Extreme and unexpected waves

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- **motivation**
- **unexpected waves**
- **rogue waves**
  - **wave-current interaction**
- **conclusion**

Project funding:

SAR NEW INITIATIVES FUND

National Search and Rescue Secretariat | Secrétariat national recherche et sauvetage

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Monsters of the deep

It came from nowhere, snapping giant ships into two….

New Scientist, June 30, 2001

I Wave watching, Vancouver Island, BC

II **Giant wave hits beach, sending four to hospital**
Middle Cove, Nfld.

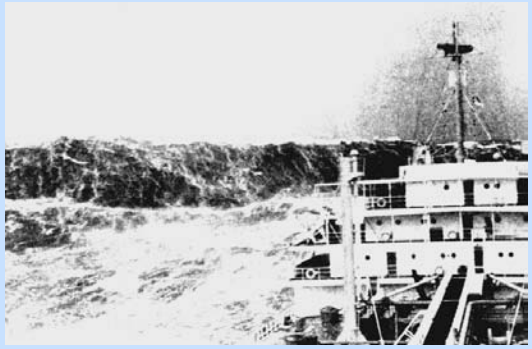
THE GLOBE AND MAIL
Sept. 2, 2008

… several dozen people were enjoying a bonfire on the beach when a giant wave came out of nowhere and rolled them over. People ran to higher ground and strangers helped keep each other from being carried out to sea.

- **large wave was not anticipated**
- **potential of causing serious damage**

Rogue wave occurrence

common *rogue wave* definition: $H_{rogue} \geq 2.2\, H_s$



$H_s = 4\sigma$: significant wave height

σ: rms surface elevation

Wave height distribution:
(linear theory, narrow-band frequency spectrum)

$$p(H) = \frac{H}{4\sigma^2} \exp\left[-\frac{H^2}{8\sigma^2} \right]$$

Rayleigh distribution

→ **Exceedance probability: $P(H>2.2H_s) \approx 1/16800$**

1 rogue wave every 1-2 days

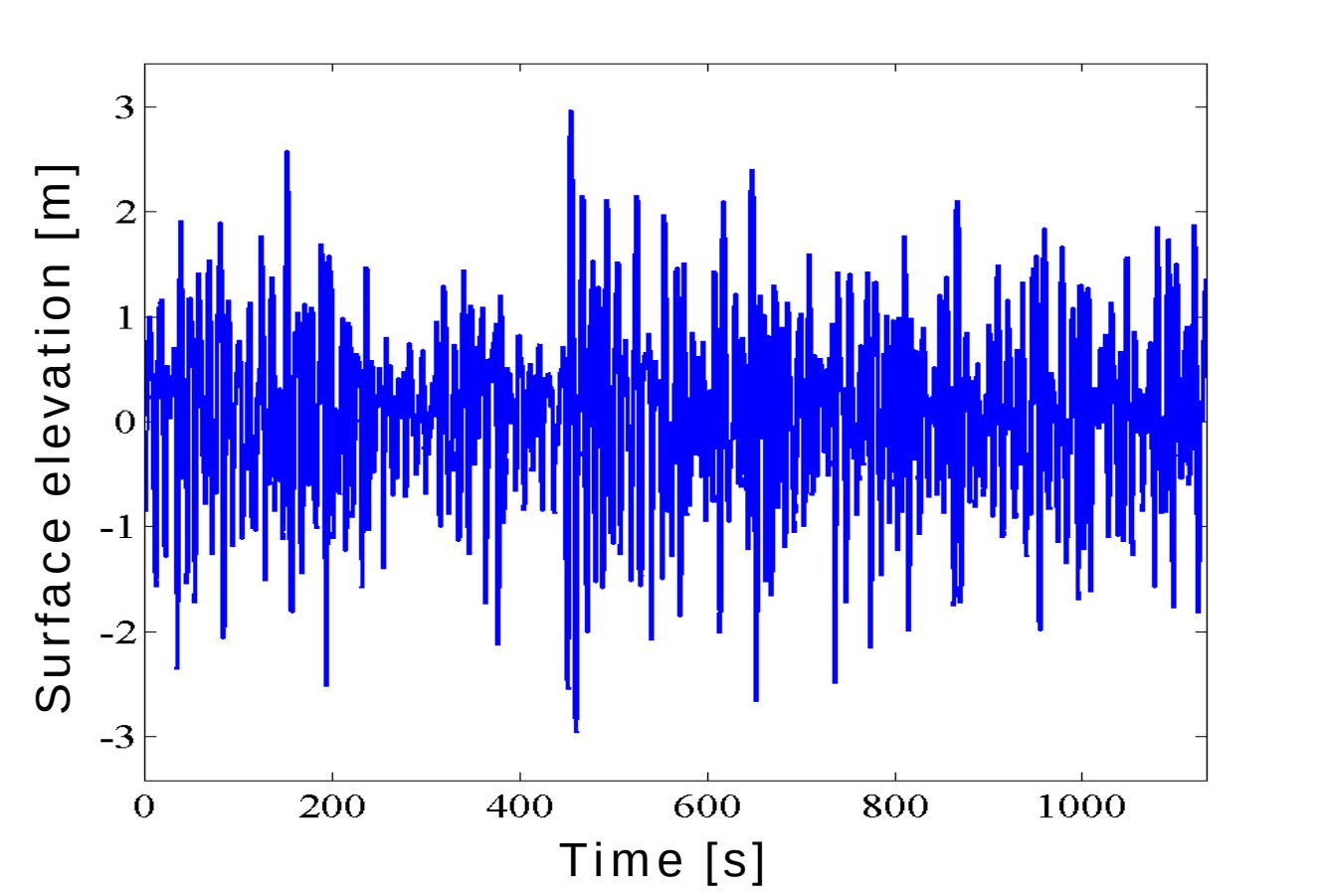
Resonant non-linear interactions may generate more frequent rogue wave occurrence

Summary conclusions

- **Unexpected waves** **exist**
  - **more frequent in water of intermediate depth**
  - **reasonable agreement with observations**

- **Extreme maximum wave heights**
  - **Strong regional effects**
  - **Rogue wave occurrence rates locked to tidal phase**
  - **Regional and temporal variability of sea state (H_s) important**

