Numerical Modeling of Storm Surges in the Eastern Mediterranean under Climate Change + Forecast Platform

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EastMed Symposium 2015

Regional Cooperation in Eastern Mediterranean Sea Research

The University of Haifa, Israel, 19-21 October 2015

Description/Aim of Research I

Storm Surge: Sea Level Variation due to
low Sea Level Pressure (SLP) + high Wind Velocities

- Increase of **coastal inundation** and erosion **risk** on coastal low-land areas
- Intense impacts on: People – Properties – Habitats – Public spaces – Agriculture
- Study area: **Mediterranean** basin
- Focus on eastern diverse topography regions: **Aegean + Ionian Seas**
- Output: **maps** of **hazard** areas + occurrence **probabilities** & **magnitudes** of **storm surge extremes** based on climate models/scenarios

Aims – Climate Change impacts on Sea Levels

- Investigation through modelling of storm surge extremes for 150 years:
Control Run (1951-2000) & A1B-scenario Run (2001-2100)
- Estimation of future magnitudes and occurrence frequencies of storm surge maxima under a mediocre to pessimistic climatic scenario for GHG emissions/concentrations
- Climate Change signal on Mediterranean coastal zone
- Estimate Sea Level extremes and inundation probabilities through CVI for Greek coastal zone

Description/Aim of Research II

Wave 4us

Objectives – Operational perspectives in Sea-state Forecasts

•Development of a high-resolution state-of-the-art **forecasting system** for waves, circulation and **storm surges** in the Thermaikos Gulf (Thessaloniki, northern Greece).

•Delivery of **3-day forecasts** through **TV** broadcasts and **web** and **GIS** applications.

•Dissemination of **high-resolution** results readily exploitable by every-day users (fisheries, aquacultures, tourism, sea-related recreational and sea-sport activities etc), environmental modellers and coastal zone management projects.

•Delivery of products **focused on areas** of special interest, like aquacultures and protected areas.

•**Alerting** public (and authorities) in cases of extreme sea level elevation events over a threshold.

Available Data: sea-surface elevations / HNHS+GLOSS gauges / 5+4 stations / 1995-2012

Signal processing: detiding + steric effects removal with high-pass filter

Numerical Model: 2-D Shallow Water Equations

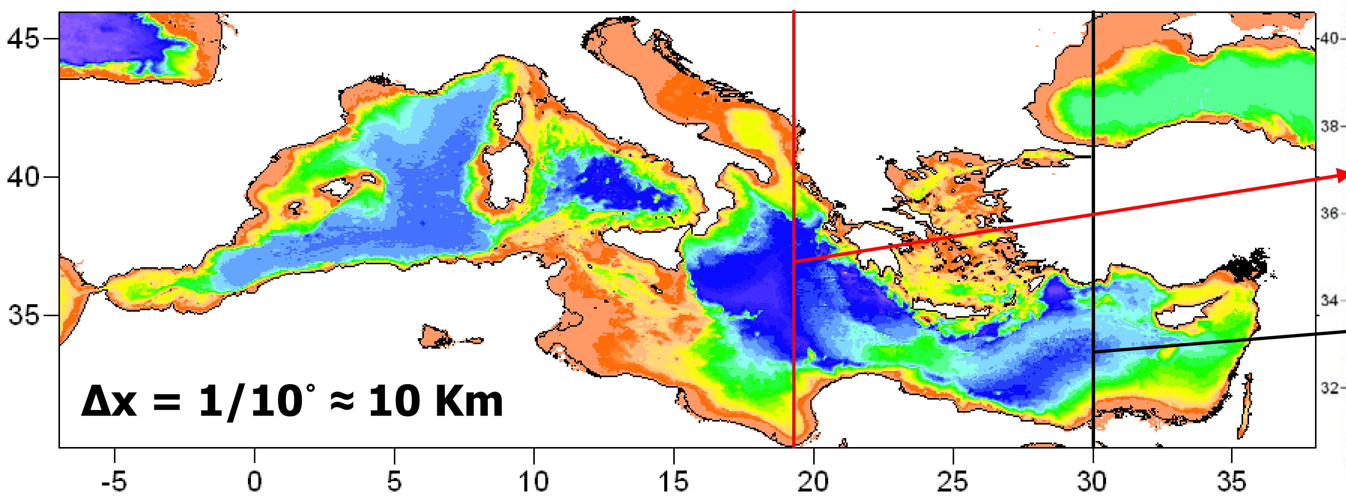
Forcing: SLP + Winds at 10m from RegCM3
historical data 20C3M (1951-2000)
IPCC SRS-A1B (2001-2100)

Results: Sea Surface Height due to meteorological effects

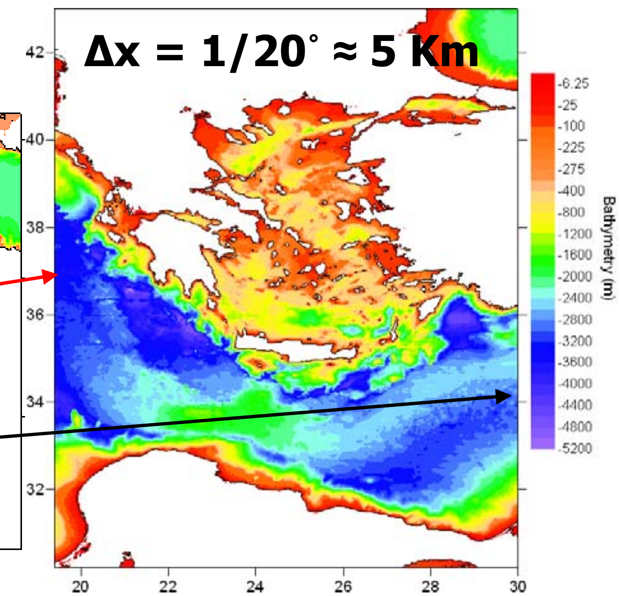
Boundaries: One-way nesting

Simulation Period: 1951-2100

MeCSSM: Mediterranean Climate Storm Surge Model



GreCSSM: Greek Climate Storm Surge Model



Study Tools Physical Features / Statistical Measures

EastMed
2015

SSH: Sea Surface Height

SSI: Storm Surge Index = Mean of 3 independent maxima SSH_{max}/year

(independent event: abstain at least 120 hrs to the next and prior)

Percent Error:

$$E\,(\%) = \frac{\overline{SSI}_{\mathrm{mod}} - \overline{SSI}_{obs}}{\dfrac{\overline{SSI}_{\mathrm{mod}} + \overline{SSI}_{obs}}{2}} \cdot 100$$

Error Index:

$$EI = \left(\overline{SSI}_{mod} - \overline{SSI}_{obs}\right) \Big/ \sqrt{\frac{\sigma^2_{SSI_{mod}} + \sigma^2_{SSI_{obs}}}{2}}$$

Climate Change Index:

$$CCI\,(\%) = \frac{\overline{SSI}_{mod}^{\,(FUTURE)} - \overline{SSI}_{mod}^{\,(PAST)}}{\overline{SSI}_{mod}^{\,(PAST)}} \cdot 100$$

Statistically **coherent** event: $SLH_{coh} \geq (m + \sigma)$ m : mean value of SSH time-series

Statistically **intense** event: $SLH_{int} \geq (m + 2\sigma)$ σ : standard deviation " "

High-order **Percentiles** for **SSH**:

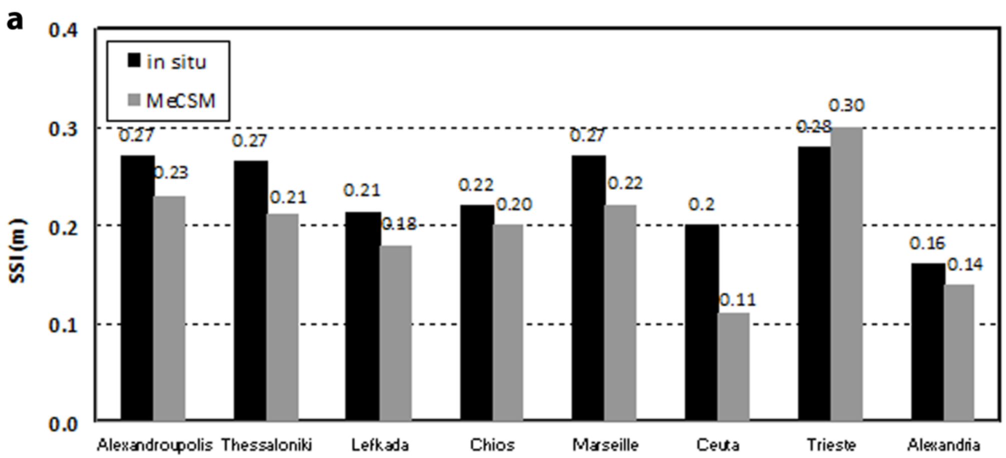
e.g. 95th percentile = indicates the value of SSH (m) below which 95% of observations in an ordered group fall

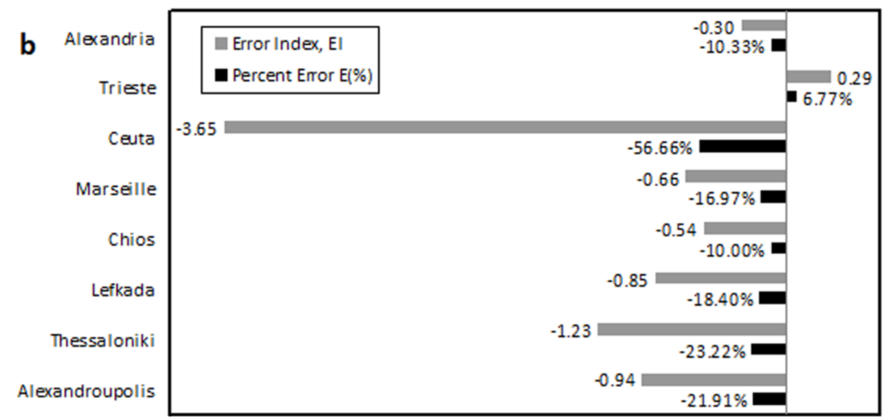
Model Validation Annual Maxima / Statistically Significant Values

EastMed 2015

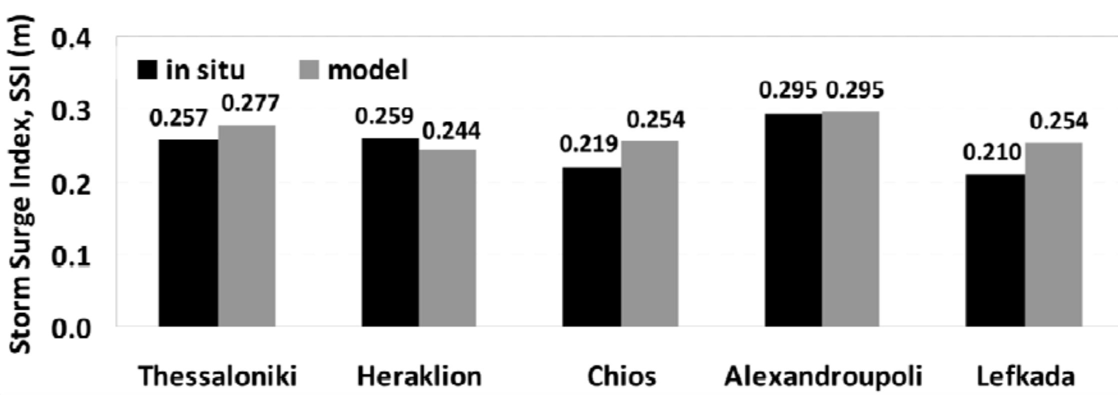
Comparisons In Situ vs. Model based on SSI (m) and Error Index

