ISPRA
Istituto Superiore per la Protezione e la Ricerca Ambientale

Sistema Nazionale per la Protezione dell'Ambiente

SUMMER SCHOOL WORKSHOP

ACTION 2020-2-21:
COPERNICUS
FOR CULTURAL HERITAGE

Cyprus University of Technology

DLR

Future climate in the Mediterranean Sea: a focus on sea-level change

Gianmaria Sannino

ENEA

13-16.06.2023

PARCO REGIONALE DELL'APPIA ANTICA
Ex Cartiera Latina - Via Appia Antica, 42

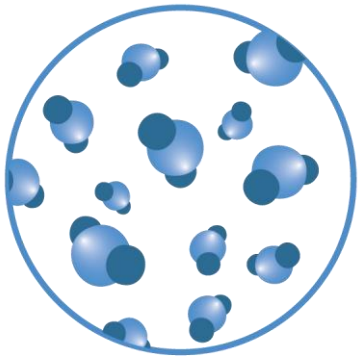
[Credit: NASA]

"Recent changes in the climate are widespread, rapid, and intensifying, and unprecedented in thousands of years.

ipcc
INTERGOVERNMENTAL PANEL ON climate change

WMO UNEP

CO_2 concentration



Highest

in at least

2 million years

Sea level rise

Fastest rates

in at least

3000 years

Arctic sea ice area

Lowest level

in at least

1000 years

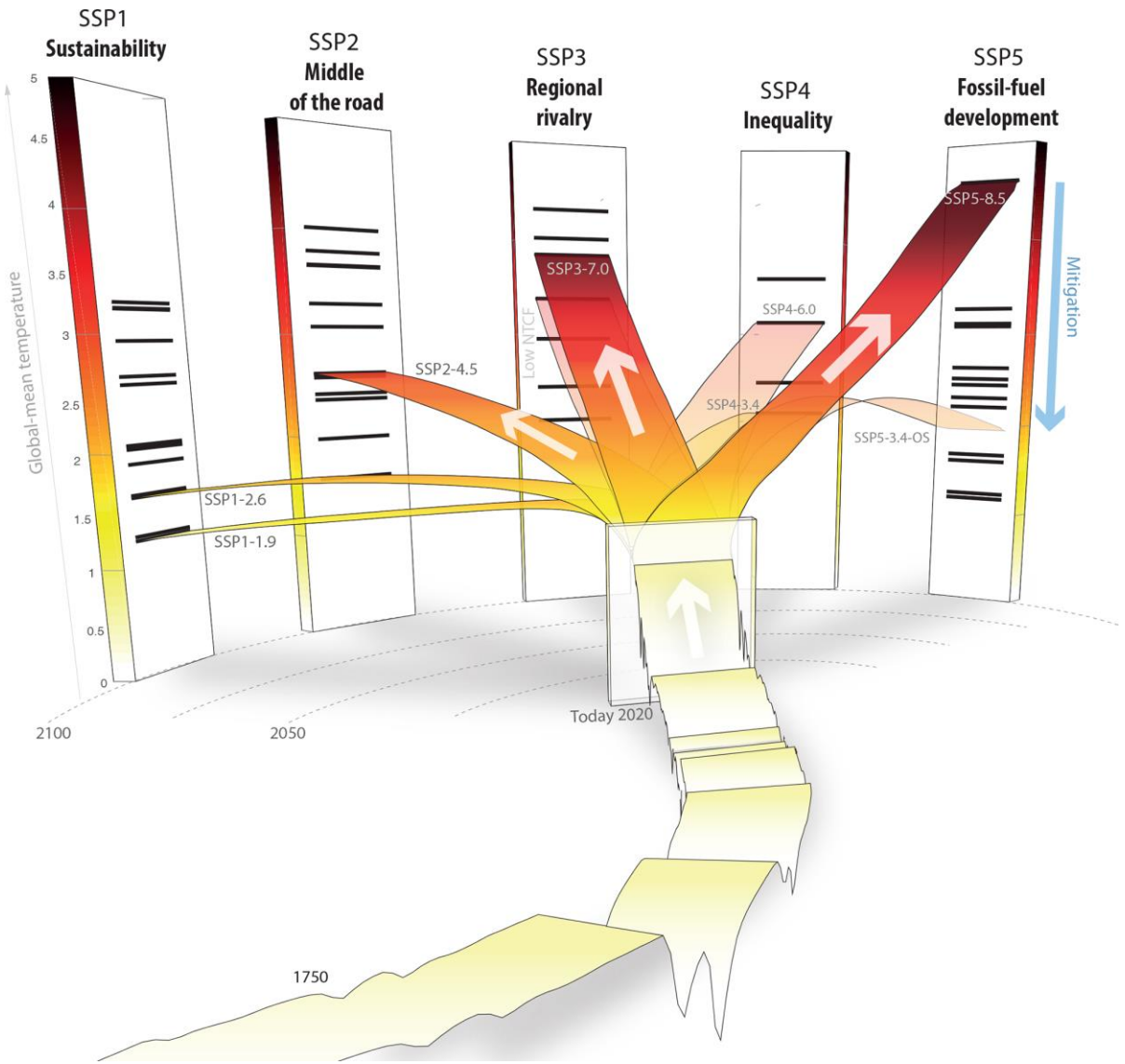
Glaciers retreat

Unprecedented

in at least

2000 years

Shared Socioeconomic Pathways & Temperature

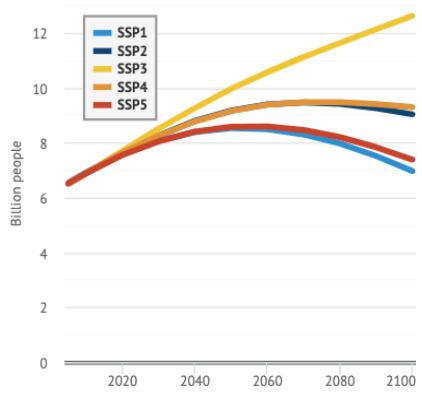


Meinshausen et al, GMD 2020

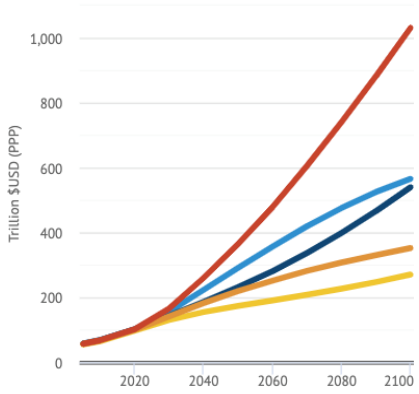
Shared Socioeconomic Pathways & Temperature

CarbonBrief
CLEAR ON CLIMATE

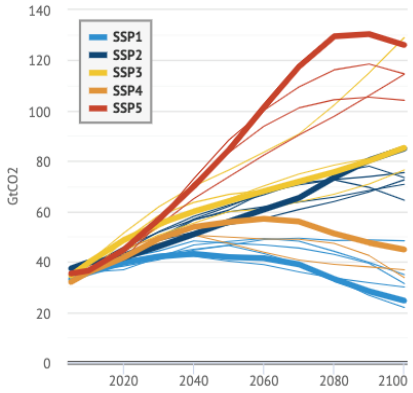
Global population



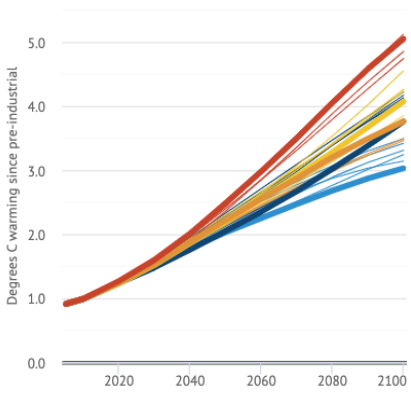
Global GDP

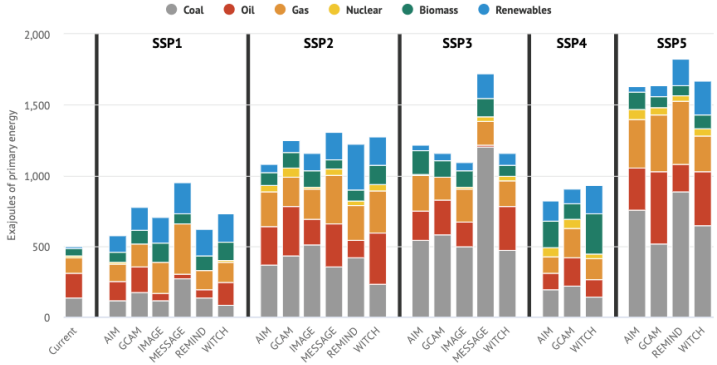


CO2 emissions for SSP baselines



Global mean temperature





SSP1 **Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation)**
The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.

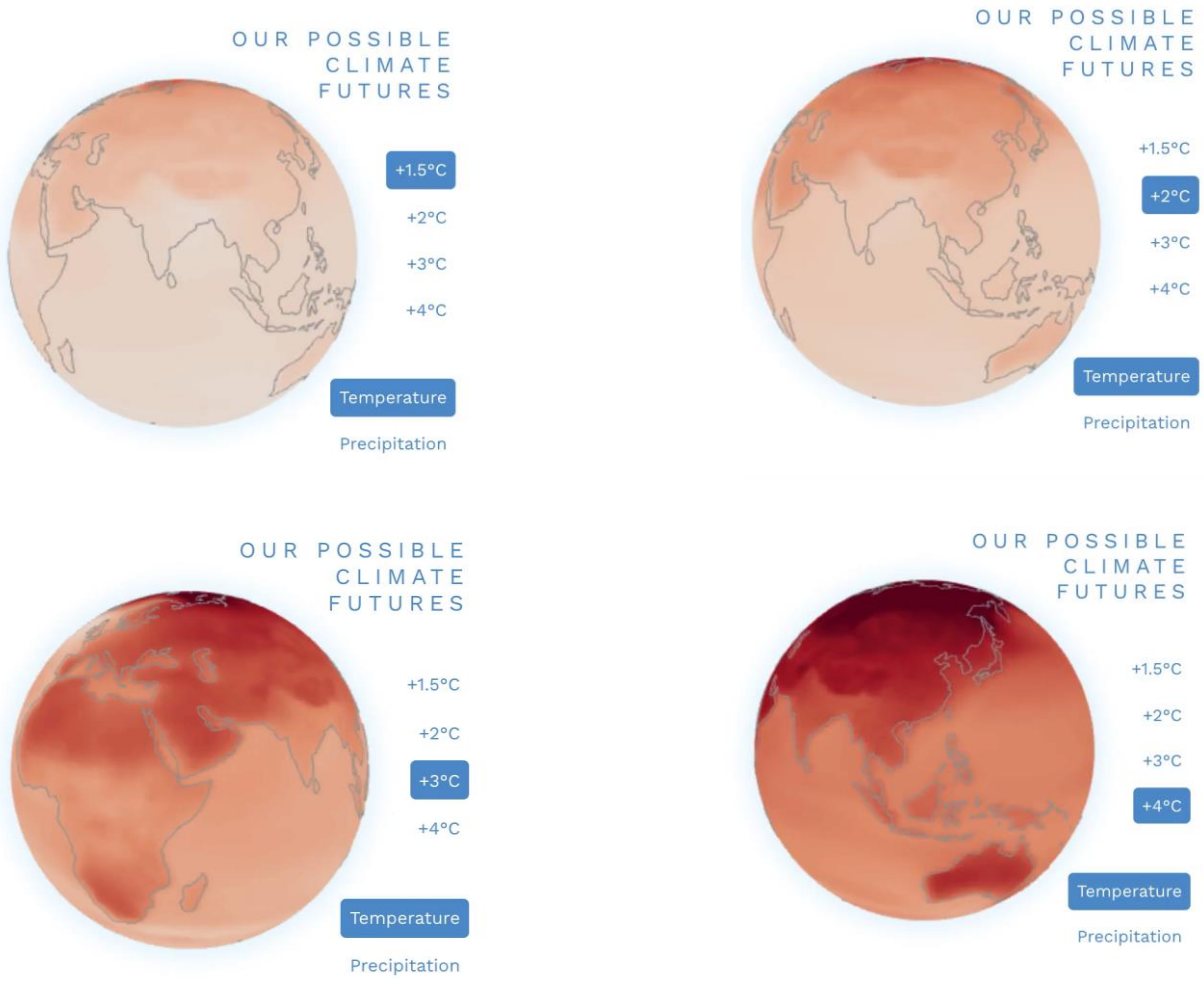
SSP2 **Middle of the Road (Medium challenges to mitigation and adaptation)**
The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain.

SSP3 **Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation)**
A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized and high in developing countries. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.

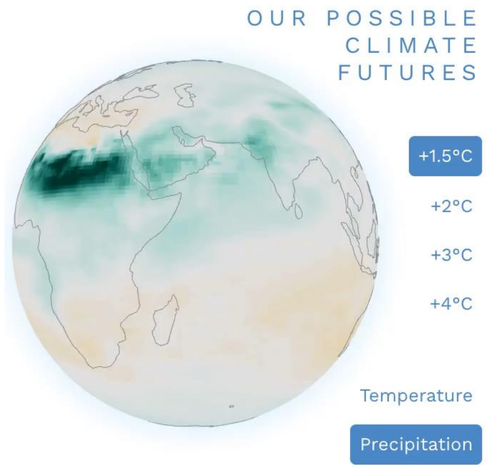
SSP4 **Inequality – A Road Divided (Low challenges to mitigation, high challenges to adaptation)**
Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Over time, a gap widens between an internationally-connected society that contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labor intensive, low-tech economy. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. The globally connected energy sector diversifies, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle and high income areas.

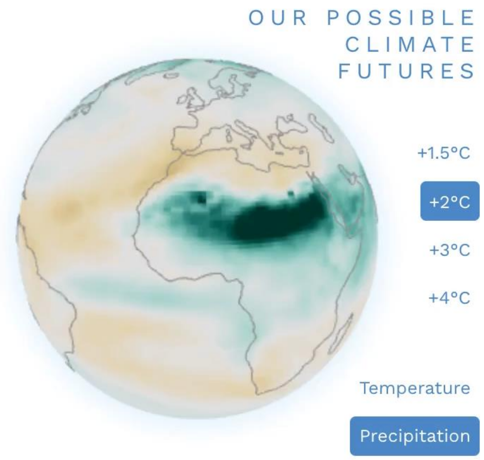
SSP5 **Fossil-fueled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation)**
This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.

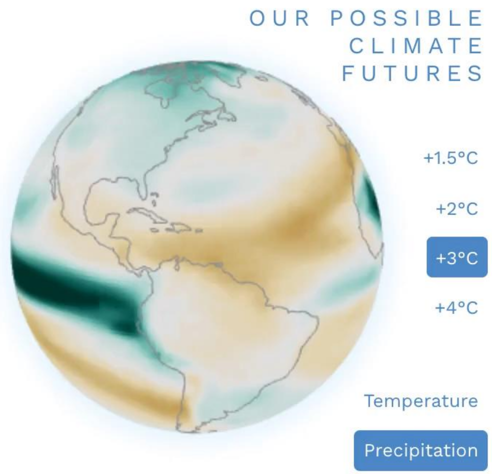
Future climate scenario

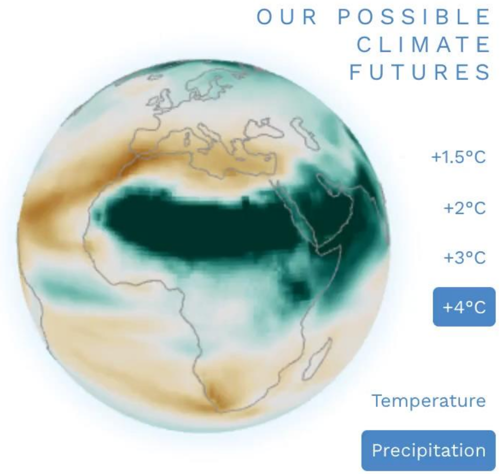


Future climate scenario

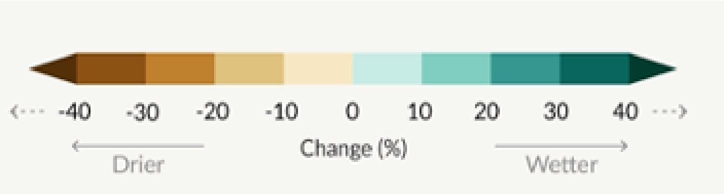




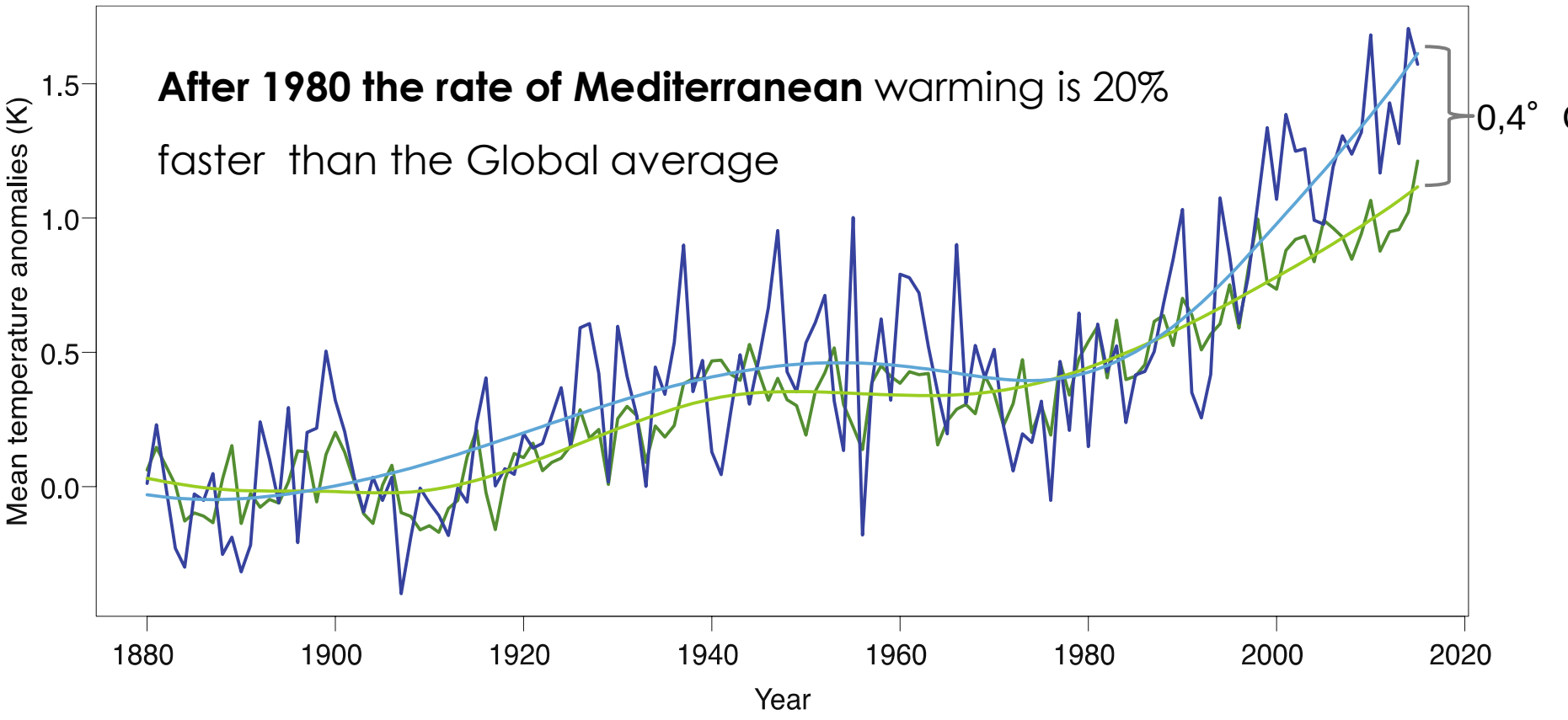




Extreme rainfall intensifies by 7% for each additional 1°C

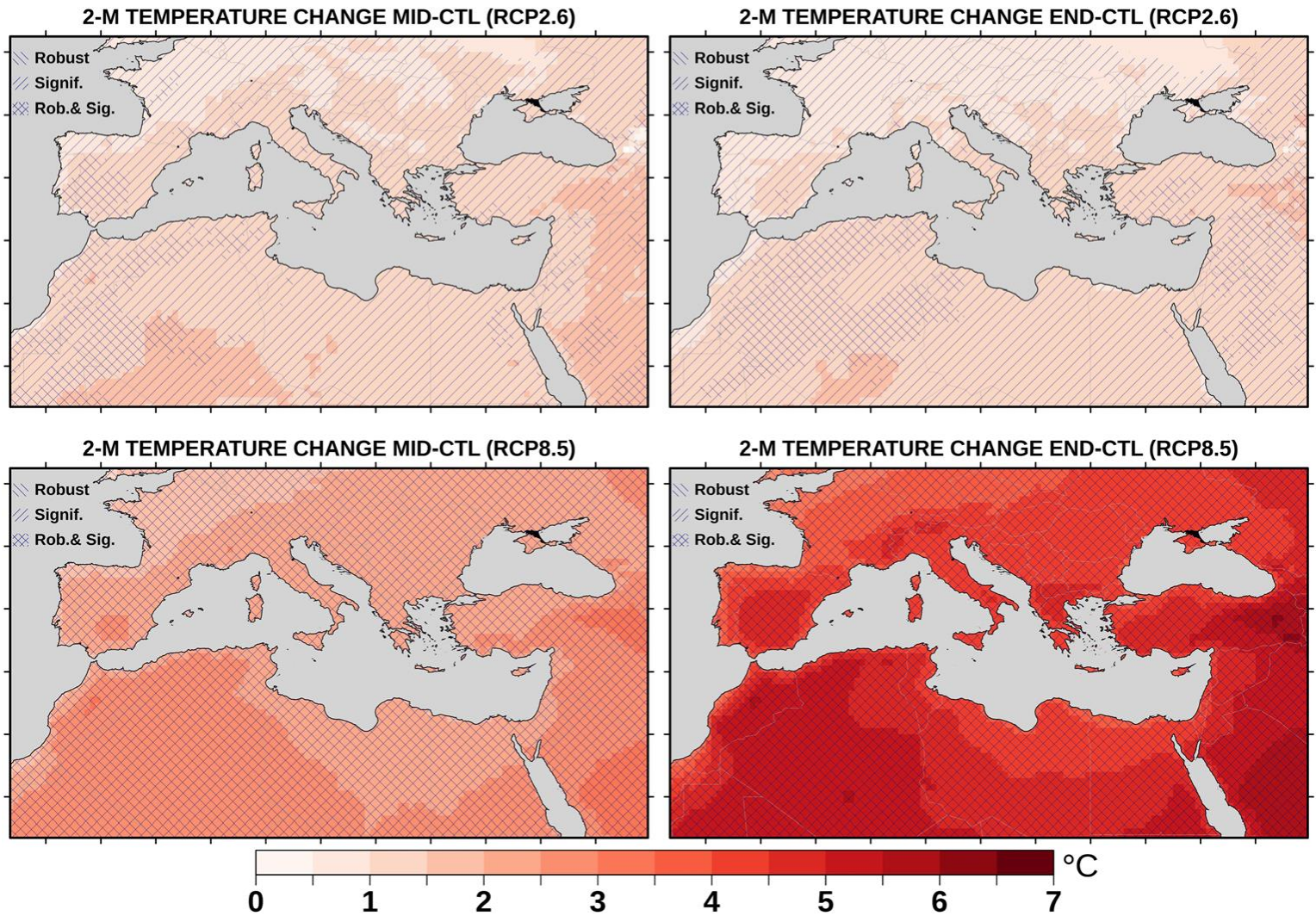


Changes in global vs Mediterranean surface temperature



Historic warming of the atmosphere at Global and Mediterranean scale. Annual mean air temperature anomalies are shown with respect to the preindustrial period (**1880–1899).** Adapted by Cramer et al. 2018 (NCC)

