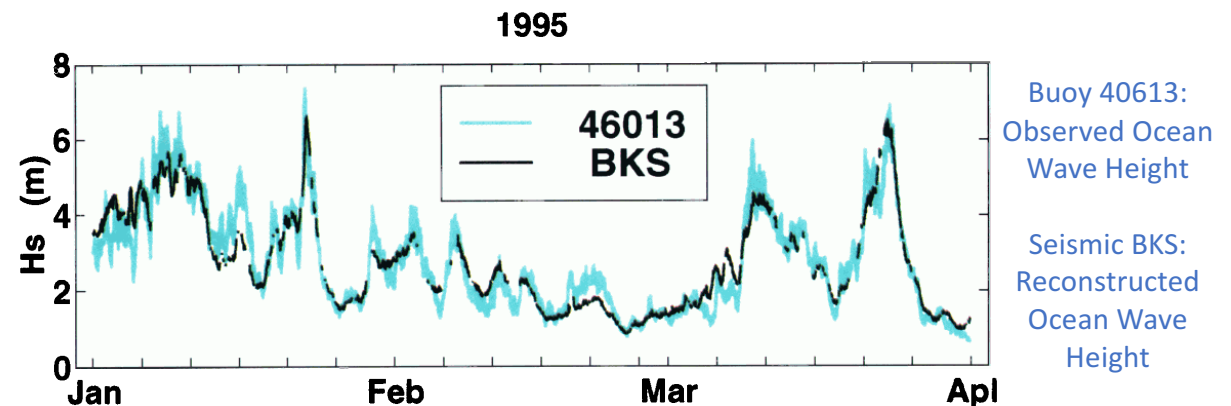
- Previous studies have shown a strong correlation between ocean wave height and microseisms amplitude.
- Previous studies have shown that ocean wave height can be recovered from seismic records, which is interesting for various applications (e.g.: recovery of historical climate parameters).
- Here we compare the performance of different seismic-to-buoy recovery methods.

Strong correlation between ocean wave height and seismic energy



Aster et al, SRL 2008

Ocean wave height can be reconstructed from seismic data



Bromiski et al, JGR 1999

Method 1:

After Bromirski et al (1999)

Develop an empirical transfer function between buoy wave spectra and seismic spectra.

1. Compute a seismic-to-buoy empirical transfer function (T_{ws}), as a ratio between ocean (S_w) and seismic (S_z) spectra.

$$T_{ws}(\omega_d) = \frac{R_s(\omega) \mathcal{W}_\theta(\omega) T_z(\omega_d) \alpha_R(\omega_d)}{\frac{S_w^2(\omega)/S_w^2(\omega)_{\max}}{S_z^2(\omega_d)/S_z^2(\omega_d)_{\max}}}$$

2. Recover ocean wave spectra from seismic spectra.

Non-linear

$$\hat{S}_w(f_d) = \left[\frac{S_z(f_d)}{\frac{4\pi^4 \rho^2 g^2}{c^2} f^3 T_{ws}(f_d)} \right]^{\frac{1}{2}} \quad (\text{Original approach})$$