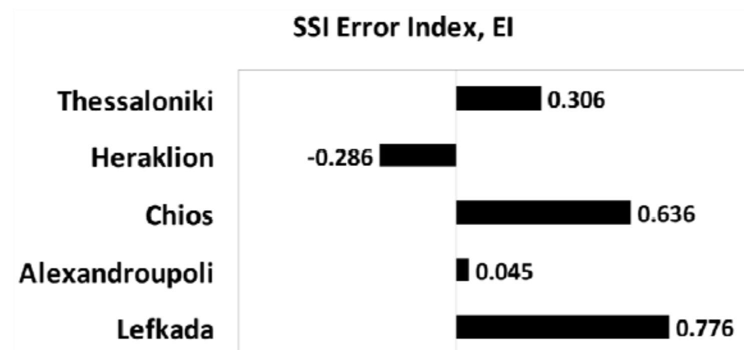
MeCSSM implementation in 8 Mediterranean stations





GreCSSM implementation in 5 Greek stations





Model Validation Interannual Maxima

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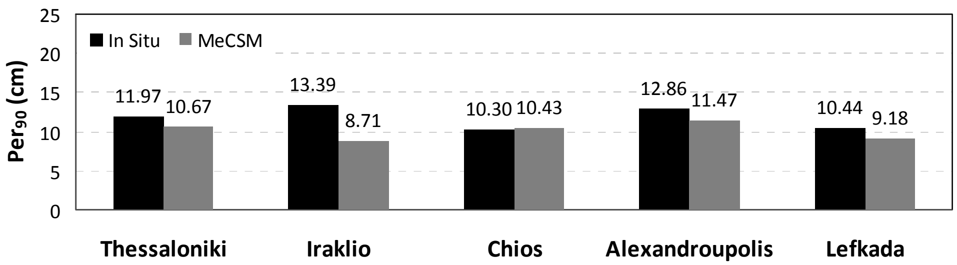
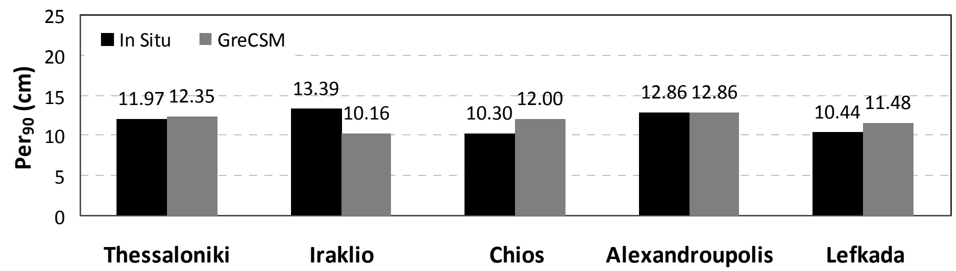
Comparisons In Situ vs. Model based on 80th, 90th and 99th Percentiles of SSH (m)

MeCSSM implementation in 5 Greek stations

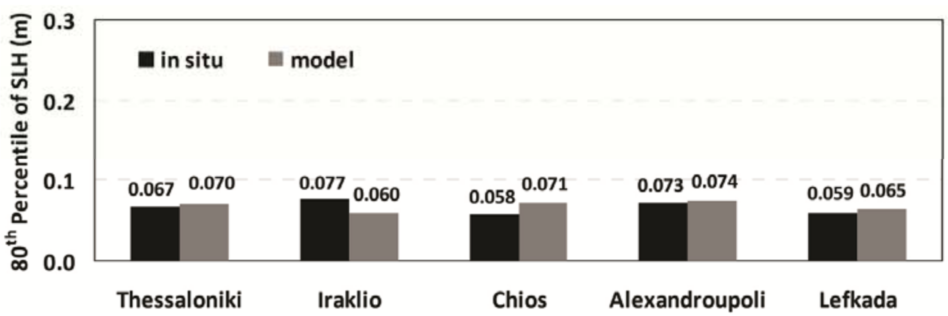


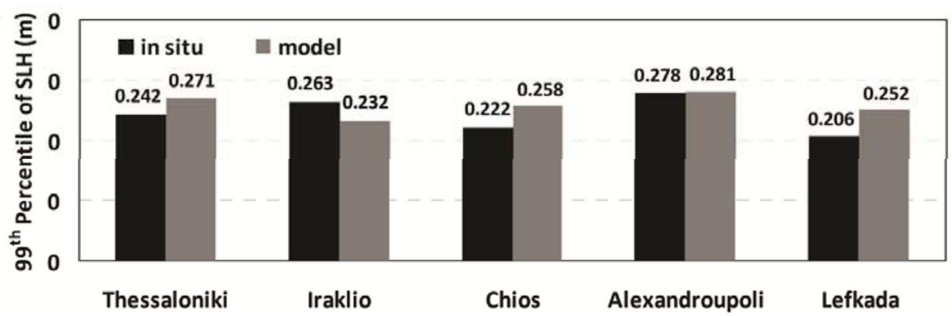
GreCSSM implementation in 5 Greek stations



- Slight improvement of GreCSSM simulations

GreCSSM implementation in 5 Greek stations





- 20% of SSH values above 5,8 ~ 8 cm and 1% of SSH values above 21 ~ 28 cm
- Acceptable performance of GreCSSM
- The highest SSH extremes in North Aegean (Alexandroupoli)

Model Validation Statistical Measures

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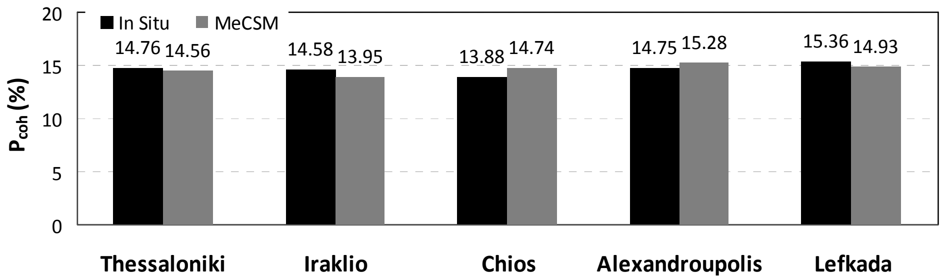
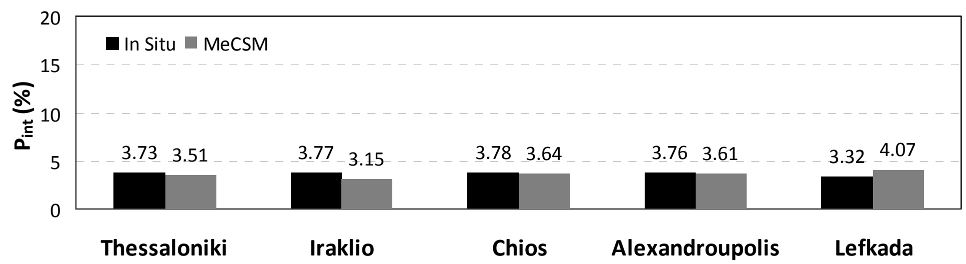
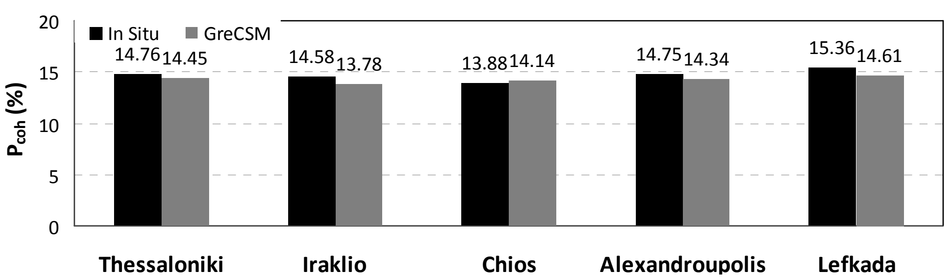
Comparisons In Situ vs. Model based on Exceedance Probabilities P_{coh} and P_{int} (%)

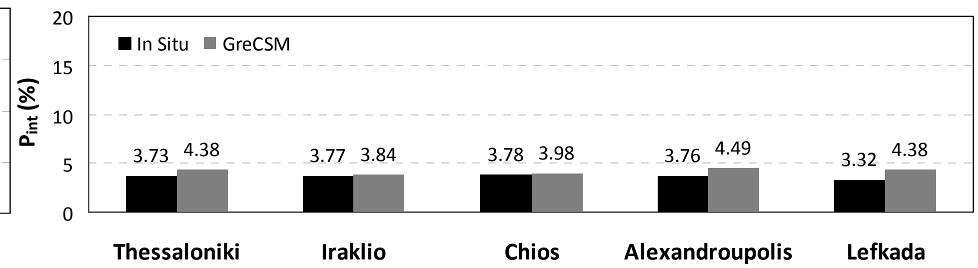
MeCSSM implementation in 5 Greek stations





GreCSSM implementation in 5 Greek stations





- Good performance of both models for the depiction of statistically coherent events
- Slight improvement of GreCSSM simulations

Results Storm Surge Seasonality

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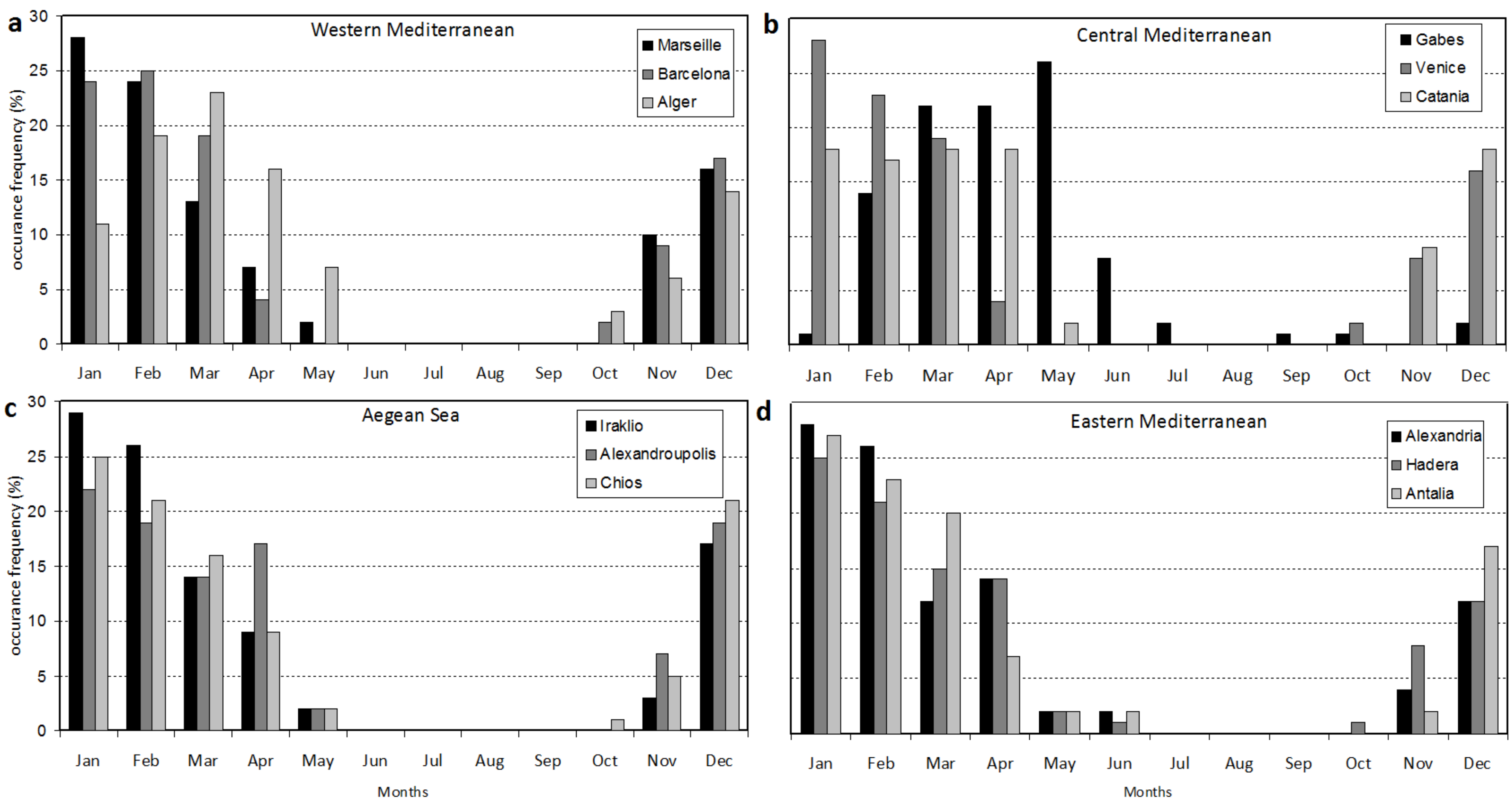
Seasonal percentage f (%) of SSH maxima occurrence at 12 locations

