1918
TALLINNA TEHNIKAÜLIKOOL
TALLINN UNIVERSITY OF TECHNOLOGY

Applications of soliton interactions in rogue wave theory and in understanding the impact of vessel wakes

(Learning from dynamics working for and against us)

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WAVE ENGINEERING

Instead of Introduction: some words from classical authors

There are three states in a human's life:

alive

dead

on sea

Anacharsis,
Scythian philosopher, VI century B.C.

Strabo makes him the (probably legendary) inventor of the anchor with two flukes

Outline

- Extremes in wave fields and single waves
- Ship waves in shallow water: threat and treasure
- Monster waves – dangerous sisters of ship waves?
- Jet currents – triggers of monster waves?
- Reaction of coasts to “new” waves

Extremes on the sea

or how “extreme” could be
an extreme (wave) event

Baltic Sea

380,000km2

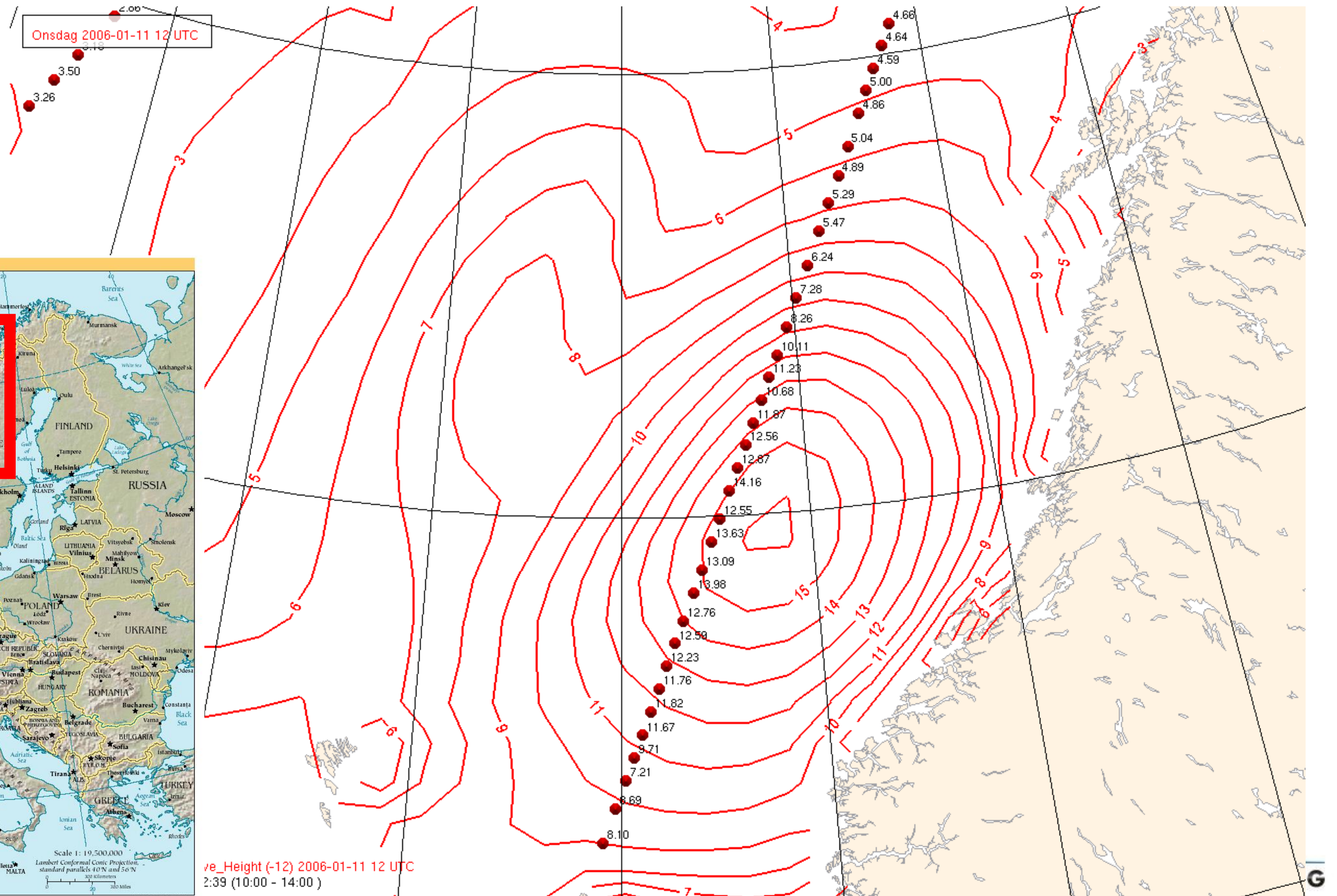
- Long coastline
- no tides
- no jet currents
- short fetch
- low winds, small cyclones
- located on the Atlantic storm track
- brackish water
- variety of different shores
- postglacial uplift

→low hydrodynamic activity

→extremely vulnerable

particularly sensitive sea area by IMO

Feb 2000 & Jan 2006: ever highest waves in North Atlantic



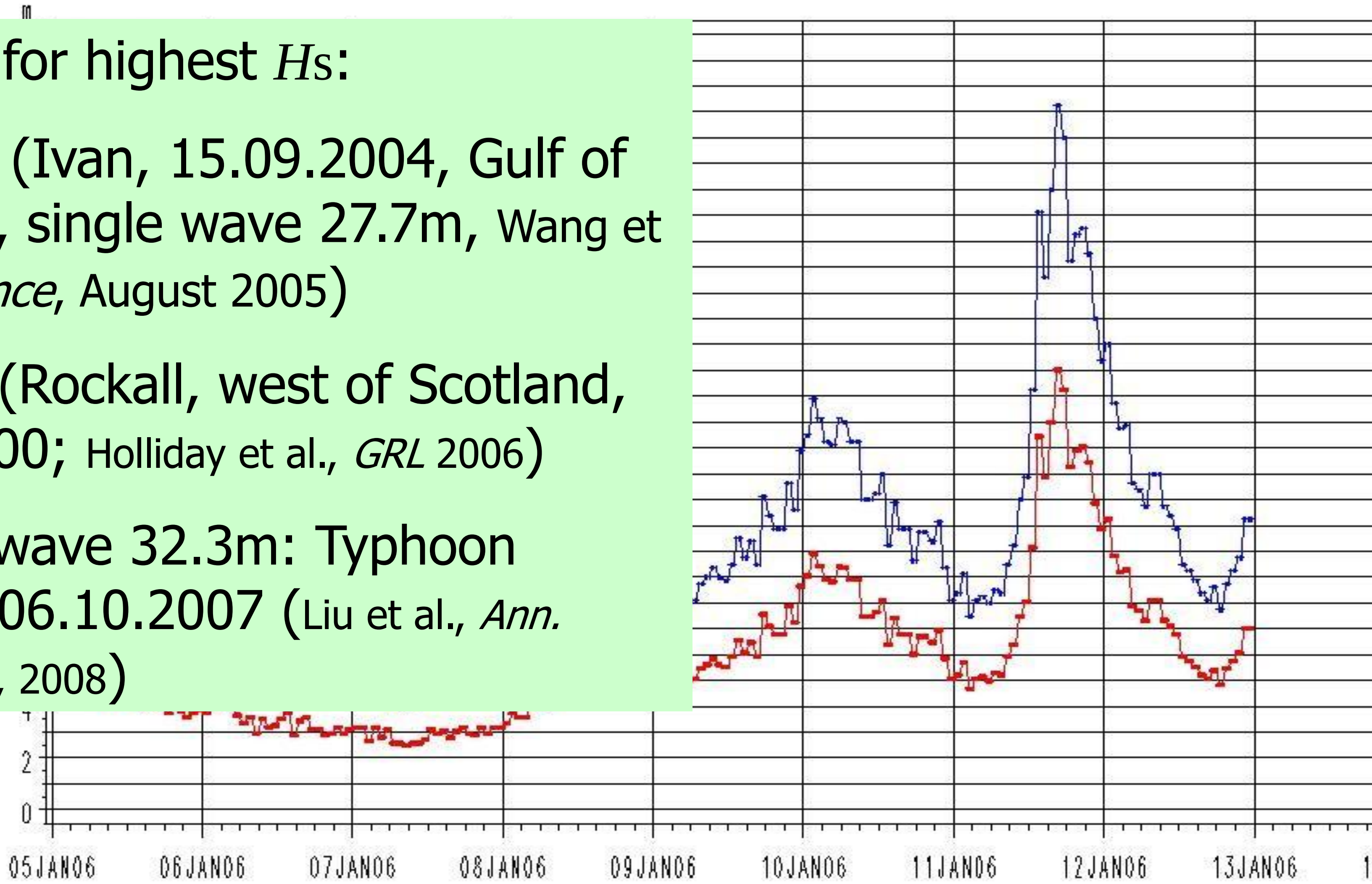
Significant wave height >17 m
single waves >27 m

Claims for highest *Hs*:

17.9 m (Ivan, 15.09.2004, Gulf of Mexico, single wave 27.7m, Wang et al., *Science*, August 2005)

18.5m (Rockall, west of Scotland, Feb.2000; Holliday et al., *GRL* 2006)

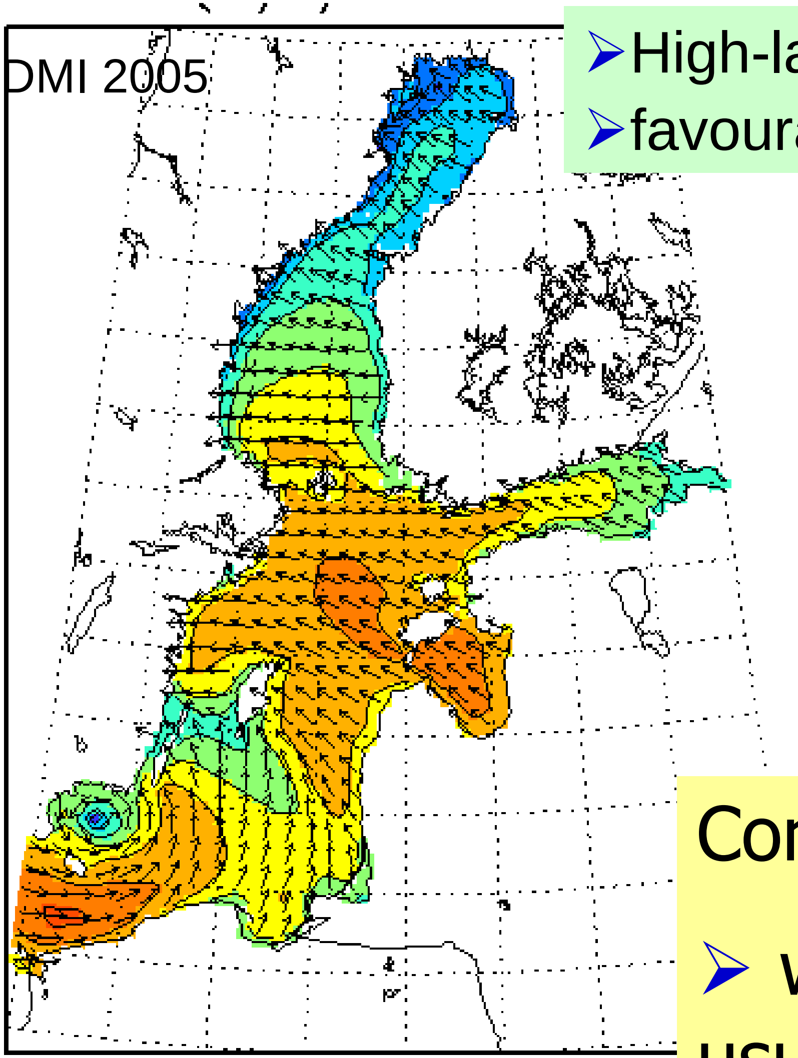
Single wave 32.3m: Typhoon Krosa, 06.10.2007 (Liu et al., *Ann. Geophys*., 2008)



CENS

Typical Baltic Sea storms:

wind direction frequently varies within even one subbasin



- High-latitude cyclones are relatively small,
- favourable conditions for large waves seldom

High & long waves may only occur if:

(i) strong wind

(ii) blows steadily

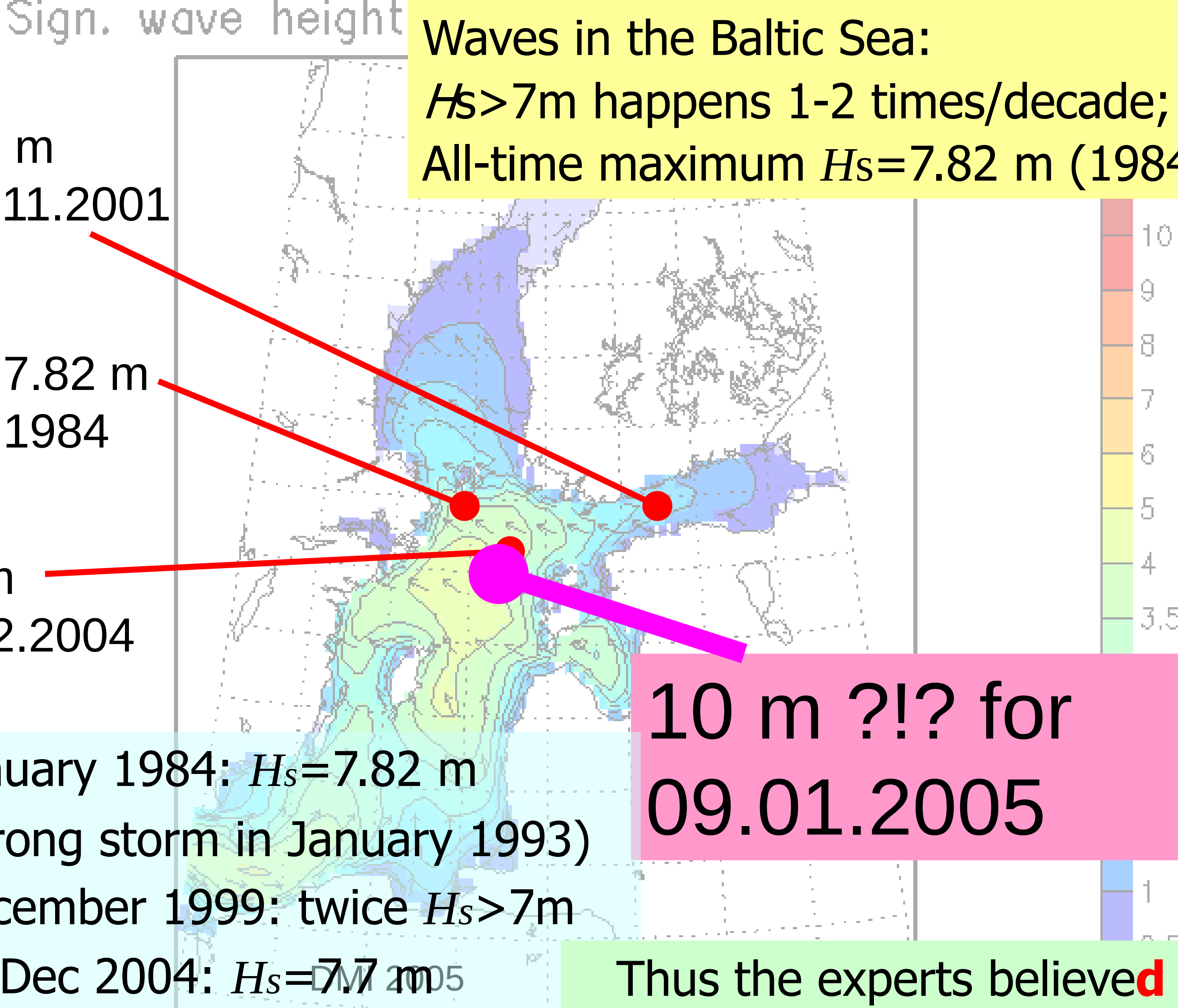
(iii) over large sea area

(iv) long time

Consequence for the Baltic Sea:

- wave heights and periods usually moderate

Waves in the Baltic Sea:
H_s>7m happens 1-2 times/decade;
All-time maximum H_s=7.82 m (1984)



5.2 m
15.11.2001

7.82 m
1984

7.7 m
23.12.2004

10 m ?!? for 09.01.2005

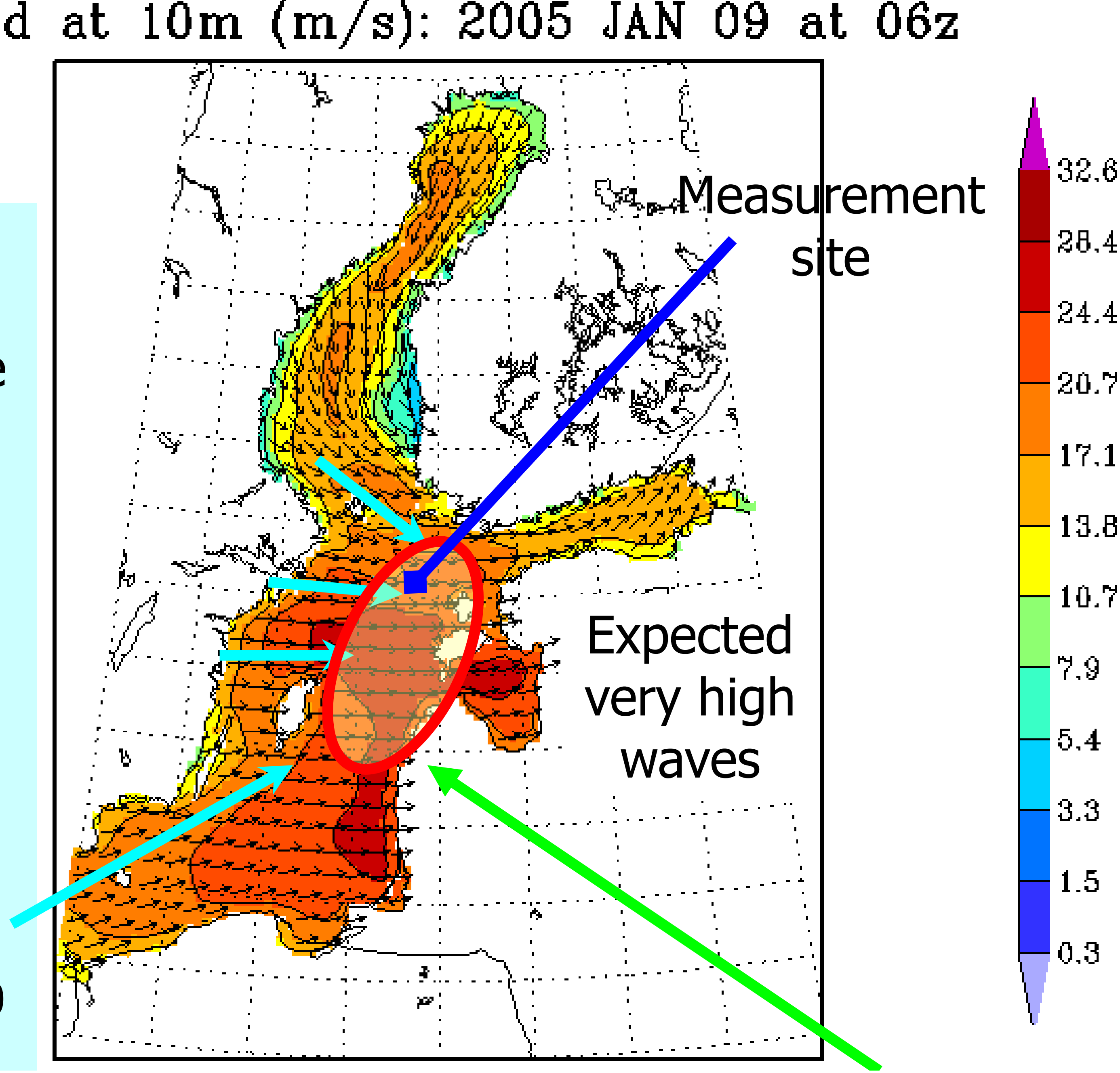
- January 1984: H_s=7.82 m
- (strong storm in January 1993)
- December 1999: twice H_s>7m
- 23 Dec 2004: H_s=7.7 m
- 09 Jan 2005: H_s=7.2 m

Thus the experts believe**d** that H_s~8-8.5 m cannot be exceeded

January 2005: probably the roughest wave conditions in the history

Partially caused by convergent wind pattern

(DMI forecast released at 06:00 GMT 7.01.2005)



Look at wind convergence pattern and imagine wave propagation!!!

