Physical Dynamics of the Coastal Zone in the Mediterranean on Annual to Decadal Scales

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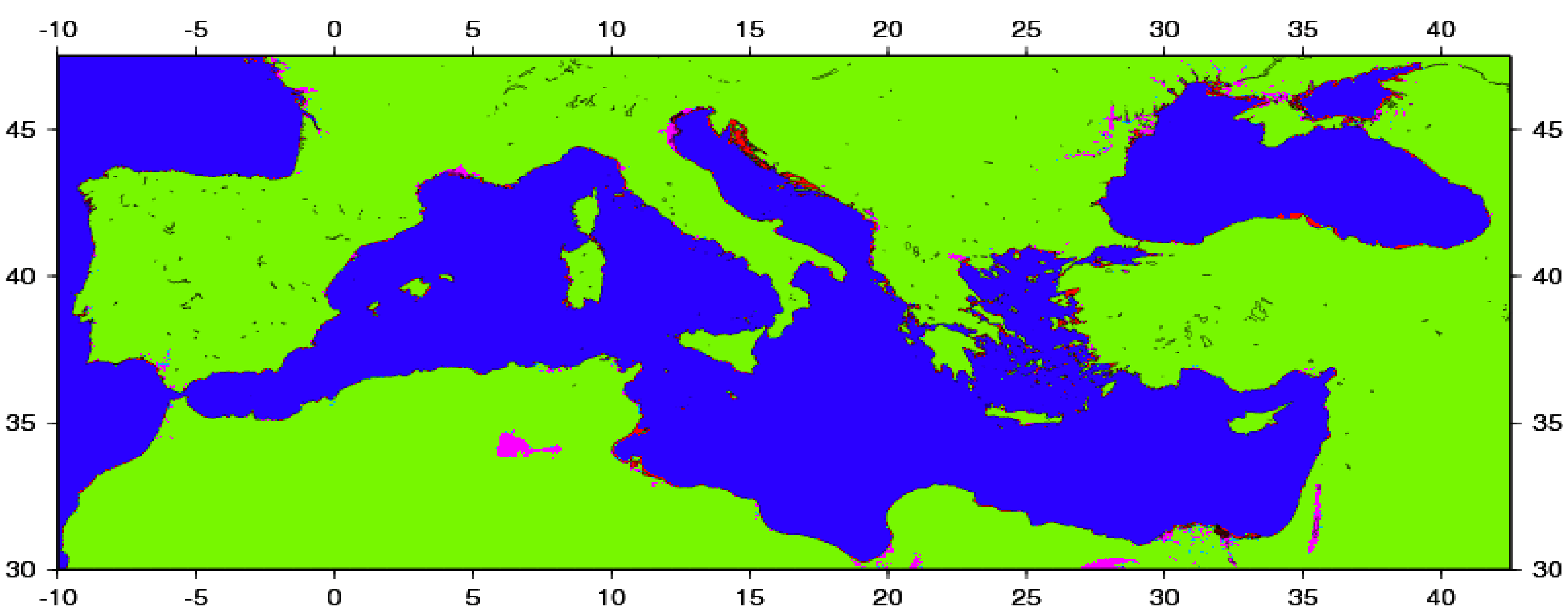
Statewide • Worldwide

Physical Dynamics of the Coastal Zone in the Mediterranean on Annual to Decadal Scales

- Local Sea Level (LSL): physical impact parameter for coastal inundation
- Temporal and spatial variability of LSL
- Forcing Factors
- Sea Level Hazards in the Mediterranean
- The Sea Level Hazards Observing System: Status and Challenges
- Sea Level Trends: Uncertainties, Predictions, Scenarios

Local Sea Level (LSL)

- LSL definition: vertical distance between sea surface and land surface
- LSL depends on many processes on a wide range of spatial and temporal scales
- For a given topography, LSL determines inundation



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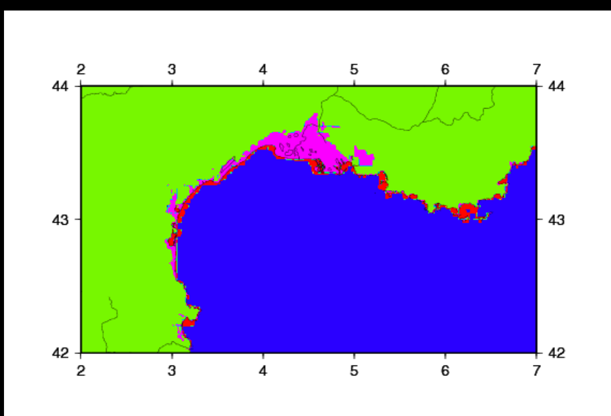
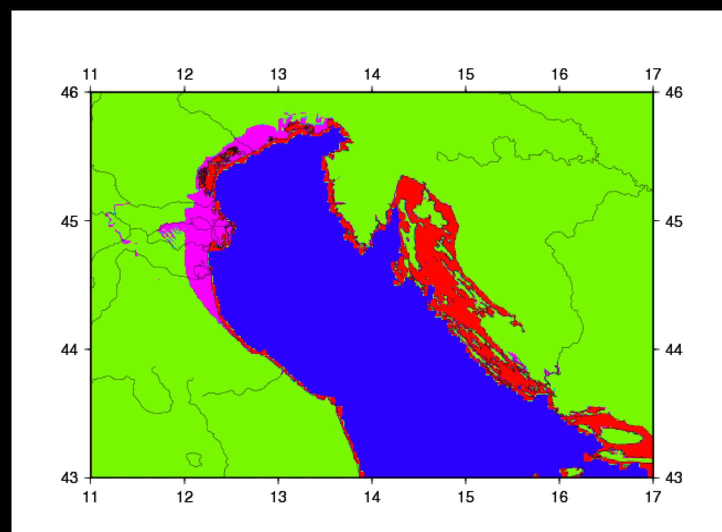
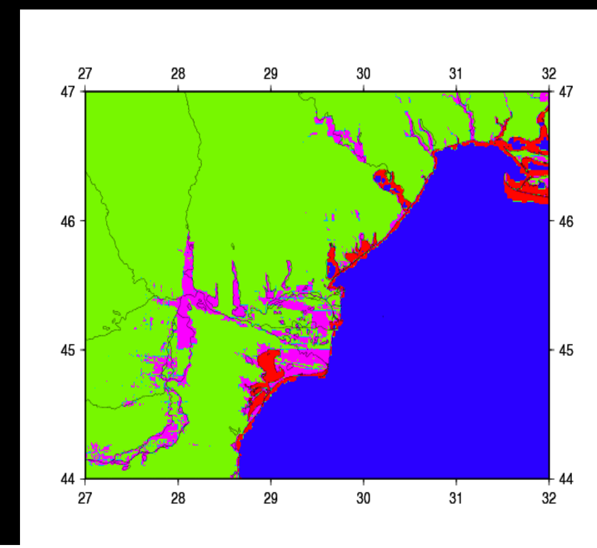
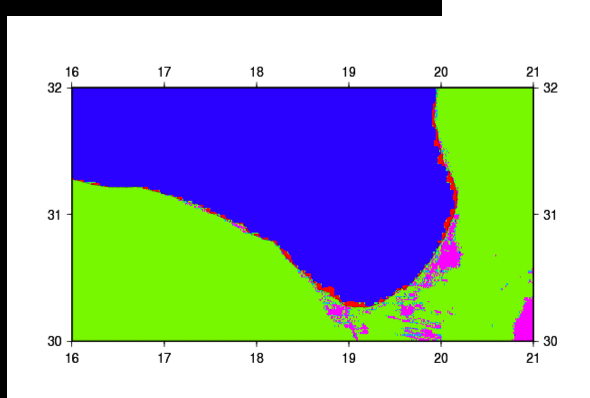
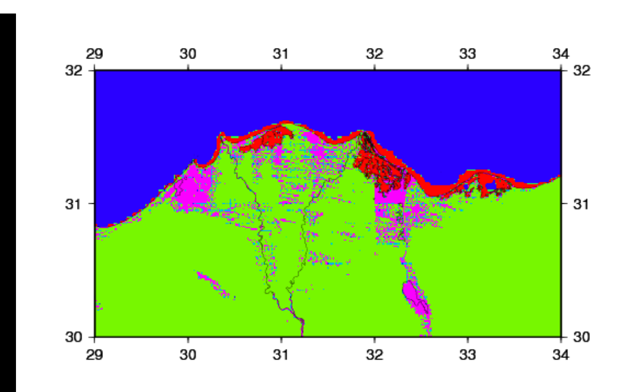










Local Sea Level (LSL)

Local Sea Level (LSL):

Sea surface

Sea floor

$$h(\phi,\theta,t) = \begin{cases} r_1(\phi,\theta,t) - r_0(\phi,\theta,t) & : \text{ ocean} \\ 0 & : \text{ land} \end{cases},$$

r_0 and r_1: geocentric positions of the sea floor and sea surface, respectiv

ϕ, θ: geographical longitude and latitude, respectively.

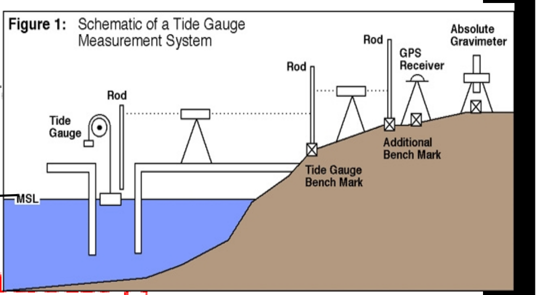
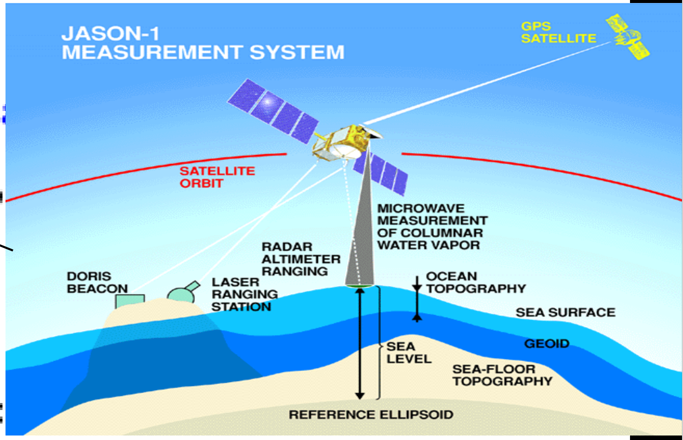


Figure 1: Schematic of a Tide Gauge Measurement System

– **LSL is an absolute quantity (i.e. reference frame indepen**

– **Sea Surface Height (SSH) is a relative quantity.**



Global Ocean Volume (GOV):

$$V_O = \int_O \mathrm{d}V = \int_0^{2\pi}\int_0^{\theta}\left(\int_{r_0(\theta,\phi)}^{r_1(\theta,\phi)} r^2 dr\right)\sin\theta \mathrm{d}\theta \mathrm{d}\phi$$

