An overview of the state-of-the-art in meteotsunami research and potential operational systems

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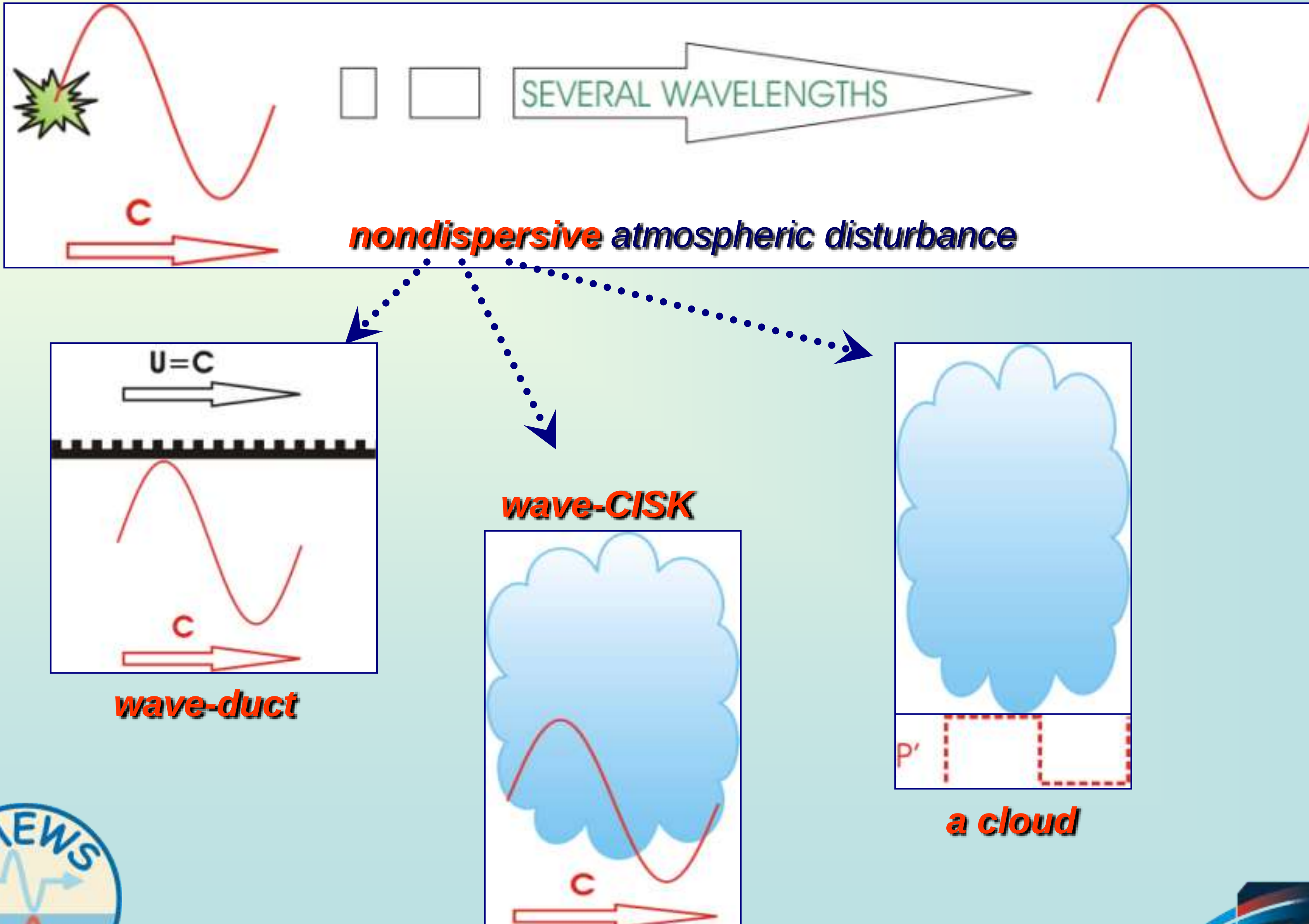
- Present knowledge on the phenomenon
  - The source
  - Air-to-ocean energy transfer (external resonance)
  - Coastal amplification (internal resonance)
- Common synoptic characteristics
- Operational possibilities

Meteotsunami, atmospherically induced destructive ocean waves in the tsunami frequency band, is multiresonant phenomenon which occur when having (Monserrat *et al*., NHESS, 2006):

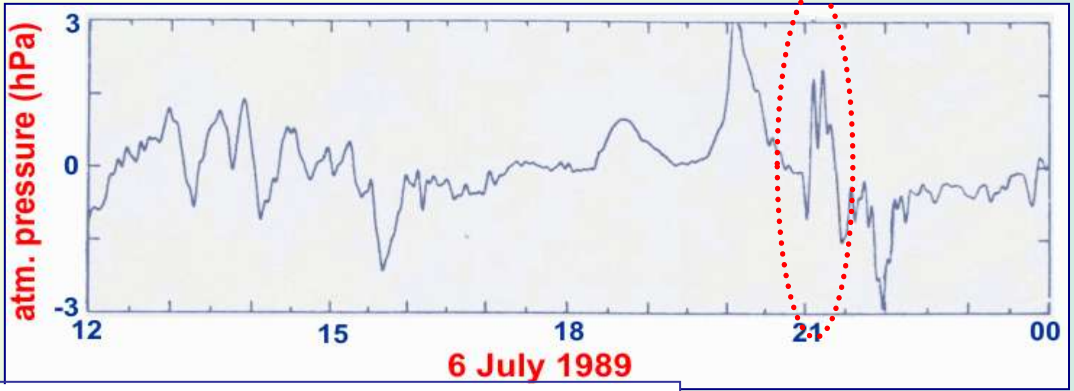
- *A harbour (bay, inlet or gulf) with definite resonant properties and high Q-factor.*
- *Strong small-scale atmospheric disturbance (a pressure jump or a train of internal atmospheric waves).*
- *Propagation of the atmospheric disturbance toward the entrance to the harbour.*
- *External resonance (Proudman, Greenspan or shelf resonance) between the atmospheric disturbance and ocean waves.*
- *Internal resonance between the dominant frequency of the arriving open-ocean waves and the fundamental harbour mode frequency.*

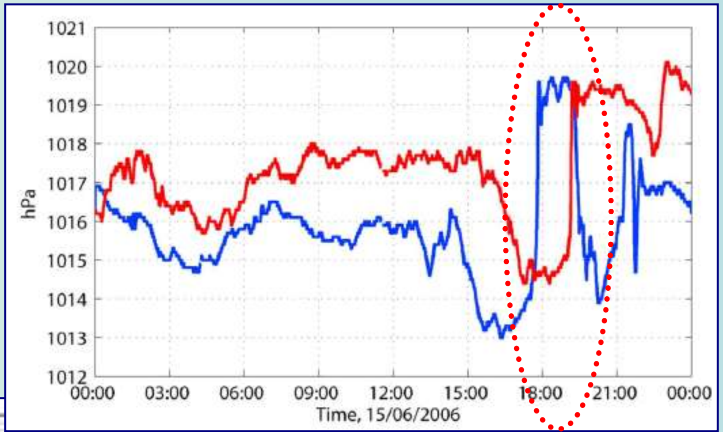
The source

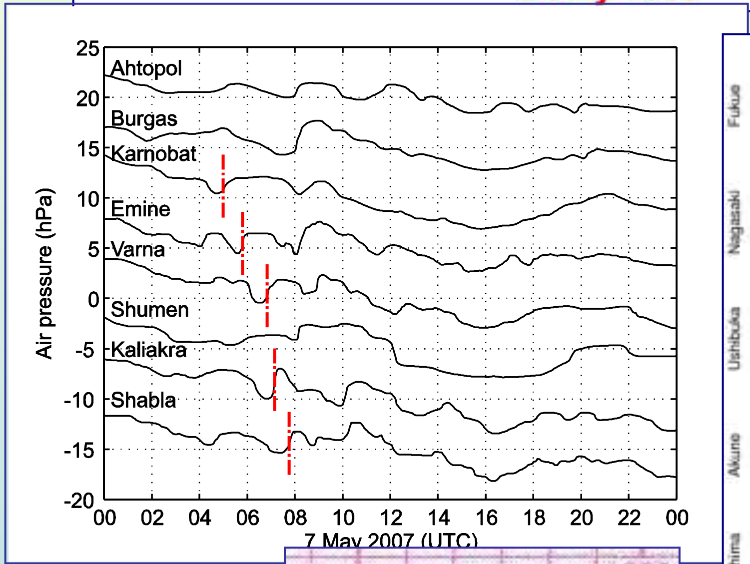

SEVERAL WAVELENGTHS
C
nondispersive atmospheric disturbance
U=C
C
wave-duct
wave-CISK
C
a cloud
P'

