100-year waves, teleconnections and climate variation

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With thanks to

BP – Dr. Colin Grant (and Statoil) for providing data

INTERESTING QUESTIONS

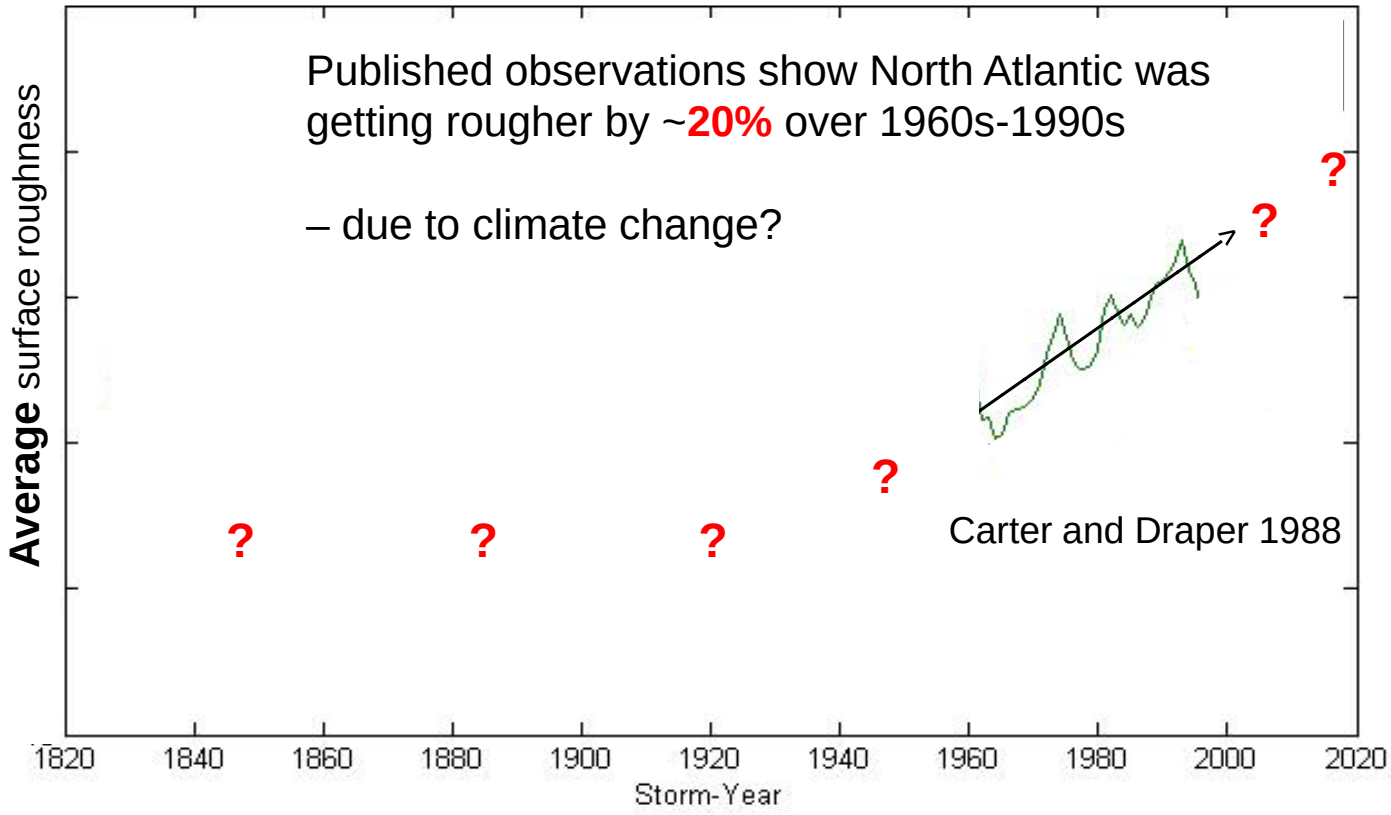
1. Is there an average wave climate at a particular location ?

2. Are the waves over the last 25 years a reliable guide to the next 25 or 100 years ?

3. Is there a link between decadal variation in extreme waves and
   global scale geophysical ‘teleconnections’,
   the North Atlantic Oscillation and the Pacific/North American pattern ?

4. Can knowledge of NAO since 1820 (or the PNA since 1950 in the Pacific) be used
   to infer a longer history for extreme wave conditions ?

Long timescale decadal changes in North Atlantic over the past ~200 years and into the future?