Global Ocean M

$$M_O = \int_O \rho$$

Water Cycle Mass Balance:

$$0 = \sum_{i=1}^{n} \frac{\mathrm{d}M_i}{\mathrm{d}t},$$

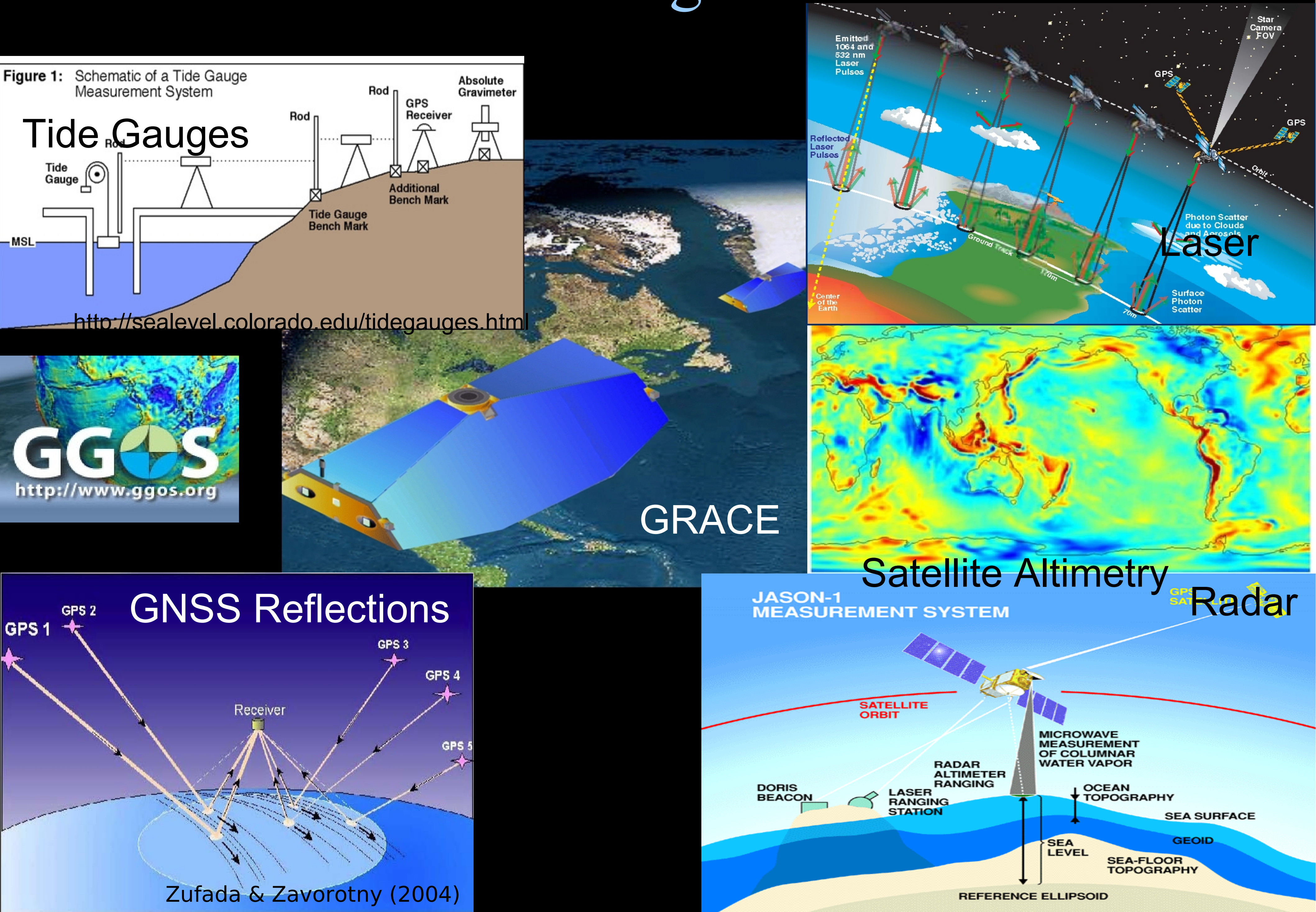
M_i: mass of the water in reservoir i,

n: number of separate reservoirs.

Volume changes:

Volume change = steric change+mass change

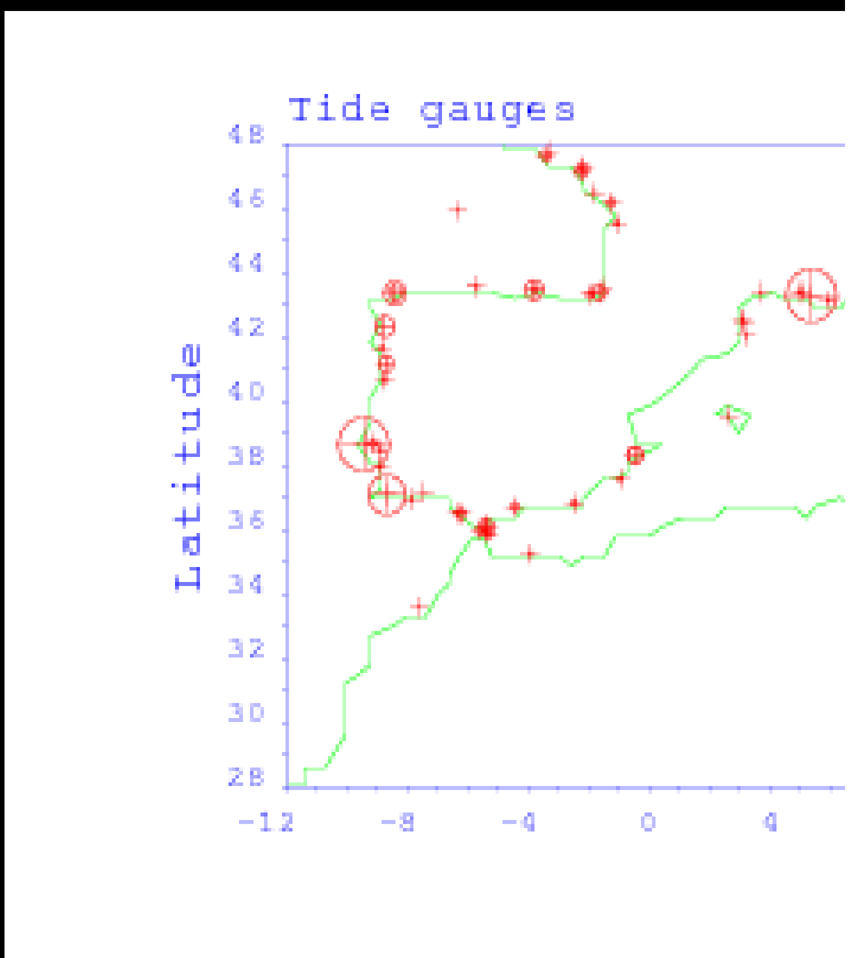
Geodetic Monitoring of LSL and SSH

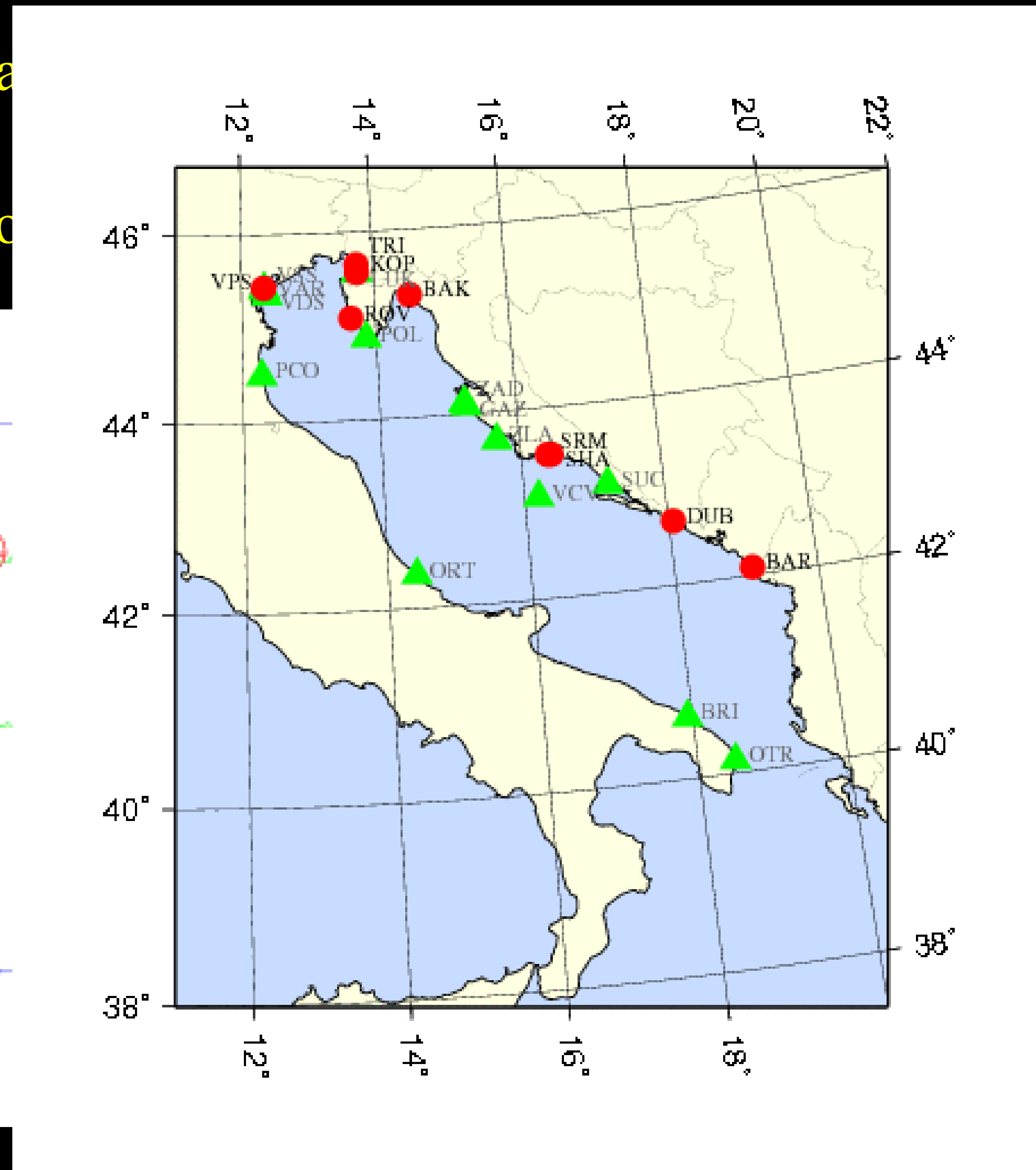


Spatial and Temporal Variability of LSL

Available tide gauge data:

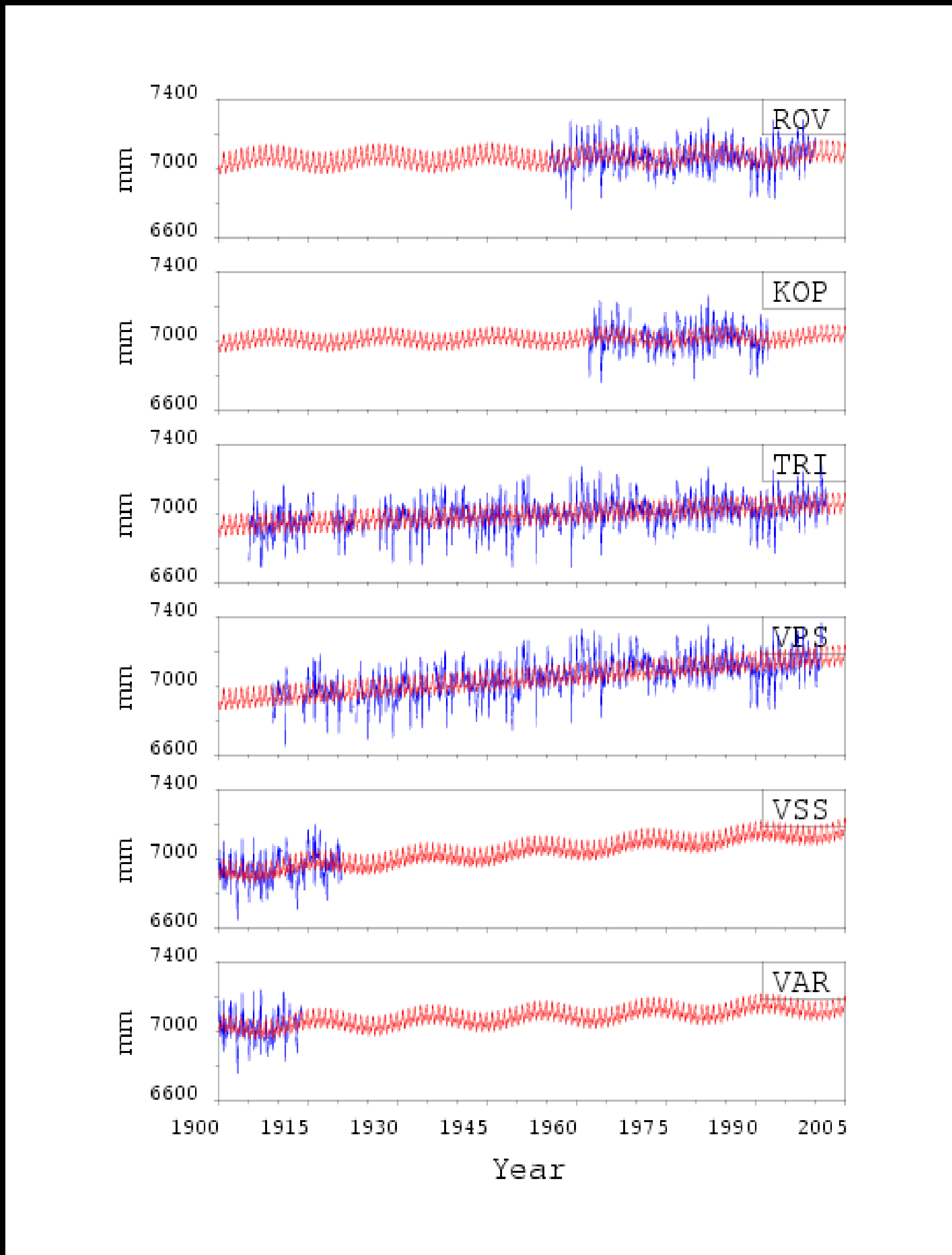
- Permanent Service for Mea
  monthly mean sea levels;
- Length of time series in mo

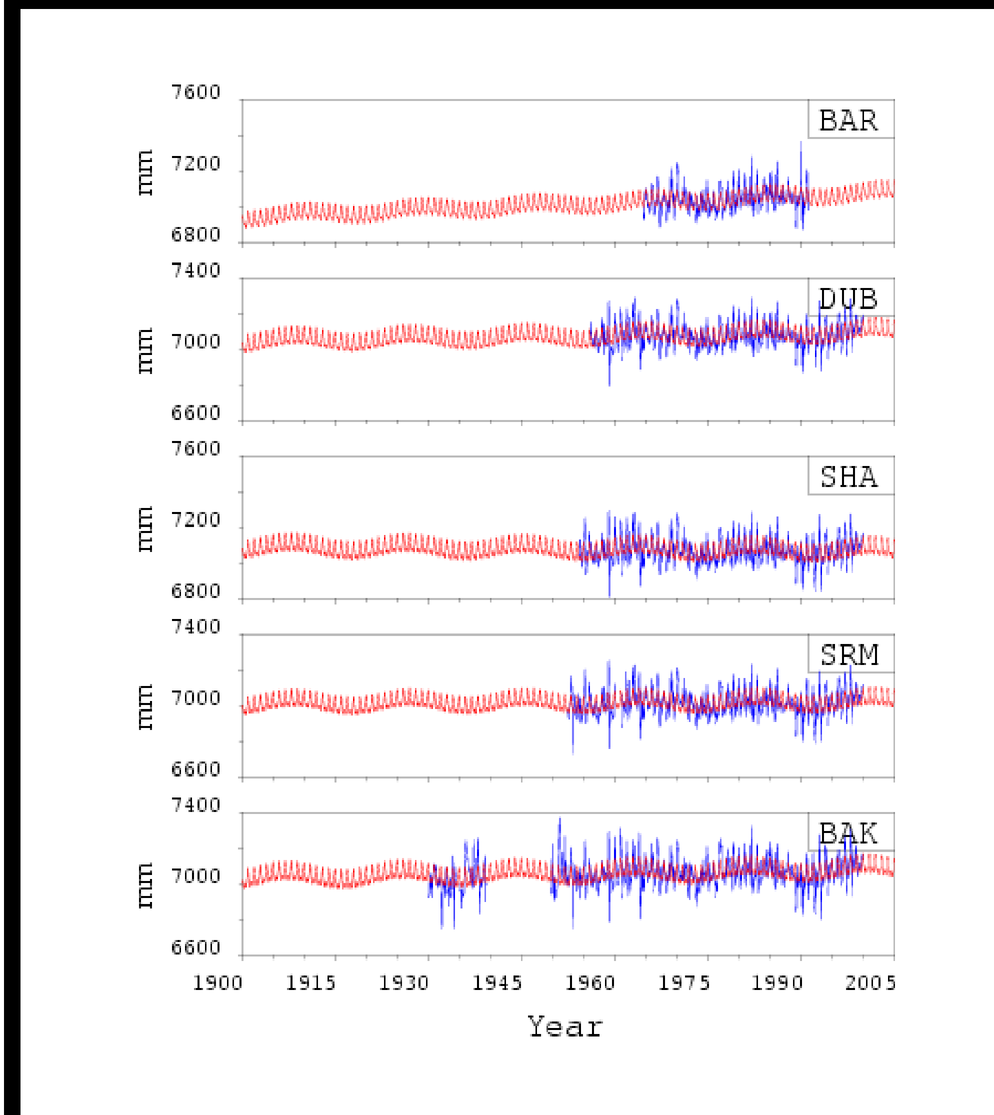




Spatial and Temporal Variability of LSL

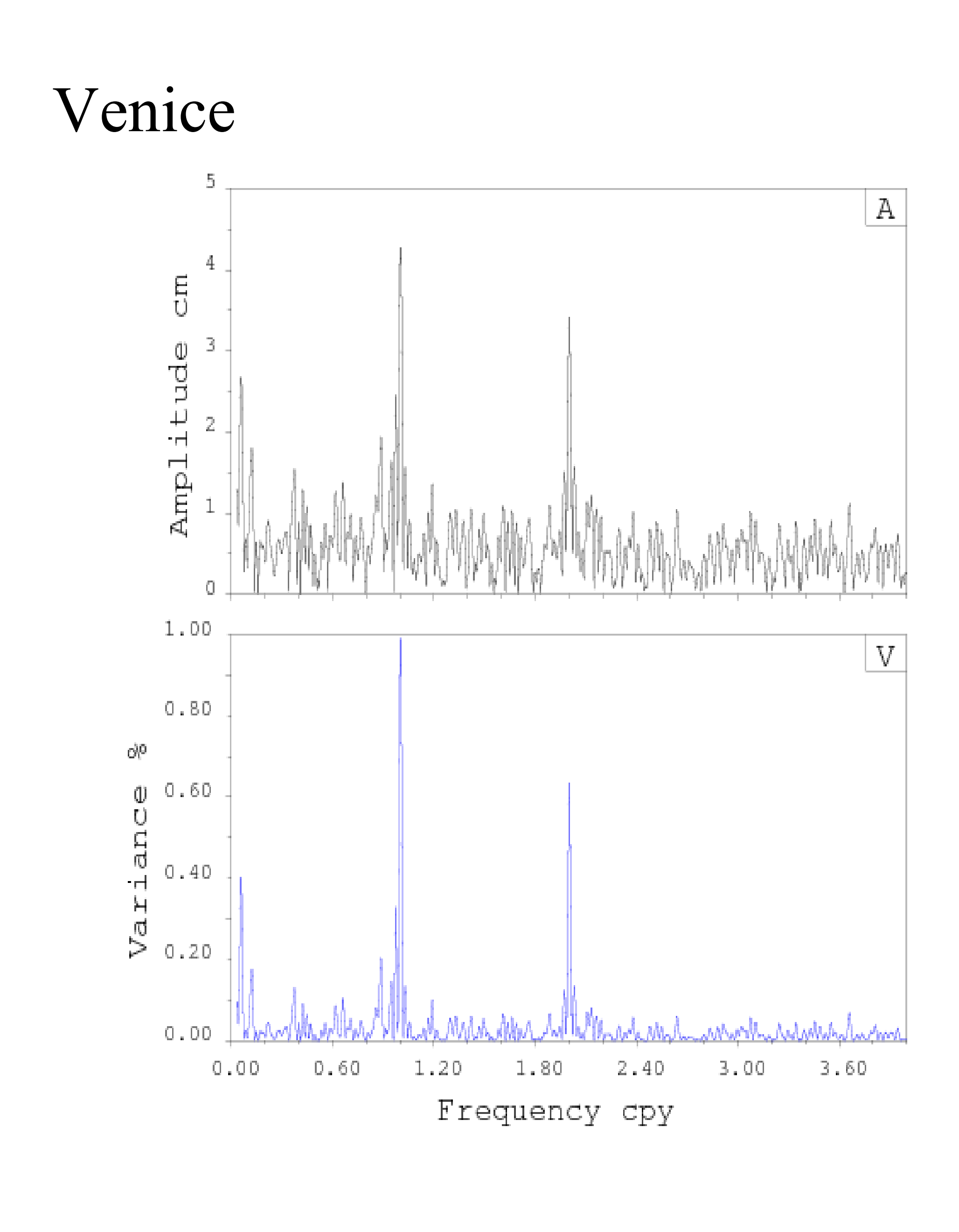
Monthly mean sea level time series; examples from the Adriatic