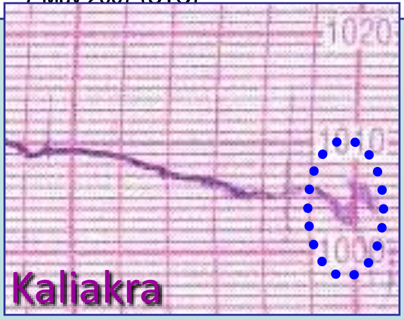
air pressure disturbance - examples

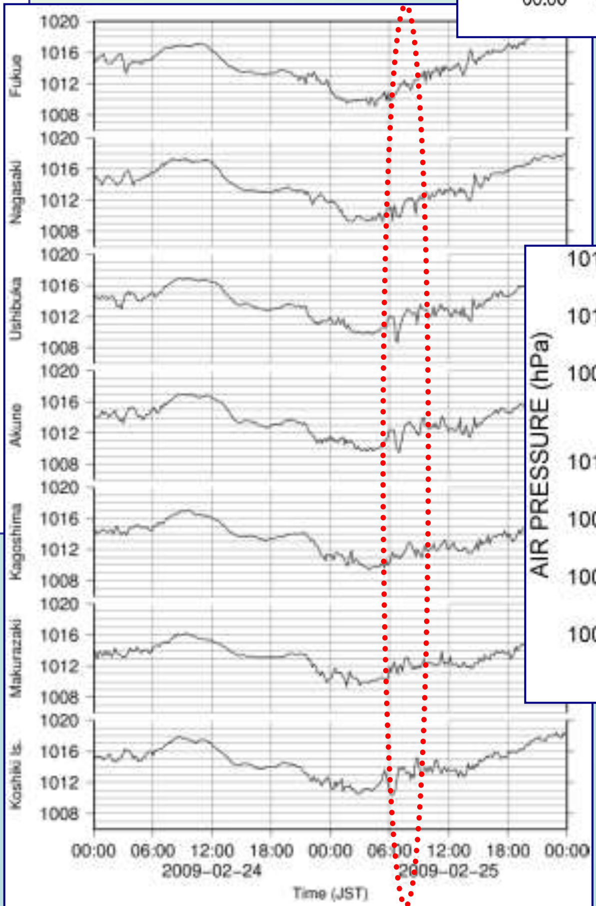
The source

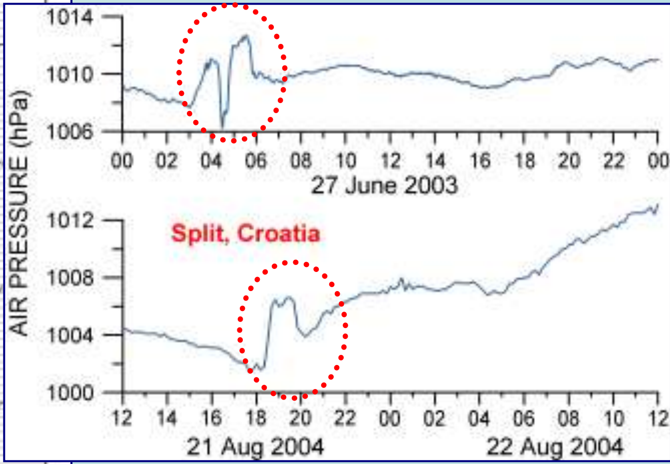








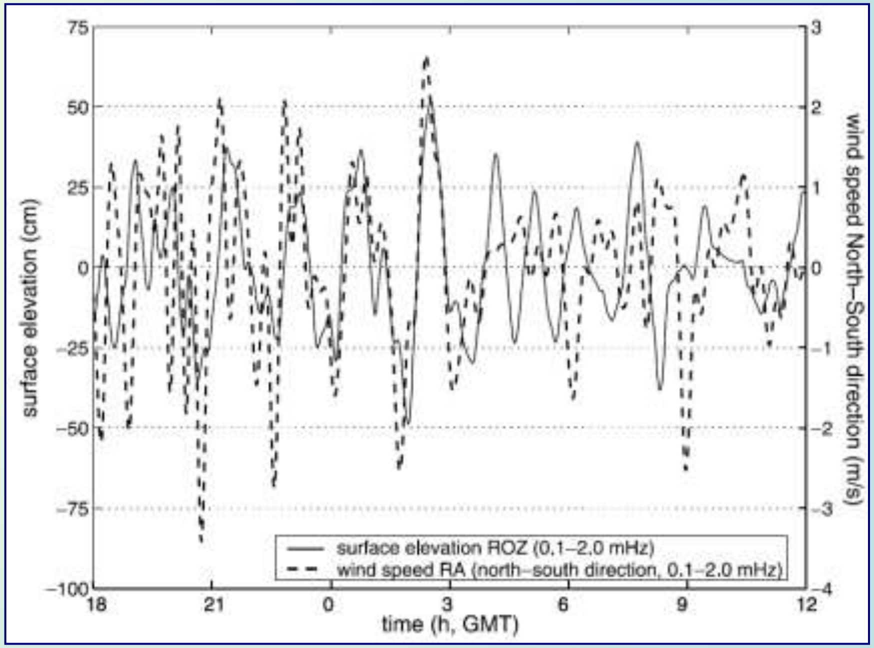




wind disturbance generation

Battjes and de Long, JGR-O, 2004:

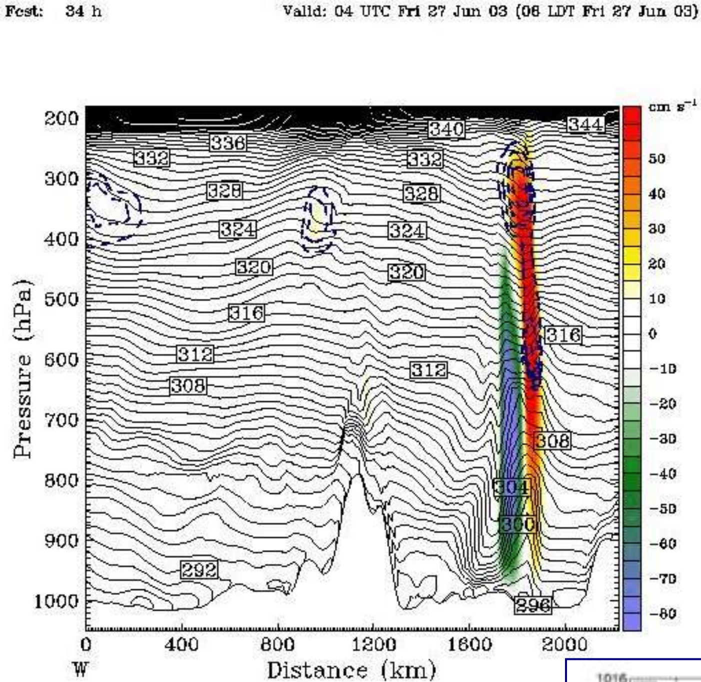
- port of Roterdam, North Sea
- cross-shore travelling wind disturbances

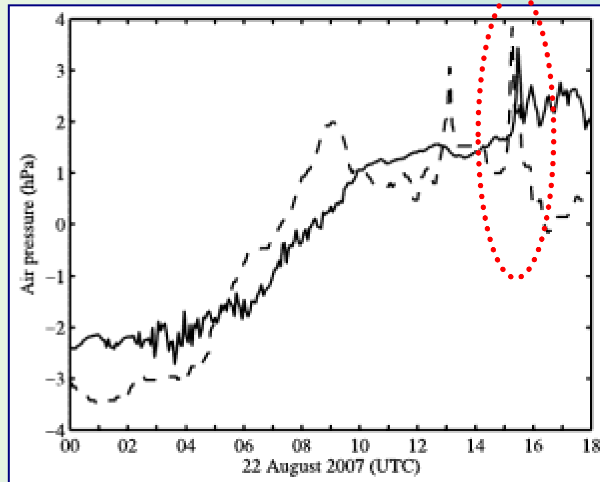


Wind gusts play a secondary role to explain the meteotsunami formation

- Vilibić et al., JGR-O, 2004
- Vilibić et al., JMS, 2005
- Renault et al., GRL, 2011

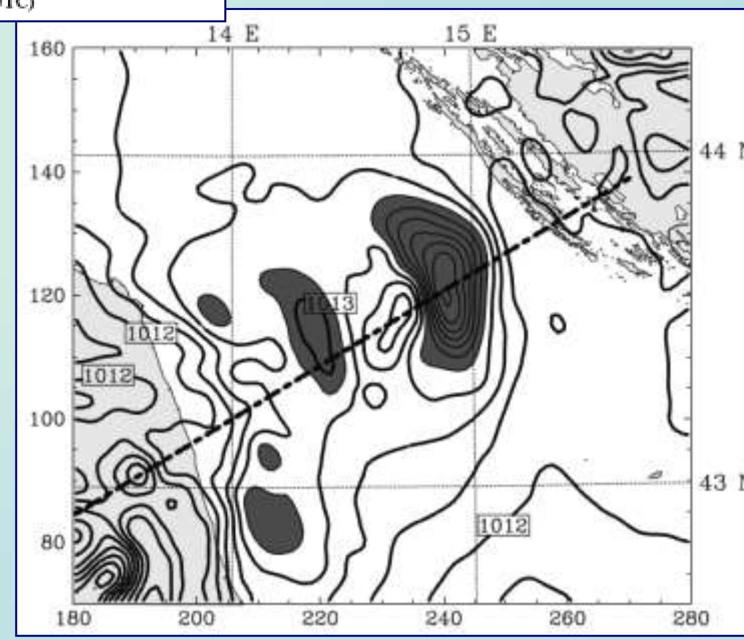
The source





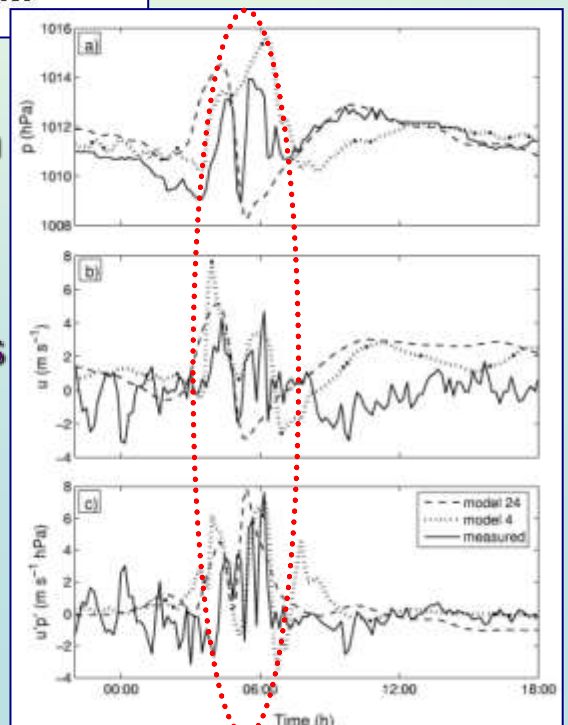
Šepić *et al.*, JGR-O, 2009:

- 22 August 2008, Adriatic
- WRF mesoscale model
- wave-duct, capped by convective instability
- generated over mountains
- width of a few tens of km
- not so good verification



Belušić *et al.*, JGR-A, 2007:

- 27 June 2007, Adriatic Sea
- MM5 mesoscale model
- wave-CISK within MCS
- no wave-duct present
- generated over mountains
- not so good verification