Unexpected waves – data example



H_s = 3.6m

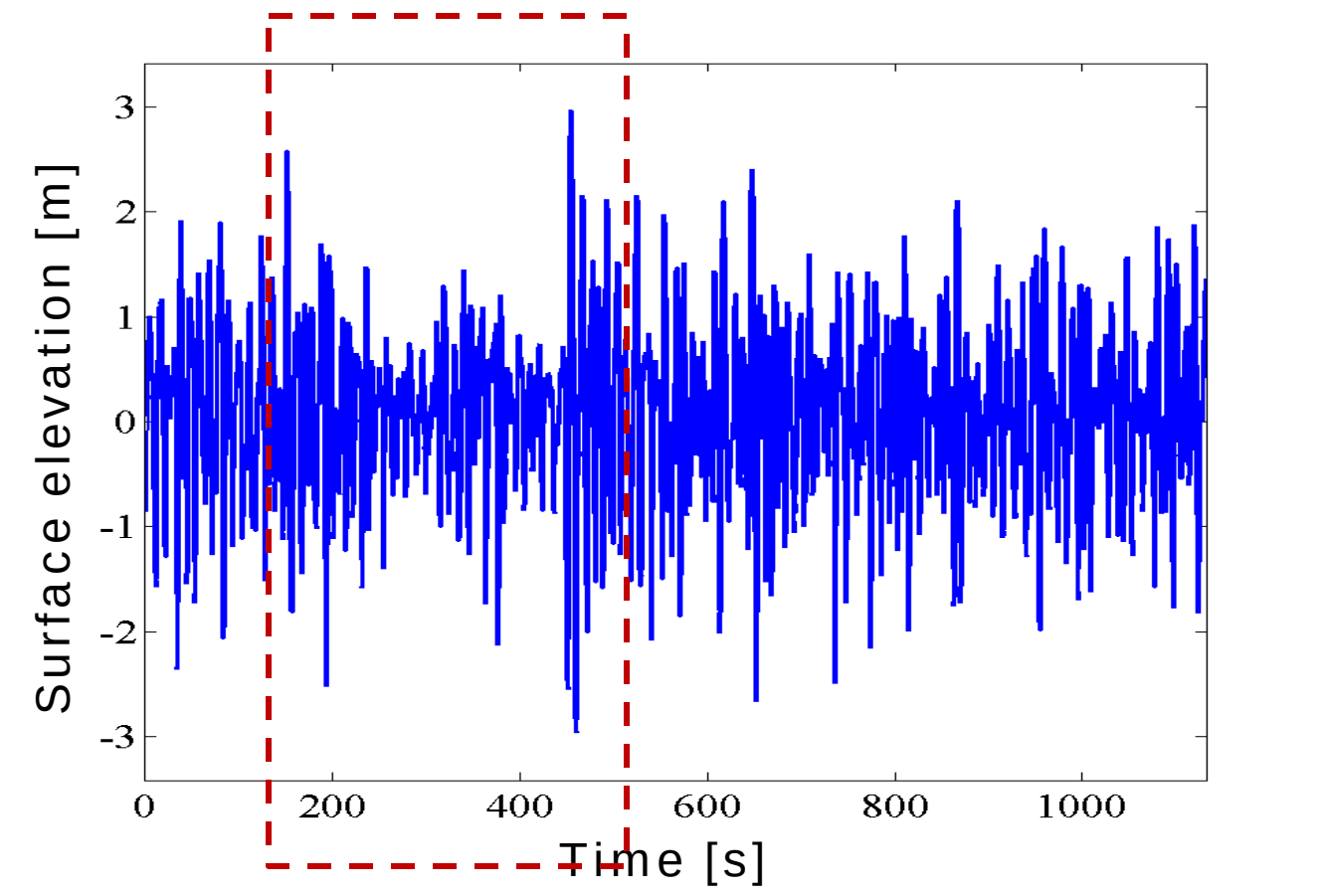
Rogue wave: H>8m

H_{max} < 6m

No rogue wave in record

MEDS226, Cape Scott, BC, Canada

Unexpected waves – data example



H_s = 3.6m

↓

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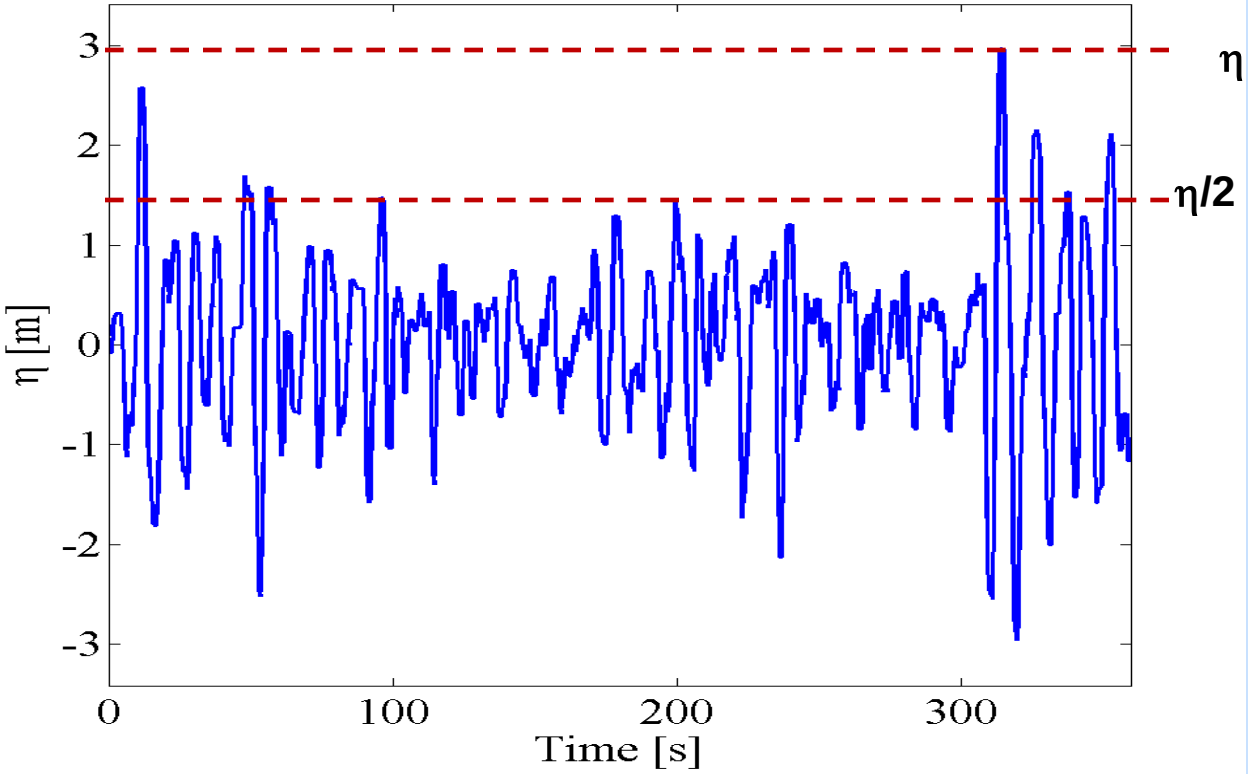
Unexpected waves – data example, simulations