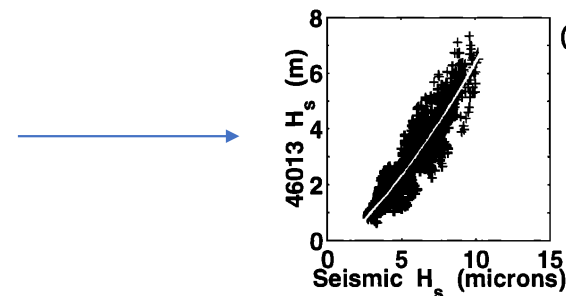
Linear

$$S_w(f_d) = [T_{ws}(f_d) \cdot S_z^2(f_d)]^{1/2} \quad (\text{This study})$$

3. Integrate the recovered ocean wave spectra to obtain significant wave height (H_s).

$$\hat{H}_s = 4 \left[\int_{f_1}^{f_2} \hat{S}_w(f_d) df \right]^{\frac{1}{2}}$$

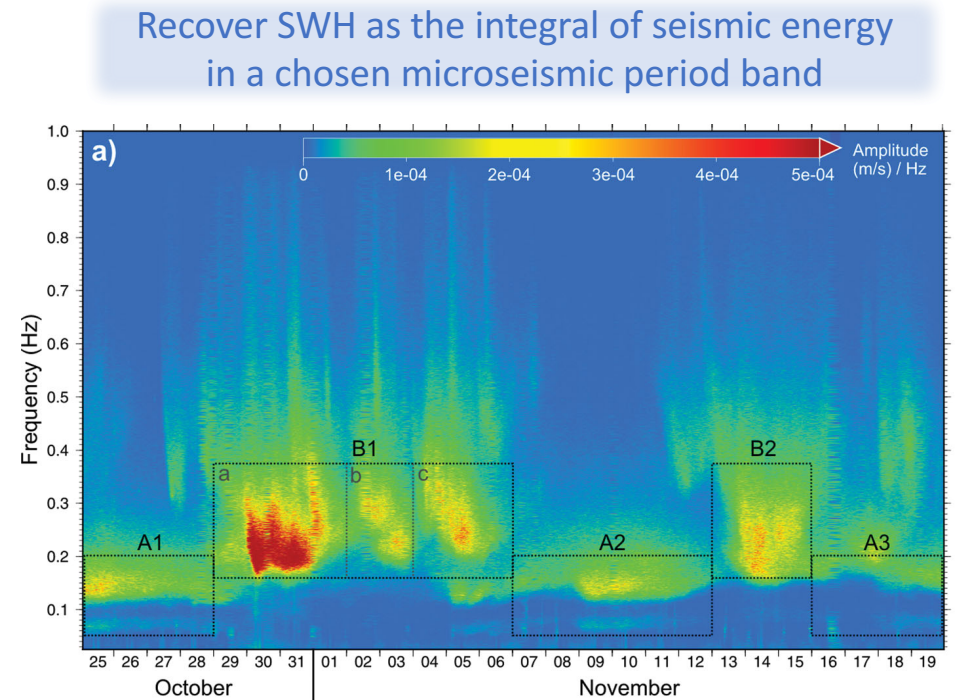
4. Re-normalize the recovered SWH using a linear or quadratic regression between observed and recovered SWHs.



Bromirski et al, JGR 1999

Method 2: After Ferretti et al (2013)

1. Recover significant wave height ($H_{1/3}$) as the integral of seismic energy (S_m) over a relevant microseismic period band. Optimize the period band (f_{min} , f_{max}) and the amplitude factors (a , b , c) by dual annealing:



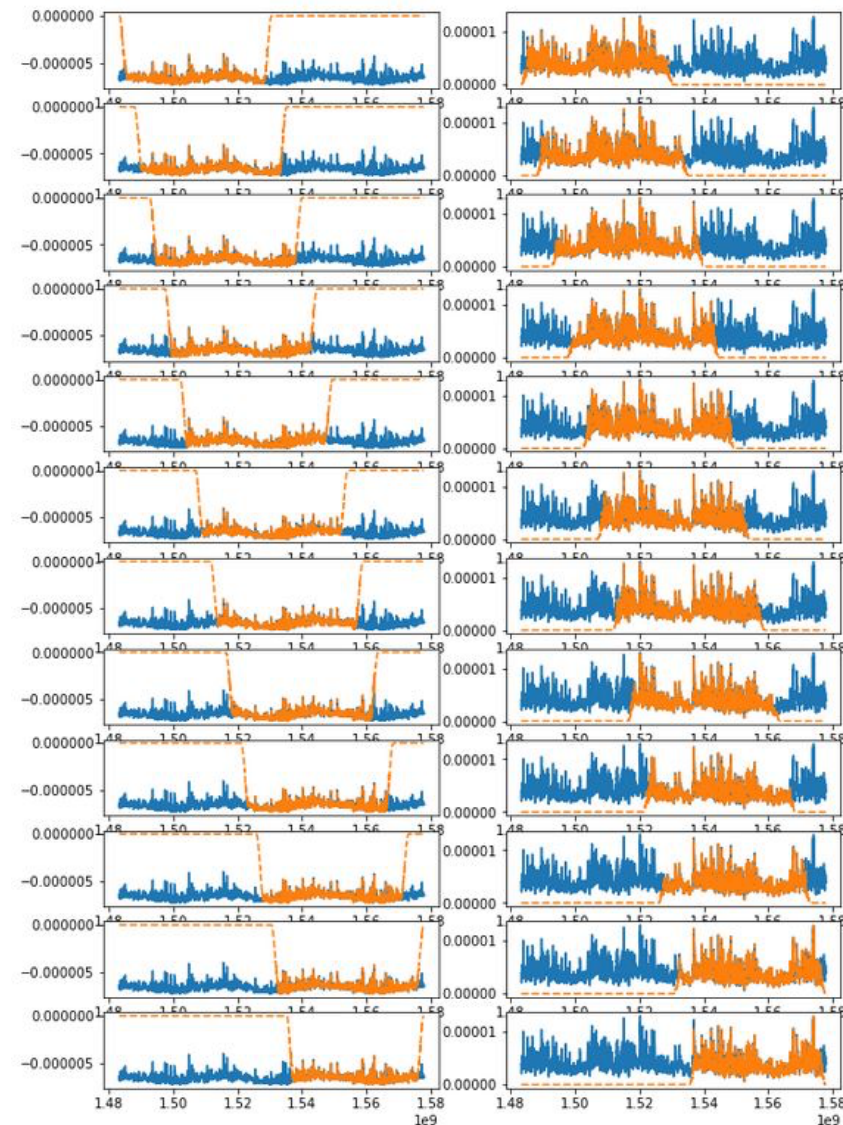
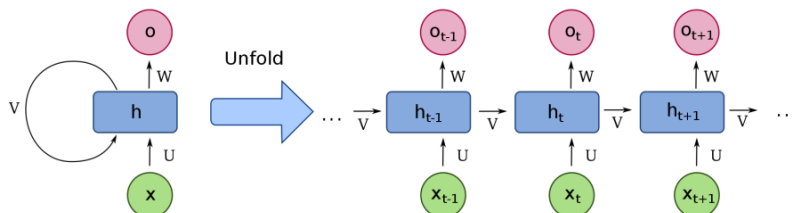
Ferretti et al, GJI 2013