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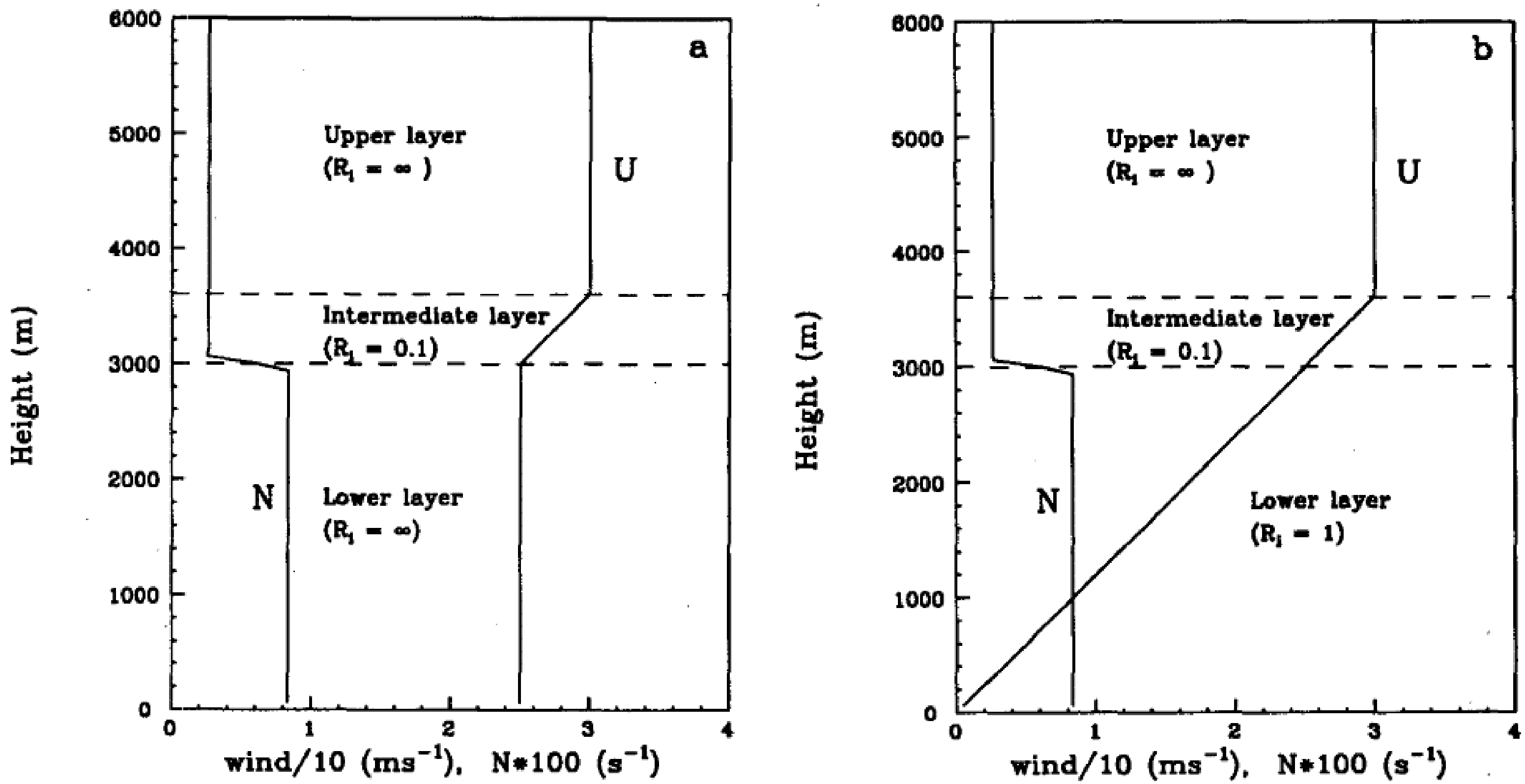
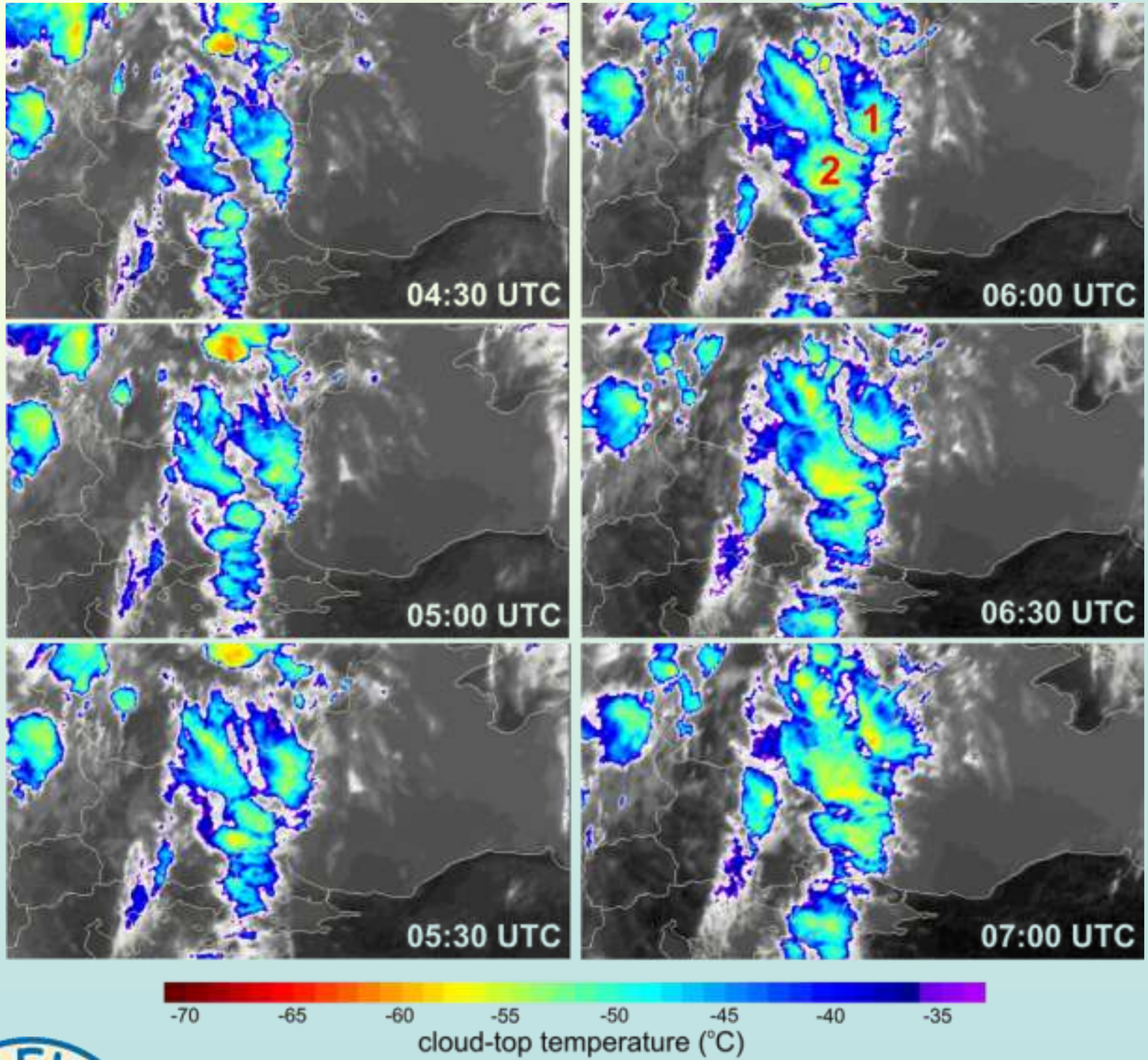


FIG. 1. Wind (U) and Brunt–Väisälä frequency (N) for the profiles used in section two, (a) with constant wind in the lower layer and (b) with constant wind shear in the lower layer. The name of the different layers and the value of the Richardson number in each layer are also indicated.

Monserrat and Thorpe, JAS, 1996:

- wave duct theory
- reflectance layer above stable layer
- wave speed equal to wind speed at reflectance layer
- wave speed dependable on the wind shear
- applied on the Balearic rissagas

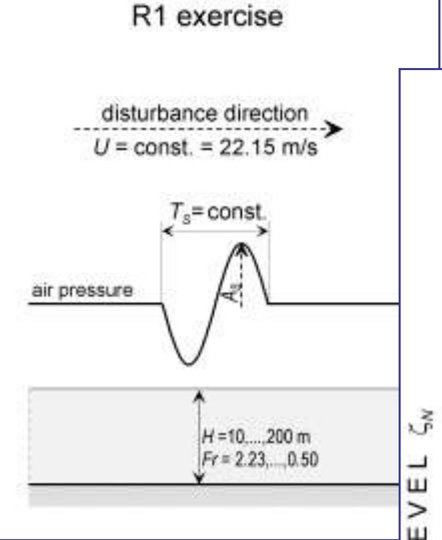
The source



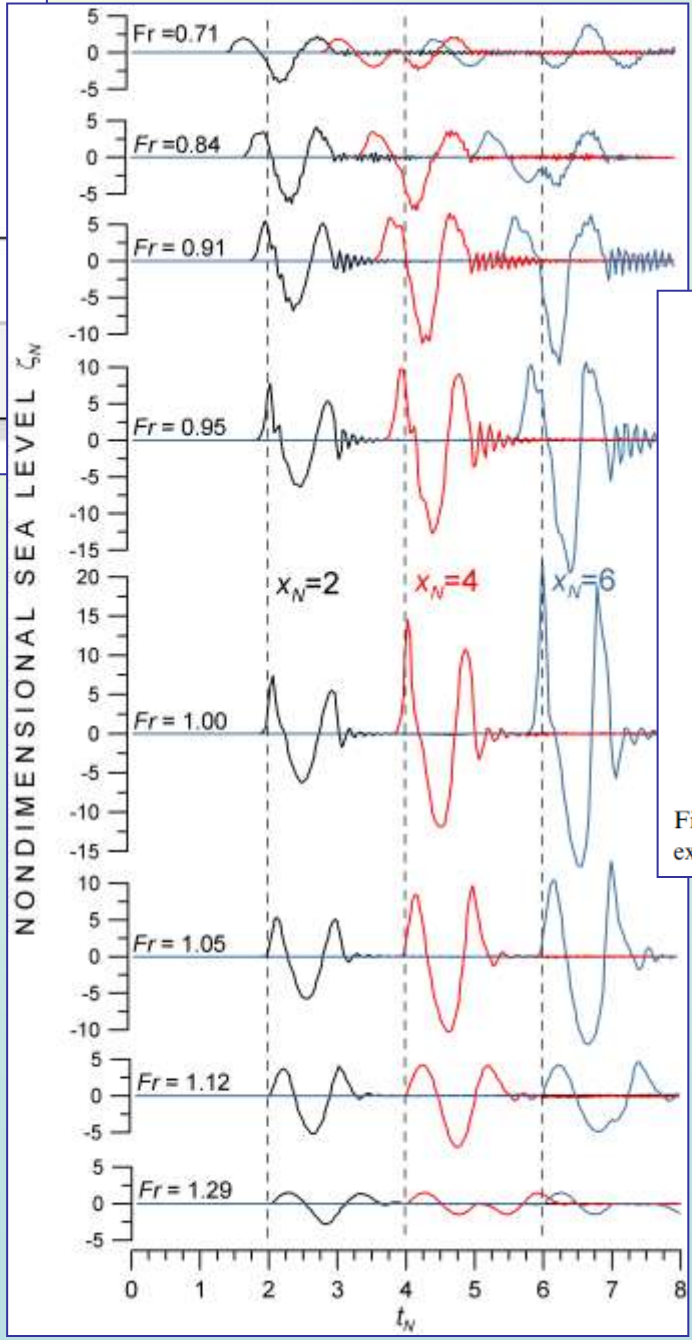
Vilibić *et al.*, JGR-O, 2010:

- 7 May 2007, Black Sea
- wave-duct, capped by a convective system
- width of a few tens of km