A wave crest twice as high as any in the preceding 30 waves.

=

unexpected wave

Monte Carlo simulations:

- **linear, random superposition,**
- **2nd order Stokes correction**
- **intermediate water depth correction**

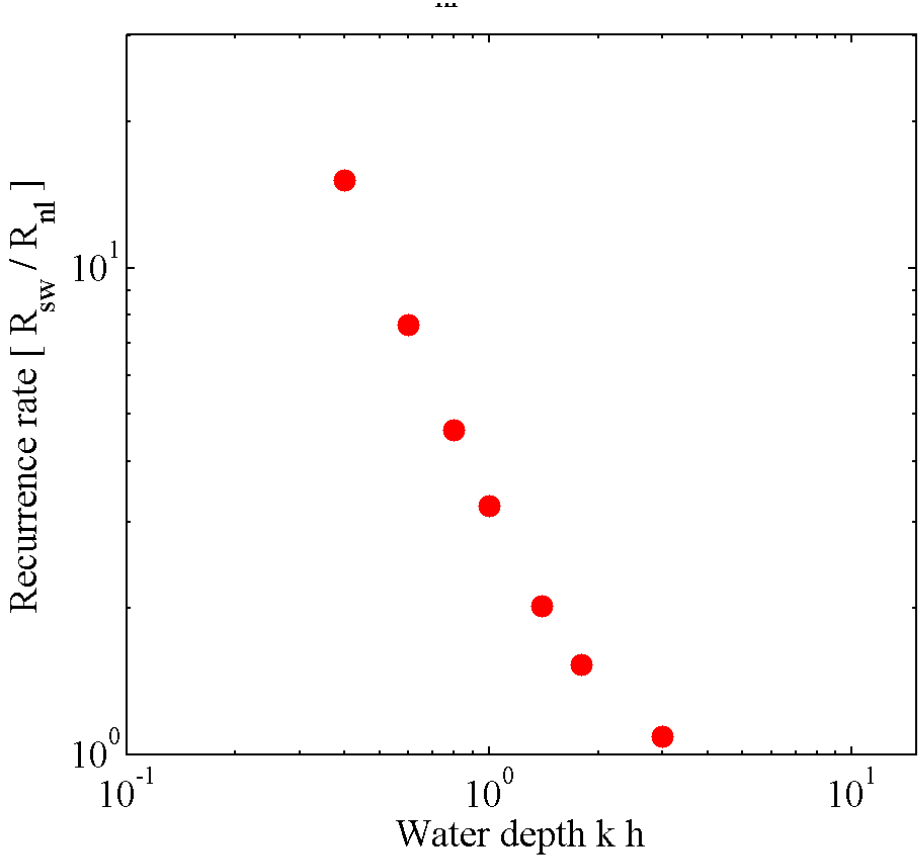
Occurrence rate of *unexpected* waves (deep water):

about 1 in 14,000 (daily)

Gemmrich & Garrett: Unexpected Waves, JPO, 2008

Unexpected waves - shallow water effect (simulations)

Enhancement of unexpected wave occurrence – relative water depth



Higher occurrence rate of unexpected waves in shallow water

Observations

Surface elevation time series from wave buoys (MEDS):

- **East Coast: 29 records**
- **West Coast: 24 records**

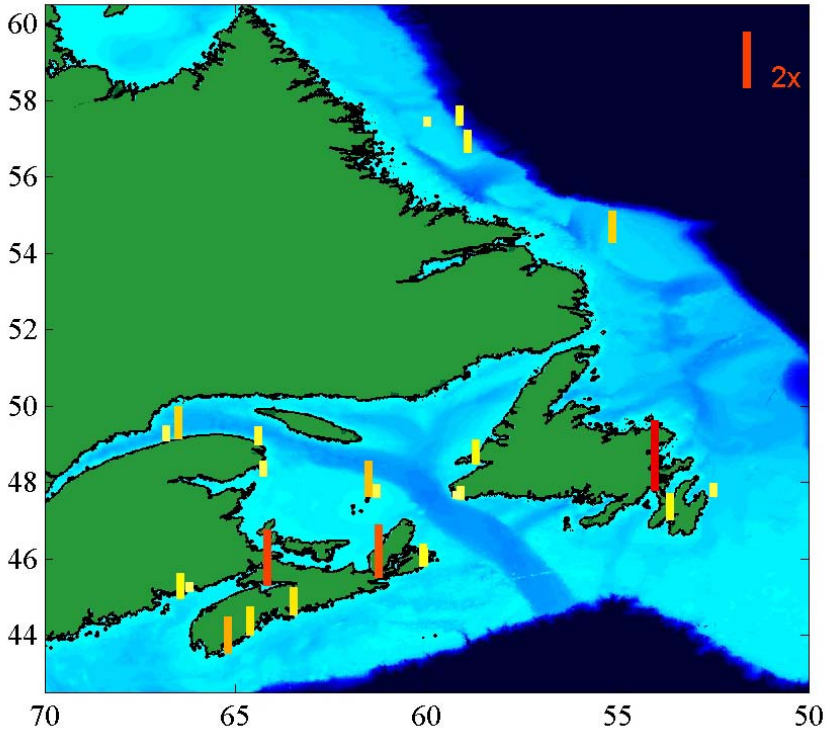
- **20-minute blocks per hour (some 3h)**

