Wave climate observed from satellites: trends and inter-annual variability

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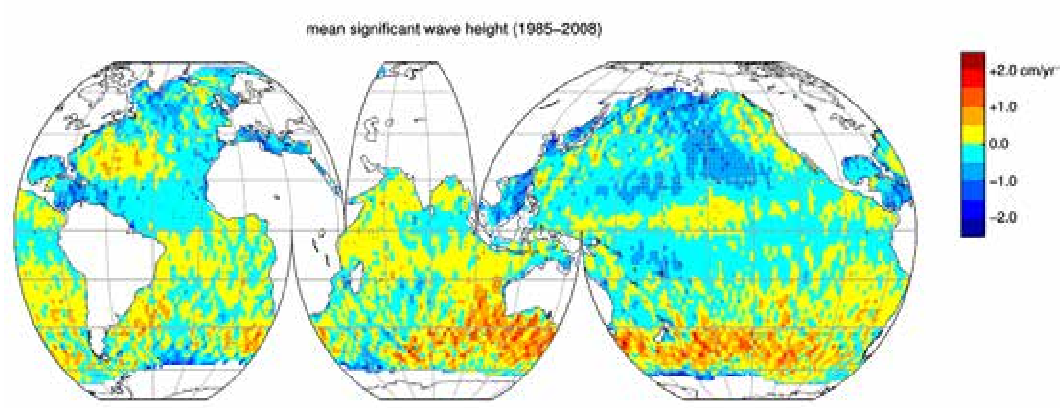
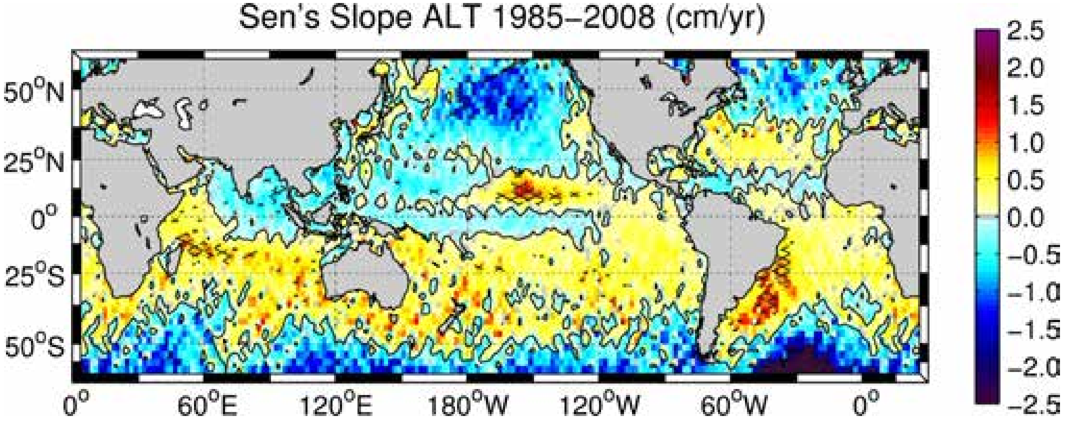
OSTST, October 23-27, Miami

Motivation

Sen's slope with Mann Kendall Test – AVR Hs





Queffeulou and Croize-Fillon, 2016

Young, Zieger, and Babanin (Science 2011)
- set the precedent

Monthly Average Hs (cm/yr) in 2 degree bins

Qualitatively agree but noticeable differences

IFR magnitudes
-higher : -S Atl ; N Pac
-lower : near Australia

No consideration of inter-annual variability!

Outline

1. Data sources
- Altimeters: 1985-2017
- Synthetic aperture radars (SAR): 1995-2017

2. Climate Analysis: Trends vs Inter-annual variability
- Mean Hs (ALT)
- Mean Lp (SAR)

3. Conclusion

4. ESA CCI+ Sea State: sampling & consistency issues

1

Datasets

-Altimeters

-SARs

2 Data sources:
ALT & SAR

Altimeters - IFREMER - Hs

-Continuous coverage since 1992

-Quality controlled and calibrated to buoys (which are not consistent!)

-Consistent between platforms

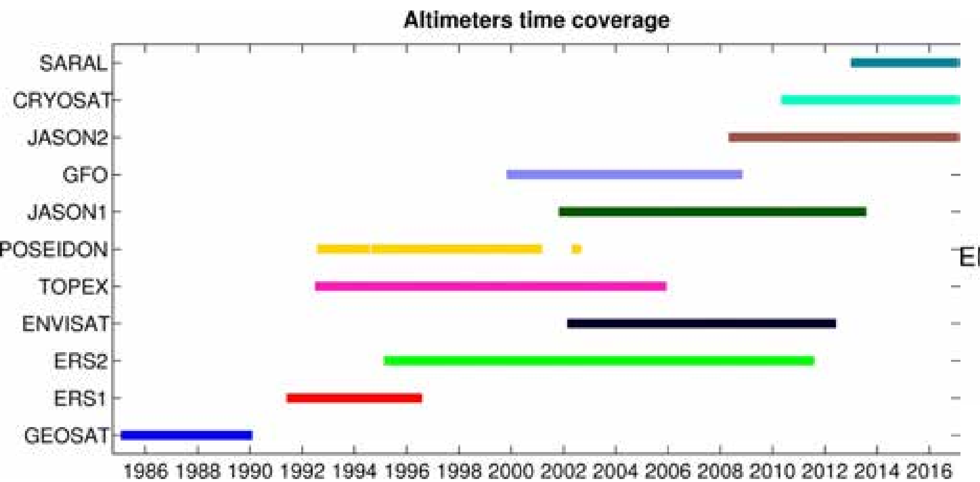
SARs - GlobWAVE - Lp

-Data gaps

-Quality controlled to buoys

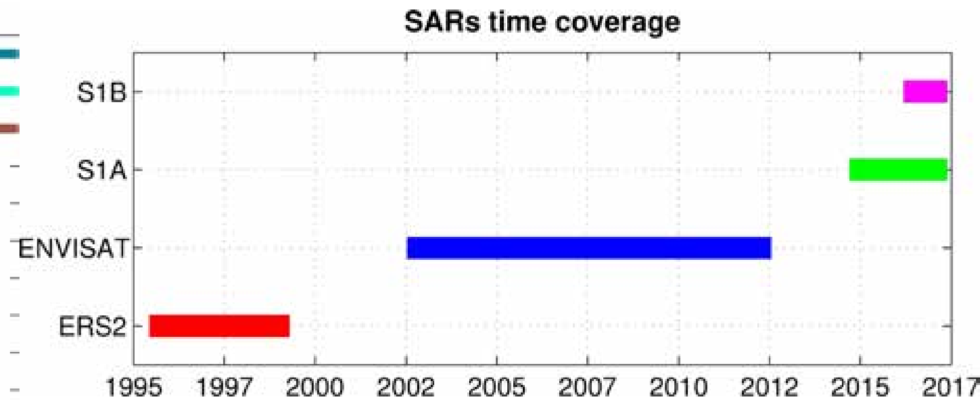
-ESA CCI+ will revisit...

*Missing HY2, Sentinel-3



Queffeulou and Croize-Fillon, 2016

*Missing ERS1



2 Data sources:
Hs & Lp PDFs

Global Hs statistics

-GEOSAT is higher

-mean is stable for 32-year period

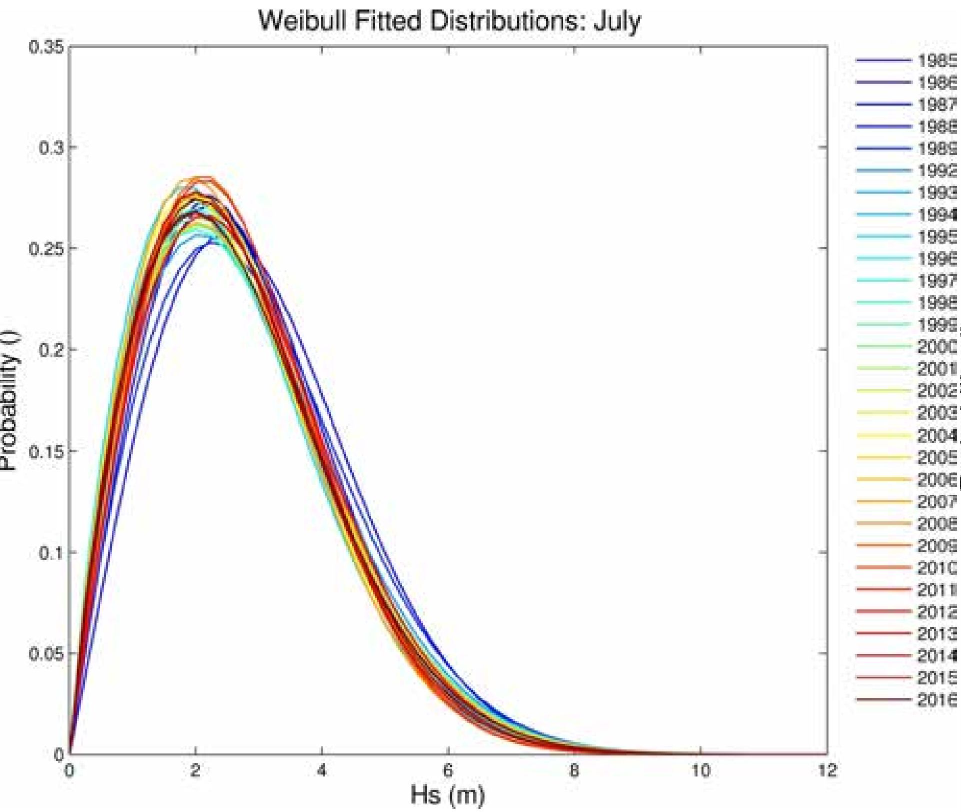
-larger deviations in extremes

Global Lp statistics (>azimuth cutoff)