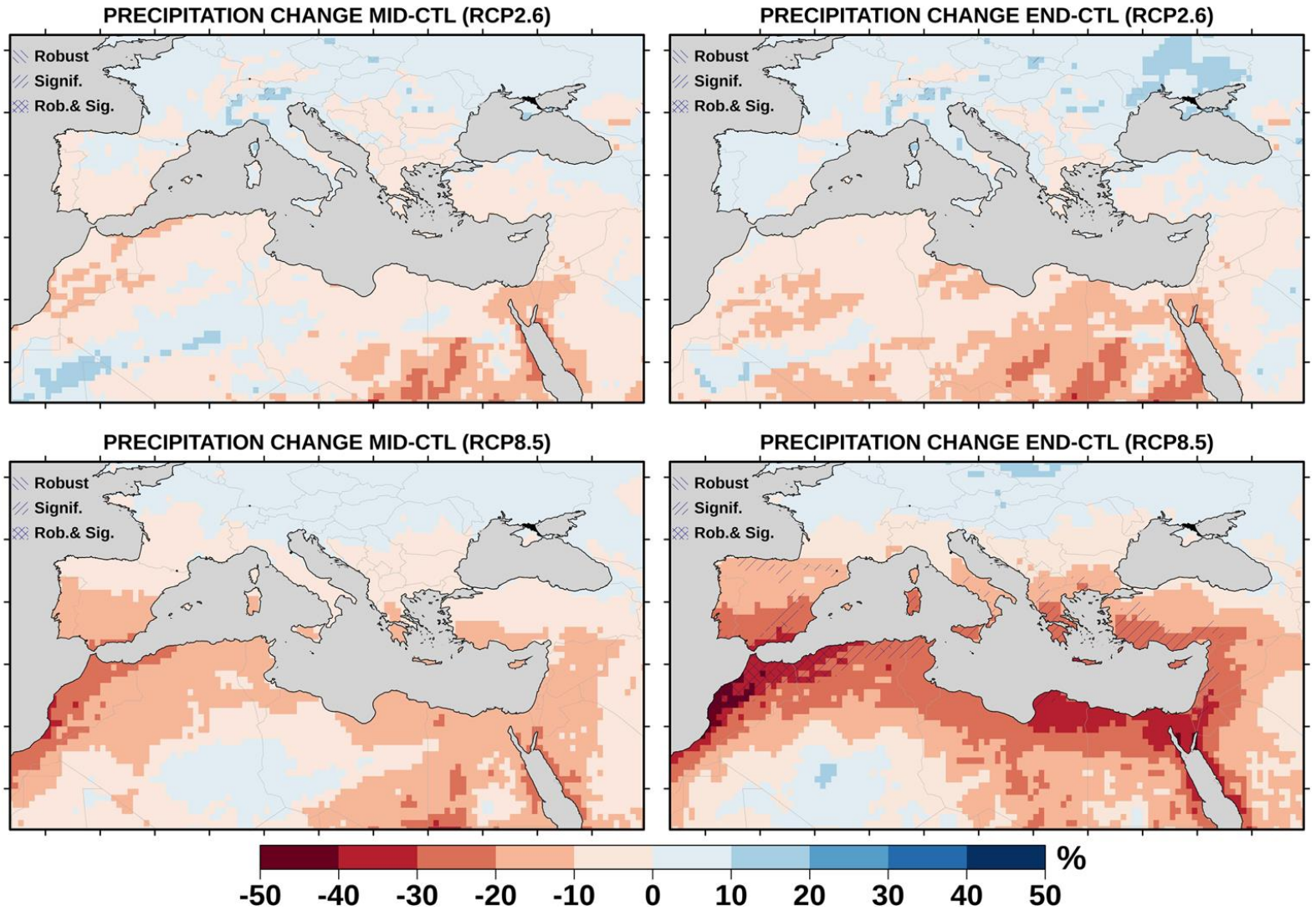
Future Mediterranean Surface Air Temperature



Zittis et al. Regional Environmental Change, 2019

Projected changes of **mean annual temperature** for mid (**MID 2046–2065**) and end (**END 2081– 2100**) of twenty-first century with respect to the reference period (CTL 1986–2005), for three RCP pathways (**RCP2.6**: top row, **RCP8.5**: bottom row). Robustness and significance are indicated c

Future Mediterranean Precipitation

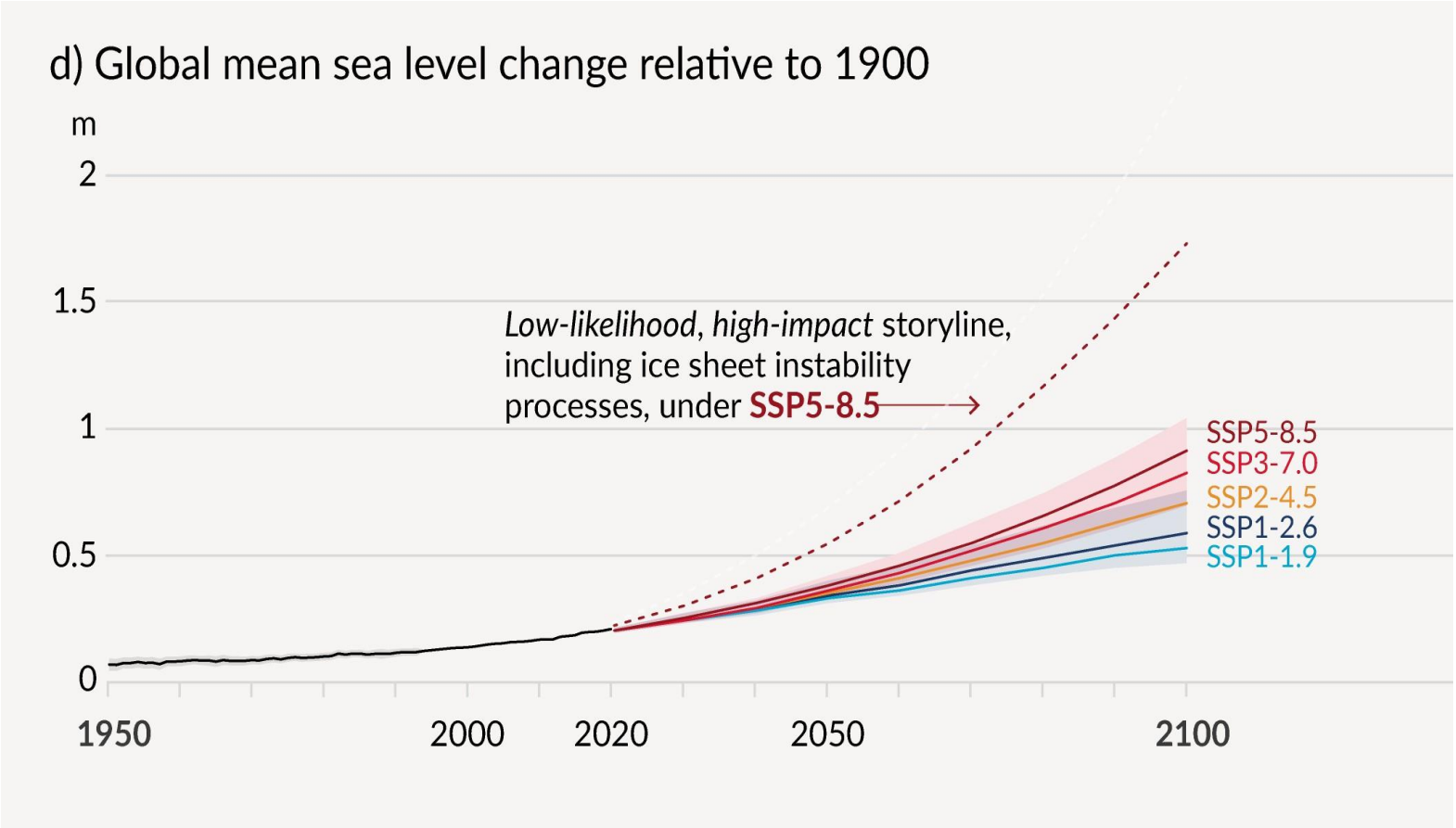


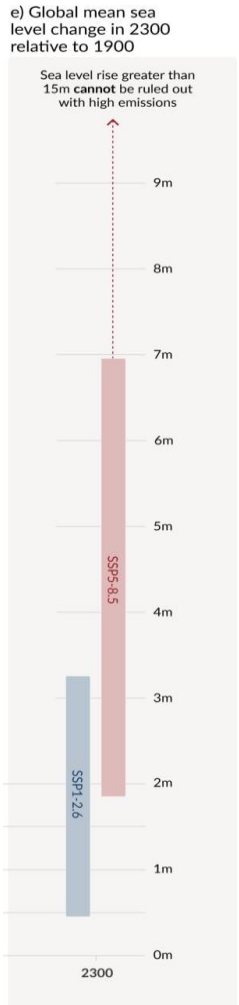
Zittis et al. Regional Environmental Change, 2019

Projected changes of **mean annual precipitation** for mid (**MID 2046–2065**) and end (**END 2081– 2100**) of twenty-first century with respect to the reference period (CTL 1986–2005), for three RCP pathways (**RCP2.6**: top row, **RCP8.5**: bottom row). Robustness and significance are indicated c

Future Scenarios global sea level

Human activities affect all the major climate system components, with some responding over decades and others over centuries

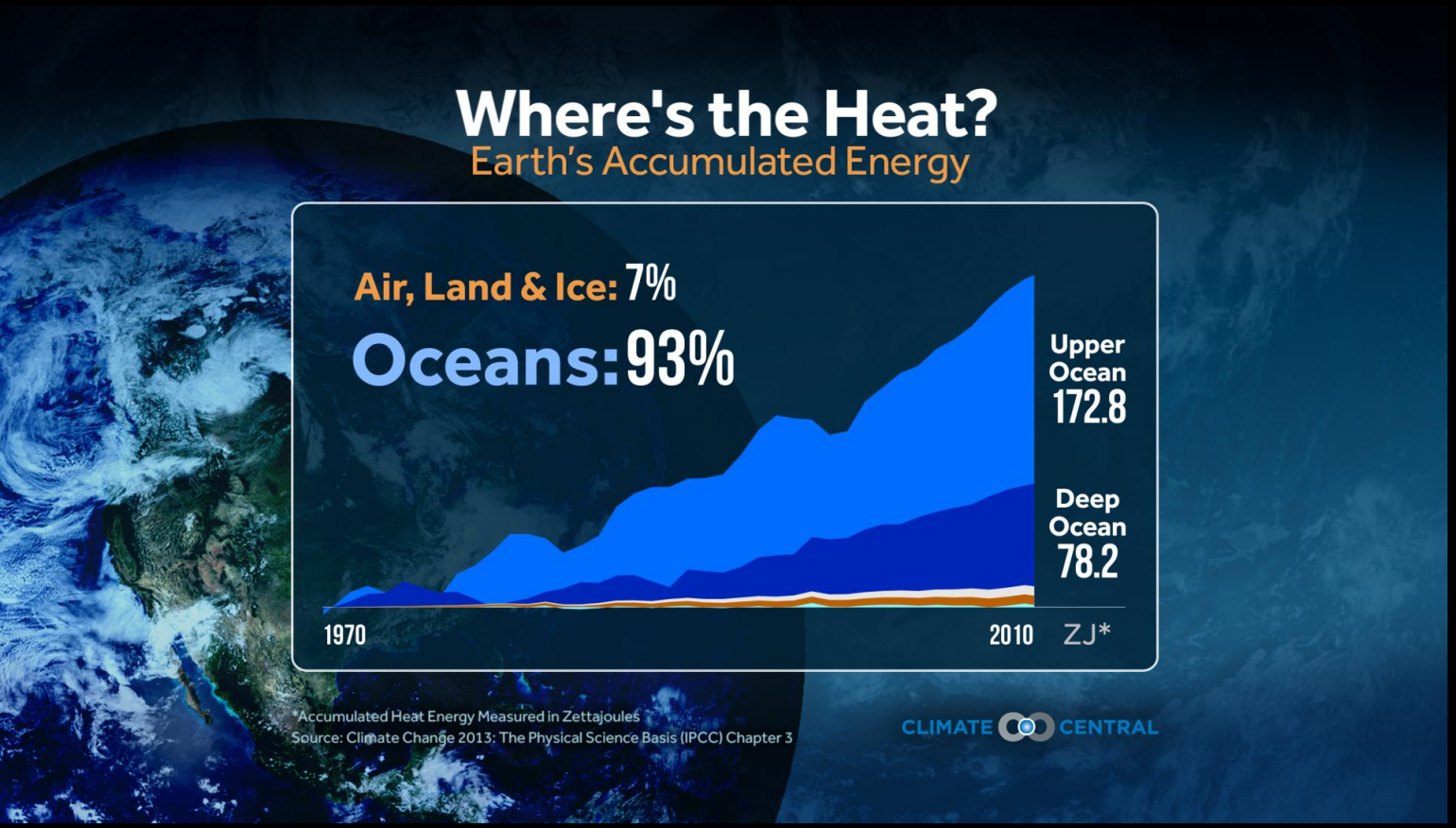




AR6 ipcc
INTERGOVERNMENTAL PANEL ON climate change

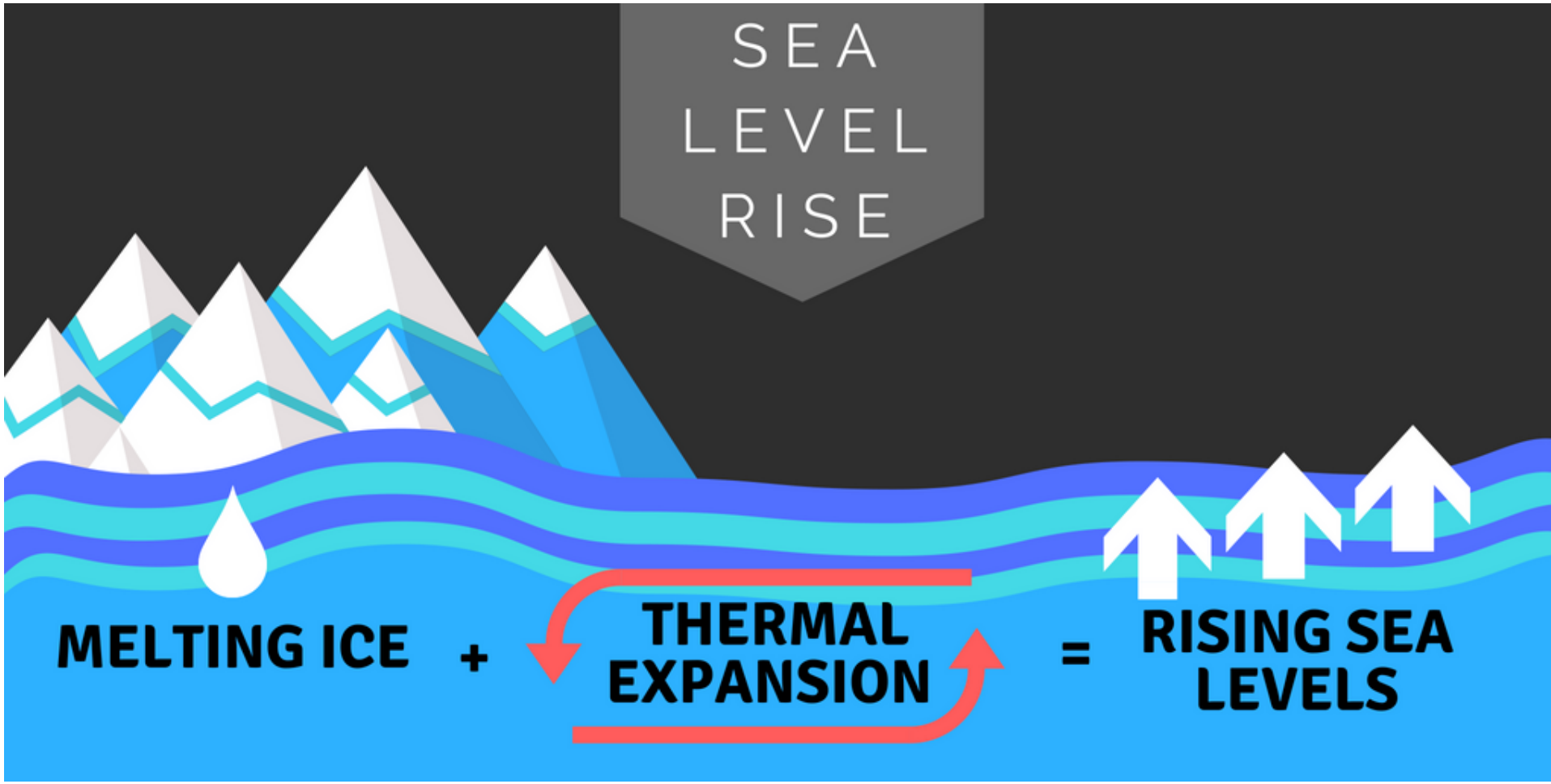
WMO UNEP

Oceans are getting warmer

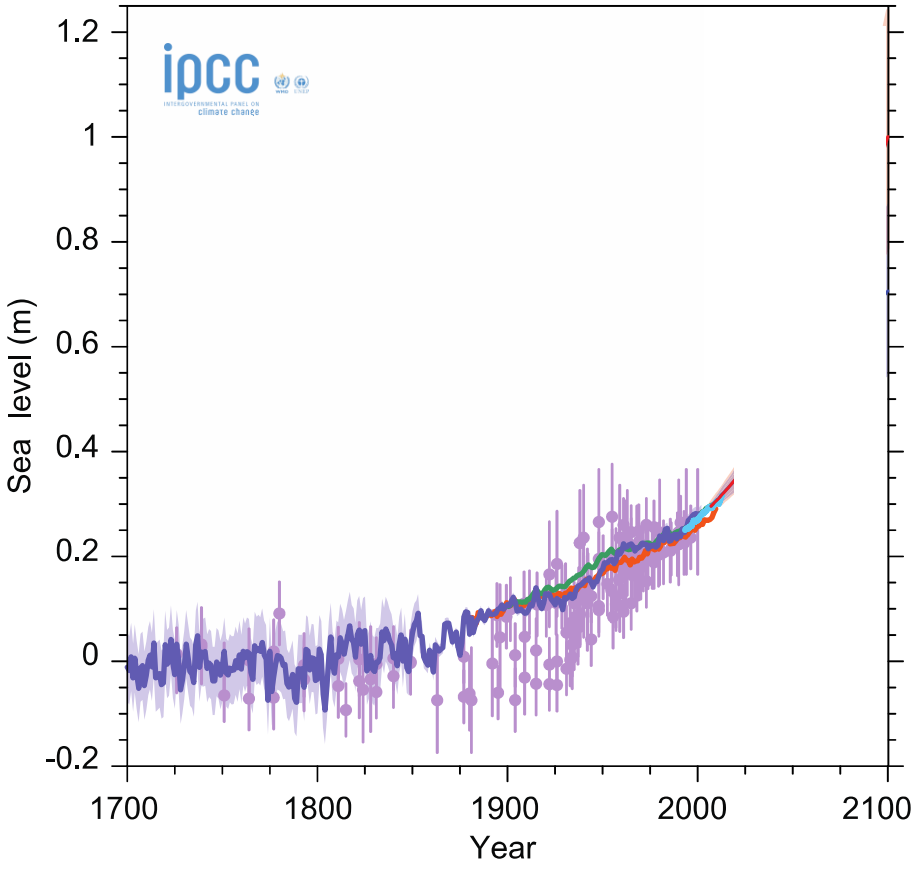


- Most of the heat went into the oceans, not the atmosphere.
- Oceans capture 25% of the CO_2 emitted into atmosphere