North Atlantic - Norwegian data from BP

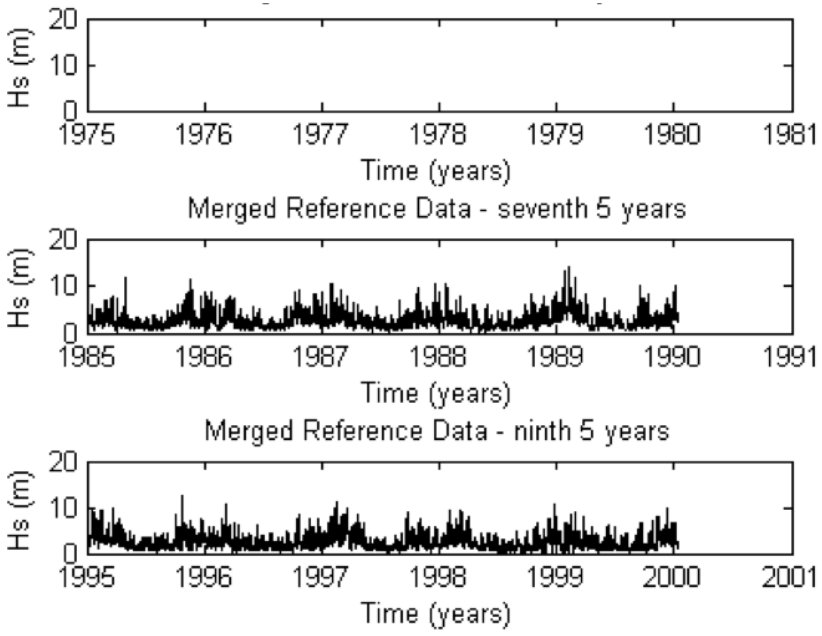
measured from buoy at Haltenbanken

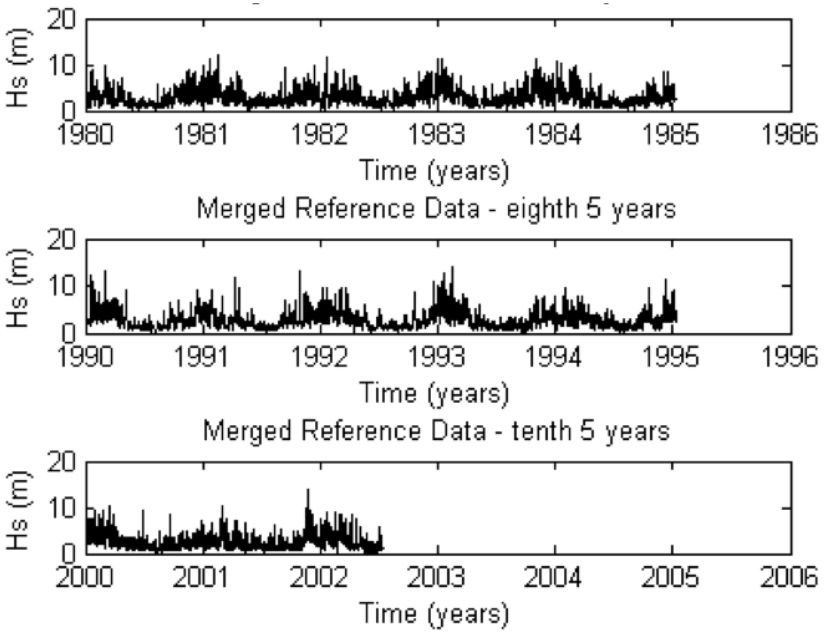
Norwegian wave data

– significant wave height (H_s=4σ) every hour from 1980-2002

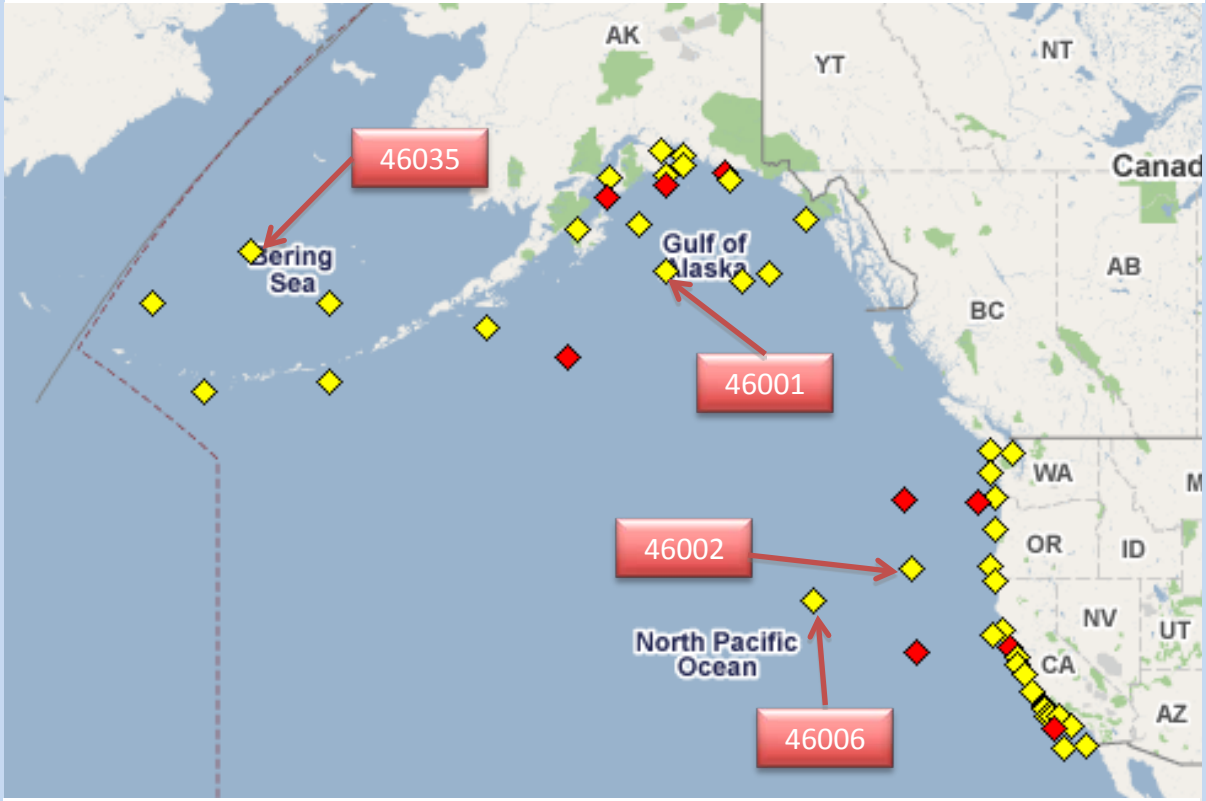
Merged dataset: Haltenbanken buoy + gaps filled from hindcast

(meteorological data converted into wave heights computationally)





Second area of study : north Pacific
– NOAA buoys with long records (>20 years)



Which location has most severe storms ?

460035 is close to the location of the rogue wave in series “The Deadliest Catch”

TELECONNECTIONS

Recurring and persistent, large-scale patterns of pressure and circulation anomalies that span vast geographical areas are known as '*teleconnections*'.

Many *teleconnections* are planetary scale, spanning oceans and continents.

Teleconnection patterns can reflect large scale changes in atmospheric wave and jet stream patterns and influence temperature, rainfall and storm tracks (www.cpc.noaa.gov).

"… the most important *teleconnections* in the Northern Hemisphere are the North Atlantic Oscillation (**NAO**) and the **PNA** (Pacific-North American) Patterns"

Hurrell et al, 2003

NORTH ATLANTIC OSCILLATION

+ ve phase

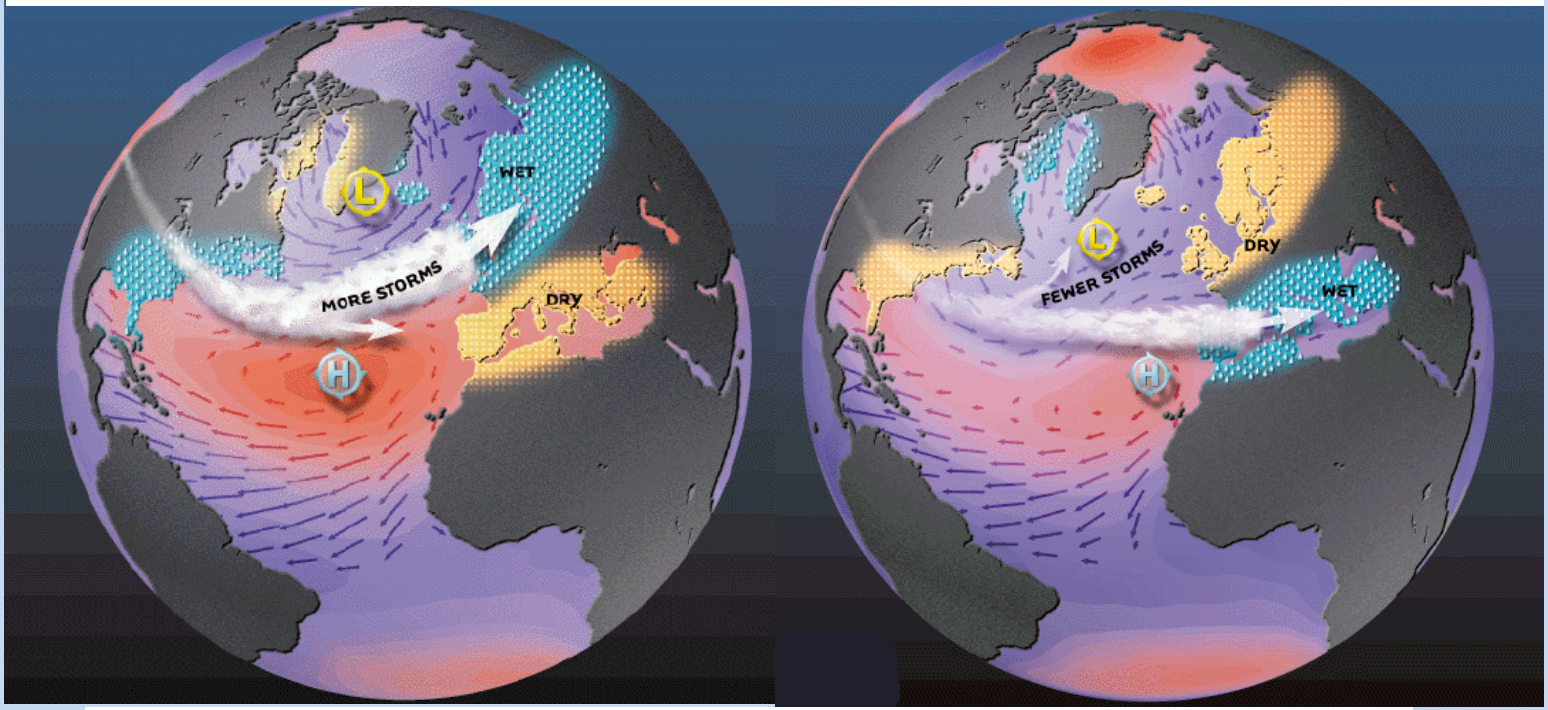
N. European winter – windy, mild and wet

more storms + northerly track

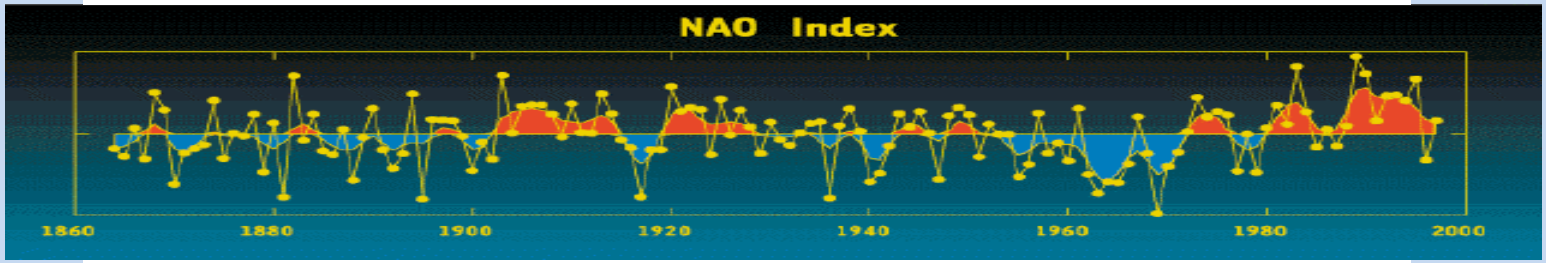
- ve phase

N. European winter – cold and dry

fewer storms + more southerly



NAO defined as average pressure difference Gibraltar-Iceland in winter



Is this teleconnection visible in the Norwegian wave data ?

http://www.ldeo.columbia.edu/res/pi/NAO/

How to characterise storm-based wave severity ?