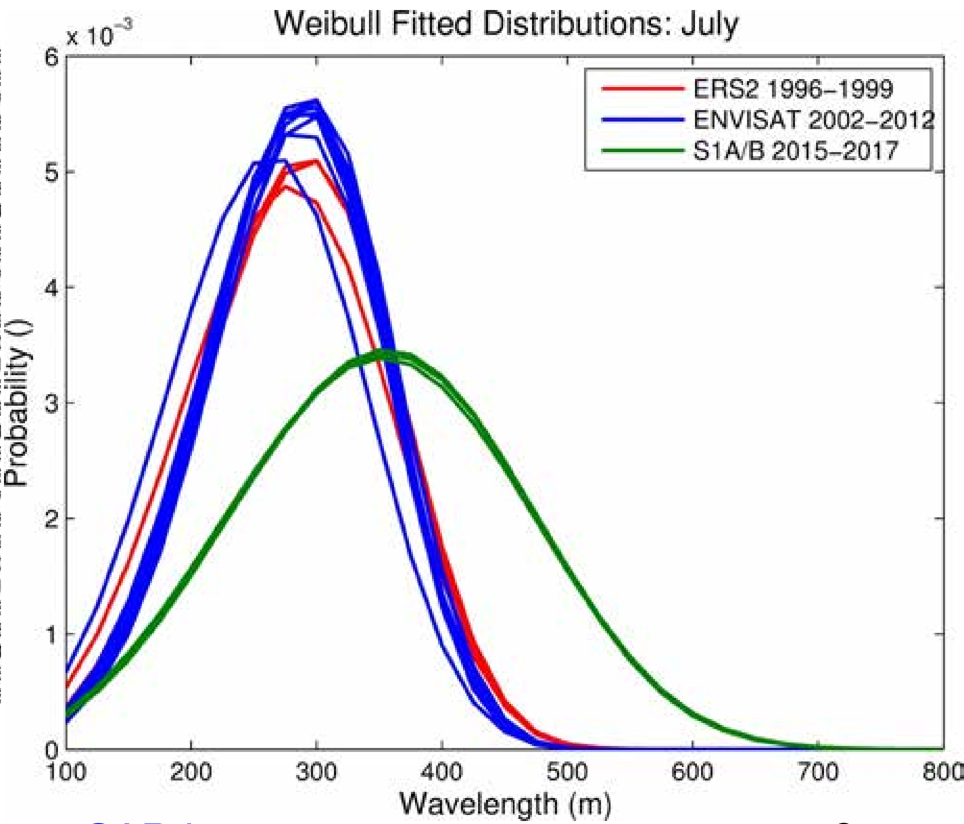
-mean agrees:ERS2 & ENVISAT

-S1A/B PDFs are very different!

-subsequent analysis uses 1995-2012



Altimeters Hs



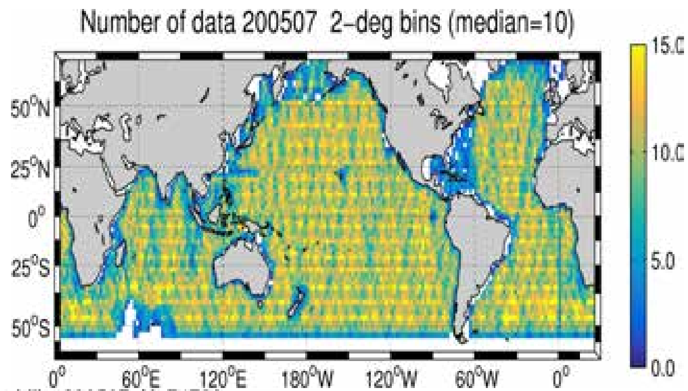
SAR Lp

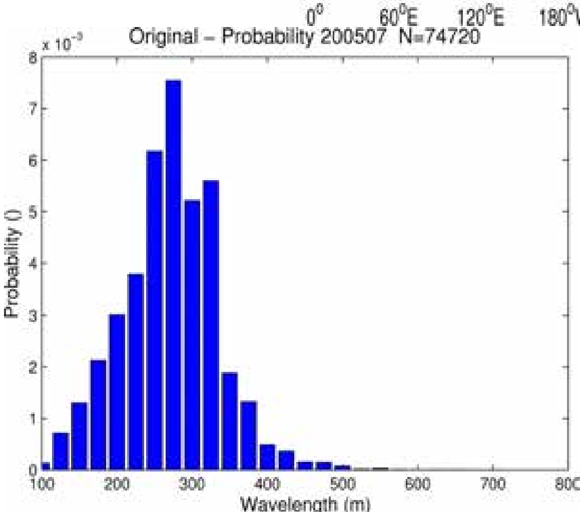
2 Data sources: SARs Lp

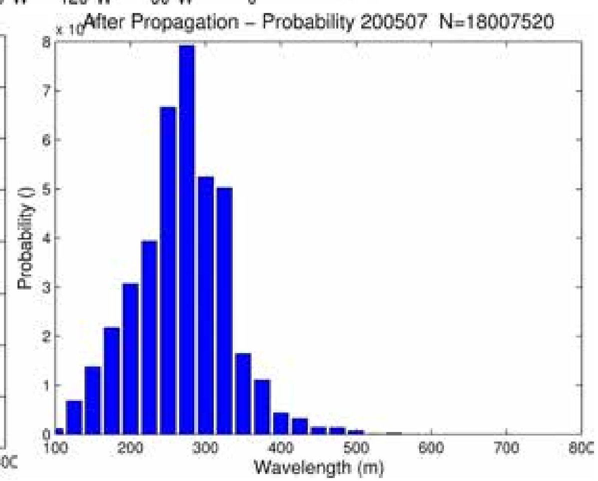
N/month are limited : ENVISAT ~ 12/month - (2 deg)

Swells decay slowly (10^{-7} m^{-1}) → forward propagate all wave partitions (>azimuth cutoff) along great circle routes at deep water group velocity

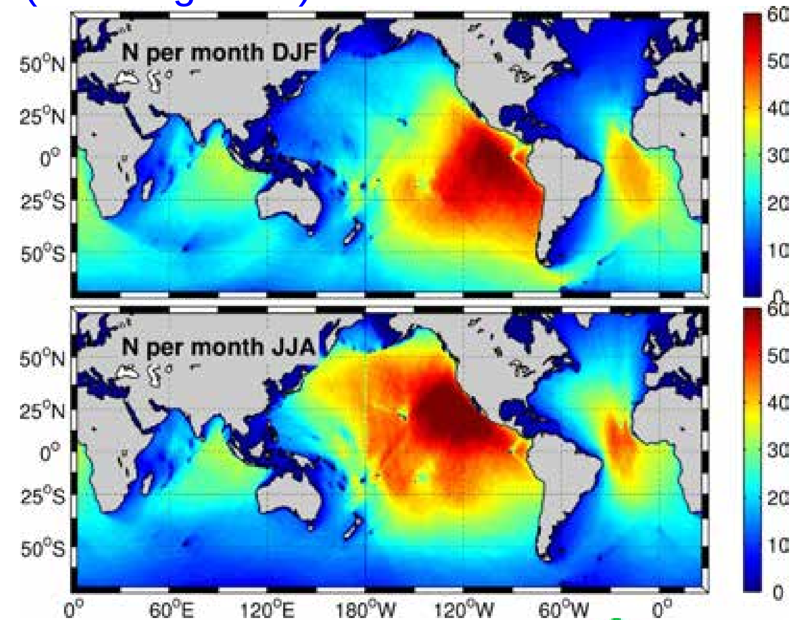
Enhances N and does NOT change the statistics!