- **longest records: 16,900 blocks**
- **(shortest record: 50 blocks)**

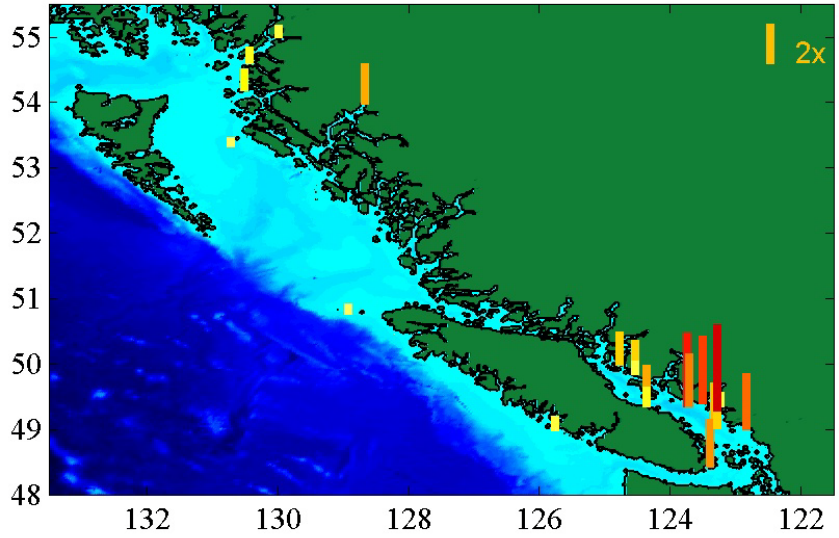
- Extract unexpected waves from each record
- compare with simulations

Normalized unexpected wave occurrence R_{obs} / R_{sim}

East coast Canada



West coast Canada



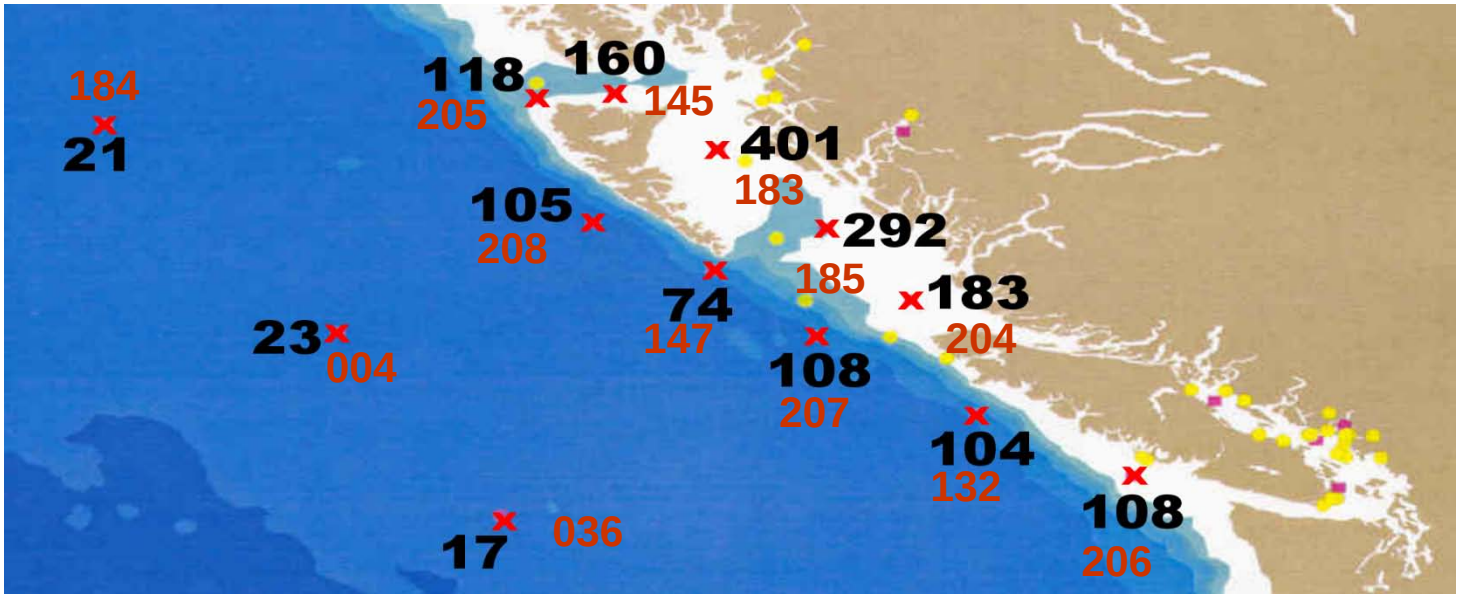
reasonable agreement between observations and simulations

→ supports assumption of random wave superposition

Gemmrich & Garrett, 2009: Unexpected waves – Intermediate depth simulations and comparison with observations. Ocean Engineering, submitted