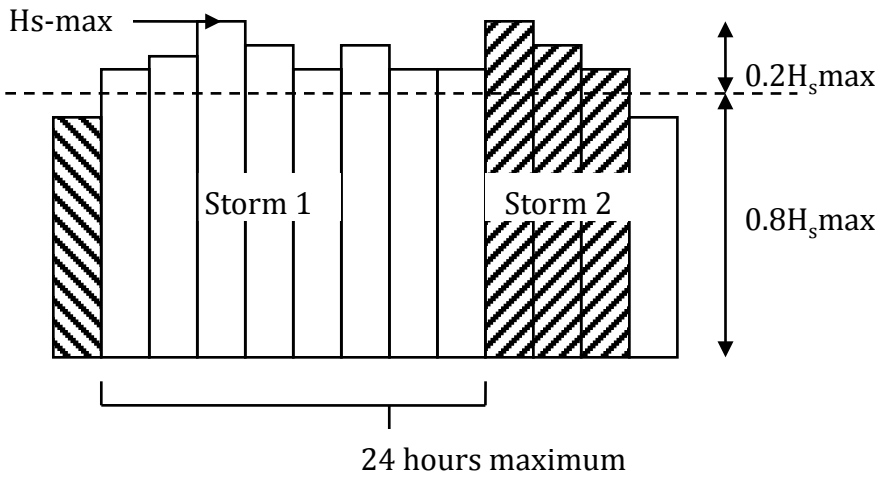
- use Peaks Over Threshold (POT) technique

- requires independent peaks : 1 number per storm

- what is a storm ?
- estimation of severity ?

- aim : robust estimate of 1 in 100-year extreme storm

Definition of a storm and storm severity

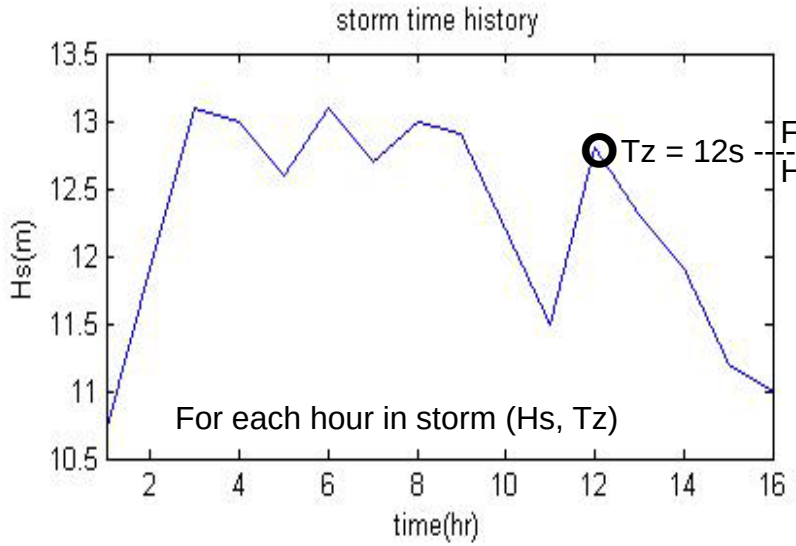


1. Identify storms in Hs record (<24hours long, Hs>0.8 Hs-max)

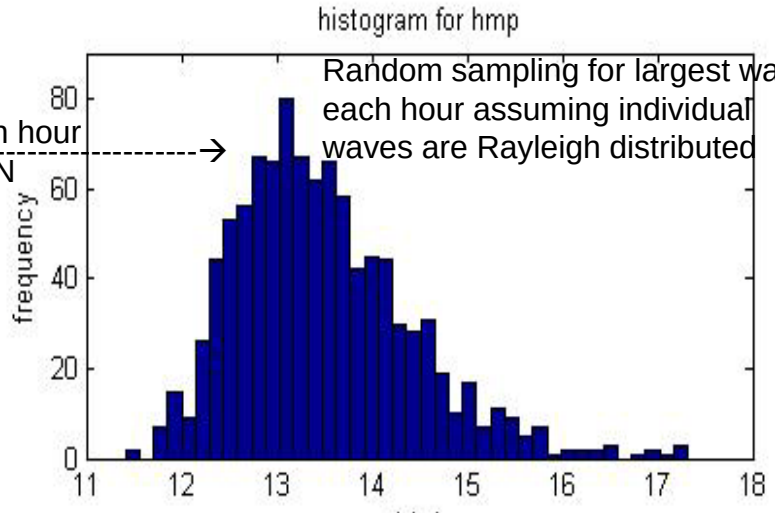
2. Choose a single parameter to capture storm strength *and* duration
   Assume individual wave heights each hour are Rayleigh distributed

3. **H_{mp} – most probable maximum wave height for each *storm***

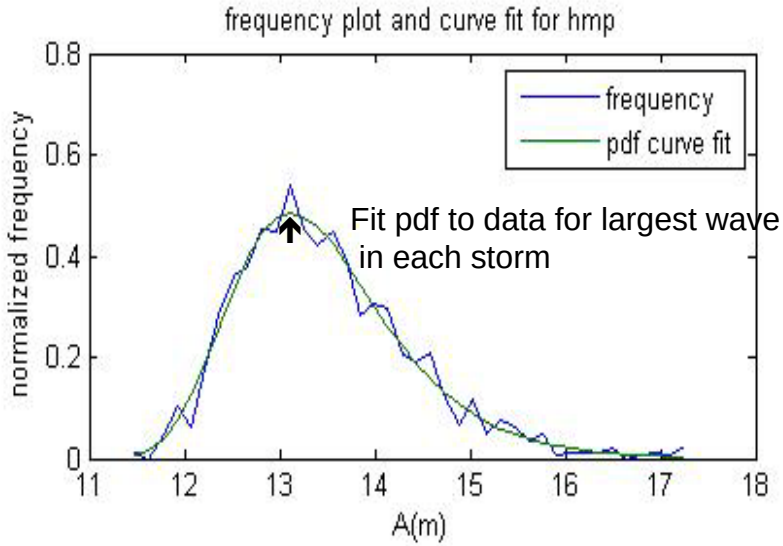
   - first introduced by Tromans and Vanderschuren 1995, OTC7683



For each hour
Hs and N



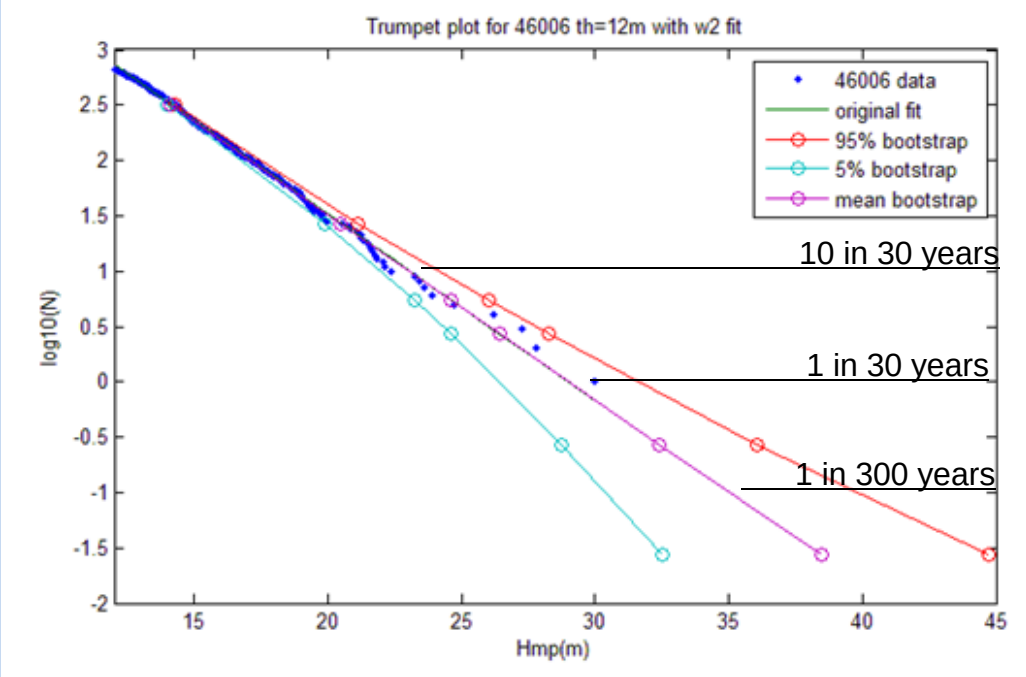
Random sampling for largest wave each hour assuming individual waves are Rayleigh distributed



buoy 46035 (Bering Straits)