for the A1B-scenario Run during the 21st century



2001-2050 Increase of Winter events

2051-2100 Decrease of Winter events Increase of Spring events

Results SSH Response to Atmospheric Fields

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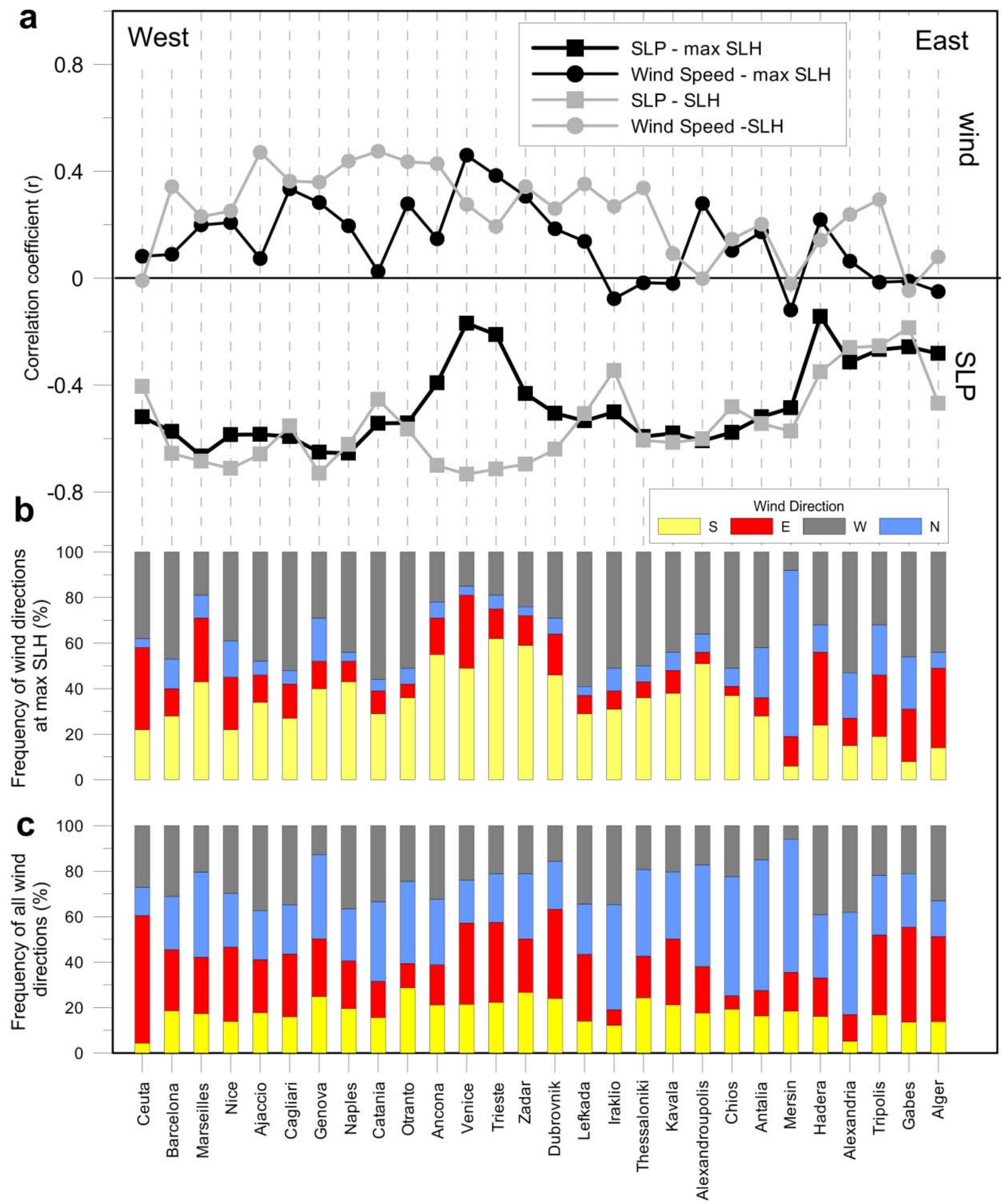
Pearson Correlation

for SLP vs. annual SSH_{max}

28 locations in the entire Mediterranean

150 yrs MeCSSM simulation

- Southern Greek coasts influenced less by SLP than other places
- Central Aegean → diverse topography (many islands) → big impact of SLP and not winds
- Influence of SLP in Adriatic and N. Ionian < S. Ionian
  High SSH mostly due to prevailing winds (Sirocco) in the area



Results Annual Storm Surge Maxima Trends

EastMed 2015

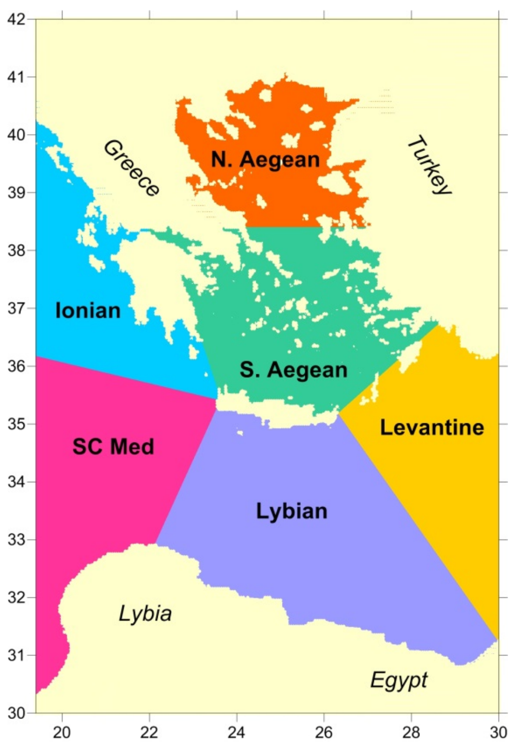
Regional sub-basins evolution trends of spatially averaged annual SSH_{max}

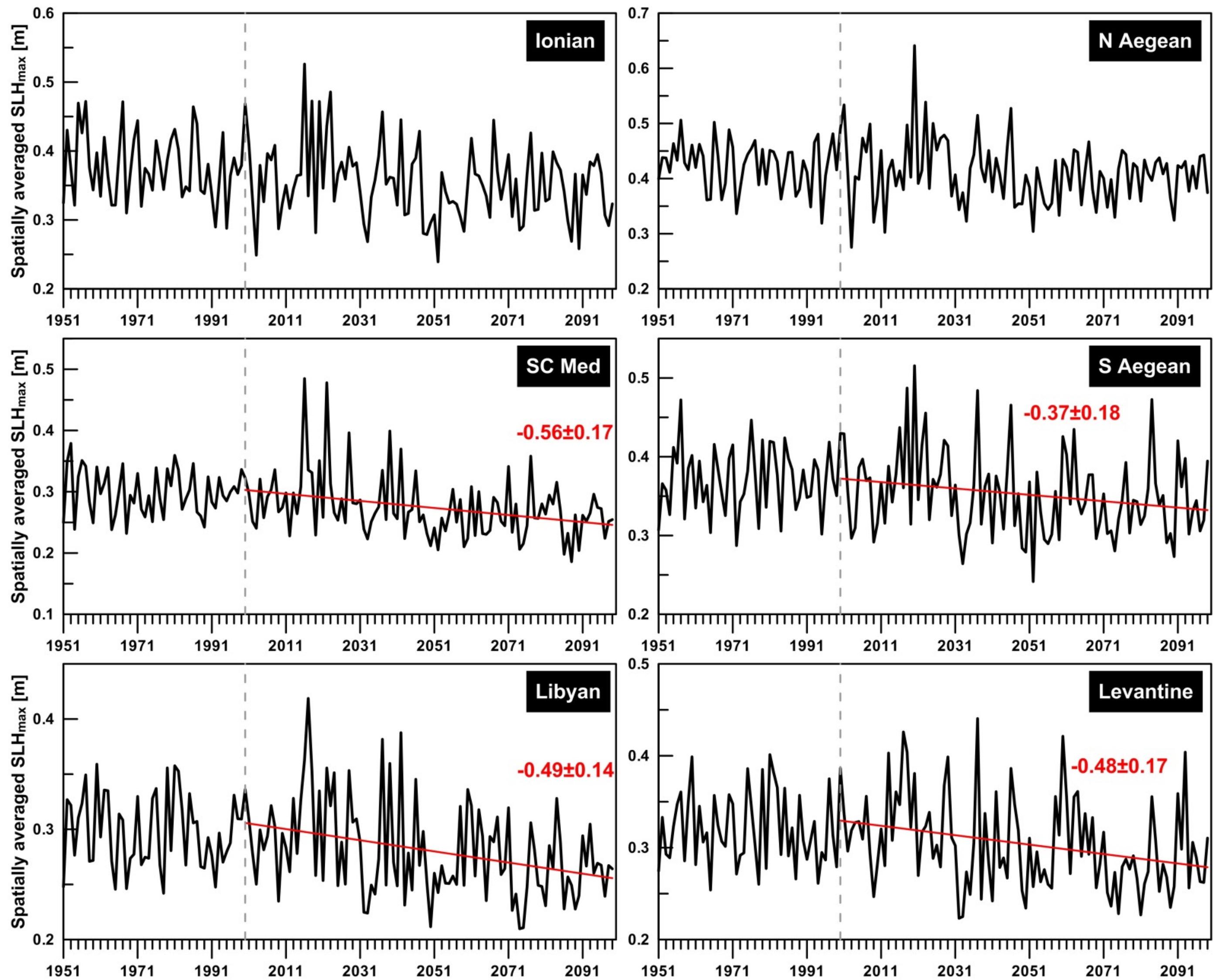
Past (1951-2000) and Future (2001-2100)

