ACCADEMIA NAZIONALE DEI LINCEI

*XXII Giornata mondiale dell'acqua*

# THE MEDITERRANEAN SYSTEM
## A hotspot for climate change and adaptation


2023

ACCADEMIA NAZIONALE DEI LINCEI

*XXII Giornata mondiale dell'acqua*

# THE MEDITERRANEAN SYSTEM

## A hotspot for climate change and adaptation

With the kind support of

Fondazione Compagnia di San Paolo

With the scientific sponsorship of

European Academies easac Science Advisory Council

IUGG IAPSO International Association for the Physical Sciences of the Oceans

IUGG IAG AIG International Association of Geodesy

Report presented to the Conference "*XXII Giornata dell'Acqua*"
(Rome, 21-22 March 2023)

Cover image
Tolomeo, *Cosmografia*, Bologna, Dominicus de Lapis 1462 [i.e. 1477], pl. I, detail.
Roma, Biblioteca dell'Accademia Nazionale dei Lincei e Corsiniana.

# CONTENTS

# *FOREWORD*

The latest AR6 Climate Report, WG2, "Impacts, Adaptation and Vulnerability", 2022, for the first time in the IPCC history devotes the Cross-Chapter Paper 4 to the Mediterraean region. This region is known for its exceptional environmental and socio-cultural richness which originates from three surrounding continents. Climate change, in its different and diverse aspects, interacts very strongly with a variety of problems resulting from urbanization, water and air pollution, biodiversity loss and degradation of land and marine ecosystems. The Mediterranean is moreover expected "to be one of the most prominent and vulnerable climate change hotspots" (AR6, WG1, 2021, Chapter 10).

Adaptation options impact all the above environmental and social aspects, especially considering that a very probable scenario for the near future will simply obey the principle of "business as usual", through simple inertia of the economic system.This conference hence focuses on the Mediterranean Sea as a climate hotspot both scientifically and regarding adaptation measures.

The conference is composed of two parts.

The first part focuses on the physical sciences of the Earth (geodesy, physical oceanography, atmospheric dynamics) with the goal of providing a scientific background aimed at establishing what is known with certainty, what is debatable, what is simply still unknown and what are the projections of future climate scenarios. Hence each scientific presentation poses one overarching question, the answer to which can be important for the global climate, the Mediterranean one and their mutual interactions.

The second part focuses on adaptation measures, which obviously depend, first and foremost, on the scientific knowledge and second on the practical possibilities.

The most obvious, and well-known example of adaptation is the network of barriers against sea level rise and extreme sea level events constructed in the Netherlands since last century, and the 21st century example of the Venice barriers (the MOSE), recently completed, for the protection of the city and its lagoon.

Further adaptation options for climate change impacts on marine ecosystems and fisheries include improving and enlarging the regional network of marine protected areas, sustainable fishery practices, developing collaborative monitoring and sustainable aquaculture.

Adaptation options to sea level rise in the Mediterranean include also more modest nature-based solutions, such as beach and shore nourishment, dune restoration, with engineering playing a major role through breakwaters, seawalls and dykes. Many engineering-based coastal adaptations, however, imply large impacts on the coastal ecosystems and the environment as well.

An extreme engineering solution is the envisioned control dam at the Gibraltar strait for mitigation of sea level rise in the entire sea.

The dam would most likely involve major impacts on the entire physical, chemical and biological properties of the basin. These, and many more options, will be discussed in the Round Table scheduled for the second day of the conference. This report summarizes the issues debated at the conference.

The short summaries provided by the speakers reflect their scientific insights as well as their preferences for possible adaptation measures. The organizers hope that this report will be of stimulus to the Mediterranean community at large for the preservation of this uniquely rich basin and of its heritage to the future generations.

**Bruno CARLI**
*Accademia Nazionale dei Lincei*

*Chair of the Environmental Committee*

**Paola MALANOTTE-RIZZOLI**
*Massachusetts Institute of Technology*

*Chair of the Scientific Committee of the Conference*

**Fernando SANSÒ**
*Accademia Nazionale dei Lincei*

*Co-Chair of the Scientific Committee of the Conference*

# ENDORSEMENT

Dear Mr. Parisi, dear colleagues, dear friends, ladies and gentlemen:

It has now been 60 years since our Co-Nobel-Laureate Syukuro Manabe demonstrated that increased levels of carbon dioxide in the atmosphere leads to increased temperatures on the earth's surface. It has been 50 years since the Club of Rome published their book The Limits of Growth. And it has been 40 years since I was able to demonstrate that the observed global warming was indeed man-made. And the Club of Rome has just updated their model in their latest publication Earth for All. How much time have we lost! How often have we repeated our warning that the longer we wait, the more expensive this problem will become for mankind?

There are several reasons in my opinion for the generally slow recognition of the urgency of the problem of climate change:

1. First, our inborne ability to ignore danger unless we are directly affected by it.

2. Secondly, our democratic systems. With elections every four or five years, and the desire to be re-elected, our politicians are hesitant to make unpopular decisions.

3. And finally, industry, which is willing to change unilaterally only if there is no economic disadvantage from that change.

Therefore, there is need for clear corporate mandates from our politicians. A vicious cycle. Or do we need an international Ecocide Law?

Now the danger is approaching closer and closer and seemingly faster and faster. The Potsdam Institute for Climate Impact Research has just published a study that shows that the US, one of the world's strongest economies, will soon be unable to cope on its own with damages caused by climate change in the form of increased and more powerful hurricanes.

The changing climate has become part of the normal experience of millions of people around the globe and is often most felt in regions, such as the Mediterranean, where the effect of centuries of environmental degradation is now being compounded by increasing temperatures.

In 2021 and 2022, heatwaves swept through the Mediterranean region, causing widespread droughts, wildfires and serious health effects for people. In 2022 in many Mediterranean countries, temperatures above 40 or even 50 degrees Celsius were observed, the highest since temperature records exist. In 2022, a marine heatwave accompanied the terrestrial heatwave in the Mediterranean.

Scientific models suggest that these were not isolated events. If greenhouse gas emissions do not decline markedly, we should expect summer temperatures in the Mediterranean to increase at a rate higher than the average global temperature increase. Even more worrying, precipitation, which in most parts of the world is expected to increase, will be reduced over large parts of the Mediterranean. This makes the Mediterranean a climate change hotspot.

In addition, the Mediterranean region has long suffered from environmental stress, going all the way back to the deforestation in ancient Greece and Rome. Intensive agriculture is leading to overuse of water resources with groundwater levels lowering year by year. Overfishing has long been going on. The amount of fish caught in the Mediterranean is no longer sufficient to feed the local population and tourists. High population density and millions of tourists annually exacerbate the environmental stress. And climate change now adds to this longstanding overuse of natural resources.

And it offers little comfort that in the wake of the present energy crisis, gas exploration in the eastern Mediterranean is being accelerated instead of using sun and wind, renewable energy resources that the Mediterranean has in abundance.

There is no scientific doubt about man-made climate change; but even though we know the cause of the illness, we still have to find the cure.

The Mediterranean is remarkably diverse in terms of geography and political, economic, cultural, and belief systems, but it also has many commonalities. Science and scientists, with their commitment to a rational analysis of the world and a long-standing practice of working together across borders, can be a major positive force in finding solutions to the climate challenge.

Sharing data, information, knowledge and scientific advances, working together across borders and disciplines, collaborating to find locally adaptable solutions, the scientific community has the noble and important task of advising policy makers and informing the public. This conference, "The Mediterranean System – A Hotspot for Climate Change and Adaptation," is a welcome opportunity to work together.

The ancients called the Mediterranean Mare nostrum, literally "our sea". So that future generations can also enjoy this beautiful and culturally rich region as their common heritage, we need to combine all our intelligence, our compassion and our efforts to preserve it for the future.

I wish you a conference with many new ideas and insights into the immense problem of reducing, mitigating, or perhaps even stopping climate change.

**Klaus HASSELMANN**
*Nobel Laureate for Physics 2021*

## WHAT ARE THE TOOLS AND METHODS TO OBSERVE SEA SURFACE HEIGHT FROM SPACE IN THE MEDITERRANEAN?

Monitoring sea surface topography with high-precision satellite altimetry began in the early 1990s with the launch of the European Space Agency's (ESA) European Remote-Sensing Satellite-1 (ERS-1) satellite (1991) and the NASA/CNES Topex/Poseidon satellite (1992). These spaceborne missions measure the distance between the satellite and the ocean surface by sending a radar wave and counting the time it takes to return, from which sea surface height can be accurately determined knowing precisely the orbital altitude of the spacecrafts. Measuring sea surface topography contributes to advance our understanding of ocean circulation and its variability from large scale to mesoscale, as well as climate-related global sea level rise and its regional variation.

Since then, to ensure continuity, several subsequent satellite missions have been launched, including Jason-1 (2001), Jason-2 (2008), Jason-3 (2016) and Sentinel-6 Michael Freilich (2021), following the path of Topex/Poseidon, providing continuous and highly accurate sea level data over the past three decades. The data from these satellites are now routinely used to monitor sea level rise, as well as for understanding the role of the oceans in the Earth's climate system. Following ERS-1, which had additional mission objectives besides the oceanographic mission mentioned above, focussing also on ice sheets, sea-ice thickness, extent and concentration, and continental surfaces, were launched ERS-2 (1995), Envisat (2002), CryoSat-2 (2010), Sentinel-3A (2016) and Sentinel-3B (2018). The French/Indian Saral/AltiKa mission in orbit since 2013 completed this constellation. The Chinese Space Agency has also launched radar altimeter missions, Haiyang-2A (HY-2A, 2011), HY-2B (2018) and HY-2C (2020).

The two satellite-series of Topex-Poseidon/Jason/Sentinel-6 Michael Freilich and ERS/Envisat/AltiKa/Sentinel-3 series, complement each other by their space and time characteristics: 10 day repeat and coarse space resolution (315 km at Equator), and ~1 month repeat and finer resolution (~80 km at Equator), respectively. Also, the inclinations are different, the ESA satellites aim at making measurements as far north as possible (up to 88° latitude) , while the Topex/Poseidon series favour lower inclination (66°) for perpendicular crossings to better derive geostrophic velocity. Figure 1 shows the two very different space coverages and how Sentinel-3 densifies the sampling ensured on the larger scale by Jason/Sentinel-6.

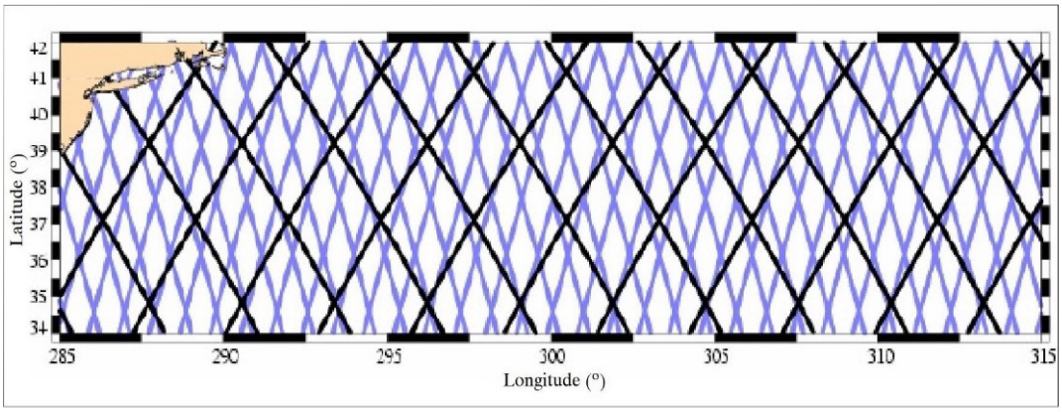


**Figure 1.** *Comparison between Jason (black) and Sentinel-3 (purple) ground tracks for a complete cycle (Source: ESA).*

In terms of spatial scales, satellite altimetry provides global coverage, allowing for the measurement of sea level changes over large geographic areas. This global perspective is crucial for understanding the behaviour of the ocean at basin scale, and for detecting regional differences in sea level trends (Legeais et al., 2018). With several altimetry satellites now flying, and more coming in the future, the coverage has drastically increased. The Mediterranean Sea is densely covered by the constellation of altimetry missions flying today. Figure 2 shows the dense coverage over the Mediterranean Sea over 14 days in August 2022 by SARAL/AltiKa (ISRO/CNES), CryoSat-2 (ESA), Copernicus Sentinel-3A/B (EC/ESA/Eumetsat) and Copernicus Sentinel-6 Michael Freilich (EC/ESA/Eumetsat/CNES/NASA /NOAA). This fast coverage far exceeds the capability of an in situ oceanographic campaign but the latter is indispensable for studying the ocean in its depth and for validation of space data.