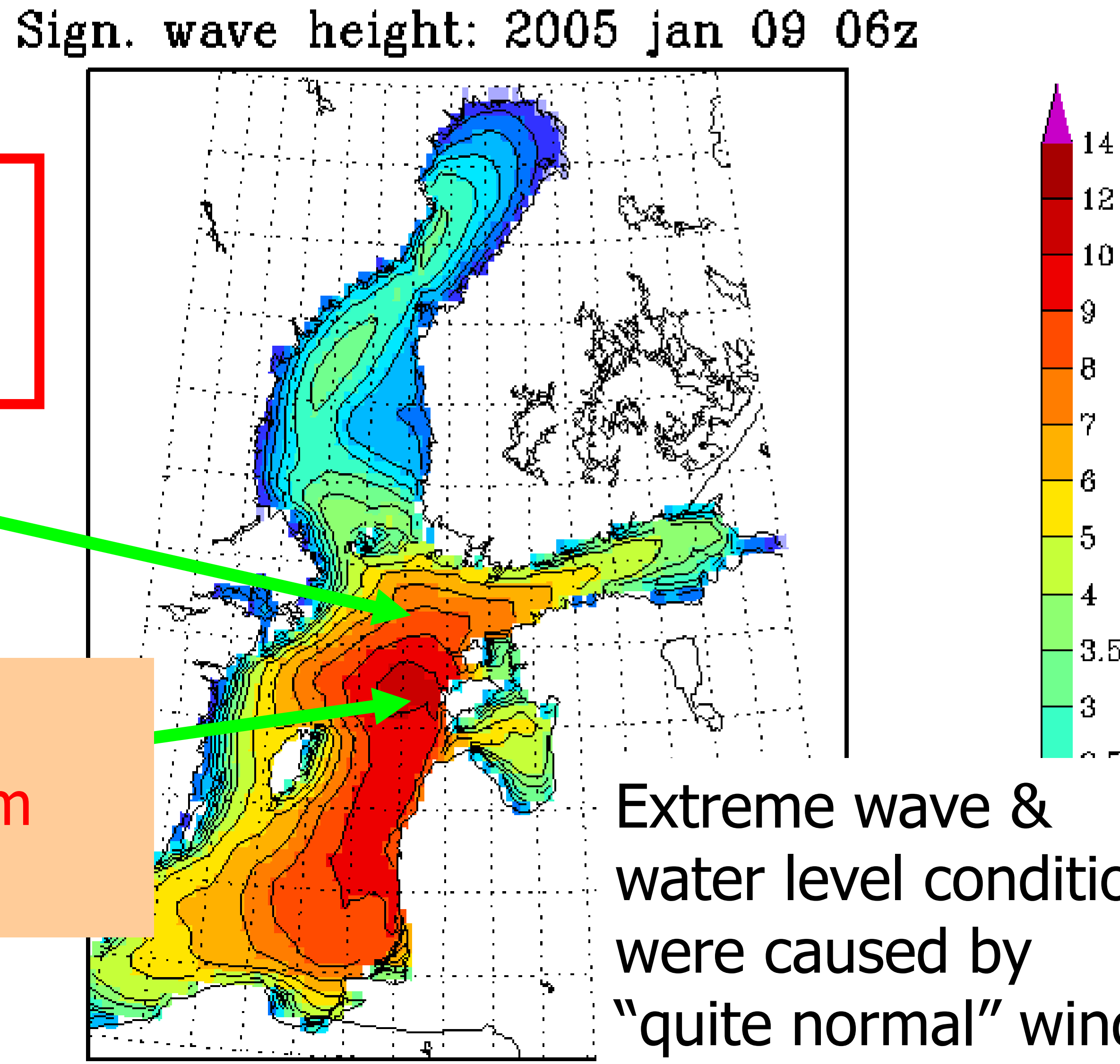
The maximum wave height this night?

Measured 7.2 m; model 8.5 m

Model >11m;

Hindcast *Hs*: ~9.5 m

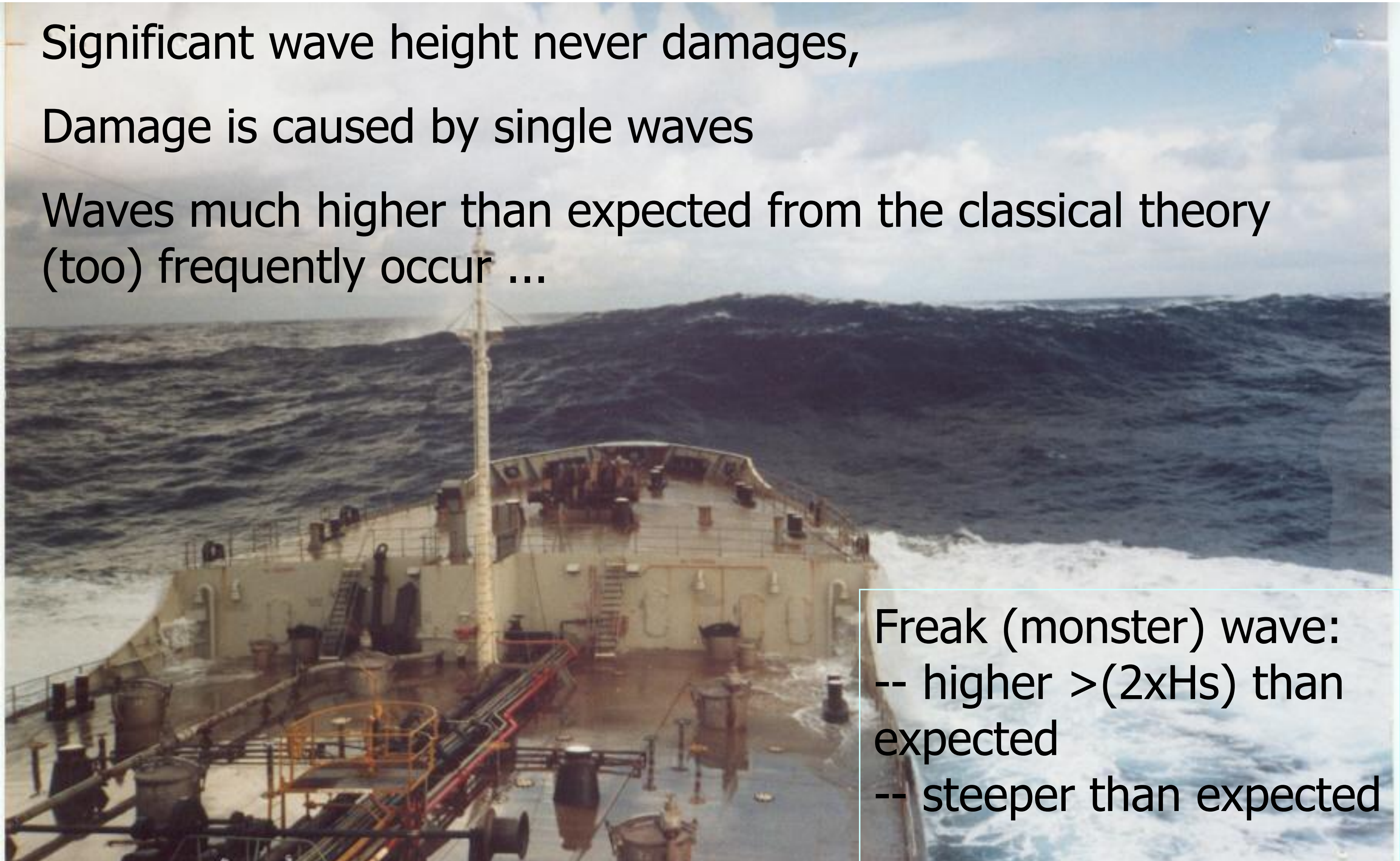
(+22% !)



Extreme wave & water level conditions were caused by "quite normal" winds (<29 m/s)

Soomere, Behrens, Tuomi & Nielsen, *Natural Hazards and Earth System Sciences*, 2008.

Dynamic extremes: monster waves



Significant wave height never damages,

Damage is caused by single waves

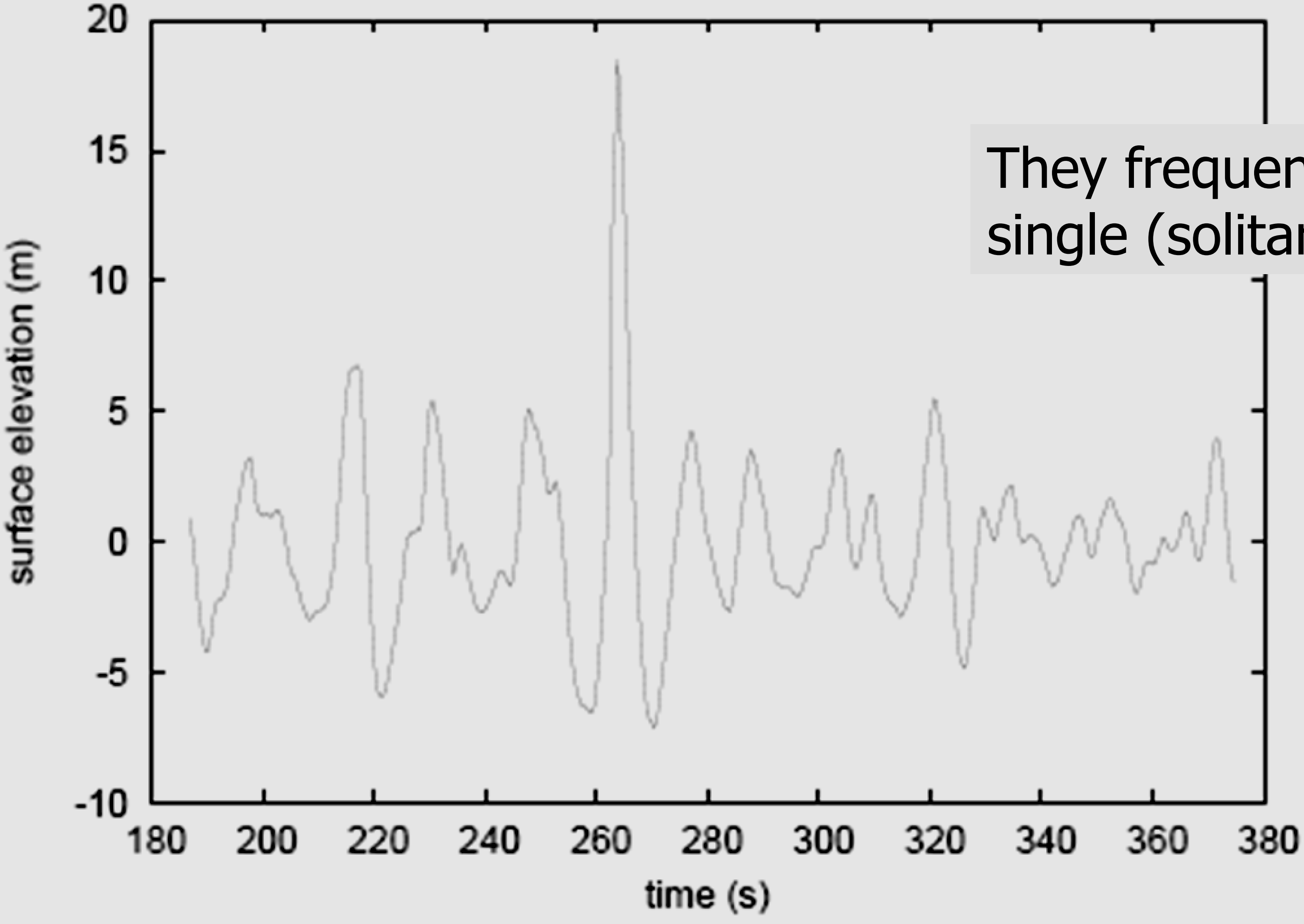
Waves much higher than expected from the classical theory (too) frequently occur ...

Freak (monster) wave:
-- higher >(2xHs) than expected
-- steeper than expected

... and frequently causing heavy damage

... or coming from unexpected direction

They do exist in the ocean: Draupner platform, 01 January 1995



They frequently are single (solitary) waves

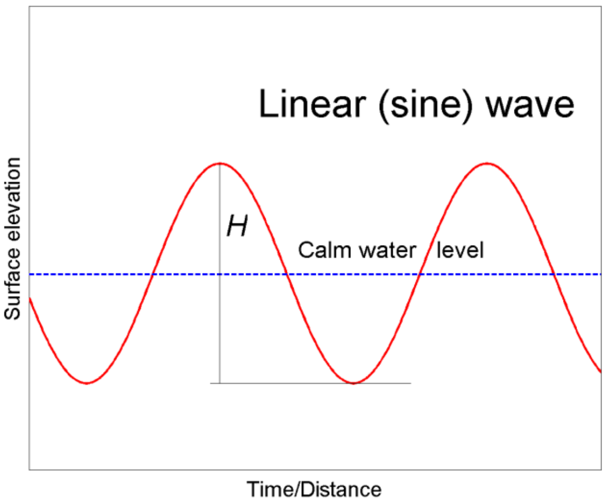
Fig. 2. Extract of Draupner time series close to the extreme wave.

Linear waves – cnoidal waves – solitons

smaller waves, almost linear

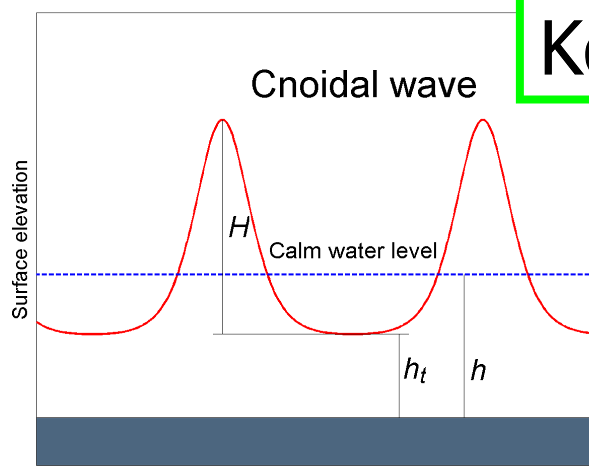
higher waves, more nonlinear

$$\eta = \frac{1}{2}k^2 \cosh^{-2}\left(\frac{1}{2}kx\right)$$

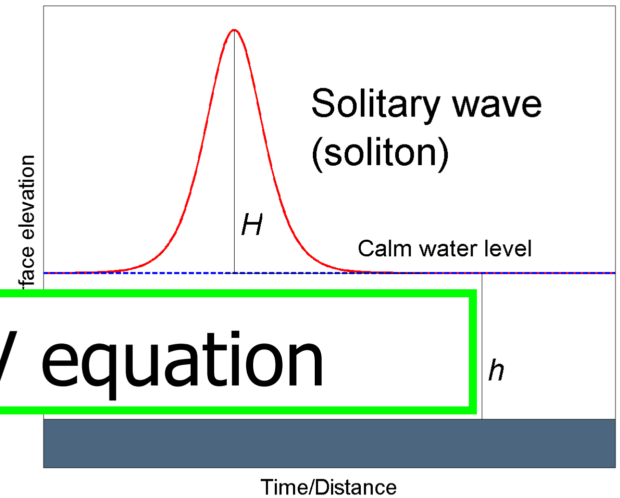


Traditionally, Airy (co)sine wave theory is used for water waves

Long waves in shallow water can be described with the use of the **cnoidal** wave theory



Name: from Jacobi elliptical functions sn, cn, dn



KdV equation

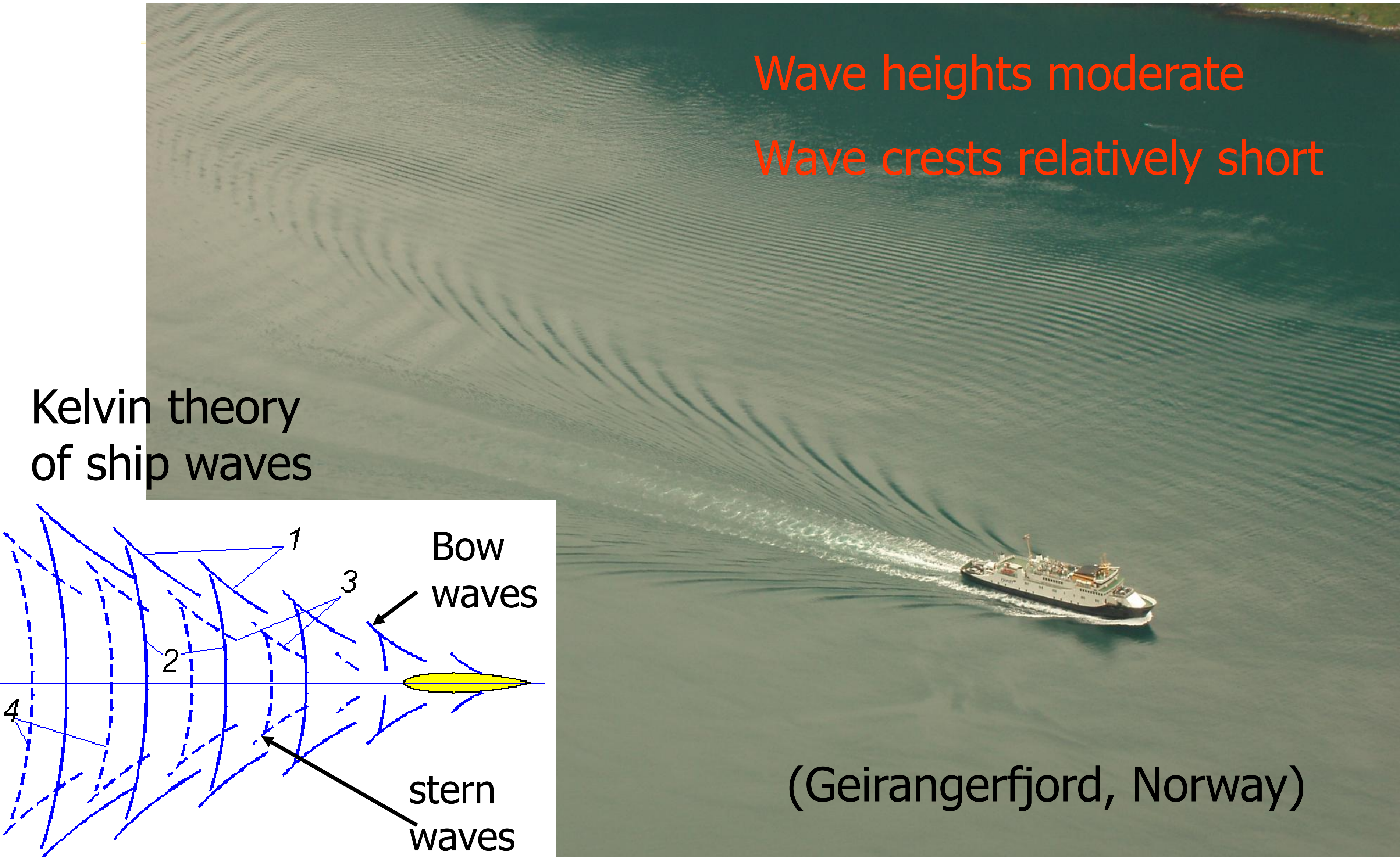
Very long waves in shallow water can be associated with solitary waves

Makers of solitons: contemporary fast ferries

Vessel waves – threat or treasure?