a. Linear relationship:
$$H_{\frac{1}{3}}^{\text{calc}} = 4c \sqrt{\int_{f_{\min}}^{f_{\max}} \frac{2}{T} |S_m(f)|^2 df},$$

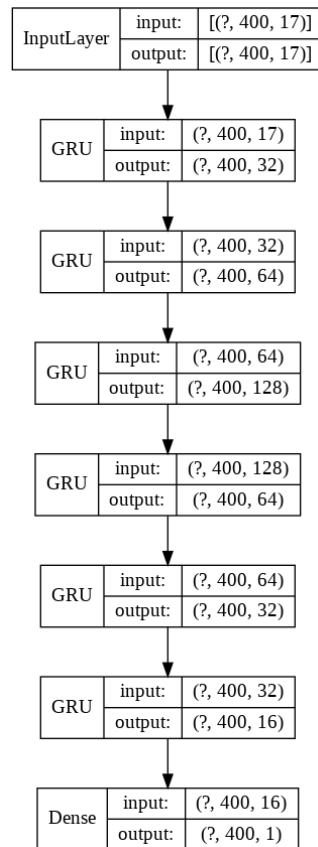
b. Non-linear relationship:
$$H_{\frac{1}{3}}^{\text{calc}} = \exp \left(a + b \ln \left(\sqrt{\int_{f_{\min}}^{f_{\max}} \frac{2}{T} |S_m(f)|^2 df} \right) \right)$$

Method 3: Neural Network

1. Divide the seismic spectra and SWH from buoy to smaller chunk vectors by the time axis.
2. Develop a Recurrent Neural Networks (RNNs) to learn the transformation from seismic spectra to SWH.