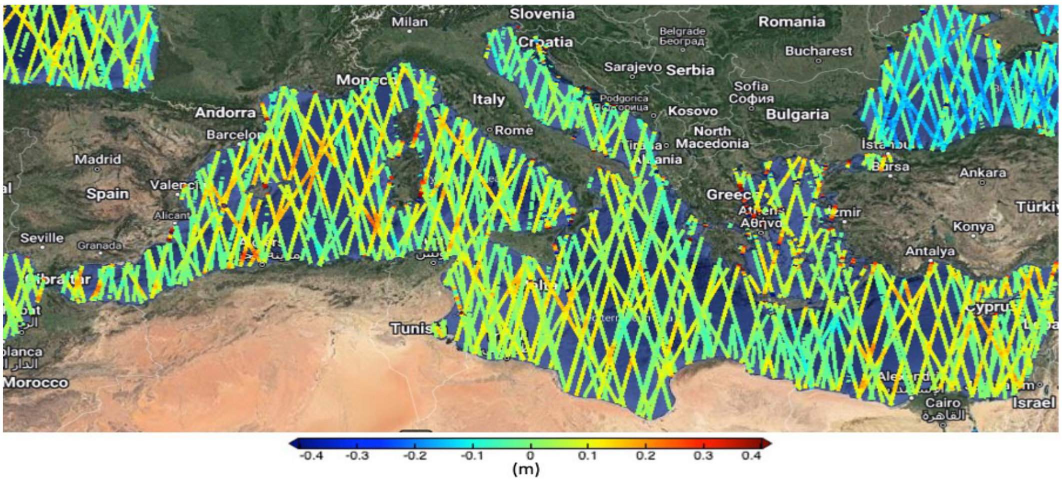


**Figure 2.** *Coverage over the Mediterranean Sea over 14 days in August 2022 (week 19 and 20) by SARAL/AltiKa (ISRO/CNES), CryoSat-2 (ESA), Sentinel-3A/B (EC/ESA/Eumetsat - Copernicus) and Sentinel-6 Michael Freilich (EC/ESA/Eumetsat/CNES/NASA/NOAA) – Copernicus. The colour exhibits the dynamic topography in metres. (Source: OceanDataLab, Ocean Virtual Laboratory).*

Furthermore, with the advent of synthetic aperture radar (SAR, delay-Doppler) altimetry, valid measurements are retrievable much closer to the coast, as close as a few hundreds of meters, with specialised retrackers such as SAMOSA+, accessible to anyone in the ESA Altimetry Virtual Lab (https://earthconsole.eu/altimetry-virtual-lab). While the along-track resolution is getting higher and higher with the development of different processing algorithms for SAR altimetry, the cross-track resolution remains very poor, of the order of 130 km at the latitude of the Mediterranean Sea for gridded products (Ballarotta et al., 2019). The best way to exploit altimetry, especially for monitoring the ocean dynamics in the coastal zone is to use to the along-track data at its time and location, rather than smoothing a grid with optimal interpolation, particularly when assimilating in high resolution coastal ocean models.

In terms of accuracy, current satellite altimeters have the capability to measure sea level with an uncertainty below the centimetre. With today's altimetry, say the 3rd generation since ERS-1, using the along-track Doppler to synthetise a very large antenna of several kilometres, the noise level has been beaten down from 1.8 cm for Envisat to 0.8 cm for Sentinel-3, for measurements averaged at 1 Hz (Dinardo et al., 2016). This level of accuracy, and its stability in time, has been crucial in detecting and monitoring the long-term trend of sea level rise (Ablain et al., 2017, Guerou et al., 2023), which is a key indicator of current global warming as it results from global changes occurring tin the climate system, such as ocean warming and land ice melting (Horwarth et al., 2022).

The Sentinel-6 Michael Freilich and SWOT (Surface Water and Ocean Topography, launched on 16 December 2022) radar altimetry missions are both designed to measure the height of the ocean surface with high accuracy and precision. Exploiting these missions together will improve our understanding of oceanic processes at short space and time scales in the Mediterranean Sea by complementing each other to improve spatial and temporal resolution: The Sentinel-6 mission provides high temporal resolution measurements, while the SWOT mission provides high spatial resolution measurements. The combination of measurements from the two missions, especially monitoring the exchanges between the inland water domain and the oceanic coastal zone, will improve our understanding of coastal dynamics, including coastal flooding and coastal erosion. Future radar altimetry missions designed to improve our understanding of processes at short space and time scales would need to offer both high spatial and high temporal resolution, which would be achieved by swath altimeters or constellations of dozens of altimeters.

While instruments and methods used to observe the sea surface topography from space in the Mediterranean region provide a wealth of information and allow for high accuracy and precision measurements, they are not sufficient to understand small-scale processes affecting the coastal zones (Dieng et al., 2021; Cazenave et al., 2022).

Satellite observations are limited in their spatial and temporal resolution, therefore they need to be complemented by other types of observations, such as high-altitude platforms (so called pseudo-satellites, airships or balloons) and in situ measurements. In situ measurements, such as those made by buoys, ships and underwater vehicles, provide detailed information on ocean processes at specific locations and times, and at depth. This information can then be used to validate and improve satellite observations, as well as to study processes that are not captured by satellite observations. Numerical models are also an important tool for testing our understanding of small-scale processes. They produce simulations of the ocean, coupled with the atmosphere, and produce predictions of future conditions. These simulations can be used to understand how different processes interact and to estimate the effects of human activities on the Mediterranean Sea. A comprehensive understanding of the Mediterranean Sea requires a combination of satellite observations, in situ measurements and numerical models.

**Jérôme BENVENISTE**
*European Space Agency*
*ESA-ESRIN, Frascati, Italy*

# HOW WELL CAN WE MEASURE THE MEDITERRANEAN SEA CIRCULATION FROM SPACE?

The general circulation of the Mediterranean Sea is characterized by an open Thermohaline Circulation (THC) cell, starting in the Strait of Gibraltar with the inflow of relatively fresh Atlantic Waters, and ending with the outflow, at the same site, of intermediate and deep saltier Mediterranean Waters. By transporting heat and salt over large distances, this circulation modulates both the short-term and climatological dynamics of the Mediterranean Sea – Atmosphere system. Its improved understanding and accurate monitoring are thus of key importance, all the more in the present context of climate change. In the Mediterranean Sea, all published studies agree on a modification of the thermohaline circulation under various twenty first century emission scenarios, with a northward shift of the eastward moving surface water veins in both the western and eastern basins and a weakening of the open-sea deep convection in the western basin (Adloff et al., 2015).

Satellite data, by providing global and continuous measurements of several ocean parameters (sea surface temperature, salinity, sea level, geoid) are a key source of information to improve the estimation of the upper-layer circulation. In particular, the launch in 2009, of the GOCE (Gravity Field and Ocean Circulation Experiment) satellite, by allowing to

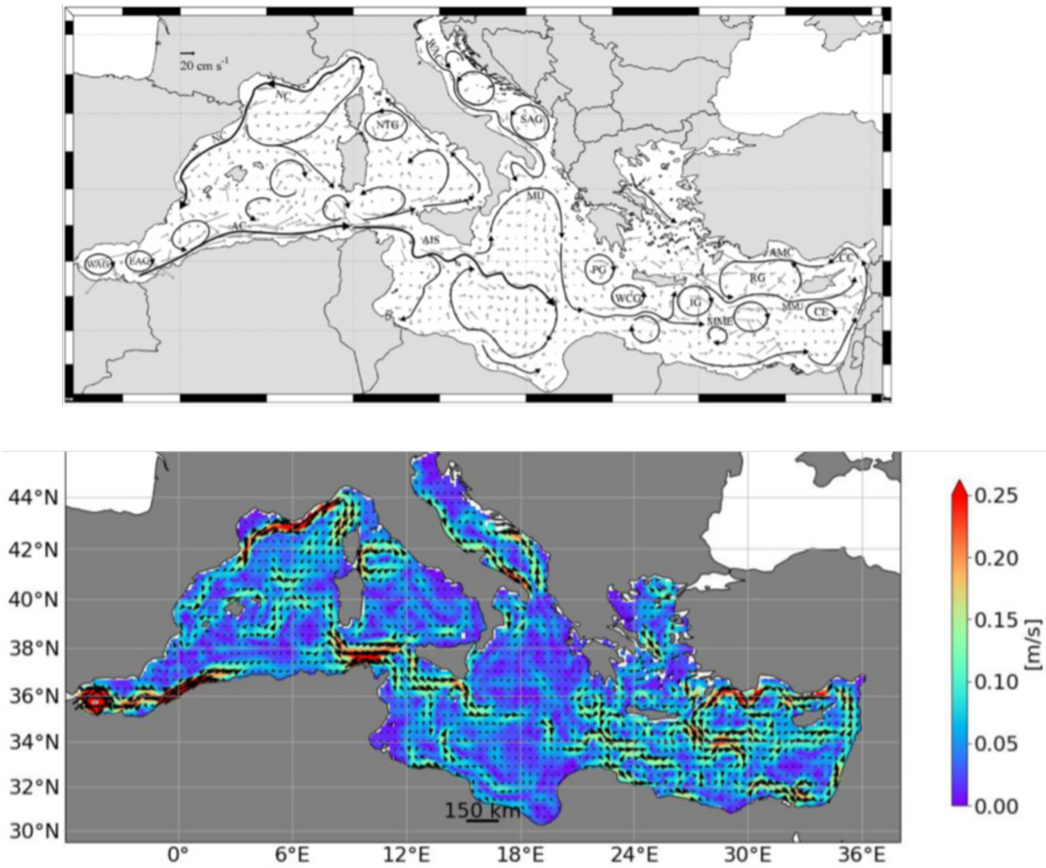


**Figure 1.** *Top: Sketch of the general surface circulation of the Mediterranean Sea from Poulain et al. (2013). Bottom: Mean surface circulation calculated from altimetry, gravity and in-situ data by Jousset et al. (2022).*

measure for the first time the Earth geoid at 100km resolution, has been a game-changer for the estimation of ocean currents from the joint use of altimeter data and gravity data (Mulet et al., 2012a). At first order (the so-called geostrophic approximation), ocean currents are indeed proportional to the gradient of the absolute dynamic topography, calculated as the difference between the altimeter sea level (above a reference ellipsoid), and the geoid height (above the same reference ellipsoid). In the global, open ocean, such data, used in synergy with in-situ measurements (Argo floats and drifting buoy velocities), have led to the development of improved current estimates, both at the surface (Rio et al, 2014a) and at depth (Mulet et al., 2012b), which are today calculated and delivered operationally, on a daily basis, within the Copernicus Marine Environment Monitoring System (CMEMS).

Methods developed for the global ocean are not always directly applicable to the Mediterranean Sea, characterized by numerous coastal areas and straits, shorter spatial scales than in the open ocean, and a rather complex surface circulation, as sketched by Poulain et al in 2013 (top plot of Figure 1) from the joint analysis of satellite and in-situ measurements. As a consequence, specific, regional algorithms need to be developed. Bottom plot of Figure 1 shows the most recent estimate of the Mediterranean Sea general circulation calculated at 4km resolution using altimeter, GOCE and in-situ measurements of sea level and velocity by Jousset et al (2022). Comparison to independent in-situ measurements of surface velocities show mean differences of the order of 10 cm/s, which represent a significant improvement compared to earlier solutions (Rio et al., 2014b) and a strong step forward regarding the monitoring from space of the Mediterranean Sea circulation.

In the near future further improvements are expected by exploiting the high-resolution data from the recently launched wide-swath altimetry SWOT (Surface Water and Ocean Topography) mission, together with regionally improved geoid models as GEOMED-2 (Barzaghi et al., 2015).

**Marie-Hélène RIO**
*European Space Agency*
*ESA-ESRIN, Frascati, Italy*

## HOW CAN GEODETIC METHODS IMPROVE THE ESTIMATE OF THE CURRENTS IN THE MEDITERRANEAN SEA?

Geodesy can provide valuable information on currents estimation based on the combination of gravity and altimetry. Gravity is standardly used to estimate the geoid undulation N, i.e. the height of the geoid over a given reference ellipsoid (see Figure 1). In a recent international test, the Colorado experiment (Wang et al., 2022), 14 international research teams have estimated the geoid undulation in an area having a complex gravity signal. This test proved that a precision of 2~3 cm in estimating the geoid can be obtained when using a dense and reliable gravity database.

As it is well-known, the geoid undulation over the ocean areas is closely related to the Mean Sea Surface Height (MSSH) with discrepancies that can reach 1~2 m at global scale (see, e.g., Rummel and Sansò, 1993).