- different from wind waves
- model of monster waves and tsunamis
- model of destructive (wave) climate changes

Classical ship wave pattern



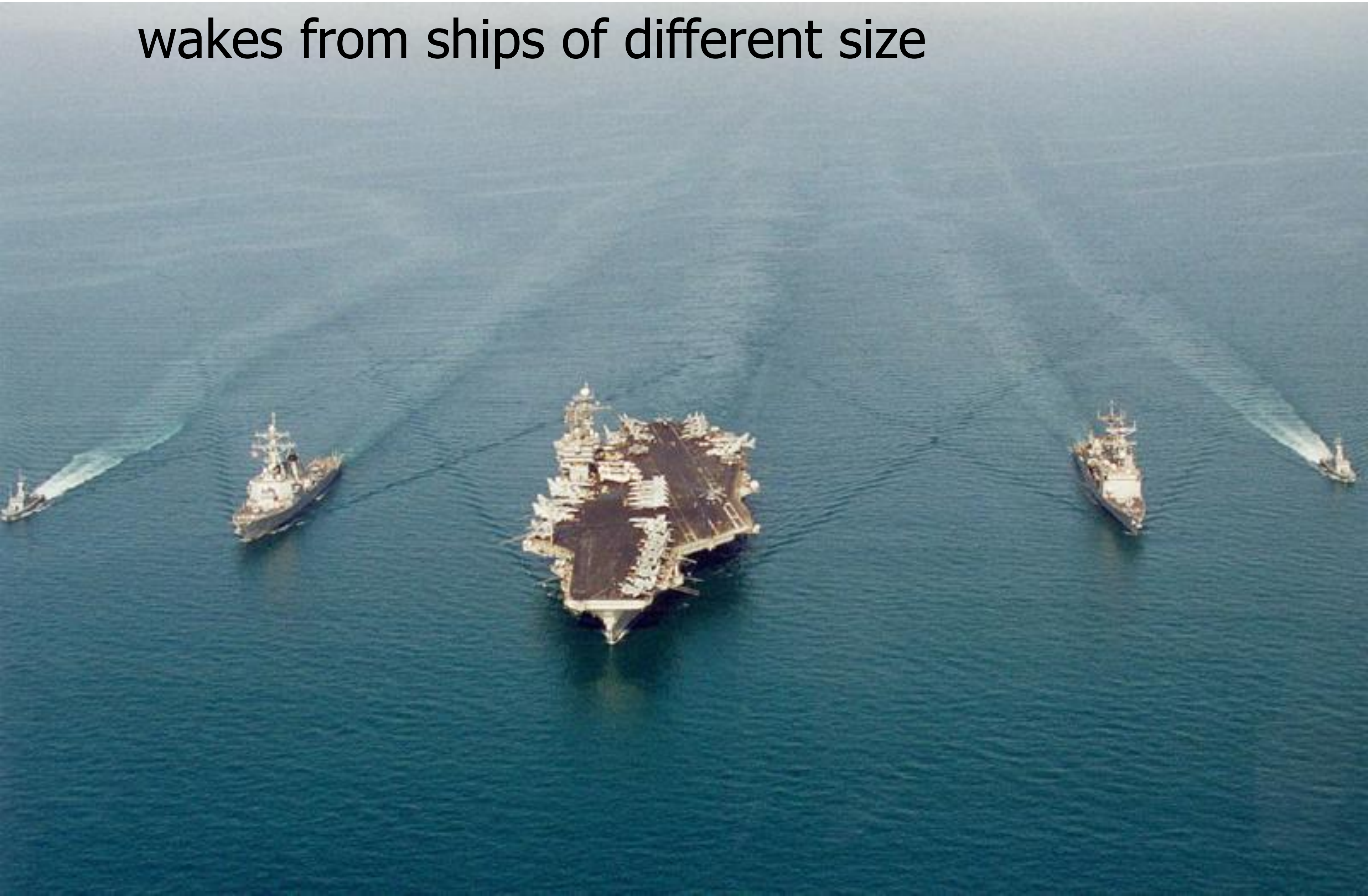
Wave heights moderate

Wave crests relatively short

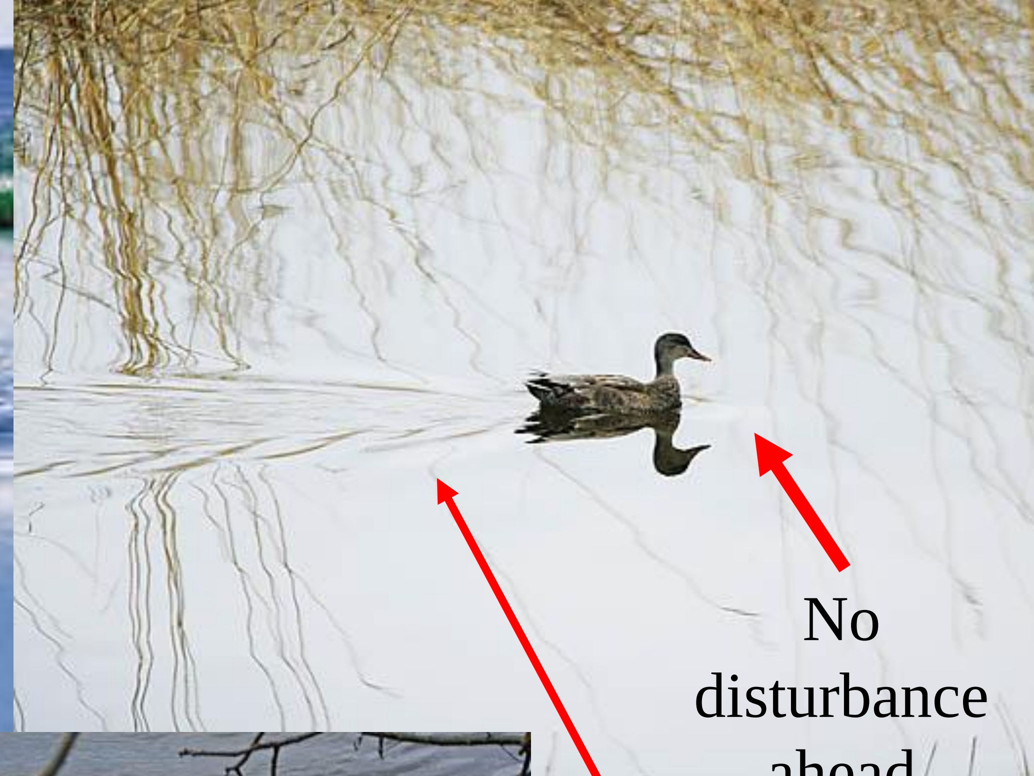
(Geirangerfjord, Norway)

Kelvin theory of ship waves

There is no difference between wakes from ships of different size



... small boats ...

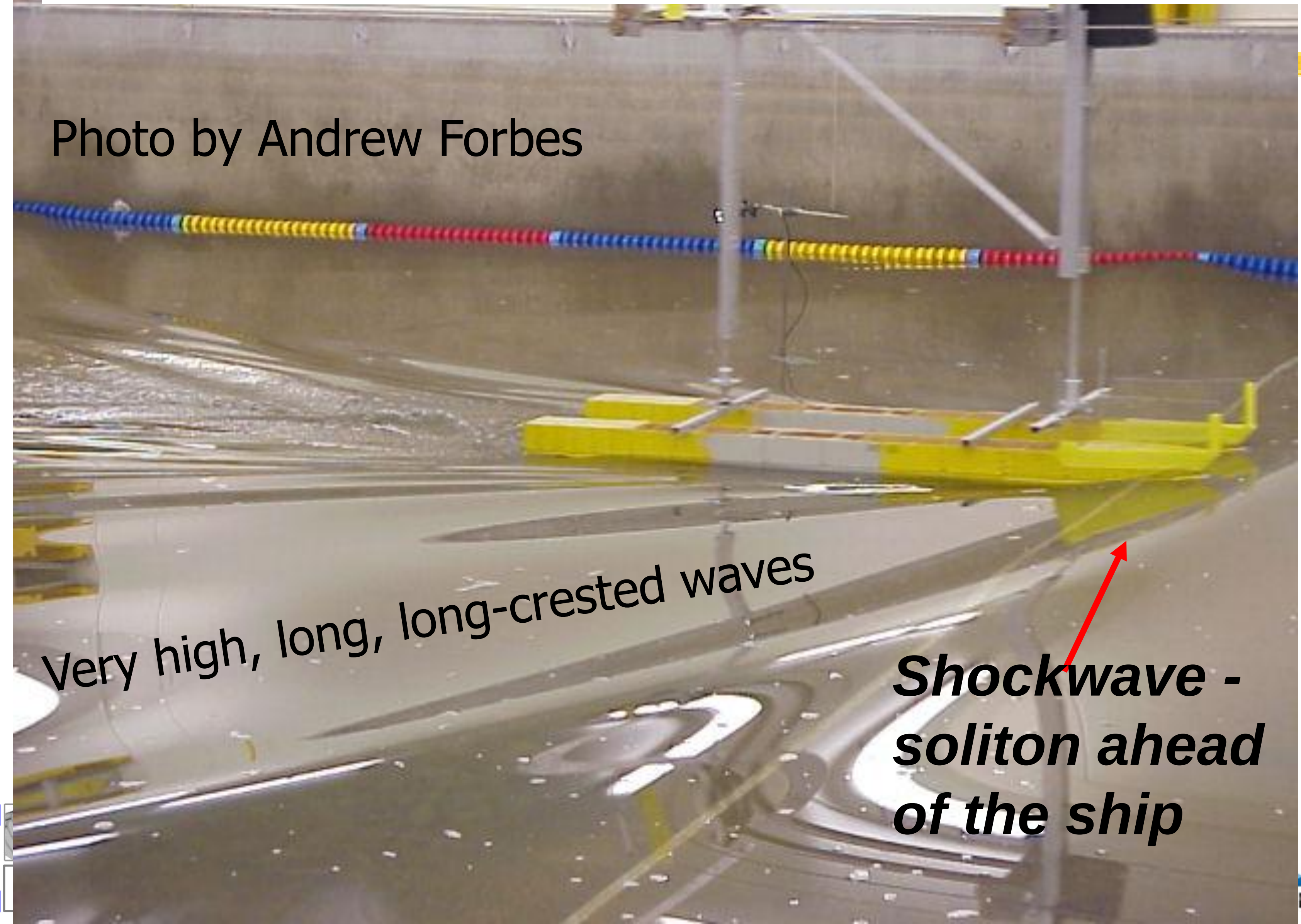


No disturbance ahead

... or duck or swan waves

Each single crest is short

... unless the disturbance moves at a large speed in shallow water



The source of difference

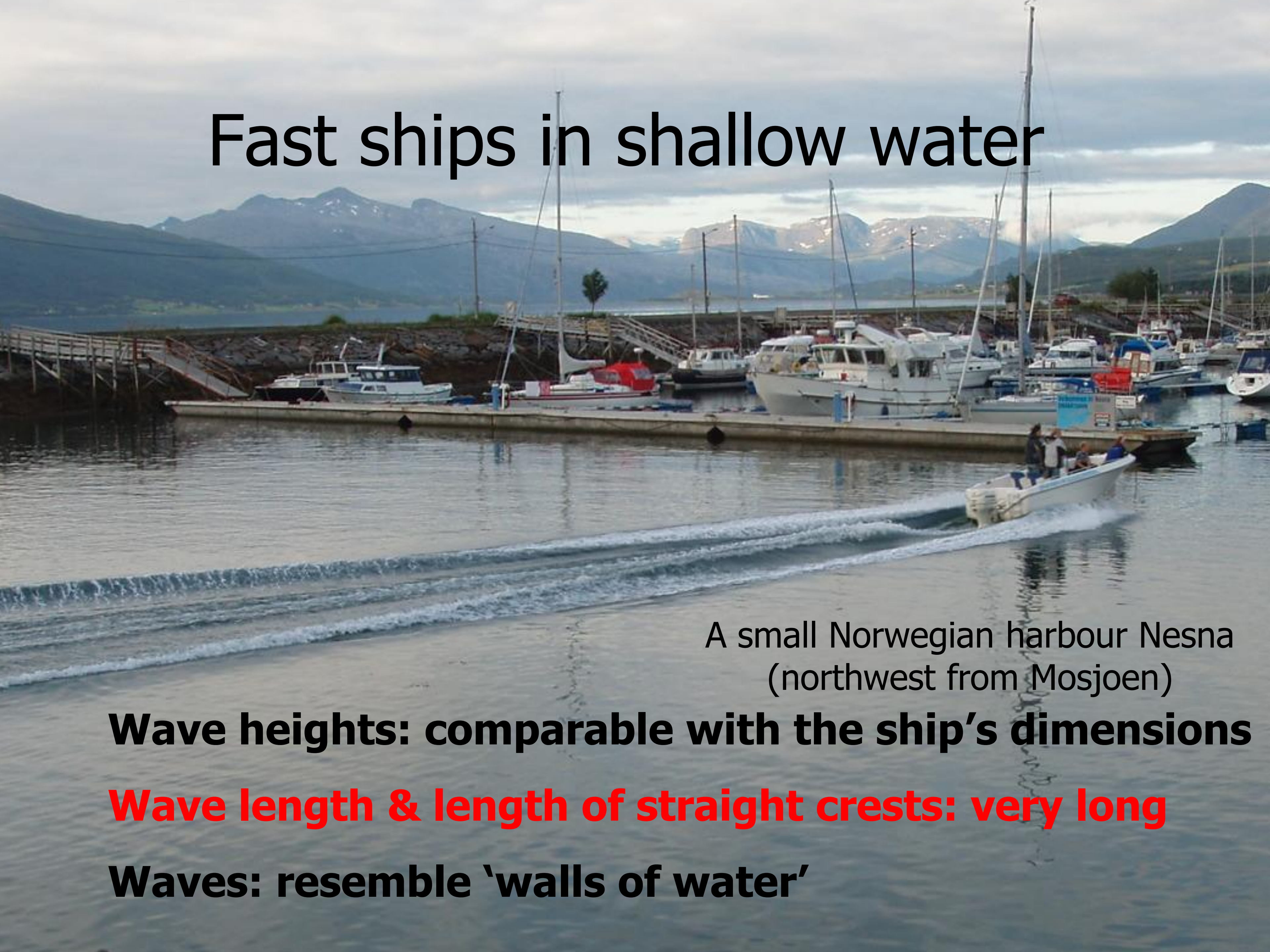
The decisive factor:

- not speed alone
- but speed *versus* water depth

FAST FERRIES

- Generation of long & long-crested waves
- In shallow water: phase speed == group speed
- both only depend on the depth

Fast ships in shallow water



A small Norwegian harbour Nesna
(northwest from Mosjoen)

Wave heights: comparable with the ship's dimensions

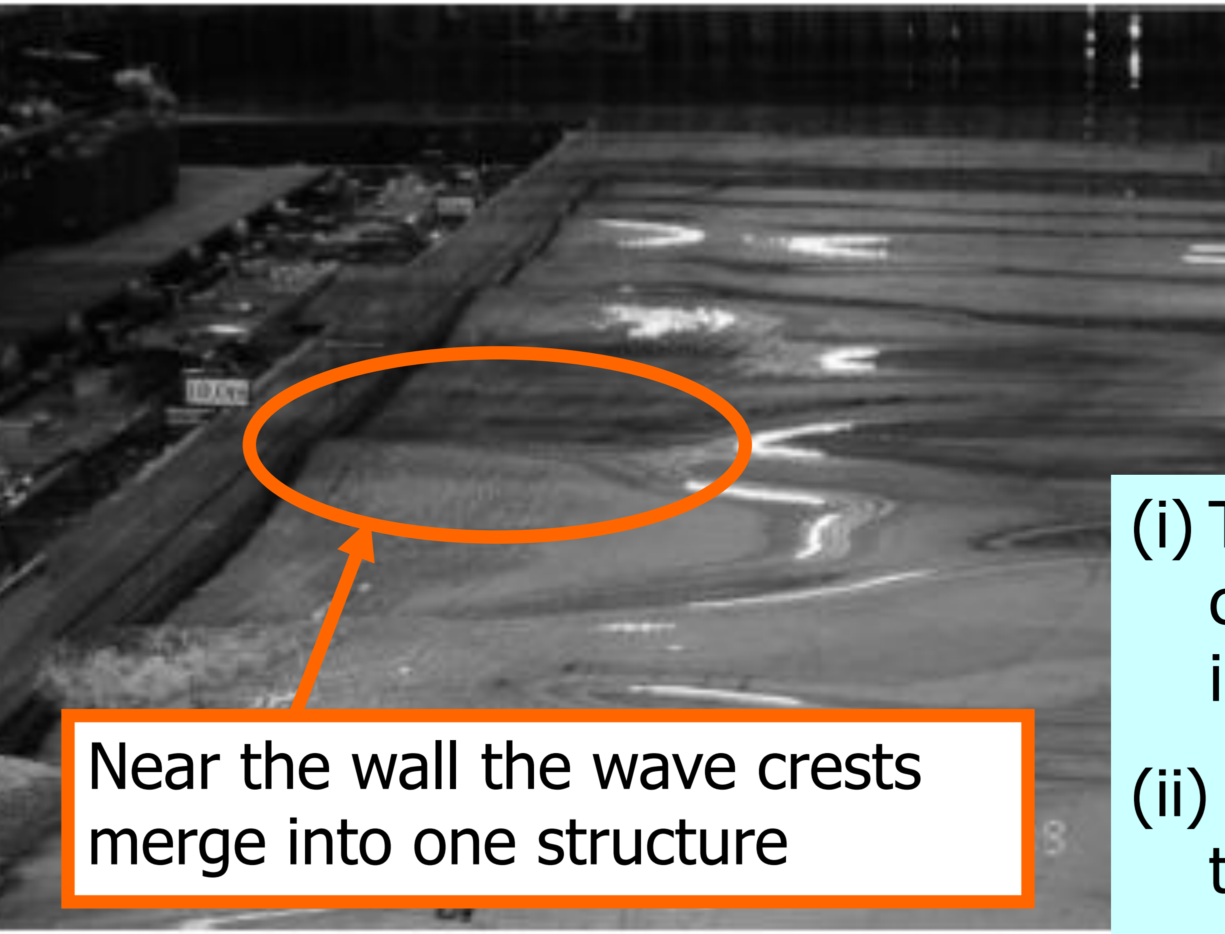
Wave length & length of straight crests: very long

Waves: resemble 'walls of water'

Ship wave in Broadwater (Gold Coast, ICS 2007 field trip) approaching a seawall

... and overtopped it

If a large-amplitude wave reflects from a wall: Mach stem



Mase, Memita, Yuhi, Kitano, Stem waves along vertical wall due to random wave incidence, Coastal Engineering 44 (2002) 339–350

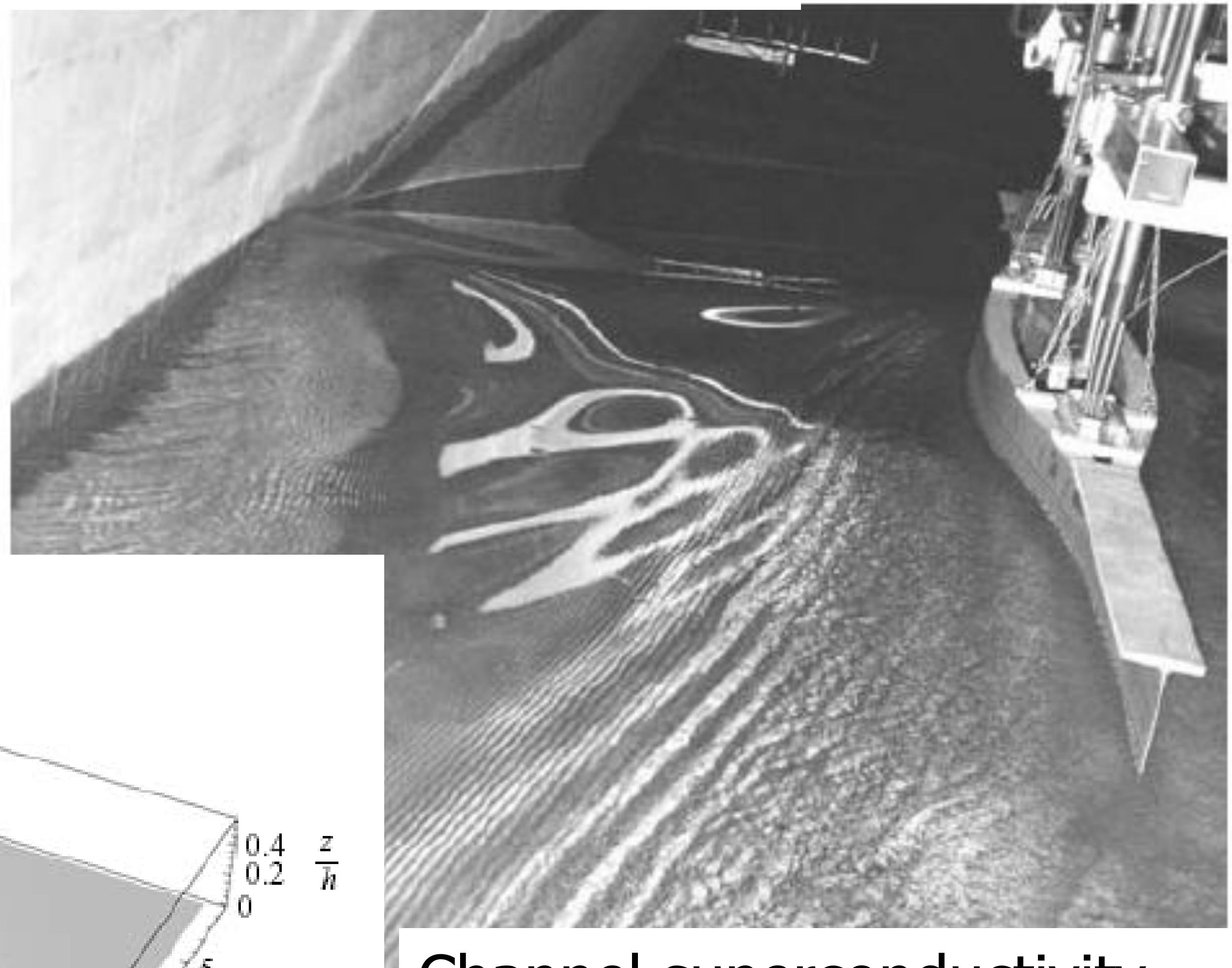
(i) The length of the common crest gradually increases