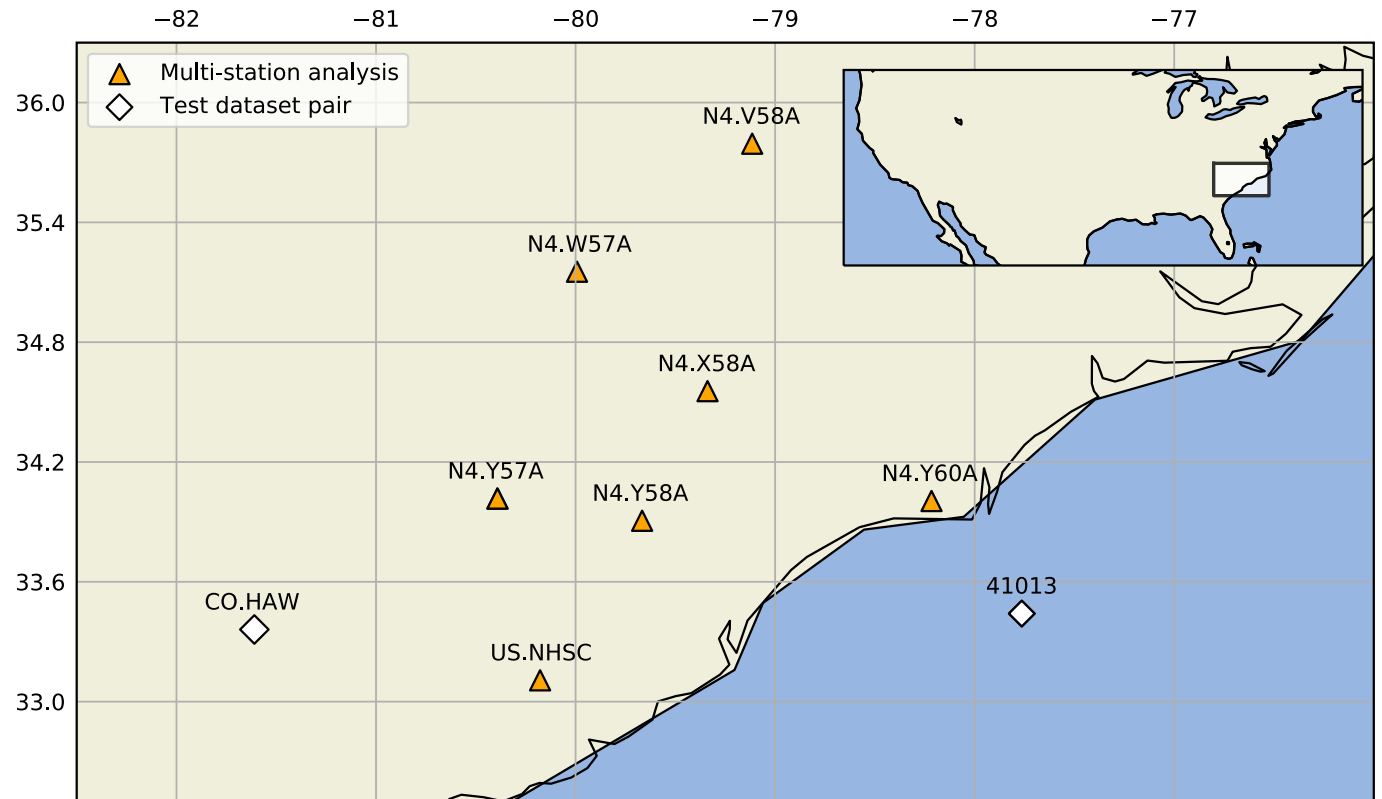
Method 3: Neural Network



The Recurrent Neural Network model contains layers of Gated Recurrent Units that take in time series of seismic data and output the significant wave height.

Data

- Ocean buoy and seismic stations located in the eastern USA.
- Ocean buoy 41013
(Available through NOAA)
- Seismic station CO.HAW.HHZ
(Available through IRIS)

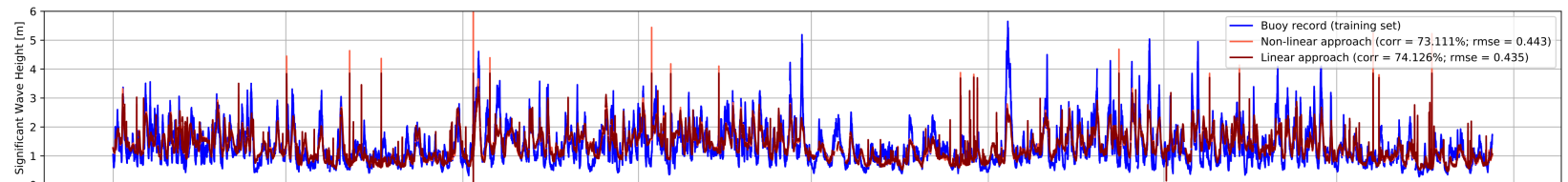


Results: Training Dataset [Data used to develop the transfer functions]

Ocean wave height – Observed at Buoy (blue) vs Predicted from Seismic Data (other colors) [2 yrs 8 mo]

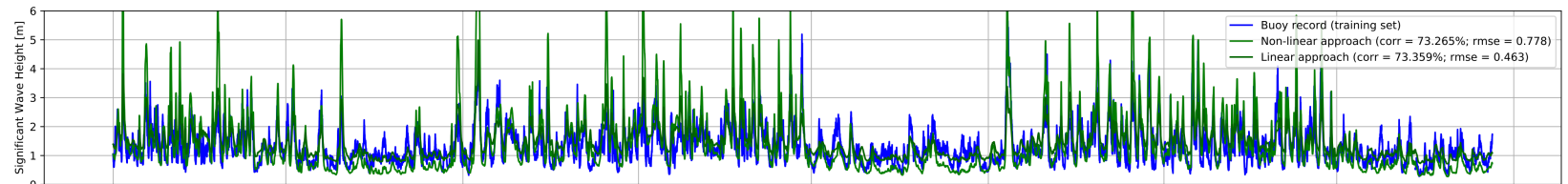
Method 1

(Bromirski et al, 1999)