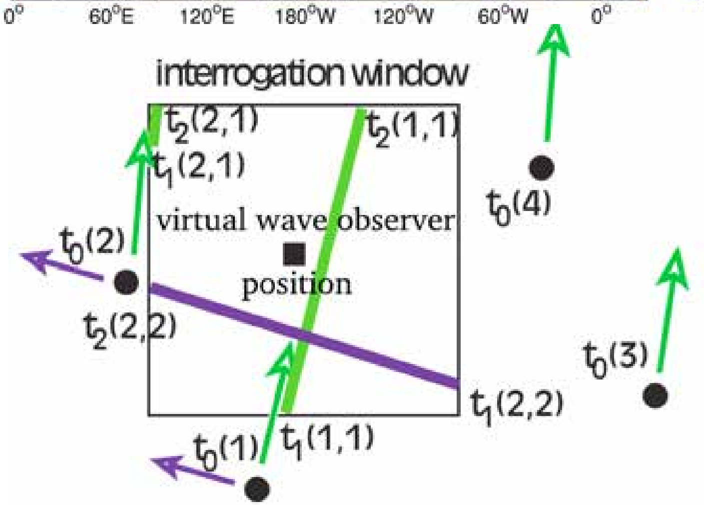






Average N: ERS2 & ENVISAT (crossing seas)





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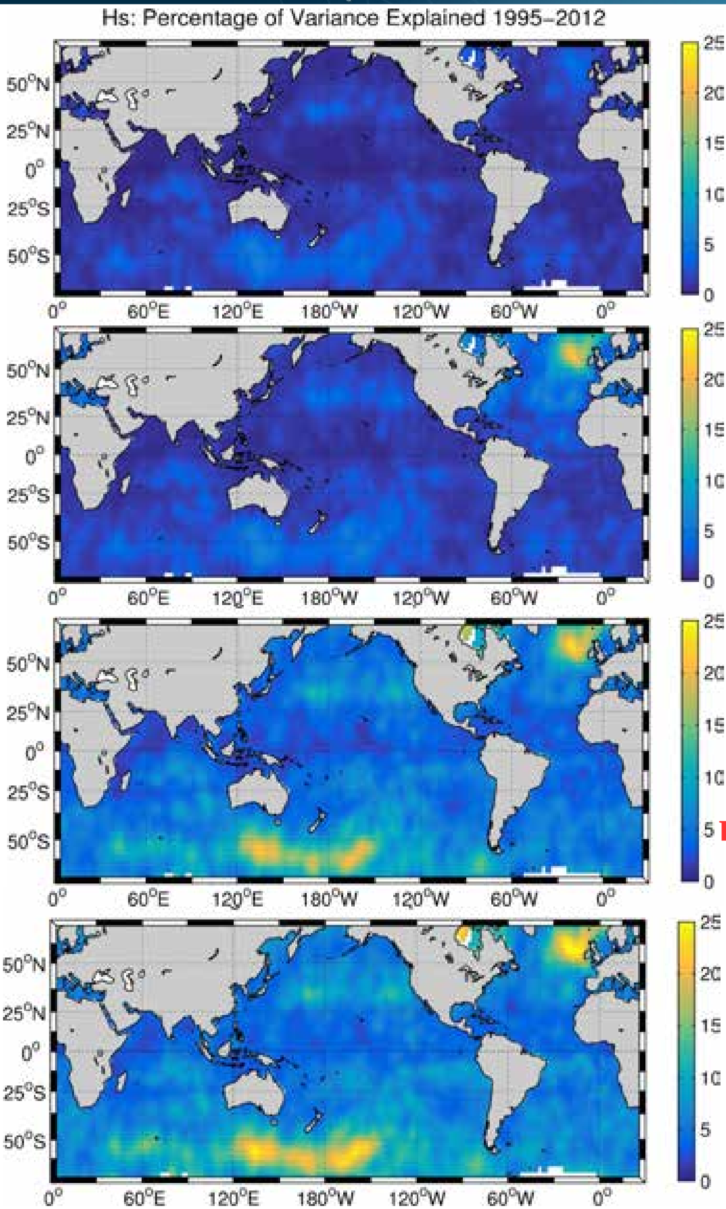
Results

-Trends vs Inter-annual variability

3 Results: Hs
Multi-variant Regression



$\eta = a_0 + a_1 t + \varepsilon$

$\eta = b_0 + b_1 t + b_2 AO + \varepsilon$

$\eta = c_0 + c_1 t + c_2 AO + c_3 AAO + \varepsilon$

$\eta = d_0 + d_1 t + d_2 AO + d_3 AAO + + d_3 AMO + \varepsilon$

1995-2012 – 18 years

Hs

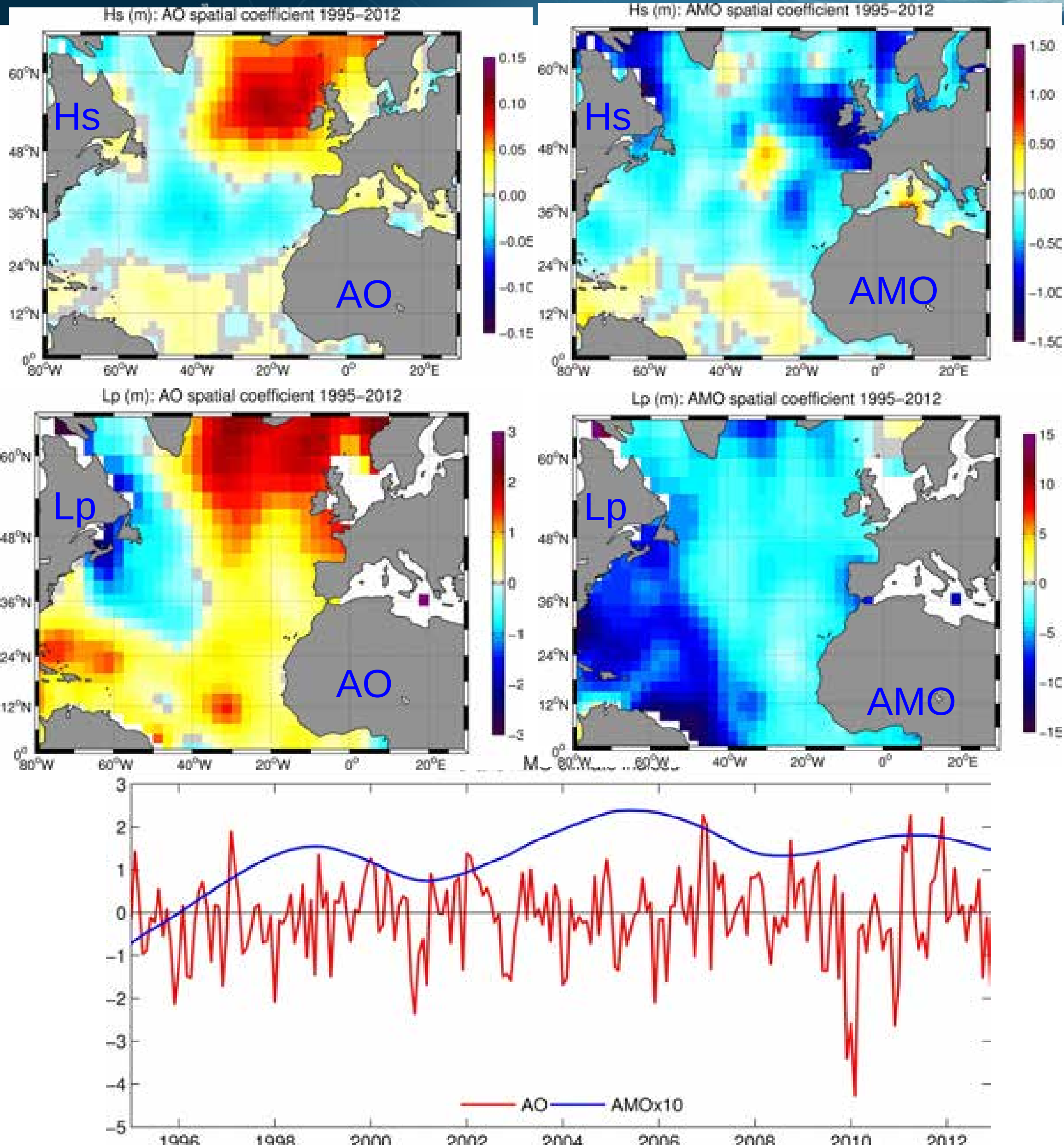
-AO and AAO explain more of the variability in the N Atl and SO >(10-20)%

-weaker relationships with ENSO, PDO, and AMO

Lp (not shown)

-weak relationships (<10%) with: NAO, SAM, ENSO, PDO, AMO,...