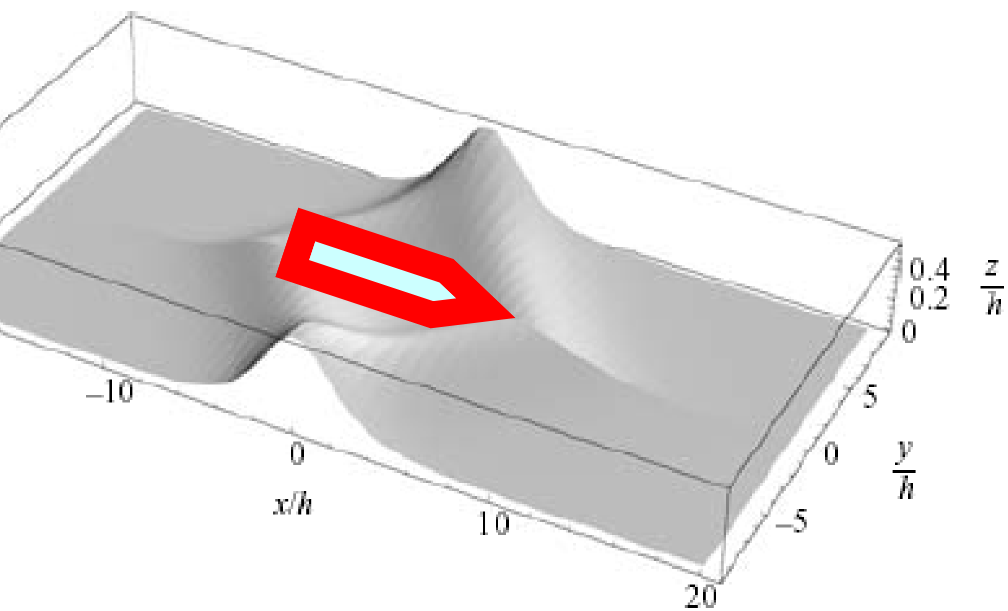
(ii) and frequently is higher than 2xincoming wave

(Yue and Mei 1980, Pedersen, 1990s)

Stable & symmetric case: when a KdV soliton reflects from a wall:

The effect can be used for zero wave resistance in channels: stern wave kills bow waves





Channel superconductivity

Chen, Sharma, Stuntz, *J. Fluid Mech.*, 2003

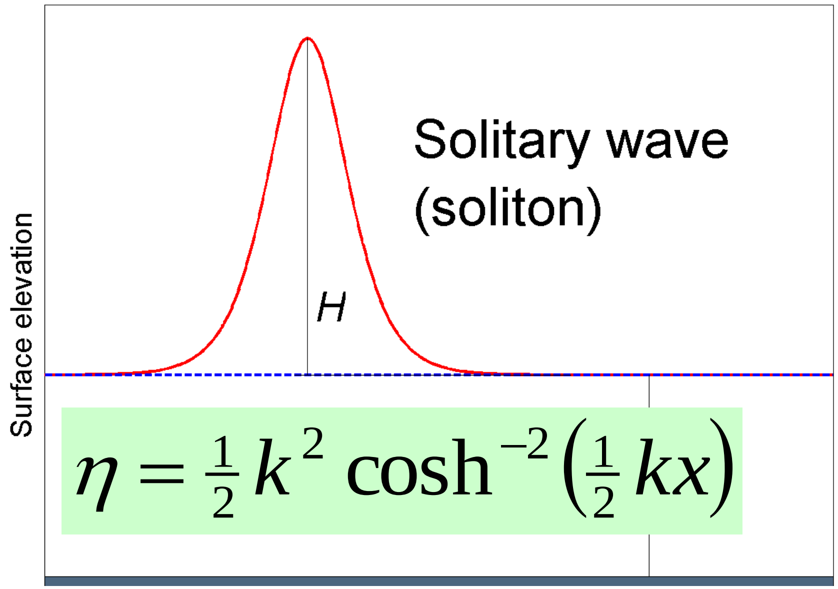
Pattern of **crossing ship waves**:

(i) Wave crests bend

(ii) Wave heights increase

KdV Crossing solitons KP

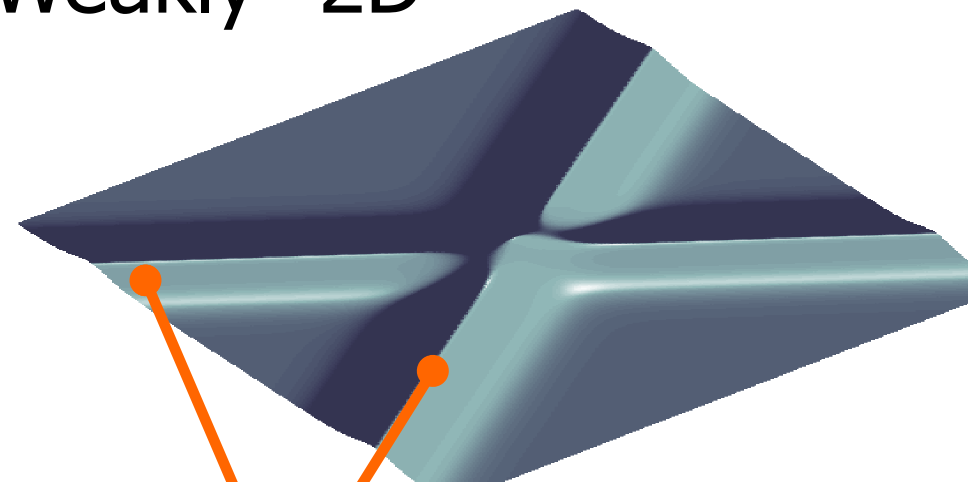
Korteweg & de Vries (1895) Kadomtsev & Petviashvili (1970)



$$\eta = \tfrac{1}{2} k^2 \cosh^{-2}\left(\tfrac{1}{2} kx\right)$$

Pseudo-2D

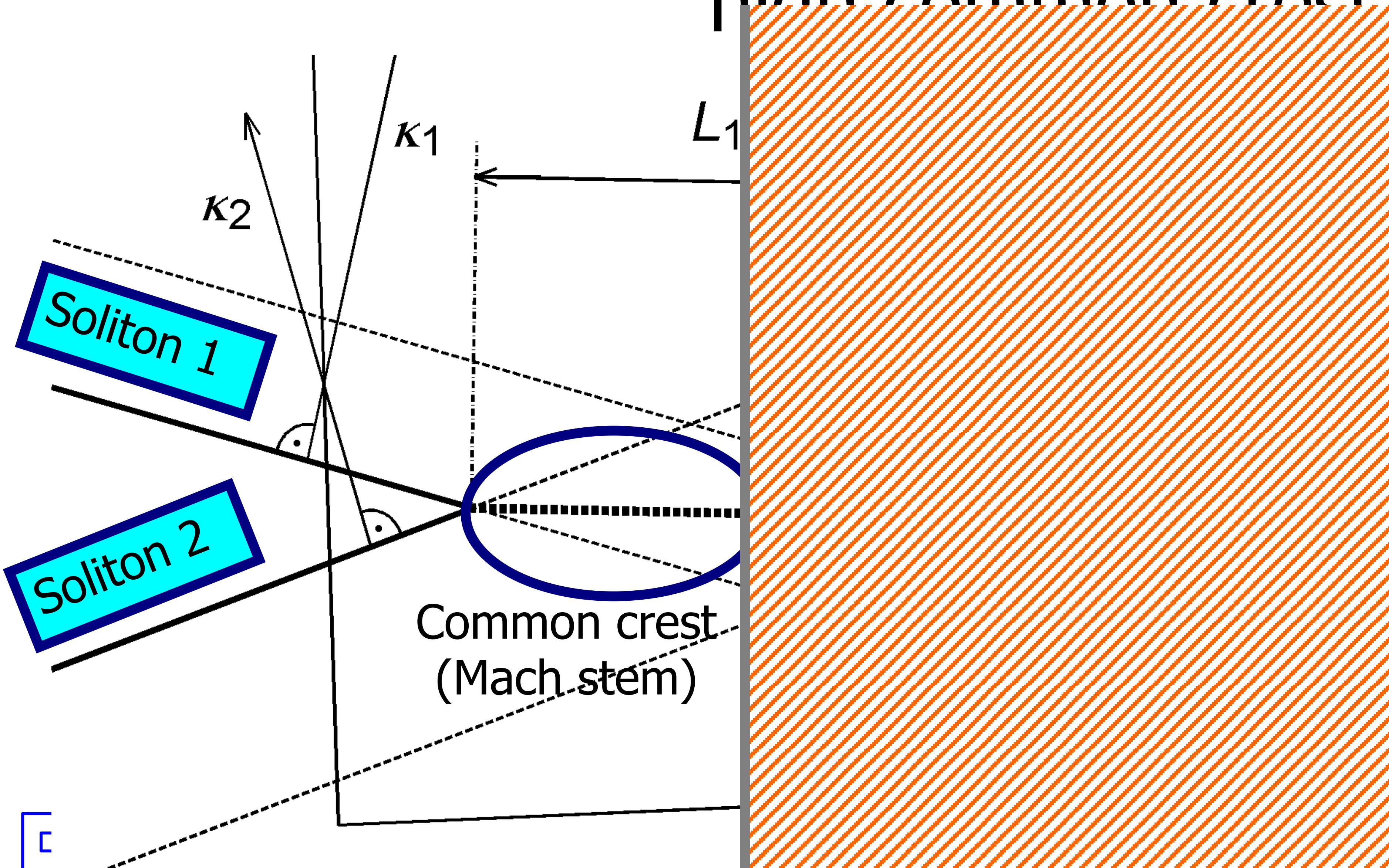
"Weakly" 2D



Single waves are KdV solitons

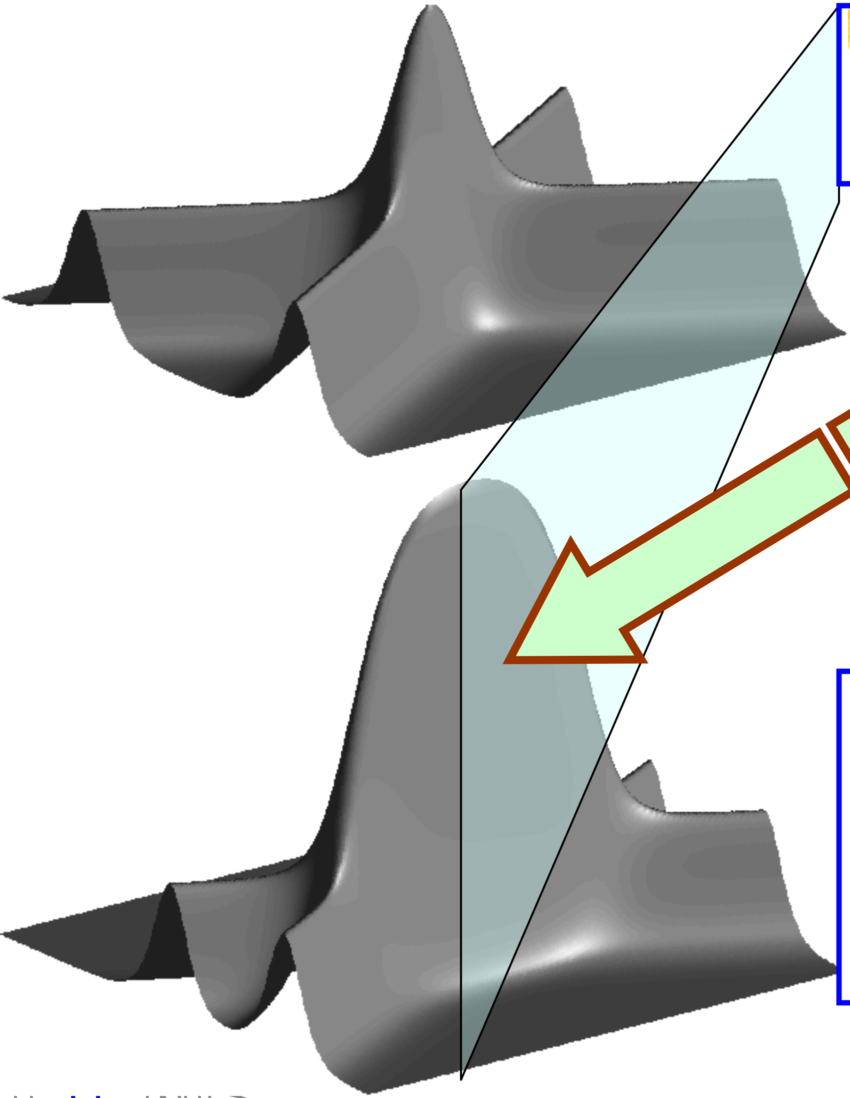
Overview of soliton interactions: Soomere, in: Encyclopedia of Complexity and Systems Science, Springer 2009, vol. 9, 8479–8504

If there is no wall: phase shift & high common crest



Peterson, Soomere, Engelbrecht, van Groesen, *Nonlinear Processes in Geophysics* 2003

Drastic variations of the elevation pattern for different crossing angles



(i) Up to 4-fold increase in the maximum elevation

Miles, *J. Fluid Mech*. 1977

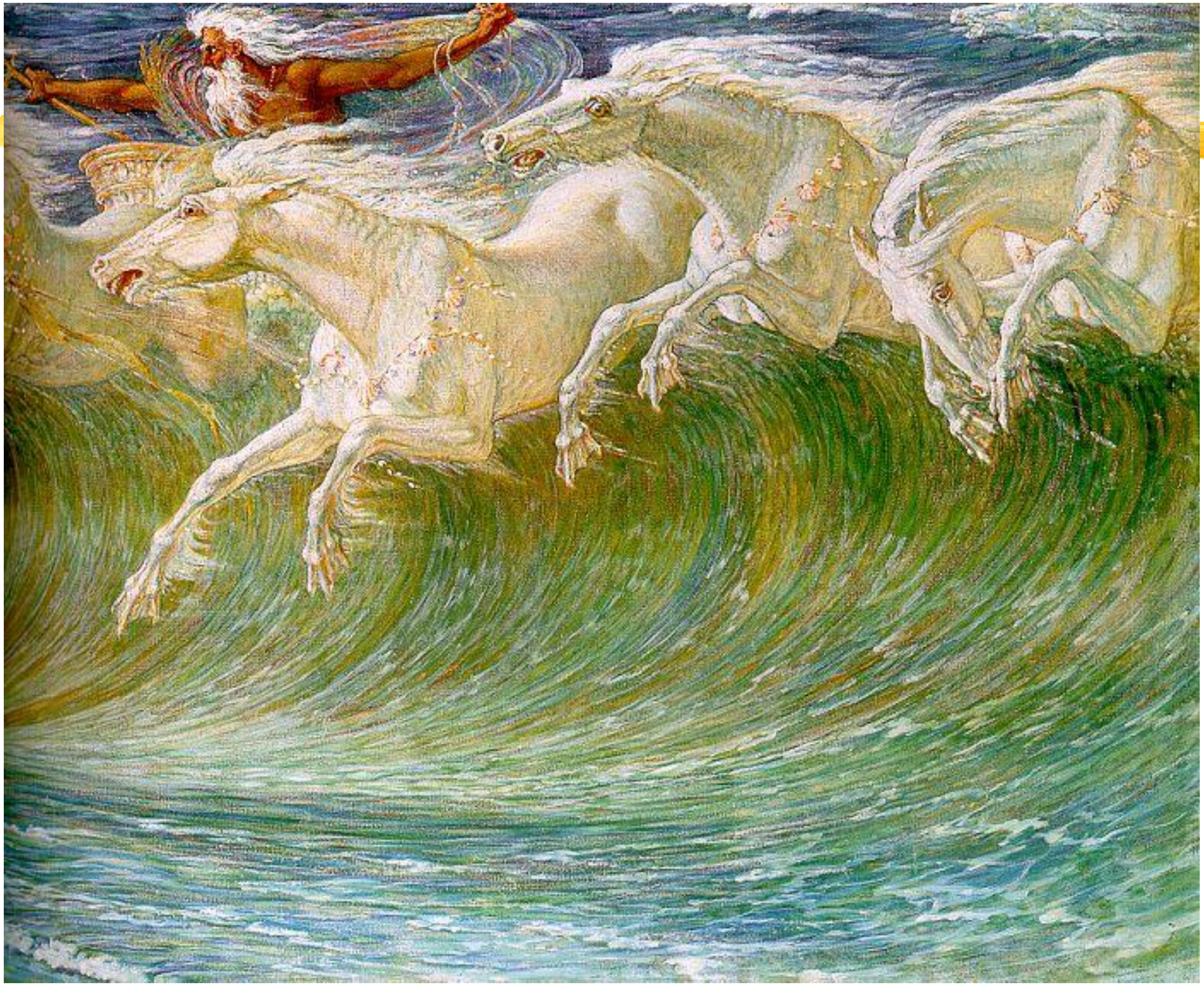
(ii) The **slope** may **8x** exceed the slope of single solitons

Soomere & Engelbrecht, *Wave Motion* 2005; *Eur. J. Mech. B/Fluids* 2006

(iii) The orientation of the crest of both the solitons changes: waves may come from another / unexpected direction

Soomere, *Phys. Lett. A* 2004

Very steep waves tend to break …



Walter Crane, Horses of Neptune, 1892

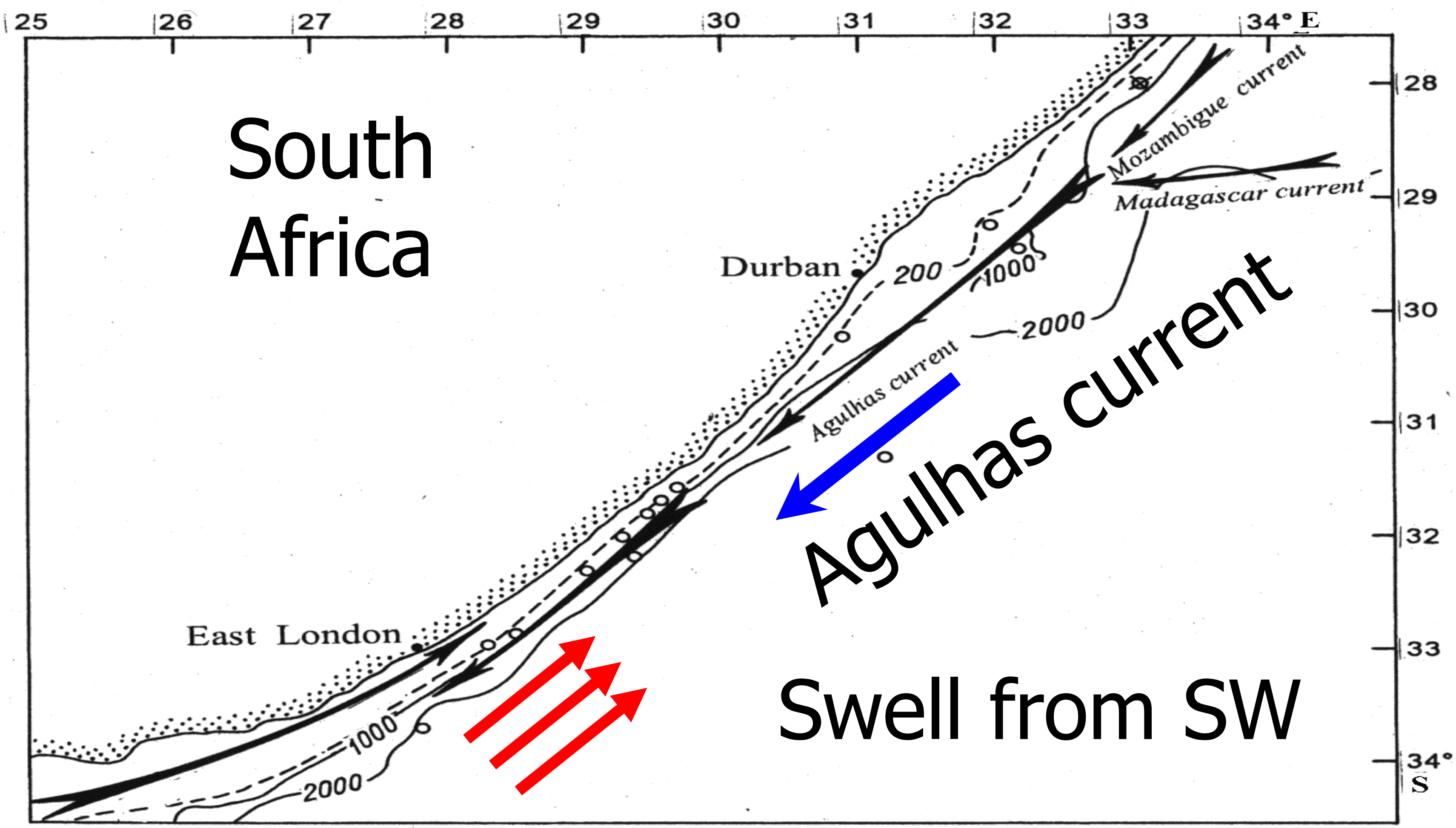
Usually, ship in rough seas tries to face waves with its bow – the most reliable part

Waves approaching from an unexpected direction: particularly dangerous

Scuttlebutt Photos: Big Waves provided by Donald Brewster - We can't vouch for the validity of these photos, but they look pretty real, and the waves look pretty big.