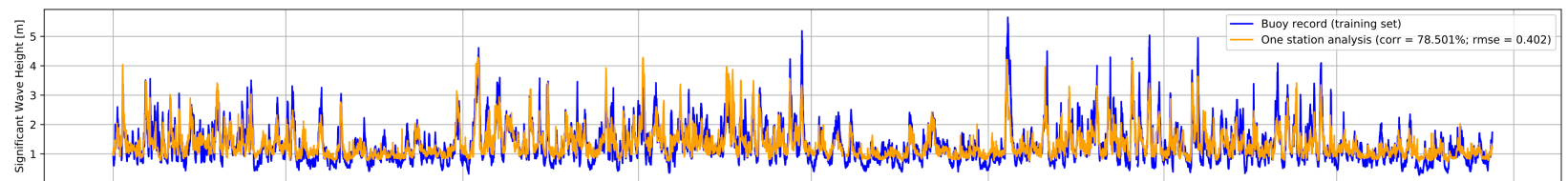
Method 2

(Ferretti et al, 2013)

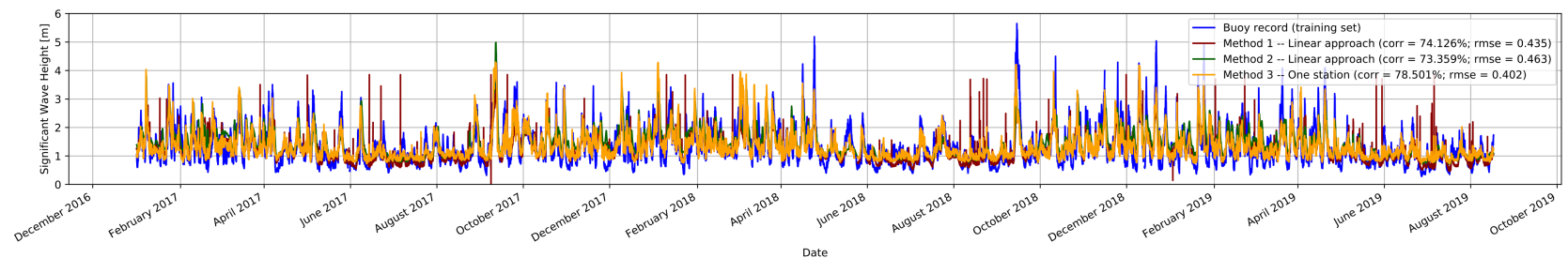


Method 3

(Recurrent Neural Network)



Methods 1, 2 and 3

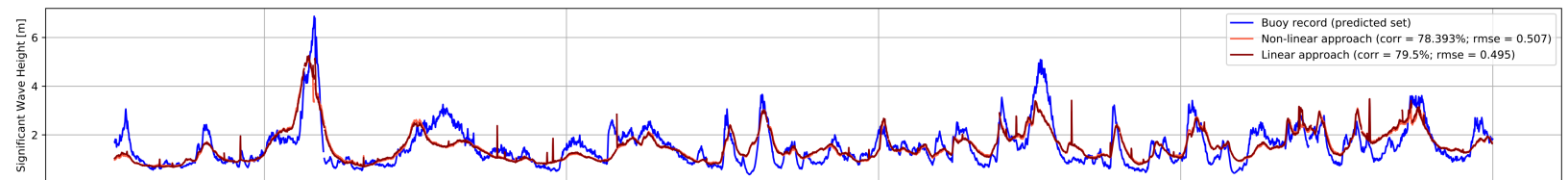


Results: Validation Dataset [Data not used to develop the transfer functions]

Ocean wave height – Observed at Buoy (blue) vs Predicted from Seismic Data (other colors) [4.5 months]