2 Results: Hs + Lp
Multi-variant Regression



$\eta = b_0 + b_1 t + b_2 AO + b_3 AMO + \varepsilon$

AO+AMO – explained 35% variance in domain

AO – typical dipole pattern

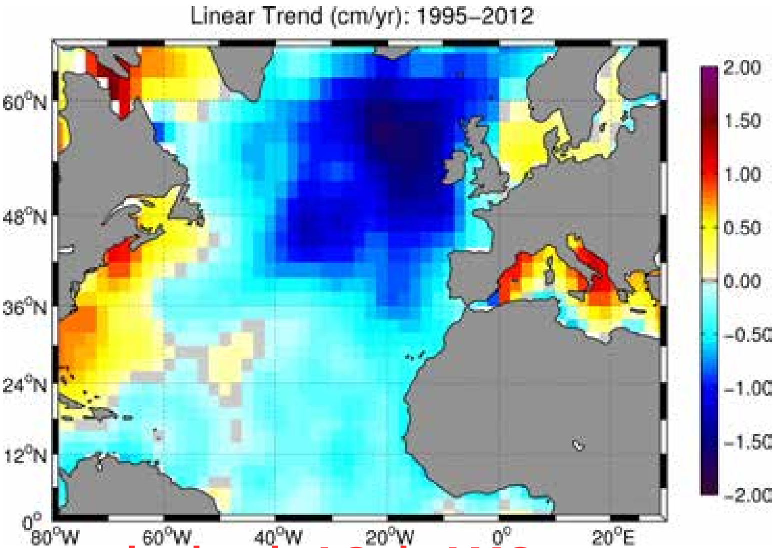
similar features in Hs and Lp

AMO: (+) during 1995-2012; loading pattern is negative

Similar features in Hs and Lp

2 Results: Hs
Multi-variant Regression

$\eta = a_0 + a_1 t + \varepsilon$

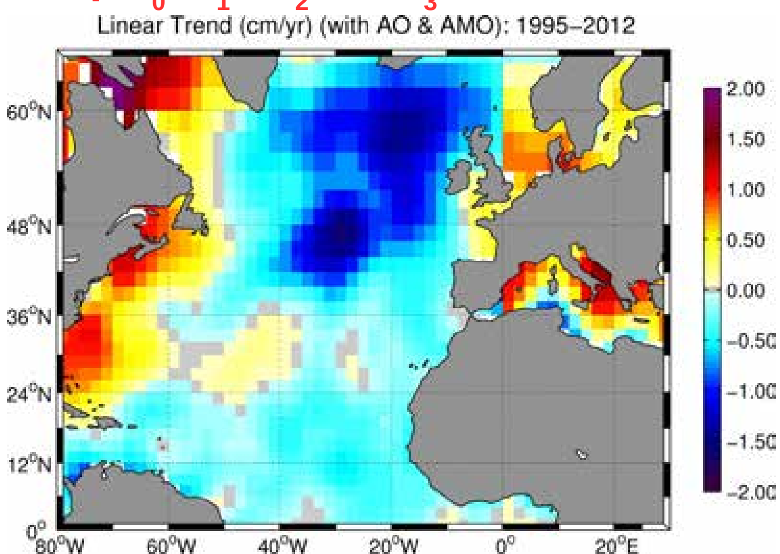


Patterns are similar

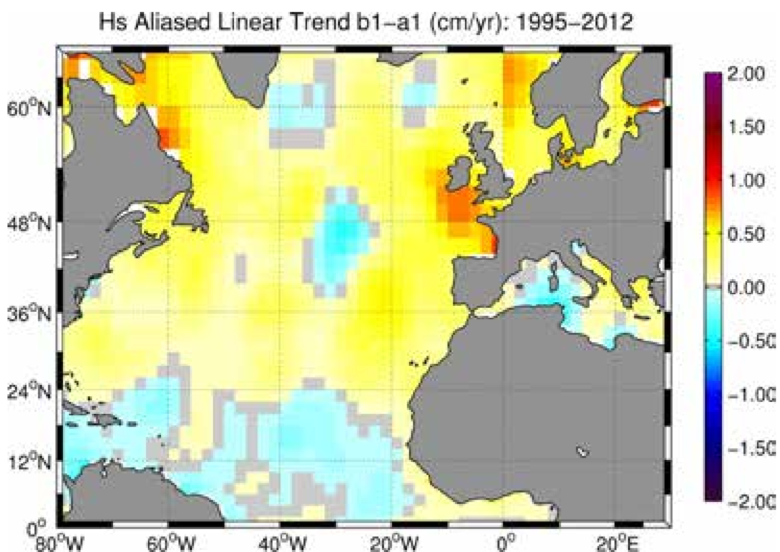
When climate oscillations are included

non stationary trend increases/decreases in N/S

$\eta = b_0 + b_1 t + b_2 AO + b_3 AMO + \varepsilon$

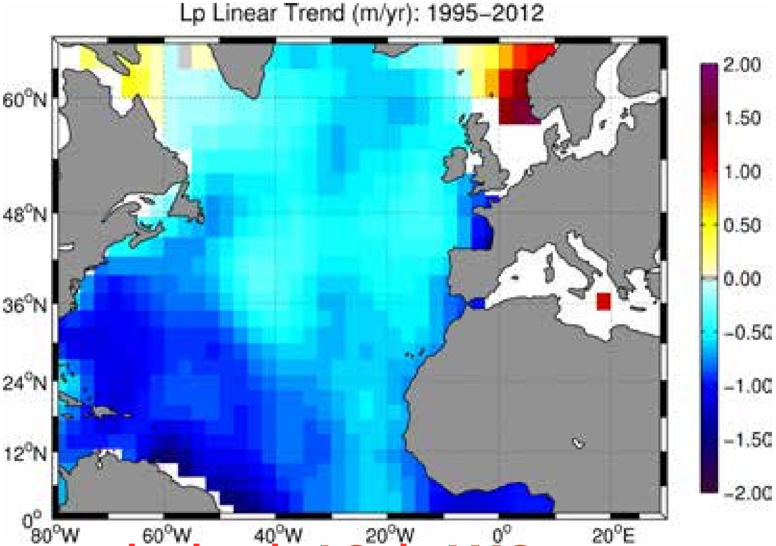


$b_1 - a_1$



2 Results: Lp
Multi-variant Regression

$\eta = a_0 + a_1 t + \varepsilon$



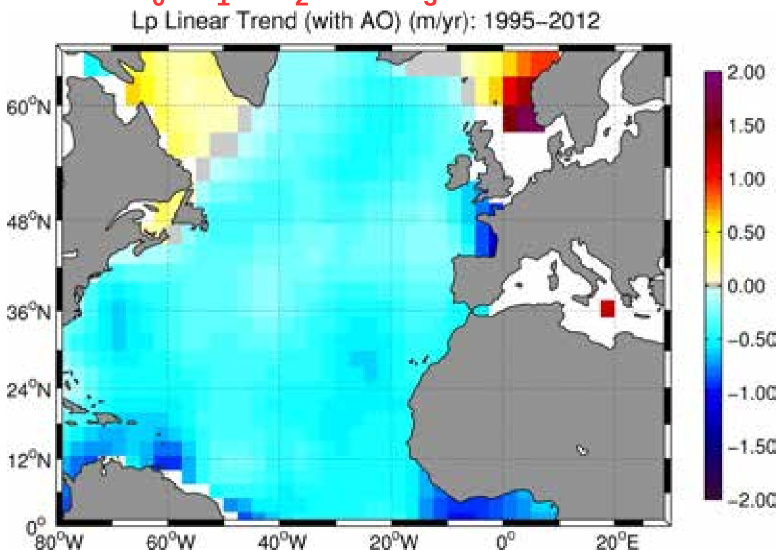
Near Norway – Hs trends disagree

Decreasing wave lengths

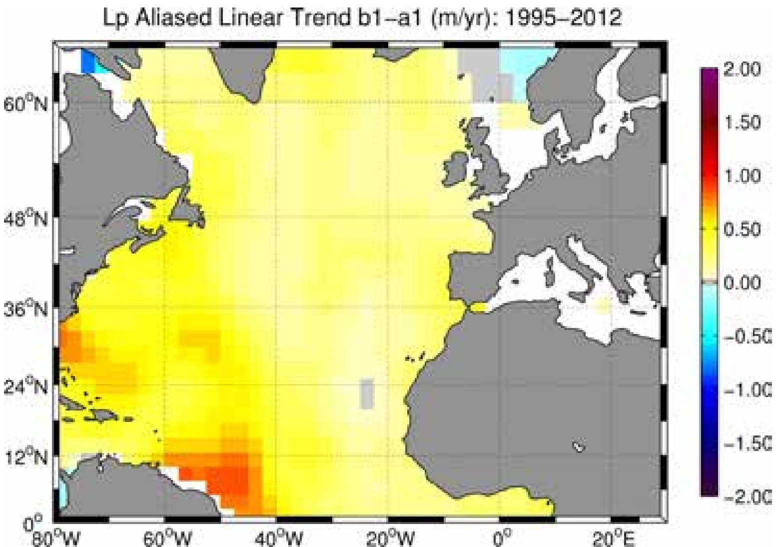
When AO & AMO are included

-non stationary trend becomes positive (less negative)

$\eta = b_0 + b_1 t + b_2 AO + b_3 AMO + \varepsilon$



$b_1 - a_1$



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Concluding Remarks

-Trend conclusion

-ESA CCI+ Sea State

3 Conclusion

Trends from Hs and Lp are surprisingly consistent!