Extreme maximum wave height analysis

Average rogue wave occurrence

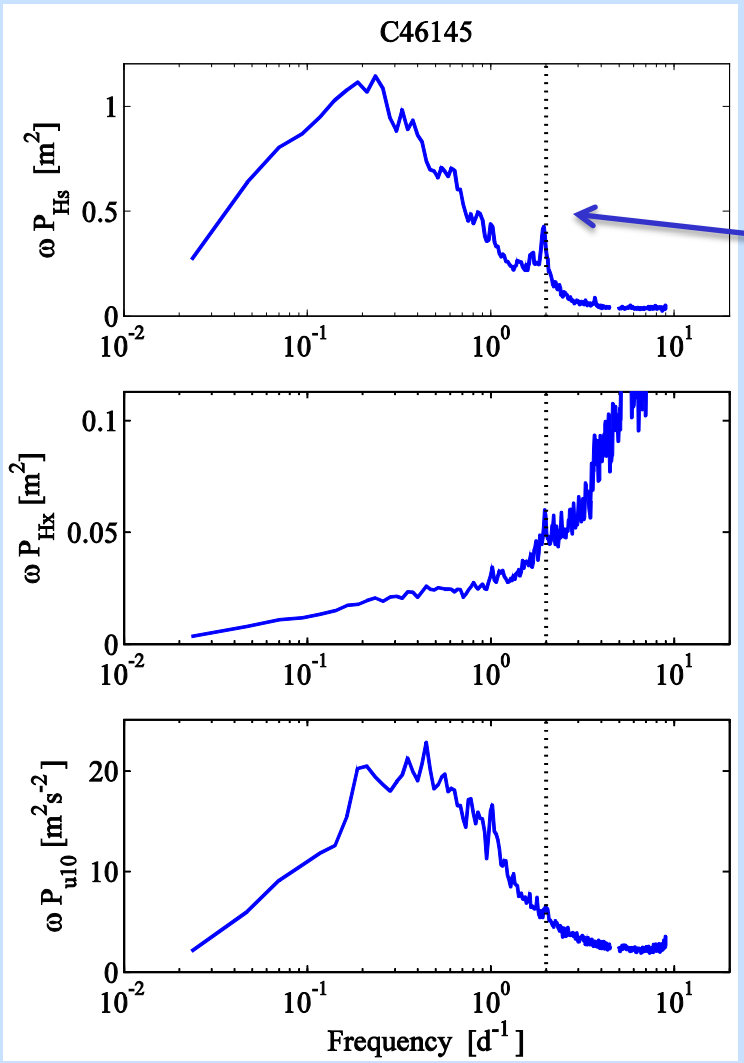


x: Locations of operational wave buoys (report hourly statistics only). C46xxx
Black number: average number of $H_{max} \geq 2.2H_s$ occurrences / year (high sea states only)

→ Rogue waves more frequent on continental shelf

Note: buoy problems more likely to result in increased *offshore* rogue wave occurrence