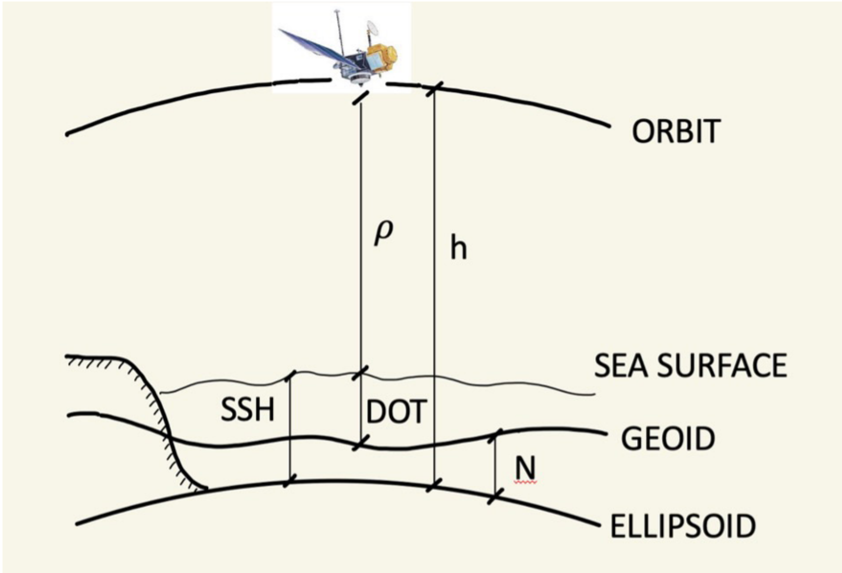


**Figure 1.** *The satellite satellite altimetry observation.*

By satellite altimetry, one can get the Sea Surface Height (SSH in Figure 1) that can be then averaged in time to get the MSSH.
The satellite altimetry equation giving the SSH is

$$\textit{Satellite Altitude } (h)\text{-}\textit{Observed Range}(\rho)=SSH \qquad (1)$$

where $h$ is known from the satellite orbit and the range $\rho$ is observed by the satellite radar altimeter. Finally, the estimate of the Mean Dynamic Ocean Topography (MDOT), which is related to the ocean circulation, is obtained as

$$MDOT=MSSH\text{-}N \qquad (2)$$

where $N$ is the geoid undulation.

In this way, information on the ocean circulation to be compared with oceanographic estimates can be provided using geodetic methodologies.

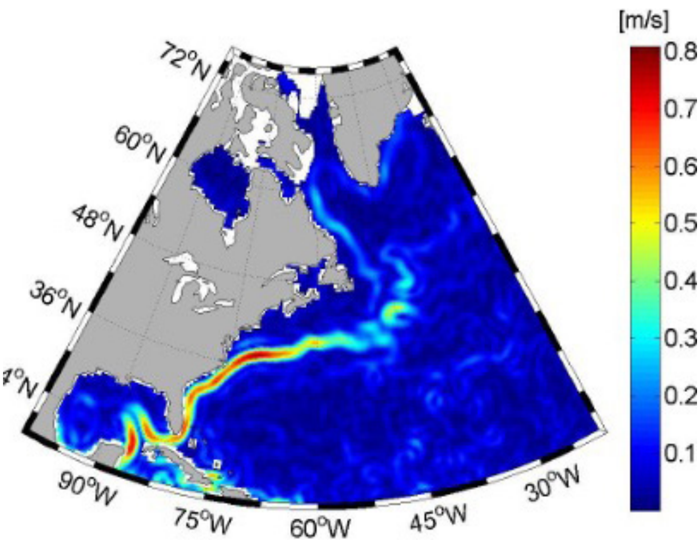


**Figure 2.** *The Gulf Stream current velocity*

As an example of this approach, the velocity of the Gulf Stream permanent current is displayed in Figure 2 as derived from the DTU MSSH (Andersen et al., 2017) and the geoid estimate based on the satellite only GOCE Global Geopotential Model (Drinkwater et al., 2023). In this context, the GeoMed2 project aims at estimating a high-accuracy and high-resolution geoid model for the Mediterranean Sea based on land and marine gravity data and GOCE/GRACE based Global Geopotential Models. The processing methodology is based on the well-known remove-compute-restore approach (Barzaghi, 2016) following both stochastic and spectral methods (Sansò and Sideris, 2013) for the determination of the geoid and the rigorous combination of heterogeneous data. In a pre-processing step, all available gravity observations for the wider Mediterranean basin have been collected, validated, homogenized and unified in terms of their horizontal and gravity system, so as to derive a reliable gravity database to be used for the determination of the geoid.

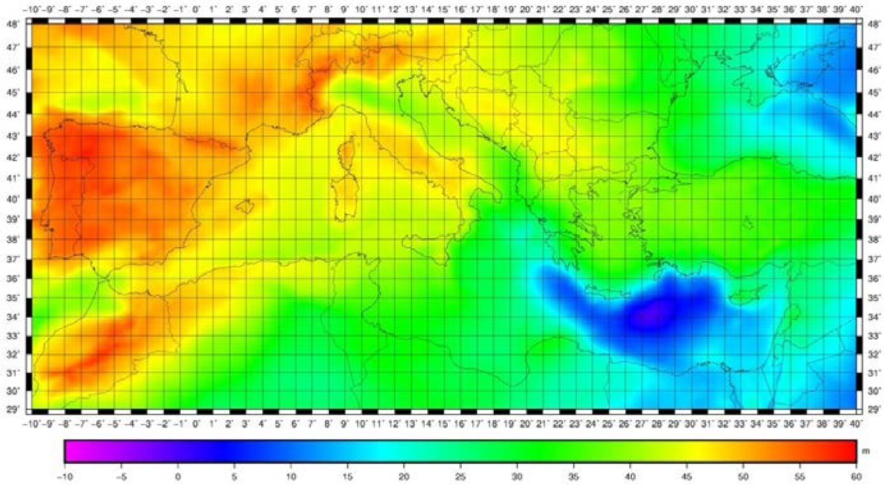

**Figure 3.** *The GeoMed2 geoid.*

In Figure 3, one of the estimates of the geoid undulation over the Mediterranean area is shown (Barzaghi et al., 2018).

This GeoMed2 geoid will be the reference surface for height-system unification within the Mediterranean Sea and will allow the definition of a high-resolution model of the MDOT to be used in estimating the circulation in the Mediterranean Sea.

**Riccardo BARZAGHI**
*DICA-Politecnico di Milano*

## ARE WE APPROACHING A TIPPING POINT OF THE ATLANTIC OCEAN CIRCULATION?

There is growing concern among scientists that the Atlantic Meridional Overtuning Circulation (AMOC), a key component of the Earth's climate system, may be slowing down and could potentially reach a tipping point in the future. The AMOC is an ocean current system that carries warm water from the South Atlantic via the tropics to the northern Atlantic and returns colder water back toward the South Atlantic, playing a crucial role in regulating global climate patterns.

However, the current state and future of the AMOC is the subject of ongoing research and scientific debate, and there is still much that is not known about this complex system and how it will respond to future changes in climate, such as rising atmospheric and ocean temperatures, melting of the Greenland Ice Sheet, and increasing freshwater inputs from rainfall and rivers.

One key piece of evidence is the "North Atlantic Warming Hole", a region of the North Atlantic Ocean south of Greenland and Iceland that is the only area of the world that has experienced a cooling over the last 100 years (see Figure 1). This phenomenon has been predicted by climate models as a result of a slowing AMOC in response to global warming (Rahmstorf et al., 2015).

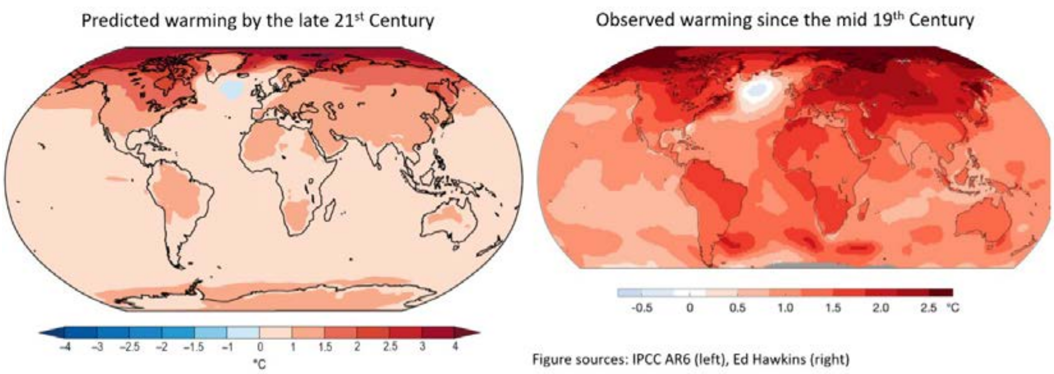


**Figure 1.** *Future prediction of global warming compared to past observed warming. Note the different scales and the remarkable "North Atlantic Warming Hole". Grey indicates lack of data.*

When looking at sea surface temperatures, models and data in higher resolution also reveal excessive warming along the US coast in addition to the warming hole (Figure 2). Both phenomena combined have been shown to be a 'fingerprint' characteristic of an AMOC slowdown by about 15% (Caesar et al., 2018). This type of fingerprint is useful to reconstruct past AMOC evolution, since we do not have long-term direct measurements of the currents.

Paleoclimate proxy data, such as sediment records, can provide valuable information about past changes in the Atlantic Meridional Overtuning Circulation (AMOC) further back in time. These data can help to place recent changes in the AMOC into a longer-term perspective and provide insights into the natural variability of the system over time. Such proxy data studies suggest that the modern slowing of the AMOC is unique in the past millennium or more (Caesar et al., 2021).

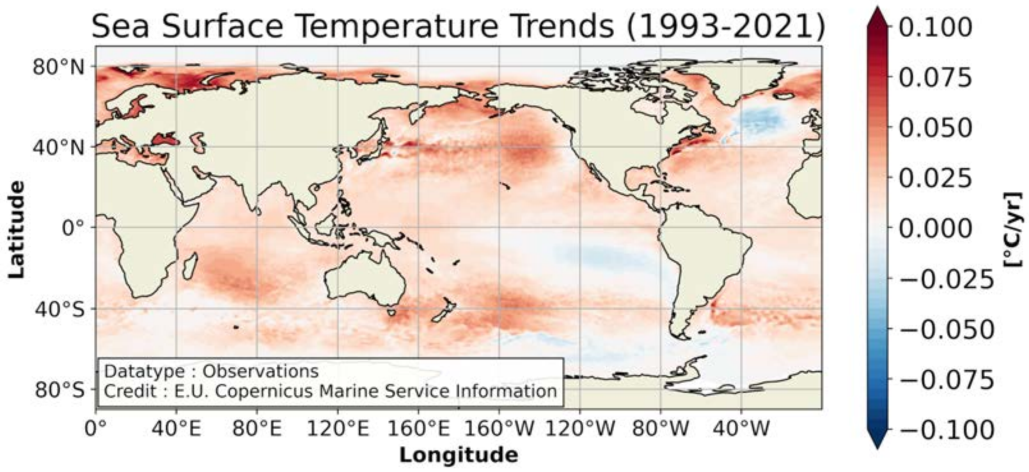


**Figure 2.** *Sea surface temperature trend 1993-2021 from satellite data. Source: Copernicus Marine Service.*

Continued melting of the Greenland Ice Sheet in the coming decades could contribute to further weakening of the AMOC, with important consequences for the ocean ecosystem, the weather in the wider North Atlantic region, regional sea levels and the ocean's ability to absorb carbon dioxide.

Moreover, the AMOC has a known tipping point beyond which it becomes unstable and grinds to a halt (Rahmstorf, 2002). The question of how close we already are to this tipping point is becoming increasingly urgent. A recent study using the established method of 'critical slowing down' of a system's variability close to a tipping point suggests that the AMOC is too close to its tipping point for comfort (Boers, 2021).

**Stefan RAHMSTORF**
*Potsdam Institute for Climate Impact Research*

## DOES THE MEDITERRANEAN SALT TONGUE AFFECT THE ATLANTIC MERIDIONAL OVERTURNING CIRCULATION? WHAT ARE THE CHANGES AND PROJECTIONS IN THE MEDITERRANEAN PHYSICAL PROPERTIES?

The Mediterranean sea is a concentration basin in which evaporation exceeds precipitation plus river runoff. Hence the balance required by volume and salt conservation at the Gibraltar strait, the "choke" point of the basin, implies an excess inflow of Atlantic Water (AW ) with respect to the Mediterranean Overflow Water (MOW) in the amount of ~ 0.07 Sv. Furthermore, the rather complex bathymetry of the strait, provides hydraulic controls at the two critical sections, the Camarilla Sills (CS) and Tarifa Narrows (TN). (Bryden and Kinder, 1991). A very high resolution of the strait bathymetry is required in numerical simulations of the basin circulation to represent such controls and the consequent flow exchanges. A further consequence, is that salinity controls the dynamics and thermodynamics of the basin. While global projections of sea level rise take into account only the thermosteric effect, the halosteric effect cannot be neglected in Mediterranean climate projections, as it can even overcome the thermosteric one. ( Marcos and Tsimplis, 2008).

The overall picture of the two upper layers circulation, the open thermohaline cell of the Mediterranean, is presented in the scheme of Figure 1.