Once impact from inter-annual variability is reduced:

N. Atlantic – trends are reduce (closer to 0) and are still negative

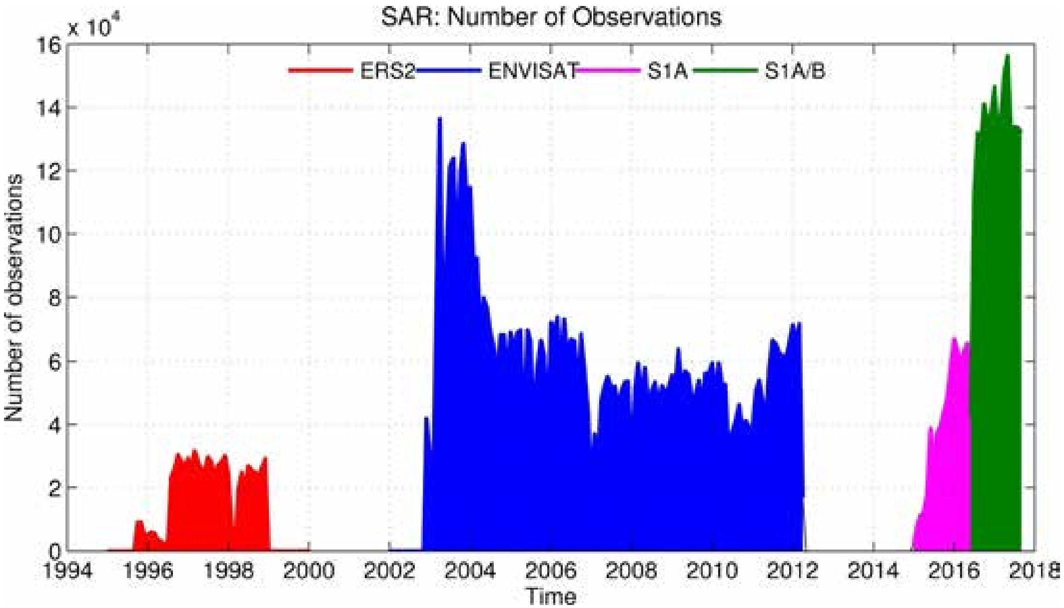
Inter-annual variability plays an important role in trends on short-time scales (<30 years)

Can we measure Hs ~1 cm/yr and Lp ~1 m/yr?

No error bars… prefer to use uncertainty ranges of variables and use Monte Carlo methods to estimate trend uncertainties

- ESA Sea State CCI+ will revisit

4 Sampling: SAR



Number of acquisitions per month (L2-product)

-2 data gaps: 1999-2003 & 2012-2015

-footprint, spatial resolution, noise are different between each platform → affecting the quality

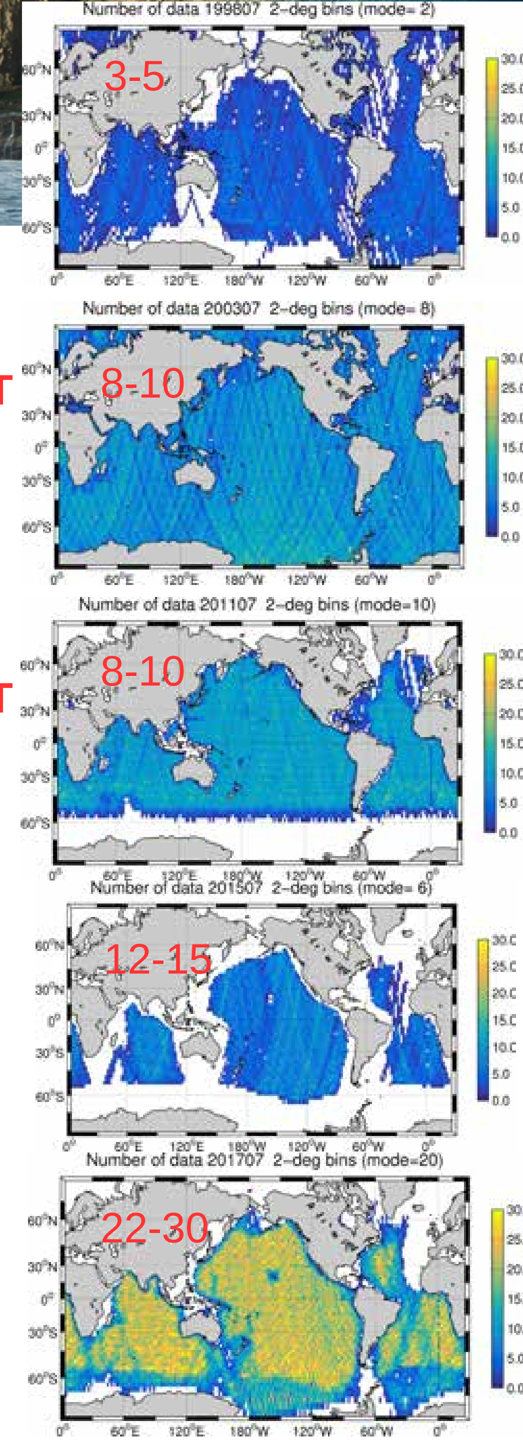
199807
ERS2

200307
ENVISAT

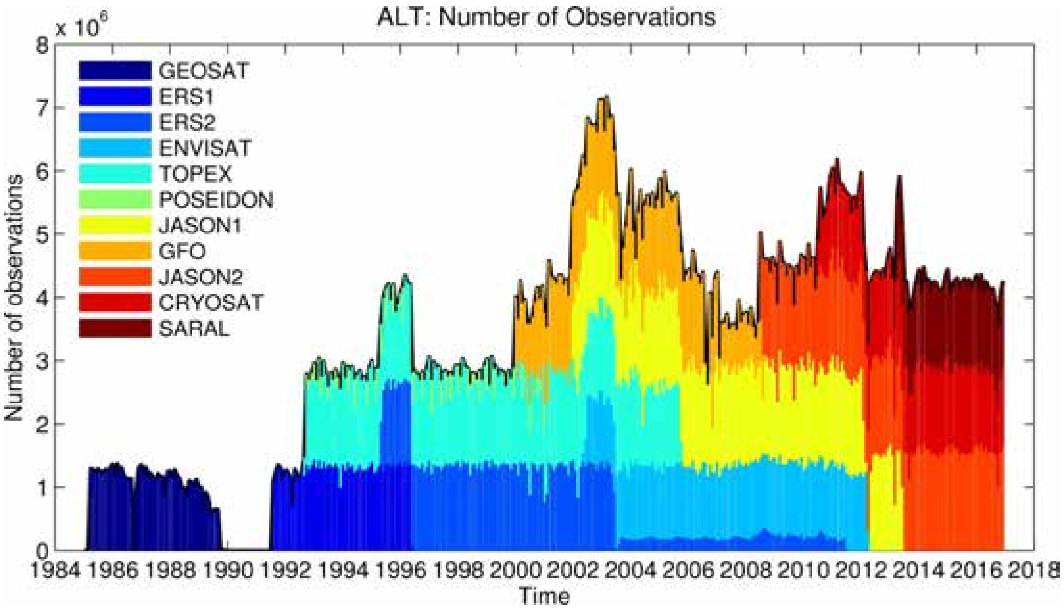
201107
ENVISAT

201507
S1A

201707
S1A/B



4 Sampling: ALT



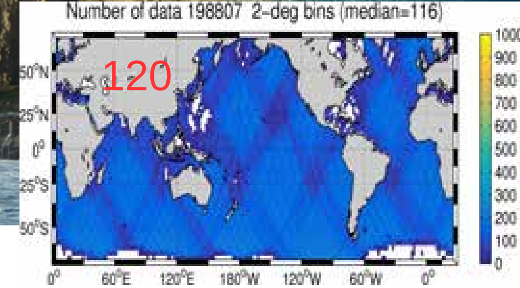
Number of Acqusitions per month (L2-product)