Spectral content of wave and wind fluctuations



H_s: significant wave height

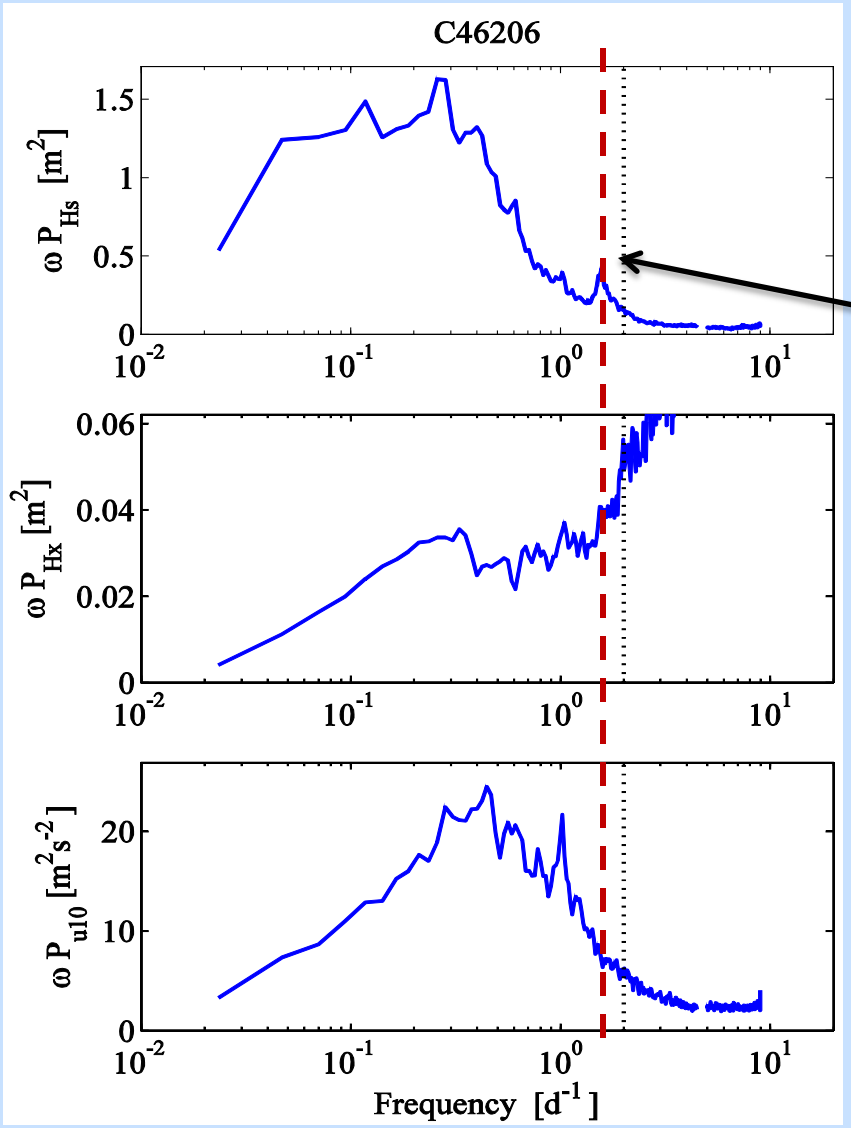
semi-diurnal peak

H_{max}/H_s :maximum wave height in 1 h

u: wind speed

no semi-diurnal peak in wind forcing
→
wave - tidal current interaction

Spectral content of wave and wind fluctuations



H_s

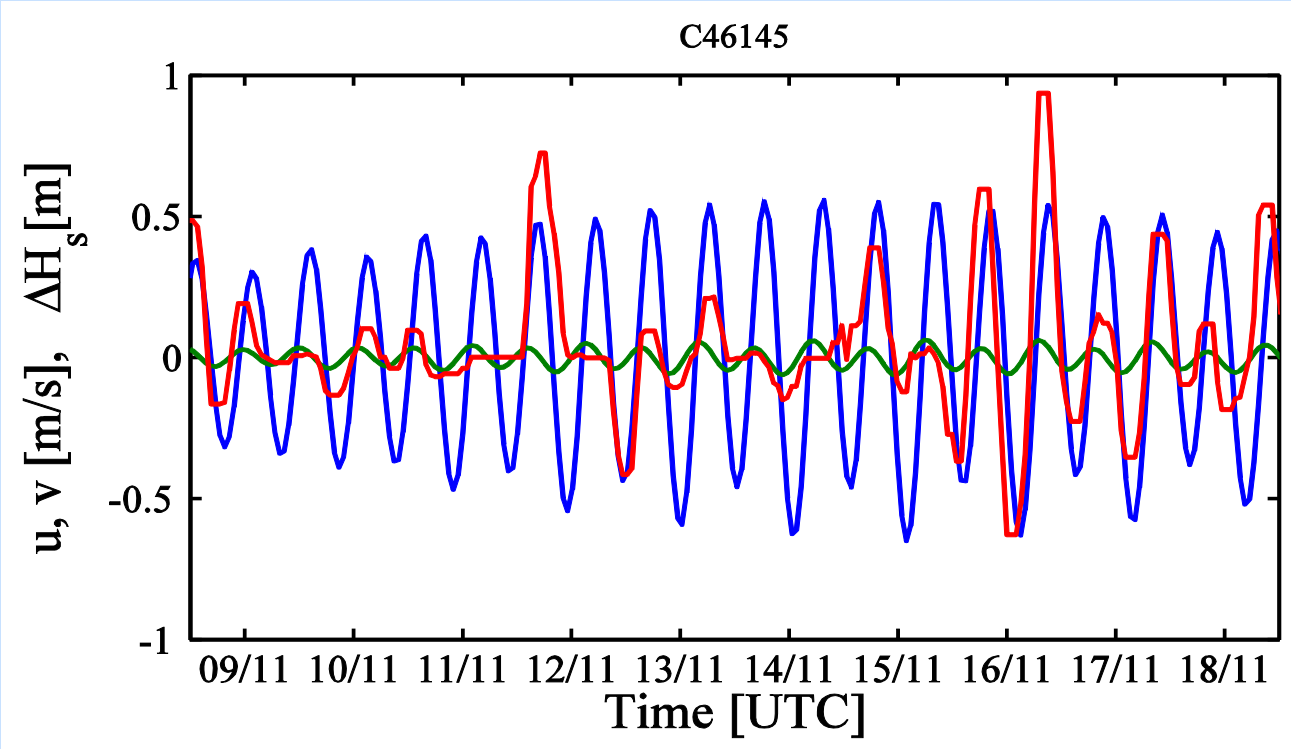
H_{max}/H_s

u

peak at inertial period

inertial period

Significant wave height – tidal current



ΔH_s : wave height fluctuations
(12h median band-pass filter)

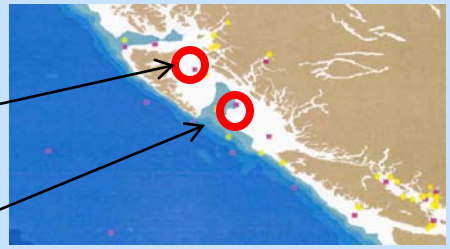
u: E-W barotropic tidal current
(positive towards E)

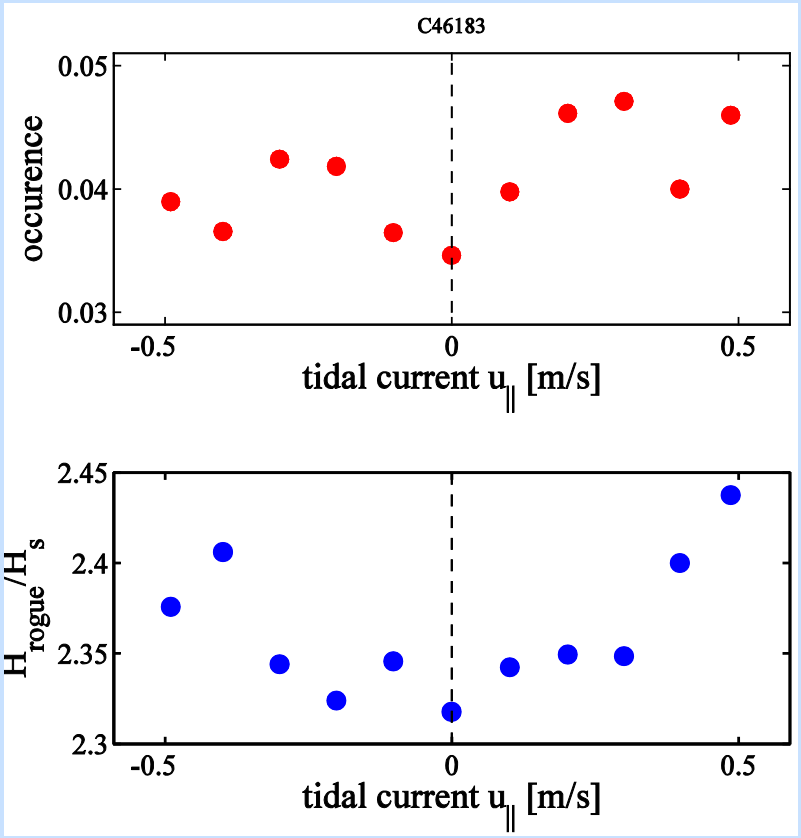
v: N-S barotropic tidal current
(positive towards N)

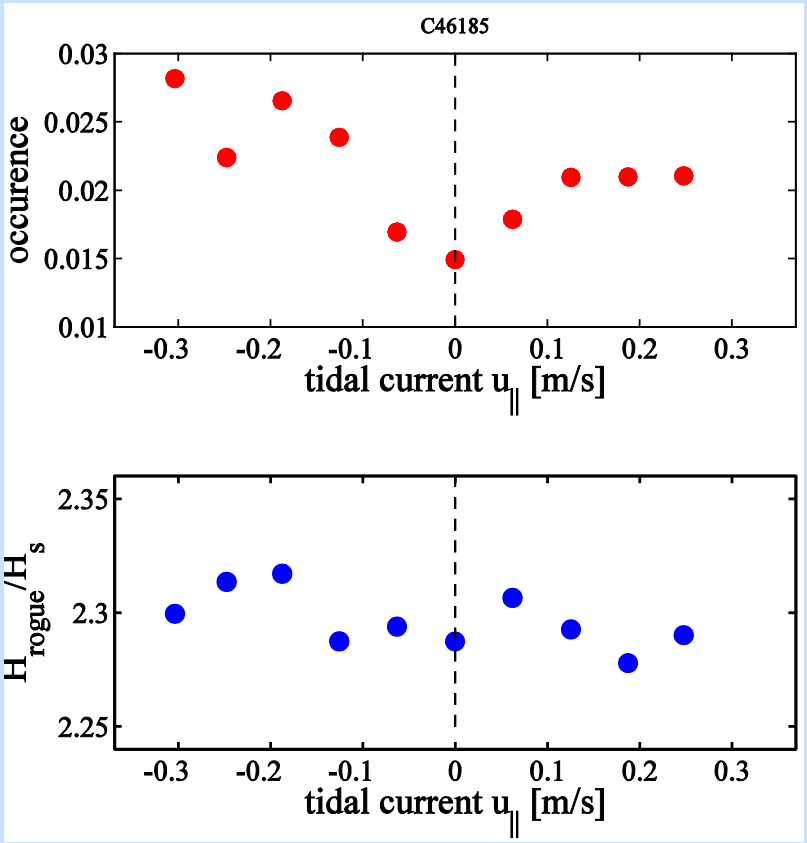
wave height fluctuations – current are in phase !