95% confidence level

Decreasing trends

-0.37 to -0.56 mm/yr





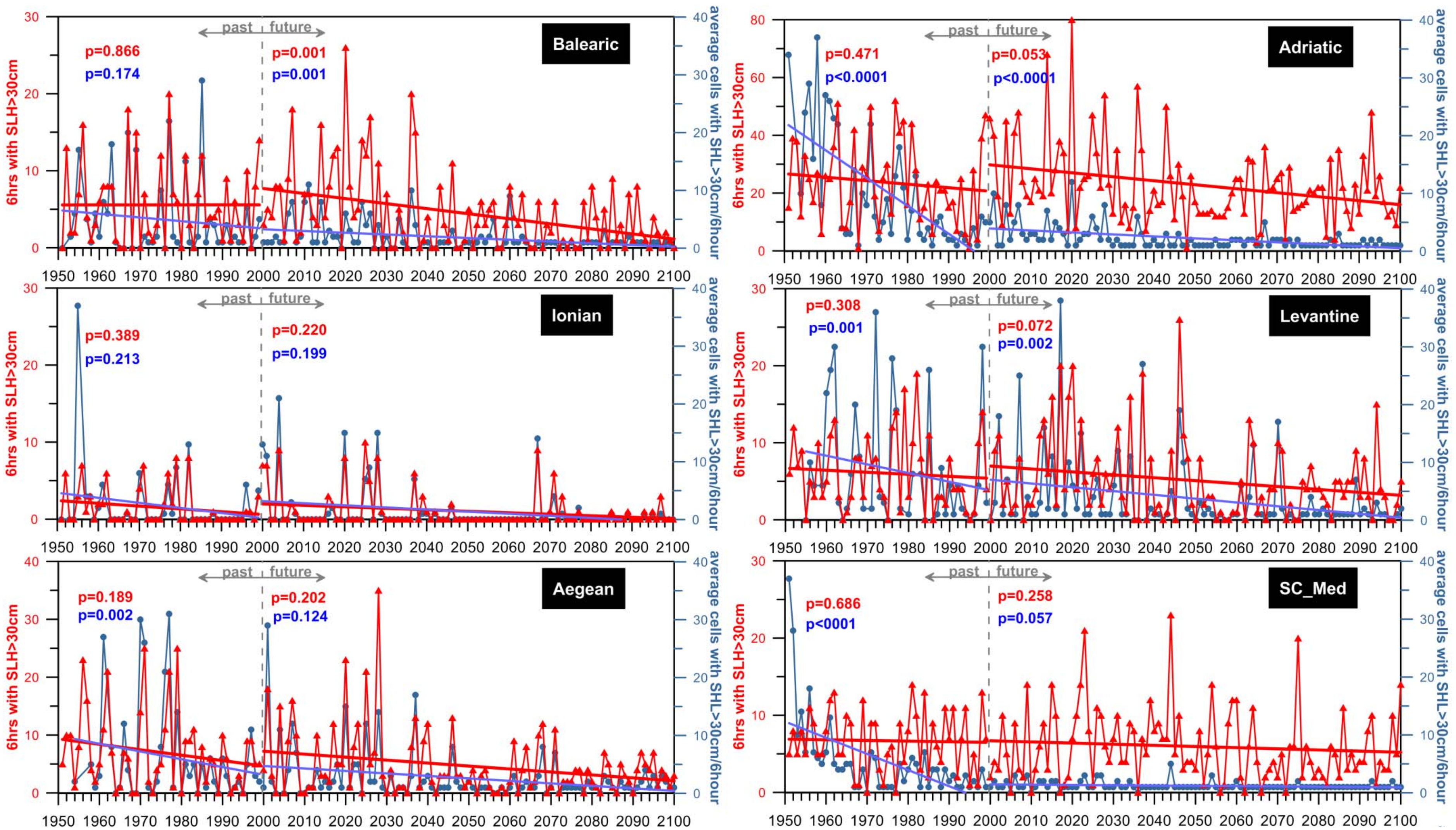
Results Storm Surge Duration/Coverage Trends

EastMed 2015

Regional sub-basins 95% confidence level evolution trends for SSH>30 cm

annual duration (hrs) and coverage area (cells)

Past (1951-2000) and Future (2001-2100)



Results Regional Maxima/Average SSH Evolution

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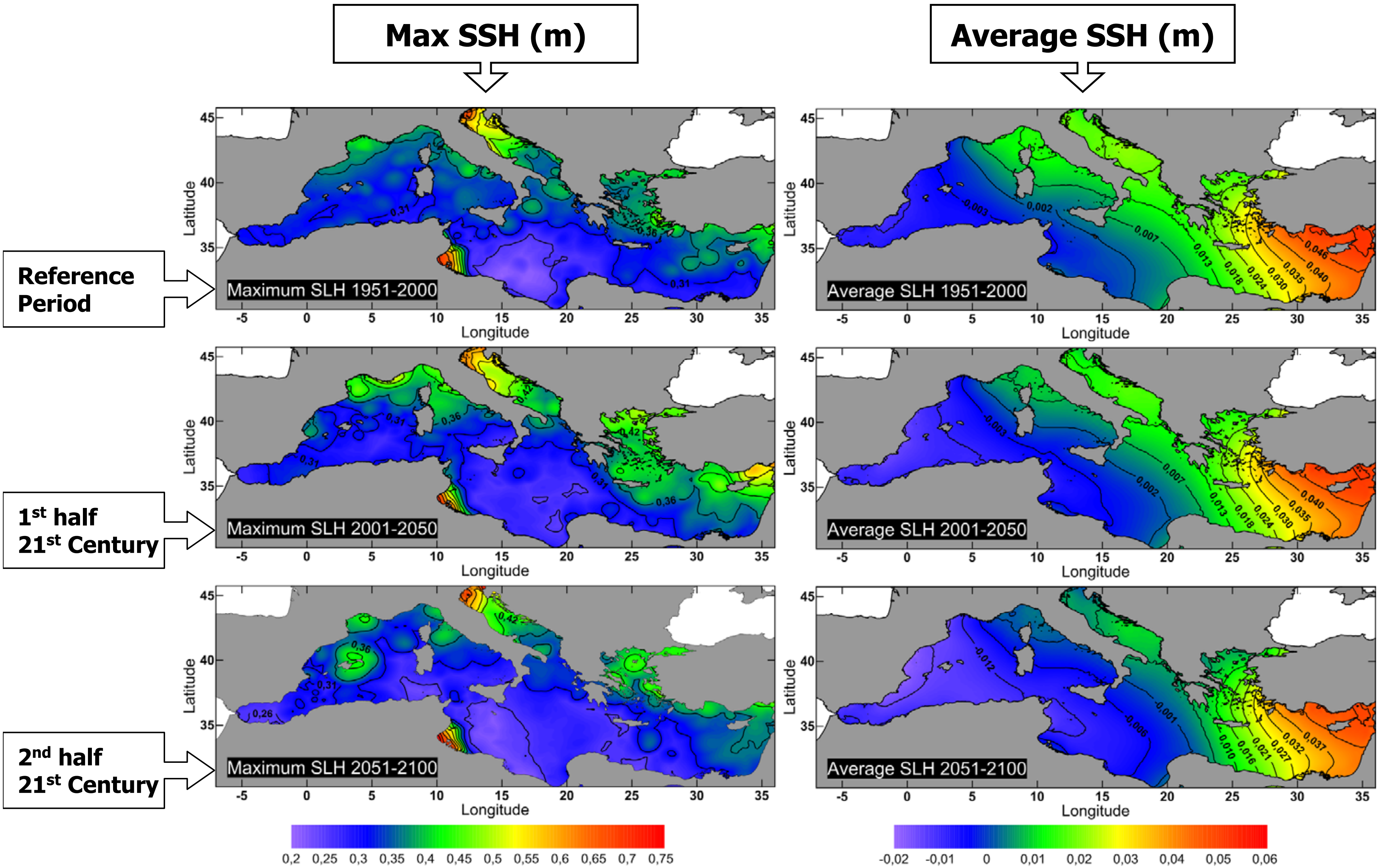

Results Mediterranean Extreme Storm Surges

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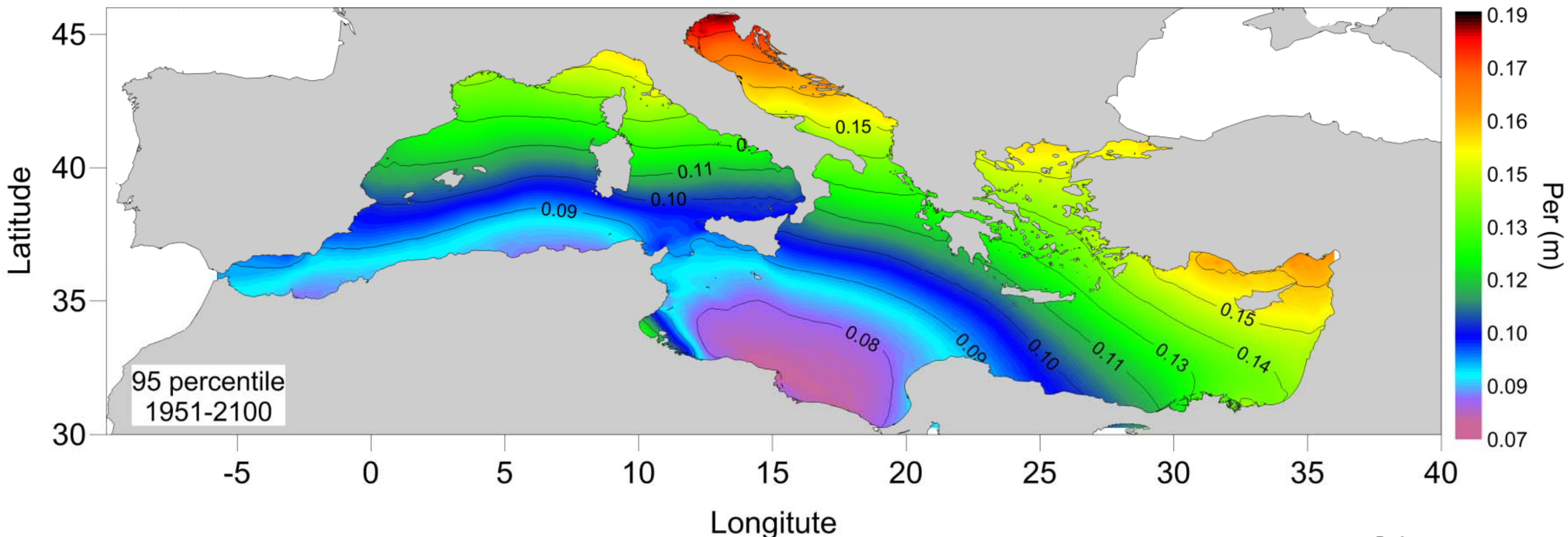
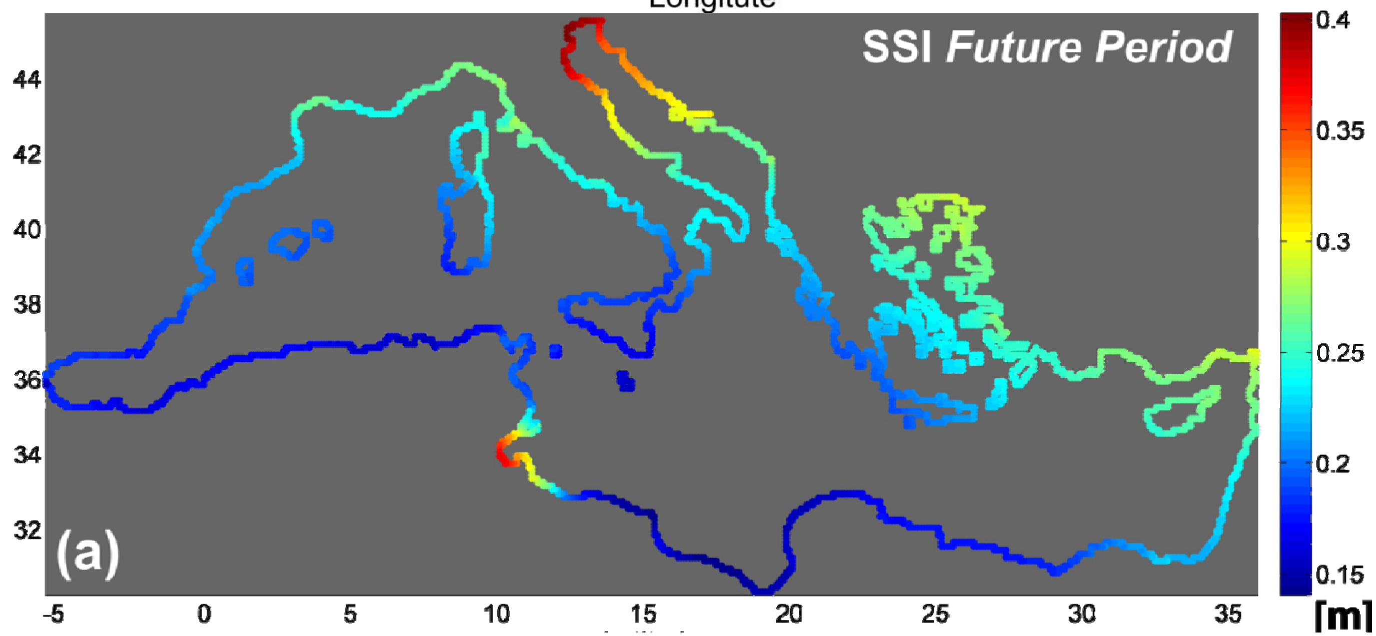
Maps of 95th Percentile of SSH (m) and SSI (m)