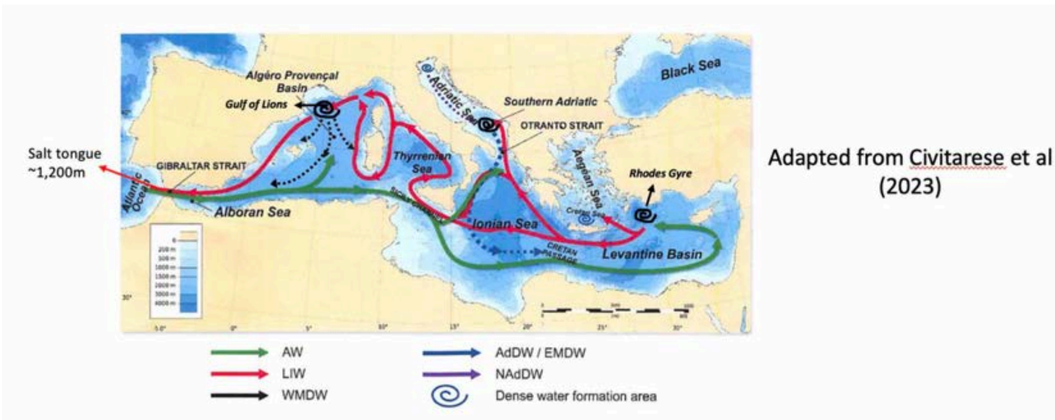


**Figure 1.** *Pathways of the two water masses, AW and LIW, of the open thermohaline Mediterranean cell.*

The inflow of AW at Gibraltar is shown in green entering and bifurcating into different branches in the surface layer of ~ 200 m thickness. In the Levantine basin, through intermediate convection at the historically recognized site of the Rhodes Gyre ( Figure 1), the light and cold AW (upper limb of the open cell) is transformed into the warm, salty Levantine Intermediate Water (LIW) through surface evaporation and related latent heat loss. LIW occupies the intermediate layer ~ 300 m. thick and constitutes the return flow which finally returns to Gibraltar exiting into the Atlantic ocean at ~ 1,200 m depth. This is the well-known salty Mediterranean tongue affecting the lower limb of the Atlantic Meridional Overturning Circulation (AMOC) also known as the Global Conveyor Belt. Also shown in figure 1 are the sites of Deep Convection reaching to >1,000 m depth. The two major sites are the first one in the Western Mediterranean, in the Gulf of Lions, where the Western Mediterranen Deep Water (WMDW) is formed, thereafter spreading in the abyssal western basin. An upwelling branch possibly joins the upper LIW in the outflow to the Atlantic. The second deep convection site in the Eastern Mediterranean is known to be in the Southern Adriatic Pit (SAP). There Eastern Mediterranean Deep Water (EMDW ) is formed, which spreads in the bottom layer eastward following the isobaths contours, as shown in figure 1, thus obeying the conservation of potential vorticity. The source of EMDW , however, was shown experimentally in 1995 to have shifted from the SAP to the Cretan sea, with deep convection leading to Cretan Deep Water (CDW) outflowing from both the eastern and western Cretan arc straits. The phenomenon, which actually started in 1991 (Malanotte-Rizzoli et. al., 1999) is known in the literature as the Eastern Mediterranean Transient (Roether et al., 1995) and has been the object of intense research in the last decades. Hence two possible equilibrium states exist for the Eastern Mediterranean deep thermohaline cell as demonstrated first by a 3-box analytical model, comprising the Southern Adriatic-Ionian-Aegean Seas (Ashkenazy, Stone and Malanotte-Rizzoli, 2012) and more recently numerically (Reale et al., 2017). The conclusion is that the two Deep Thermohaline Cells of the Mediterranean are very different. The Western one is open through the Gibraltar strait. The Eastern one is closed, with multiple equilibria, and constitutes the Eastern Mediterranean Conveyor belt. For these phenomena the Mediterranean basin can be considered as a laboratory for global ocean processes (Malanotte-Rizzoli and Robinson, 1993). In particular, the Eastern basin is also a laboratory of contrasting ecosystems (Malanotte-Rizzoli and Eremeev, 1999).

Figure 2a shows the classical picture of the pattern of North Atlantic currents at different vertical levels. The blue cell in the Labrador sea is the site where the North Atlantic Deep Water (NADW) has been experimentally proven to be formed through deep convection. The NADW constitutes the lower limb of the AMOC, i.e., the Deep Western Boundary Current (DWBC). The yellow arrows show the pathways of the MOW. Figure 2b shows the details of the Mediterranean salty tongue exiting from Gibraltar and propagating into the Atlantic interior at 1,200 m depth for the year 2020. The yellow arrows show again the inferred pathways for the MOW water. Two hypotheses have been proposed for how the MOW reaches the Labrador sea and preconditions the deep convection and consequent formation of NADW.

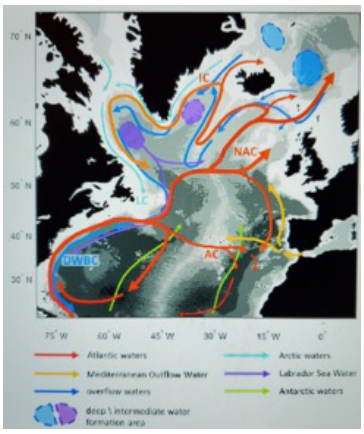


**Figure 2a (left).** *Pattern of the North Atlantic currents and of the polar convective cells as indicated in the figure.*

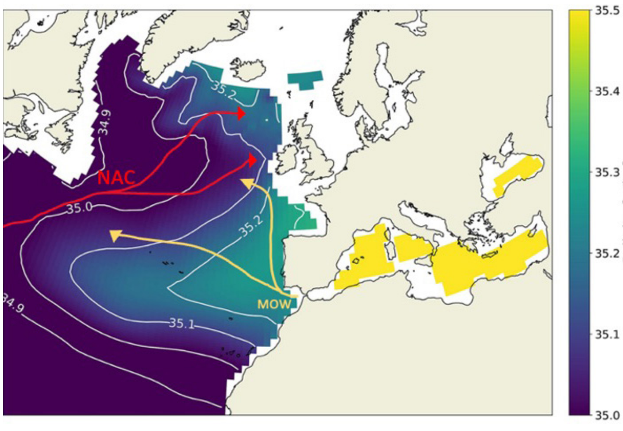


**Figure 2b (right).** *Average salinity field at 1,200 m depth for the year 2020 from the GODAS dataset. In yellow are the pathways of the MOW towards the North Atlantic Current (NAC) in red.*

The first hypothesis is direct advection on the isopycnal surfaces from Gibraltar to the Labrador sea (Reid, 1979). The second, and more plausible one, is a process of "peeling off' and successive mixing both laterally and vertically of the MOW with the waters of the two branches of the NAC (Lozier et al., 1995). Neither one has been definitively proven. Only one modeling effort has been reported in the literature, by Rahmstorf (1998) with an ocean OGCM forced by a rudimentary atmosphere. It shows that the MOW has a small, but significant effect, on the AMOC meridional transport increasing it by 1 Sv. Even with this very simplified modeling configuration, the integration time for the AMOC to equilibrate is of 5,000 years. A modeling recipe for clearly demonstrating the MOW effect would involve: 1. A global climate model like those used in the IPCC. 2. A regional Mediterranean model with a sufficiently high resolution to resolve the Gibraltar strait. 3. A two-way coupling between the global and the regional Mediterranean model at a boundary in the Atlantic interior outside Gibraltar. Such a complex configuration would require an integration time > 10,000 years at least to reach an equilibrated global thermohaline circulation under the effect of the MOW. Considering the multiple causes that can induce a collapse of the AMOC, the Mediterranean outflow does not seem to be a probable one. There is another way, though , through which the MOW pathways can be investigated and proven: the use of the ARGO floats. The NASA ARGO program was started in 1999. In the period 1999-2019 more that 3,000 floats were launched. The floats sink to a depth of 1,000 m and start their upward/downward profiling from the surface to 2000 m over a cycle of 10 days. At this time, two million temperature/salinity profiles and subsurface velocity observations are available. The global ARGO array of floats is shown in figure 3. The North Atlantic floats exiting from Gibraltar over 20 years could be used to prove, or disprove, the effect of the MOW on the northern NADW cells. Hence, there is yet no definitive answer to the question posed in this paper.

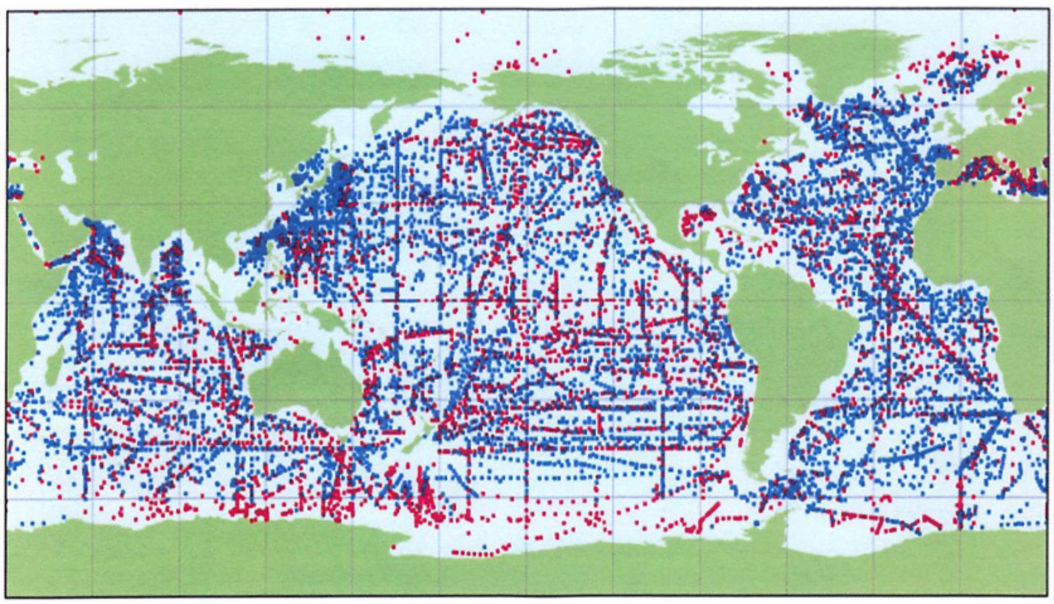

**Figure 3.** *Global ARGO array of floats in 2020.*

The 2021 AR6 IPCC report devotes a section in Chapter 10 to the Mediterranean sea. The only data analysis considers only land stations (Fig.10.20.b) and reports increased warming over land, Mediterranean summer vs. global warming (Fig.10.21.d). Cross-chapter Paper 4 , 2022 is richer in providing observational updates on climate change in the region, even though its main objectives are vulnerability, adaptation and sustainable development as addendum to the report of IPCC WGII.

On the other side recent observational reports (Copernicus Ocean State Report, 2022) as well as modeling simulations under climate change scenarios (RCP2.6, RCP4.5, RCP8.5, Soto-Navarro et al., 2020) are in agreement in projecting a considerable warming across the entire Mediterranean basin by the end of the century as a result of the decrease of heat losses to the atmosphere and an increase in the net heat input through the Gibraltar strait. Salinity is also projected to increase with a clear zonal gradient and a large positive salinity anomaly in the eastern basin. These changes in temperature and salinity modify the characteristics of the main water masses as the new waters become saltier, warmer and less dense along the 21st century. In particular deep water formation in the western basin (Gulf of Lions) has been absent in the last 13 years and is expected to further decrease in the future. Decreases in deep water formation, even though smaller, are expected to occur also in the convective cells of the Southern Adriatic Pit and in the Aegean Sea. The lack of ventilation of the deep layers, if continued, may produce important changes in the deep sea ecosystems.

**Paola MALANOTTE-RIZZOLI**
*Massachusetts Institute of Technology*

## DOES CLIMATE CHANGE IMPACT THE PHYSICAL DRIVERS BEHIND MARINE HEATWAVES IN THE MEDITERRANEAN SEA?

The Mediterranean Sea (Med) is considered a "hotspot" region for climate change and depending on the greenhouse emission scenario, the annual mean basin sea surface temperature (SST) is expected to increase from +1.5 °C to +3 °C at the end of the 21$^{st}$ century relative to present-day. This significant SST rise is likely to intensify episodes of extreme warm ocean temperatures in the basin, named as Marine heatwaves (MHWs), which are known to exert substantial pressure on marine ecosystems and related fisheries around the world. These statistically rare climate episodes can occur in the coastal or open, surface and/or deep ocean, extending horizontally up to thousands of kilometers, while forcing abrupt and severe changes in marine biodiversity and ecosystem functioning, on timescales from days to months.

Climate change has dramatically increased their frequency, duration and intensity over the past century, at a global level, causing, for example, unprecedented mass mortalities of marine species, seabirds, kelp forests, seagrass and other coastal vegetation, triggering also extensive species migrations, abrupt shifts in community composition (e.g. tropicalisation), coral bleaching, and harmful algal blooms, apart from resulting in loss and/or degradation of ecosystem services. As a cascading effect, MHWs have prompted significant socio- economic ramifications on commercially valuable fisheries, as a response to MHW- related declines of fish stocks, which can ultimately lead to economic and political tensions between nations, as well as on the aquaculture industry, with disease outbreaks in commercially important species.