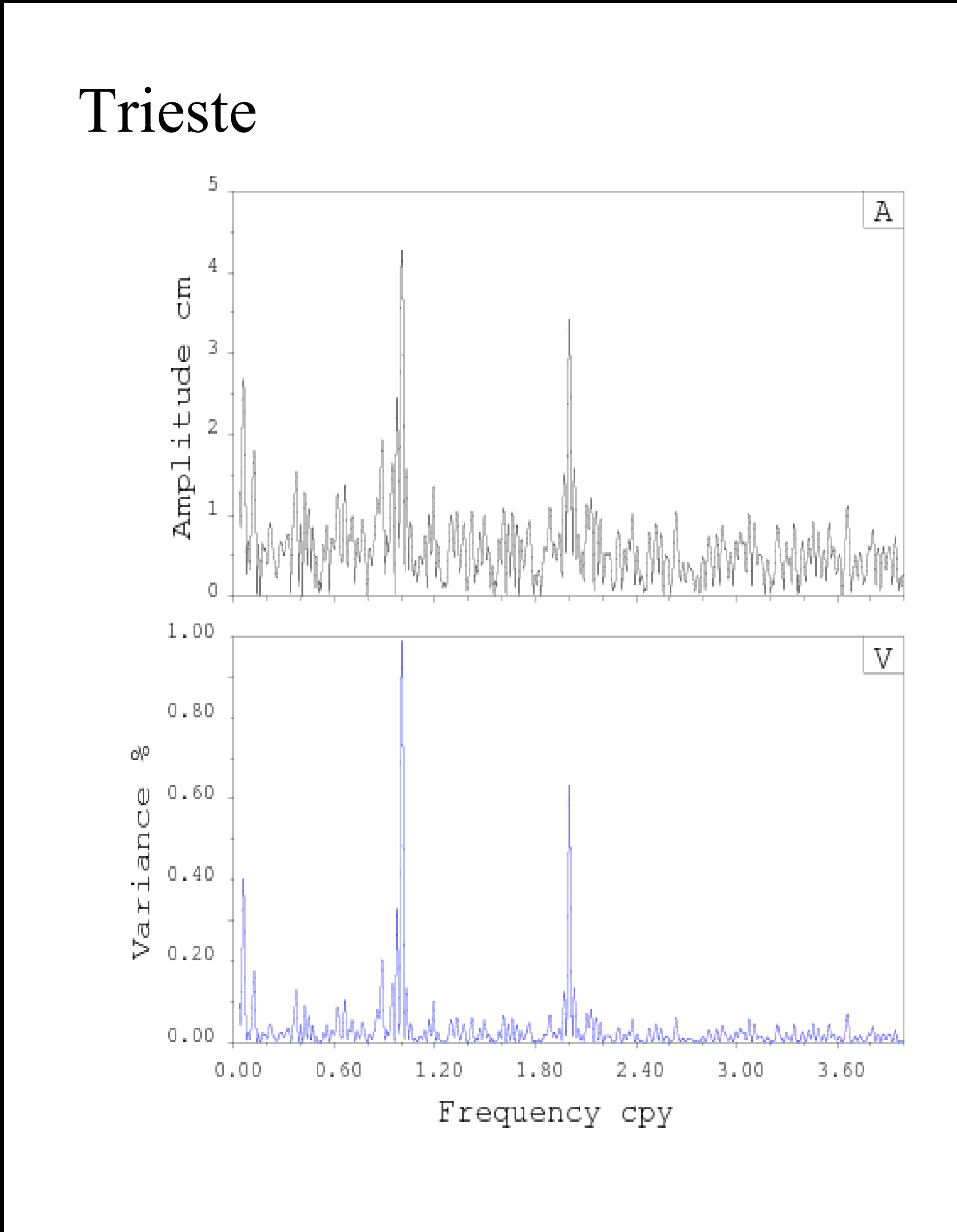




Spatial and Temporal Variability of LSL

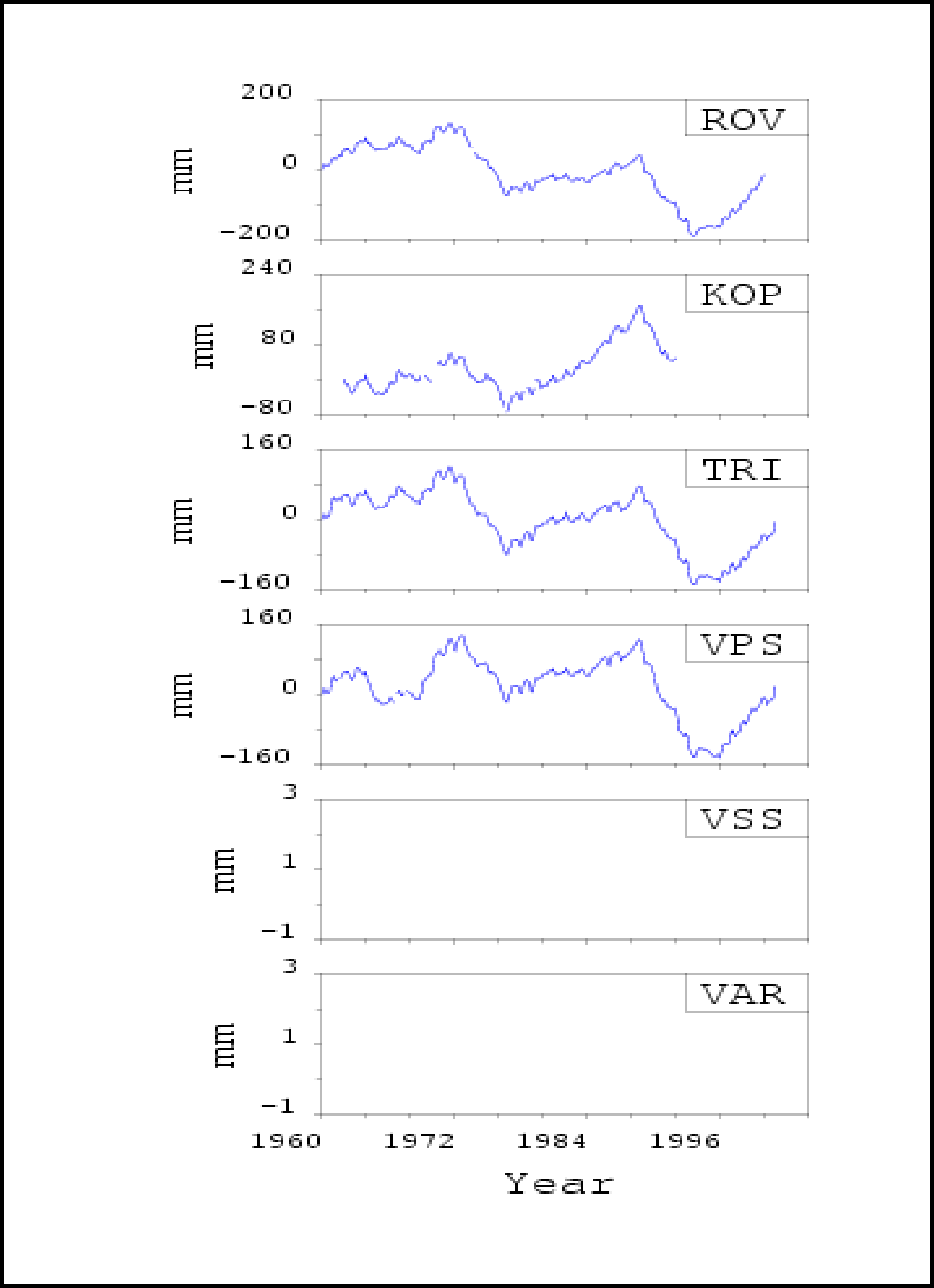
Intraseasonal to interdecadal spectra

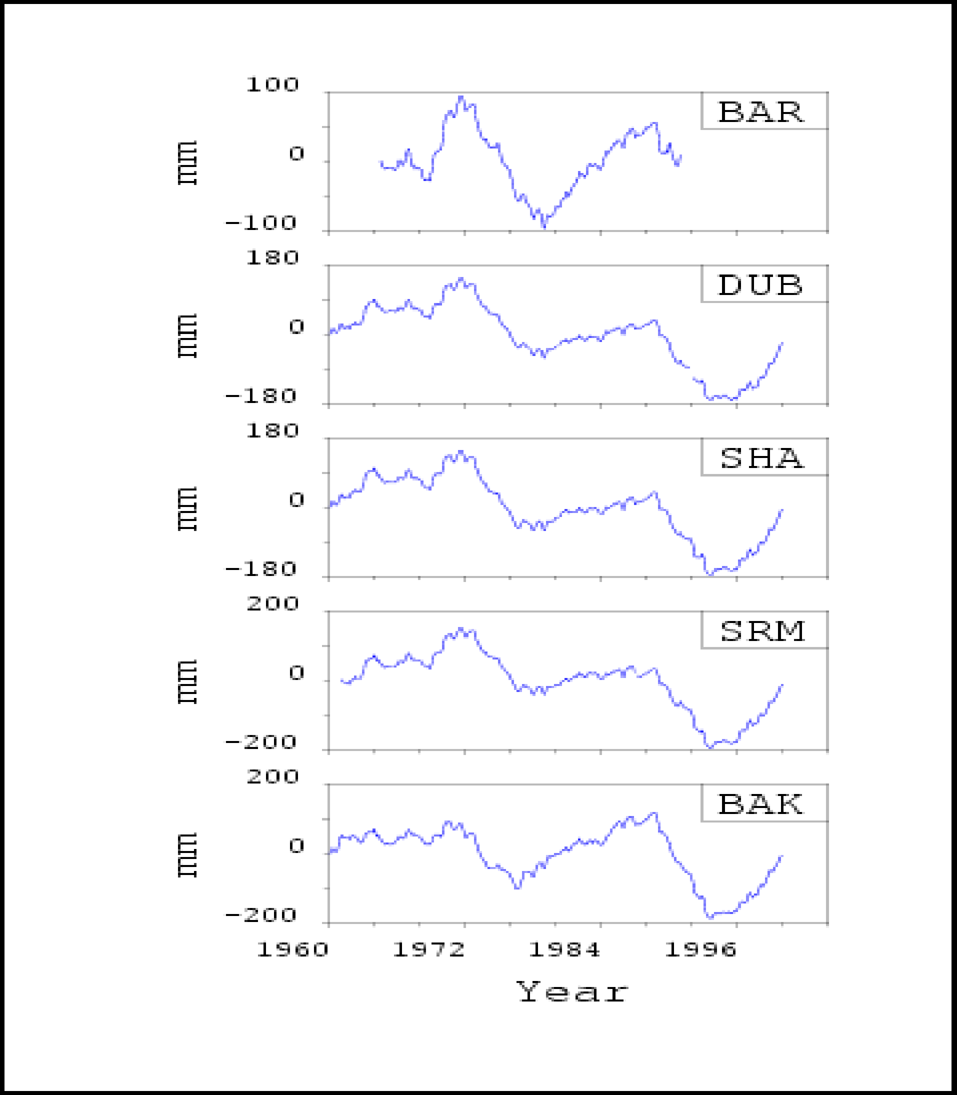




Spatial and Temporal Variability of LSL

Interdecadal variability





Spatial and Temporal Variability of LSL

Secular trends

Examples for interval 1950-2000

Name	Type	N	A_K	ϕ_K	A_{Sa}	ϕ_{Sa}	A_{Ssa}	ϕ_{Ssa}	δ
VENEZIA (PUNTA DELLA	RLR	484	16.3	0.307	43.2	2.815	33.9	3.161	0.5
TRIESTE	RLR	492	21.6	0.282	40.8	2.961	34.9	3.164	0.4
KOPER	RLR	344	17.7	6.163	33.0	2.880	27.4	3.045	0.2
ROVINJ	RLR	477	22.4	0.370	44.7	2.720	28.1	3.102	0.0
BAKAR	RLR	480	29.5	0.542	39.5	2.420	33.2	3.051	0.2
SPLIT RT MARJANA	RLR	466	23.4	0.283	37.1	2.234	29.8	2.995	0.0
SPLIT HARBOUR	RLR	480	24.1	0.358	40.2	2.166	29.6	2.988	-0.2
DUBROVNIK	RLR	475	22.5	0.258	43.3	2.186	23.7	3.000	0.3
BAR	RLR	319	17.6	5.883	41.1	1.902	22.1	2.885	1.3

Main results:

Consistently small trends in the second half

Larger than average trends in first half of 20-th century

Forcing Factor

Local Sea Level (LSL) = high-frequency part + low-frequency part

High-frequency part of LSL equation:

$$h_{\mathrm{hf}}t = w(t) + h_{\mathrm{tidal}}(t) + h_{\mathrm{atmos}}(t) + h_{\mathrm{seiches}}(t) + h_{\mathrm{tsunami}}(t).$$

Important for projection of maximum flood levels

Result of local and regional processes.