for the entire simulation period (1951-2100) and the A1B-scenario Run (2001-2100) respectively

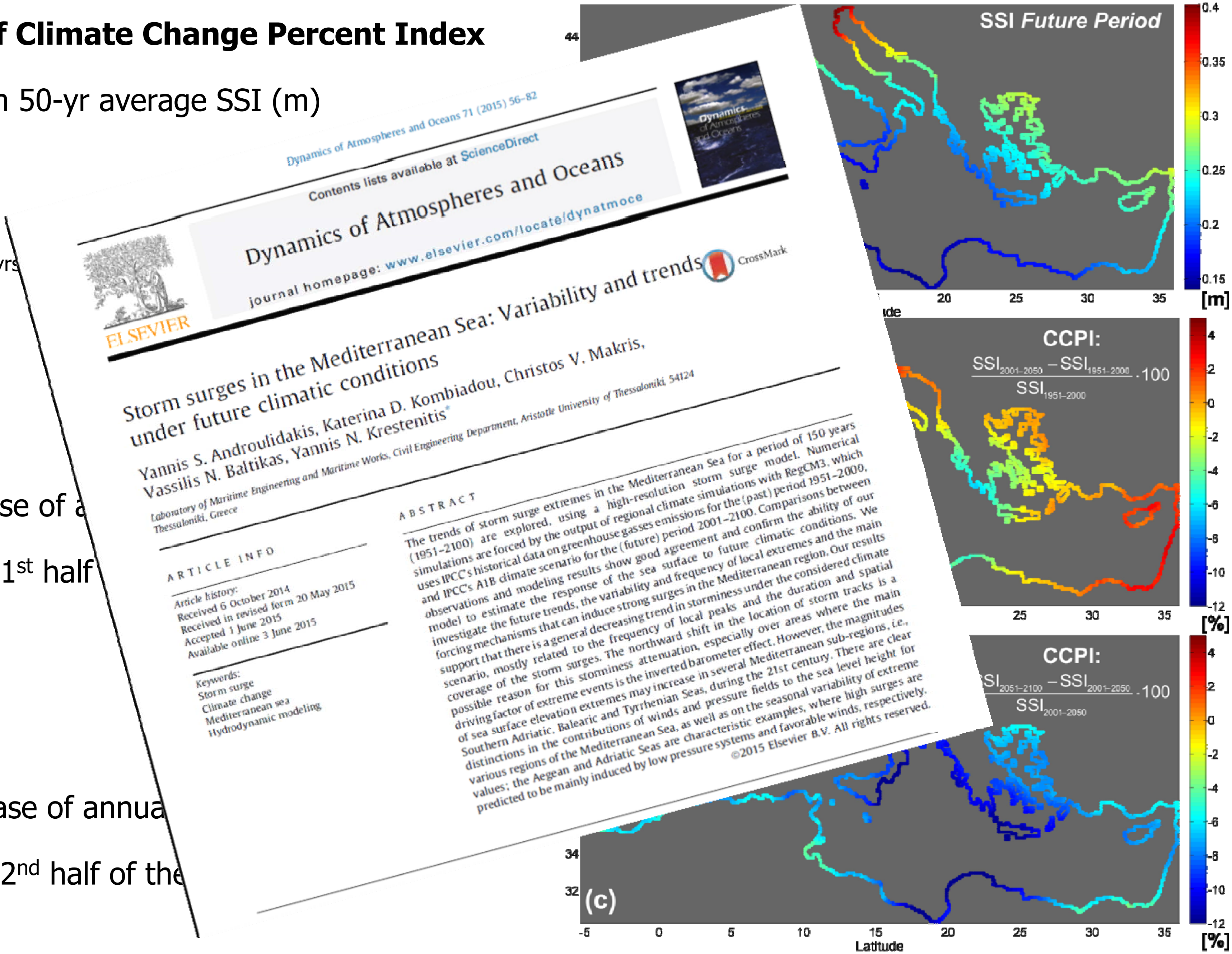




Maps of Climate Change Percent Index

based on 50-yr average SSI (m)

- SSI^{100yrs}
- Increase of a
  in the 1st half
- Decrease of annua
  in the 2nd half of the



Dynamics of Atmospheres and Oceans 71 (2015) 56–82

Contents lists available at ScienceDirect

Dynamics of Atmospheres and Oceans

journal homepage: www.elsevier.com/locate/dynatmoce

ELSEVIER

Storm surges in the Mediterranean Sea: Variability and trends under future climatic conditions

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ARTICLE INFO

Article history:
Received 6 October 2014
Received in revised form 20 May 2015
Accepted 1 June 2015
Available online 3 June 2015

Keywords:
Storm surge
Climate change
Mediterranean sea
Hydrodynamic modeling

ABSTRACT

The trends of storm surge extremes in the Mediterranean Sea for a period of 150 years (1951–2100) are explored, using a high-resolution storm surge model. Numerical simulations are forced by the output of regional climate simulations with RegCM3, which uses IPCC's historical data on greenhouse gasses emissions for the (past) period 1951–2000, and IPCC's A1B climate scenario for the (future) period 2001–2100. Comparisons between observations and modeling results show good agreement and confirm the ability of our model to estimate the response of the sea surface to future climatic conditions. We investigate the future trends, the variability and frequency of local extremes and the main forcing mechanisms that can induce strong surges in the Mediterranean region. Our results support that there is a general decreasing trend in storminess under the considered climate scenario, mostly related to the frequency of local peaks and the duration and spatial coverage of the storm surges. The northward shift in the location of storm tracks is a possible reason for this storminess attenuation, especially over areas where the main driving factor of extreme events is the inverted barometer effect. However, the magnitudes of sea surface elevation extremes may increase in several Mediterranean sub-regions, i.e., Southern Adriatic, Balearic and Tyrrhenian Seas, during the 21st century. There are clear distinctions in the contributions of winds and pressure fields to the sea level height for various regions of the Mediterranean Sea, as well as on the seasonal variability of extreme values; the Aegean and Adriatic Seas are characteristic examples, where high surges are predicted to be mainly induced by low pressure systems and favorable winds, respectively.

Further Research Coastal Inundation Risk for Climate Change

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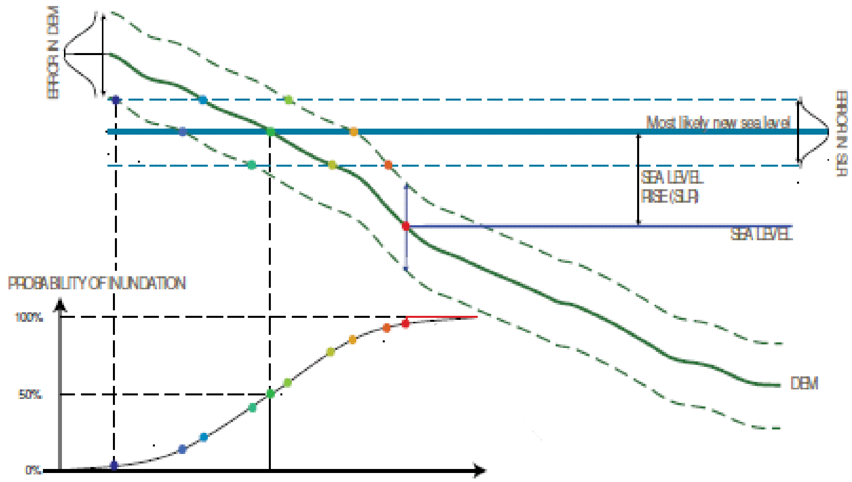
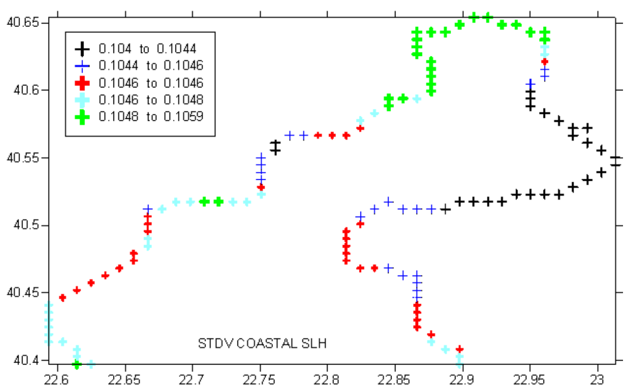
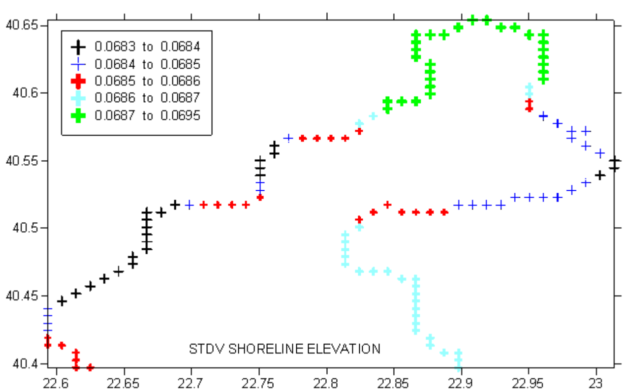