Causes of Sea Level Rise



Global sea level since 1700



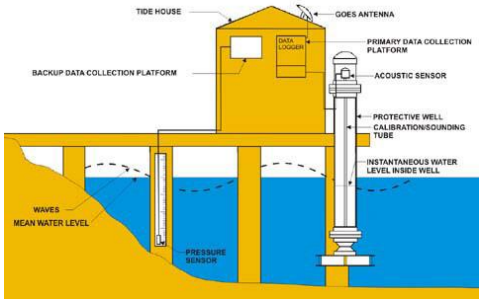
Rate during 1901-1990 was 1.50 ± 0.2 mm yr^{-1}

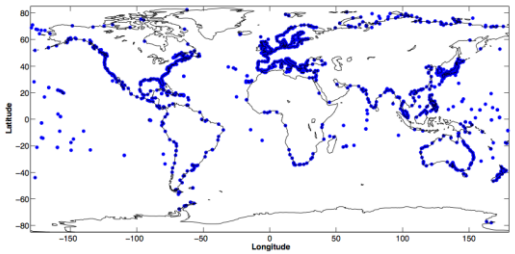
Rate during 1993-2010 was 3.07± 0.37 mm yr^{-1}

Rate during 2005-2017 was **3.50± 0.2 mm yr^{-1}**

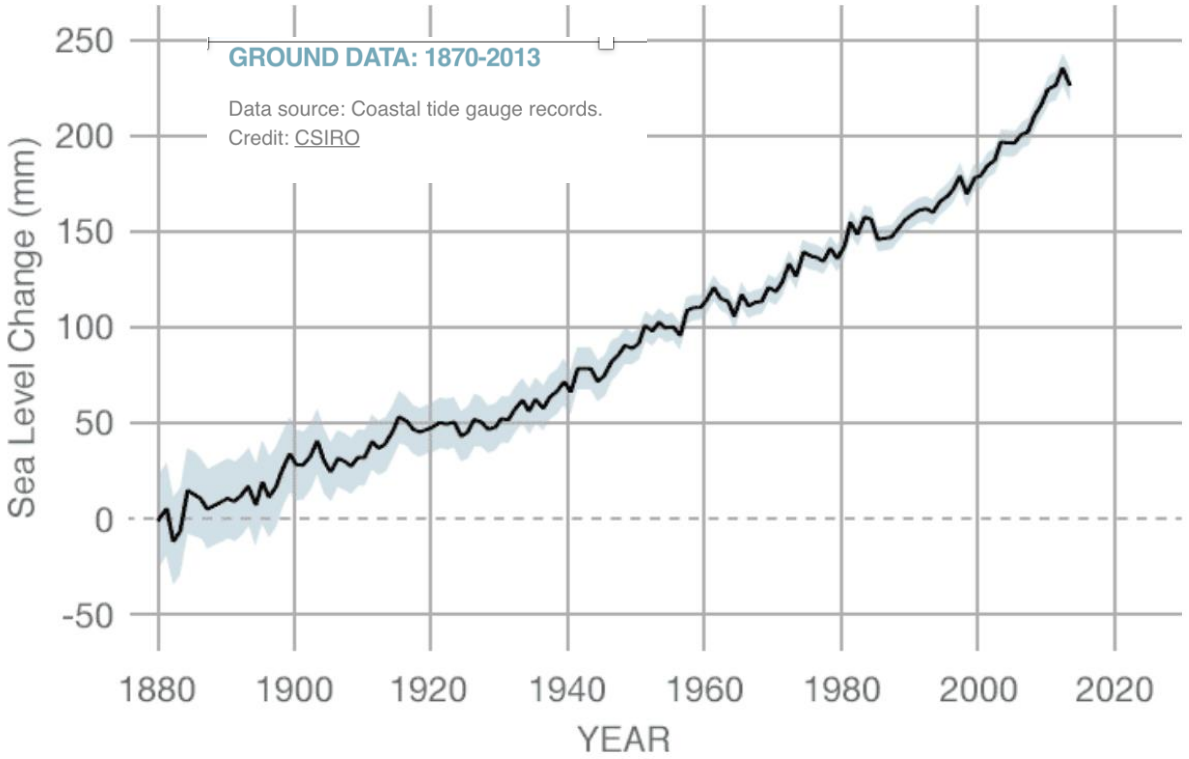
Compilation of paleo sea level data, tide gauge data, altimeter data.

Global sea level since 1880





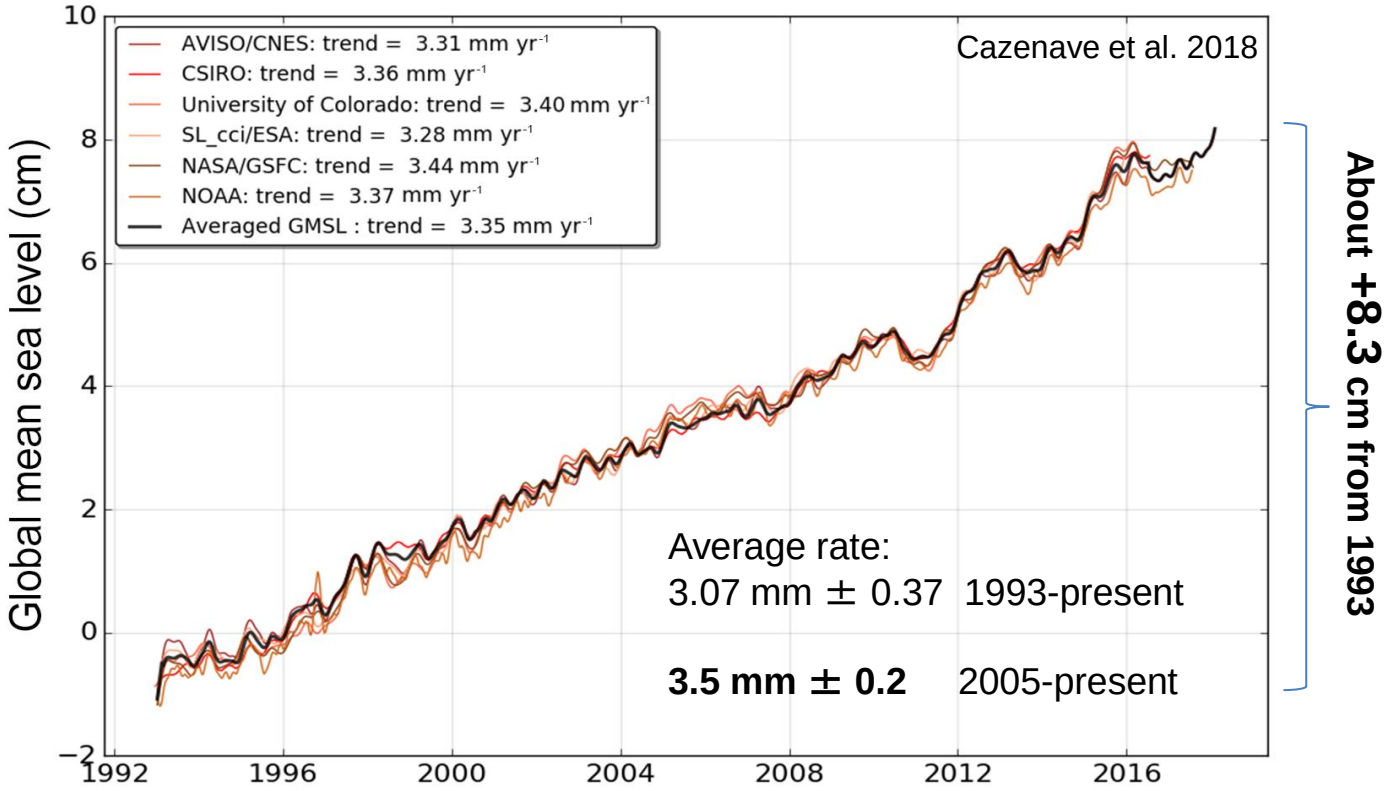
Spatial distribution of the **1420** tide gauges



Change in sea level since 1880 as observed by coastal tide gauge*

About +25 cm from 1880

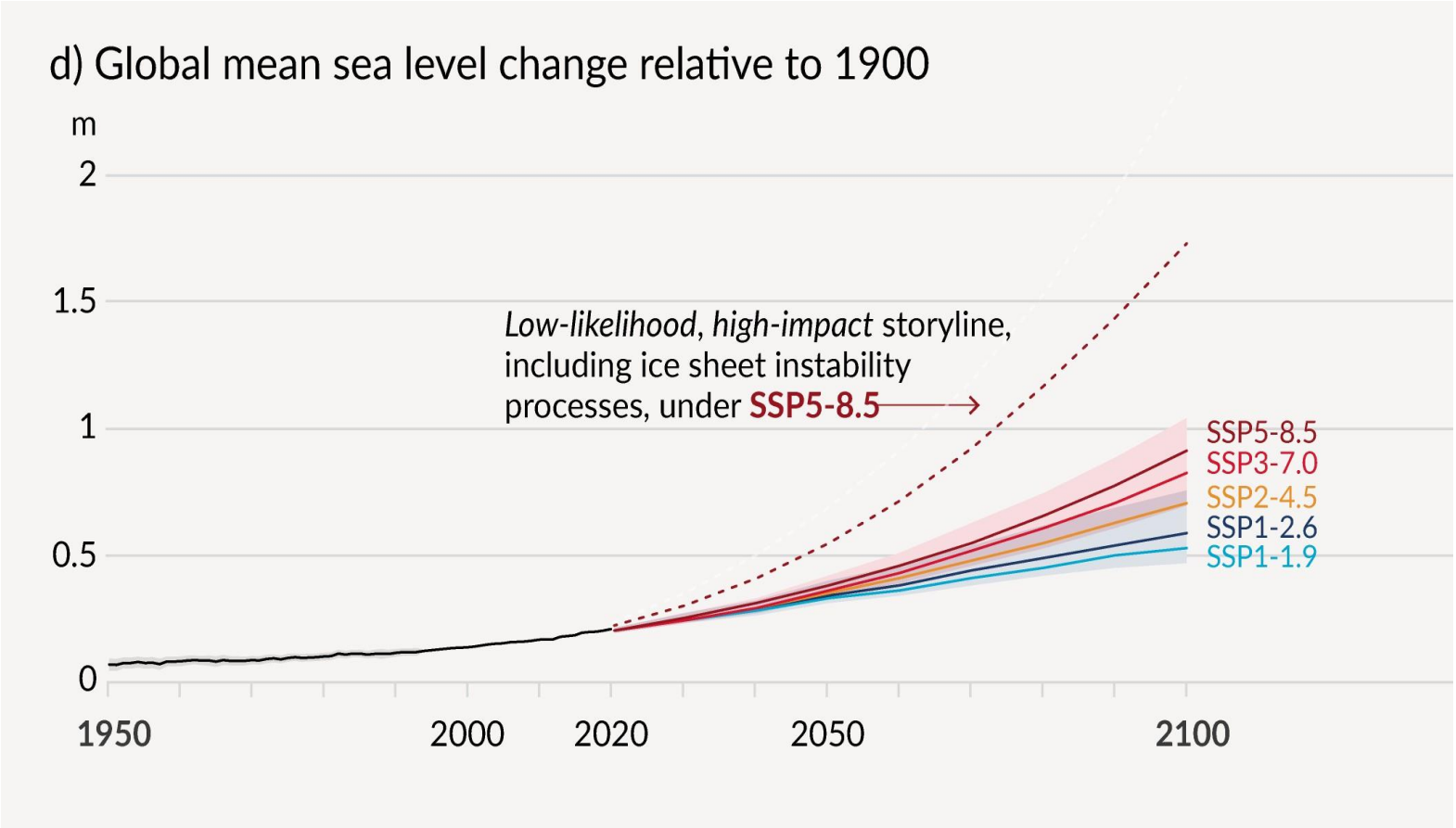
Global sea level since 1993

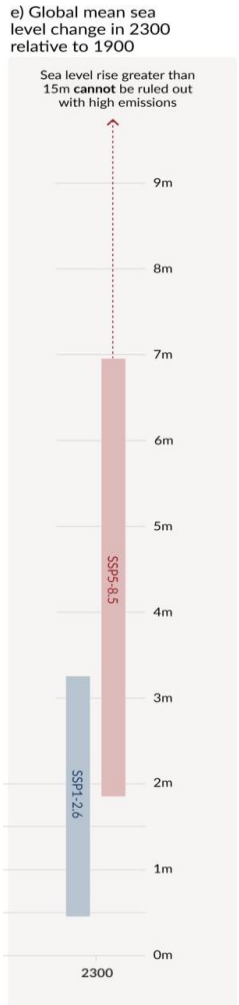


Change in sea level since **1993** as observed by satellites.

Future Scenarios global sea level

Human activities affect all the major climate system components, with some responding over decades and others over centuries

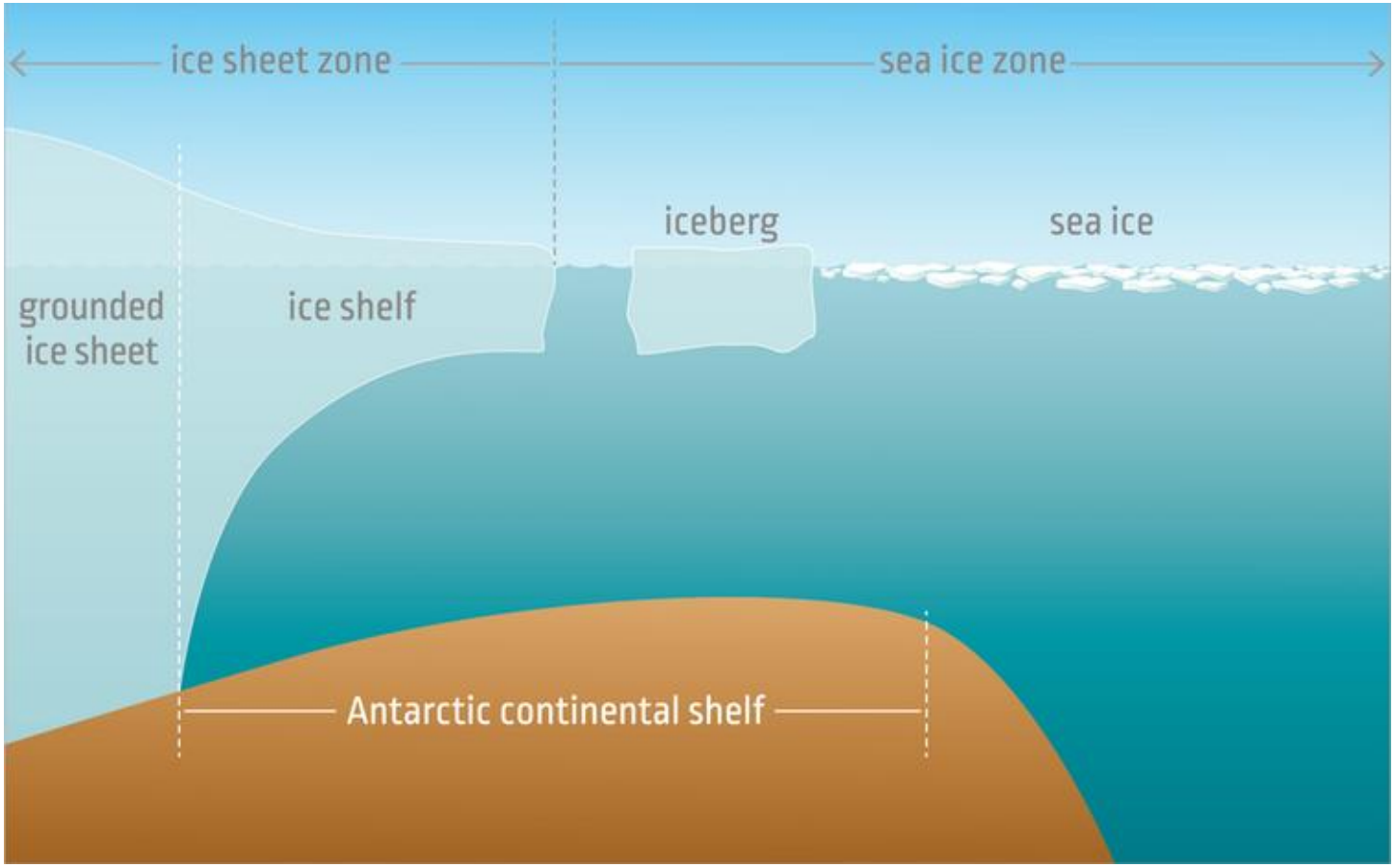




AR6 ipcc
INTERGOVERNMENTAL PANEL ON climate change

WMO UNEP

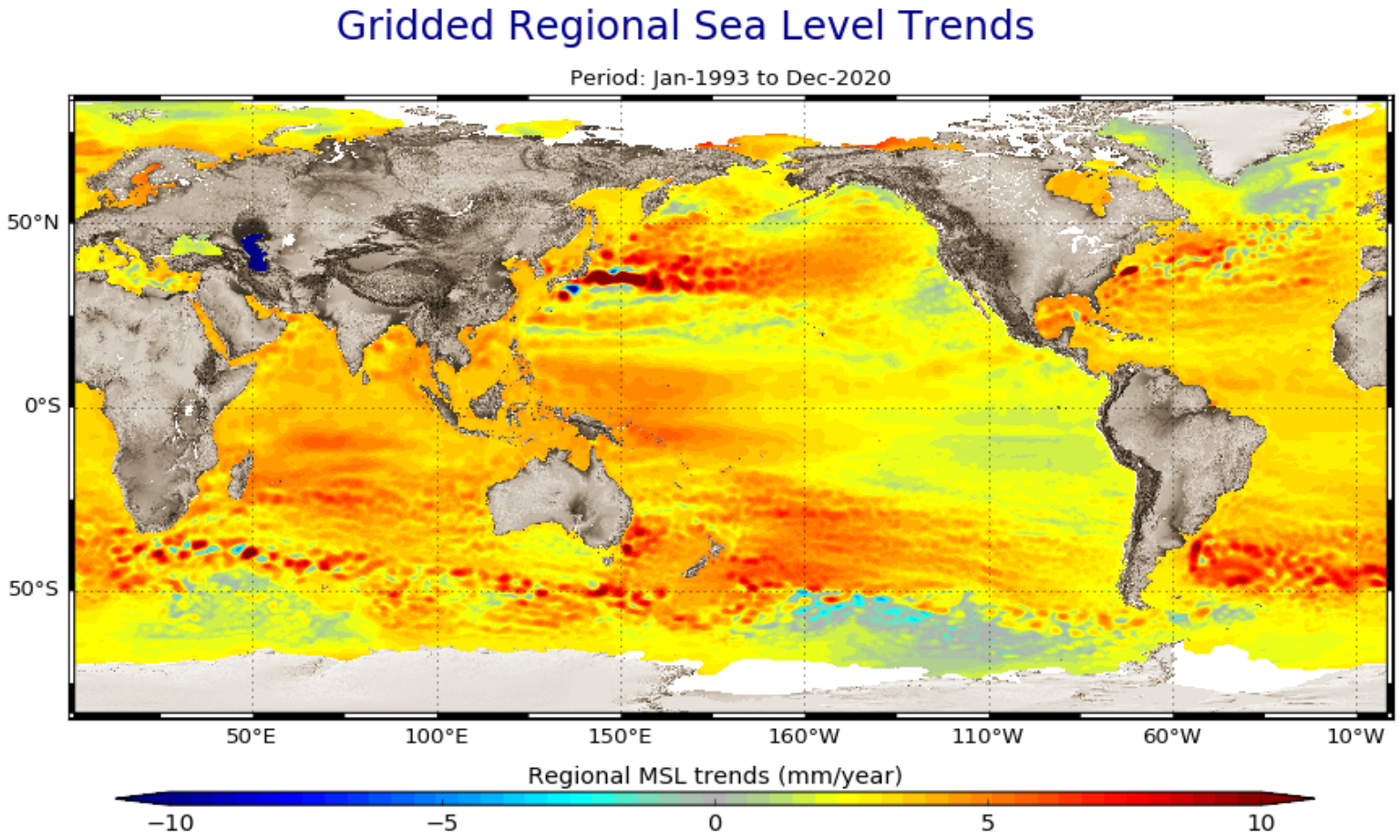
ANTARCTIC STABILITY



Regional Sea Level

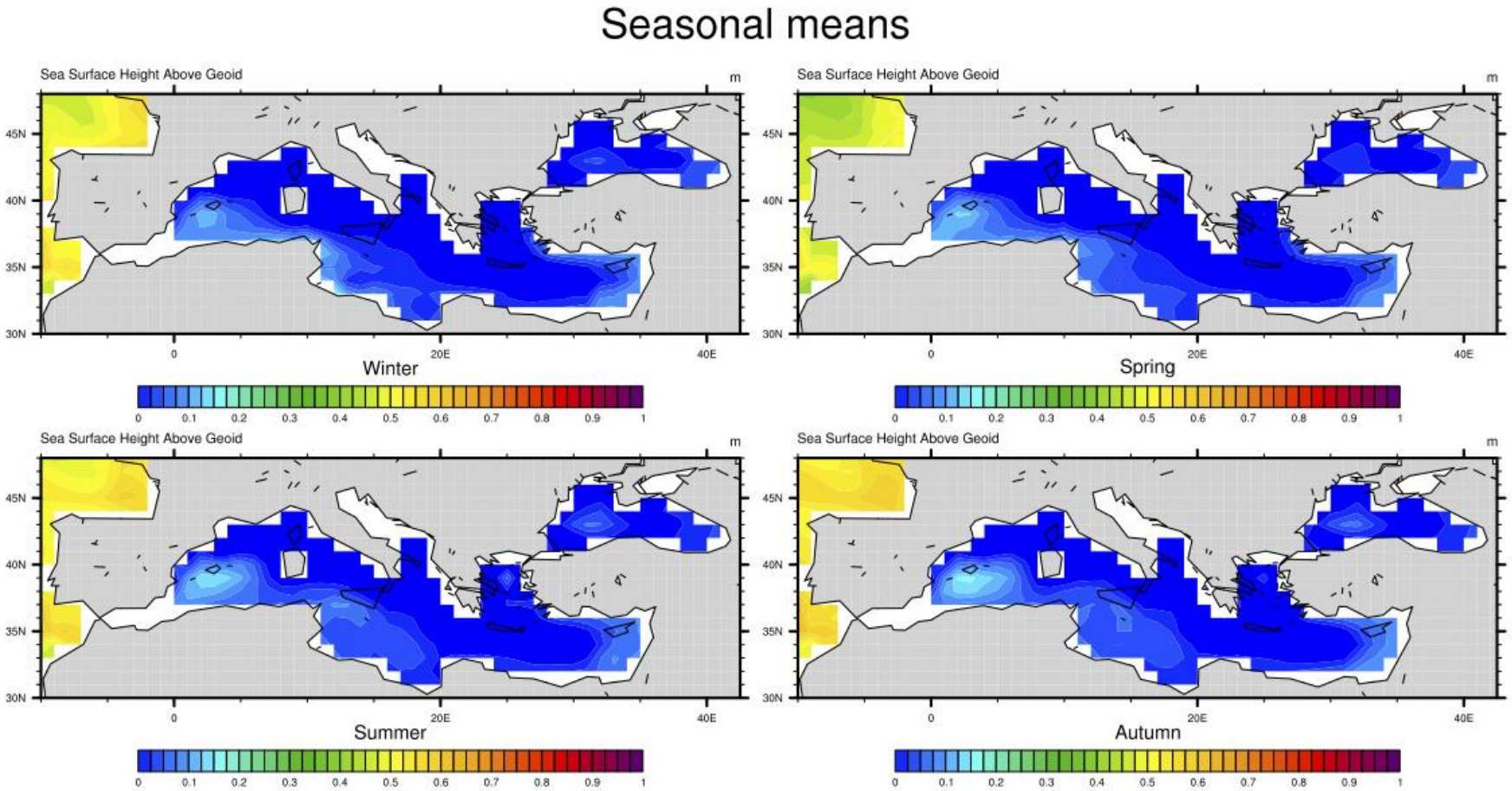
Regional gridded sea level trend over the period 1993-to present (in mm/year) from the multi-mission Ssalto/Duacs data.