H_{mp} = most probable maximum individual wave height

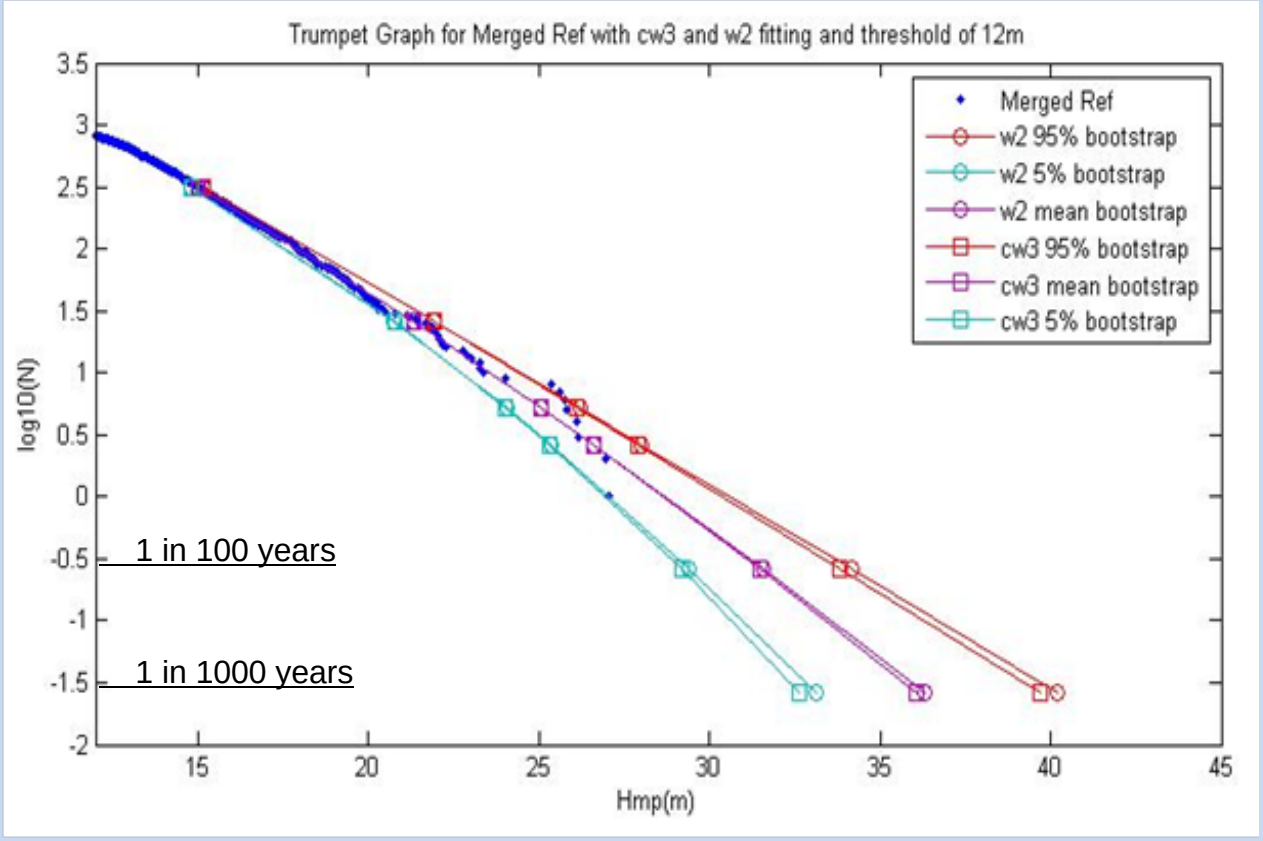
- captures both severity of storm (H_s values *and* duration)



Extreme value statistics - based on largest ~10^3 storms

Rank storms in order, largest (labelled 1) to smallest (labelled N)

Weibull fit to tail of exceedance plot of (H_{mp} vs. Rank order)



Return period x10 requires H_{mp} x ~1.16

Norwegian buoy data

Comparison of 2 fitting forms
– both examples of 'thin exponential-type tails' in extreme value theory

$Log_{10} N = a + b H_{mp}^{c}$ - W2

$= A + B H_{mp} + C H_{mp}^{2}$ - CW3

Results for extreme storm severity from buoy data

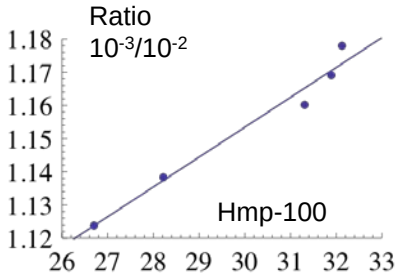
Point	$H_{s\text{-}max}$	H_{mp} 100-yr	H_{mp} 1000-yr	Ratio $10^{-3}/10^{-2}$
46001	13.88*m*	26.7*m*	30.0*m*	1.124
46002	13.50	28.2	32.1	1.138
Haltenbanken	13.97	31.3	36.3	1.160
46035	15.40	31.9	37.3	1.169
46006	16.32	32.1	37.8	1.178

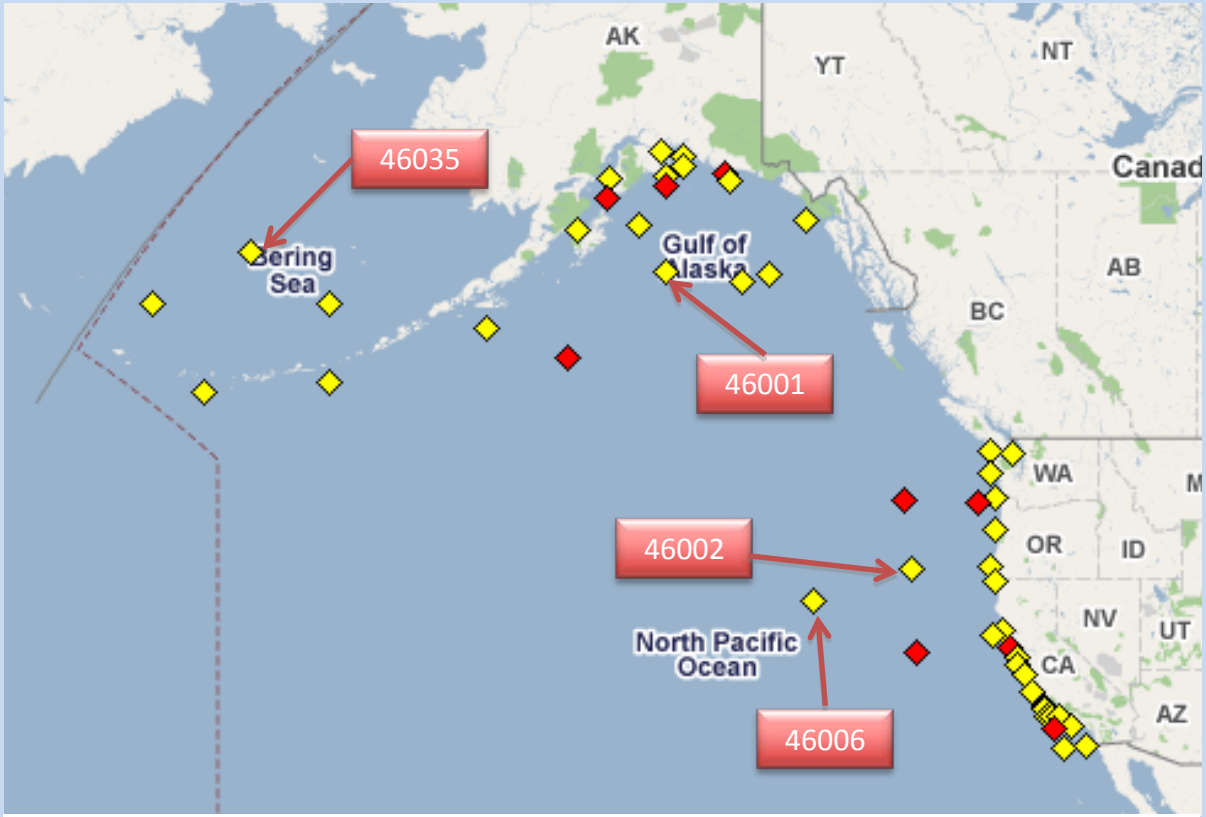
This ratio is important for long-term reliability

100-year waves in open ocean winter storms are BIG !