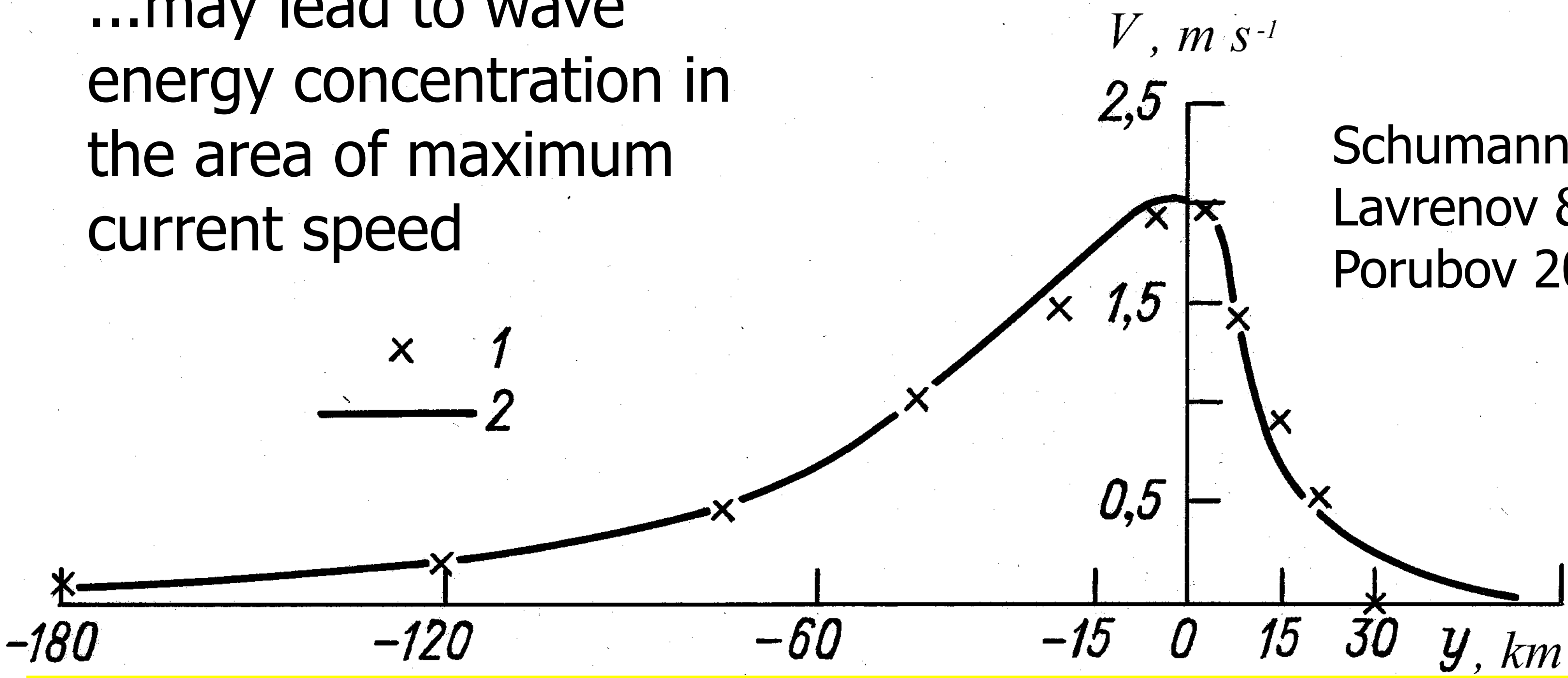
Acute & changing danger:

frequently evident in the vicinity of jet currents:
waves running against current become high and steep



Spatial structure of the Agulhas current: waveguide and trap

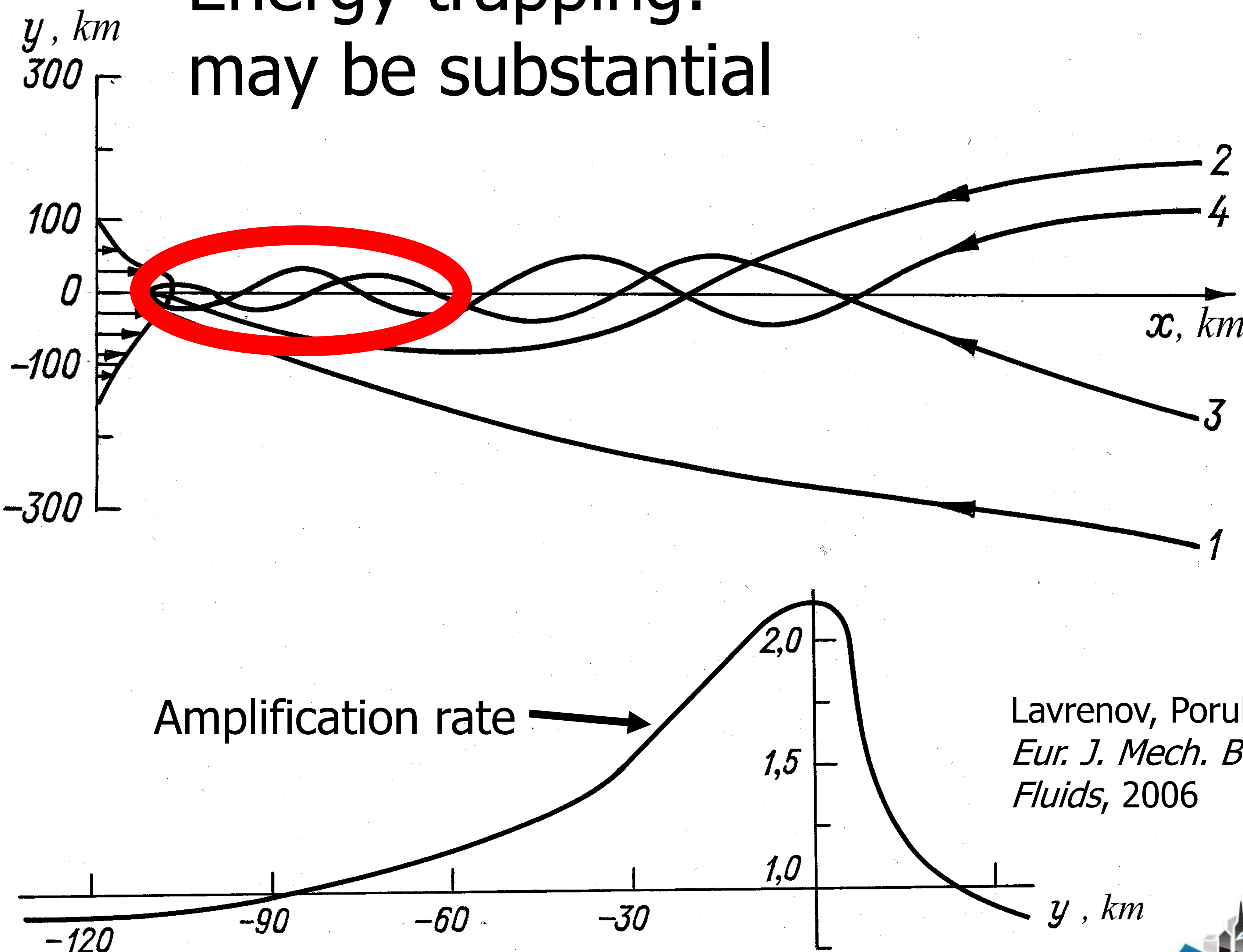
...may lead to wave energy concentration in the area of maximum current speed



Schumann 1976, Lavrenov & Porubov 2006

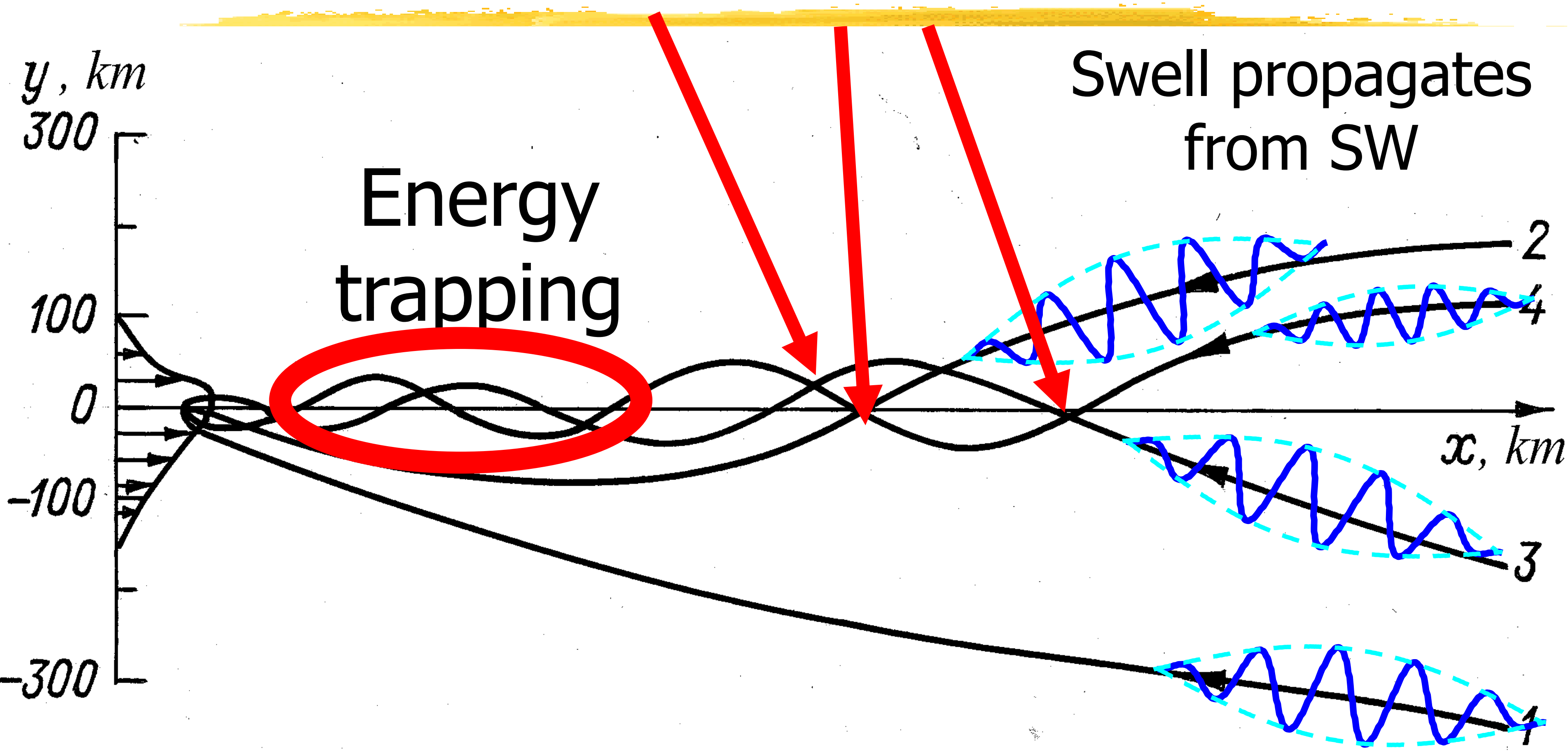
The reason: refraction – tendency of wave rays to turn towards area of larger current velocities – analogue to refraction towards smaller depths

Energy trapping: may be substantial



Lavrenov, Porubov, *Eur. J. Mech. B Fluids*, 2006

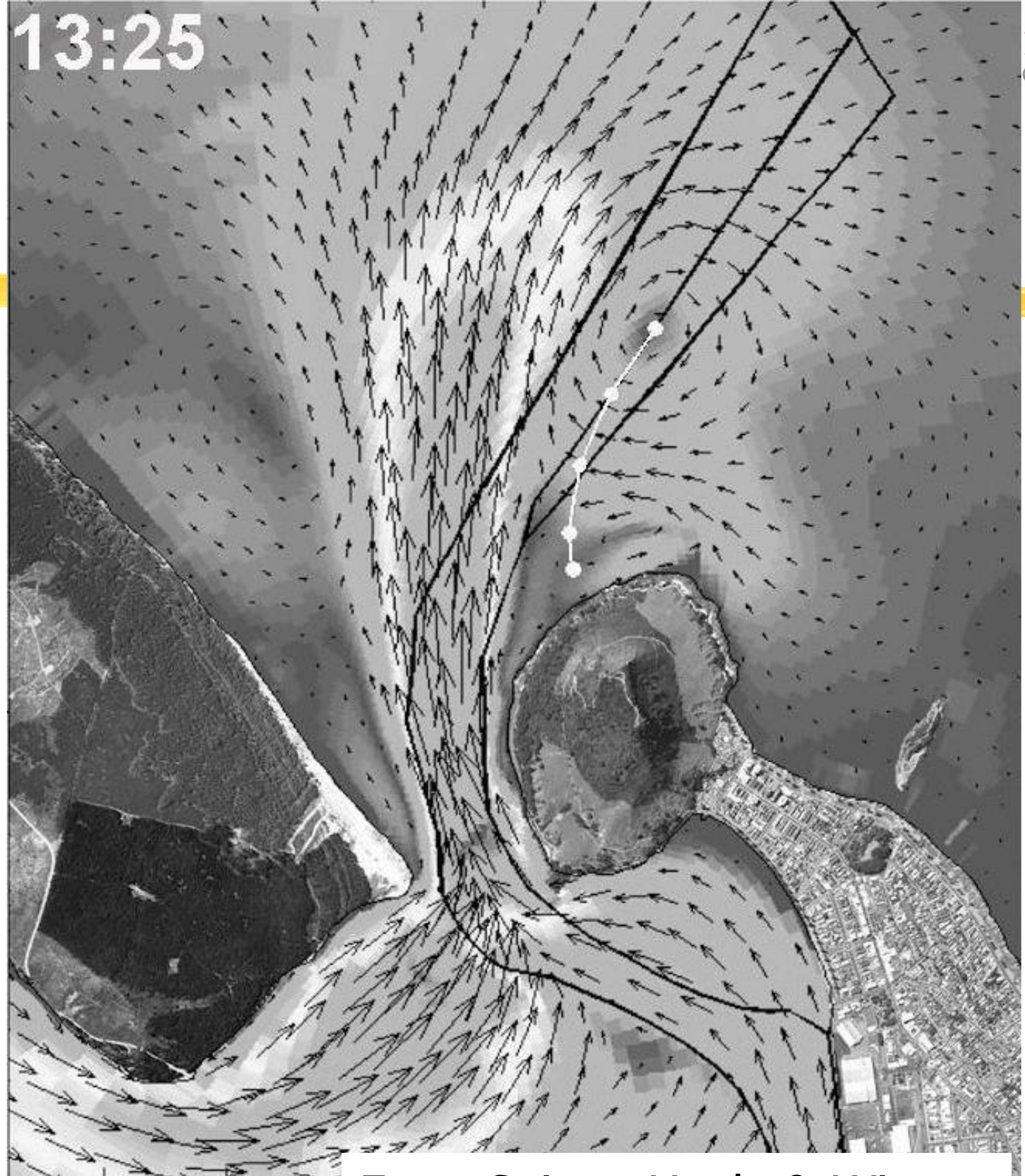
Extreme danger: crossing of long waves redirected by refraction



Soomere 2005,
cited in Lavrenov, Porubov, *Eur. J. Mech. B Fluids*, 2006

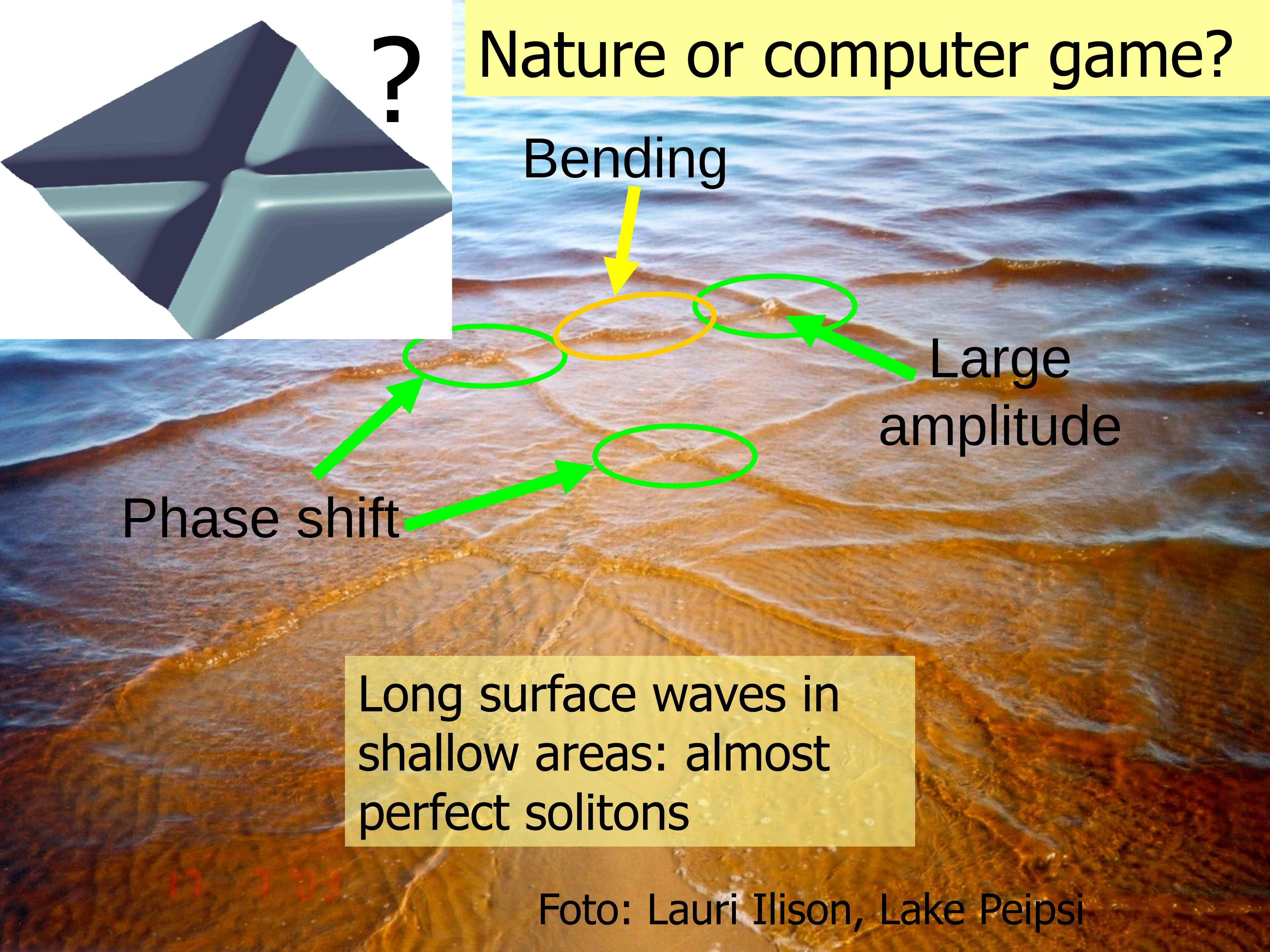
No need for Agulhas: an ebb jet would do the job!