The grid resolution is of a 1/4 of a degree.



Global climate models: present climate seasonal means

The total population of the Mediterranean countries grew from 276 million in 1970 to 412 million in 2000 (a 1,35 % increase per year) and to 466 million in 2010. The population is predicted to reach **529 million by 2025** (176 milion along the Mediterranean coasts).



Mediterranean sea level reproduced by CMIP5* global models (present climate)

*Coupled Model Intercomparison Project

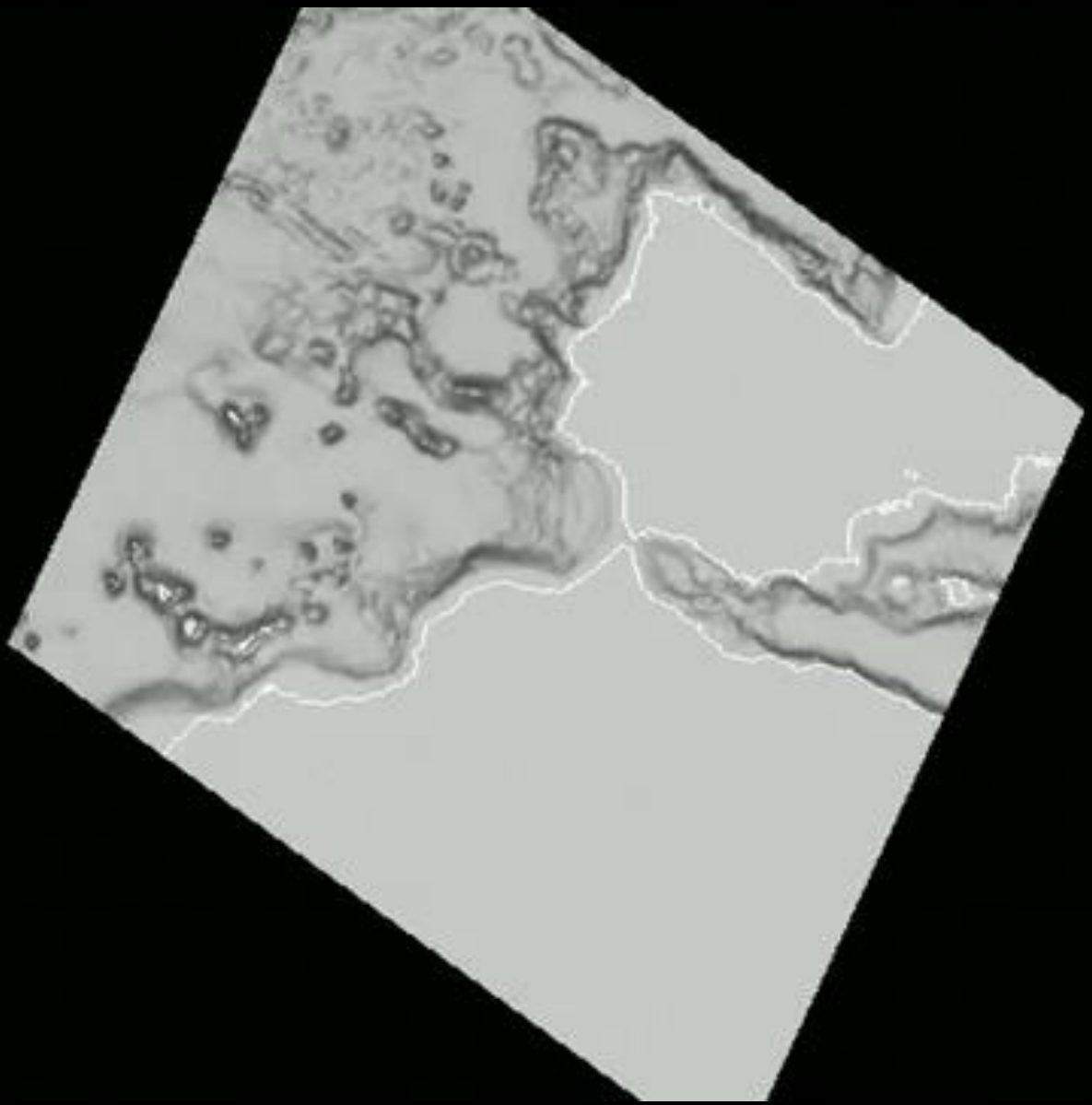
SROCC & IPCC AR6 – WGI Chapter 9

*The **SROCC** estimated regional sea-level changes from combinations of the various contributions to sea-level change from **CMIP5** climate model outputs, allowing comparison with satellite altimeter and tide-gauge observations. Closure of the regional sea-level budget is complicated by the fact that **regional sea-level variability is larger than GMSL variability** and there are more processes that need to be considered, such as vertical land movement and ocean dynamical changes.*

*Since **CMIP6** models are of fairly coarse (typically ~100km) resolution, and even the models participating in HighResMIP (near 10km resolution) do not capture all the phenomena that contribute to coastal ocean dynamic sea-level change, there is low confidence in the details of ocean dynamic sea-level change along the coast and in semi-enclosed basins, **like the Mediterranean**, where **coarse models can misrepresent key dynamic processes**.*

Background geography

Strait of Gibraltar Background: 3D Bathymetry



Strait of Gibraltar Background

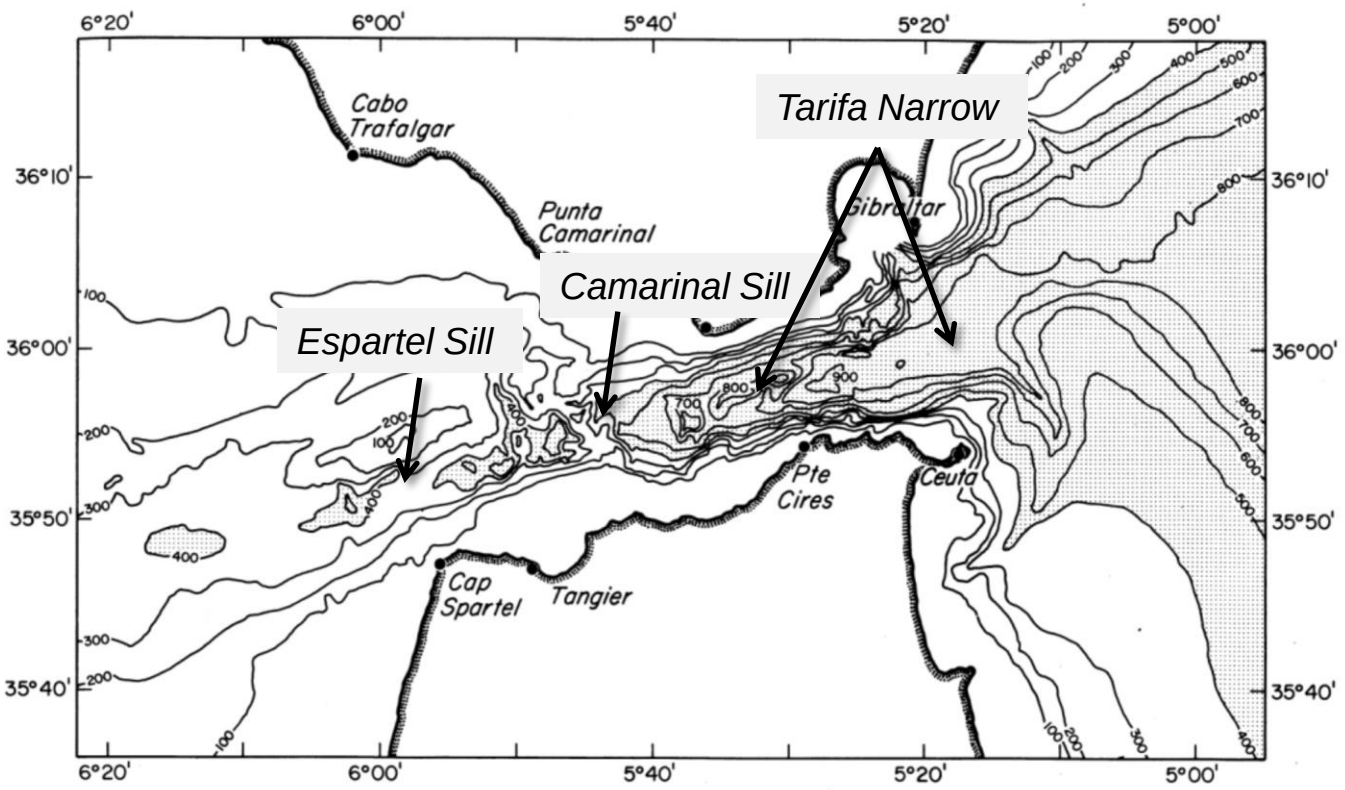


Chart of the Strait of Gibraltar, adapted from Armi & Farmer (1988), showing the principal geographic features referred to in the text.

Areas deeper than 400 m are shaded

Strait of Gibraltar Background: Physics

Strong mixing and entrainment mainly driven by the very intense tides.

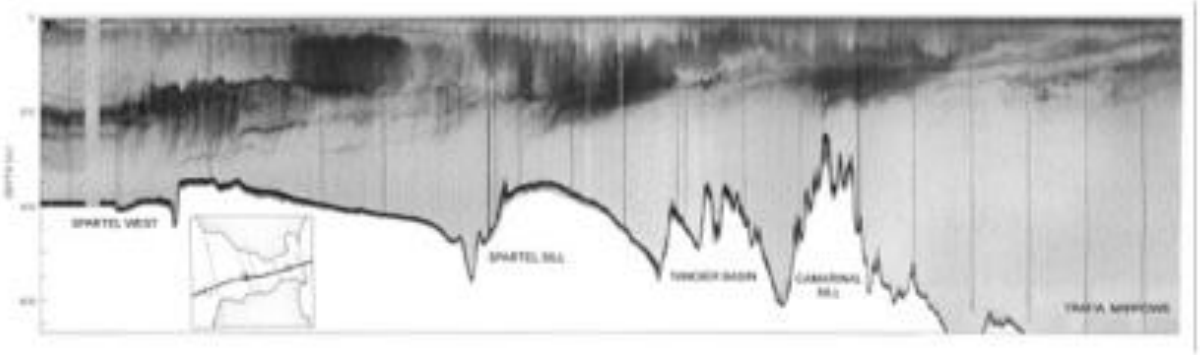


Figure 2. Transect of the Strait [From Armi and Farmer, Farmer and Armi.1988]

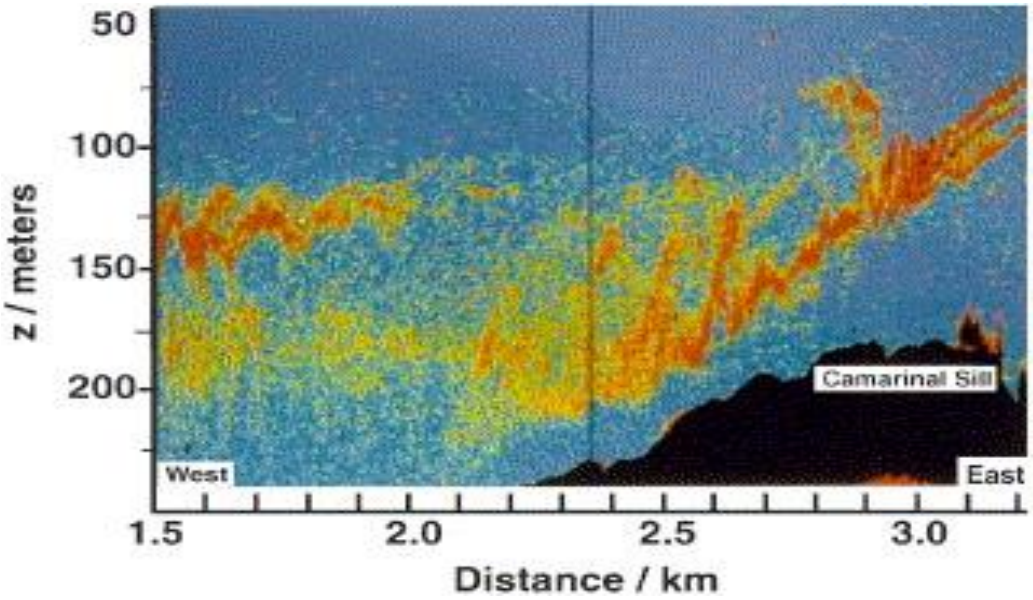
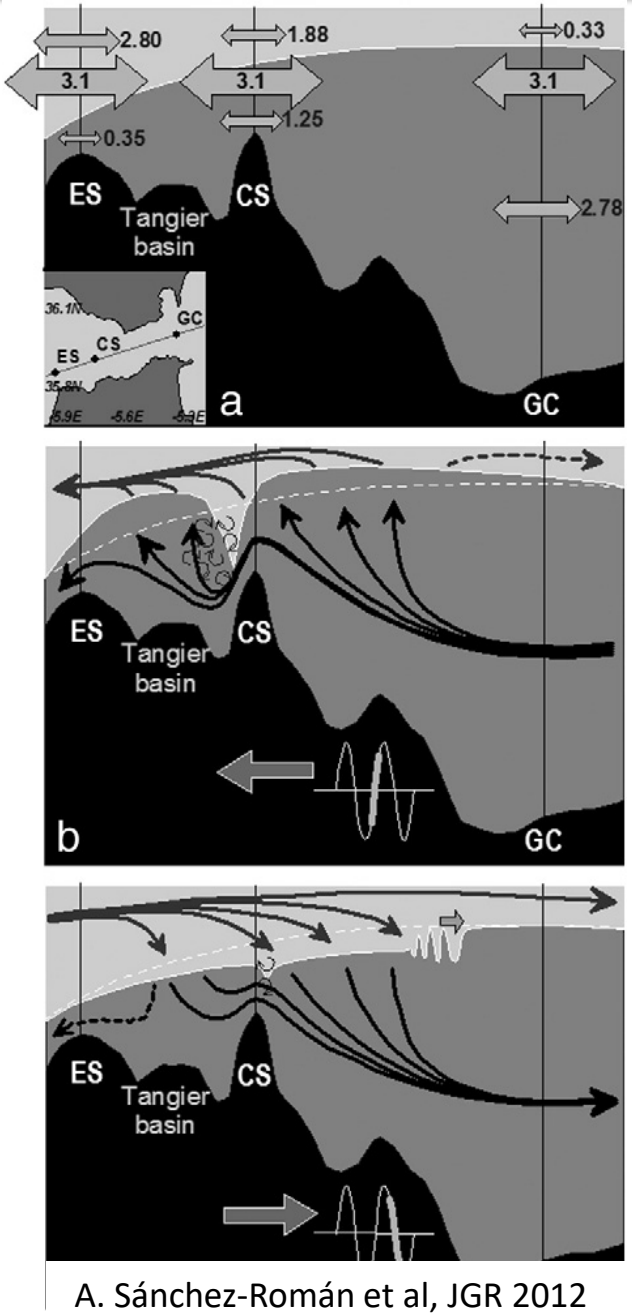
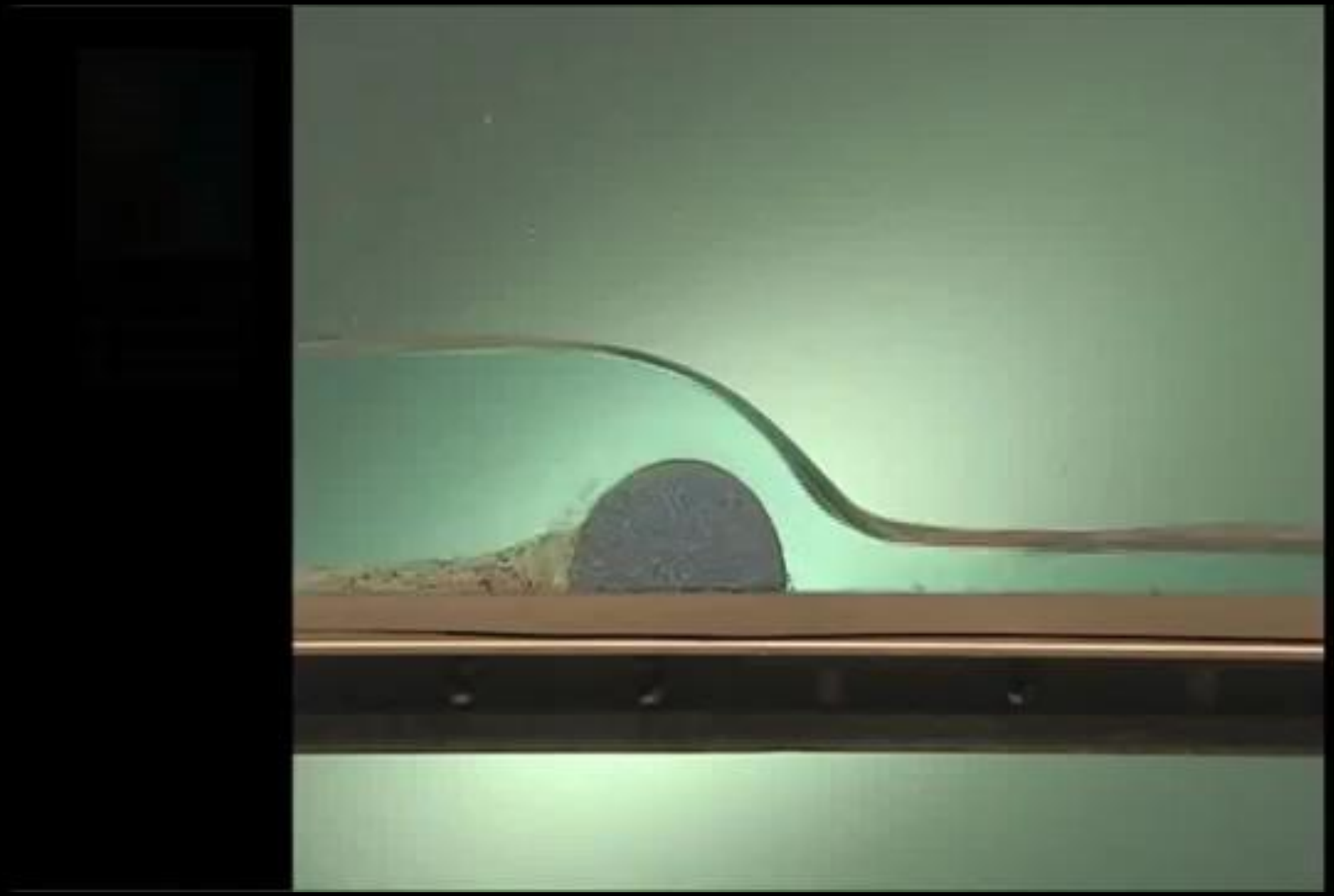


Image of acoustic backscatter during ebb tide over Camarinal Sill in the Strait of Gibraltar (Wesson and Gregg, 1994)