Weibull fits seem robust

results consistent for north Pacific and offshore Norway





Storm severity ranking

46001 < 46002 < 46035 ~ 46006

Perhaps most interesting difference is 46002 to 46006

$H_{mp\text{-}100}$ at 46006 = $H_{mp\text{-}1000}$ at 46002

Long-term variation of extreme wave height

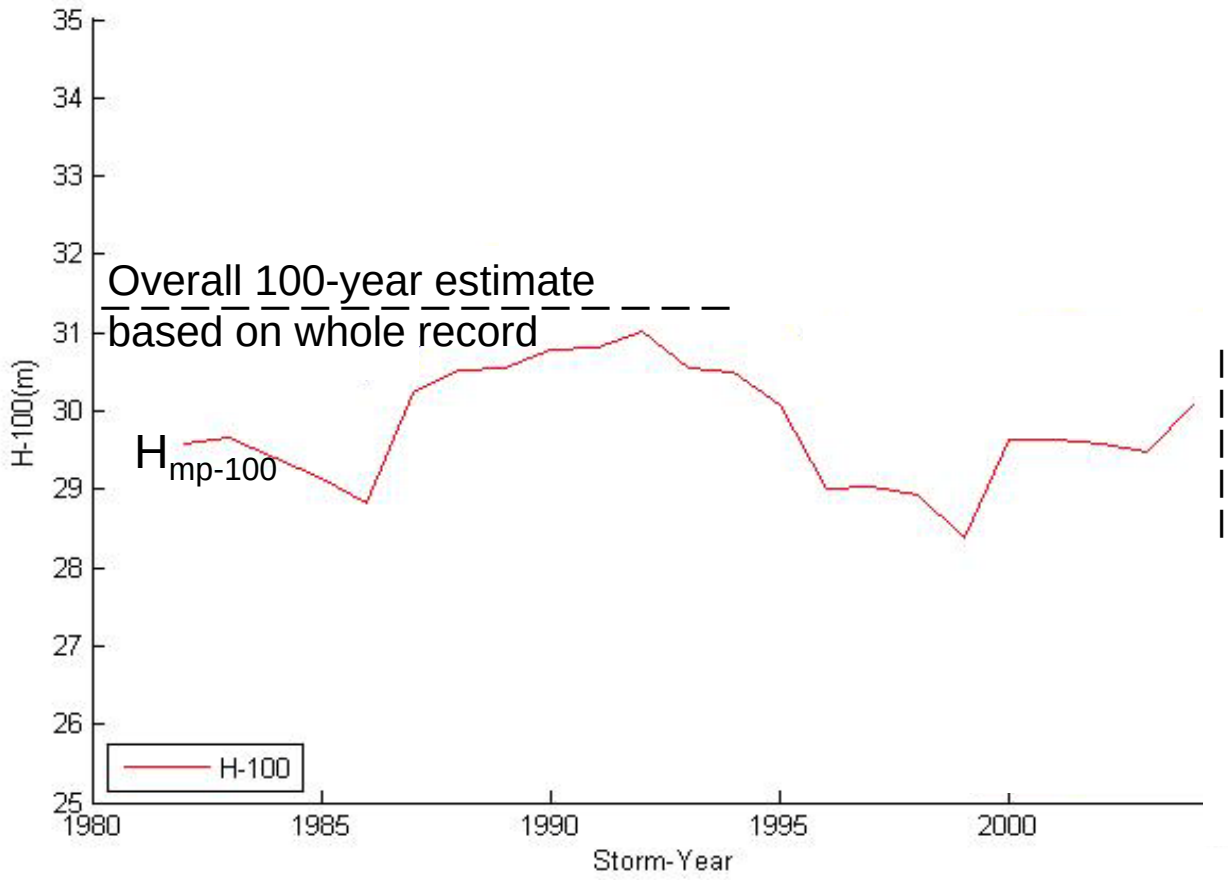
1. POT works well but needs ~100 storms above (sensible) threshold. Perhaps ~20 significant storms each winter

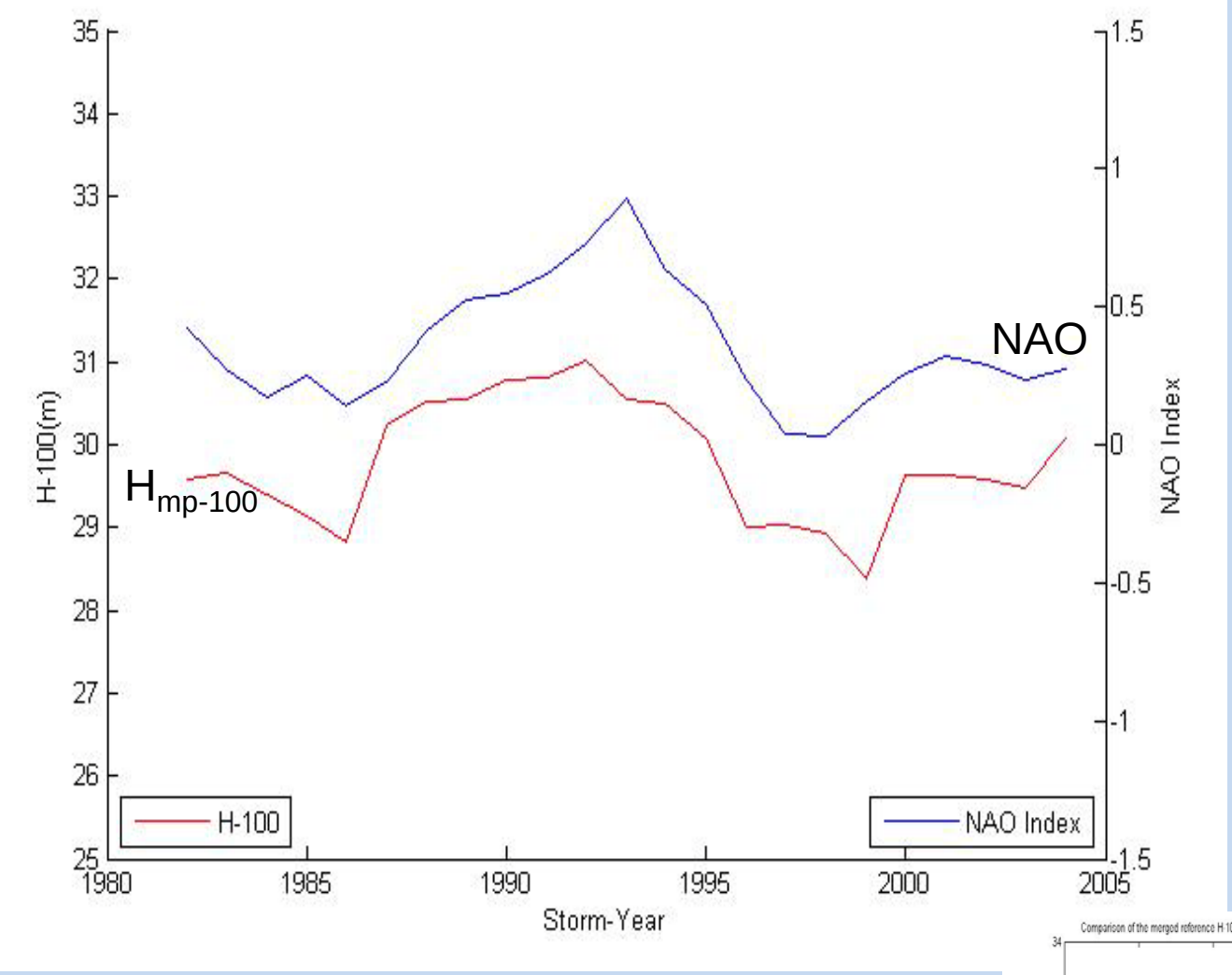
2. Use 5-year data window, giving ~100 storms as required

3. Estimate 100-year extreme wave for 5-year data window, then slide window across entire data record

4. Estimate of long-term variation of extreme wave height

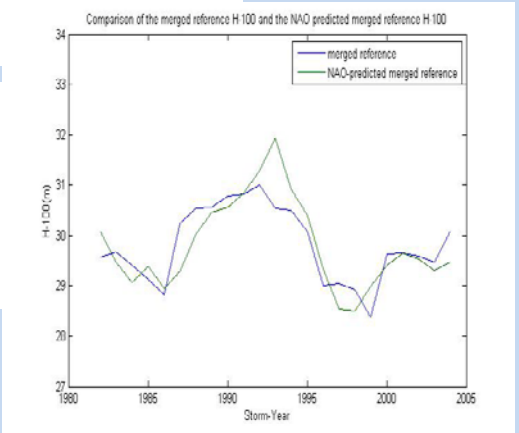
5-year sliding window estimate of 100-year storm severity for Haltenbanken buoy offshore Norway – varies *significantly*