Forcing Factor

Low-frequency part of LSL equation:

Contributing factors for LSL (monthly time scales and longer):

$$\delta h_{\mathrm{M}}(\vec{x},t) = S(\vec{x},t) + C(\vec{x},t) + A(\vec{x},t) + I(\vec{x},t) + G(\vec{x},t) + T(\vec{x},t) + P(\vec{x})(t-t_0) + V_0(\vec{x})(t-t_0) + \delta V(\vec{x},t) + B(\vec{x},t)$$

S: steric changes
C: changes in ocean currents
A: changes in atmospheric circulation
I: changes in the mass of the large ice sheets
G: changes in continental glaciers
T: changes in terrestrial hydrosphere
P: postglacial rebound
V_0: secular vertical land motion
δV: non-linear vertical land motion
B: changes in shape and extent of ocean basins.

Comments on the relation between mass changes (exchange and redistribution) and LSL

Spatially variable due to interaction of gravitational and visco-elastic response of the solid Earth and LSL to loading.

Important for projection of mean sea level

Result of local, regional and global processes!

Forcing Factor

Atmospheric Forcing

Regression analysis:

$$h(t) = A_{\mathrm{Sa}} \sin(\omega_{\mathrm{Sa}} + \phi_{\mathrm{Sa}}) + A_{\mathrm{Ssa}} \sin(\omega_{\mathrm{Ssa}} + \phi_{\mathrm{Ssa}}) + a + bt + \alpha p(t) + \beta \sigma_{\mathrm{E}} + \gamma \sigma_{\mathrm{W}}$$

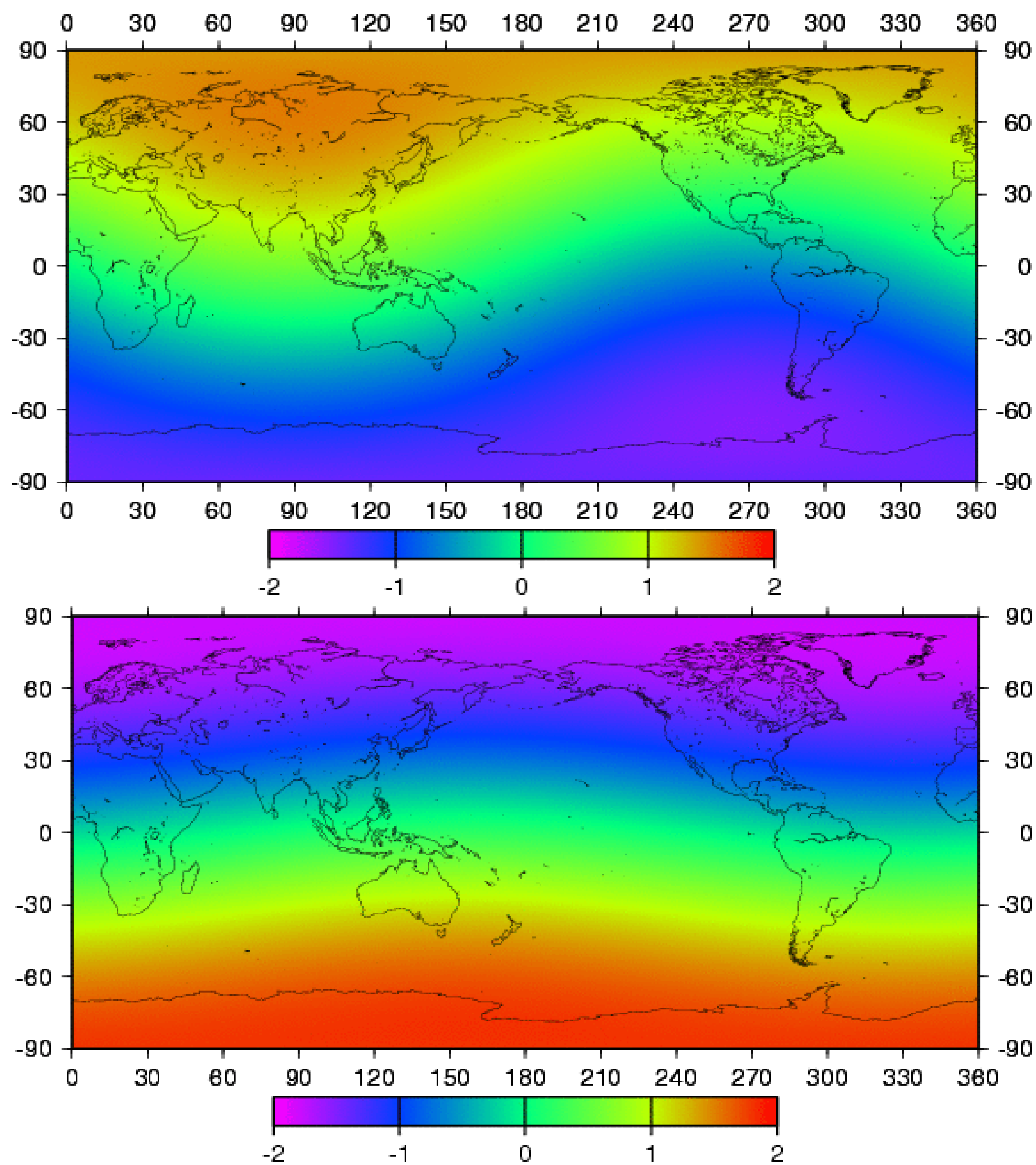
$$\sigma_i = w_i \sqrt{w_{\mathrm{E}}^2 + w_{\mathrm{N}}^2}$$

Main results:

- Response to air pressure forcing not equilibrium
- Atmospheric forcing reduces seasonal cycle amplitude and shifts phase
- Atmospheric forcing reduced LSL trends in the time window 1950 – 2000 by almost 1 mm/yr.
- Atmospheric forcing does not affect 16-17-year transient signal

Forcing Factor

Vertical land motion: *needs to be given with respect to Center of Mass of the whole Earth System (CM).*



mm/yr

Apparent vertical motion due to relative motion of Reference Frame Origin (RFO)

ITRF97 minus ITRF2000

ITRF2000 minus ITRF2005

Effect on global sea level: 0.4 mm/yr *(Plag, 2005)*

Effect on LSL +- 2 mm/yr

Forcing Factor

Ice sheets (and other) mass exchange: *spatially variable fingerprint.*

Present-day changes in:

* Ice sheets
* Glaciers
* Land water storage

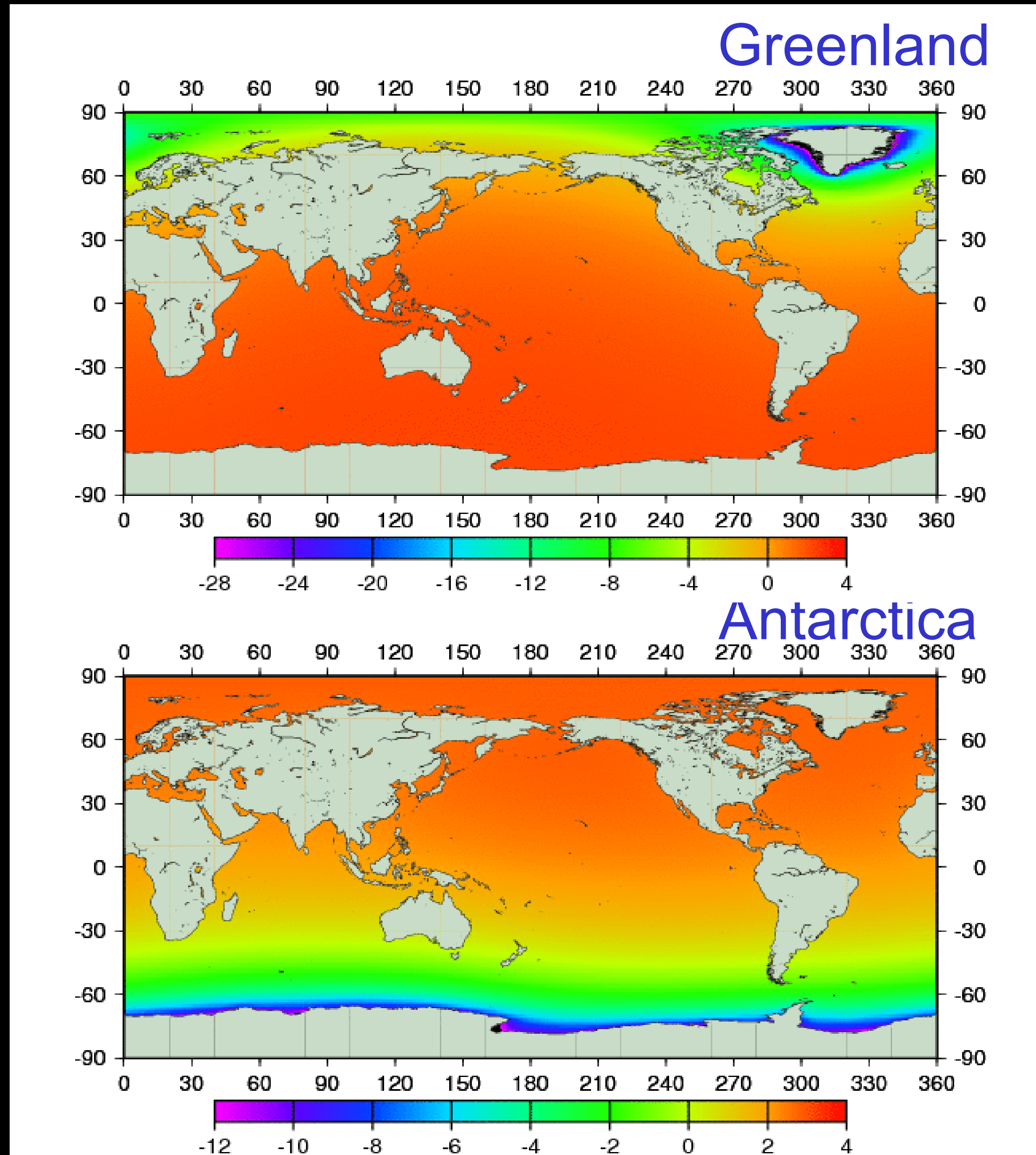
Finger-print functions: *describe the effect of a unit ice mass change in a given area on sea level.*

Solution of the static sea level equation for a unit linear trend over a given ice mass area.