Given the recently documented impacts of extreme ocean temperatures, assessing changes in MHW characteristics and their drivers in the context of climate change is of vital impor-

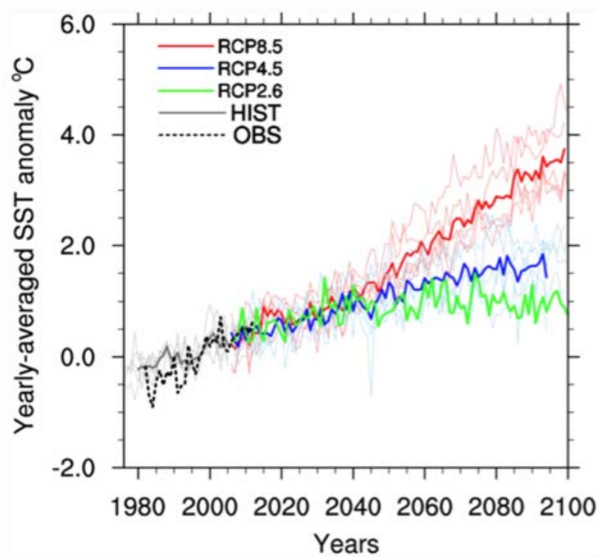


**Figure 1.** *Basin-mean, yearly averaged SST anomalies with respect to HIST (1976-2005). Bold colors represent the Med-Cordex multi-model average and lighter colors are the individual simulations. RCP2.6 scenario has only one simulation (CNRM), HIST run is illustrated in grey and observations in dashed black (Darmaraki et al., 2019).*

tance, especially for regions such as the Med, where over 480 million inhabitants live along its coasts. In addition, MHWs in the Med have been associated with a range of local-ecological impacts and their frequency has increased since the early 1990s. However, these events are not uniformly distributed in space and time due to their various drivers. Depending on the location and the season, their generating mechanisms are a result of local-scale oceanic and/or atmospheric influences (e.g., currents, atmospheric heatwaves) acting collectively with or separately from modulating large-scale circulation patterns (e.g., NAO). While the latter features may offer a degree of predictability of these events, in timescales from weeks to months, it is often the case that local-scale physical processes are the ones ultimately promoting or inhibiting the development and intensity of the events regionally and at daily timescales.

To date, only a few studies have addressed the regional physical processes behind individual past MHWs in the Med. In fact, we know more about how much the intensity, duration and impacts of MHWs are projected to increase throughout the 21st century, due to anthropogenically induced climate change, than we know of why this increase is expected to occur. Most of the studies on the drivers of MHWs, have based the predictability of regional events on the future large-scale climate forcing, by which they can be affected remotely. That is, any future changes in the dominant local-scale physical processes due to climate change are poorly understood or addressed, even though their variations can critically affect the evolution of ocean temperature anomalies at timescales relevant for synoptic-scale forecasting. Due to the lack of systematic assessment of the local-scale generating mechanisms behind MHWs in the Med, it remains an open question how these mechanisms might change due to climate change in the future relative to the present and how different greenhouse gas emission scenario, may (or may not) alter their spatiotemporal distribution.

**Sofia DARMARAKI**
*University of Athens*

# 3 METEREOLOGY AND ATMOSPHERIC DYNAMICS

## IS CLIMATE CHANGE IN THE MEDITERRANEAN BASIN PECULIAR COMPARED TO OTHER REGIONS?

The lands around the Mediterranean Sea host a diversity of different climates: arid along a large fraction of the southern shores, properly called Mediterranean in many central areas close to the sea, humid continental in the interior of peninsulas and cold (alpine) in the mountain ridges along the north (Lionello et al., 2012; 2023). **Increasing temperatures and chang of precipitation regimes tend to move these climate types northwards**, increasing the fraction of arid areas and decreasing substantially the extent of areas with cold alpine climates (Ali et al., 2022).

**Anthropogenic warming is expected to be particularly large in the Mediterranean basin in summer.** Global warming is an unequivocally observed consequence of anthropogenic climate change and it is very likely to reach a value in the range from 3.3° to 5.7°C in a very high emission scenario (IPCC 2021, Summary for Policymakers). The increase of temperature varies spatially: it is virtually certain that land areas will continue to warm more than the ocean surface and there is high confidence that the Arctic will continue warming above twice the rate of global warming (IPCC 2021, Summary for Policymakers). Within this global picture the Mediterranean is expected to warm at an annual rate comparable to those of the other land areas at similar latitudes, but much more in summer, exceeding 50% the global rates in the continental interior (Lionello and Scarascia, 2018; Doblas-Reyes et al., 2021). Consequently, at a 4° C global warming level in the Mediterranean most nights will be warm and there will be no cold days (Lionello and Scarascia, 2020). Different mechanisms have been proposed to explain the anomalously large past warming of the Mediterranean in summer. They include the role of Atlantic Multidecadal Variability (Suttong and Dong, 2012), decrease of anthropogenic aerosol concentrations (Nabat et al., 2014), reduced cloudiness (Pfeifroth et al., 2018), limits to evaporation due to low soil moisture (Lorenz et al., 2016; Zampieri et al., 2009) and a superposition of these factors (Mariotti and Dell'Aquila, 2012). Particularly, the increasing moisture atmospheric demand and suppression of evaporation due to low soil moisture are mechanisms supporting the Mediterranean summer warming in the future (Lorenz et al., 2016; Zampieri et al., 2009). Not only the terrestrial, but also the marine environment is warming at an unprecedented rate in the last decades (Pisano et al., 2020) leading to a further increase of marine heatwaves intensity and frequency in the future (Darmaraki et al., 2019).

**Precipitation is expected to decrease in the future in the Mediterranean basin while**, at global scale, there is high confidence in both its past and future increase (Douville et al., 2021). In fact, such increase is not valid for all regions and the Mediterranean basin is among those where, on the contrary, a future precipitation decrease is expected (Lionello and Scarascia, 2018). Though there is medium confidence on past trends of land precipitation in the Mediterranean because their magnitude and sign depend on time period and study region, there is high confidence on a future precipitation decrease, though with uncertainties in its magnitude (Lionello et al., 2012; Lionello and Scarascia, 2018; Cherif et al., 2020; Gutierrez et al., 2021; Ali et al., 2022). Mechanisms leading to this decrease differ between the cold (wet) and warm (dry) seasons. Precipitation decrease in the cold season is mainly driven by the decrease of cyclones (Lionello and Giorgi, 2008; Zappa et al., 2015). Precipitation decrease in the warm season is attributed to various factors: increased land-sea temperature contrast leading to isolation of land areas from humidity advection (Drobinski et al., 2020), decreasing lapse-rate, increasing stability and other thermodynamic changes (Rowell and Jones, 2006; Brogli et al., 2019), increased adiabatic descent (associated with more intense Indian Monsoon) of air masses over the eastern Mediterranean with consequent reduced humidity and lack of convection (Rodwell and Hoskins, 1996). Moreover, anthropogenic warming will further increase the existing difference in intensity of precipitation and hydrological extremes between North and South Mediterranean (Lionello and Scarascia, 2020).

**The Mediterranean environment is becoming drier with longer and more intense droughts, and this trend will continue in the future.** There is medium confidence that agricultural-ecological droughts (lack of moisture in the soil caused by lack of precipitation and a large atmospheric evaporative demand) have globally increased and high confidence they will further increase in the future (Douville et al., 2021). There is high confidence that the Mediterranean is a region where decrease of soil moisture and future aridification will be particularly large (Douville et al., 2021; Tramblay et al., 2020; Samaniego et al., 2018). In fact, the positive precipitation–evaporation budget in the Mediterranean land areas in the cold season is sustained by the cyclonic activity, which is expected to decrease in the future (Reale et al., 2022). The negative precipitation-evaporation budget in the warm season is caused by mean flow moisture divergence, which is expected to become stronger, because of increasing atmospheric humidity and strengthening of the mass divergence (Seager et al., 2014; D'Agostino and Lionello, 2020).

Finally, the risks posed by climate change in the Mediterranean region are particularly critical because of **high levels of exposure and vulnerability**: large and growing urban population exposed and vulnerable to heat waves; a large and growing number of people in settlements posed at risk by sea level rise; serious and growing water scarcity, already experienced today in North Africa and the Middle East; growing demand for water from agriculture for irrigation; economic dependence on tourism (at risk due to temperature increase and international policies to reduce emissions from air travel and cruises); exposed ecosystems (marine, wetlands, rivers, mountain areas) endangered also by unsustainable practices (Cramer et al., 2018; Ali et al., 2022).

**Piero LIONELLO**
*University of Salento*

## TO WHAT EXTENT THE KNOWLEDGE OF METEOROLOGICAL HIGH-IMPACT PHENOMENA CAN SUPPORT THE INTERPRETATION OF CLIMATE CHANGE EFFECTS IN THE MEDITERRANEAN?

The climate change manifests itself through modification of meteorological phenomena, often leading to more intense weather events such as extreme precipitation. To improve our understanding of extreme weather, its evolution and associated impacts, advancements are required on several levels, including a better understanding of processes and dynamics characterizing present-day extreme weather phenomena.

Heavy precipitation is often the main trigger for natural disasters. Many studies have reported a growing evidence of a general intensification of extreme precipitation events at global scale, associated with climate warming, both in recent trends and in future projections. Increasing temperature allows more moisture in the atmosphere available to rainstorm and it also act to increase the instability leading to convective phenomena. However, the atmospheric circulation modifies the regional responses, determining the moisture transport pathways and the occurring location of precipitation extremes. Changes in extreme precipitation on regional scale can be substantially different from those on the global scale (Pfahl et al., 2017).

Due to its unique characteristics, resulting from the geographical location and the complex orography surrounding a nearly enclosed sea basin, the Mediterranean region is particularly prone to natural hazards related to the water cycle as heavy rainfall and floods. The Mediterranean presents substantial regional and seasonal variability in precipitation distribution and extreme events occurrence. It is very sensitive to global climate change, and despite the foreseen overall Mediterranean climate drying, heavy precipitation events are expected to increase especially along the northern rim of the basin (Tramblay and Somot, 2018). Still important uncertainties remain; thus, gaining a better understanding and characterization of the physical processes conducive to extreme weather events represents an important step to fill our knowledge gap and to identify and interpret future changes.

Two ingredients are required for extreme precipitation to occur, moisture supply and lifting of the moist air. Synoptic and mesoscale systems provide these ingredients, while locally heavy rains are also modulated by temperature gradients, determining slantwise and vertical stability, flow convergence and orographic forcing. Atmospheric rivers, cyclones and mesoscale convective systems have been identified among the key phenomena at different spatial scales, decisive for the occurrence of extreme precipitation events in the Mediterranean. To assess their role and possible modifications in a warmer climate, it is necessary to understand and disentangle the interacting processes that characterize their development.

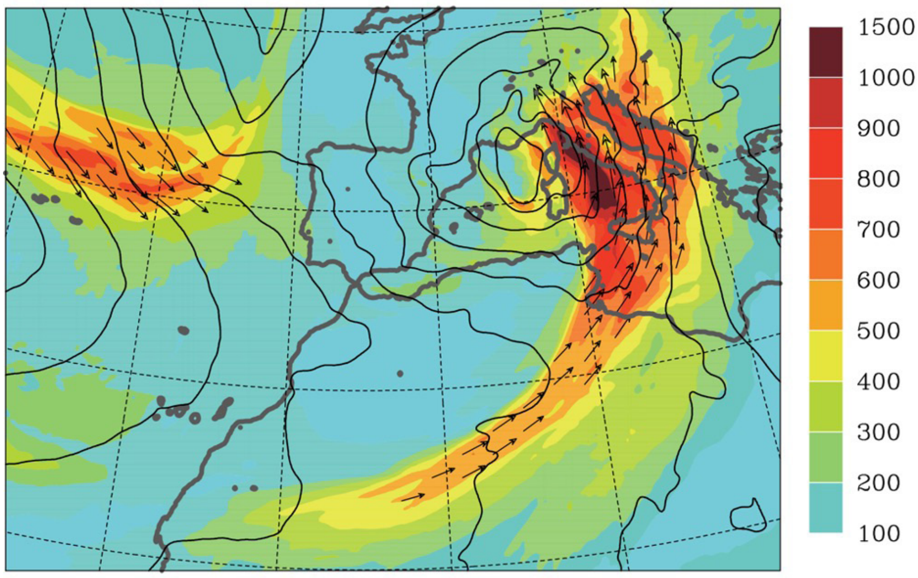


**Figure 1.** *Integrated water vapour transport (kg/m/s) revealing the atmospheric river during the "Vaia" storm on 29 Oct. 2018 (Davolio et al., 2020).*

Atmospheric rivers (Ralph et al., 2018), long and narrow structures of strong water vapor transport from tropical areas, have recently emerged as a relevant feature leading to extreme precipitation events in the Mediterranean, since they largely contribute to the moisture supply, often exceeding that due to local evaporation from the sea. The evolution of atmospheric rivers in a warmer climate deserves deeper analysis, but seems mostly modulated by moisture availability. Mediterranean cyclones (Flaounas et al., 2022) are the main modulator of the mesoscale variability and the water budget in the region. The large majority of extreme rainfall events are associated with cyclones of diverse intensity and dynamics, close to the heavy rain region and driving the moisture supply. Recent efforts have been aimed at classifying cyclones upon the governing processes that lead to their development. This can support the evaluation of climate and weather models, and improve our understanding of future changes and impacts. Finally, the mechanisms supporting mesocale convective systems have been disclosed in different mountainous coastal areas (Khodayar et al., 2021), under typical synoptic situations. However, severe convective storms and their effects (tornadoes, hail, etc.) lack of observational records and involve very small scale processes whose direct simulation turns out to be challenging even for high-resolution models. Therefore, an improved process-level understanding, through meteorological studies, represents a suitable approach for the analysis of climate change effects on these local scale phenomena.