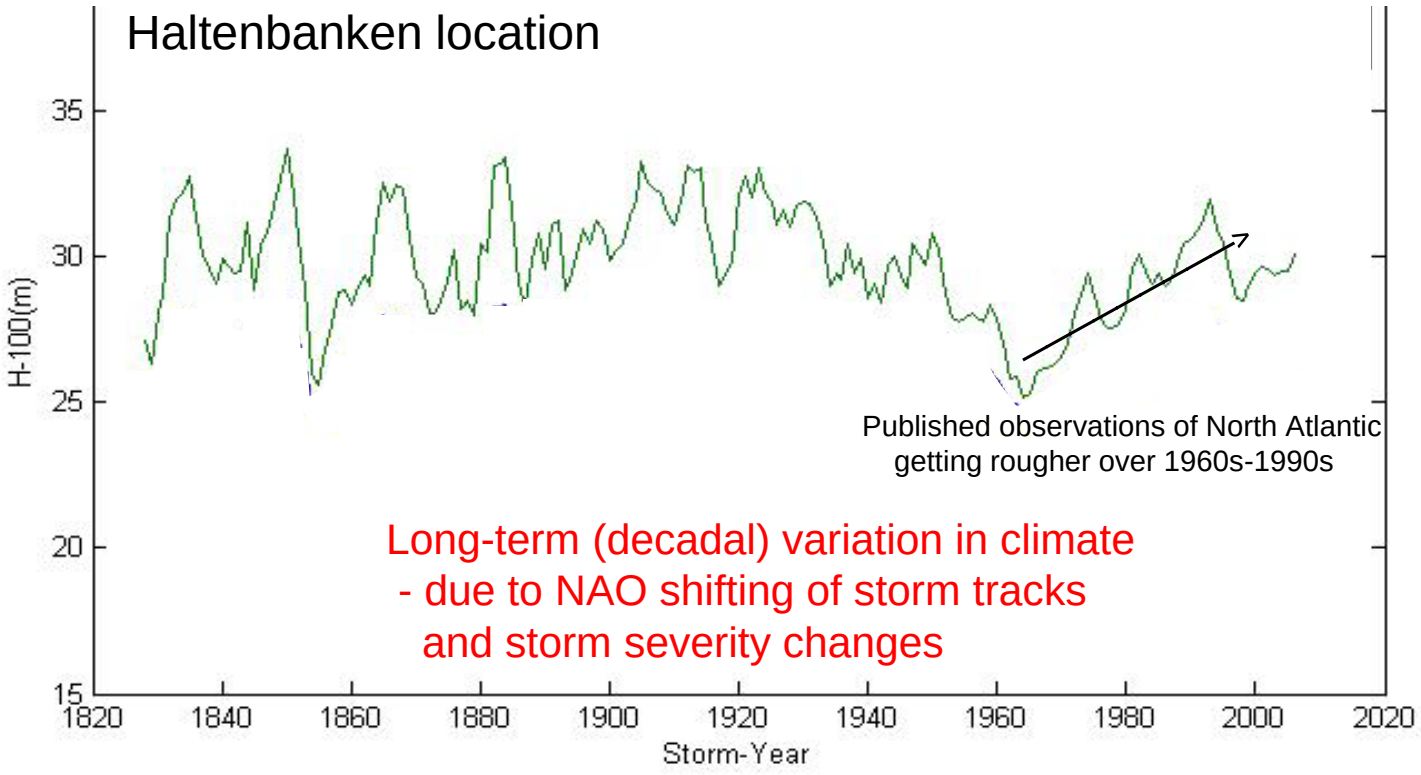


Strong relation between 5-year sliding window based estimates for 100-year wave offshore Norway and North Atlantic Oscillation

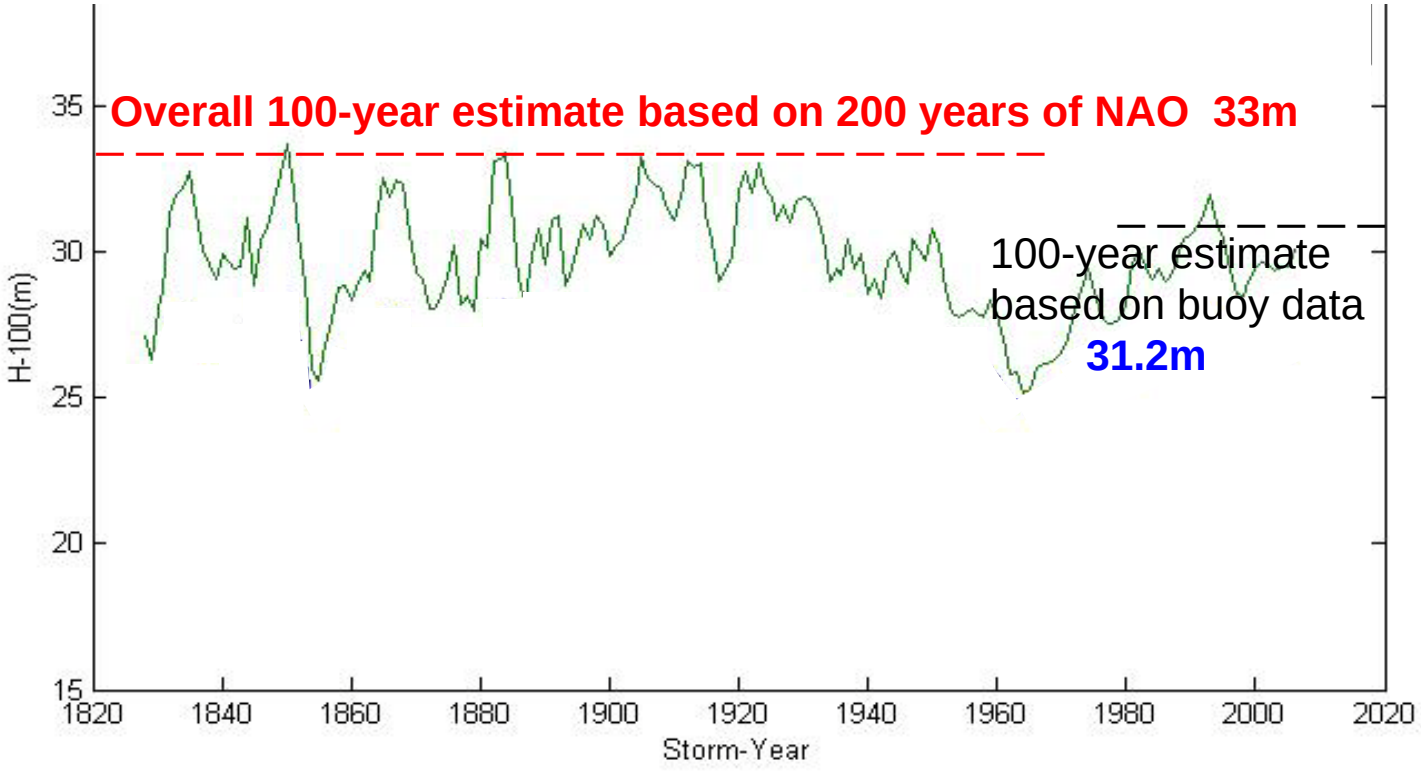
Correlation H_{mp-100} = 4 NAO + 28.6 m a coincidence ?



5-year sliding window
NAO-based prediction of long-term extreme wave climate



NORTH ATLANTIC - Haltenbanken
5-year sliding window prediction of long-term extreme wave climate



DESIGN wave height variation 25-33m has occurred over last 200 years and in the absence of climate change would presumably continue

What about variability in North Pacific ?