Simplifications:

- spherically symmetric Earth model
- elastic (up to century time scales)

More on LSL forcing:
http://geodesy.unr.edu/hanspeterplag/projects/sealevel/



Sea Level Hazards in the Mediterranean

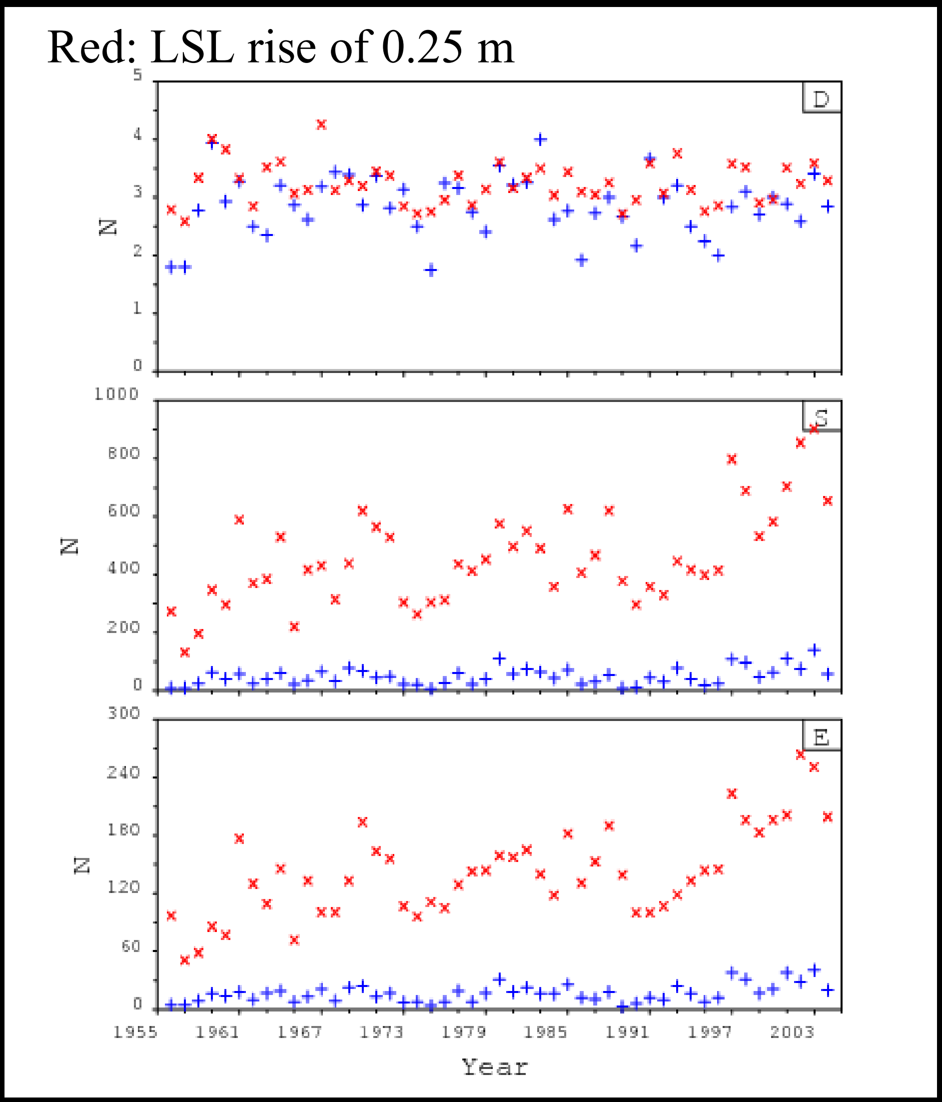
Example Venice:

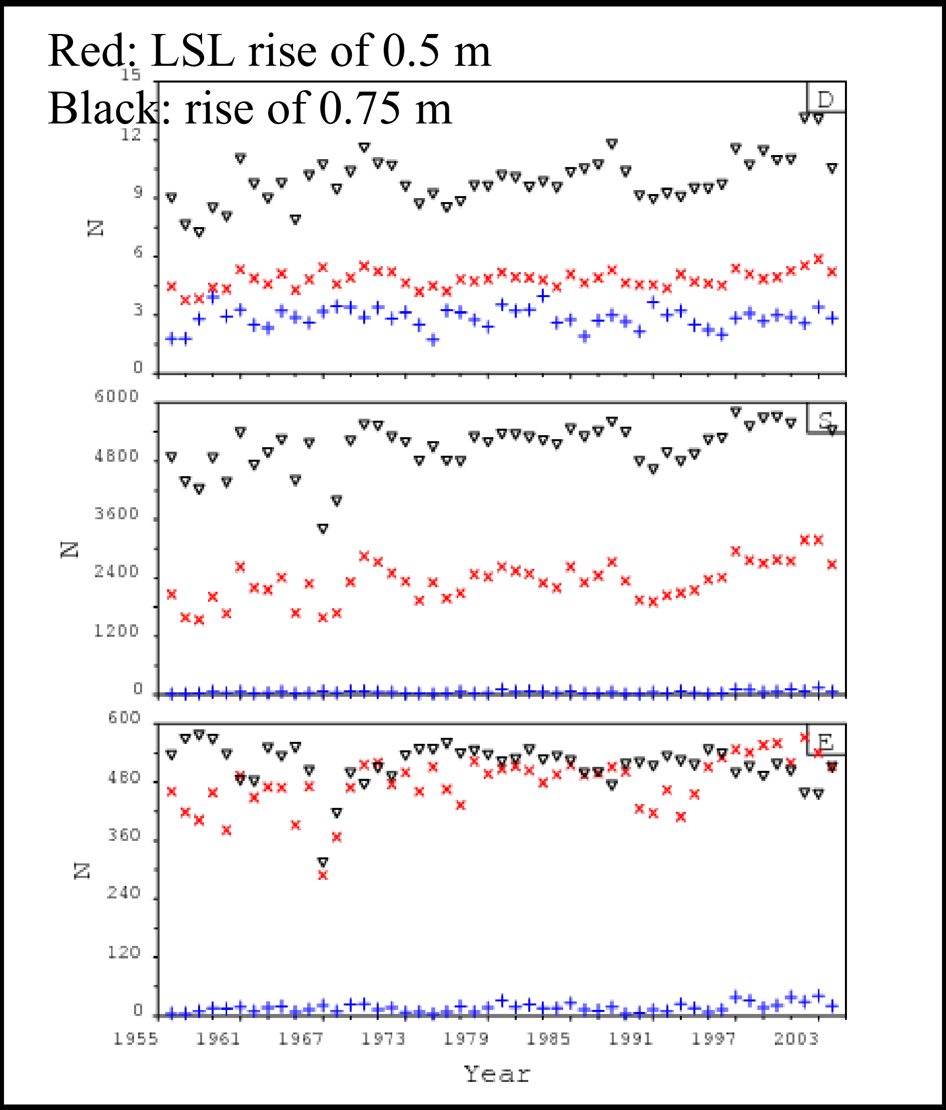
- Frequent flooding causes problems for buildings

Sea Level Hazards in the Mediterranean

Example Venice:

- Frequent flooding causes problems for buildings
- Frequency of flooding increases due to subsidence/LSL rise

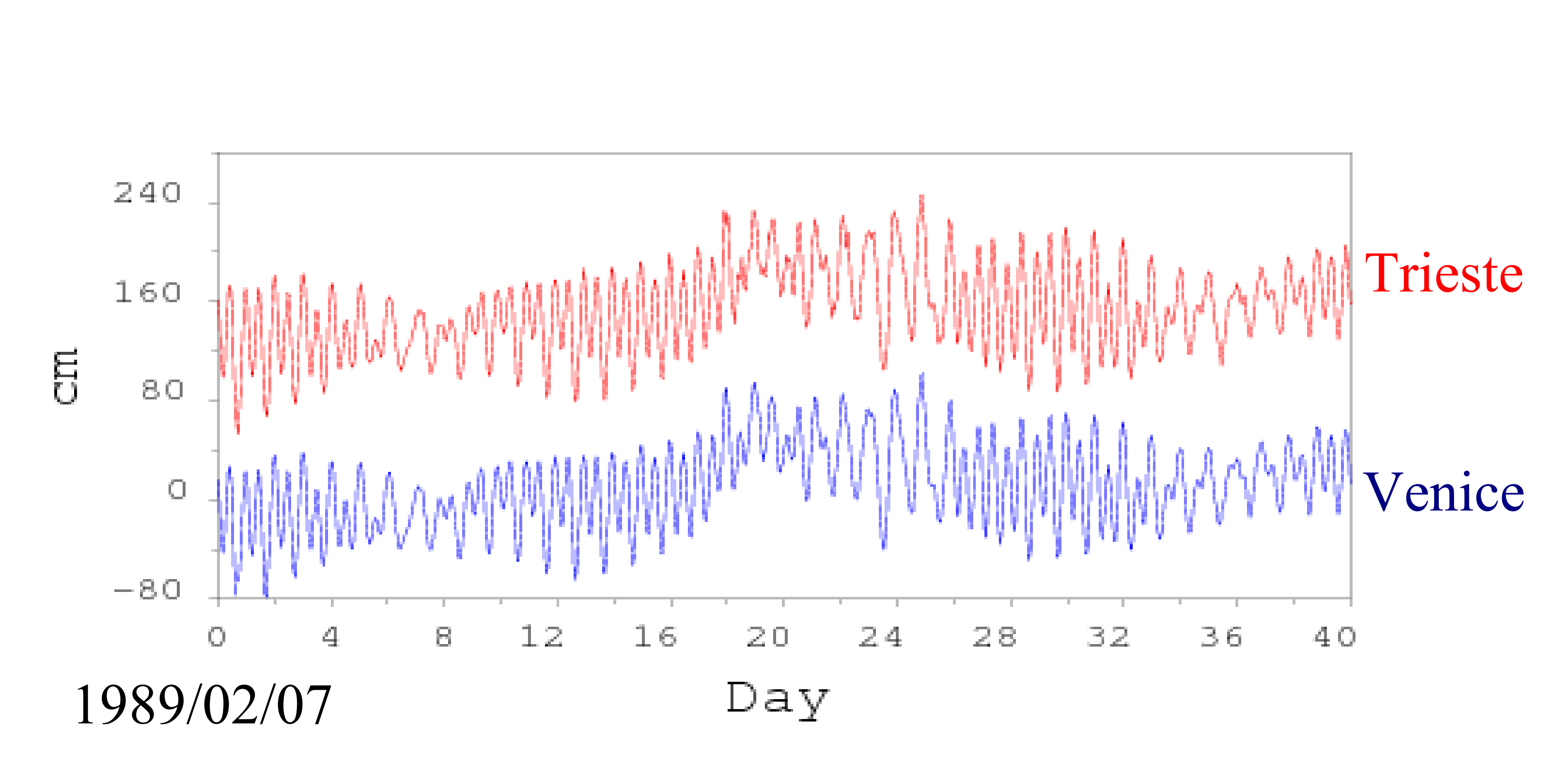




Sea Level Hazards in the Mediterranean

Example Seiches:

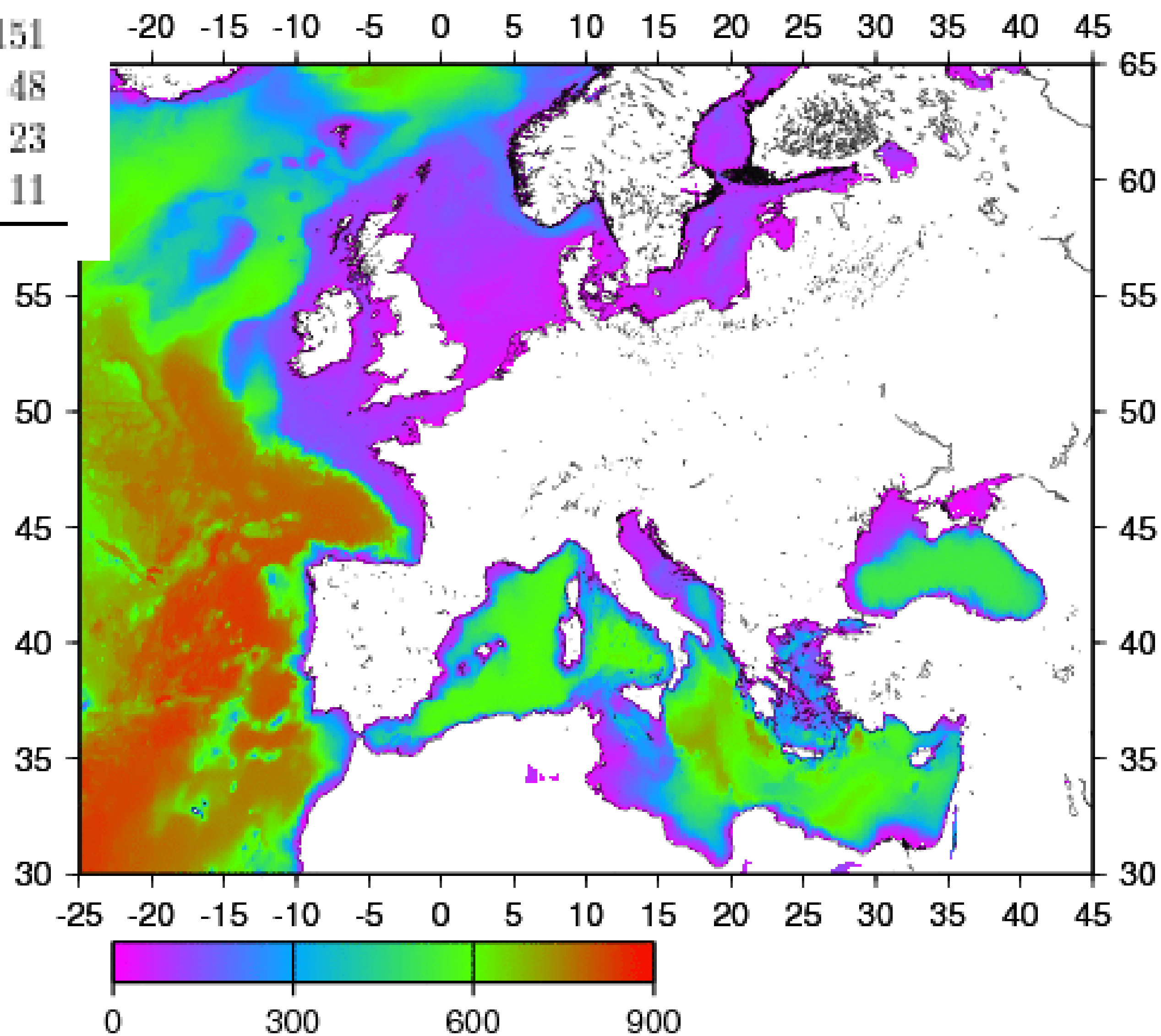
- Can have large amplitudes and cause sudden coastal flooding
- Atmospherically forced



Sea Level Hazards in the Mediterranean

Water depth (m)	Velocity (km/h)	Wave length (km)
7000	943	282
4000	713	213
2000	504	151
200	159	48
50	79	23
10	36	11

Example Tsunamis

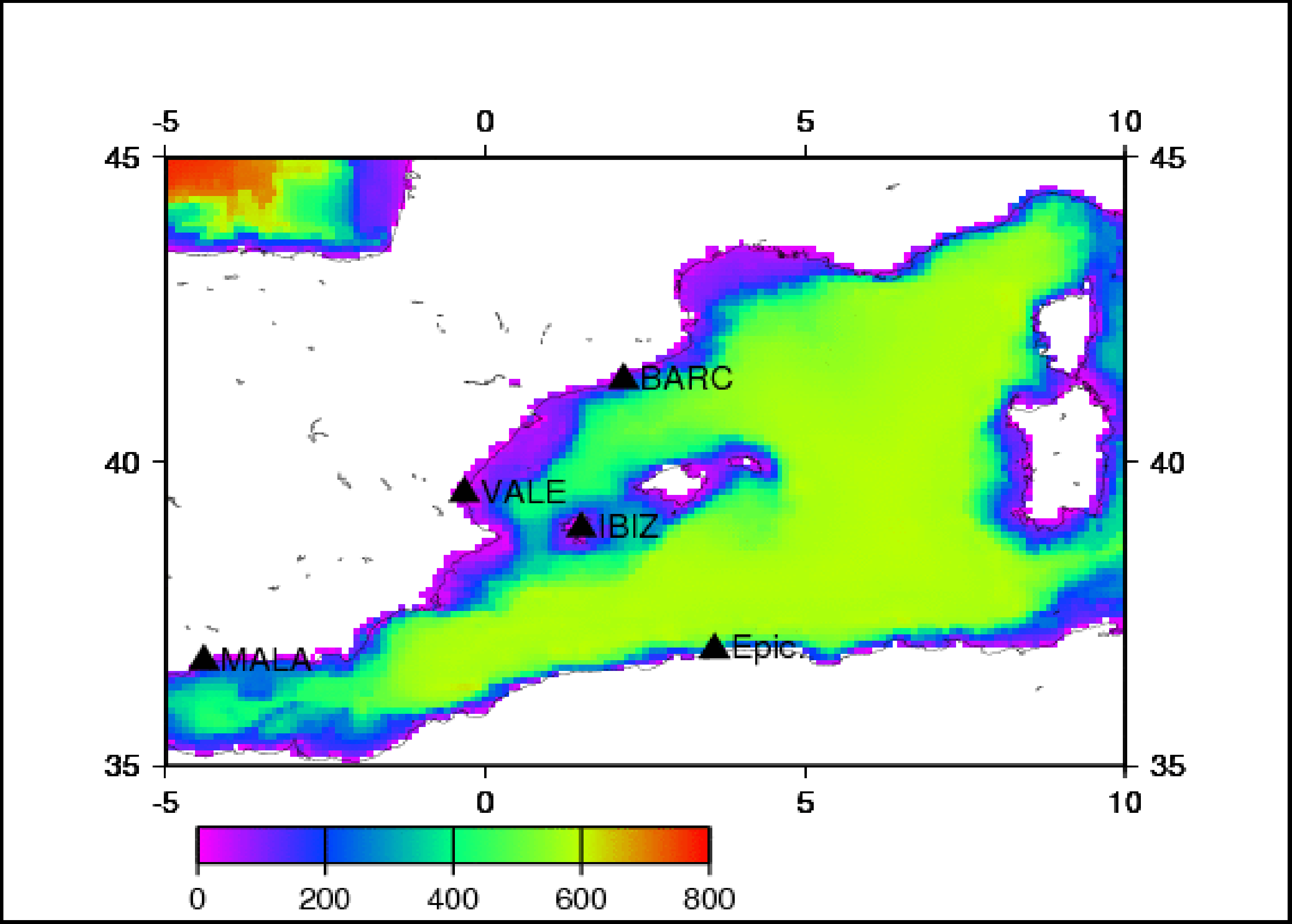


Sea Level Hazards in the Mediterranean

Example: Tsunami of May 21, 2003

Earthquake: Boumerdes, Algeria, May 21, 2003; Mw=6.8; about 50 km east of the capital city of Algiers

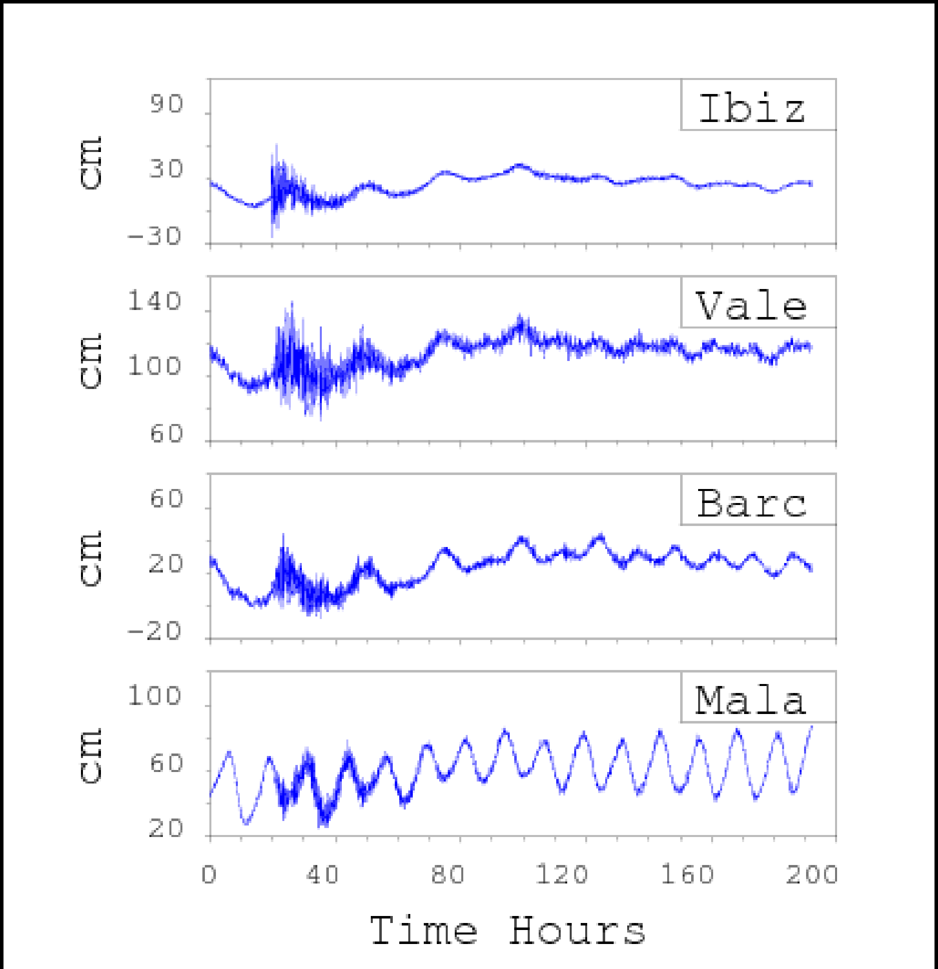
Stations are: Ibiza, Valencia, Barcelona, and Malaga.