-1 data gap: 1990-1991

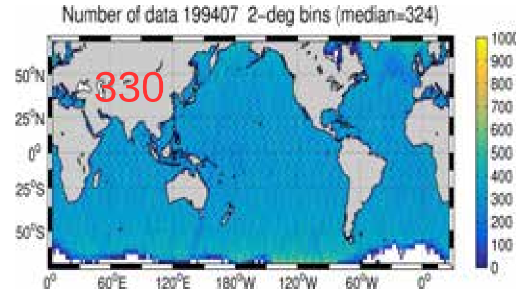
-2-3 orders of magnitude more than SAR

-oceans are continuously observed >1993 with more than 2 platforms

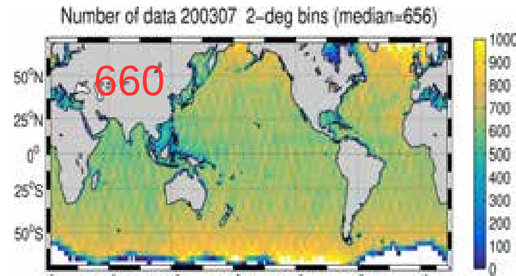
198807
1 SAT



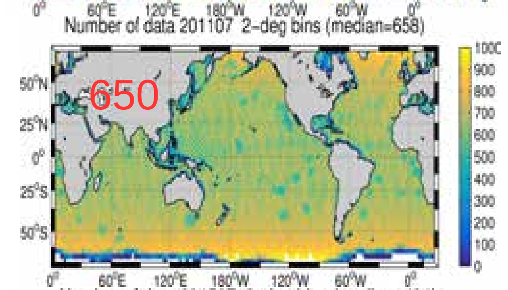
199407
2 SAT



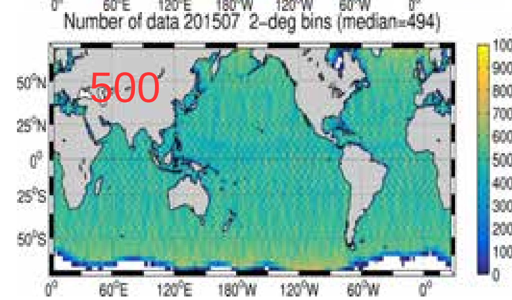
200307
5 SAT



201107
5 SAT

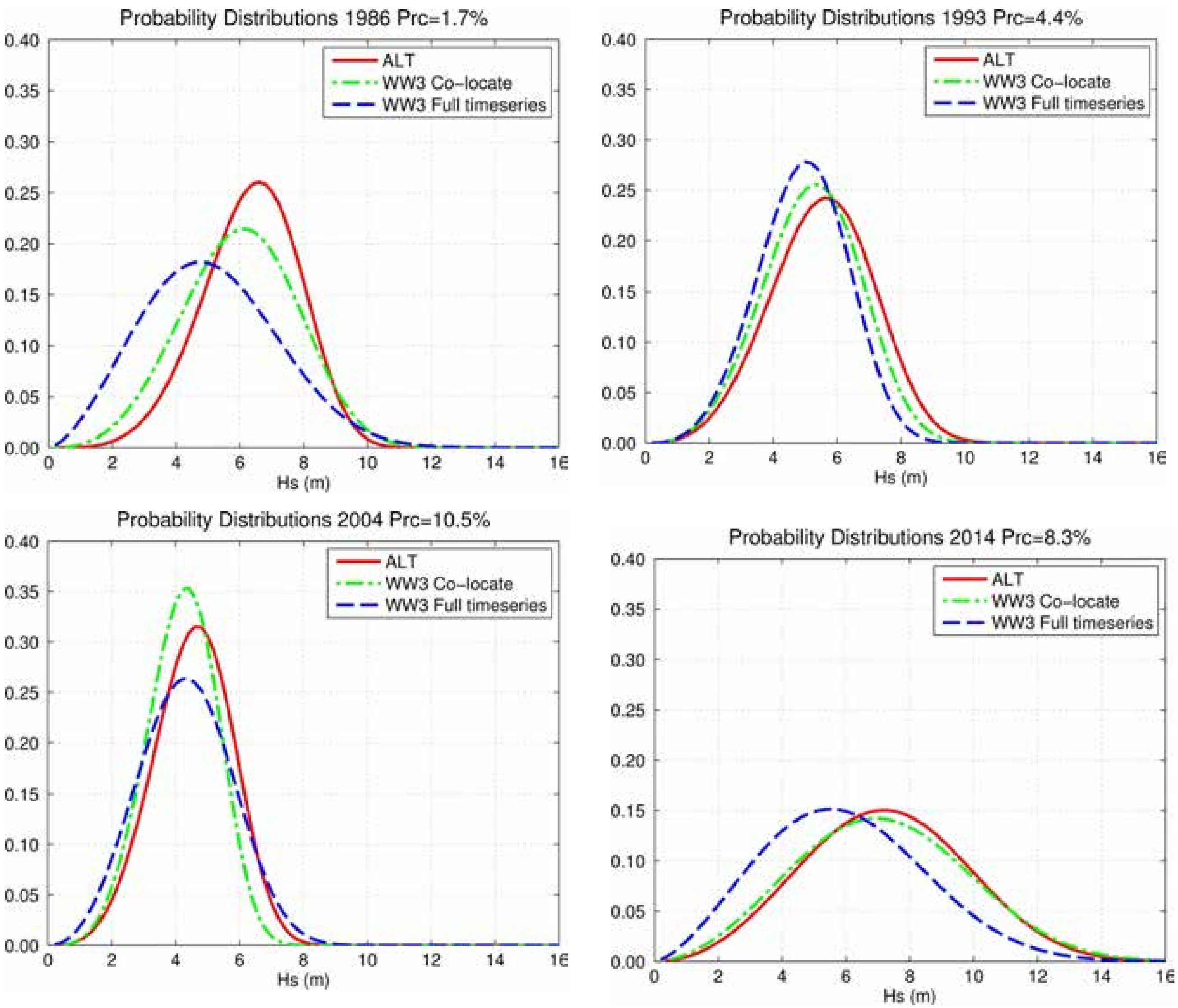


201507
3 SAT



4 Sampling
ALT: N. Atlantic

$$F(x;\sigma,\gamma)=(\gamma/x)(x/\sigma)^{\gamma}\exp\{-(x/\sigma)^{\gamma}\}$$



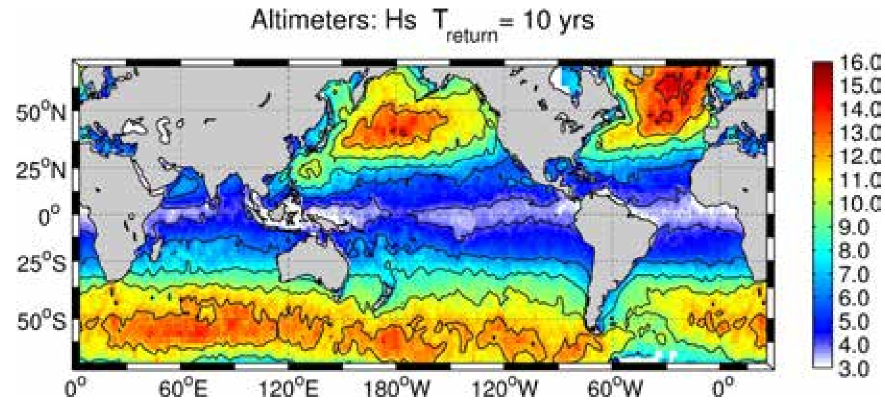
WW3 relative to ALT: underestimates (shifted to the left)