External resonance
Proudman resonance



$$Fr = \frac{U}{\sqrt{gH}}$$



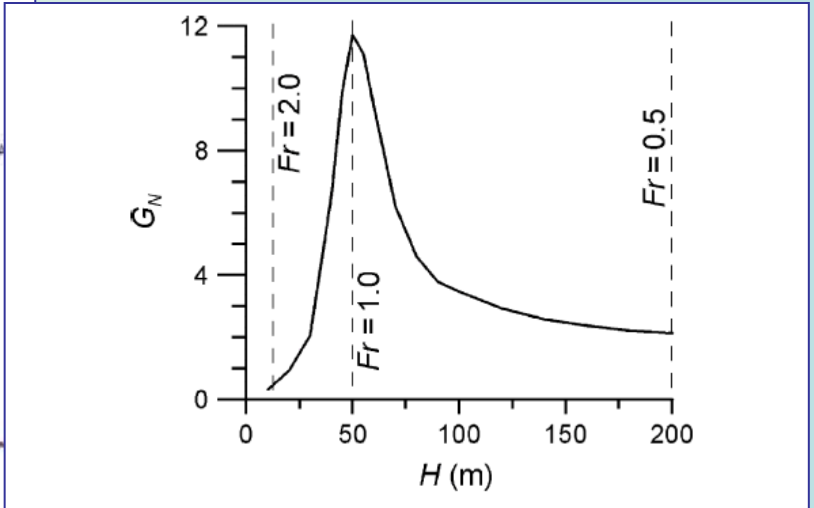


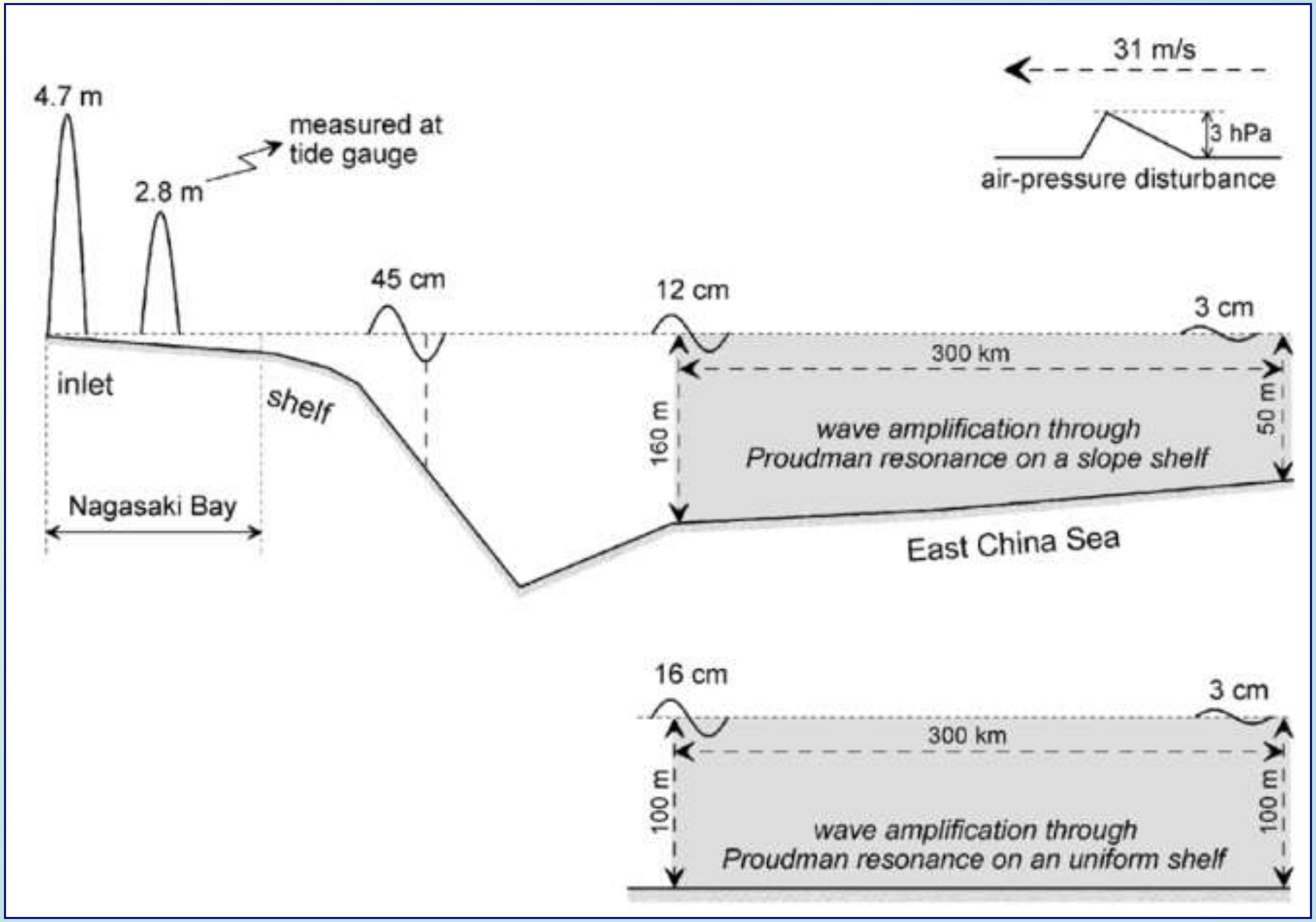
Fig. 5. Frequency-averaged gain G_N modelled for various H and Fr (R1 exercise, $T_S = 30$ min).

Vilibić, CSR, 2008:

- open ocean resonance quite sensitive to depth changes

External resonance

Proudman resonance

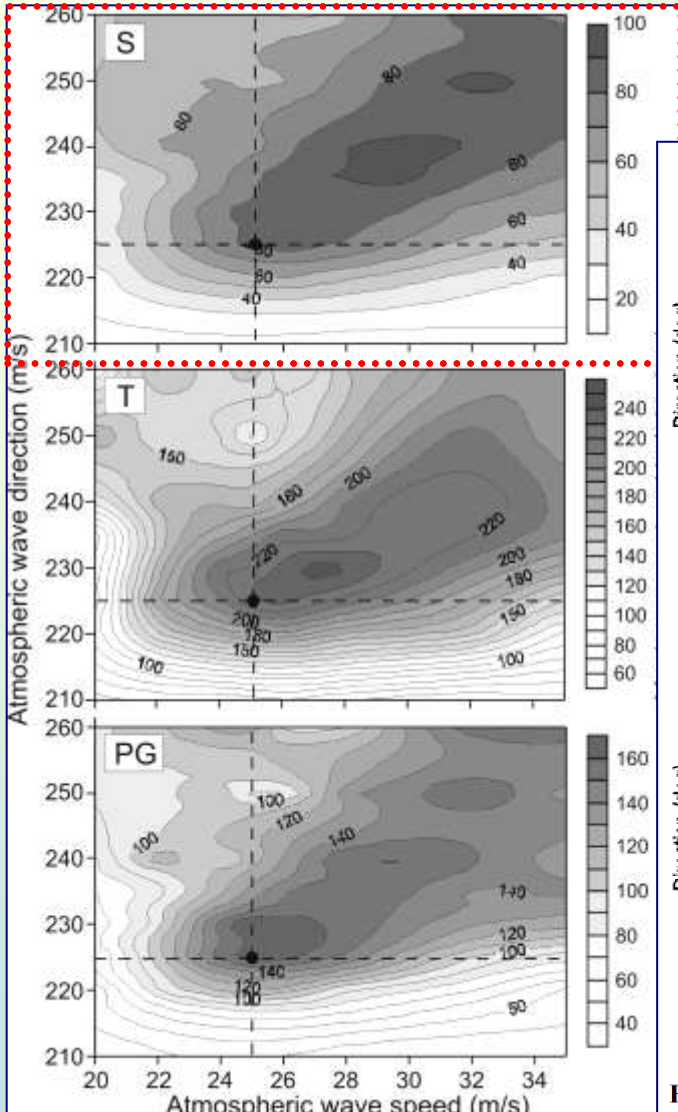


Vilibić, CSR, 2008:

- the presence of a slope is reducing the resonance efficiency

External resonance

Proudman resonance



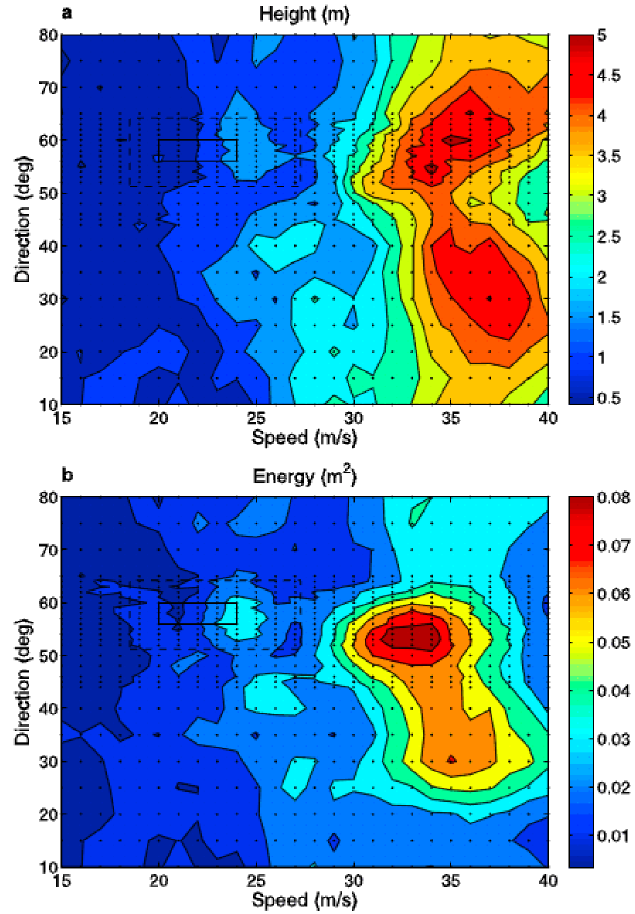


Figure 11. (a) The difference between the maximum and minimum sea level heights and (b) the integral of the sea level energy density spectrum obtained for the head of Vela Luka Bay by forcing the Adriatic model with the boxcar air pressure perturbation traveling at various speeds (c) and directions (γ). Each dot represents a run of the Adriatic model; the total number of runs is 754. The solid rectangle indicates the ranges of speeds and directions determined by *Orlić* [1980], and the dashed rectangle marks the ranges obtained in this paper by assuming that the timing error of barographs used in the Adriatic in 1978 was ±10 min.

Vilibić *et al.*, PAGEOPH, 2008

Orlić *et al.*, JGR-O, 2010:

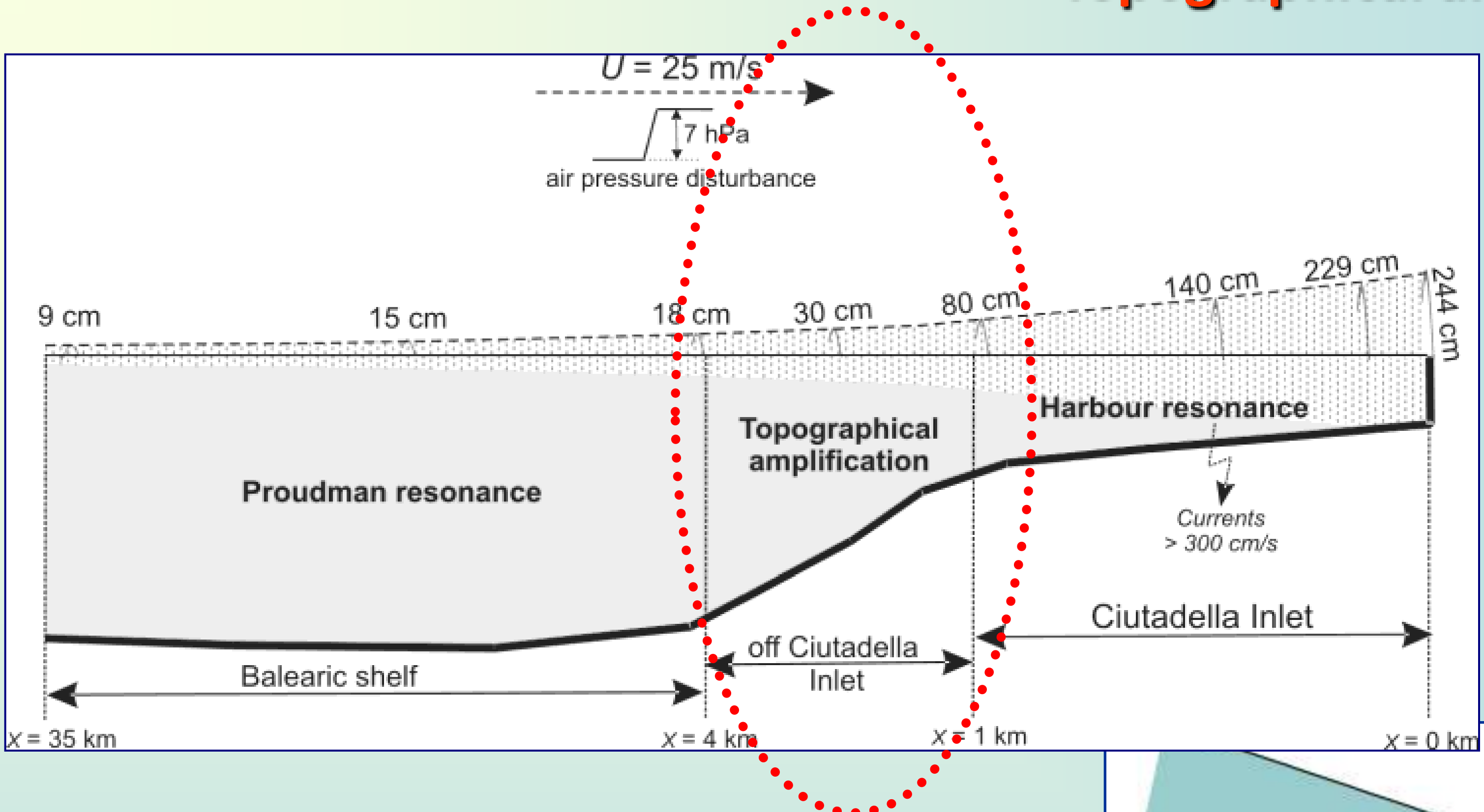
- external resonance at a particular area is favoured by a range of atmospheric disturbance speeds and directions