qualitatively consistent with quasi-homogeneous approximation (Tolman, JPO 1990)
but much larger amplitude

Rogue waves – tidal current







Fraction of 1h-records containing a rogue wave

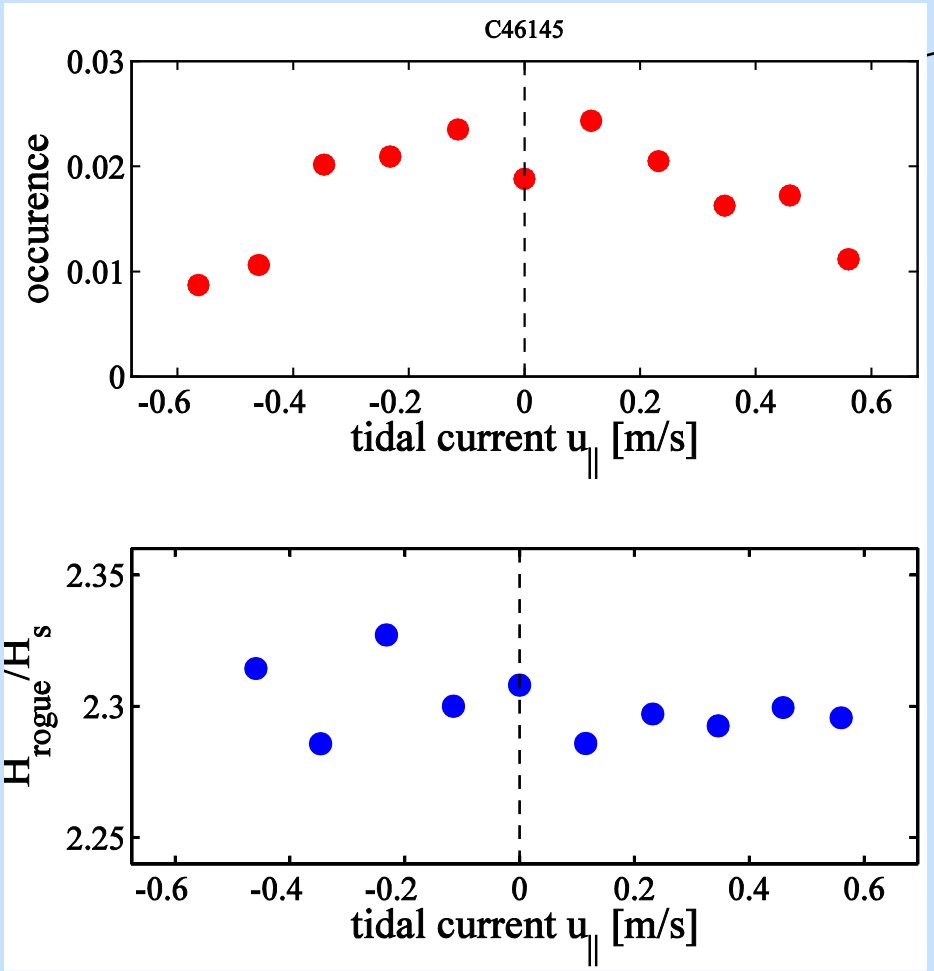
Median height of rogue wave

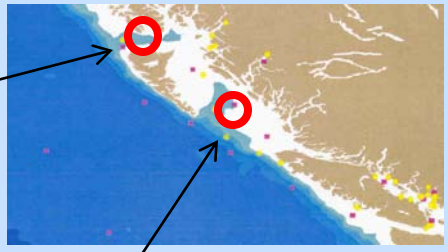
$u_{||}$: tidal current component parallel to wind

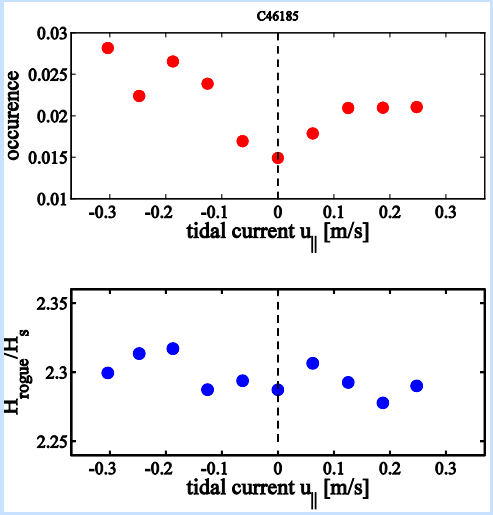
- **Increased rogue wave occurrence during strong currents**
- **Bigger rogue waves during strong currents**

rogue: $H_{max} \geq 2.2 H_s$, $H_s \geq$ median(H_{s_all})