Full time series from WW3 shifts

-Mean to left

-higher probability in largest waves

4 Sampling ALT: Extreme Hs (TR=10 yrs)

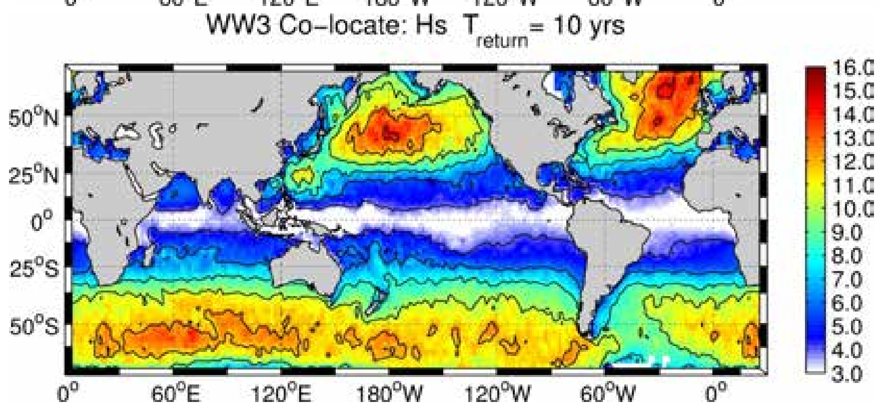


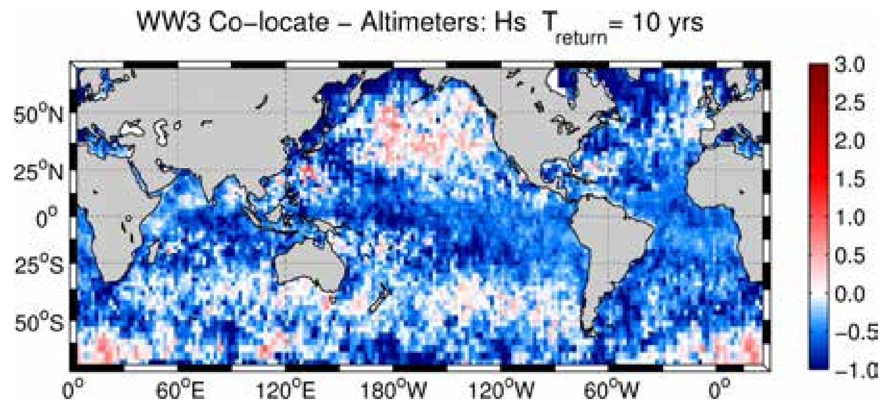
$$F(x;\mu,\sigma,\gamma)=\exp\{-[1+\gamma(\frac{x-\mu}{\sigma})^{(-1/\gamma)}]\}$$

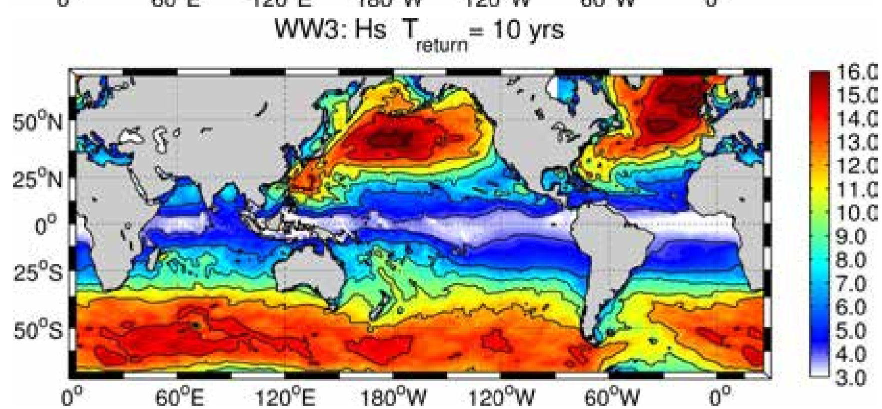
Annual maximum using GEV 1985-2016

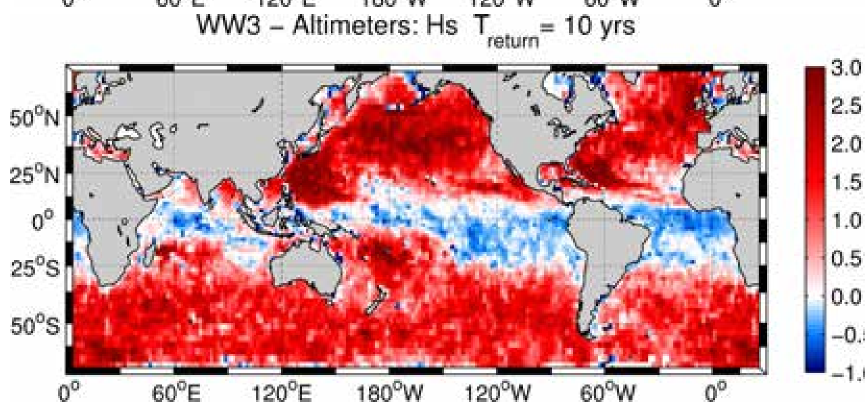
Altimeters miss important events!

Full time series >2.5 m compared to ALT









Thank you

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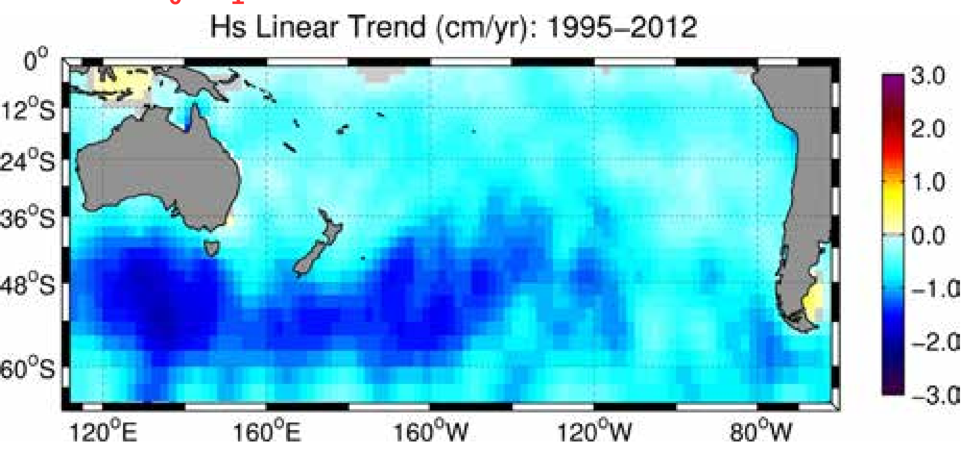
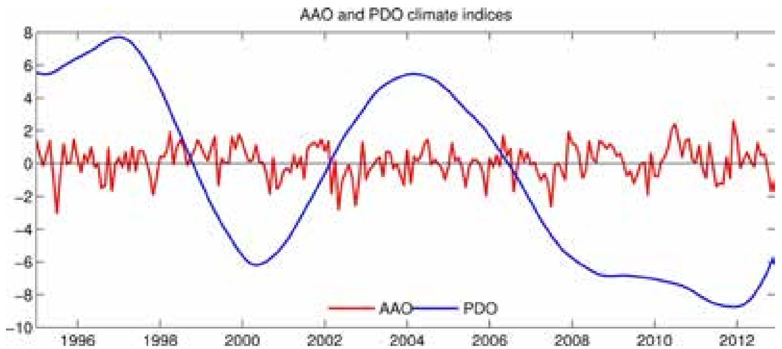
2 Results: Hs South Pacific

$\eta = a_0 + a_1 t + \varepsilon$

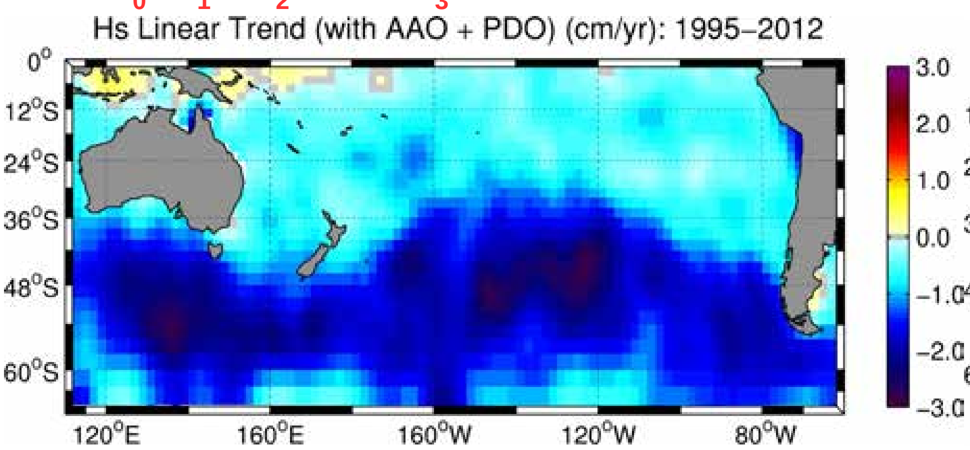


Decreasing Trends!