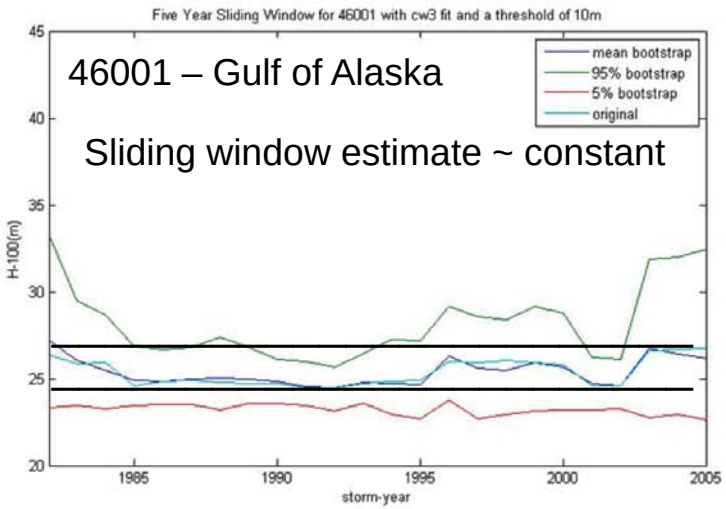
Teleconnections: at least 4 discussed in literature for North Pacific

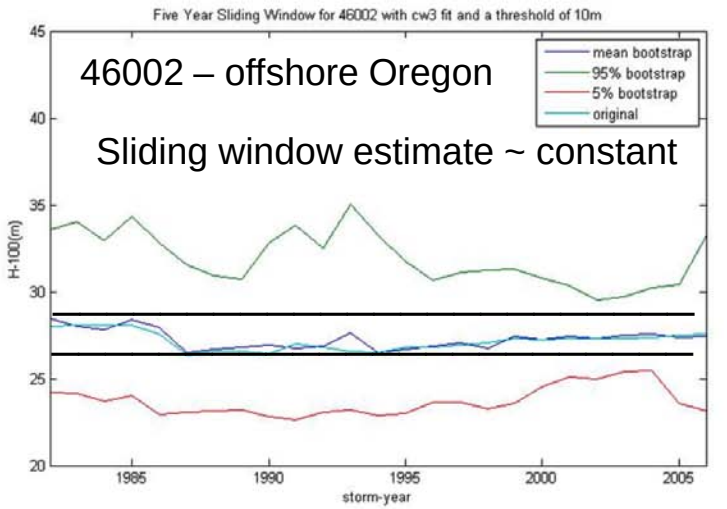
Pacific / North American (PNA) - atmospheric

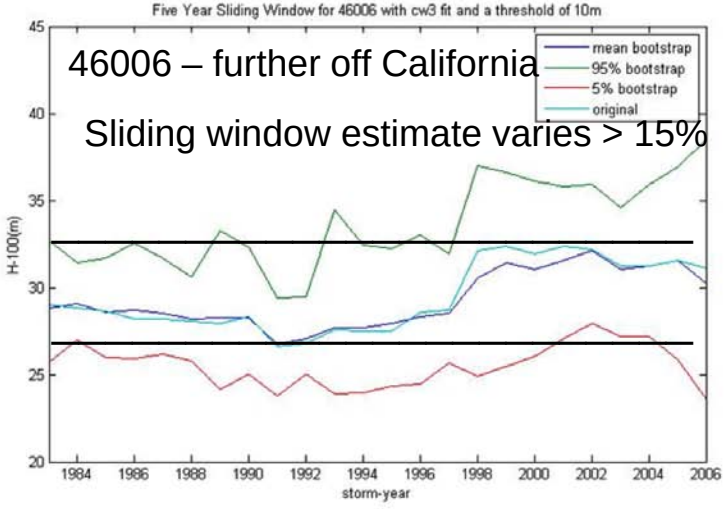
East-Pacific North-Pacific (EP/NP) - atmospheric
El Nino Southern Oscillation (ENSO) - sea surface temp
Pacific Decadal Oscillation (PDO) - sea surface temp

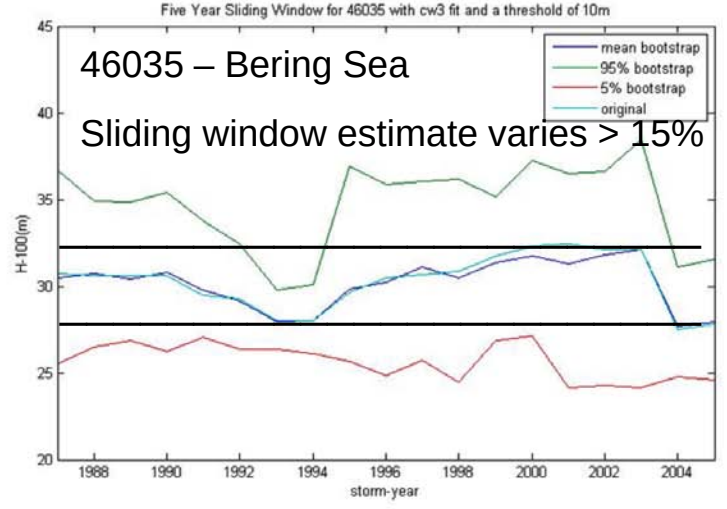
North Atlantic Oscillation (NAO) - atmospheric

Arctic Oscillation (AO) - atmospheric


Five Year Sliding Window for 46001 with cw3 fit and a threshold of 10m
46001 – Gulf of Alaska
Sliding window estimate ~ constant
mean bootstrap
95% bootstrap
5% bootstrap
original
H-100(m)
storm-year


Five Year Sliding Window for 46002 with cw3 fit and a threshold of 10m
46002 – offshore Oregon
Sliding window estimate ~ constant
mean bootstrap
95% bootstrap
5% bootstrap
original
H-100(m)
storm-year


Five Year Sliding Window for 46006 with cw3 fit and a threshold of 10m
46006 – further off California
Sliding window estimate varies > 15%
mean bootstrap
95% bootstrap
5% bootstrap
original
H-100(m)
storm-year

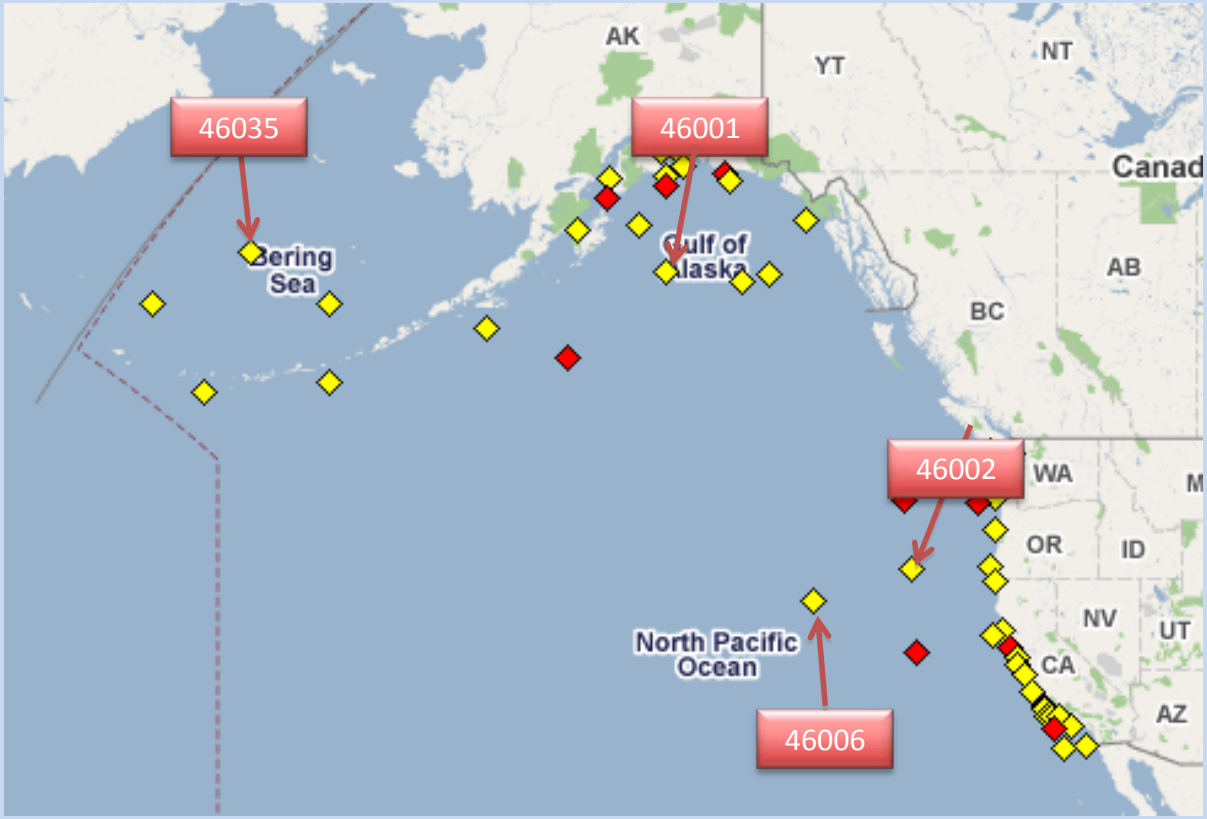

Five Year Sliding Window for 46035 with cw3 fit and a threshold of 10m
46035 – Bering Sea
Sliding window estimate varies > 15%
mean bootstrap
95% bootstrap
5% bootstrap
original
H-100(m)
storm-year