**Silvio DAVOLIO**
*Institute of Atmospheric Sciences and Climate (CNR-ISAC)*

## HOW CAN WE MAKE AN ASSESSMENT OF A SPECIFIC HAZARD AT THE REGIONAL SCALE AND HOW CAN THE UNCERTAINTY ESTIMATION STRENGTHEN CLIMATE PROJECTIONS?

Climate change is affecting every region of the world and this effect increases with the increase of global warming. The higher the global warming will be, the more regions will experience the changes of climate conditions responsible for impacts for the society and ecosystem (climatic impact-drivers CIDs; Ruane et al., 2022) and the number of changes will also be proportional to the warming. (Arias et al., 2021). To be able to assess the impact of climate change at the regional or local scale  on a specific CID, or better known in the negative expression as hazard, we need information regarding the climate evolution in that region spanning the entire range from the past to the future and deriving from multiple lines of evidence.

The way we can achieve this is by using multiple data sources, methodologies and approaches starting with process understanding of all mechanisms and feedbacks relevant at the regional scale for that specific region, including attributional evidence of human induced changes; by gathering of all the observational data available from stations, satellite gridded products; by using model projections from both global climate models (GCMs), regional climate models (RCMs) and statistical downscaling, from all coordinated experiment, like for example coupled model intercomparison projects (CMIP) or the coordinated regional climate downscaling experiment (CORDEX).

Once all the information is collected, it needs to be adequate to be used. This means that the observations for example need to have a spatial and temporal coverage that is avoiding to create spurious observational trends; the number of model simulations should be sufficient to be able to estimate the different source of uncertainty (Hawkins and Sutton, 2009); the attribution studies if available need to show solid evidence of human induced signal.

All this information will form the lines of evidence that can be used to shape the overall assessment, providing that each line of evidence shows a robust and convincing signal per se. This means that for example given a CID, several indicators could be used to represent it, therefore, for both observations and projections, the trend needs to show robustness in respect to the choice of the indicator. Moreover the physical explanation must apply to both the observed and projected trend and of course the two need to be coherent. As a final step, all the lines of evidence have to point in the same direction showing that a process understanding exists of why there is an observed and consistent projected trend and all is in line with the available event attribution studies (Coppola et al., 2021).

This methodology can be applied in all regions and at multiple scale depending on the available information, and for different CIDs. As a results for each region we can assess the impact of climate change on multiple CIDs and establish a different level of robustness according to the final uncertainty level that we reach.

The climate change assessment at regional and local scales can be improved. Parametrization of physical processes in climate models is one of the major source of uncertainty and often an increase in model resolution is not obviously associated with a decrease of uncertainty especially for indicators of climate extremes or CIDs (Iles et al., 2020). But models able to explicitly represent the convection, seem to be a promising way to decrease the model uncertainty for at least precipitation extremes often associated with hazards (Ban et al., 2021; Pichelli et al., 2021). More research is needed in this direction including the use of bigger domains and longer simulation time periods.

**Erica COPPOLA**
*The Abdus Salam International Centre*
*for Theoretical Physics, Trieste, Italy*

## HOW TO DISENTANGLE SEA LEVEL RISE AND A NUMBER OF OTHER PROCESSES INFLUENCING COASTAL FLOODS?

On 12 November 2019 at 21:50 UTC the sea level reached a maximum in Venice, which caused the flooding of about 85% of the city (Cavaleri et al., 2020). With the sea level height of **189 cm** above the so-called '*Zero Mareografico Punta Salute (ZMPS)*', this was the second largest sea level height ever recorded at the Venice station 'Punta della Salute'. The event was forecasted by the operational modeling system (Cavaleri et al., 2020) and was hindcasted by a machine learning system (Rus et al., 2023), but was in both cases underestimated by about 40 cm. With the aim of explaining the underestimation, a series of numerical filters have been applied on the sea level time series and therefore a number of processes responsible for the Venice flood have been isolated (Ferrarin et al., 2021). The results obtained are briefly overviewed here.

To begin with, the tidal signal, which contributed **36 cm** to the 2019 maximum, is removed from recorded sea level. The residual sea level thus computed is shown in Figure 1. It is further decomposed into four different contributions.

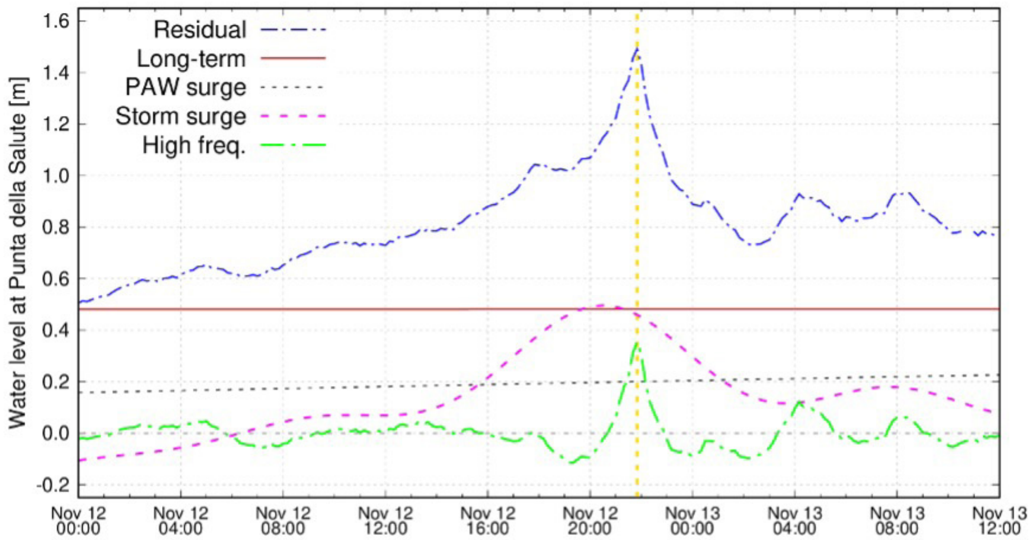


**Figure 1.** *Residual sea level recorded in Venice on 12 and 13 November 2019 and its decomposition into four contributions (Ferrarin et al., 2021).*

The first of these contributions is the long-term one, characterized by time scales of O(1 year) and larger, and it equals to **48 cm**. The contribution includes relative sea level change (amounting to an increase of 34 cm relative to the 1884-1909 interval for which the ZMPS zero is defined) as well as annual-scale variability (contributing 14 cm to the 2019 event). The relative sea level change was to a similar extent influenced by vertical land motion and sea level rise. The latter merits a special attention. It was initially considered as a linear increase – i.e., interannual and decadal-scale variability was removed from annual sea levels by fitting a straight line to the data. The procedure has been followed by Polli (1938) in his pioneering paper, in which the Venice and Trieste data were analyzed, and by a number of later investigators including Emery and Aubrey (1991) who have paid attention to the whole Mediterranean. Subsequently, it was recognized that the sea level rise could represent a nonlinear change. Thus, Mosetti (1961) and several other authors have documented a deceleration of the Adriatic and Mediterranean sea level in the middle of the 20th century, Marcos and Tsimplis (2008) have shown that the Mediterranean sea level was stable during the following decades, whereas Orlić and Pasarić (2013) have detected an acceleration that commenced in the area in the late 20th century. Eventually, it has been concluded that the Mediterranean sea level was strongly influenced by multidecadal variability, characterized by the 60-80 year period (Orlić et al., 2018). The multidecadal signal was much more pronounced in the Mediterranean Sea than in the world oceans (Dangendorf et al., 2019). The Mediterranean signal was capable of occasionally canceling the sea level rise, as, for example, during the 1950-1990 interval when the regional air pressure and wind forcing, as well as the regional contraction of the water column, counteracted a global mass increase (Orlić et al., 2018). Recently, it has been shown that the multidecadal variability of the Adriatic sea level could be related to the Atlantic Multidecadal Variability (AMV, Zanchettin et al., 2022).

The second contribution to the residual sea level has a time scale of O(10 days), being related to the passage of planetary atmospheric waves (paw) above the sea and the consequent variability of the air pressure and wind. As has initially been shown by Penzar et al. (1980), a trough of planetary atmospheric wave brings about raising of the sea surface, a crest supports its lowering. During the whole of November 2019, a trough dominated over the Mediterranean Sea and the resulting paw surge contributed **21 cm** to the sea level extreme.

The residual sea level is also considerably influenced by the third contribution to it, having a time scale of O(1 day). The contribution includes storm surges and basin-wide seiches, the former driven by and the latter triggered by synoptic-scale atmospheric disturbances. In the Mediterranean area, the synoptic atmospheric scale is dominated by mid-latitude cyclones, and their influence on the sea has been often investigated starting with the pioneering paper published by Kesslitz (1911). During the 2019 event, the cyclone propagated over the Ligurian and Tyrrhenian Seas and brought about a decrease of the air pressure and a strengthening of the southern, sirocco wind above the Adriatic. The basin-wide seiches were not pronounced on this occasion but the storm surge did contribute respectable **47 cm** to the sea level maximum.

The final, fourth contribution to the residual sea level has a time scale of O(1 minute) – O(1 hour). The high-frequency contribution is controlled by mesoscale atmospheric disturbances, which could resonantly generate so-called meteotsunamis that propagate from the open sea into a coastal basin but could also directly influence a coastal basin. First analyses of the meteotsunamis in the Adriatic Sea have shown that they are shaped by the open-sea resonance in the North Adriatic (Caloi, 1938) and by both the open-sea and coastal resonances in the Middle Adriatic (Orlić, 1980). As for the direct forcing of a coastal basin, it has been known for a while that the wind set-up could be significant in the Lagoon of Venice, due to its small depths and despite its small horizontal extent (Pirazzoli, 1981). On 12 November 2019, the mesoscale atmospheric disturbance had the form of a secondary depression that travelled off the Italian coast, from Ancona to Venice, at a speed of about 12 m/s. A meteotsunami was formed due to a resonant coupling of the depression with the gravity waves in the open sea, and, additionally, a set-up was supported inside the lagoon by the winds related to the depression. Together, they contributed **37 cm** to the 2019 event, with a larger part provided by the meteotsunami (28 cm) and a smaller part added by the wind set-up (9 cm).

The decomposition described above suggests why the flooding event was underestimated by both the operational modeling system and the machine learning system: because the difference between observed sea height and computed values was almost equal to the high-frequency part of residual sea level, it appears that the source of the problem was the secondary depression causing meteotsunami and local set-up. When preparing the sea level forecast, a rather low-resolution meteorological forecast was used, which did not adequately reproduce the secondary depression. When later a higher-resolution meteorological simulation was utilized to force the oceanographic model (Ferrarin et al., 2021), the simulated sea levels came much closer to the observations thus suggesting the way the operational modeling system could be improved. As for the sea level hindcast, the problem was obviously related to the fact that the meteotsunamis and the local set-ups had rarely contributed to the flooding of Venice (Lionello et al., 2021). It remains to be seen whether inclusion of the 2019 event into the atmospheric and sea level training data could improve the machine learning system.

The basic assumption behind the present method of decomposition is that the various processes contributing to the sea level variability are linearly superimposed. There are some indications that nonlinear interactions are at work, manifested in the anticorrelation of tides and residual sea levels in Venice (Ferrarin et al., 2022). The statistical finding, however, proved difficult to interpret, which implies that the interactions are probably not very pronounced.

Finally, there is a question of how the coastal floods will change under the future climate conditions. Usually, the issue is addressed by considering the sea level rise and the change of synoptic-scale atmospheric processes. Yet, the present decomposition of residual sea level implies that other phenomena could be important, and, in particular, that the change of dynamics of planetary atmospheric waves could influence the frequency of occurrence of flooding events. It has already been observed that global warming, which is more pronounced in the Arctic than in the equatorial region, supports an increase of amplitude and a slowing down of planetary atmospheric waves (Francis and Vavrus, 2012). At the same time, it has been found that the frequency of Venice flooding events increased, with the most dramatic example coming from the year 2019 when the flood was recorded not only on 12 November but – with somewhat smaller heights – also on 13, 15 and 17 November (Lionello et al., 2021). The series of events was obviously related to a trough of planetary atmospheric wave persisting above the Mediterranean throughout November 2019, thus suggesting that the atmosphere-sea dynamics is already changing at the planetary scale.