(The closer the ship is to a harbour, the more likely it is hit by a rogue wave?)



Entrance to Tauranga Harbour

From Spiers, Healy & Winter, *J. Coastal Res*. 2008


Nature or computer game?
?
Bending
Large amplitude
Phase shift
Long surface waves in shallow areas: almost perfect solitons
Foto: Lauri Ilison, Lake Peipsi

Thanks to Miguel Onorato & Al Osborne

Goat Island, NZ, April 2007

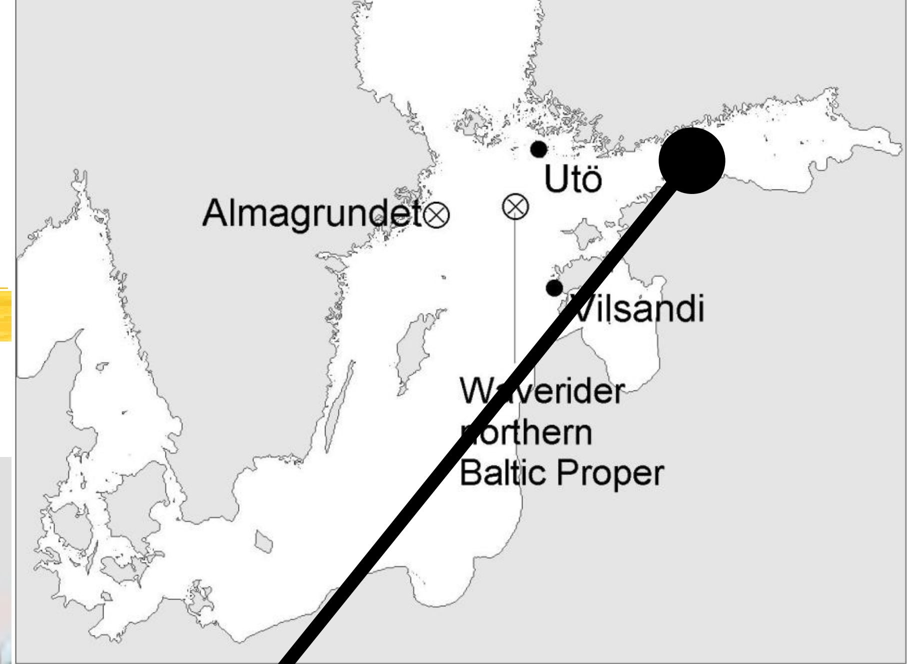
Harilaid Island, Estonia, Sept 2007

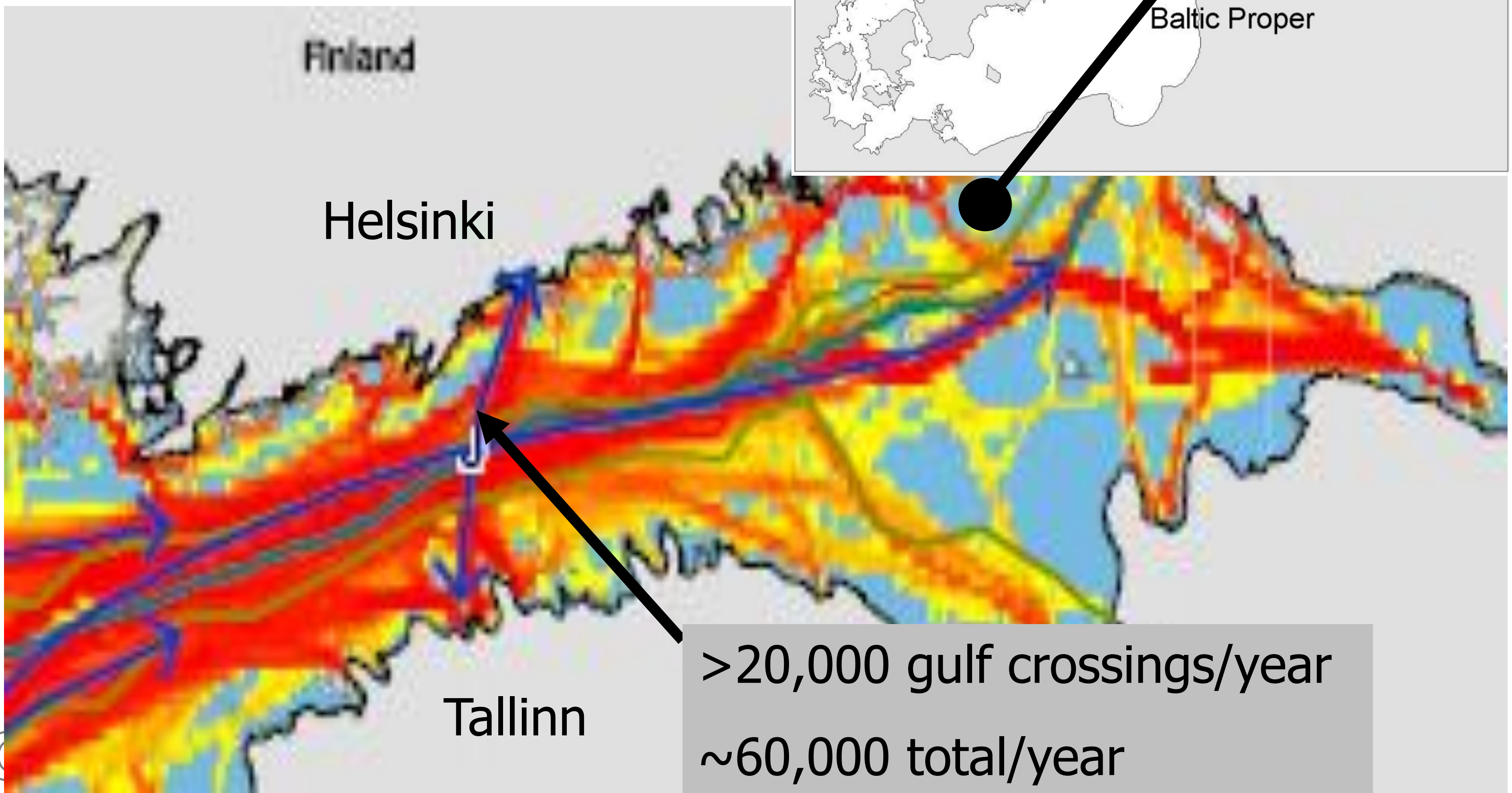
Ship waves: a model of wave climate changes

Possible changes to the wave field

- Heights (incl. extremes and averages)
- Periods / lengths
- Propagation / approach direction
- Internal / group structure
- Presence of monster (giant, rogue) waves