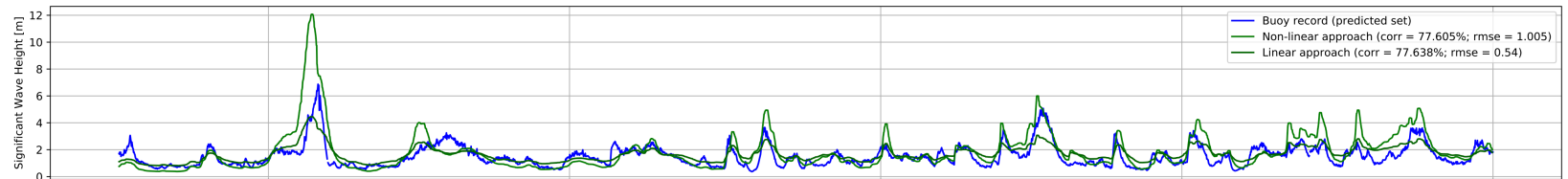
Method 1

(Bromirski et al, 1999)



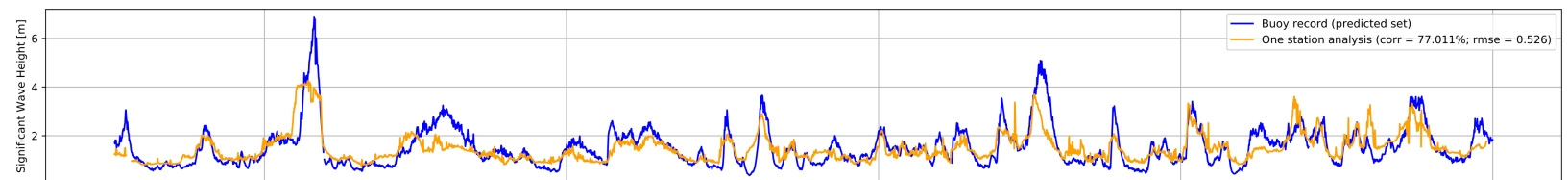
Method 2

(Ferretti et al, 2013)

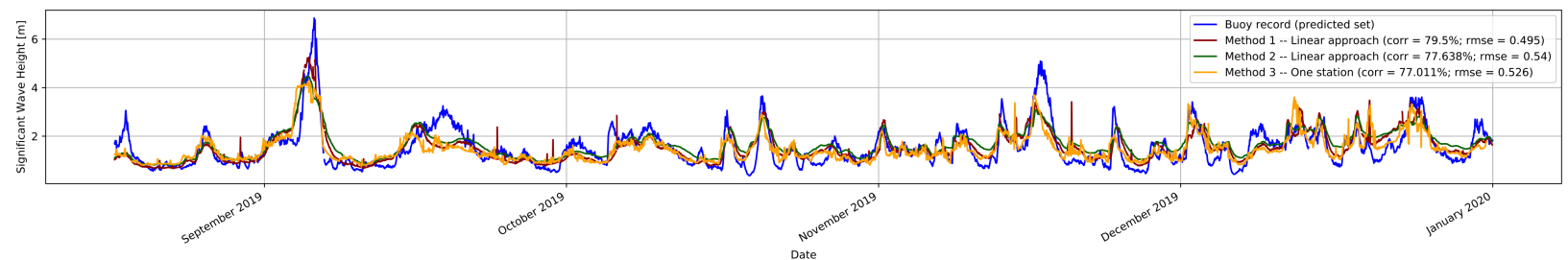


Method 3

(Recurrent Neural Network)