**Mirko ORLIĆ**
*Croatian Academy of Sciences and Arts*

## IS THERE AWARENESS OF THE EXPECTED SCENARIOS OF SEA LEVEL RISE ALONG THE MEDITERRANEAN COASTS AMONG THE POPULATION, STAKEHOLDERS AND POLICY MAKERS?

Global Sea Level (GSL) data from tide gauge networks, radar altimeters and ground observations agree with an unprecedented sea level acceleration since the mid-19th century. Presently, the GSL is rising at about 4 mm/year, a rate more than twice that observed in the 20th century (Fox-Kemper et al., 2021; Palmer et al., 2021). The rise has been addressed to global warming caused by human activities that are continuously adding greenhouse gases in the atmosphere. This process is triggering the melting of ice caps and glaciers and the thermal expansion of the oceans, leading to a rising sea level (Oppenheimer et al., 2019). Global Sea Level Rise (GSLR) projections by 2100 AD predict a likely rise in the range of 0.28-0.55 m to 0.63-1.02 m, relative to the period 1995-2014, for very low and very high emission scenarios, respectively (66% confidence SSP1-1.9 and SSP5-8.5) (IPCC, 2021). In addition, a possible faster melting of the Antarctic ice sheet could trigger a SLR rise up to 2.3 m by 2100 and up to 5.4 m by 2150 (Bakker et al., 2017; Kopp et al., 2017; DeConto et al., 2021). Besides the eustatic factor, along the coasts natural phenomena such as the vertical land motion (VLM) as a consequence of the Glacial Isostatic Adjustment (GIA), tectonics and volcanic activity can exacerbate the local SLR in subsiding areas (Anzidei et al., 2014; Lambeck et al., 2010). The combination of the above contributions represents a dramatic factor of hazard for about one million of people living along the global coasts. Also the Mediterranean basin is exposed to the effects of SLR, especially along the low elevated coastal plains, river deltas, lagoons and reclamation area. These areas are often experiencing dramatic beach retreat, coastal erosion, marine flooding and salinization of the water tables due to the infiltration of salt water that are causing the 85% of the damage costs (Bouda et al., 2017). Natural and anthropogenic land subsidence in the Mediterranean is increasing the exposition to flooding and inundation (Anzidei et al., 2021), causing the submergence of ancient coastal settlements (Benjamin et al., 2017), historical cities like Venice, in Italy (Vecchio et al., 2019) and small islands (Anzidei et al., 2017).

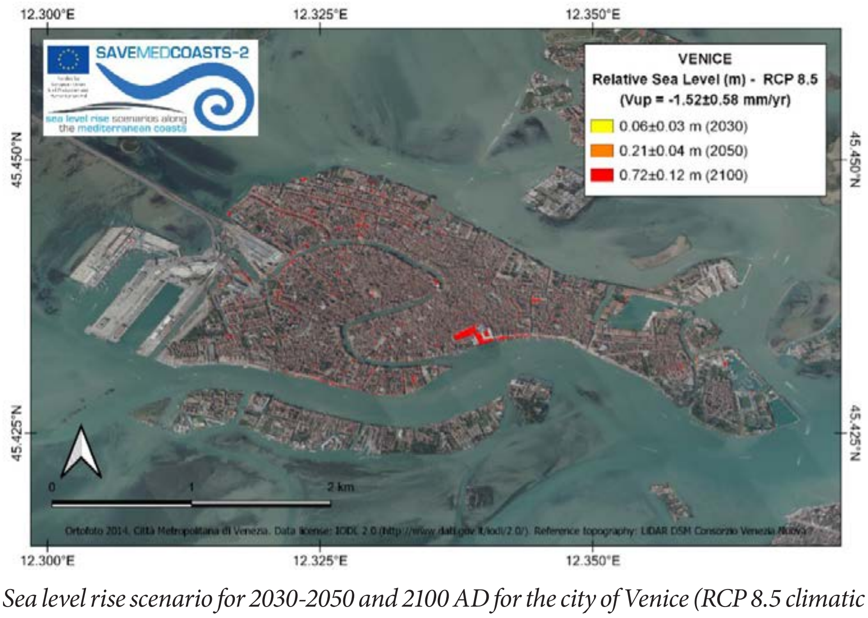


**Figure 1.** *Sea level rise scenario for 2030-2050 and 2100 AD for the city of Venice (RCP 8.5 climatic scenario; VLM at 1.52±0.58 mm/yr) in absence of the MOSE system (map from the SAVEMEDCOASTS2 Project).*

The projected economic loss due to the retreat of coastlines in natural and cultural heritage sites in Southern Europe is estimated at 18 billion of euros for the period 1908-2080 (Marios Karagiannis, 2017). Since many Mediterranean countries are heavily dependent on tourism and other coastal activities (e.g., agriculture, farming, and maritime industry), the social and economic impacts of the SLR are very significant and urge for mitigating strategies. For example, in Catalonia (Spain) the SLR is projected to lead to a decline of 20% in the area's tourism-related GDP (Garola et al., 2022), whereas rice production in the Ebro River Delta is expected to decrease significantly, reducing farmers' profits by up to 300 euros per hectare (Genua-Olmedo et al., 2016). The risks associated to the SLR are not yet well understood by the population, claiming for an adequate awareness to implement appropriate mitigation and adaptation policies. A more consolidated collaboration among scientists, decision-makers and stakeholders involved in the management of the various aspects and effects of climate change and SLR, is needed to fill the gap between science and policy. Furthermore, there is a lack of local stakeholder involvement in decision-making regarding SLR. Decision-makers and land planners often fail to recognise the importance of their knowledge about the local environmental and socio-economic characteristics. Therefore, stakeholders feel powerless, or even removed, from the causes, impacts and solutions to SLR.

Here we show the state of the art of the RSLR projections in view of the contribution of VLM as estimated from geodetic data. We also focus on the analysis of selected stakeholders engaged in the SAVEMEDCOASTS2 project (www.savemedcoasts2.eu) from Mediterranean areas that are highly vulnerable to the impacts of SLR (Loizidou et al., 2023).

**Marco ANZIDEI**
*Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy*

## "THE FUTURE IS NOT WHAT IT USED TO BE": HOW DO WE PREPARE FOR CHANGING CLIMATE-DRIVEN EXTREMES?

The consensus about ongoing climatic changes, their anthropogenic origin, and the need for both mitigation and adaptation measures is ever widening at the global scale. Observations and climate models quantify past and future changes with improved resolution and accuracy, and indicate that increased rates of sea level rise, frequencies of extreme flood and storm events, as well as drought durations and intensities, await us in coming decades. On the front of mitigation, a consensus is growing about the necessity of quickly reducing greenhouse gas emissions to avoid global warming beyond 2 degrees Celsius, though little has been done in this direction. We must therefore act, in parallel with efforts towards climate change mitigation, to quickly implement adaptation measures to "climate proof" our infrastructures and avoid a dramatic increase in risk of economic damage and life losses.

Critical infrastructure, such as bridges, fluvial levees, dams, coastal defenses, or urban drainage systems, are built for a "useful service life" of 50 to 100 years and beyond, and thus will experience extremes that will be very different from past ones. While this is now an accepted notion, a gap exists in our ability to translate climate change projections into applicable design methodologies that will permit our infrastructure to withstand changing extremes. The problem is two-fold. Firstly, one must obtain regional to local projections of the characteristics of the relevant driving factors, such as rainfall, winds, or storm surges. This remains challenging particularly when local or short-duration events are of interest. Secondly, we must devise and adopt methods to estimate extreme-event probabilities for natural processes that will change over time. The methods currently in use, on the contrary, postulate stationarity, i.e., that past events are representative of the future and that the data on which these methods are applied do not exhibit change. Projections through the current century, exhibiting the systematic changes that are characteristic of climatic change, and thus cannot be "processed" through traditional methodologies that assume stationarity. In order to climate proof our societies, we need methods for quantifying extreme events under changing conditions, such that past observations and projections may be used to infer future extremes. Here I exemplify the above issues by focusing on hazards of wide interest and impact. The probability associated with extreme storm surges in Venice (Italy), and elsewhere, is affected by a sea level rise rate that is certain to accelerate (see Figure 1).

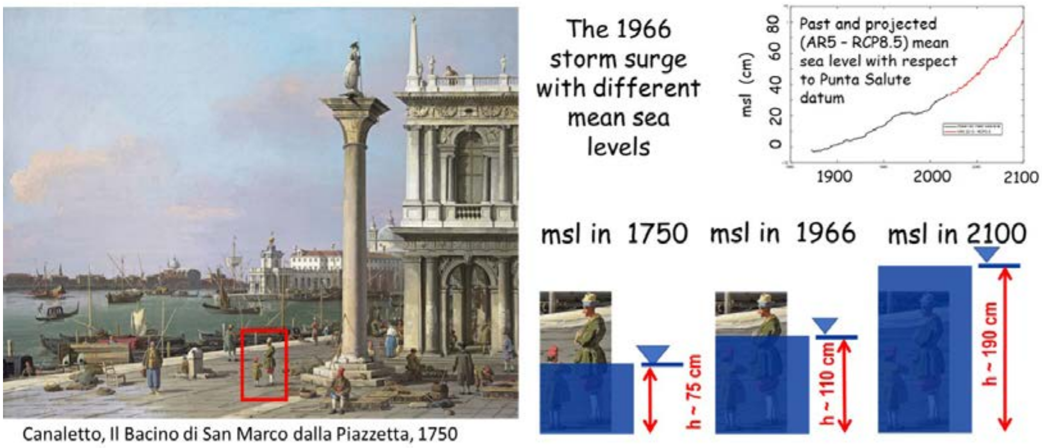


**Figure 1**. *Visualization of the water level in St. Mark square in Venice associated with the 1966 storm surge and superimposed to the mean sea level in different centuries. Canaletto was a venetian "vedutista painter", who used a camera obscura to preserve the scale of the painted view.*

Methods are here discussed that are particularly suited to account for non-stationary behavior. They will be used to explore extreme storm-surge changes in the Mediterranean area and elsewhere. Further illustrative examples of the benefit and insight afforded by analysis methods that explicitly allow for non-stationary behavior will be focused on extreme rainfall, hurricane intensity, and droughts and meteotsunamis.

**Marco MARANI**
*Università di Padova, Italy*
*Duke University, USA*

# CLIMATE CHANGE AND SEA LEVEL RISE: WHAT CAN WE LEARN FROM FLOOD PROTECTION OF SINKING DELTAS, INCLUDING THE NETHERLANDS AND VENICE?

**Introduction**
Coastal flooding will increase as a result of climate change. Sea level rise (SLR), induced coastal erosion, changing storm patterns, more rainfall and more extreme river discharges are existential threats to coastal urban areas. Examples are the Rijn-Meuse-Scheldt delta in The Netherlands, the Ganges-Brahmaputra delta in Bangladesh, the Yangtze River delta at Shanghai in China, the Po delta in Italy, the Ciliwung delta at Jakarta, Indonesia and the Nile delta in Egypt. Deltas once cultivated and urbanized have a tendency to subside (sink) as a result of drainage and ground water extraction. The Netherlands and the Po-Delta are typical examples. These deltas have a long history of flooding and coastal protection, others are entering a similar trajectory.

The question central in this paper is: how will these delta's, their communities and governments cope with climate change and sea level rise, changing storm patterns and more extreme rainfall. Over the next few decades, a 1 in a 100-year storm and flood event is likely to turn into a 1 in 10 years event (IPCC 2022), and the 1 in 100-year event is expected to become more extreme than ever experienced. There is a growing literature what can be done. Engineering interventions are usually suggested such as sea walls, storm surge barriers and nature based solutions. However, over the years the discussion is moving beyond technical solutions and includes societal and cultural issues and conditions such as governance, institutions and financing arrangements (Hinkel et al., 2018).

This paper illustrates the various approaches and strategies for flood protection with examples from different deltas. Next it reviews and evaluates the approaches in Netherlands and Venice, followed by a discussion on lessons learned from 50 years of experience in Venice and The Netherlands.

**Response strategies**
**A protection strategy** usually includes the building of new or the strengthening of existing seawalls around the low-lying area, often including water management measures and pumping stations. The goal is to increase flood-safety of the low lying land and urban areas.
**In an accommodation strategy** more frequent flooding is more or less accepted. Infrastructure and managerial measures ensure that social and economic life can continue such

**Figure 1.** *"Protection": sea wall, Louisiana built after Hurricane Katrina .*

**Figure 2.** *"Accommodation": Hamburg City of Bridges.*

as in Hamburg Germany.  An accommodation strategy often includes innovative technical measures such as bridges and floating homes. It may also include nature based solutions such as wetlands that reduce the flood levels.