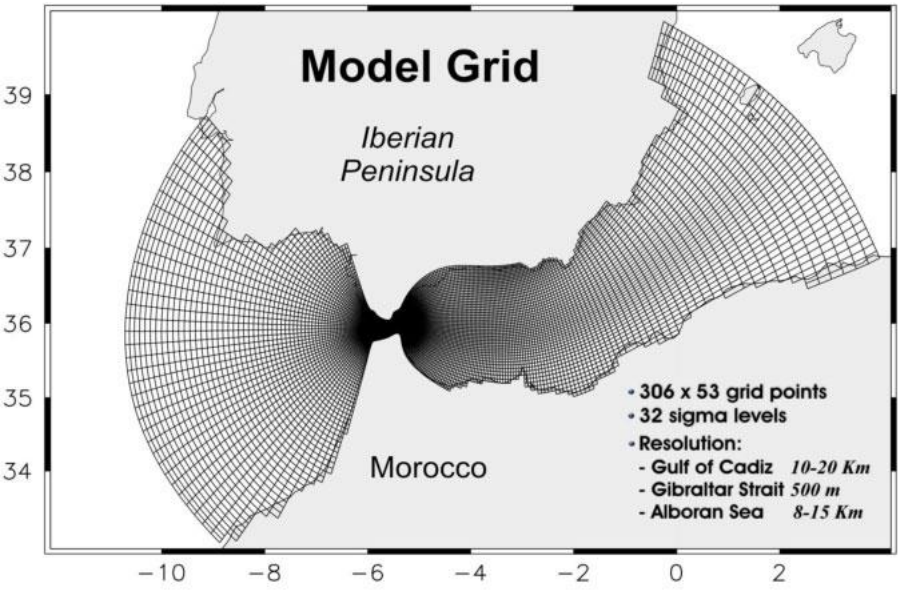


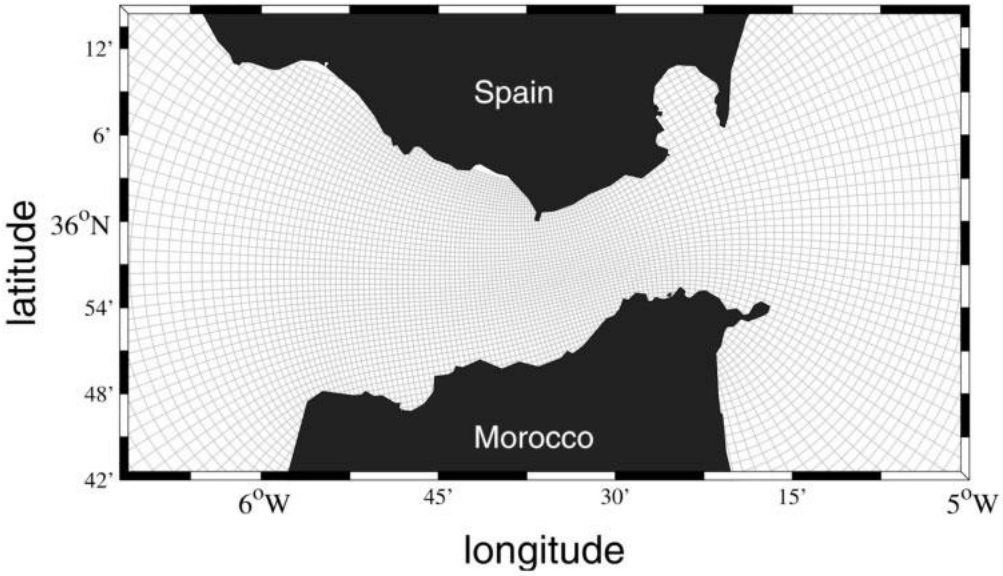
A. Sánchez-Román et al, JGR 2012

Hydraulics jump: an example



Sub-basin Model (POM): Cadiz – Gibraltar - Alboran





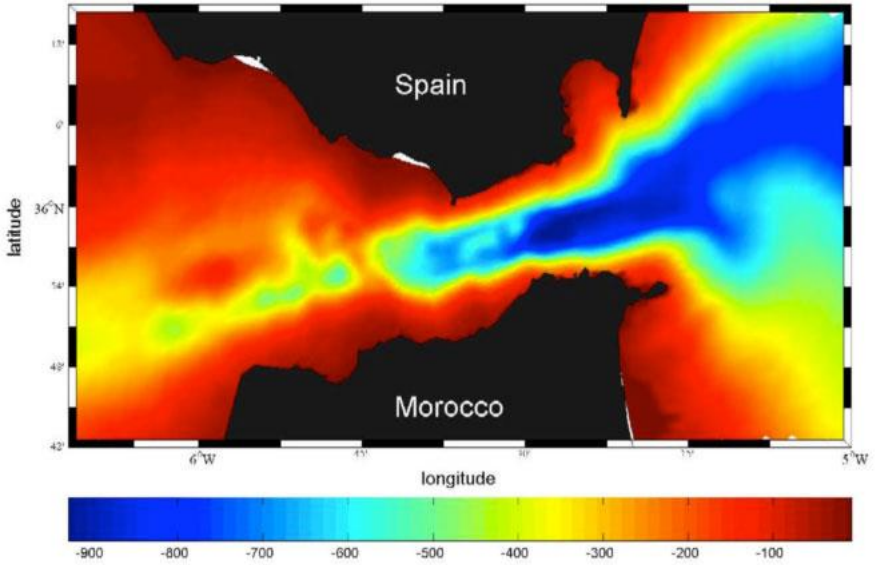
Modified POM

Minimal Hor. Resolution: < 500 m

External Time-Step: 0.1 sec

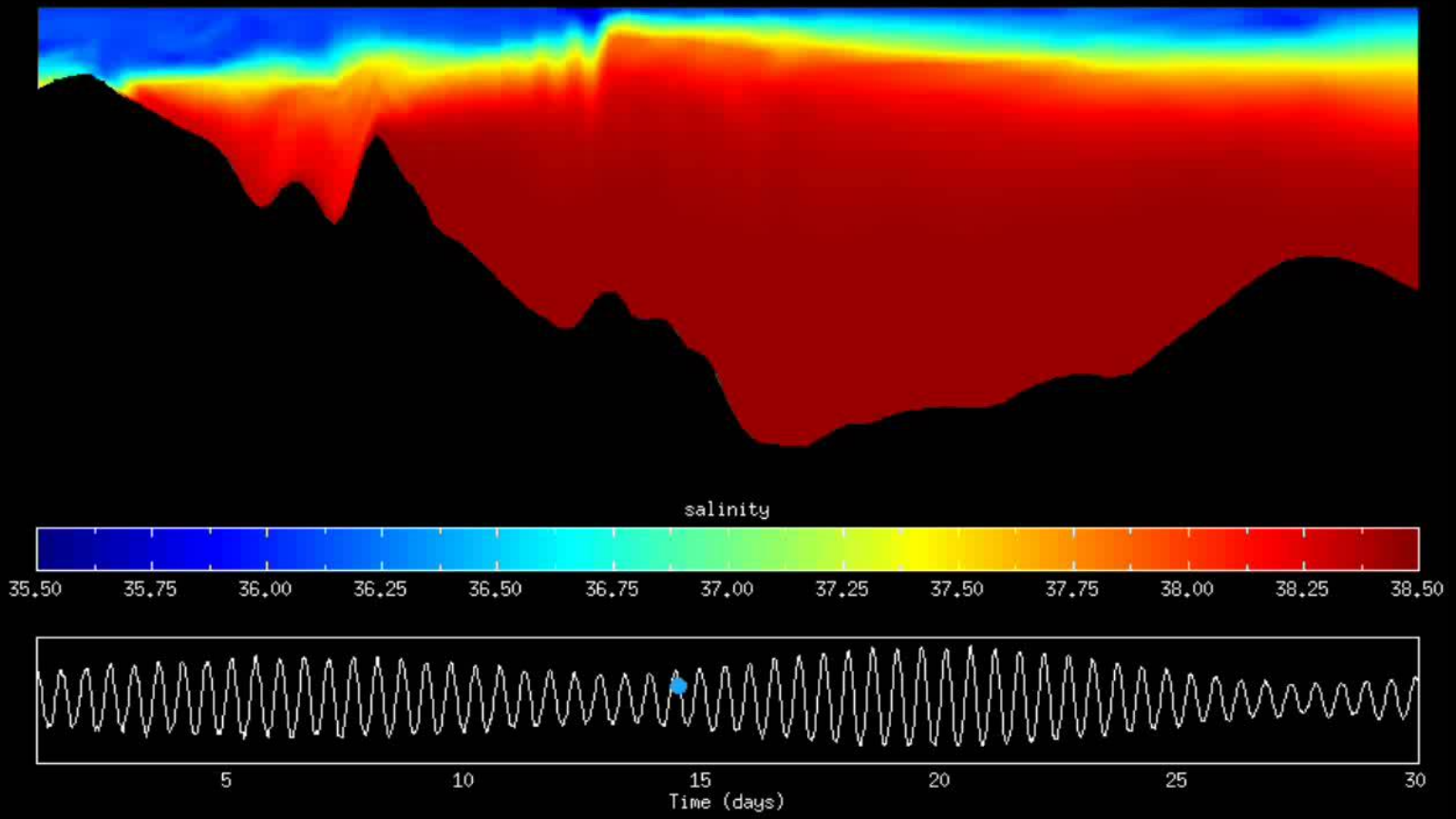
O_1 K_1 diurnal tidal component

M_2 S_2 diurnal tidal component



- Sannino et al, JGR-Book, 2013
- Sannino et al, JPO, 2009
- Sanchez et al, JGR, 2009
- Garrido et al, JGR, 2008
- Garcia-Lafuente et al, JGR, 2007
- Sannino et al, JGR, 2007
- Sannino et al , NC, 2005
- Sannino et al, JGR, 2004
- Sannino et al, JGR, 2002

Sub-basin Model (POM): Cadiz – Gibraltar - Alboran



salinity along-strait section

Sub-basin Model (POM): Cadiz – Gibraltar - Alboran

Tidal Components comparison
Surface elevation

TABLE 1. Comparison between Observed and Predicted Amplitudes A and Phases P of M_2 tidal elevation.

			Observed M_2		Predicted M_2		Predicted - Observed		
Location	Latitude	Longitude	A,cm	P,deg	A,cm	P,deg	A,cm	A,%	P,deg
			Tsimplis et al. (1995)						
Gibraltar	36 ° 08′	05 ° 21′	29.8	46.0	29.5	46.0	-0.3	1.0	+0.0[a]
			García-Lafuente (1986)						
Pta. Gracia	36 ° 05.4′	05 ° 48.6′	64.9 ± 0.2	49.0 ± 0.5	67.6	53.8	+2.7	4.1	+4.5
Tarifa	36 ° 00.2′	05 ° 36.4′	41.5 ± 0.2	57.0 ± 0.5	43.5	49.7	+2.0	4.8	-7.3
Pta. Cires	35 ° 54.7′	05 ° 28.8′	36.4 ± 0.2	46.5 ± 0.5	35.0	54.9	-1.4	3.8	+8.4
Pta. Carnero	36 ° 04.3′	05 ° 25.7′	31.1 ± 0.2	47.5 ± 0.5	30.8	47.4	-0.3	0.9	-0.1
			Candela et al. (1990)						
DN	35 ° 58′	05 ° 46′	60.1	51.8	58.2	57.8	-1.9	3.1	+6.0
DS	35 ° 54′	05 ° 44′	54.0	61.8	54.1	64.1	+0.1	0.2	+2.3
SN	36 ° 03′	05 ° 43′	52.3	47.6	52.3	52.9	0.0	0.0	+5.3
SS	35 ° 50′	05 ° 43′	57.1	66.8	56.8	67.4	-0.3	0.5	+0.6
DW	35 ° 53′	05 ° 58′	78.5	56.1	76.6	62.7	-1.9	2.4	+6.6
TA	36 ° 01′	05 ° 36′	41.2	41.2	43.5	49.7	+2.3	5.5	+8.5
AL	36 ° 08′	05 ° 26′	31.0	48.0	30.0	49.7	-1.0	3.2	+1.7
CE	35 ° 53′	05 ° 18′	29.7	50.3	29.5	51.5	-0.2	0.6	+1.2
DP5	36 ° 00′	05 ° 34′	44.4	47.6	42.1	47.6	-2.3	5.1	+0.0

[a]Calibration.

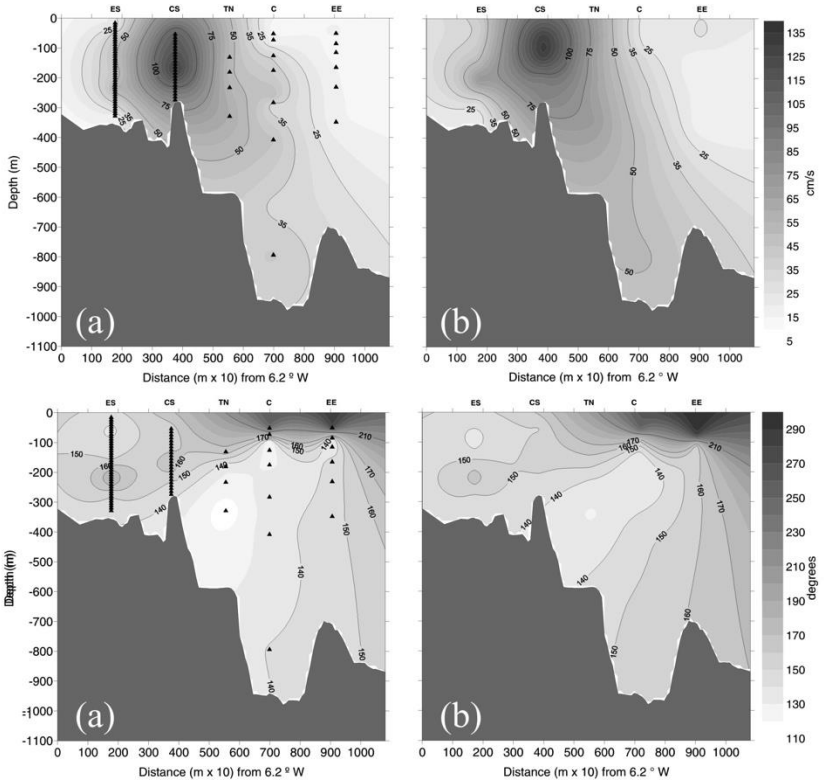
Max Differences:
Amp: 3.6 cm
Pha: 11°

Sannino et al.,JPO, 2009

Tidal Components comparison
Along-strait velocity

(a) Data

(b) Model



(a) Data

(b) Model

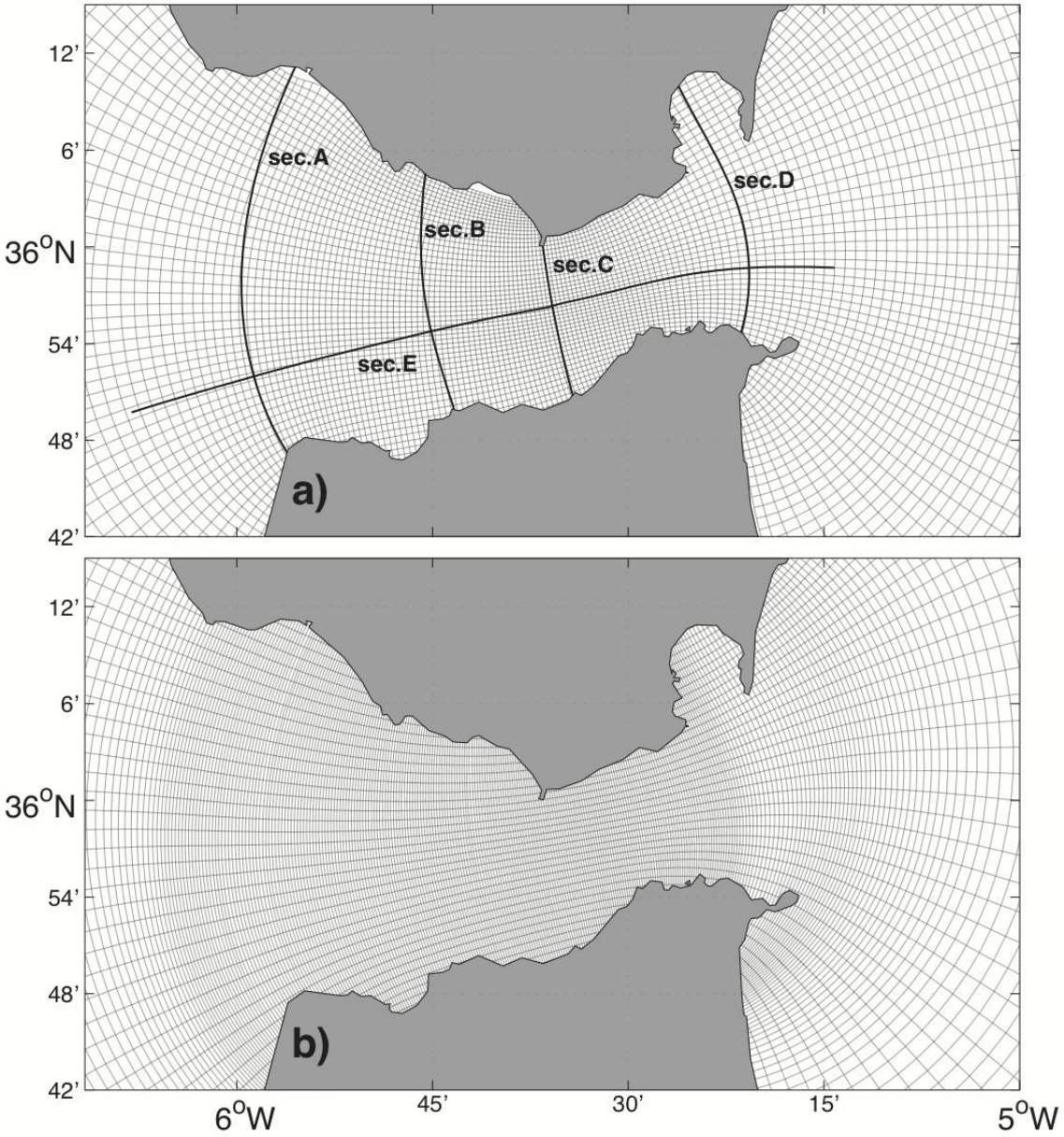
Max Differences:
Amp: 10 cm s^{-1}
Pha: 20°

Sánchez-Román et al., JGR, 2009

MITgcm vs POM : model grids

POM grid
Max resolution
300 m

MITgcm grid
Max resolution
25 m
(only 25% of the actual grid is shown)