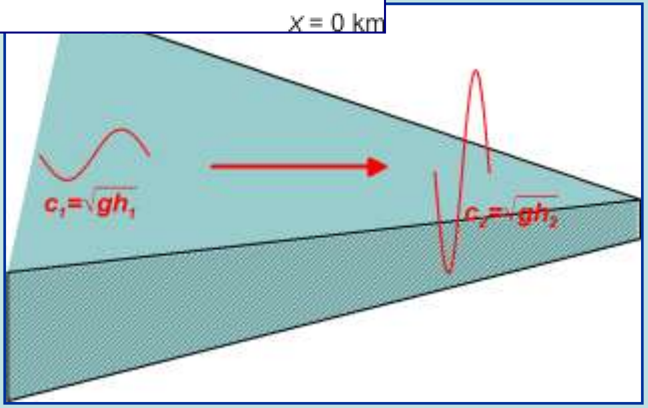
External resonance

Propagation of the atmospheric disturbance toward the entrance to the harbour. → ***not always true***

→ ***reflection?***

Topographical amplification

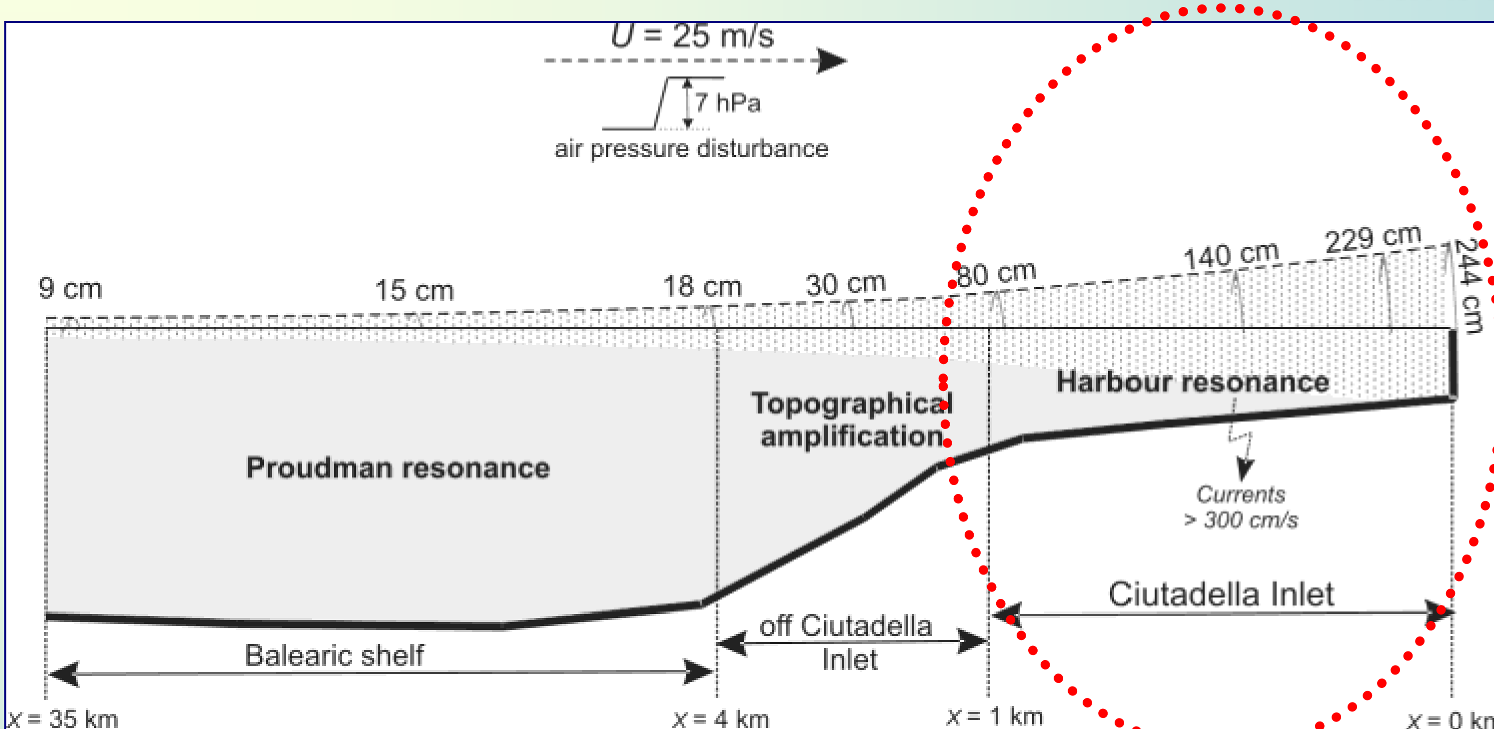




Vilibić *et al.*, PAGEOPH, 2008:

- topographical amplification is as for any tsunami waves

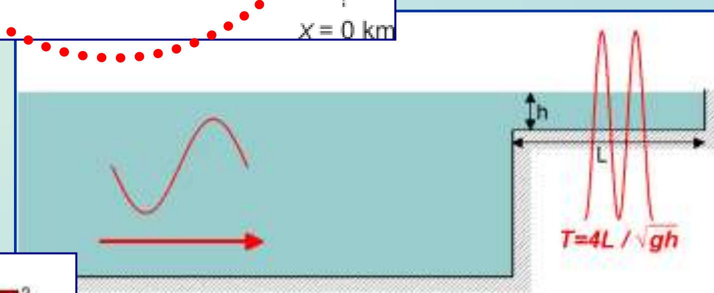
Harbour resonance

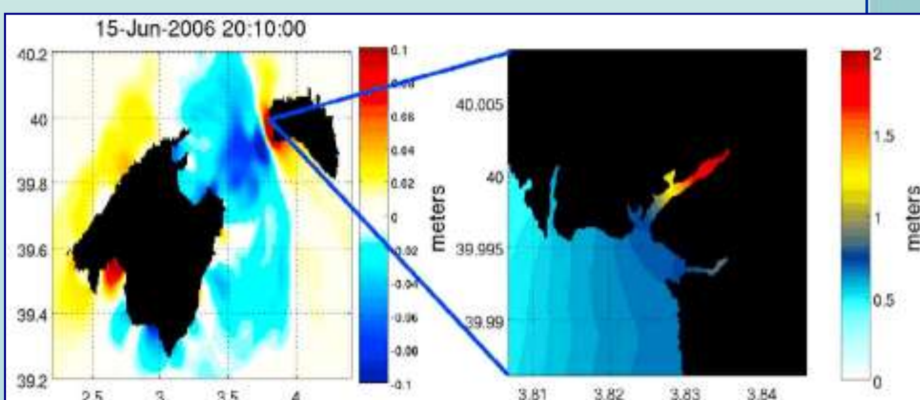


Vilibić *et al*., PAGEOPH, 2008

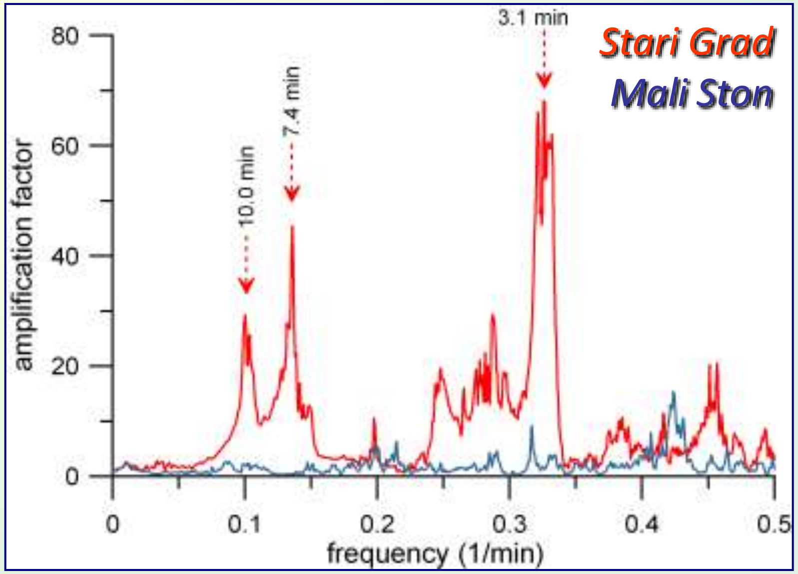
Renault et al, GRL, 2011

- harbour resonance is as for any tsunami waves





Harbour resonance



Vilibić and Šepić, PCE, 2009:

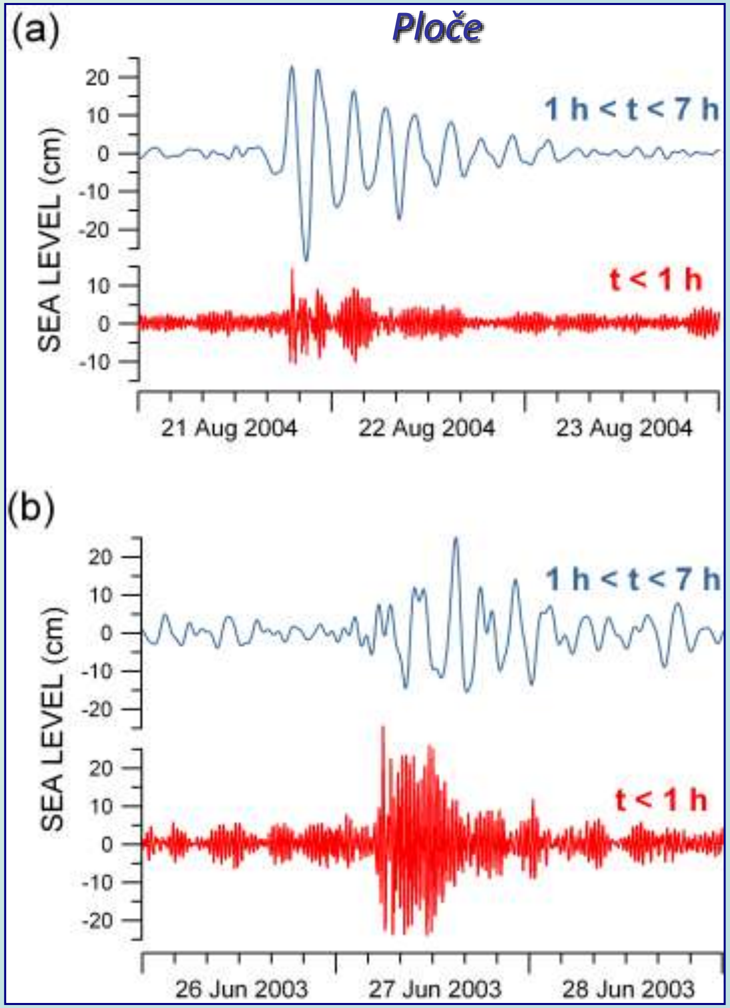
- amplification factor vary with frequency

$$H^2(f) = \frac{1}{(1 - f/f_0)^2 + Q^{-2}(f/f_0)^2}$$

$$Q^{-1} = \frac{dE/dt}{\omega E} = 2\beta$$

$$Q = \frac{L}{l}, \text{rectangular basin}$$

Rabinovich, 2009

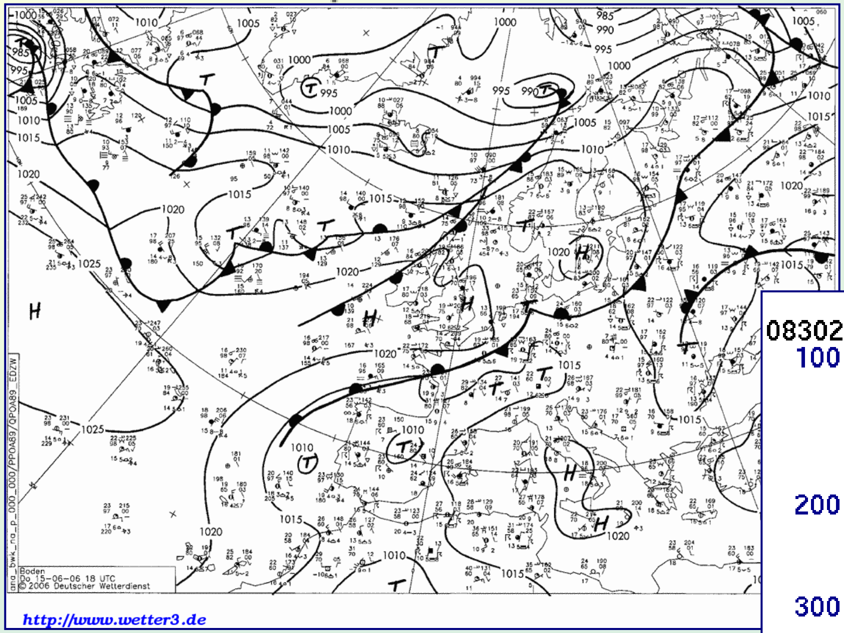


Vilibić, JMS, 2005:

- energy of incoming waves do matter

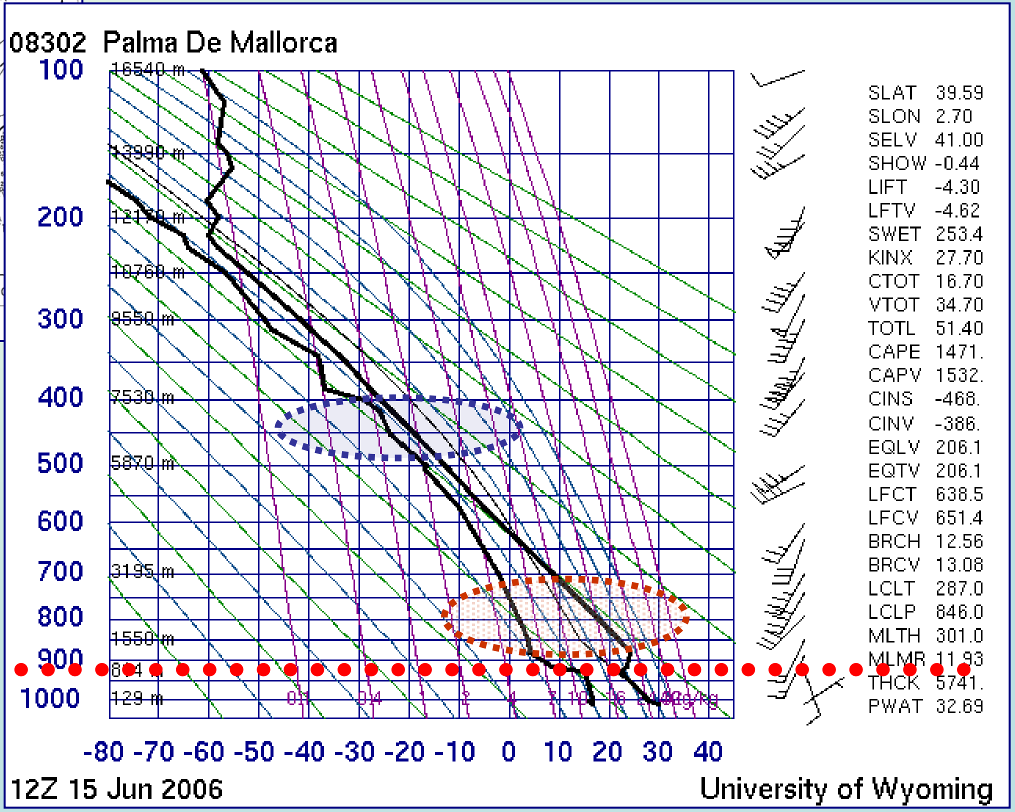
Synoptic characteristics

(1) low level Mediterranean air with weak surface depression



(2) warmer African air blowing around 850 hPa isobaric

(4) an instable layer between the African air and colder upper air



(3) an inversion layer separating (1) and (2)

rissaga warning system – Balearic Islands

Synoptic characteristics

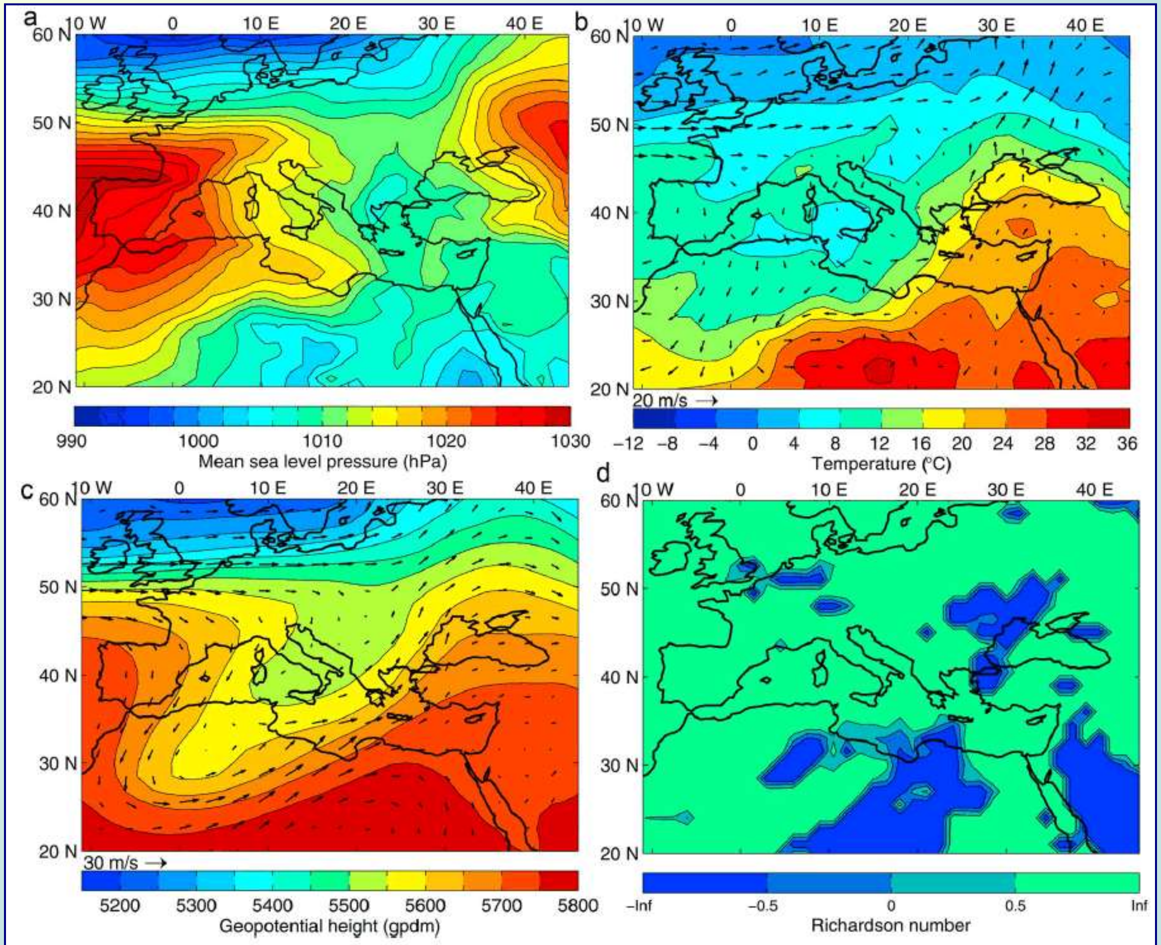
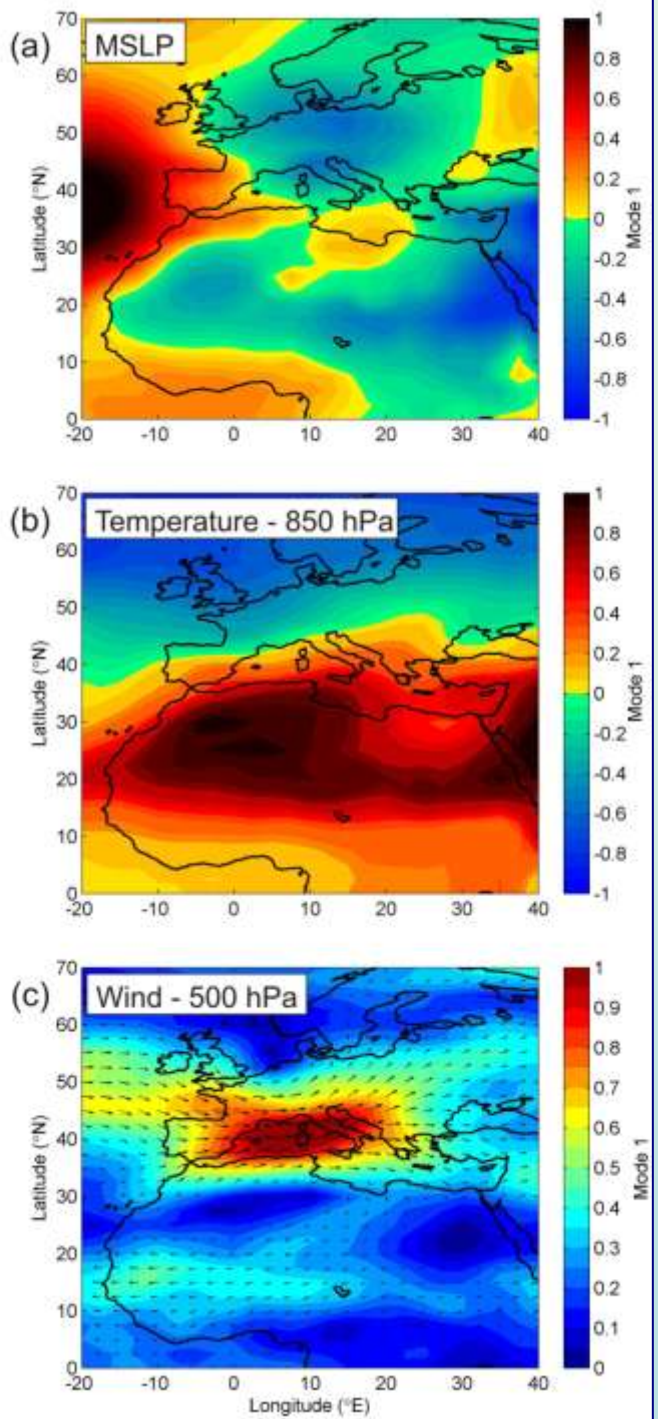