Ship routes in the Gulf of Finland -- a major highway



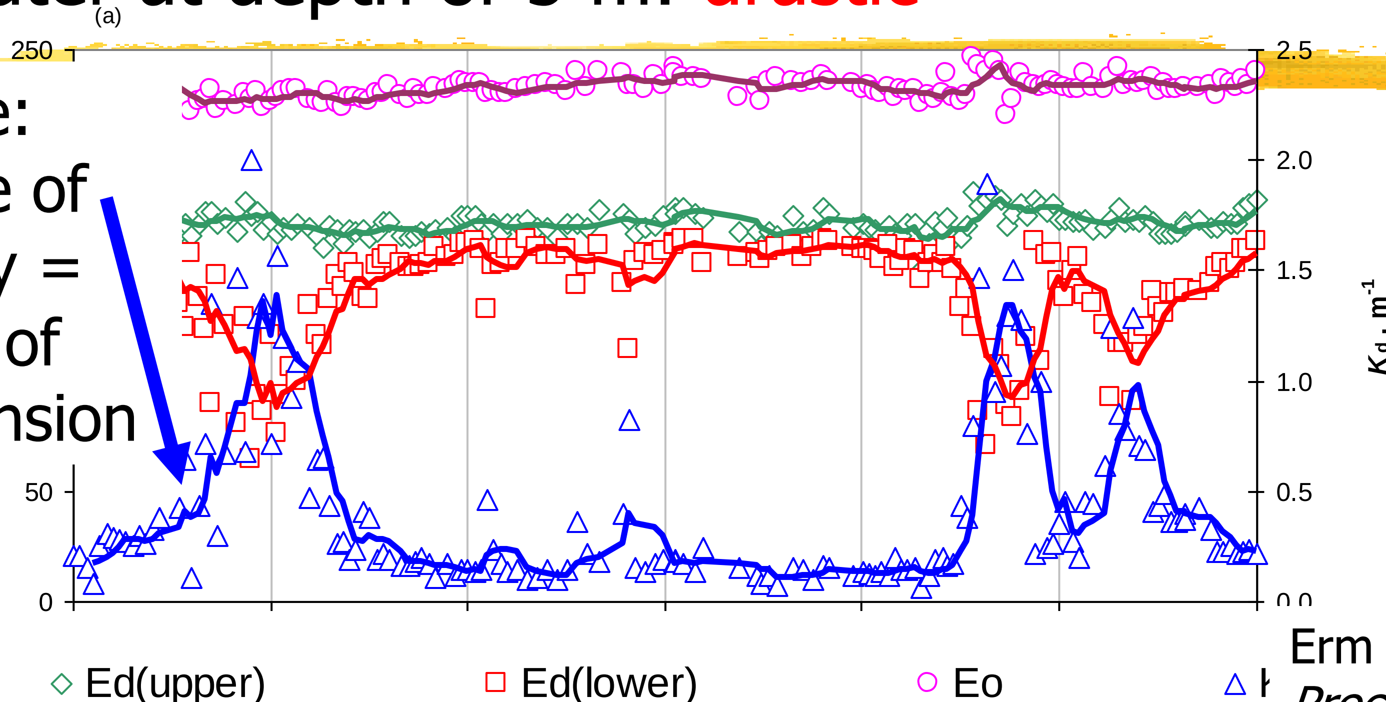


>20,000 gulf crossings/year

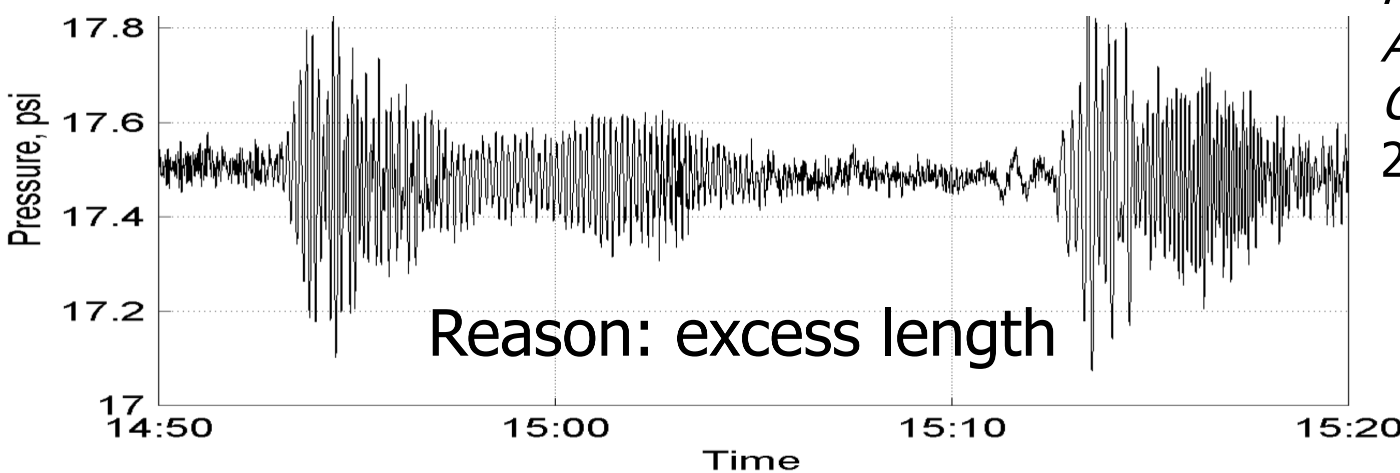
~60,000 total/year

Changes of optical properties of sea water at depth of 5 m: drastic

Blue line: measure of turbididy = amount of resuspension

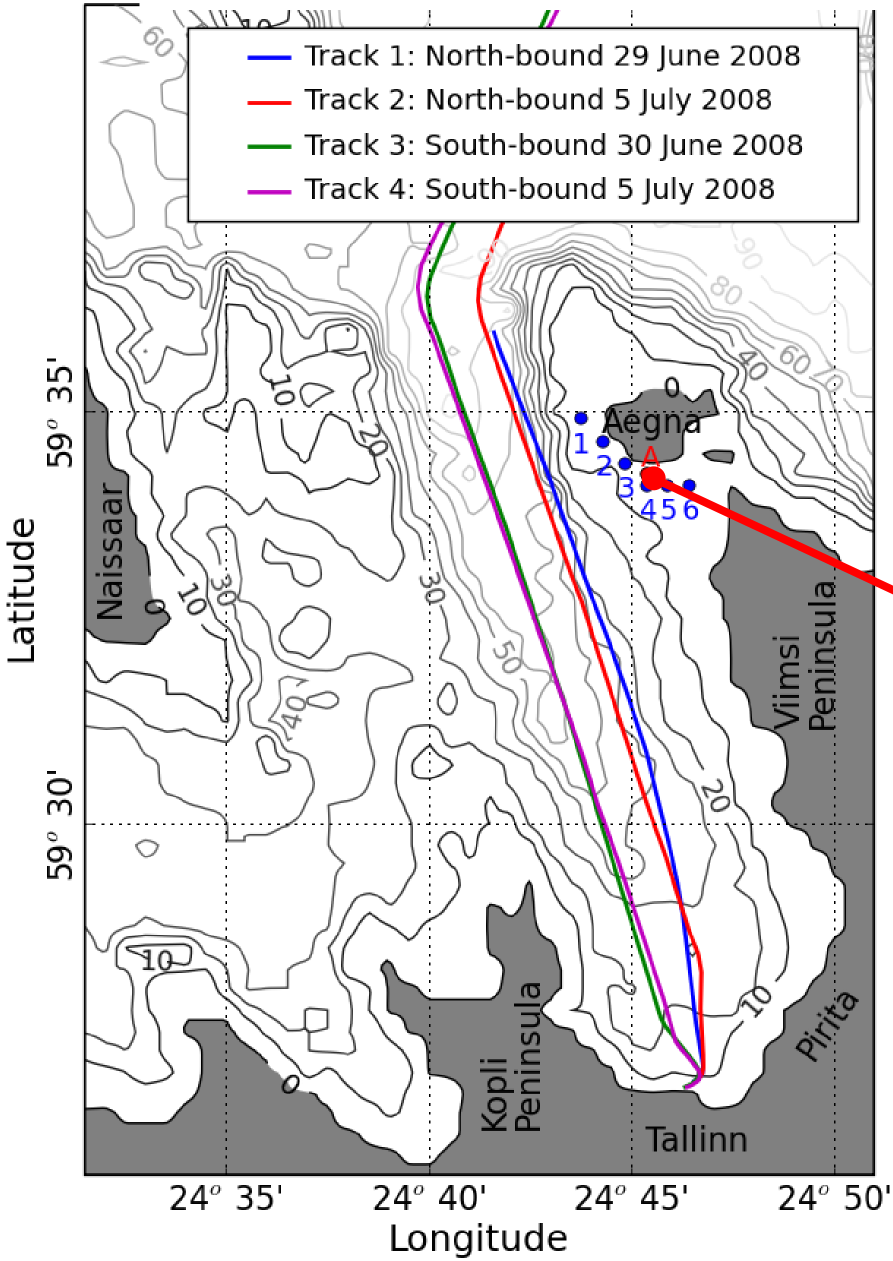


Erm & Soomere, *Proc. Estonian Acad. Sci*. 2004; *Oceanologia* 2006

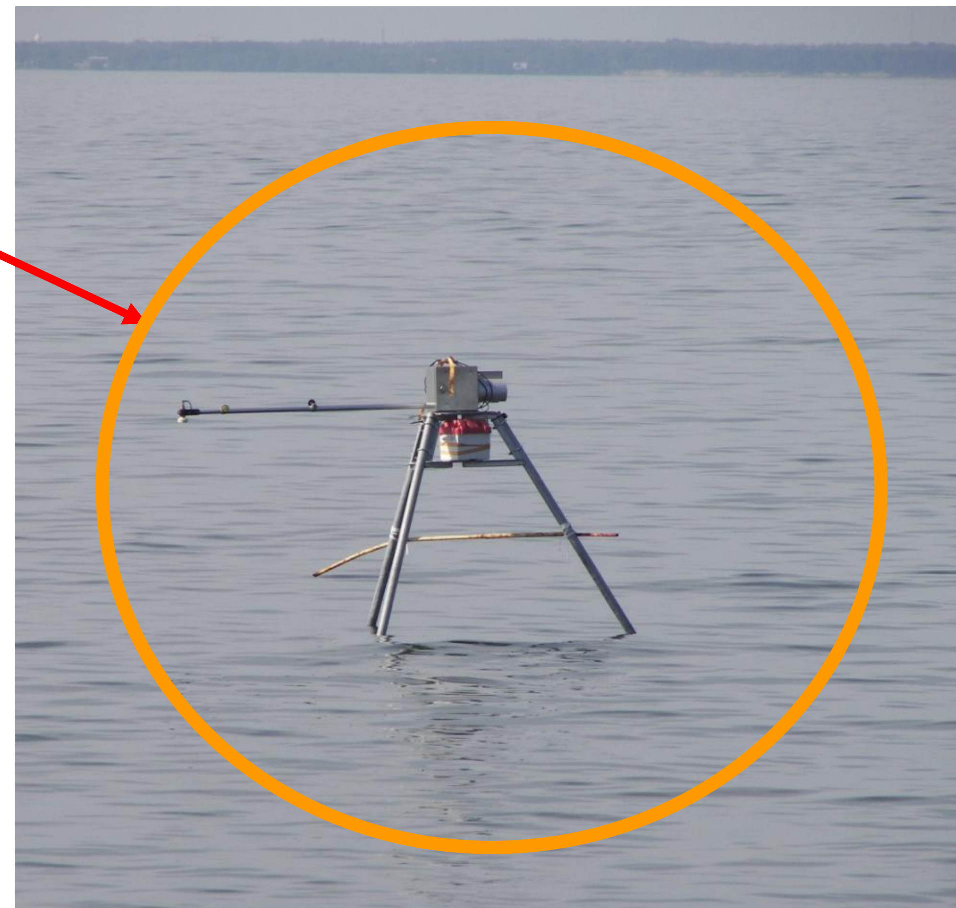


Reason: excess length

Measurements in Tallinn Bay in 2008

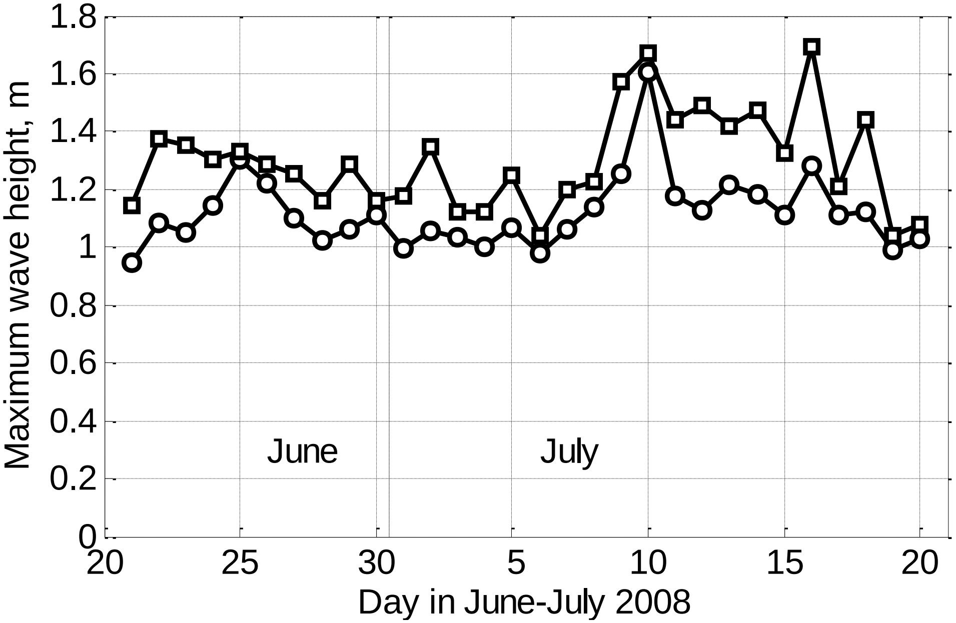


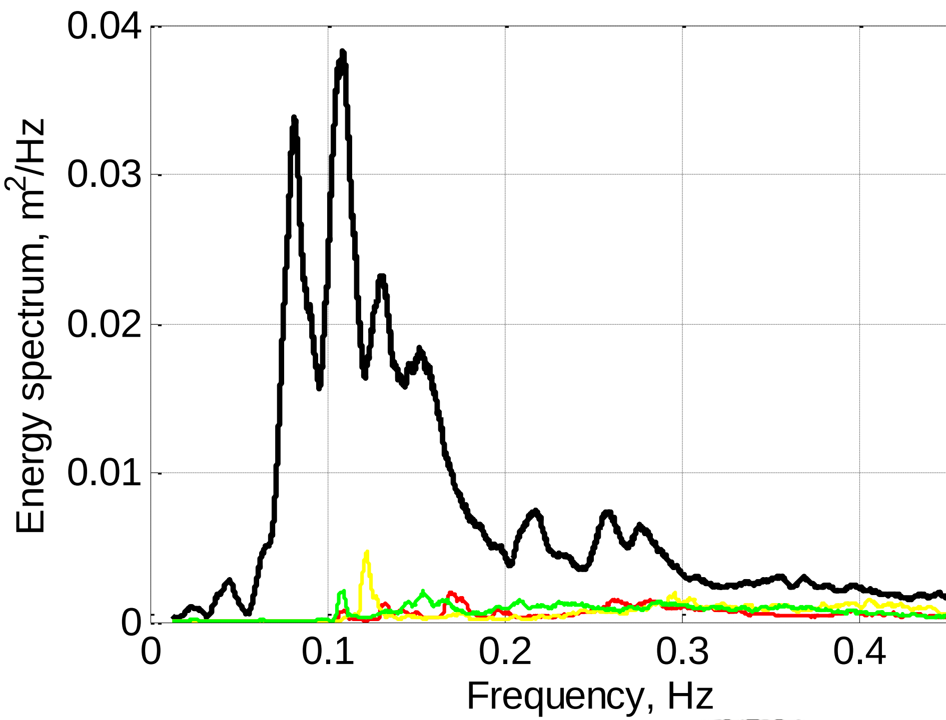
Question: How do ship wakes impact the coast?



Ship wakes are:

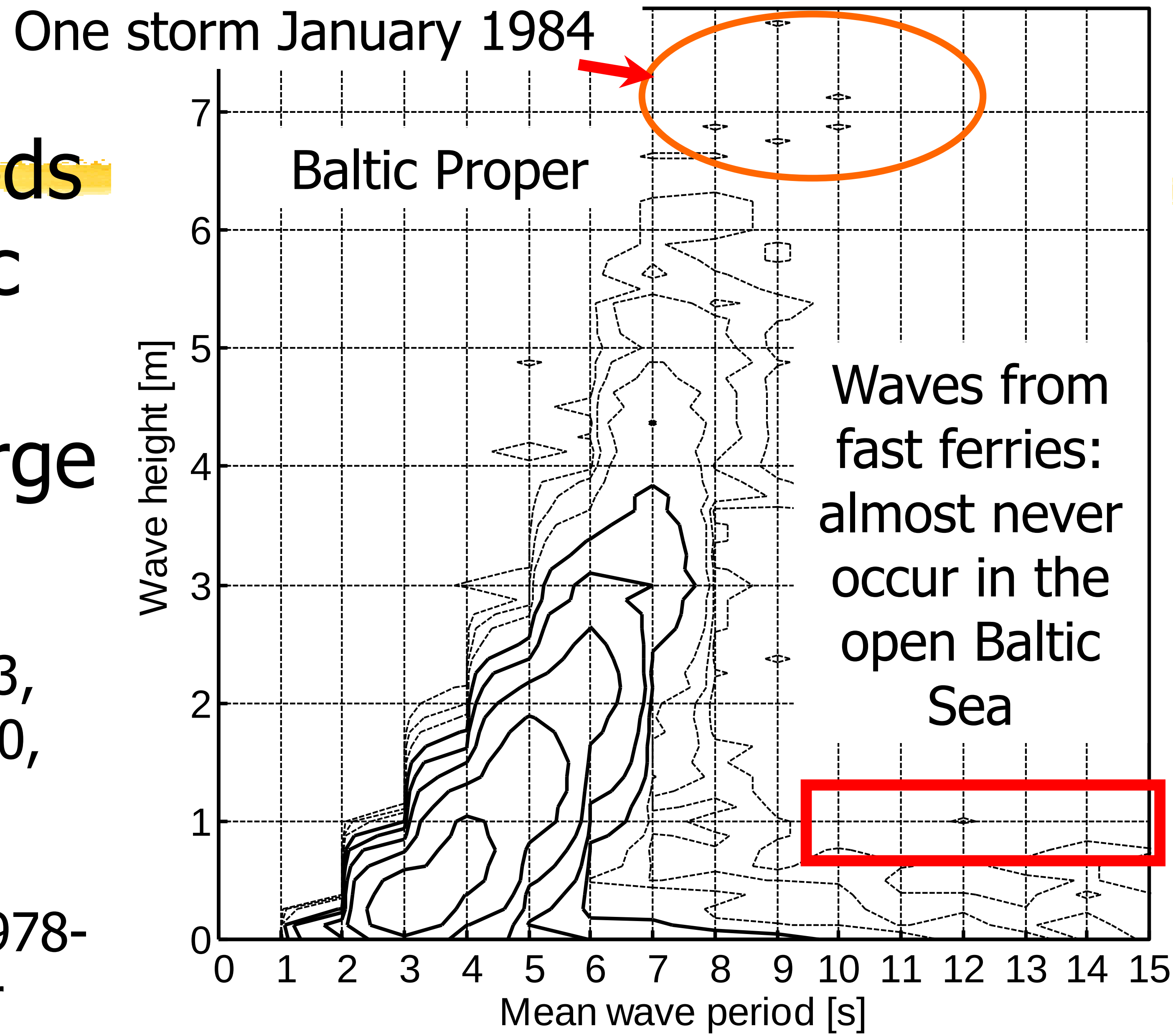
- of reasonable height
  - Typical highest wave ~0.8-1 m
  - ~top 2-5% of wind waves
  - form 5-8% of total wave energy
- with very long periods
  - Largest ship wave ~10-15 s
  - Typical for wind waves 3-4 s





Wave periods in the Baltic Sea: short even for large waves

Isolines for 1, 3, 10, 33, 100, 330, 1000 and 3300 cases, Almagrundet 1978-1995 each hour

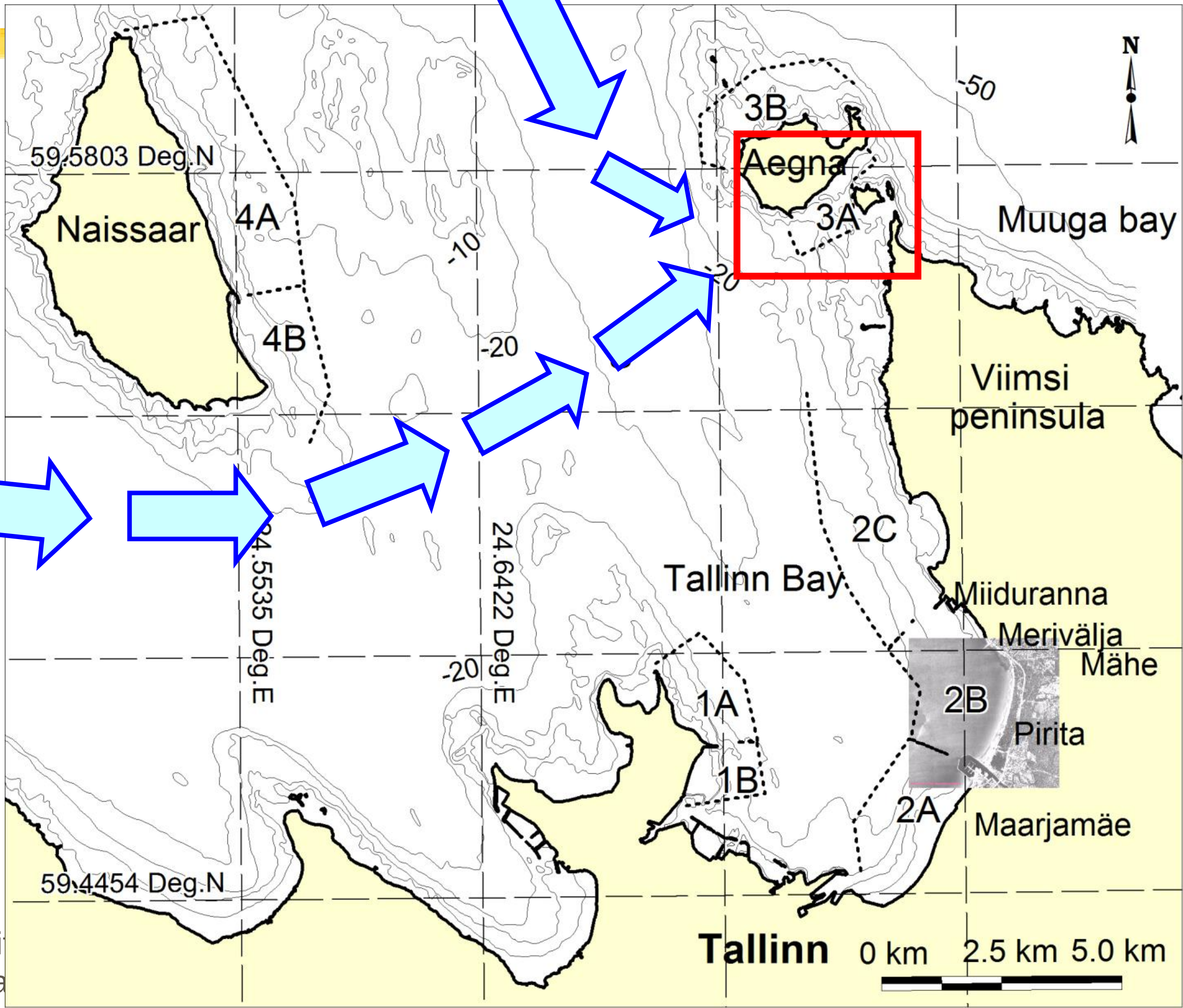


Broman et al. (2006) *Oceanologia* 48 (S)