Methods 1, 2 and 3

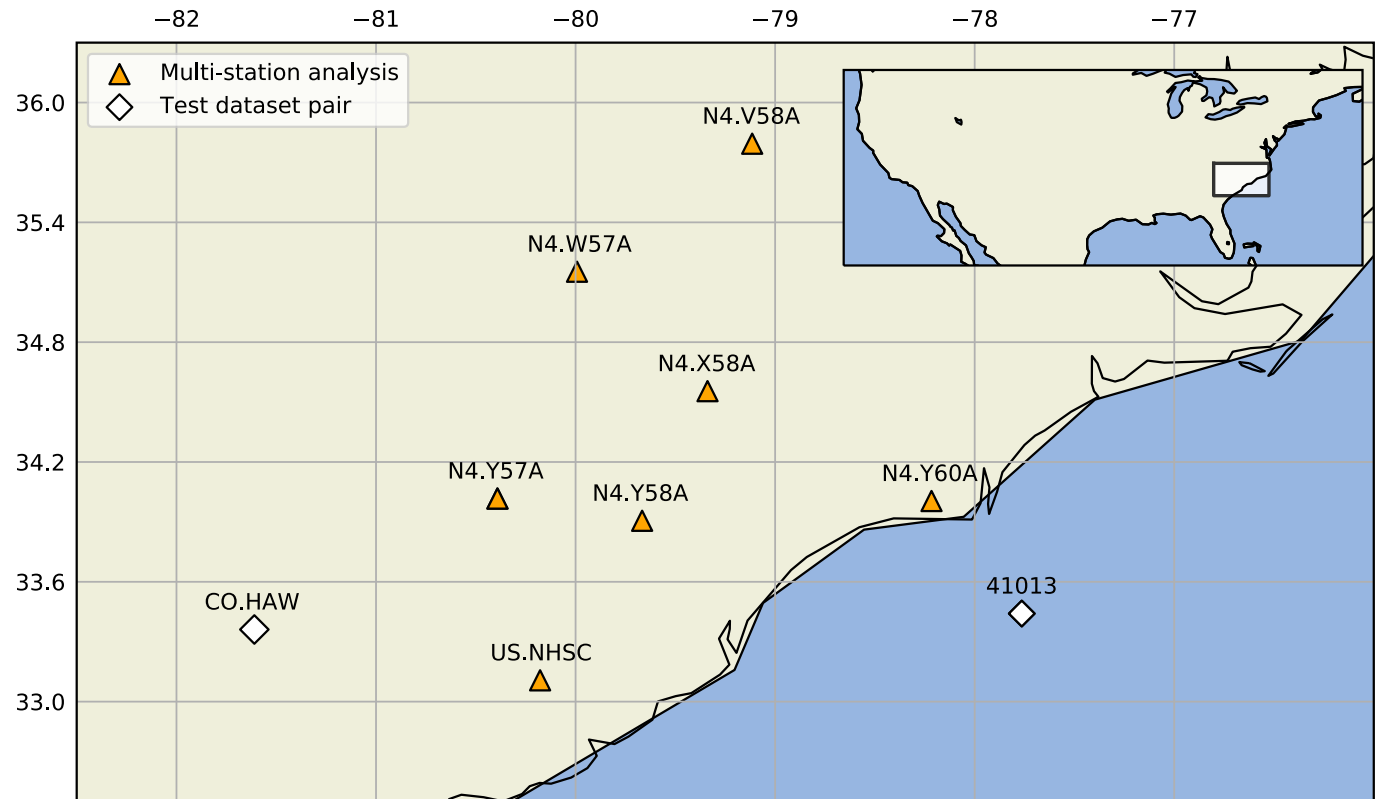


Results

		Method 1 (Bromirski et al, 1999)		Method 2 (Ferretti et al, 2013)		Method 3 (Neural network)
		Linear	Non-linear	Linear	Non-linear	
Period Band		2 – 4 s	2 – 4 s	2 – 4 s	2 – 4 s	1 - 17 s
Training dataset	Correlation	74.1%	73.1%	73.4%	73.3%	<u>78.5%</u>
	RMS	0.435	0.443	0.462	0.778	<u>0.402</u>
Validation dataset	Correlation	<u>79.5%</u>	78.4%	77.6%	77.6%	77.0%
	RMS	<u>0.495</u>	0.507	0.540	1.005	0.526

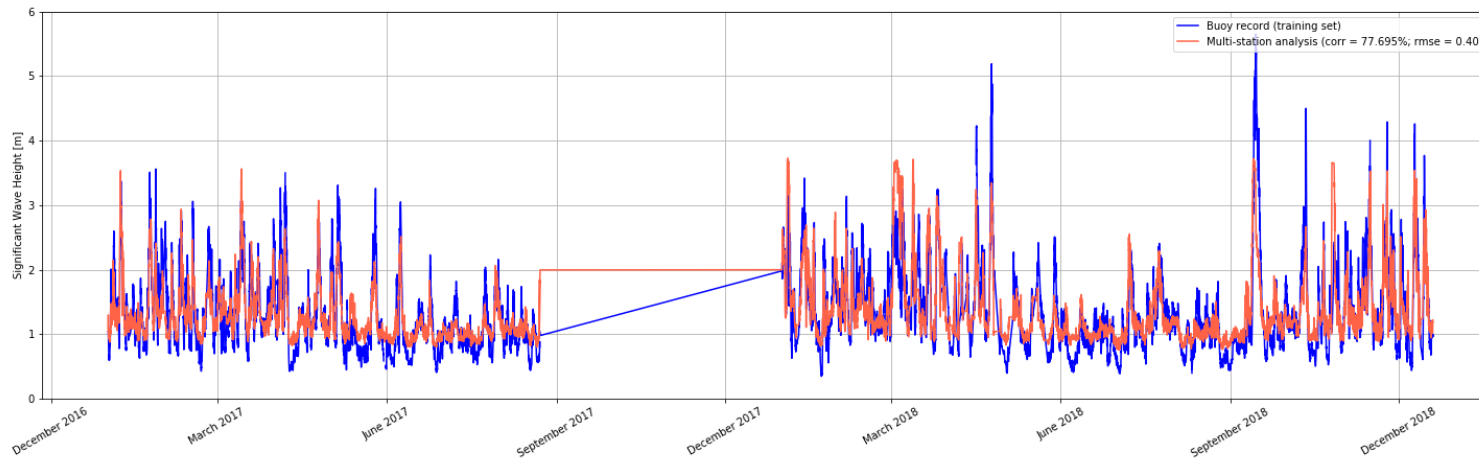
What if we use several seismic stations, rather than just one?