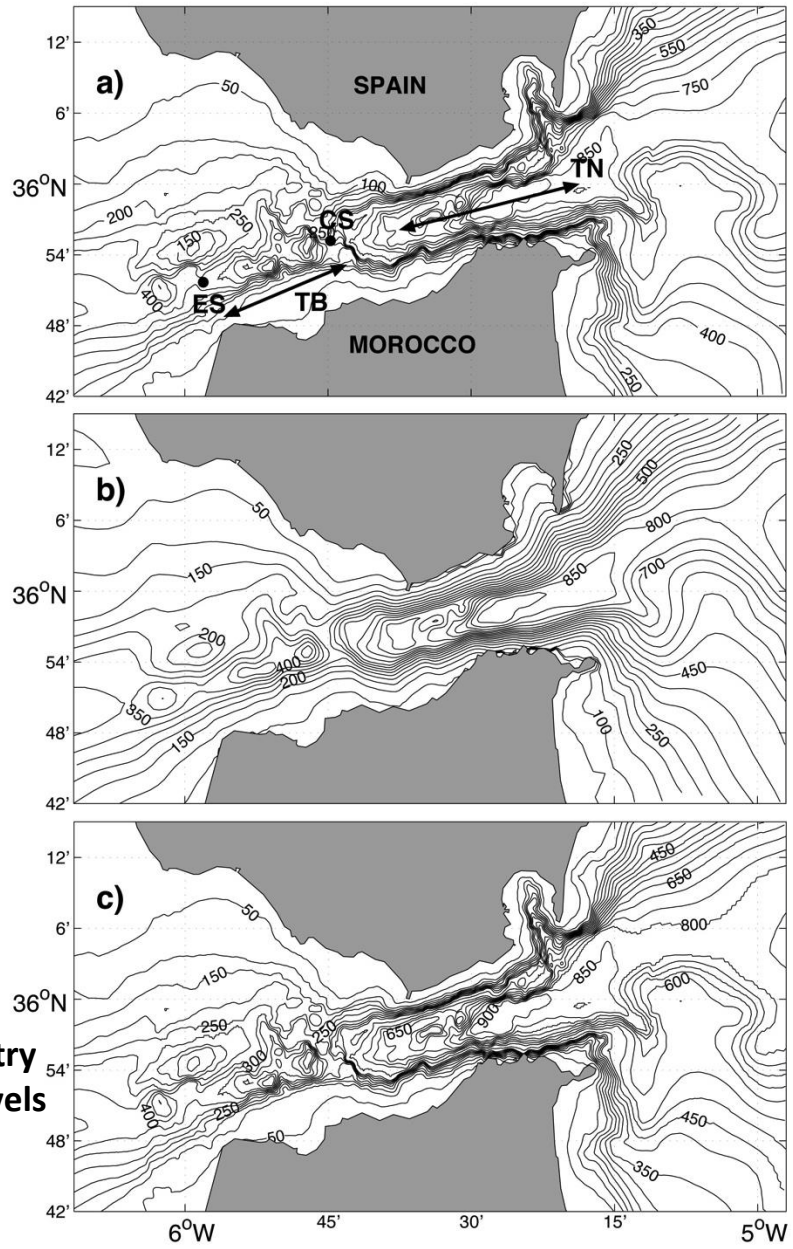
Sannino et al 2014

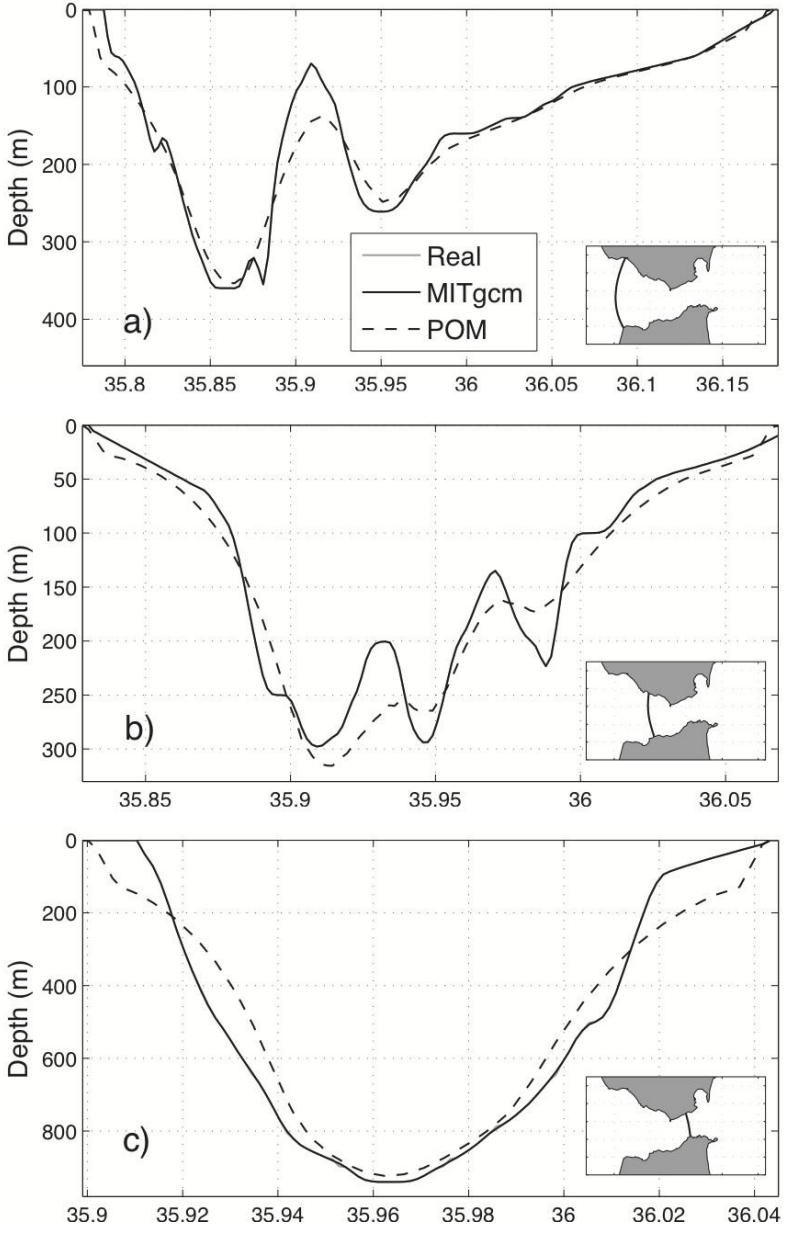
MITgcm vs POM : model bathymetry

Real bathymetry

POM bathymetry
32 sigma-levels

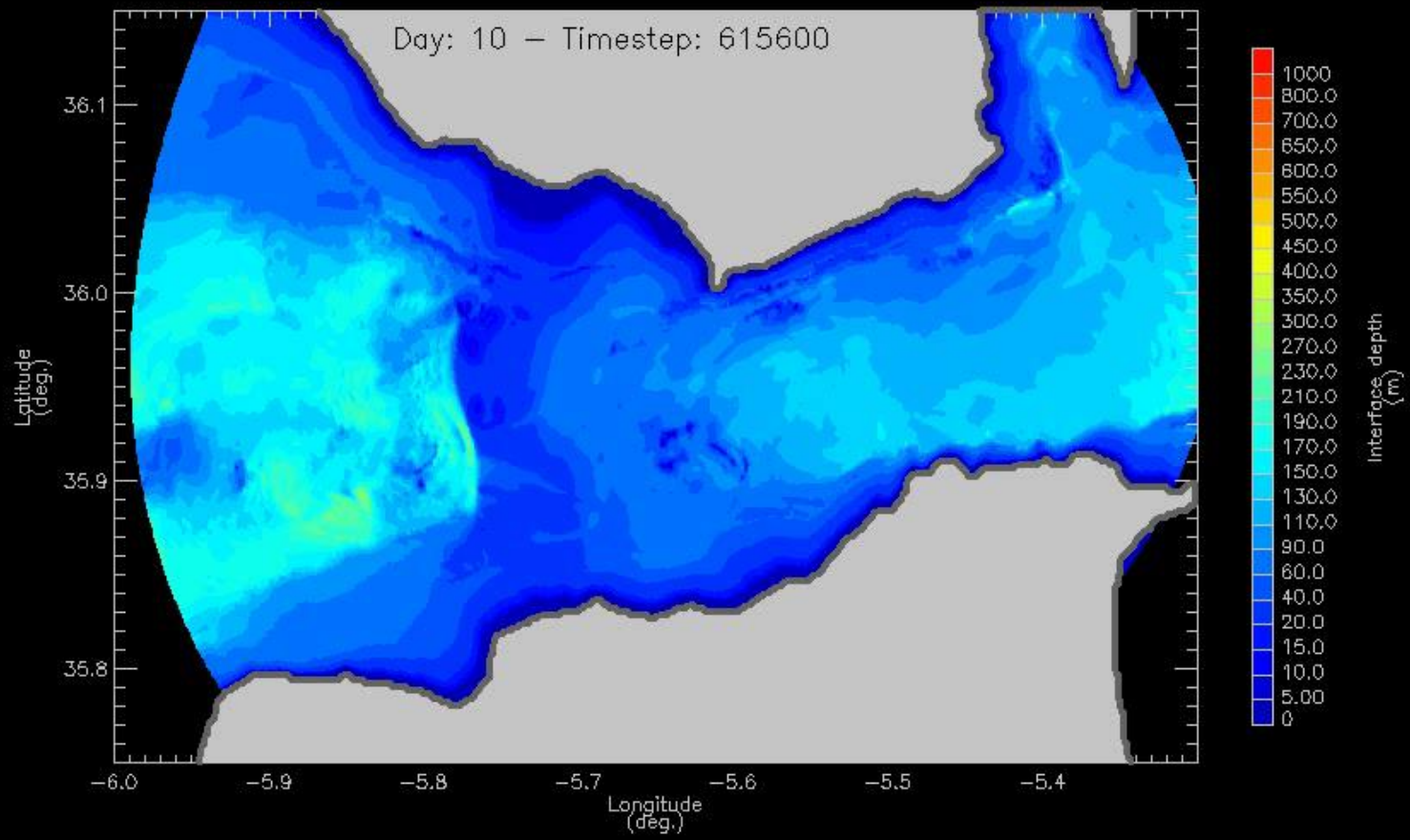
MITgcm bathymetry
53 vertical zeta-levels
(partial cell)





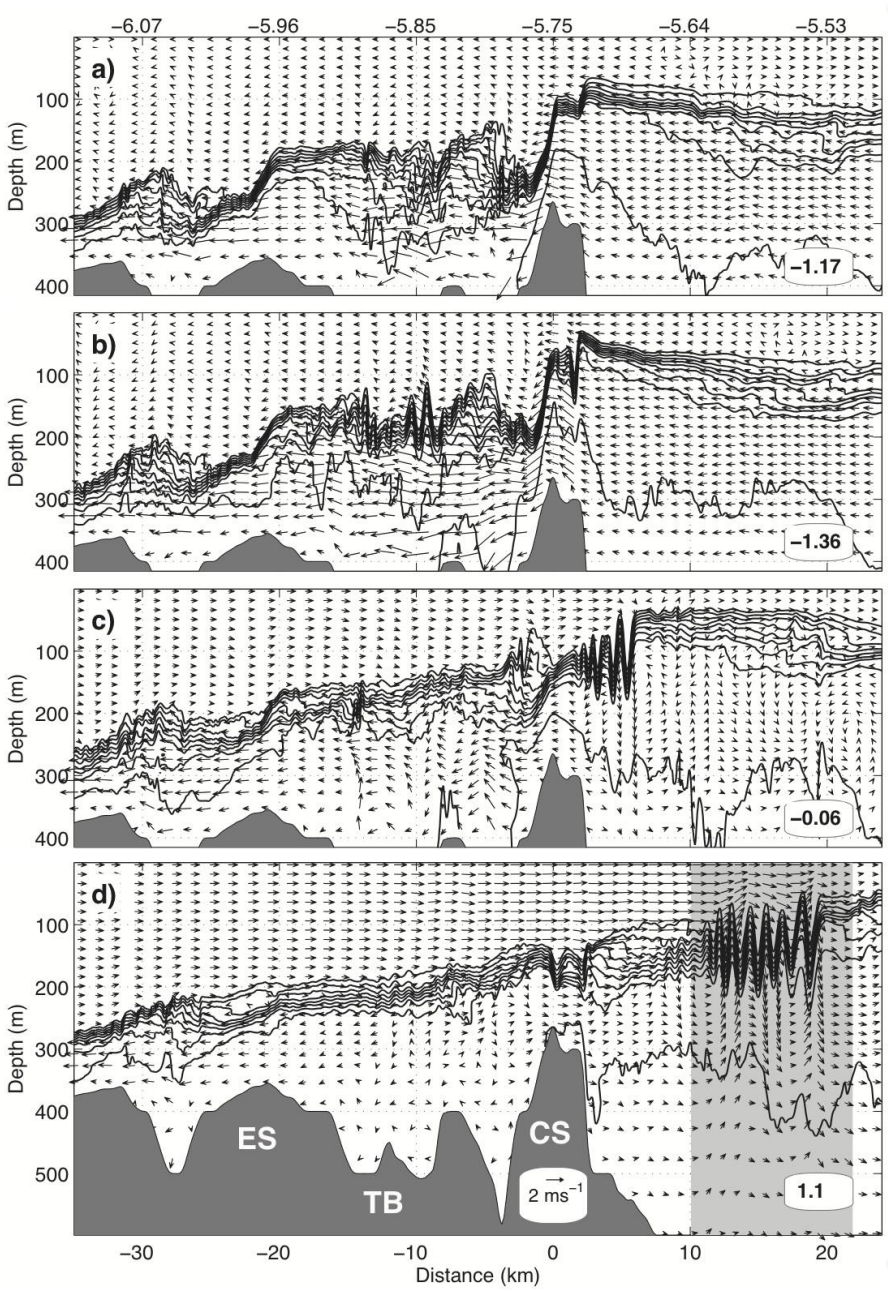
Sannino et al. JGR, 2014

MITgcm model simulation



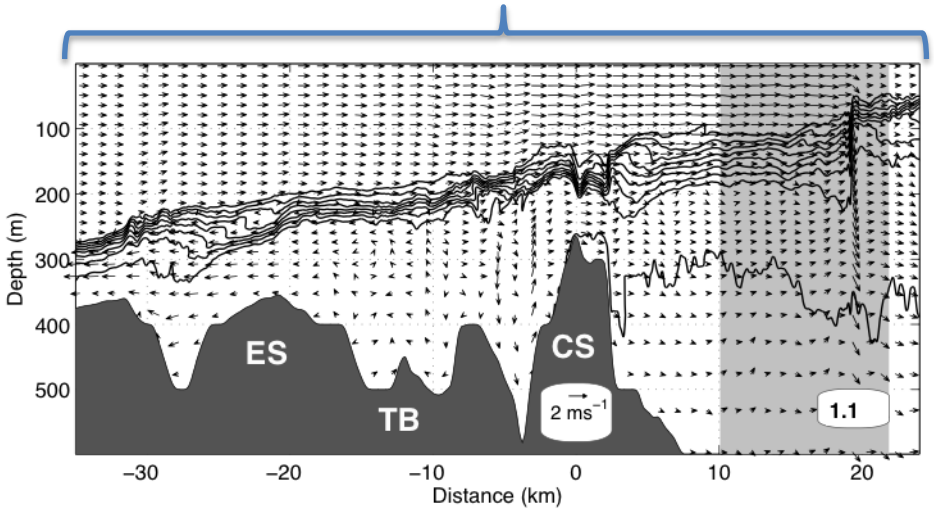
Interface depth evolution

MITgcm sensitivity to non-hydrostaticity



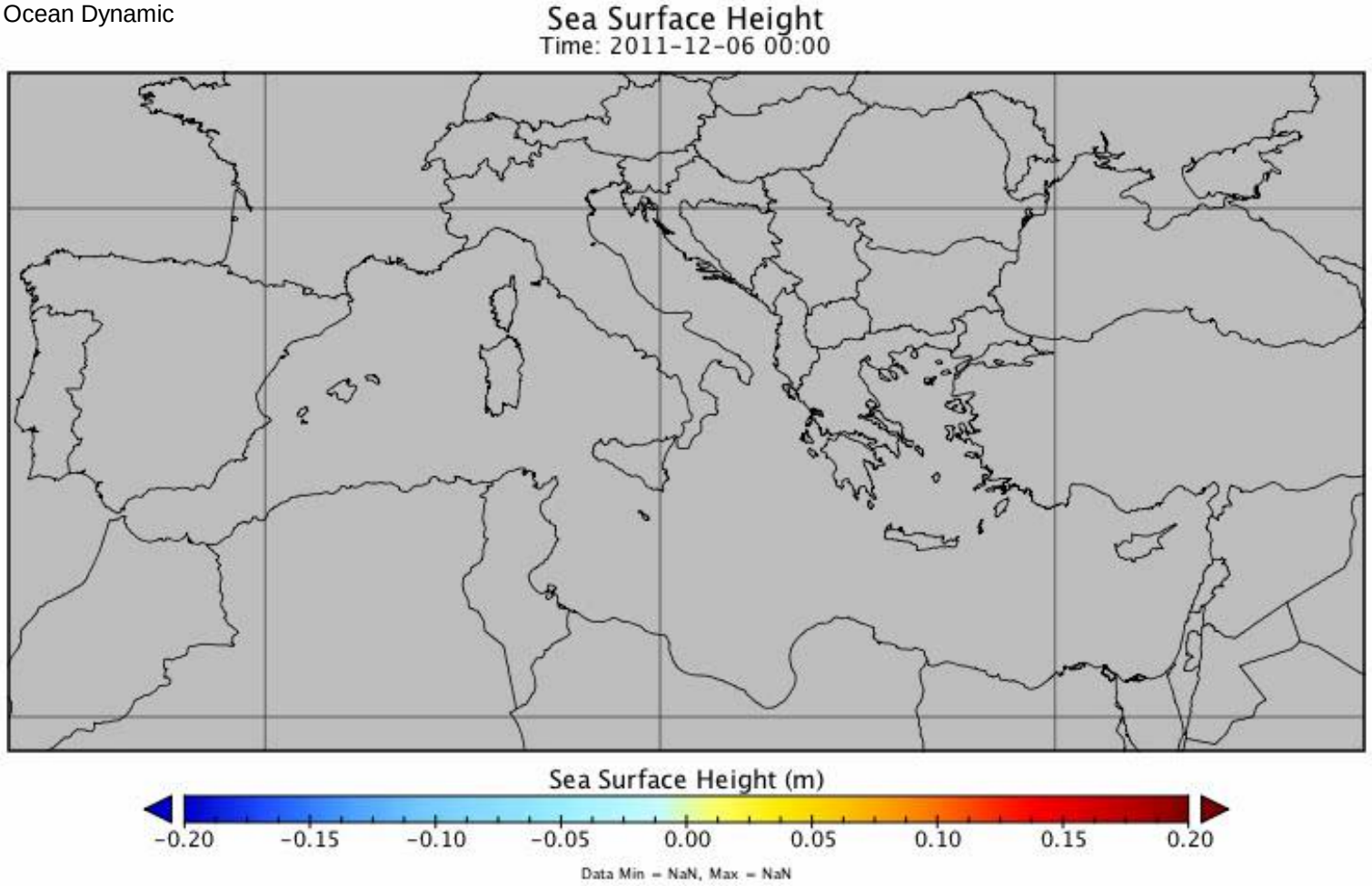
MITgcm NON Hydrostatic

MITgcm Hydrostatic



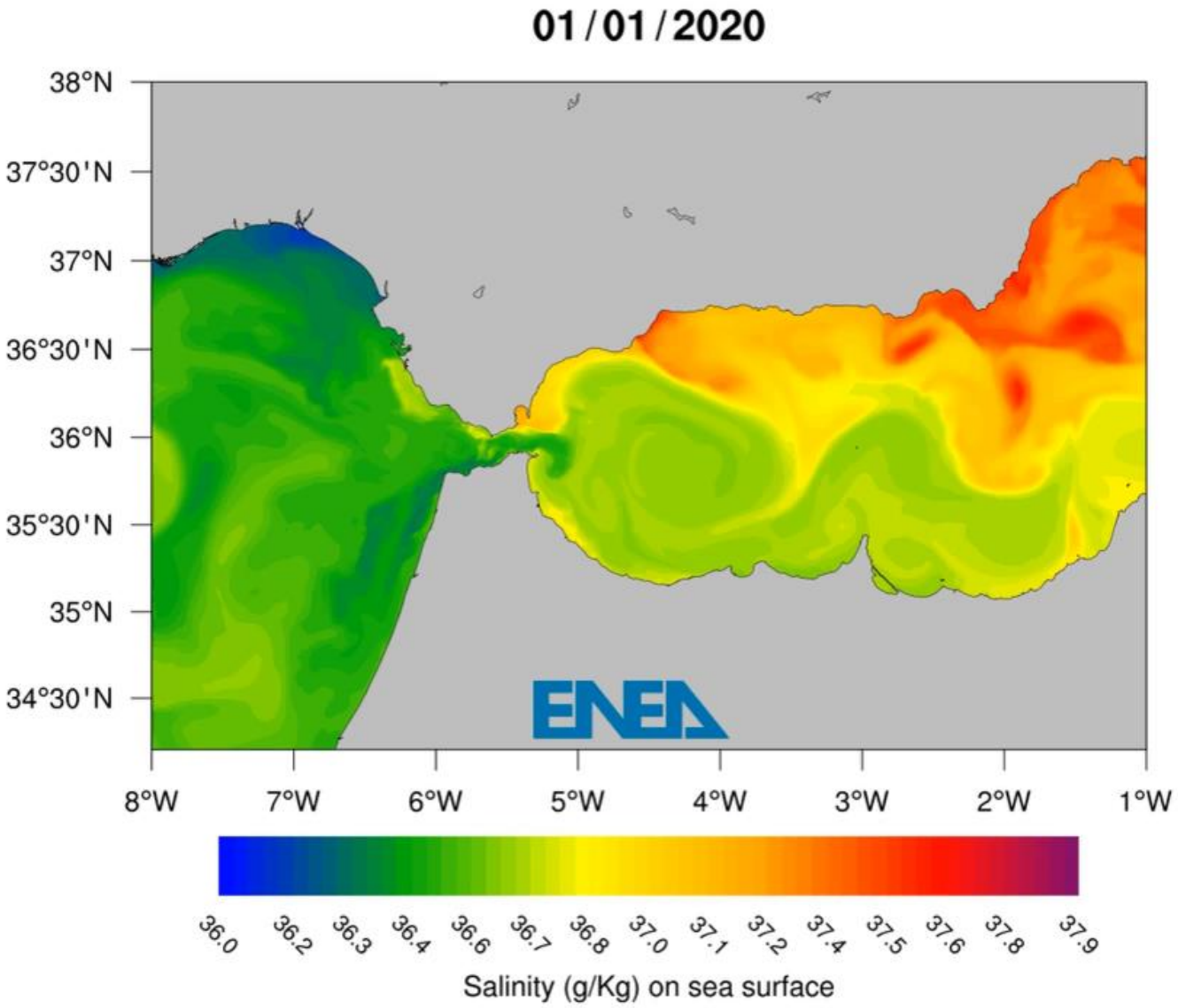
ENEA Climate Model

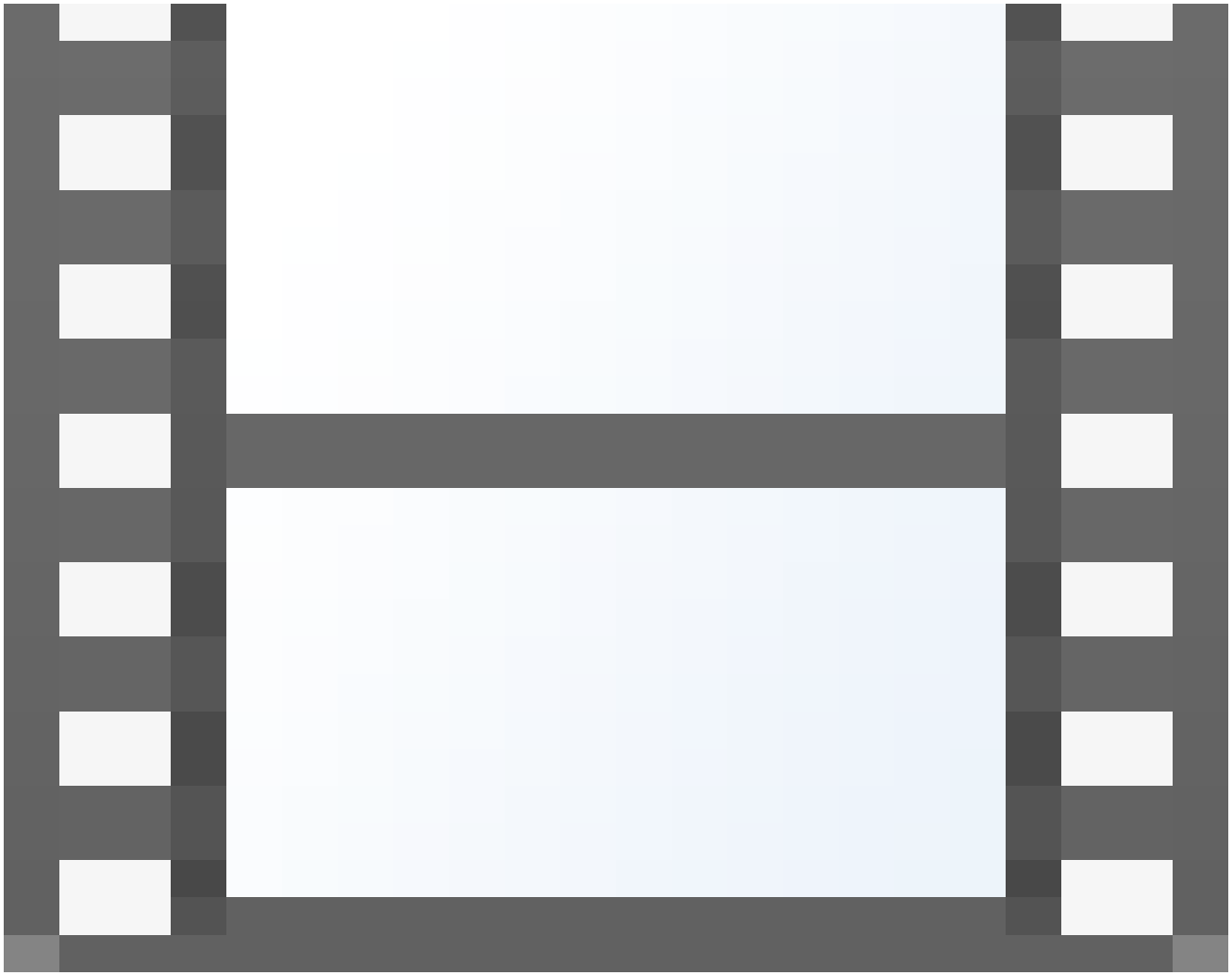
Palma et al 2019 – Ocean Dynamic



MITgcm – Explicit Tides (M2,S2, K1, O1) – Lateral Tide + Tidal Potential
Average resolution 1/16° (7 Km)
Minimum resolution at Gibraltar (230m) and Turkish Straits (90m)
100 Vertical Levels