Rogue waves – tidal current





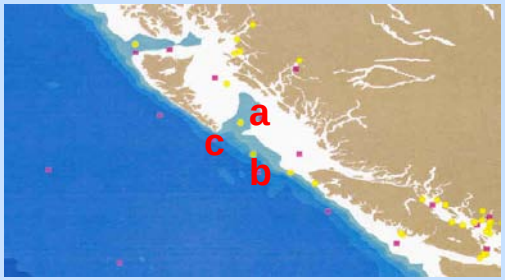


Highest rogue wave occurrence during strong currents

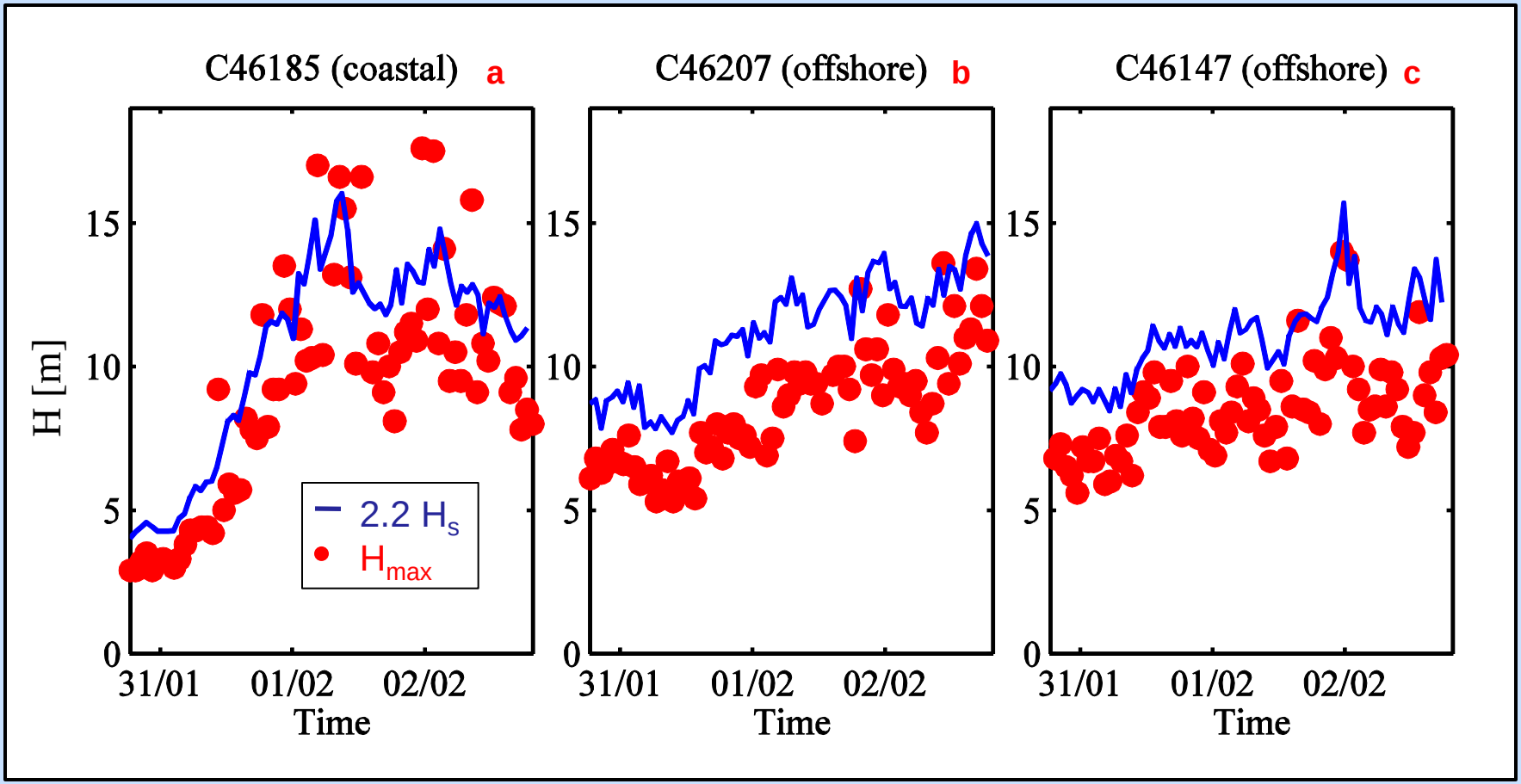
Strait vs. shelf sea ?

Highest rogue wave occurrence during weak currents

Regional wave fields



Rogue wave occurrences:



Strong spatial and temporal fluctuation of background wave field

→ Apparent high rogue wave occurrence may be due to non–stationarity of wave field

Conclusion

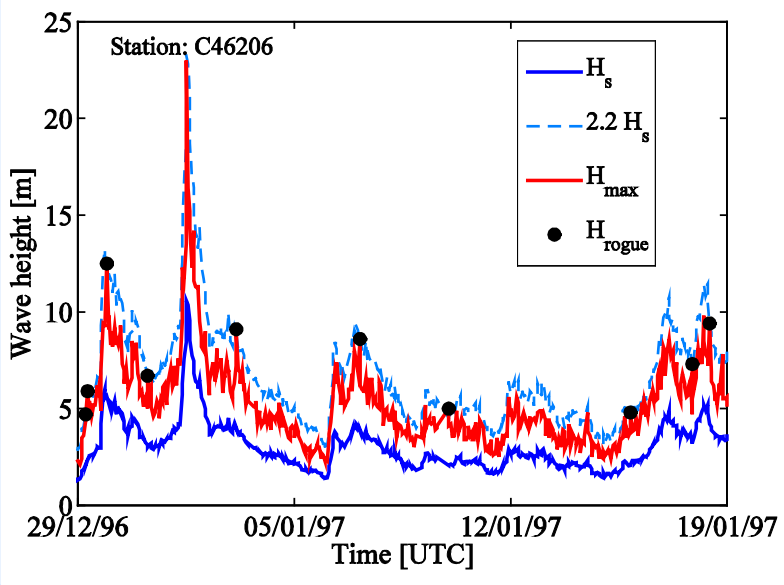
unexpected waves are expected

- simulations agree with observations
- unexpected waves are 5 – 15 times more frequent in intermediate depth
  (up to 5 events per day)

relevant to: recreational boating, visitors to beaches, instrument deployments

extreme waves are expected

- strong regional effects: More frequent on shelf
- wave height (H_s, H_{max}) modifications due to tidal currents are significant (>1.5m)
- surprisingly, wave and current are in phase (Dixon Entrance, C46145)
- rogue wave occurrence rates locked to tidal phase.
- regional variability of sea state (H_s) important



not every large wave is a rogue