Depiction of the proposed coastal zone flood model under Climate Change





FUTURE STEPS

1) Combined RMS error:

$$STDV = \sqrt{\left(STDV_{H_{DEM}}^{2} + STDV_{H_{SLR,Y}}^{2}\right)}$$

2) Return Levels of SSH (m) through **GEV**:

$RV_{SSH,Y}$ for year Y = 2015, 2030, 2050, 2070, 2100

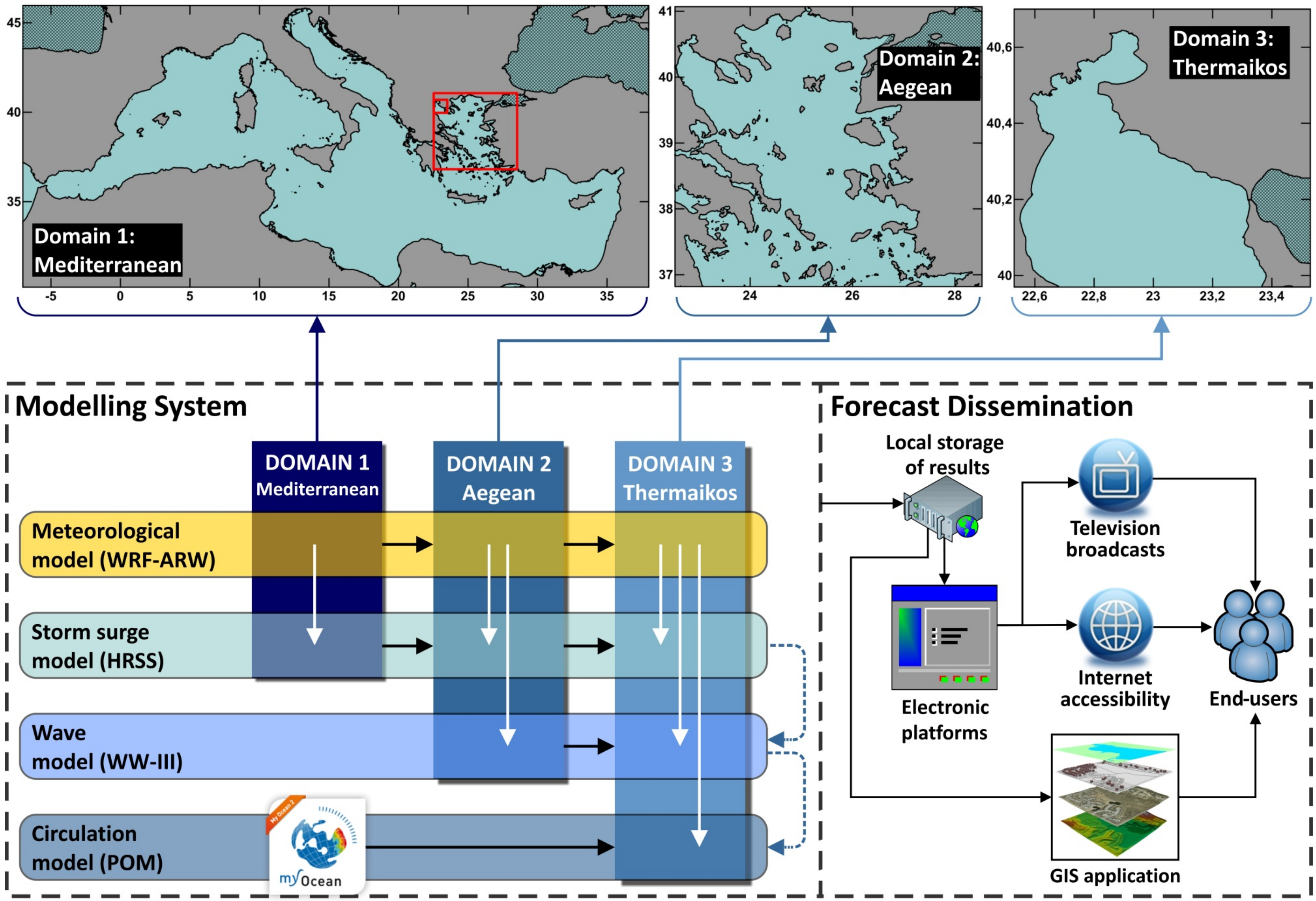
3) Combined Sea Level Rise $H_{SLR,Y}=SLR_{Y}+RV_{SSH,Y}$

4) Probable inundation based on Z:

$$Z = \left|\frac{H_{SLR} + H_{DEM}}{STDV}\right|$$

5) Categorization of a coast based on inundation probability P (%) by cumulative normal distribution curve

Application domain – Model coupling – Schematic representation of forecast apps



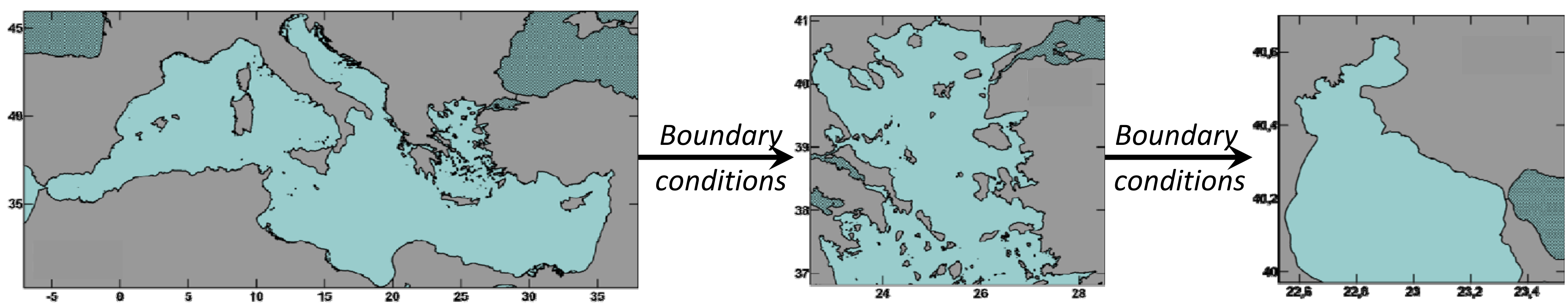
WaveForUs Storm Surge Model

High Resolution Storm Surge (HRSS) model

HRSS is a 2-D hydrodynamic model that simulates the changes to the mean Sea Level Height (SLH) taking into account:

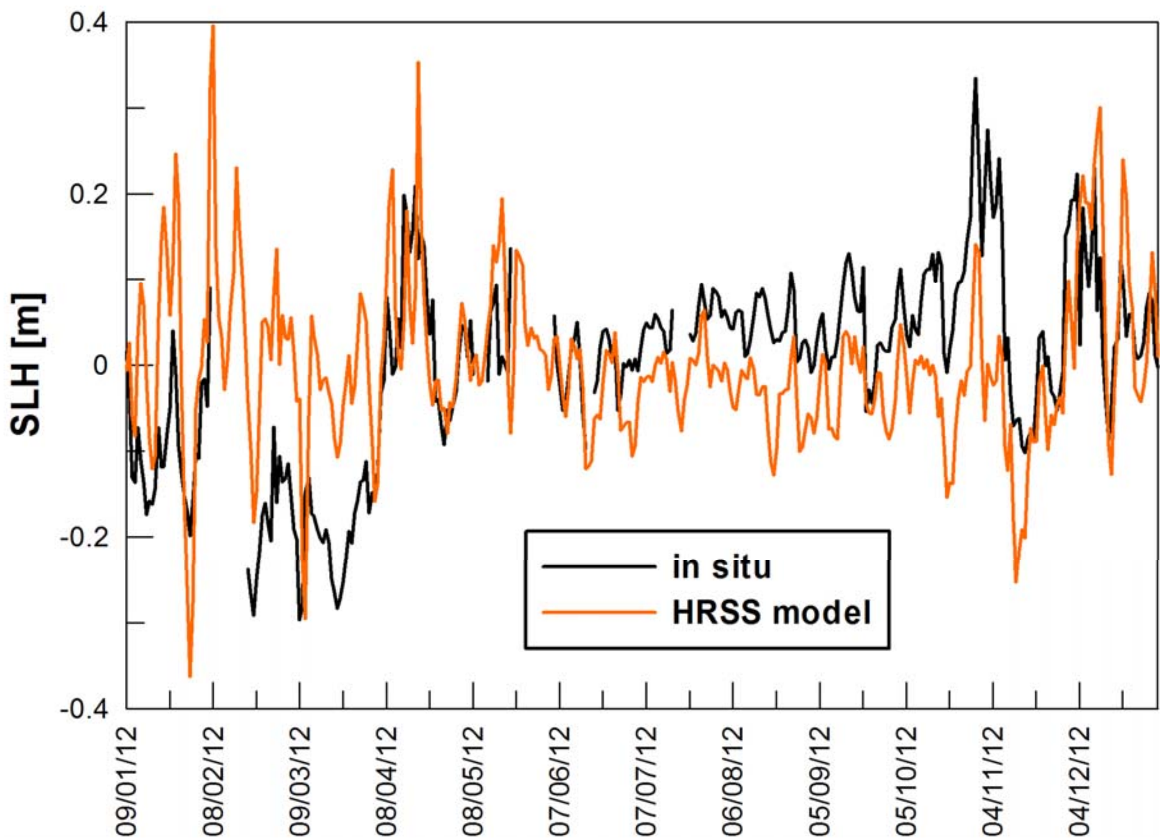
- Atmospheric forcing (wind and pressure fields)
- **Astronomical Tides** – Tidal Model (Schwiderski, 1980)
- Geostrophy
- Surface and seabed shear stresses
- **Impact of waves** (superposition with WW-III wave-induced sea surface set-up)
- Model results: **SSH** & **depth averaged currents**

15 Km x 15 Km | **5 Km x 5 Km** | **1.68 Km x 1.68 Km**



HRSS model validation using insitu tidal gauge data from the Thessaloniki port

Local comparisons with HNHS point-measured data



- plausible reproduction of SSH evolution
- representation of local maxima
- low MAE (0.094m±0.068m)
- depreciation (July-October)
- tidal gauge inside the port basin → local phenomena (reflections, oscillations, etc)

WaveForUs Validation HRSS for the Mediterranean

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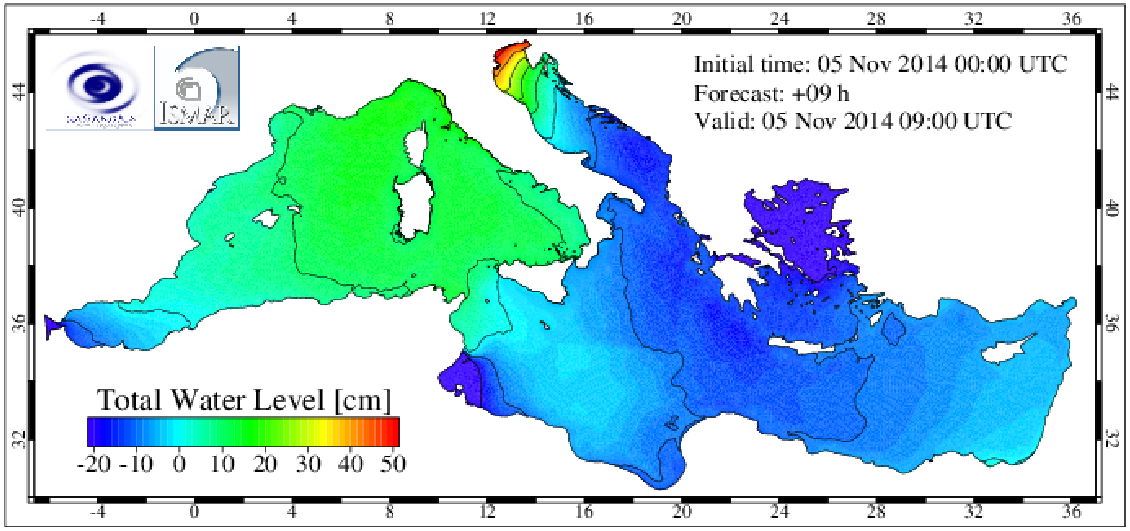
HRSS model validation using comparison against KASSANDRA Project's map data