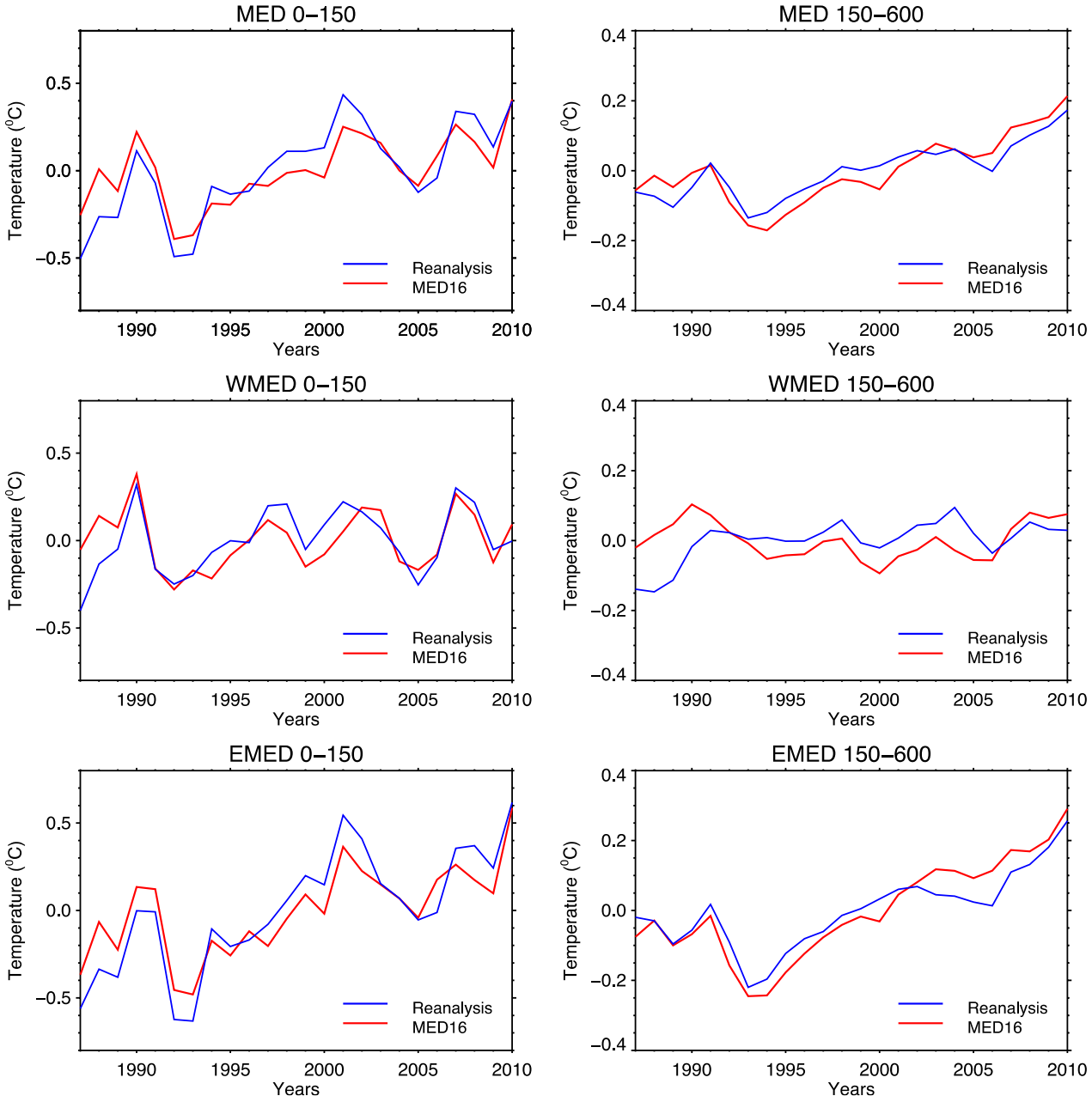
Venice flooded by highest tide in more than 50 years





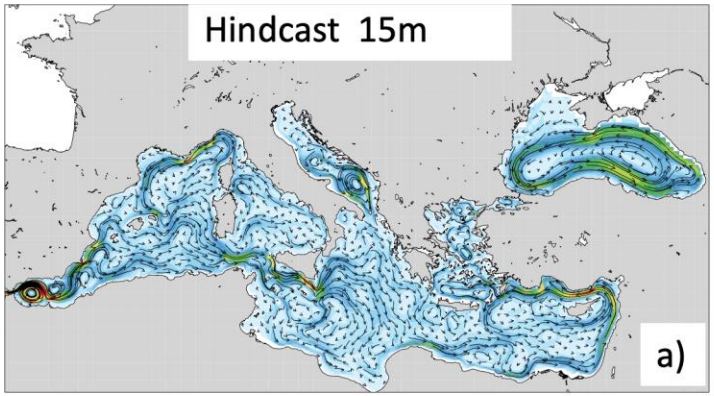
ENEA Climate Model

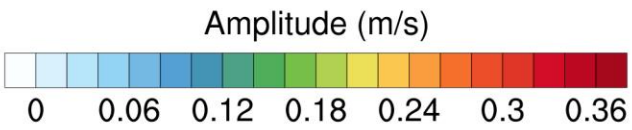
Reanalysis (blue) and hindcast (red) time series of temperature anomalies ($^{\circ}C$; annual values) for the upper (0-150 m) and intermediate (150-600 m) layers, for the Mediterranean Sea, and the western and eastern sub-basins

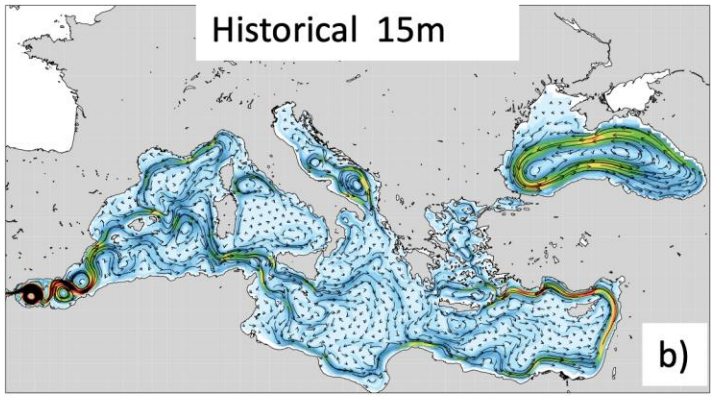


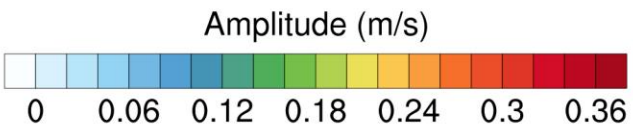
ENEA Climate Model

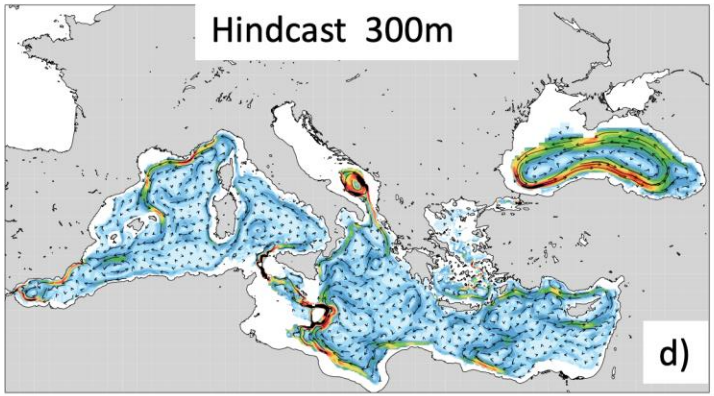
Surface (15 m of depth) and intermediate (300 m of depth) circulation, averaged over the simulation periods of the hindcast (left panel) and of the historical (right panel) experiments

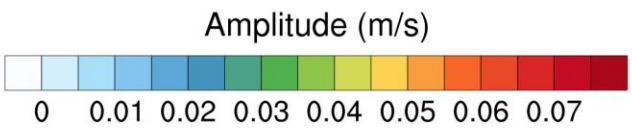


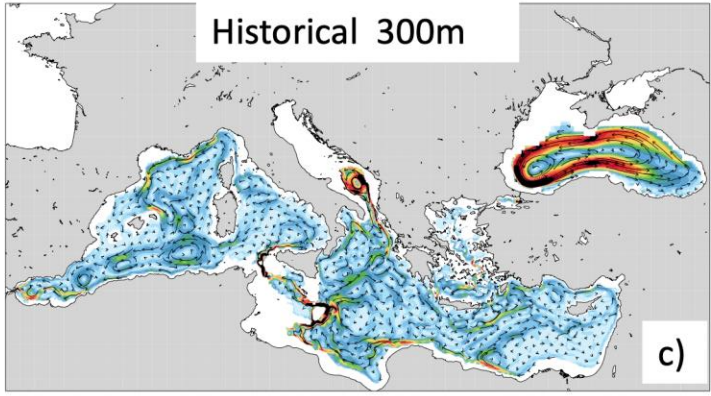


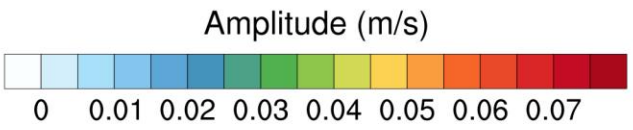






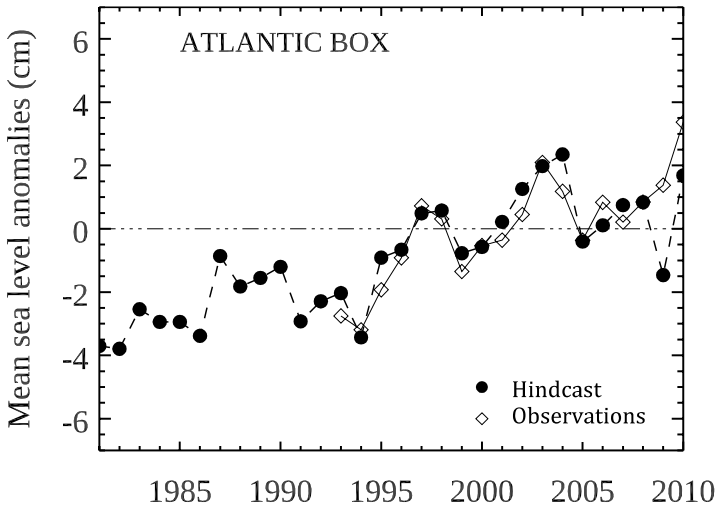


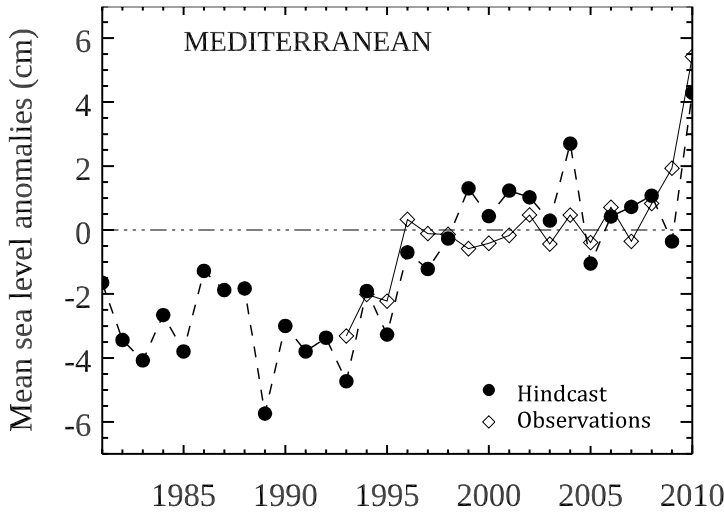


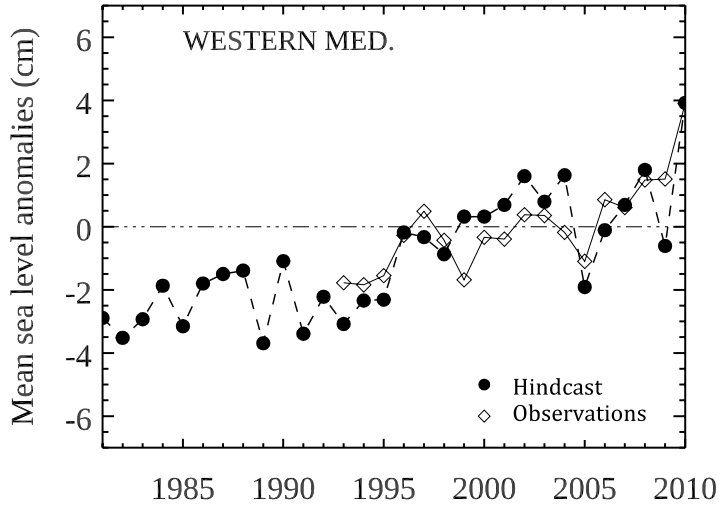


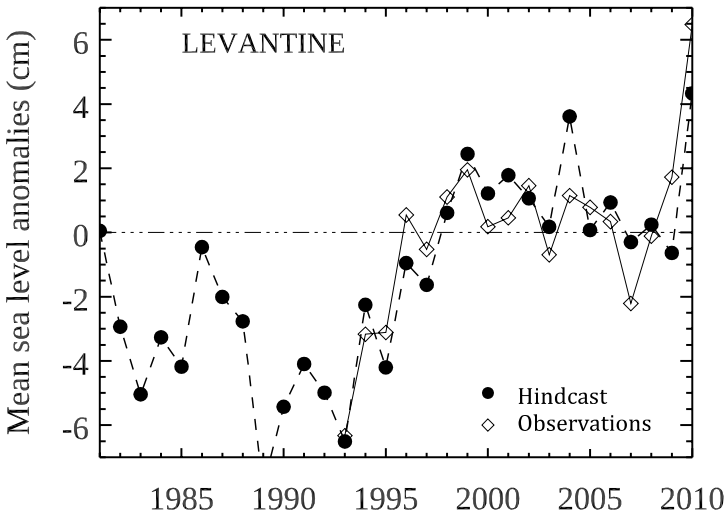
Future (2100) Mediterranean Sea Level

Interannual variability of the sea-level anomaly in different basins: whole Mediterranean (panel a), western and eastern sub-basins (panels b-c). Black dots denote values computed from the hindcast simulation, and diamonds those from the observations



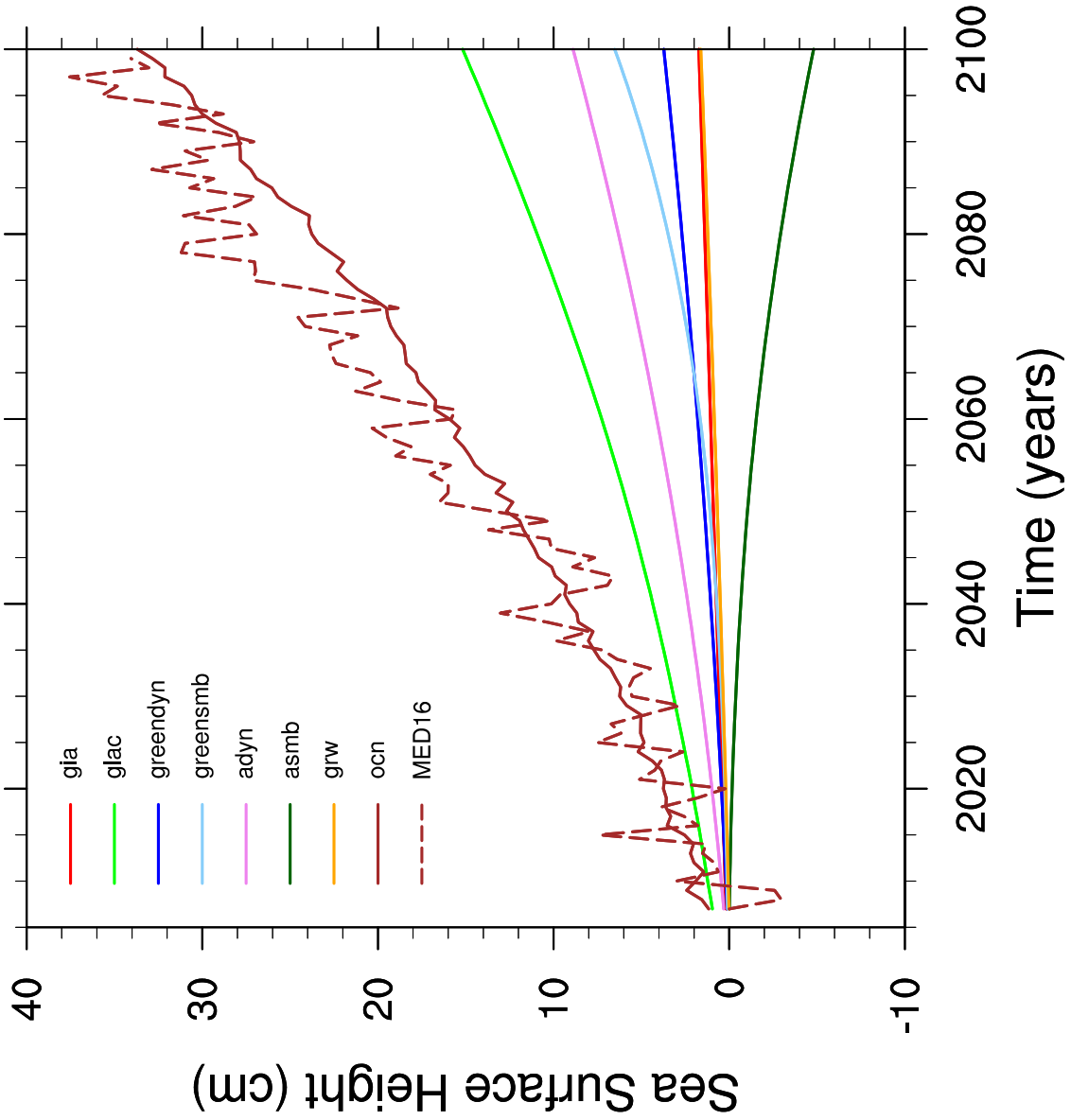






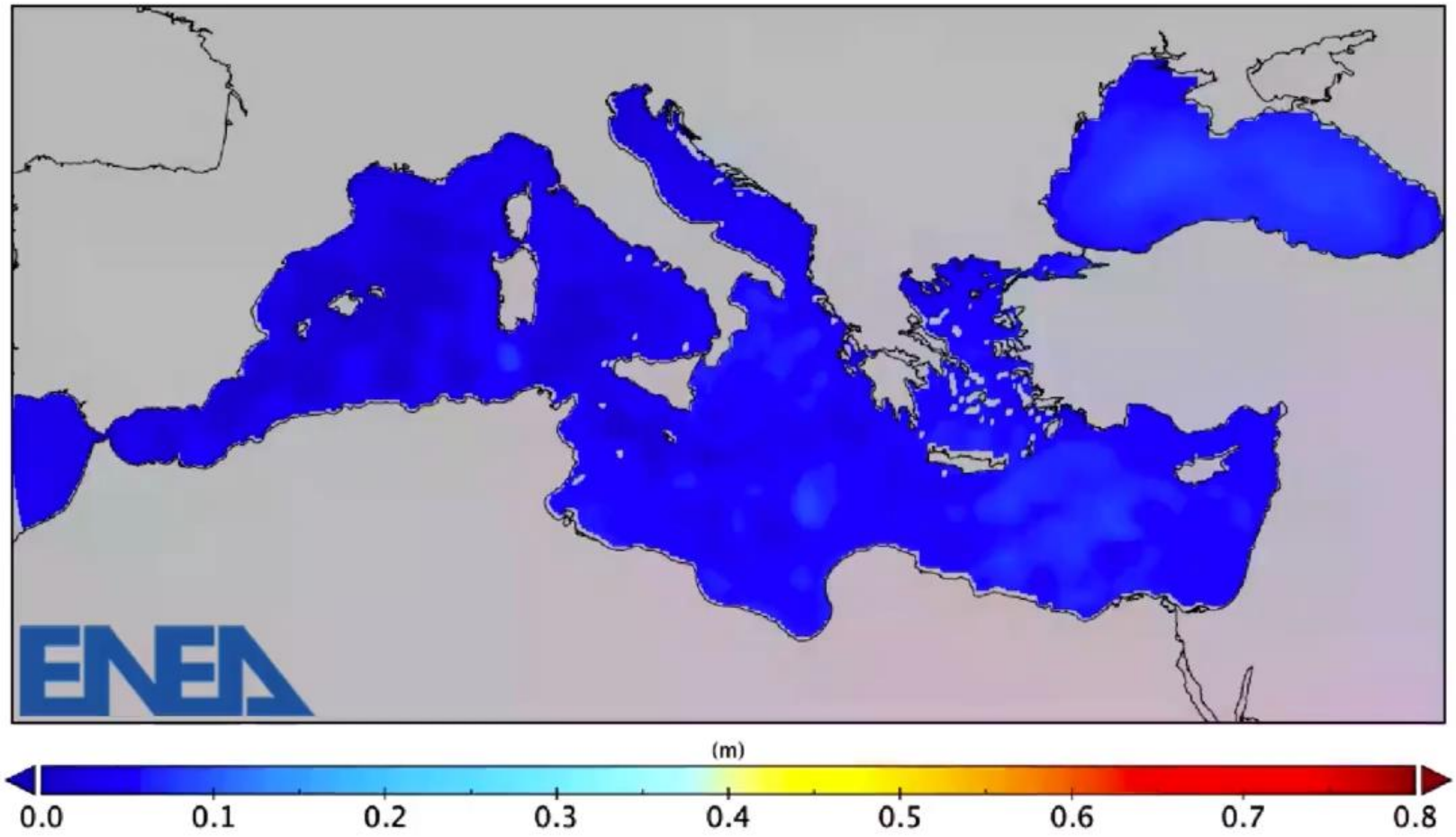
Future (2100) Mediterranean Sea Level

Time evolution of the components contributing to the projected mean sea level in the Mediterranean under the RCP8.5. Solid lines represent the central estimate over available models