Correlations coefficients (R^2)
between 100-year H_{mp-100} and climate indices for north Pacific

Buoy	PNA	EP/NP	Nino3.4	PDO	NAO
46001	0.41	0.09	0.10	0.13	-0.49
46002	0.65	-0.31	-0.07	0.48	-0.45
46006	0.74	-0.25	-0.49	-0.15	-0.56
46035	0.48	-0.53	-0.64	-0.14	-0.49

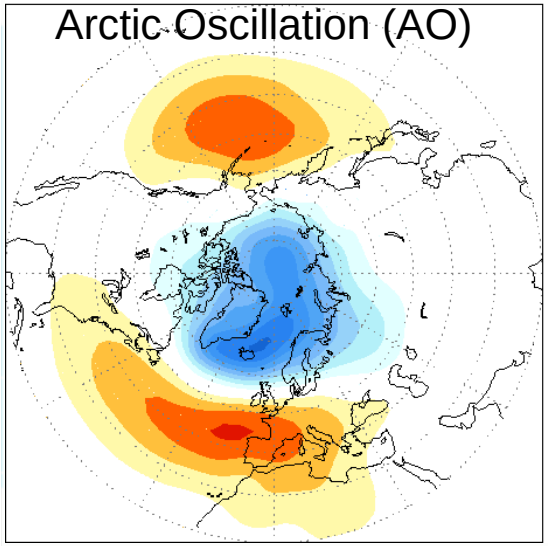
Virtually constant

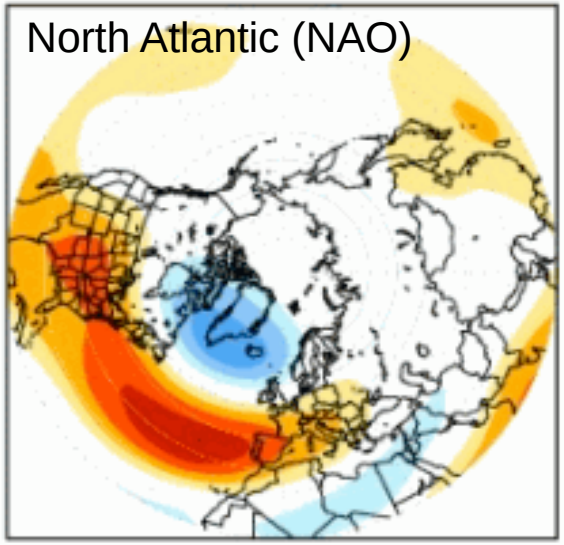
Variation > 15%

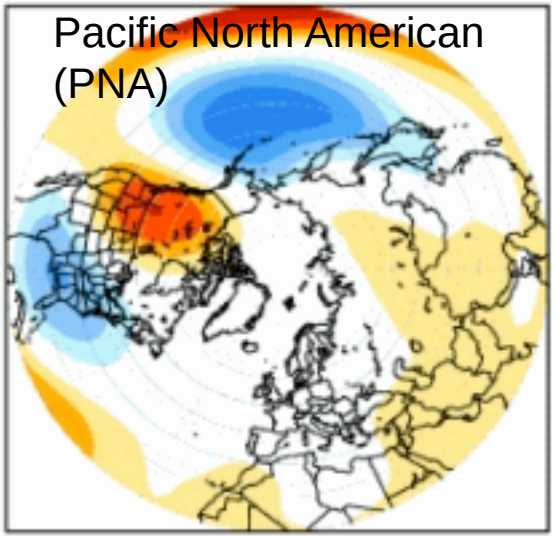


R^2=0.83
for Haltenbanken

CLIMATE OF NORTH PACIFIC IS MORE COMPLICATED THAN NORTH ATLANTIC
- and the form of the various atmospheric pressure-based indices doesn't help







January anomalies of atmospheric pressure

- clearly these are linked

http://www.cpc.noaa.gov/

In conclusion :

1. Is there an average wave climate at a particular location ?
   YES but the average must be over several decades
   - there is a lot of decadal variability (in general)

2. Are the waves over the last 25 years a reliable guide to what may happen in the next 25 or 100 years ?
   MAYBE – in North Atlantic 1960s-80s were unusually benign

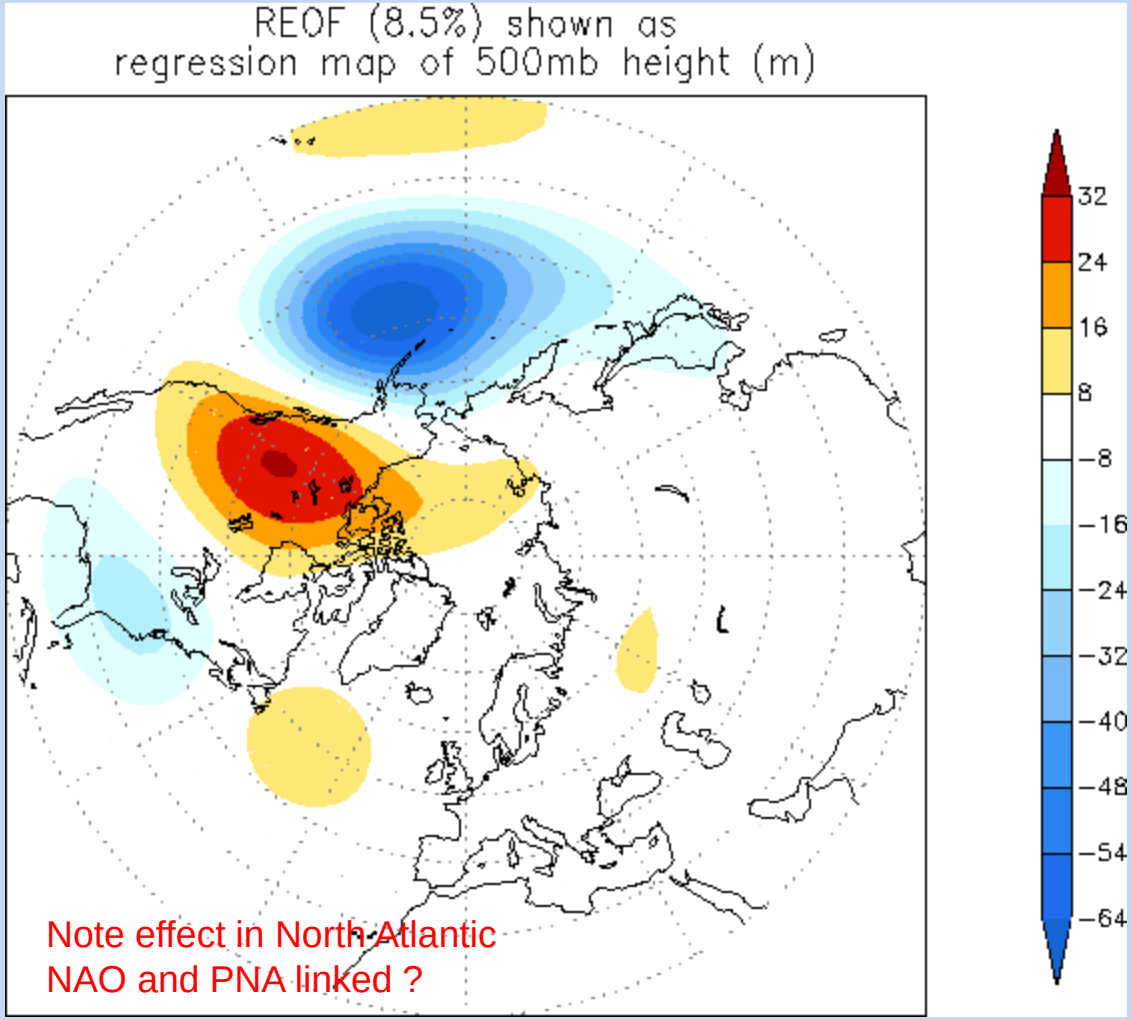
3. Is there a link between decadal variation in extreme waves and global scale 'teleconnections',
   North Atlantic Oscillation and the Pacific/North American pattern ?
   YES – a very strong and simple link in North Atlantic
   but Pacific is more complex with several patterns playing roles

4. Can knowledge of NAO since 1820 (or the PNA since 1950) be used to infer longer term variation in extreme wave conditions ?
   YES – for North Atlantic,
   MAYBE – for North Pacific, but environment is constant or more complex

Pacific North American Oscillation (PNA)

– strong effects at some locations in north Pacific, negligible at others

– visible in wave data ?



www.nws.noaa.gov

Both NAO and PNA are atmospheric phenomena – unlike ENSO which is oceanic (SST-based)