Spatial comparisons with similar operational systems



KASSANDRA

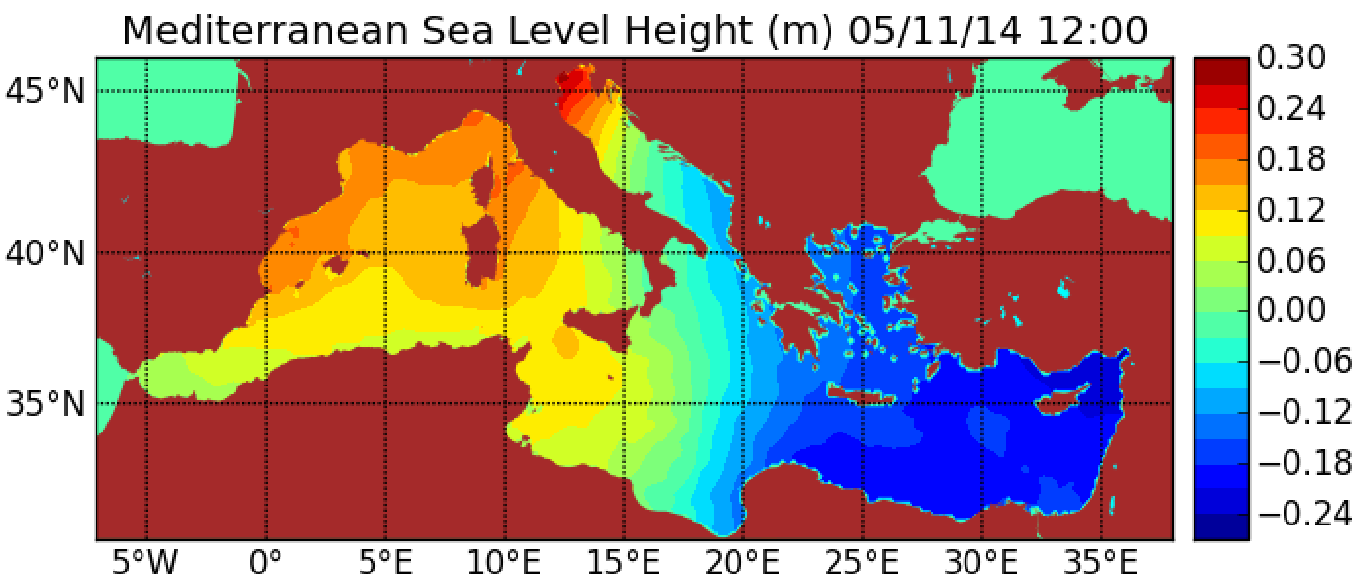
Storm Surge System*

MSL [m]

05/11/14

09:00 UTC

*http://kassandra.ve.ismar.cnr.it:8080/kassandra



HRSS

MSL [m]

05/11/14

10:00 UTC

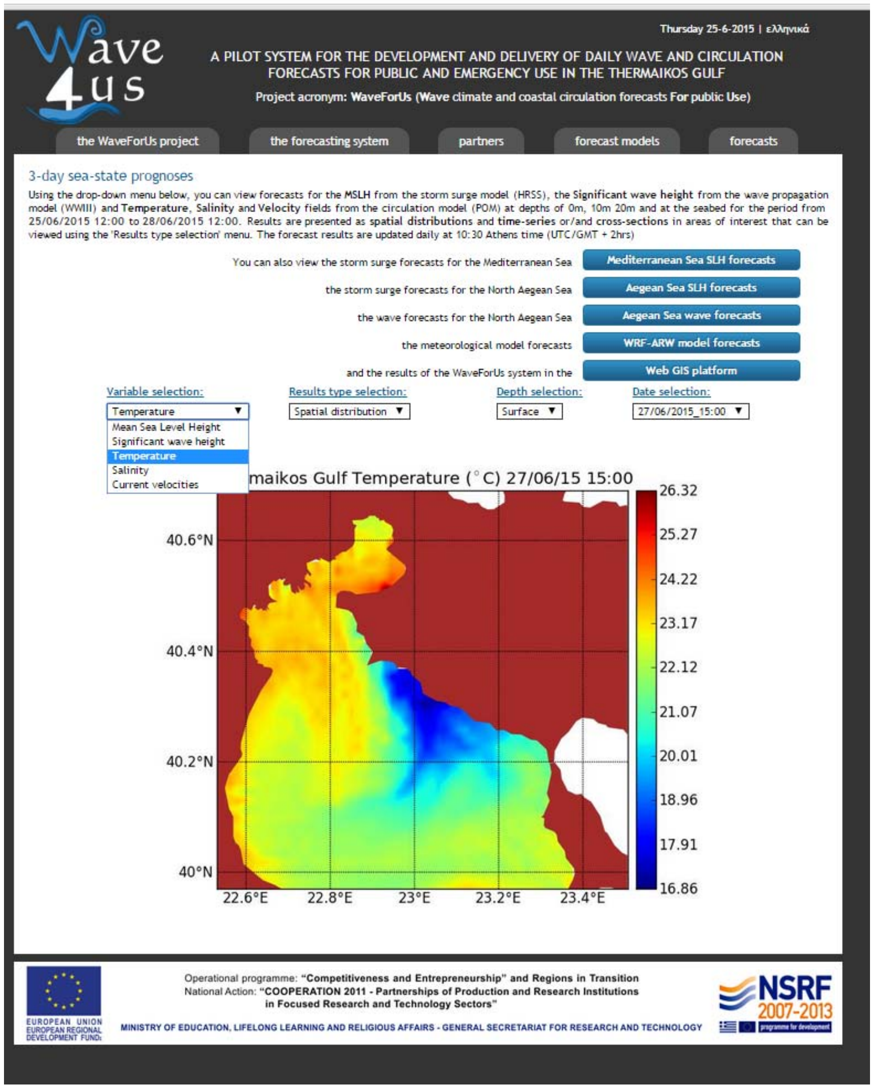
WaveForUs Dissemination Project Website & TV broadcasts

EastMed 2015

High-resolution forecast dissemination channels

http://wave4us.web.auth.gr/index_eng.html

Daily 3-day forecasts at **10:30**



DION/ATLAS TV Broadcasts

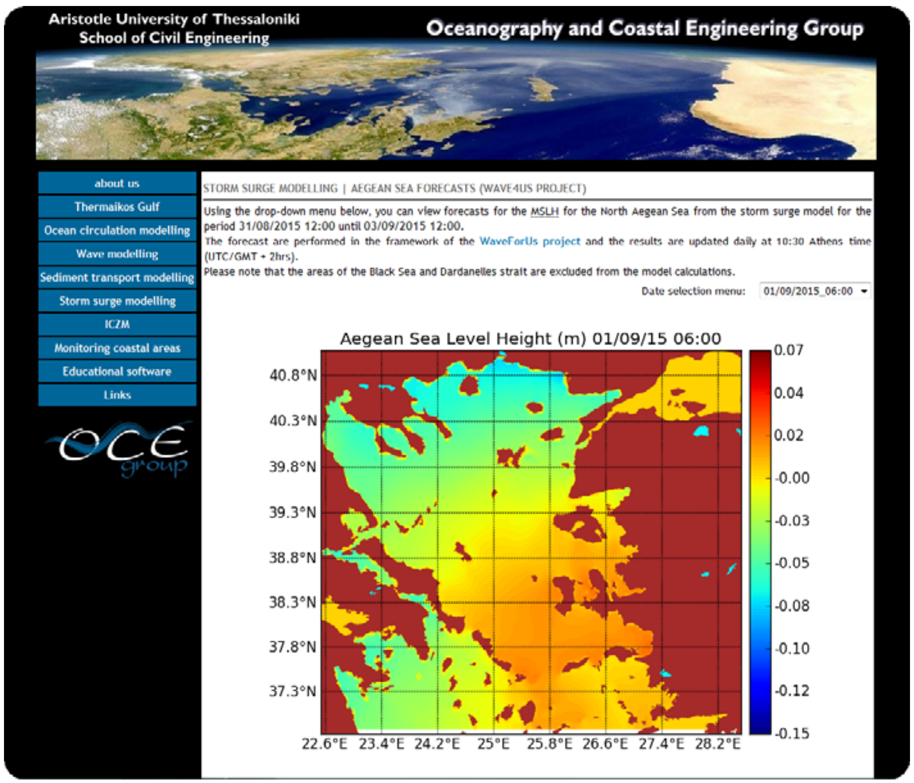
Local northern Greek TV Channel

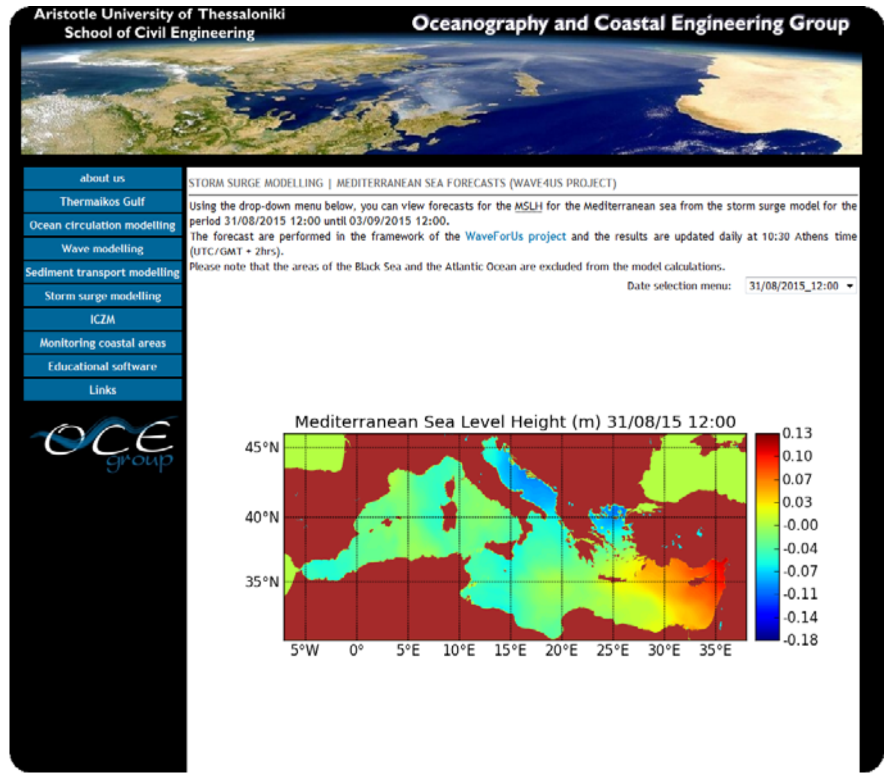
WaveForUs Dissemination OCE Website & Web-GIS Platform

Forecast dissemination channels

Daily 3-day forecasts at **10:30**

http://coastal.web.auth.gr/





http://ecoplan.static.otenet.gr:8079/WForUsApp/AppStart.html

Conclusions MeCSSM and GreCSSM

- Acceptable to good performance of climatic storm surge model in Mediterranean, Aegean and Ionian seas is verified by in situ observations (annual, absolute maxima and statistical measures)

- North Adriatic SSH maxima highest in the Mediterranean
North Aegean SSH maxima higher than Central/South Aegean and Ionian

- Absolute extreme of annual SSH maxima is estimated to increase in the 21st century under IPCC SRS-A1B

- Seasonal occurrence of Storm Surge maxima is estimated similar in all stations in the future

- Signals of Climate Change Impact based on annual extremes on the coastal zone:
Increase in the 1st half of the 21st century
Decrease in the 2nd half of the 21st century

- Evolution of annual SSH maxima (2000-2100) in regional seas appears to slightly increase around the middle of the 21st century and decline towards 2100. Average SSH remains stable from the past to 2050 and is estimated to decrease slightly ~1 mm in the Levantine Sea

- Storminess attenuation corroborated: Storm Surge events duration and spatial coverage are estimated to decrease with 95% confidence in all regional seas of the Mediterranean

- Final Step: Greek coastal zone categorization based on inundation risk due to return levels of storm surge induced SSH

Conclusions WaveForUs

- WaveForUs is already providing daily forecast results through the program webpage (http://wave4us.web.auth.gr/), a web-GIS application and 6 daily TV broadcasts.