Figure 2. Synoptic charts as obtained from the ECMWF reanalysis fields of 7 May 2007 12:00 UTC: (a) surface air pressure, (b) temperature and winds at 850 hPa level, (c) geopotential height and winds at 500 hPa level, and (d) minimum Richardson number R_i at heights between 600 and 300 hPa.

Vilibić *et al*., JGR-O, 2010:

- synoptic setting for the Black Sea meteotsunami similar to the Adriatic and the Balearic meteotsunami settings

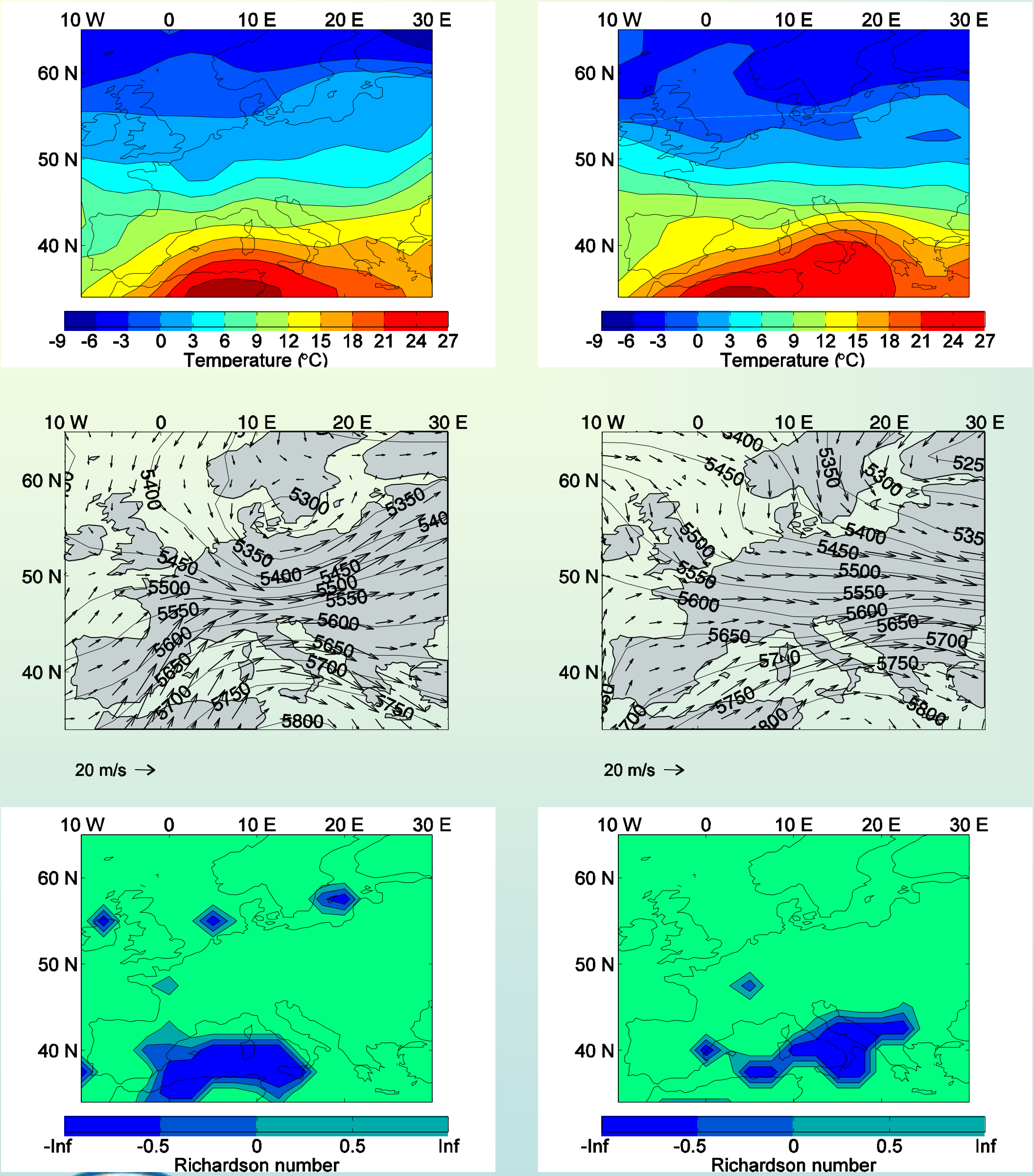
Synoptic characteristics



Šepić and Vilibić, JGR-O, submitted:

- first EOF of 16 strongest meteotsunamis measured at Rovinj (northern Adriatic)
- 99% SLP variability
- 89% 850-hPa T variability
- 45% 500-hPa wind variability

Synoptic characteristics



25 September 1990 (12 UTC) 26 September 1990 (12 UTC)

Šepić et al., PCE, 2009

- teleconnections between the Balearic and the Adriatic meteotsunamis due to synoptic settings
- out of the 32 “rissaga” events, 16 coincided with high-frequency sea level oscillations in Dubrovnik
- oscillations in Dubrovnik were more likely to happen if oscillations in Ciutadella were moderate or strong

Operational possibilities

- *Monitoring synoptic conditions*
- *Monitoring ground parameters (air pressure)*
- *Monitoring ocean parameters*
- *Real-time satellite observations*
- *Real-time meteo and ocean numerical models*

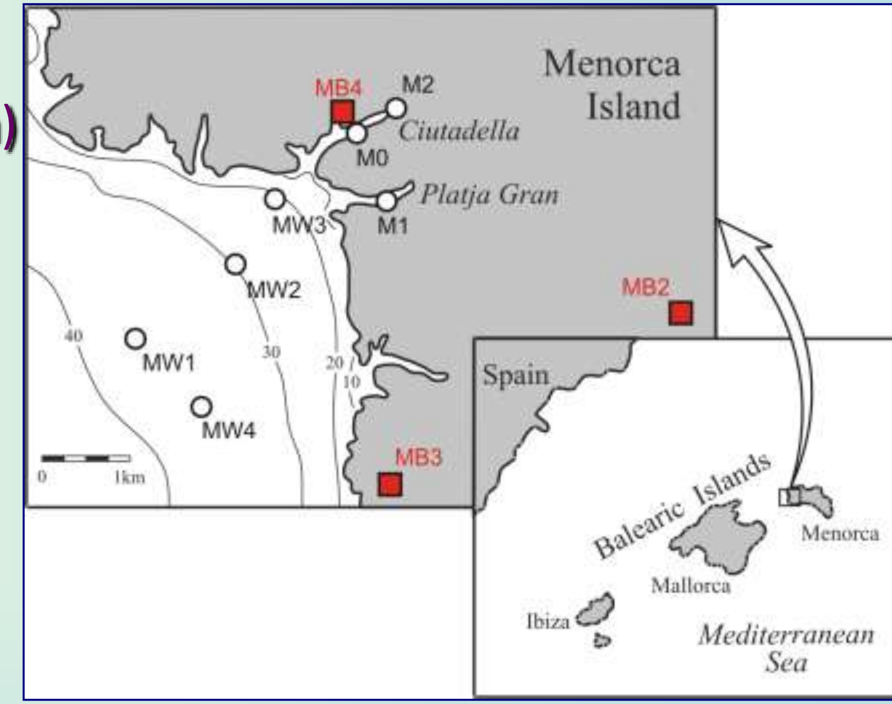
Monitoring ground parameters

Operational possibilities

- Resolution max 1 min
- Real-time (latency max a few minutes)
- High-accuracy sensors (max 0.1 hPa or 1 mm)

Microbarographs

Coastal buoys



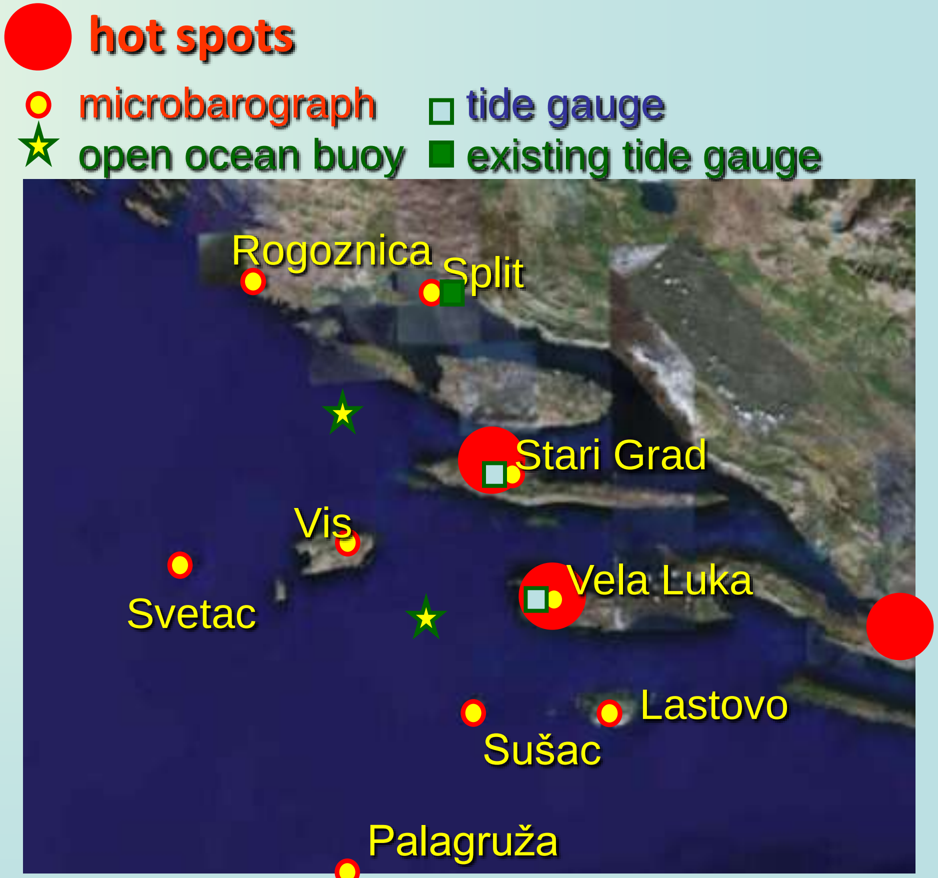
At least three triangles stations for determination of atmospheric disturbance speed, direction and dispersiveness