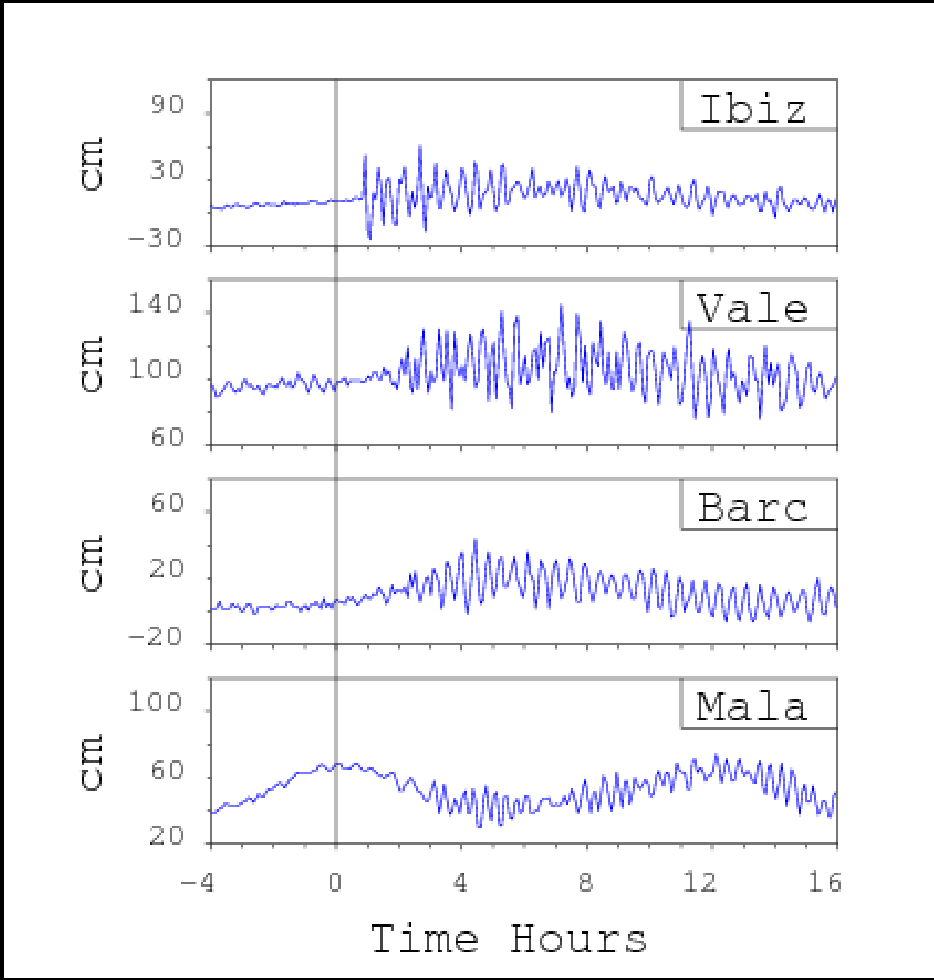
Sea Level Hazards in the Mediterranean

Example: Tsunami of May 21, 2003

Seven days starting at t0 =0:00 UTC, May 21, 2003.



Excerpt around the earthquake, with T0 =18:44 UTC, i.e. the time of the earthquake initiation.



Sea Level Hazards in the Mediterranean

Example Stromboli:

- Landslides on Sciara del Fuoco cause tsunamis
- Two landslides on December 30, 2008
- Tsunami with maximum wave height of 5-10 m

Sea Level Hazards in the Mediterranean

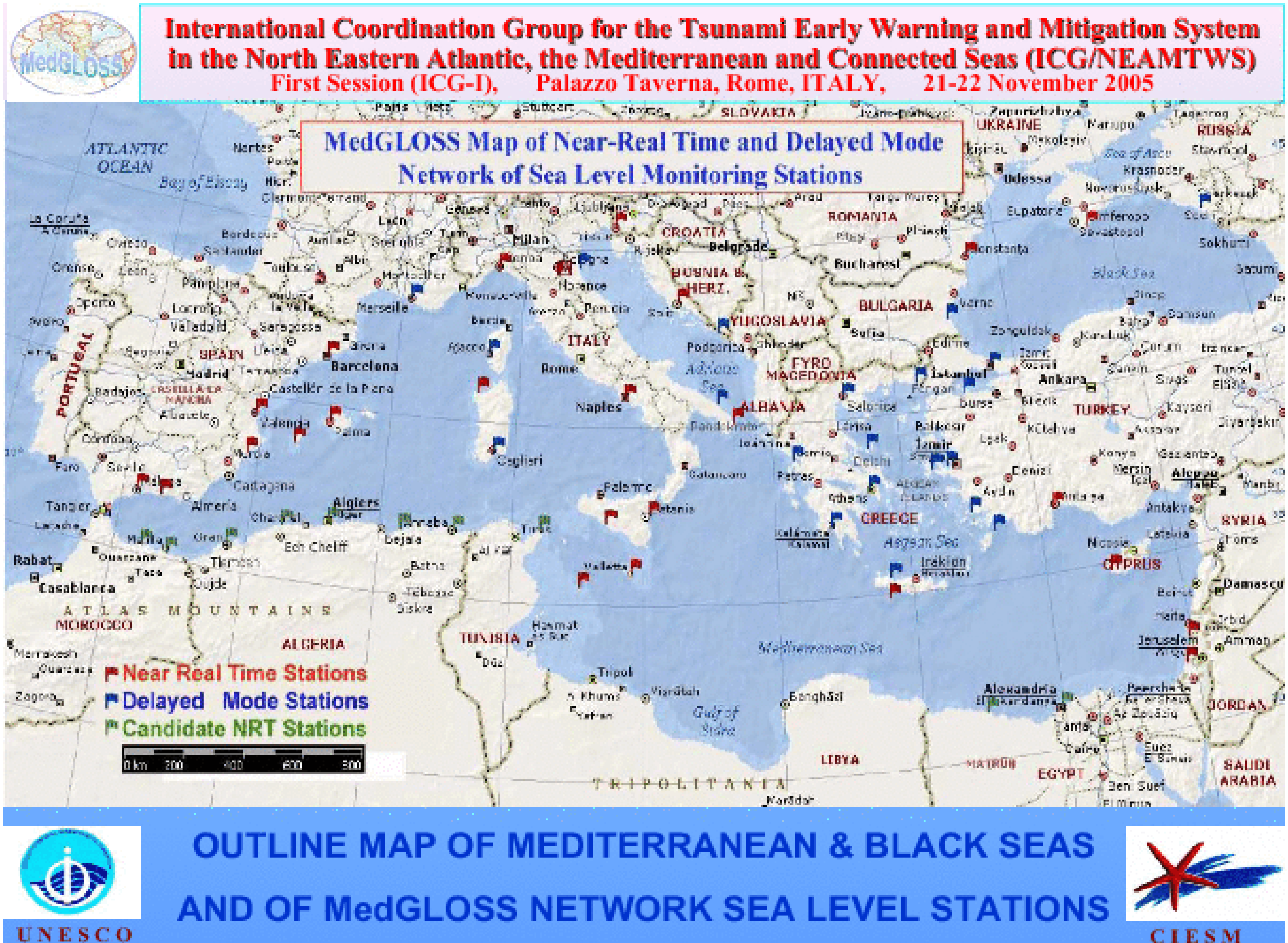
Summary:

- Subsidence/LSL rise
- Seiches
- Storm surges
- Tsunamis
- Saltification

Sea Level Hazards Observing System

Application	Amplitude accuracy	Time accuracy	Spatial resolution	Temporal resolution	Latency/record length	Mode
Tsunami	5 cm	10 seconds	100 km	30 s	1 minute	LLM
Seiches	5 cm	< 1 minute	50 km, depending on location	30 s	< 10 minutes	LLM
Storm surges	10 cm	< 1 minute	100 km	10 minutes	1 hour	LLM
Depressions	5 cm	1 minute	< 50 km, depending on location	15 minutes	1 hour	LLM
Tides and other oceanographic applications	1 cm	< 30 s	10 to 500 km, depending on location and coast line geometry	1 hour	Records of 1 months to several years	DM
Studies of intraseasonal sea level variations	1 cm	1 minute	50 to 500 km, depending on location and phenomenon	1 hour, 1 day or 1 month, depending on time scales considered	Records of several years to century	DM
Studies of annual to decadal sea level variations	< 1 cm	1 hour	100 to 1000 km, depending on location and time scale considered	1 month	Records of decades to centuries	DM
Studies of secular changes	< 1 cm, stability < 1 mm/yr	1 hour to 1 day	10 to 1000 km, depending on location and vertical land motion	1 month	Records of several decades to centuries	DM
Model validation Tsunami	1 to 5 cm	< 1 minute	100 km	30 s	Records of 1 to several days	DM
Model validation GCM (barotropic and baroclinc)	1 cm	1 minute	100 km or less	10 minutes to 1 hour	Records of up to several years	DM
Model validation seiches (local, barotropic GCMs)	1 cm	< 1 minute	50 km or less	30 sec	Records of several days	DM

Sea Level Observing System: Status and Challenges



Rosen, 2005

Sea Level Observing System: Status and Challenges

Main challenges:

- *Tide gauge distribution*
- *low latency tide gauges*
- *co-location with GPS/GNSS*
- *deep ocean buoys (like DART)*
- *Low latency determination of magnitude and displacement field*
- *tsunami prediction models*

Predictions, Uncertainties, and Scenarios

Five types of uncertainties

Manning and Petit (2003, IPCC Theme paper):

- **Incomplete or imperfect observations (aleatoric uncertainties):** vertical land motion, reference frame, oceanographic observations;

- **Incomplete conceptual framework (epistemic uncertainties):** with respect to climate system (including ocean circulation and thermal expansion : Yes; with respect to mass-sea level relation: No;

- **Inaccurate description of known processes:** one-dimensional models, incomplete mass redistribution, gravitationally inconsistent models;

- **Chaos:** With respect to climate system: Yes; for mass-sea level: No;

- **Lack of predictability:** ice sheet behavior, ocean warming, circulation.

Predictions, Uncertainties, and Scenarios

"*Uncertainties affecting available scientific results need to be explained clearly and in ways that avoid confusion and assist policy makers and non-specialists when considering decisions and risk management*" (Manning and Petit, 2003).

Past and Current LSL Changes:

Main uncertainties:

- Steric effect not well known due to lack of data;
- Vertical land motion still uncertain in a geocentric reference frame;
- Mass redistribution/Geoid variations not well constrained;

Consequences:

- Separation of the different factors contributing to LSL not satisfactory
- Large uncertainties map into future scenarios creating a wide range of possible sea level changes

Predictions, Uncertainties, and Scenarios

"*Uncertainties affecting available scientific results need to be explained clearly and in ways that avoid confusion and assist policy makers and non-specialists when considering decisions and risk management*" (Manning and Petit, 2003).

Future Sea-level Changes:

Main epistemic uncertainties:
Spatial variability in thermal expansion.
Dynamic response of **ice sheets** to climate forcing (large spatial variations).

- **Main goal of scenario analysis:** Characterize uncertainties for less predictable aspects of future projections
- **Main approach:** Make different assumption about the forcing
- The case of **climate change**: consider a range of reasonable emission scenarios.

The case of **Local Sea Level**: consider a range of reasonable ocean warming and ice sheet scenarios combined with model output for ocean and atmospheric circulation, vertical land motion, and LSL fingerprints

Consequence of epistemic uncertainties:
Range of plausible LSL scenarios for most locations is **very large**.

Summary and Conclusions

- LSL is the coastal impact parameter, which depends on local, regional and global processes.
- Sea level hazards include subsidence/LSL rise, seiches, surges, and tsunamis.
- The sea level hazards observing system is not well developed with large differences on the northern and southern coast.
- Uncertainties in predictions of future LSL result mainly from epistemic uncertainties concerning the climate system, in particular ocean circulation, thermal expansion, and the response of the ice sheet to climate forcing
- Incomplete and insufficient observations aggravate the problems in understanding past, present and future LSL changes
- Reducing the uncertainties requires better global monitoring: GEOSS, IGWCO, GOOS, GLOSS, GGOS, ...