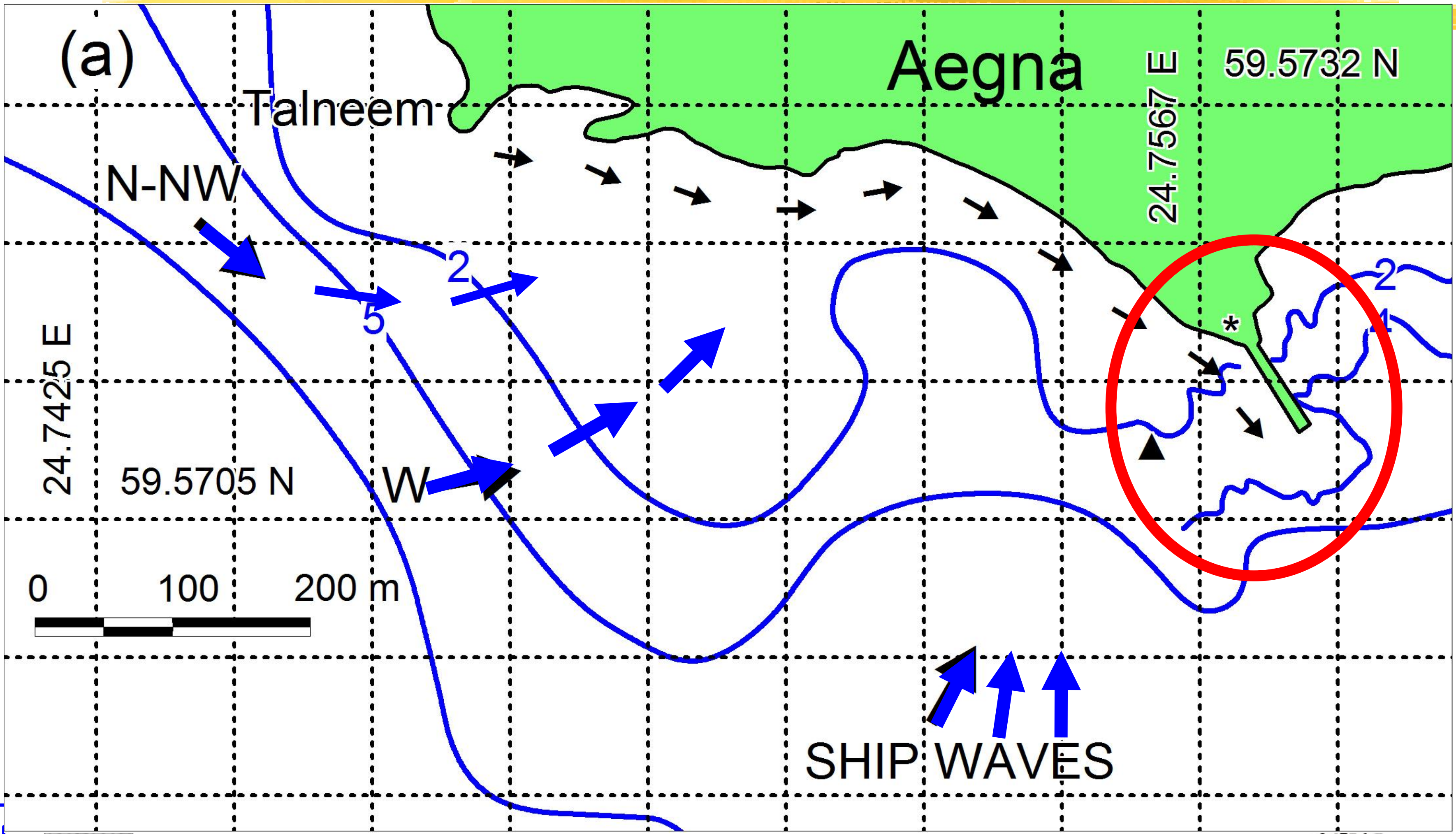
Dominant waves

N-NW storms

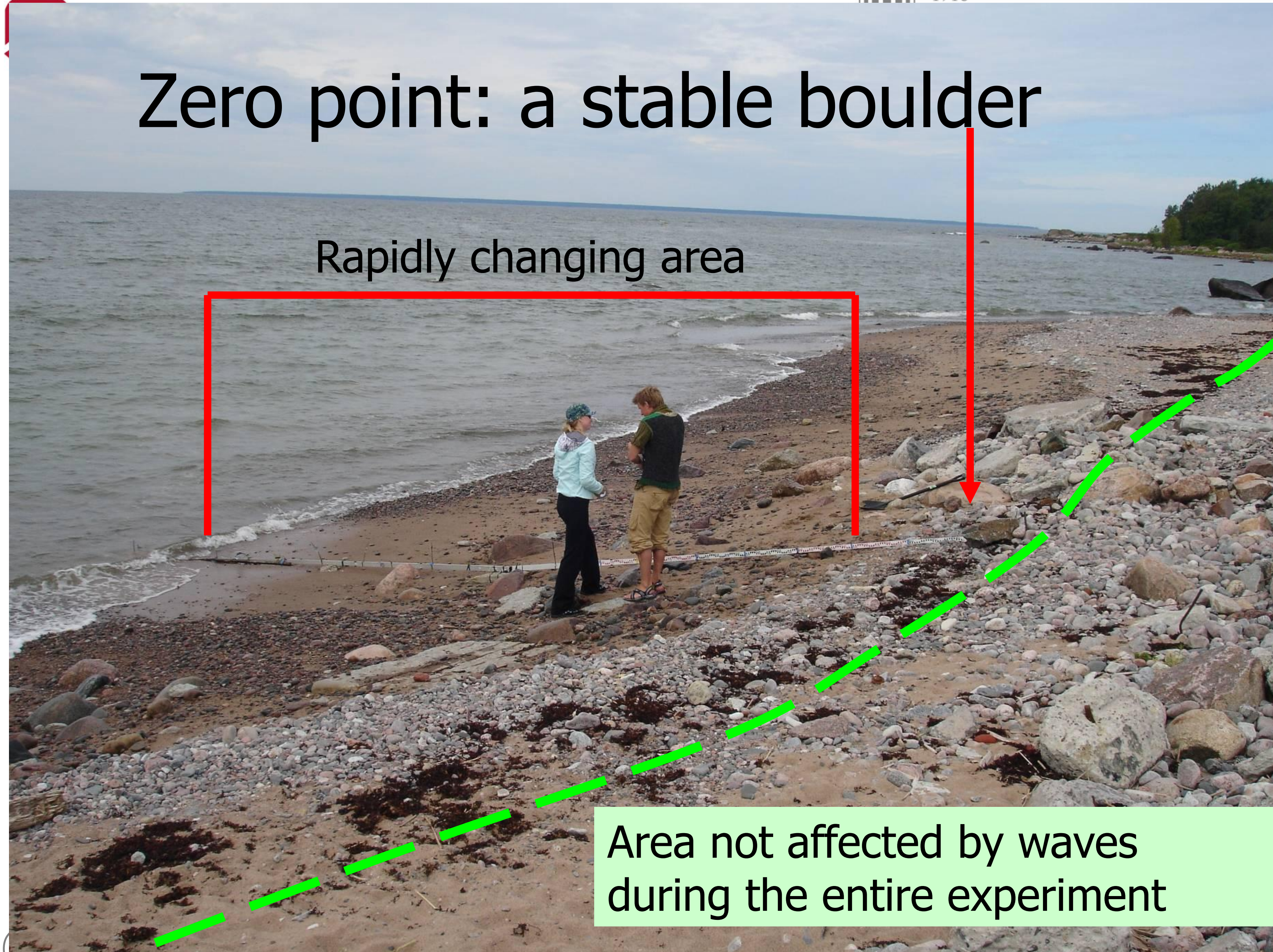
Western storms



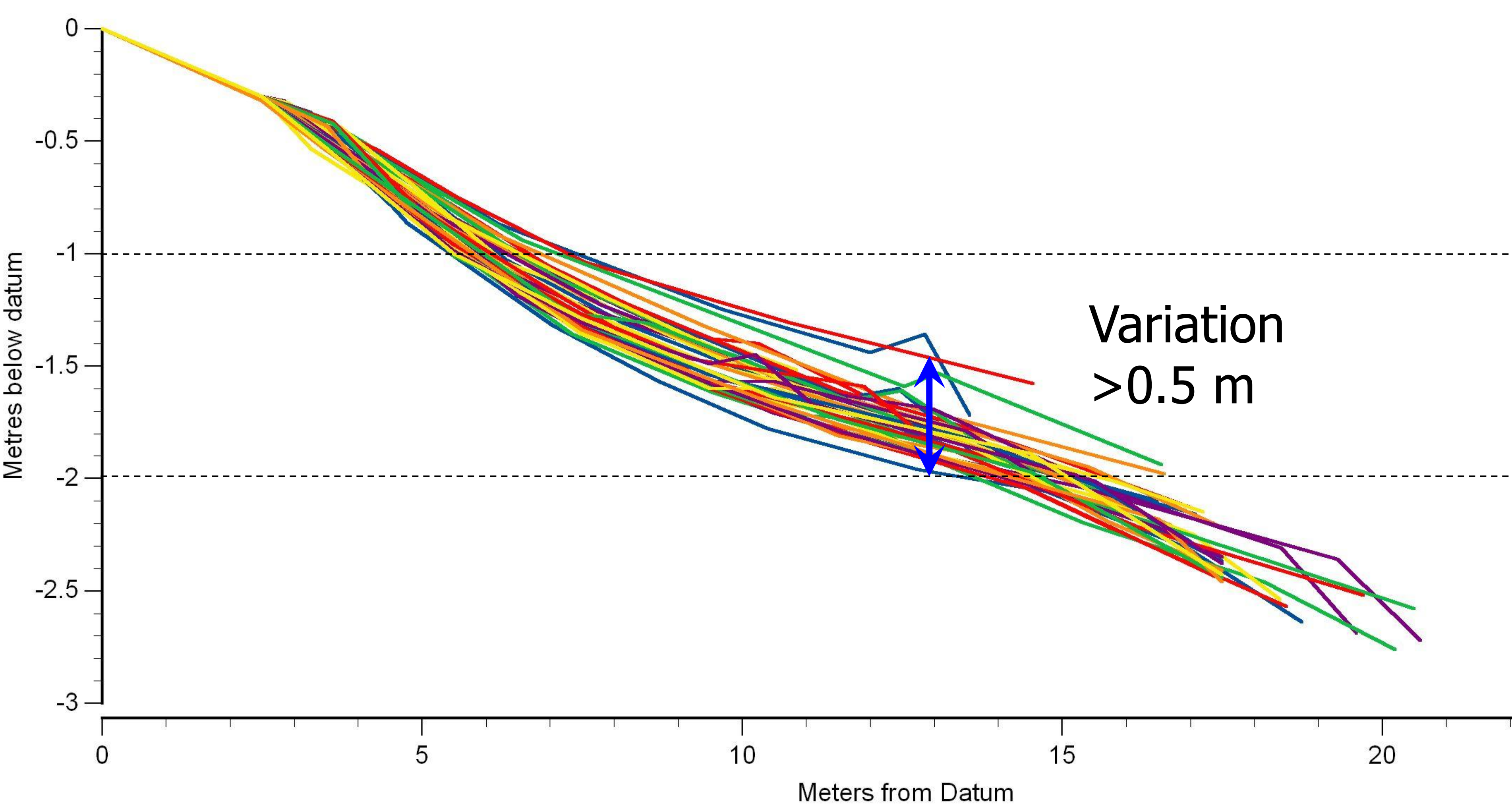
Natural and vessel-wake-induced transport patterns



Zero point: a stable boulder



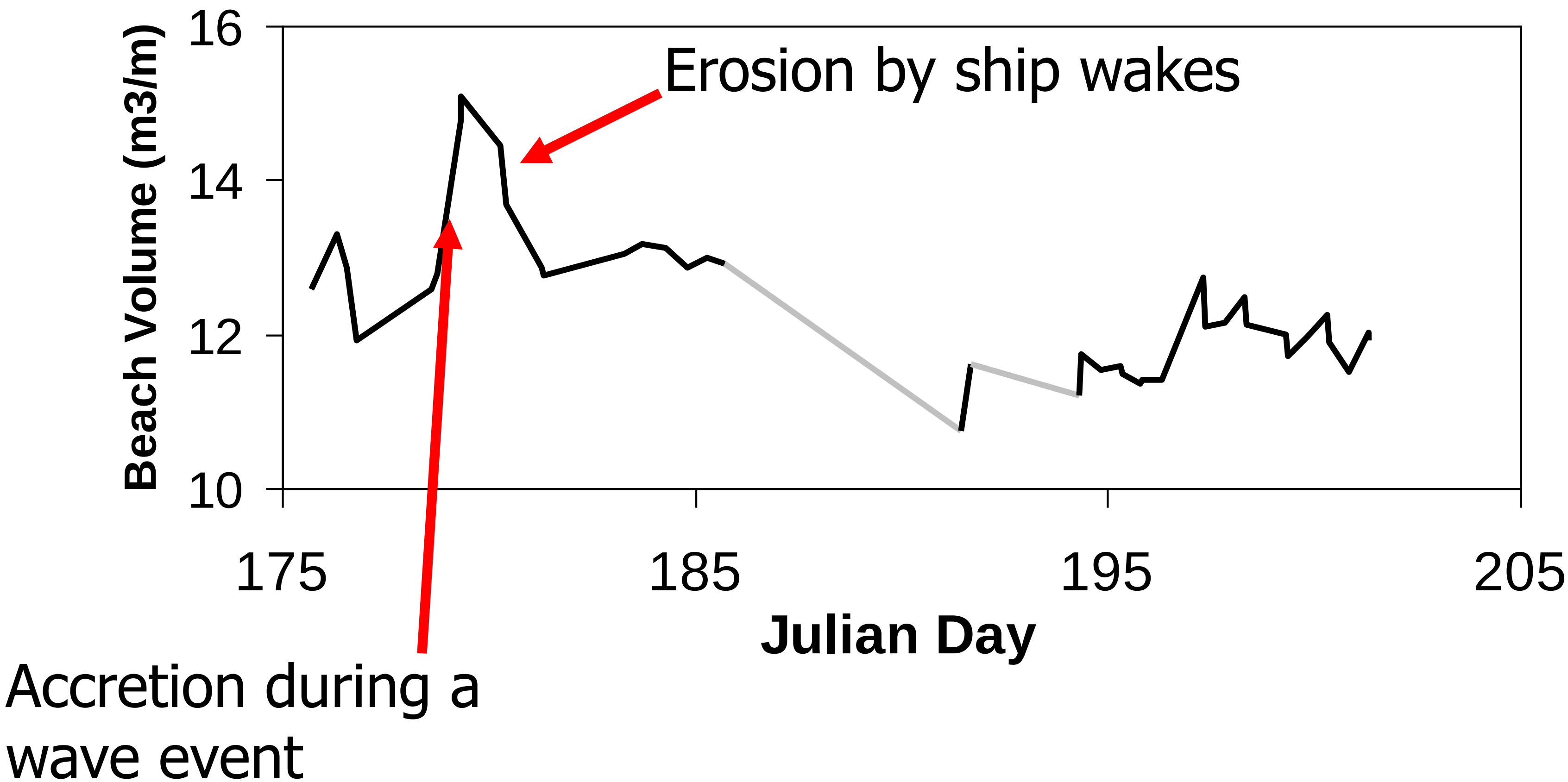
Variations of the height of the dry beach



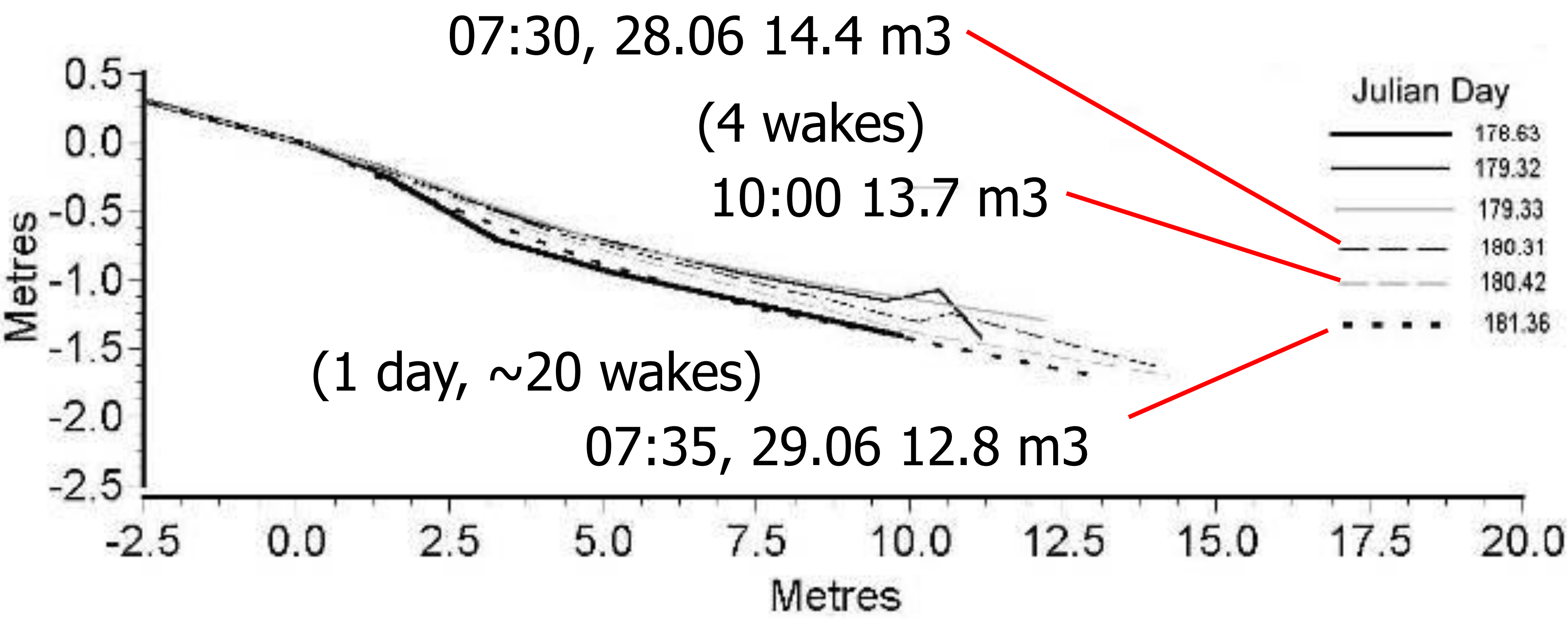
Two appearances of the beach

Before Calm period After

Changes to the dry beach volume



Rapid beach response on calm days



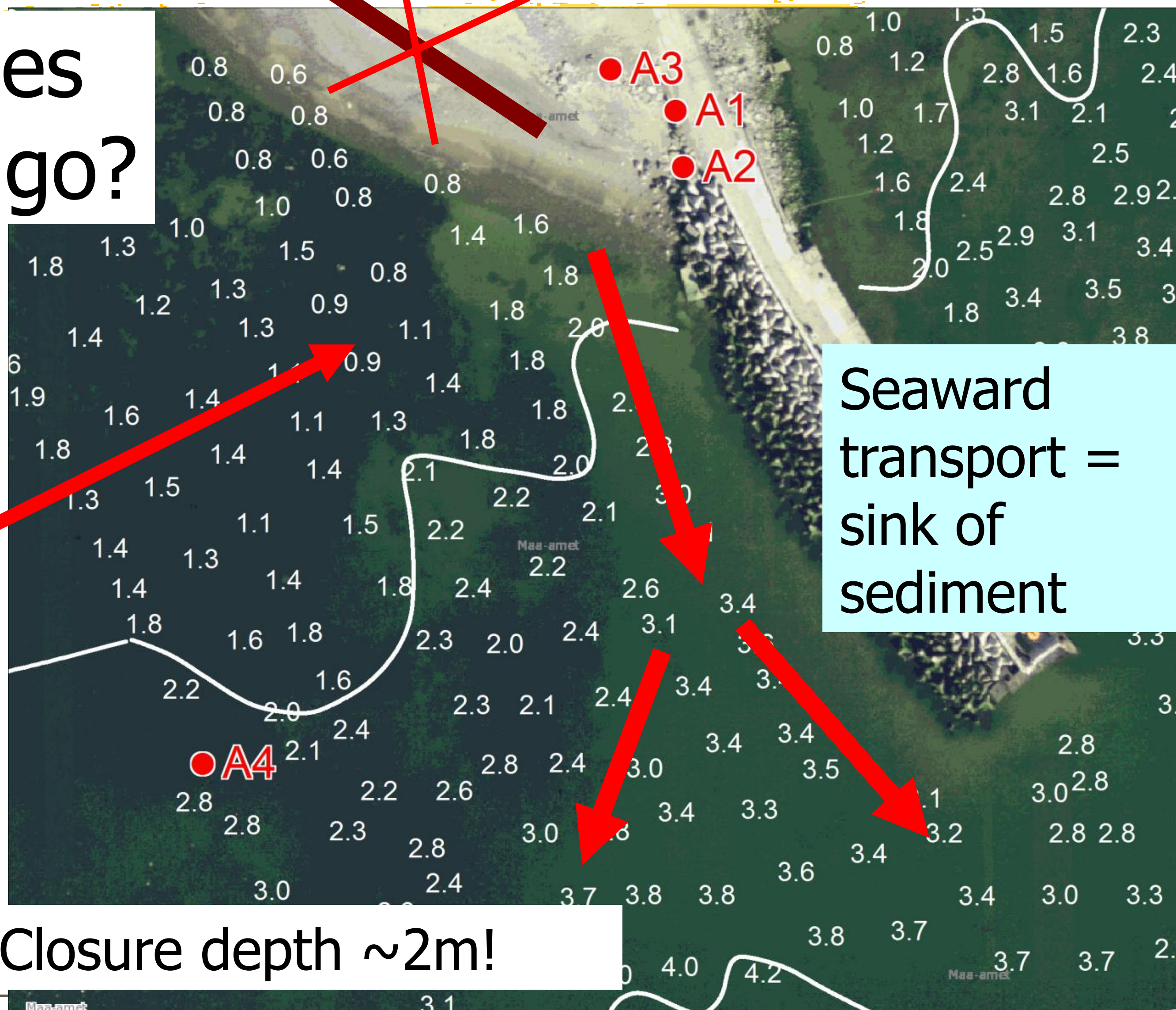
Although some ship wakes may move sediment to the West ...

There is no evidence of accretion to the West of the study site

No evidence of westwards transport ?

Where does sediment go?

No fine sediment in this area

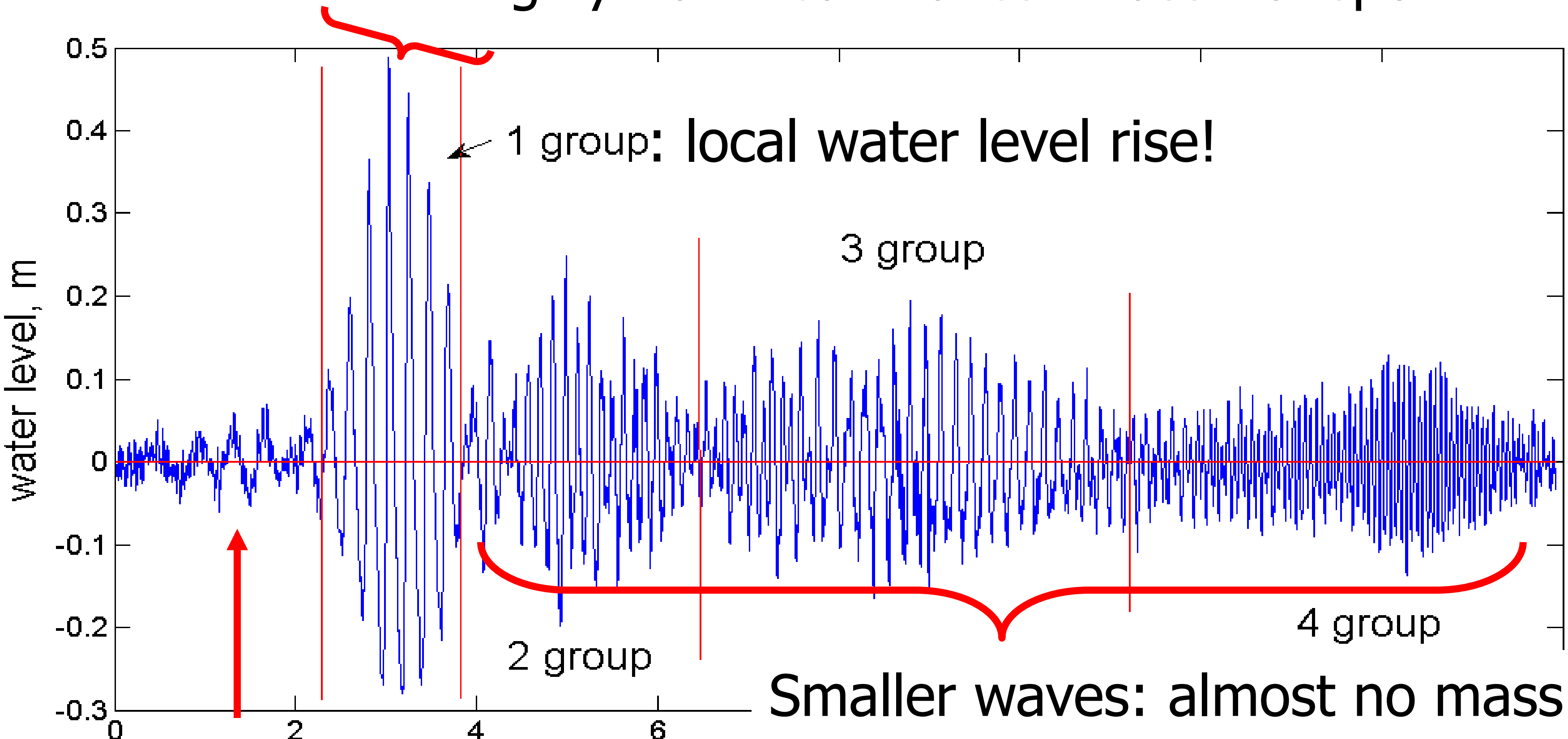


Seaward transport = sink of sediment

NB! Closure depth ~2m!

Possible reason: group structure

Highly nonlinear waves: mass transport



Almost perfect solitons carry water with them

Smaller waves: almost no mass transport; oscillations superposed with a strong backflow

Why intense transport seawards? (a speculation)

- Group structure of the wakes
  - ensemble of high & long waves concentrated into 1-2 minutes
- Precursor solitons and high, nonlinear leading waves
  - carry a lot of water to the coast (~10 m3/m)
  - create local short-term wave setup
- followed by strong backwash
  - superposed by oscillations created by the “tail” of the wake

A selection of lessons (1)

Crossing shallow-water waves:

- up to 4-fold amplification of wave height
- up to 8-fold slope amplification
- change of orientation of wave crests ⇒ side hits for ships?
- easily created by topographic refraction
- may be created by temporary (ebb) jets

A selection of lessons (2)

- Ship wakes may have extremely strong impact on almost equilibrium beaches
- Large & rapid effects possible at medium-energy coasts (ship wakes: <10% of total wave energy)
- A new option: seaward transport of sediment, to the depths >>closure depth
- The impact:
  - most severe where ship wake field is almost unidirectional
  - mirrors effects of potential changes of wave climate
  - may become evident very rapidly

Lesson to take home

There are many ways of smart use of the existence of dynamical patterns on the sea

- (both natural and man-made)
- for detecting, understanding and mitigating changes
- for protecting valuable & vulnerable areas

People’s response to environmental change in the light of Anacharsis

Some never learn
(even not from obvious failures) (clear majority)

Some learn from the past (quite few smart people)

Some face the challenge to foresee and cope with the changes

A “must” for the wave & coastal community


Wishing nice & friendly sea
to everybody!