(but located ahead of affected area)

Monitoring ground parameters

Operational possibilities

Pilot network of microbarographs (middle Adriatic Sea)

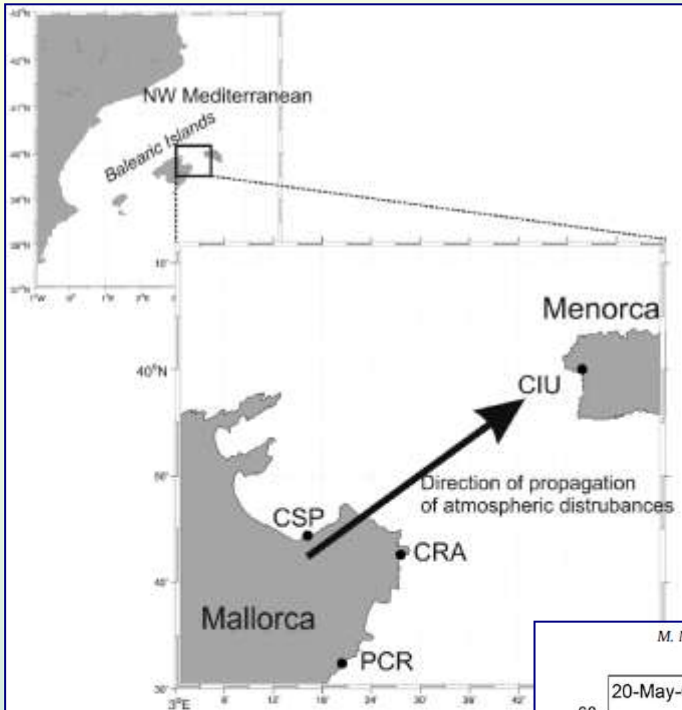


A proposal for early warning network (middle Adriatic Sea)

Such a network will allow for detection of potentially dangerous atmospheric disturbances 30-120 min prior to the occurrence of a meteotsunami

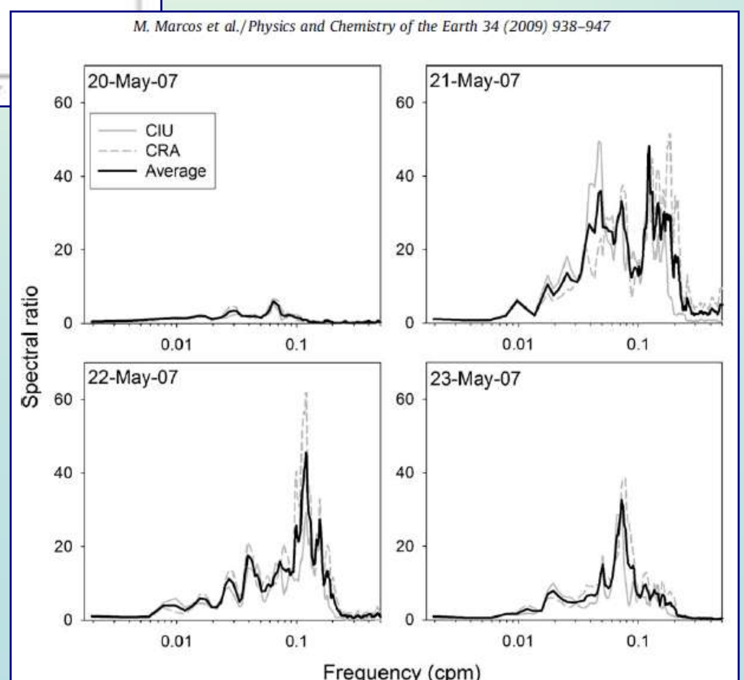
Monitoring ocean parameters

Operational possibilities



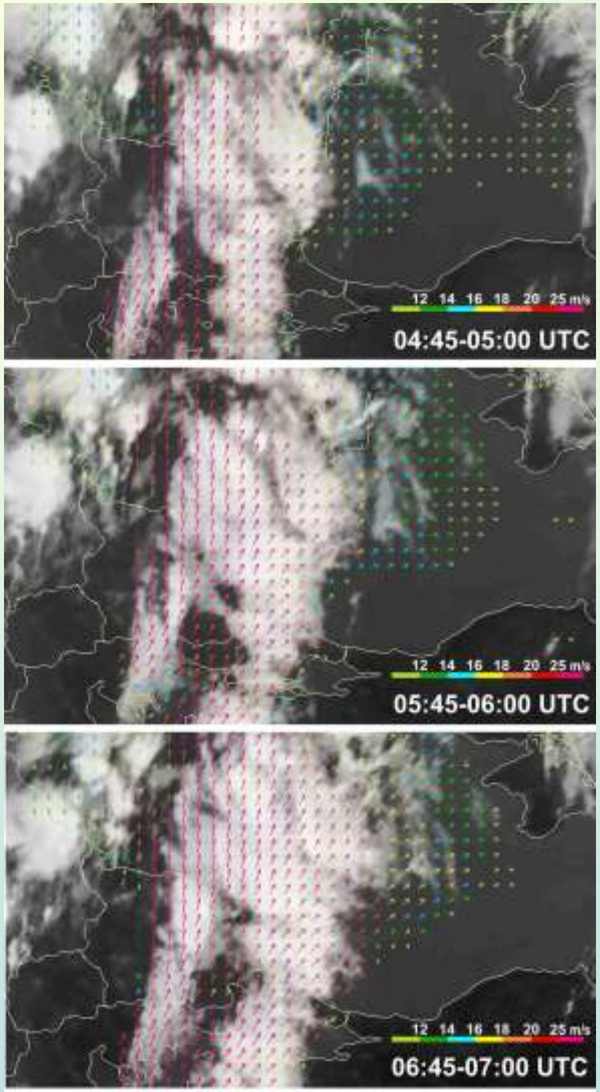
It could be possible to use sea level oscillations observed at CRA to predict incoming rissaga events in Ciutadella Harbour. These predictions could form part of a rissaga warning system designed to mitigate the damages inside the harbour. Similar approach probably could be used for some other regions of the Mediterranean where meteotsunamis occur, in particular for the eastern Adriatic: certain 'beacon' sites can play the role of predictors for ports and harbours with probable destructive seiches.

Marcos et al., PCE, 2009



Real-time remote observations

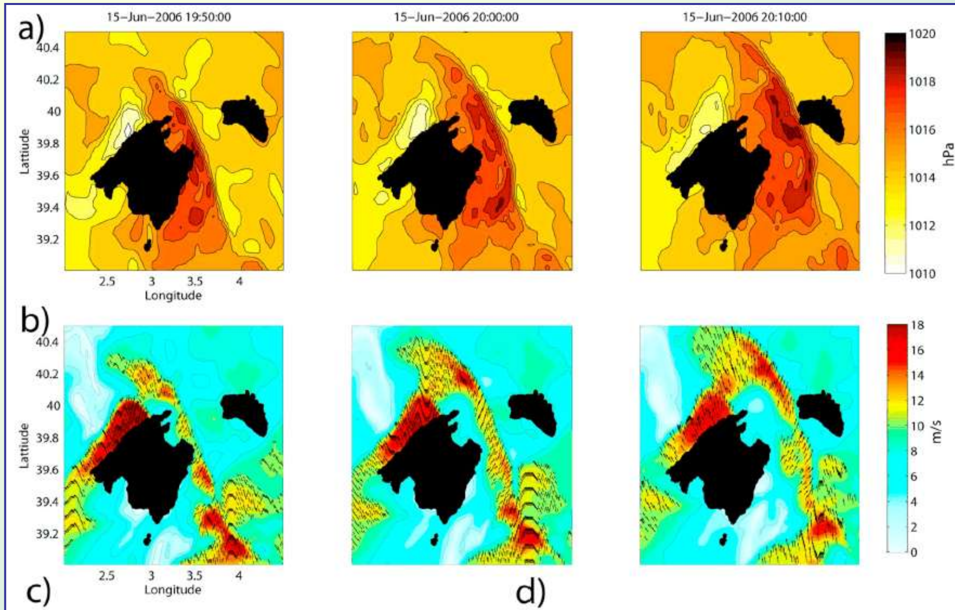
Operational possibilities

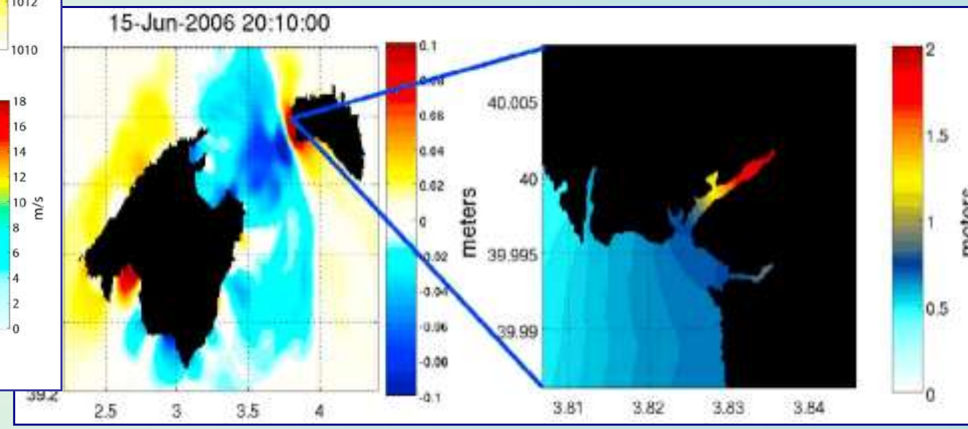


Estimation of cloud-top speed, and the connection to the base wind velocity

What about meteo radar network?

Real-time meteo and ocean numerical models **Operational possibilities**





Overall, the approach we considered here shows that under certain atmospheric conditions meteotsunamis associated with travelling atmospheric waves and/or convective systems can be forecasted. It is important to note that the use of standard meteorological forecast output at 3-hour intervals would not generate the meteotsunami in the ocean model. The pressure oscillation must be resolved to about 2 minutes in order to capture the sudden pressure change of order 0.3 hPa/min that appears to be required for sizeable Proudman resonance.

Renault et al., GRL, 2011

Instead of conclusions …

- *There is a substantial progress on meteotsunami research*
- *Operational meteotsunami systems are at the beginning of its development*