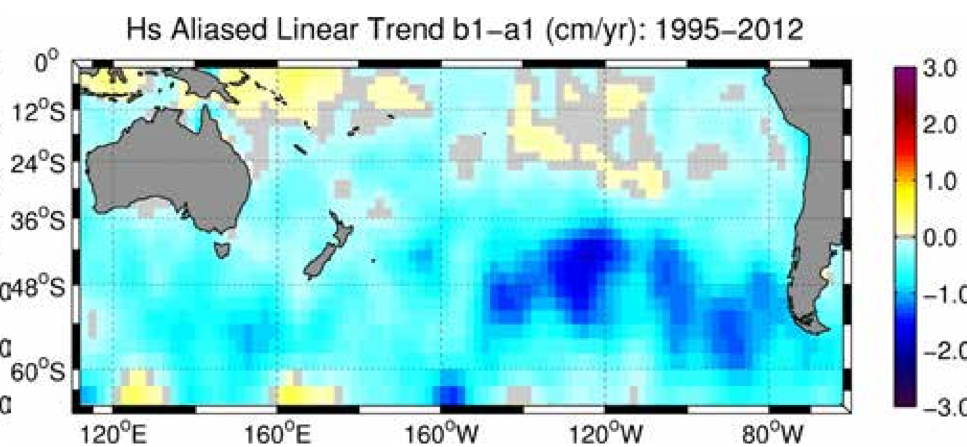
When climate oscillations are included trend decreases (becomes negative)



$\eta = b_0 + b_1 t + b_2 AAO + b_3 PDO + \varepsilon$

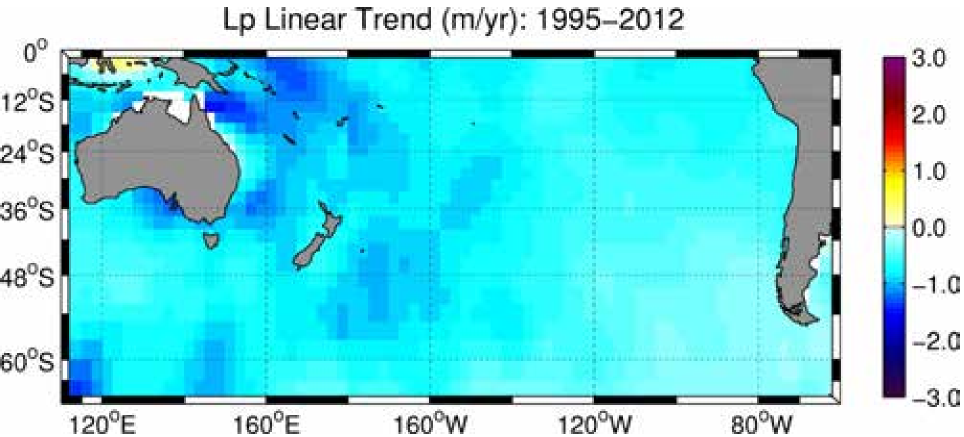


$b_1 - a_1$



2 Results: Lp South Pacific

$\eta = a_0 + a_1 t + \varepsilon$

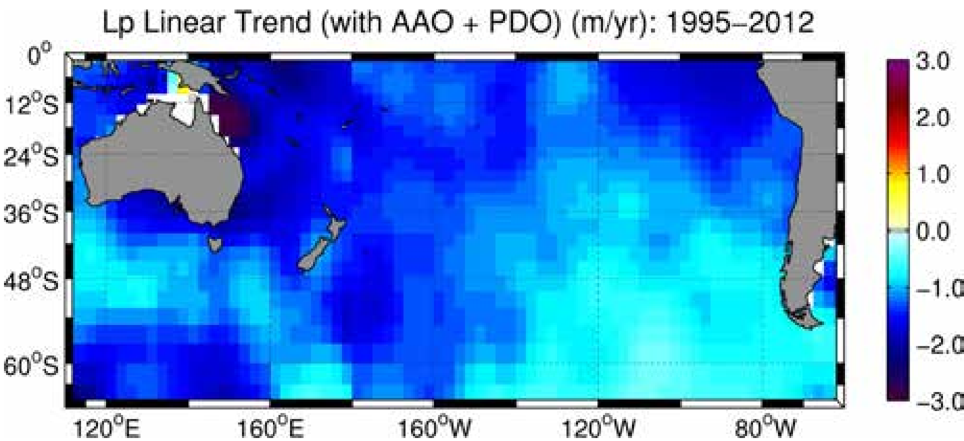


Decreasing Trends similar to Hs

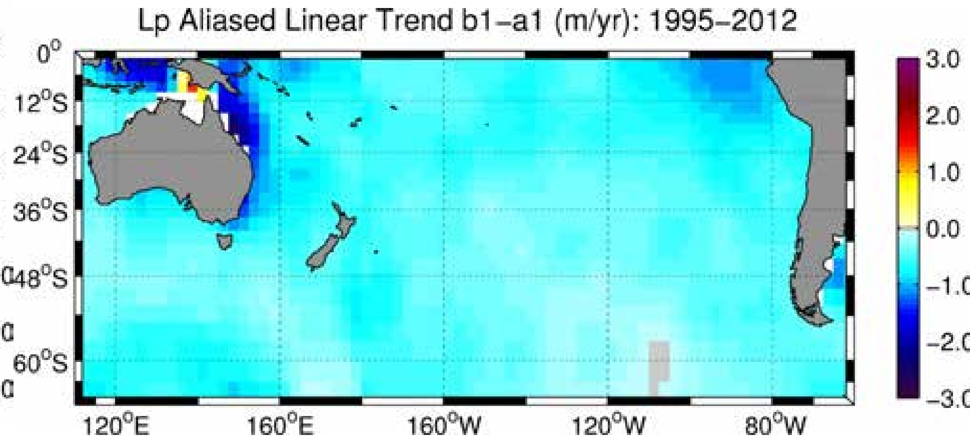
When climate oscillations are included trend decreases (becomes negative)

Can we measure ~1 m/yr?

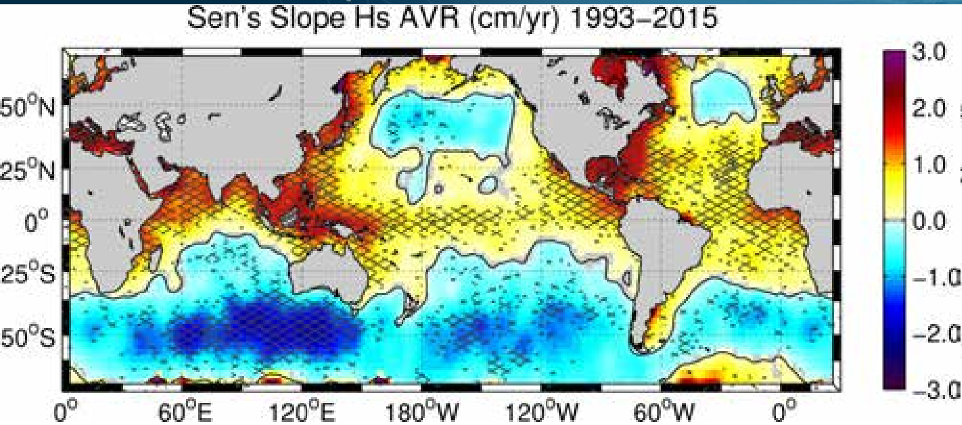
$\eta = b_0 + b_1 t + b_2 AAO + b_3 PDO + \varepsilon$

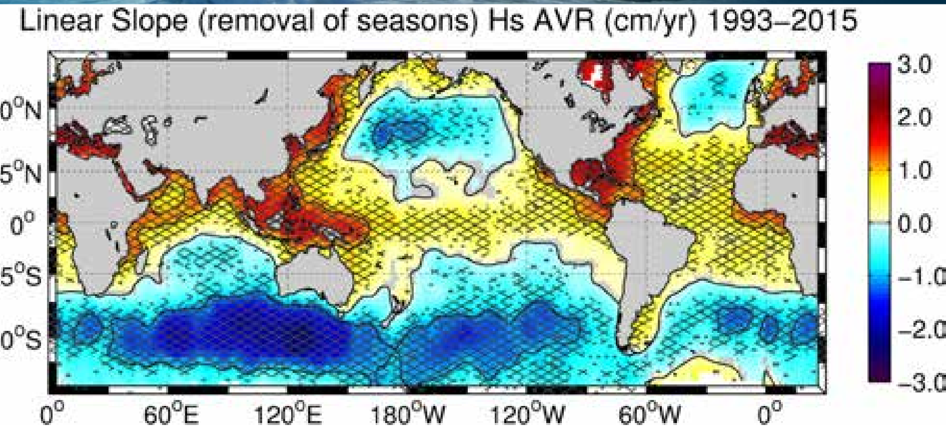


$b_1 - a_1$



3 Results:
Method comparison





Same method as Young et al., Science 2011

Linear trend with removal of seasons

$\eta = a_0 + a_1 t + \varepsilon_a$

Sen's slope with Mann-Kendall significance test

Linear trend with significance test

Patterns are nearly similar between the two methods: 1993-2015

Need to have Hs precision ~1 cm/yr