- Evaluation of the simulations showed the effectiveness of the sea-state forecasts is quite satisfactory. Acceptable to good performance of forecast storm surge model in the Mediterranean, Aegean and Ionian seas is verified by in situ observations.

- The WaveForUs forecasting system may be a very useful and somewhat reliable tool for users and their everyday sea-based activities.

- On-going work:

Survey with questionnaires in order

- to evaluate the public response to the WaveForUs system
- to produce more friendly-user products to general public and more useful products to professionals

Acknowledgements

1. This research has been co-funded by the EU (European Social Fund – ESF) and Greek national funds through the Operational Program **Education and Lifelong Learning** of the National Strategic Reference Framework (NSRF) Research Funding Program: **THALES – Investing in knowledge society through the European Social Fund** under the Project **CCSEAWAVS**. **WaveForUs** project is funded by the national action **COOPERATION 2011:** Partnerships of Production and Research Institutions in Focused Research and Technology Sectors in the framework of the operational program **Competitiveness and Entrepreneurship** (NSRF 2007-2013)

2. The authors are grateful to Y. **Tegoulias**, C. **Anagnostopoulou** and D. **Tolika** (Dept. of Meteorology and Climatology, AUTh) for providing the atmospheric fields produced by RegCM3 model and used as forcing input for the storm surge simulations of our study.

3. The authors are also grateful to **MedGLOSS** and **HNHS** for providing in situ tide-gauge data used for validation of the storm surrge model performance, and **MyOCEAN (Copernicus)** for initial condition fields in the Mediterranean.

Co-financed by Greece and the European Union

Ministry of Education, Lifelong Learning and Religious Affairs - GSRT
O.P. Competitiveness and Entrepreneurship (OPC II), O.P. Macedonia-Thrace

Model Validation Local Maxima Occurrence

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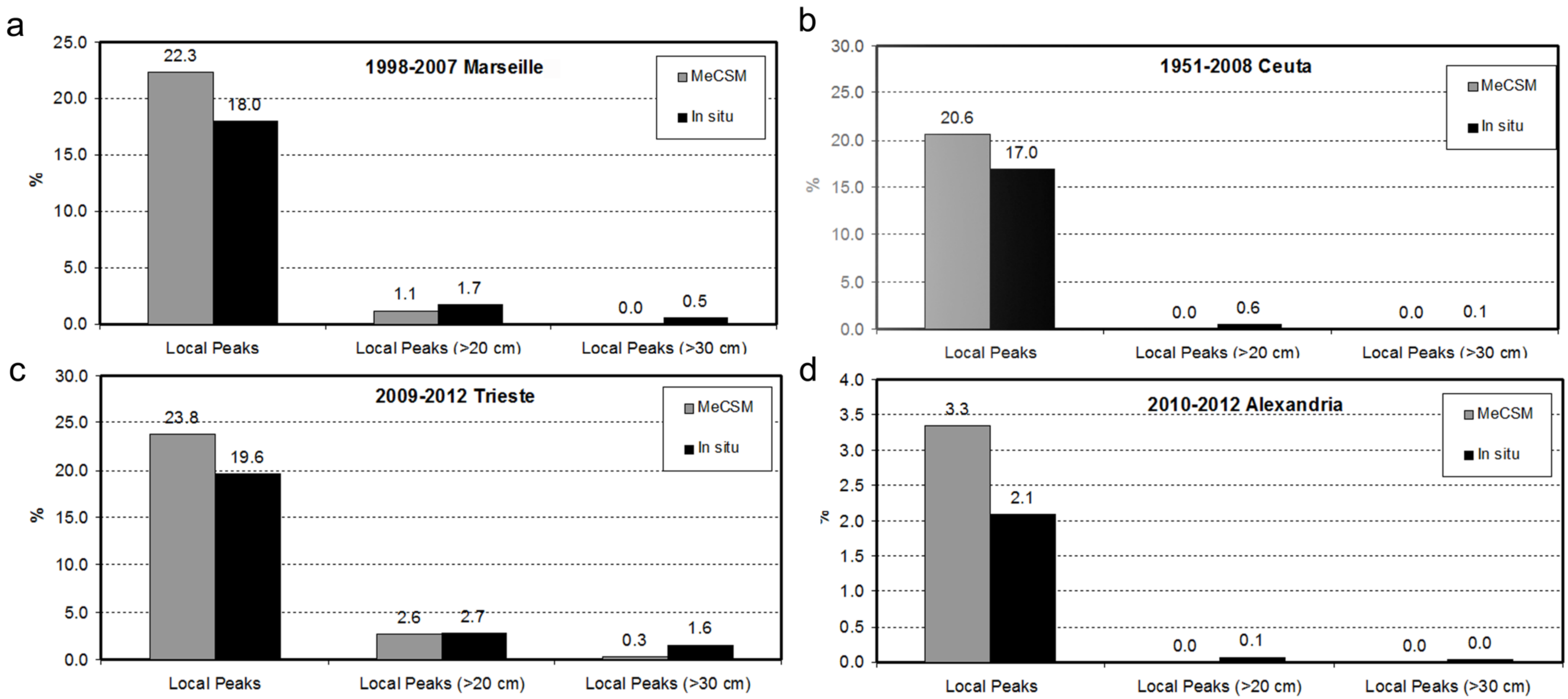
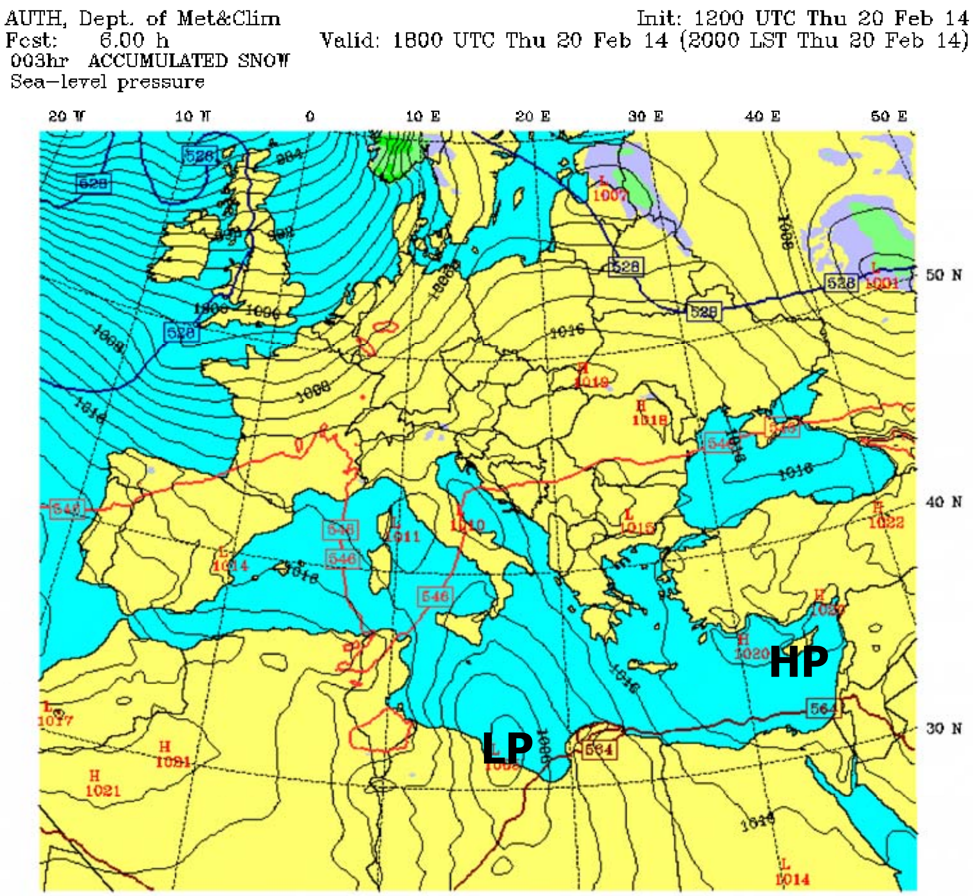
Comparisons In Situ vs. Model based on Percentage of Local Maxima (%)

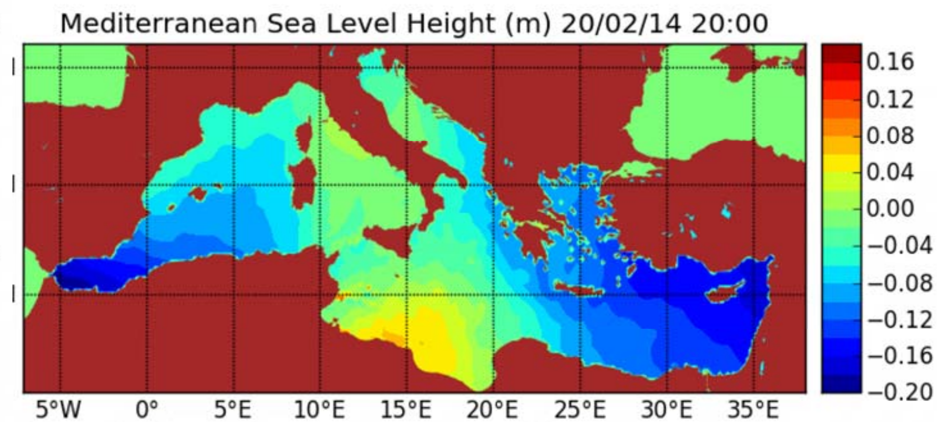
MeCSSM implementation in 4 Mediterranean Stations



HRSS model results of MSL compared to the SLP forcing field by WRF-ARW



LP → sea level **rise**
HP → sea level **drop**



Atmospheric Pressure SLP
WRF-ARW: Mediterranean domain

Mean Sea Level MSL
HRSS: Mediterranean domain