- We use the same data as before, but now use additional seismic stations (orange triangles in the map).



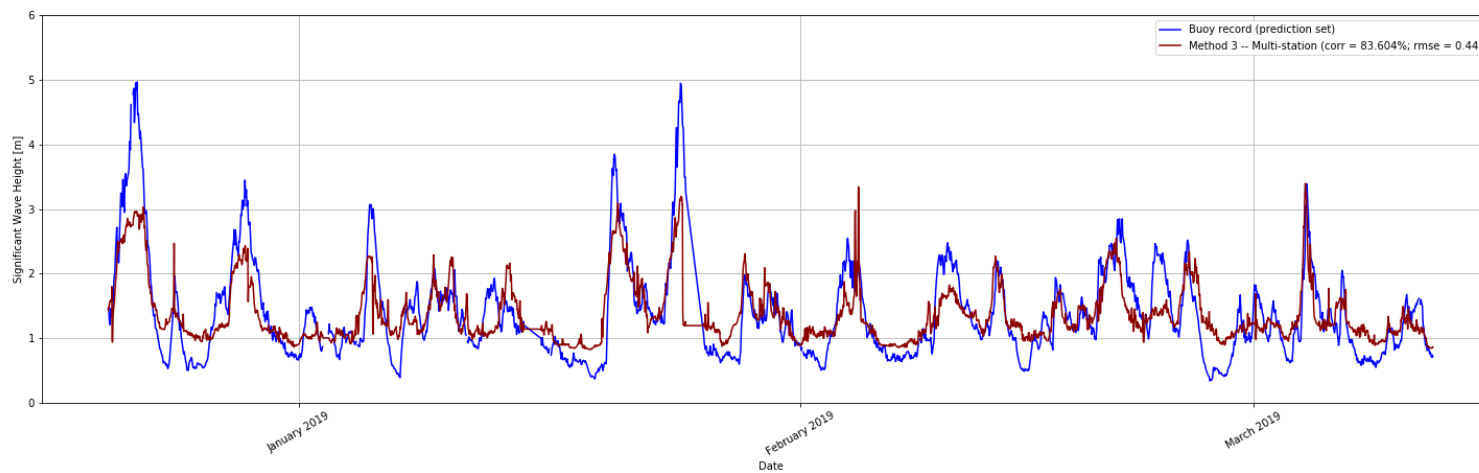
What if we use several seismic stations, rather than just one?

[Results for method 3 – recurrent neural network – only]



Training Dataset

Correlation: 77.7%
RMS: 0.406



Validation Dataset

Correlation: 83.6%
RMS: 0.441

Summary

- We compared three different methods to infer ocean wave height from seismic data:
 - Method 1 (after Bromirski et al, 1999): Develops an empirical transfer function between spectral ocean buoy and spectral seismic data.
 - Method 2 (after Ferretti et al, 2013): Optimizes significant wave height as a scaled integral of observed spectral seismic data.
 - Method 3 (based on a neural network): Uses a recurrent neural network to output ocean significant wave height from input seismic data.
- The three methods are able to successfully recover ocean wave height from seismic data, with correlations between observed and validation datasets of 70%-80%
- Methods 1 (after Bromirski et al, 1999) and 2 (after Ferretti et al, 2013) perform slightly better when they implement linear relationships between ocean wave height and seismic data.
- Method 3 (based on a neural network) is more successful at reproducing the training dataset, but method 1 (after Bromirski et al, 1999, but employing a linear relationship) is better able to reproduce the validation dataset.
- The frequency range of the analysis is critical for a successful result. The methods can only reproduce well coastal wave heights when focusing on short-period secondary microseisms ($T = 2-3$ s)
- The performance of the prediction improves when several neighboring stations are used rather than just one.