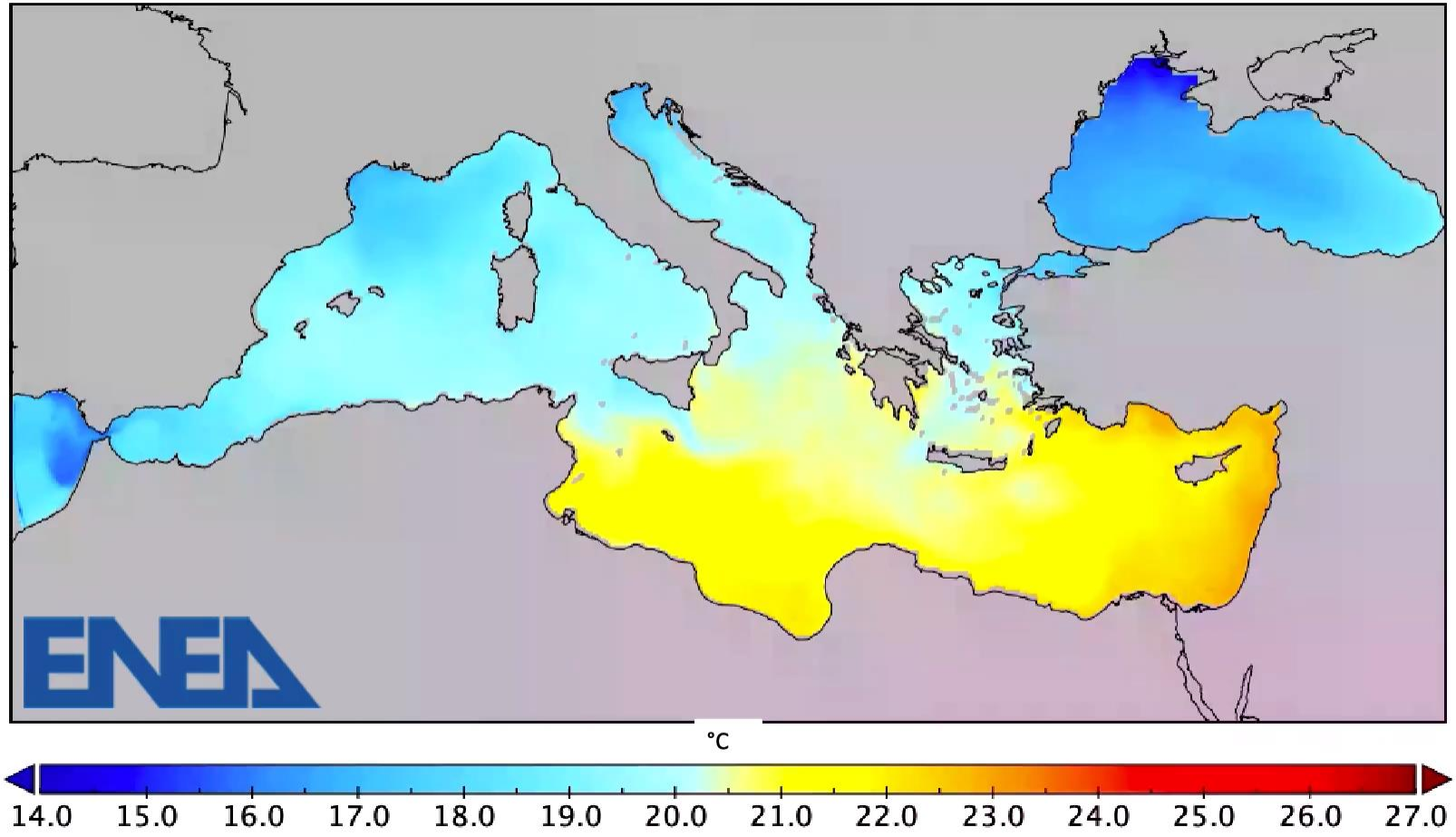
Sea level rise projection – rcp 8.5

2022



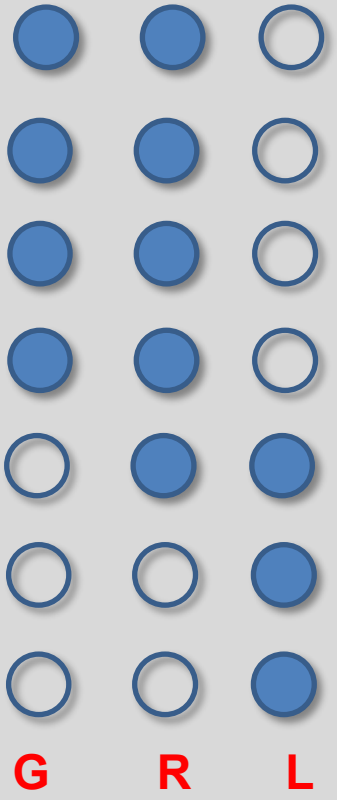
Surface Temperature projection – rcp 8.5

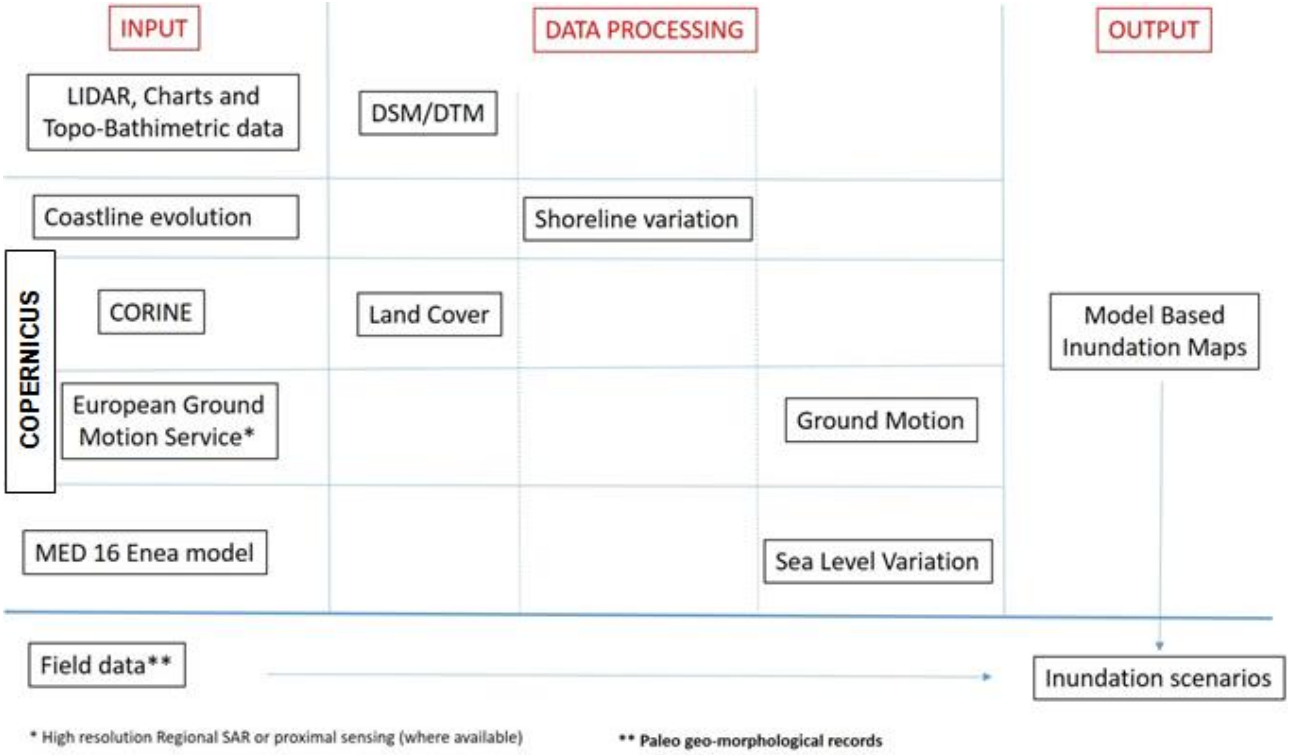
2022

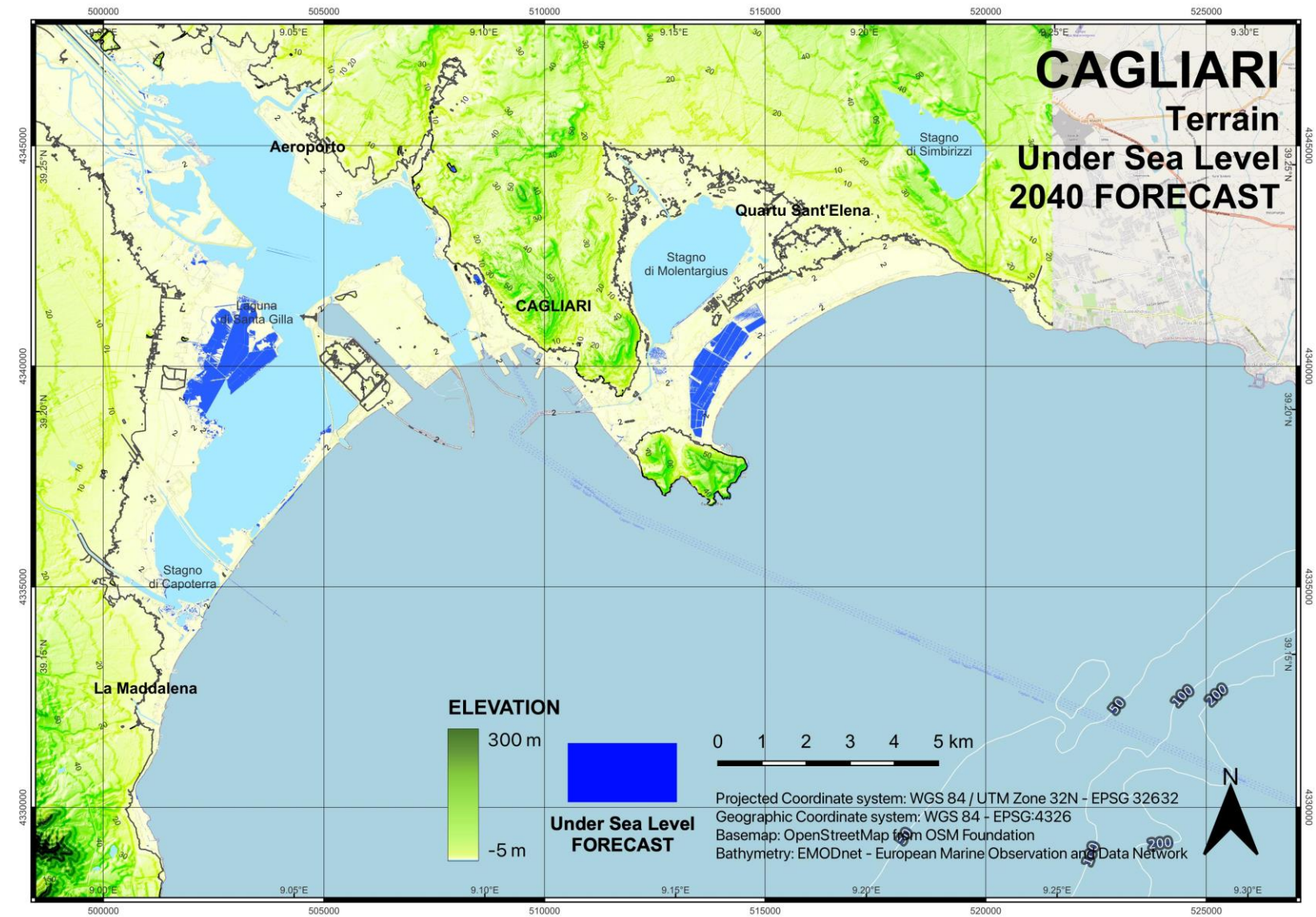


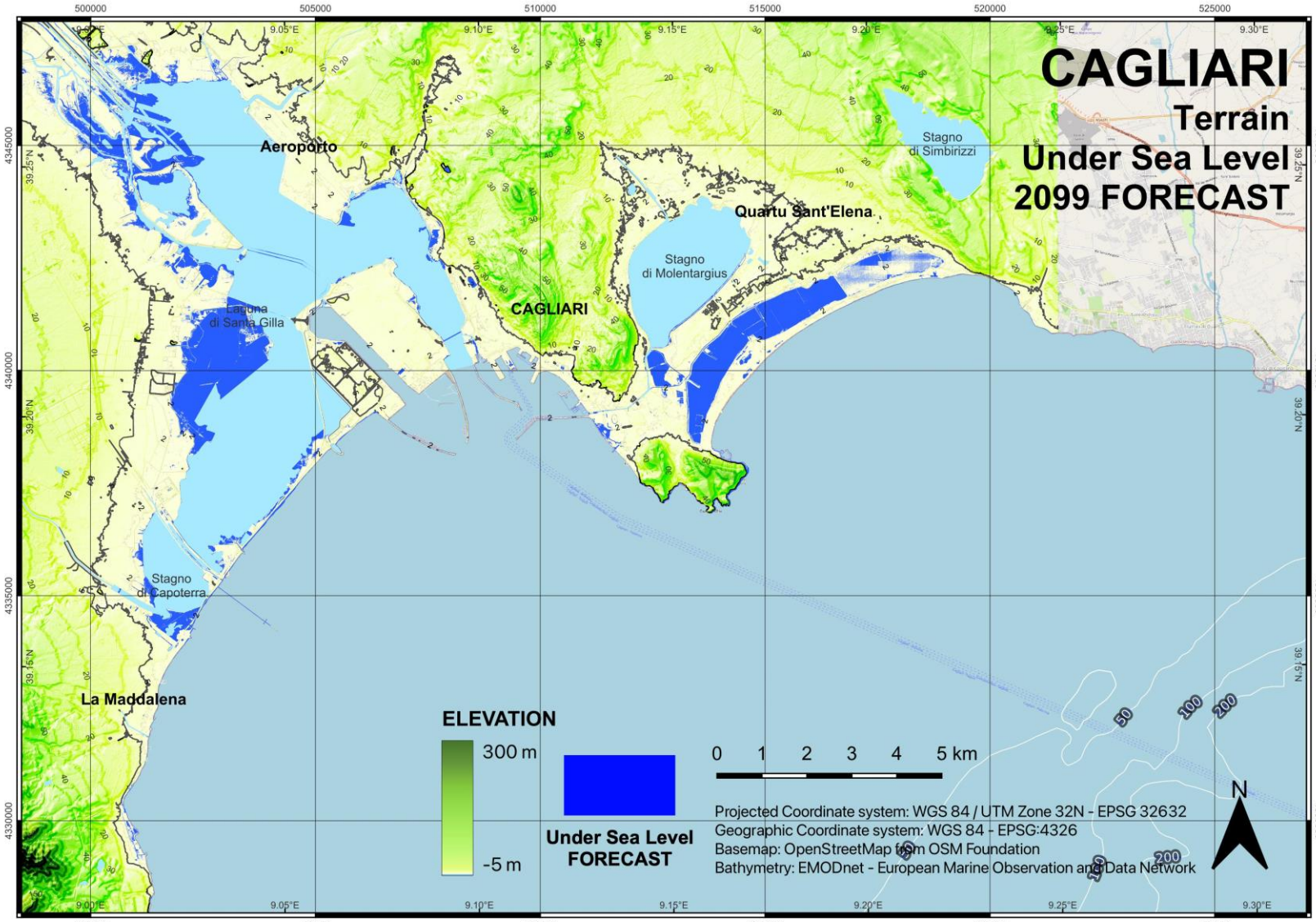
Causes of R-SLR at Gobal, Regional and Local scale

- Melting Greenland and Antarctica
- Melting Glaciers and ice caps
- Ocean Thermal expansion
- Ocean Circulation
- Postglacial rebound, self-attraction and loading
- Land Hydrology
- Tides, Storm surge, Subsidence




INPUT
DATA PROCESSING
OUTPUT
LIDAR, Charts and Topo-Bathimetric data
DSM/DTM
Coastline evolution
Shoreline variation
COPERNICUS
CORINE
Land Cover
Model Based Inundation Maps
European Ground Motion Service*
Ground Motion
MED 16 Enea model
Sea Level Variation
Field data**
Inundation scenarios
* High resolution Regional SAR or proximal sensing (where available)
** Paleo geo-morphological records


CAGLIARI
Terrain
Under Sea Level
2040 FORECAST
Aeroporto
Stagno
di Simbirizzi
Quartu Sant'Elena
Stagno
di Molentargius
CAGLIARI
Laguna
di Santa Gilla
Stagno
di Capoterra
La Maddalena
ELEVATION
300 m
-5 m
Under Sea Level
FORECAST
0 1 2 3 4 5 km
Projected Coordinate system: WGS 84 / UTM Zone 32N - EPSG 32632
Geographic Coordinate system: WGS 84 - EPSG:4326
Basemap: OpenStreetMap from OSM Foundation
Bathymetry: EMODnet - European Marine Observation and Data Network
N
50
100
200
500
200
500000
505000
510000
515000
520000
525000
4345000
4340000
4335000
4330000
9.00°E
9.05°E
9.10°E
9.15°E
9.20°E
9.25°E
9.30°E
39.25°N
39.20°N
39.15°N

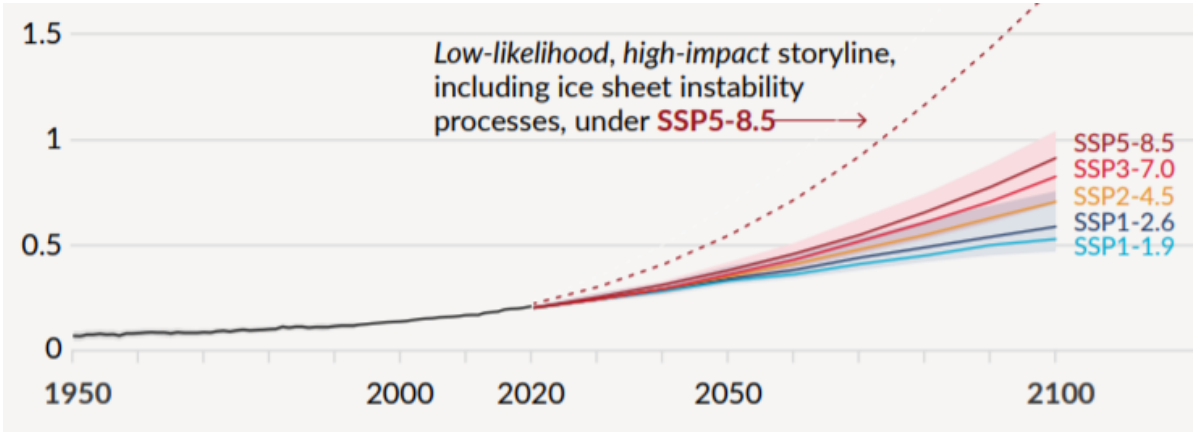

CAGLIARI
Terrain
Under Sea Level
2099 FORECAST
Aeroporto
Stagno di Simbirizzi
Quartu Sant'Elena
Stagno di Molentargius
CAGLIARI
Laguna di Santa Gilla
Stagno di Capoterra
La Maddalena
ELEVATION
300 m
-5 m
Under Sea Level FORECAST
0 1 2 3 4 5 km
N
Projected Coordinate system: WGS 84 / UTM Zone 32N - EPSG 32632
Geographic Coordinate system: WGS 84 - EPSG:4326
Basemap: OpenStreetMap from OSM Foundation
Bathymetry: EMODnet - European Marine Observation and Data Network

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003598.

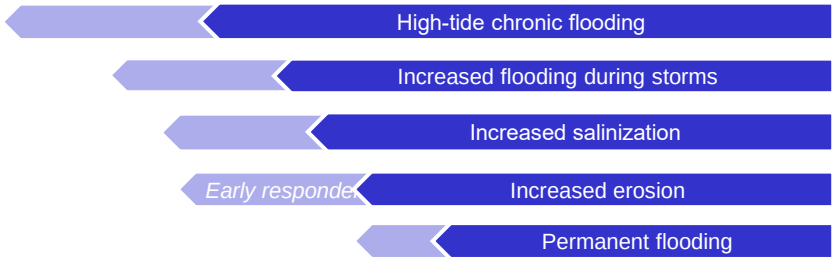
CoCliCo

coastal climate core services

Why CoCliCo ?



Natural variability dominates ➔ *Stylized times of emergence* ➔ *Sea-level rise impacts dominate*



IPCC, AR6 WG1, 2021

Sea level will rise at least by 0.3 to 0.6m in 2100 and continue rising for centuries.

The potential impacts for coastal flooding are a major source of concern for Europe.

The impacts of sea-level rise are starting to emerge from natural variability.

Adaptation is becoming urgent because planning and implementing adaptation often requires decades.

Gianmaria Sannino
gianmaria.sannino@enea.it