**A planned retreat strategy** implies that land areas including urban areas are given up, thus replaced by sea or wetland. Such a strategy is usually developed for rural coastal areas where the cost of coastal protection is much higher than the benefits of protecting the land and human settlements. It sounds cruel, but the good side is that it provides clarity for the existing inhabitants and land owners. The national or regional government announces for example 30 years in advance that public funds will not become available for long term coastal protection. This is rational and transparent but in practice nearly always perceived as controversial by the general public as illustrated by the case of Fairbourne in the UK.

**Figure 3.** *"Planned retreat": Fairbourn in Wales UK just below sea level spring tide now. In 30 years, it will no longer be safe to live there. UK policy implies retreat; public protest.*


**Figure 4.** *"Do nothing" Miami Florida, climate change is not on the political agenda.*

A do-nothing strategy can be found in regions where climate change is not on the agenda. This can be seen in countries where other major existence or survival issues are considered more important than long term coastal planning issues. It can also be seen in countries and regions where climate change is politically denied. Individual inhabitants, land and home owners, and coastal communities will have to find their own solutions.

**The Netherlands and Venice**

The Po delta and the Rijn-Meuse-Scheldt delta have much in common, in particular their economic and cultural history.  Collective water and land management arrangements were at the basis of their governance systems. Their history illustrates how major infrastructural water works provided economic prosperity. History also illustrates that nearly all major interventions in coastal infrastructure and sea walls were triggered by high impact flooding events. The delta plan in the Netherlands was initiated only after the disastrous 1953 storm surge. The Mose solution for Venice was triggered by the 1966 flood. Both coastal protection plans have taken 30 to 50 years to be fully implemented. Both plans have been evaluated on the basis of a cost benefit analysis. In both cases the cost of "full protection" was in the same order as an accommodation alternative.

In Venice as well as in the Netherlands a combination of delta prosperity and delta identity made the difference. The engineering approach served as an example for many other deltas, i.e., the Thames Barrier in London, the Ems Barrier in Germany, the Petersburg barrier in Russia, the Seabrook and the INHC barrier in New Orleans. It should be borne in mind that these major flood protection works were mainly required to compensate for long term subsidence and not in view of climate change. This leads to the question central in this paper: Is such a "coastal protection" approach in response mainly to subsidence a wise and a feasible strategy to address sea level rise?

**From exploring of impacts to adaptive planning of interventions**

Many studies on climate change carried out over the last few decades focused on the impact of climate change. Impact studies were often meant to demonstrate the urgency of limiting climate change. The reports and the media often had images of completely submerged coastal mega cities and their deltas. Indeed, the urgency of limiting climate change is fully justified when considering the long term, 100 to 500 years of sea level rise effects. But the images used are not correct in many cases. Adaptation makes the difference. Several delta's have a long-term history of environmental and coastal protection, others such as Vietnam and Bangladesh are on the way. Hinkel et al. (2018) illustrate the progress made in adaptation in coastal regions across the world. They demonstrate that even limited coastal protection works will greatly reduce the geographic and economic impact and the cost of sea level rise at least for the next 50 to 100 years.

When a cost benefit analysis indicates that a "protection" or an "accommodation" strategy may be feasible, it is recommended to develop a so-called "dynamic adaptive planning" (Haasnoot et al., 2013; Ranger et al., 2013). Such a planning starts with the development of a series of possible trajectories of sea level rise over time, each with their own sequence of interventions. Such trajectories usually start with an exploration of the first 30 to 50 years and then continue to cover a period for example until 2300. The art of dynamic adaptive planning is to make sure that the first steps in flood protection will support and not counteract a range of possible next steps and subsequent steps. This way a wide range of future trajectories can be mapped. The level and rate of SLR will determine the trajectory that will be followed in practice. The idea of dynamic adaptive planning is that investments in the early stages of flood protection will not be stranded assets in future or be in the way of possible next steps.

**Start with considering the coming 50 to 80 years**

In order to evaluate any response strategy, one should compare the social, environmental, economic and cultural losses of "do nothing" with the benefits of intervening, considering a defined time period. The public debate is often focused on the longer term say 100 or 300 years as climate change is a long-long-term issue. High-end projections for 2300 range from 2.50 up to 10 meters sea level rise. Such projections usually generate innovative out of the box solutions. Although justified in itself such a long-long term discussion distracts from an evaluation of short term practical approaches. An interesting example is the MOSE (MOdulo Sperimentale Elettromeccanico) in Venice. The opposition against MOSE primarily argued that the mobile gate intervention is not a sustainable solution as it will not work when sea level rises beyond 50 or 60 cm. The argument was: it may be better to leave the lagoon open and fully focus on accepting an ever increasing flooding frequency. Another suggestion was to fully close the opening as in the end this would be necessary anyway. The reasoning behind the MOSE solution may be effective only for a limited amount of time, i.e., a limited amount of sea level rise is true but that does not disqualify the intervention. MOSE can be seen as buying time while considering and evaluating the next steps.

International efforts trying to keep global temperature rise below 2 degrees and preferably below 1.5 degrees are partly successful. While 20 years ago temperature rise projections included a 5 to 6 degree warming. This has come down now to projections between 2 and 3 degrees. This implies that the lower IPCC scenarios (RCP 2.6) have a higher probability than the higher (RCP 8.5) scenarios. RCP 2.6 scenario includes a sea level rise projection ranging from 29 to 59 cm by 2100.

The mobile gates, MOSE, can function reasonably well up to a rise in sea level of 40 cm. The lagoon will slowly become more brackish because of more frequent closures of the lagoon but the tidal flushing can be maintained. Beyond 0,40 m SLR incremental technical and managerial adjustments of MOSE will enable the system to function up to a level of about 60 cm SLR. Thus for an estimated period of 80 years, until 2100. Beyond that major interventions will be required, i.e, the lagoon will probably need to be closed-off from the Adriatic. As a consequence Venice Lagoon will become a fresh water system. Additional pumping and flushing will be required to manage the fresh water quality and quantity. This may be considered disastrous from a nature conservation and human welfare point of view, still one should bear in mind that Venice is far better off than nearly all other coastal areas in the world. Venice flood protection works including MOSE can be seen as the first step in a dynamic adaptation trajectory.

The protection works in the Netherlands, including the "storm surge" barriers are likely to follow a simililar pathway. Over time it will have to be decided to either fully close the gates / barriers (and port of Rotterdam) or leave them open and heighten the dikes along the tidal rivers.

To conclude: Even though climate change and in particular sea level rise will continue for many ages to come, we do not have to solve it all today. In case we find solutions that will work for he next 50 to 100 years like Venice flood protection works, such solutions are definitely worthwhile provided the cost are reasonably in line with the social, environmental, economic and cultural benefits. It is important though to design and evaluate a series of possible future trajectories to ensure that interventions of today will not create stranded assets when the next steps need to be taken.

**Pier VELLINGA**
*Vrij Universitat Amsterdam,*
*The Netherlands*

# 5 ROUND TABLE ON ADAPTATION: TECHNICAL CHALLENGES AND POLICIES

## INTRODUCTION AND COMMENTS

As one of this session's contributors says, the Mediterranean is a melting pot: its shores cross 22 countries whose populations contain many ethnic groups with different religions and cultures. It has seen the birth and decline of some of the most advanced civilisations of their time, and more than its fair share of wars. Such a rich history has endowed it with abundant cultural assets including hundreds recognized by UNESCO as World Heritage Sites. On its northern boundary, waters enter from the European Alps, while on its southern boundaries, water flows from mountains thousands of kilometres to the south. The sea itself has undergone extreme fluctuations, essentially drying out before opening to the Atlantic five million years ago.

Although connected to the Atlantic, the Mediterranean is quite different. Tides are limited because of the small extent and the narrow connection with the Atlantic Ocean. Evaporation exceeds rainfall and river discharge, so that water flows in from the Atlantic Ocean through the Straits of Gibraltar at around 70,000 $m^3$/s. This cool and relatively low-salinity water circulates eastwards and, as it warms and increases salinity, ultimately sinks to form the Levantine Intermediate Waters that return westwards, before exiting the Mediterranean at depth through the Strait of Gibraltar. The time taken to complete this circuit is of the order of 100 years, but local water circulation can shift substantially during short time weather events that in turn affect deep water formation and circulation patterns. The biota that live in these waters still support a fishing industry that produces ca. 700,000 tonnes of fish and shellfish from ca. 75,000 vessels, and half a million jobs along the value chain (FAO, 2022). However, 73 percent of commercial species remain overfished with fishing pressures double what is considered sustainable.

Climate change is affecting the sea in terms of reduced precipitation on the surrounding lands, sea level rise which may approach one metre by the end of the century, and warming of the surface waters which is now extending to the deepest parts, with the risk of stratification and very high temperatures increasing the risk of mass mortality events. This in turn will impact the ecological system, posing a threat to biodiversity and even an existential threat to some habitats. Currently hypoxic events are localized but increasing as mean temperatures rise; such dead zones add to stresses on historical food webs leading to increases in simpler food webs dominated by algae, invertebrates and jellyfish.

The above is the background against which this roundtable considers the potential for adaptation, technical challenges and policies. Our first distinguished speaker is Anny Cazenave who asks "How can we adapt to sea level rise in full Mediterranean"? Satellite-based monitoring has shown a global mean sea level rise of ~10 cm over the past three decades, but this is accelerating with a wide range of forecasts for the rest of the century (0.6-2 m); after 2100, it will continue to rise and even if Paris Agreement targets to hold the mean global surface temperature rise below 2 °C were to be met, global sea level rise is predicted to rise a further 50 to 450 cm by 2300.

The modest present-day sea level rise has already had significant effects on some low-lying coastal regions (particularly during extreme events). Moreover, local factors superpose on the global mean so that adapting to such uncertainties is a complex problem, and it is also essential to consider coastal impacts of sea level rise in combination with extreme weather events. The main strategies available are: (1) engineering protection, (2) soft protection, (3) accommodation (4) ecosystem-based adaptation, and (5) retreat. There remain many data shortages for the Mediterranean which limits the power of models to predict future levels and their spatio-temporal resolution. There is a need  for improved observational coverage (many coastal regions lack tide gauges), together with measurements from altimeter satellites and from stations to measure vertical land motions. With better data, models can be improved to strengthen decadal predictions and provide better coastal sea level projections with higher resolution that also take into account the small scale coastal processes that may cause sea level at the coast to differ from offshore. Such information can better inform decisions on adapting to extremes events.

The next contributor to this roundtable is Francisco Garcia Novo who describes the current degraded state of the "melting pot" of the Mediterranean Sea due to the large inputs of chemical contaminants, organic pollution and sediments, while development had removed much of the area's natural landscapes including wetlands. Conflict continues to hamper sustainable development, and migration adds an additional burden on the sea as a route of passage from Africa to Europe. There is a family of Mediterranean challenges which demand joint research: on sea level rise, effects on salinity, behaviour of currents, ecosystem effects from overfishing and alien species, eutrophication from high nutrient containing rivers, as well as mercury contamination. These require adequate management based on collaboration between all countries bordering the sea. This could be combined with more collaboration on energy production, water use, species protection and ecosystem restoration and other fields.

Fausto Guzzetti asks how disaster risk reduction can respond to a changing climate, drawing on the background of Italy's long history of geophysical and meteorological hazards. As climate change increases some threats, it may become increasingly difficult to insulate infrastructure from unpredictable extremes, and so reducing risks should rely on enhanced early warning systems based on sound science. This could be achieved with existing knowledge and technologies, and policymakers do not need to wait for more research. However, to cope effectively with geophysical and meteorological hazards we need to combine expertise between all the physical, environmental, economic, social, and human elements that characterize hazards and their consequences.

Mirko Orlić asks if temperature hiatuses can influence the perception of climate change due to the regional effects of the Atlantic's multidecadal variability. When this enters its cool phase, temperature rises may moderate so that it may appear that the pace of warming has slowed. In previous cycles, such periods were associated with a decline in public interest in climate change but this was less likely in future since projections suggest that all the trends will stay positive. While such temporary slowdowns may buy some time to implement adaptation strategies, it appears unlikely that public support for adaptation will be weakened.

Finally, Christos Zerefos considers how best to protect the many rich cultural resources in general and the UNESCO Heritage sites in particular. A primary threat was on the coastal edge, as exemplified by Venice, which is the subject of a keynote speech by Pier Vellinga, who provides an overview of "Adaptation of coastal regions and cities: The Netherlands and the Venice MOSE". One comprehensive study (Kapsomenakis et al., 2022) ranks the hazards posed by climate change to the 244 heritage sites around the Mediterranean, taking into account extreme heat, fire risk, heavy rainfall, frost, aridity and sea level rise. 34

monument sites fall within a "High" hazard group and 13 heritage sites in the "Extreme" hazard category. Earlier studies (Reimann et al., 2018) have identified 49 World Heritage Sites in low-lying coastal areas of the Mediterranean containing many that are already at risk from 100-year floods (37) and from coastal erosion (42). Policymakers can thus know where adaptation is most urgently needed, but each case requires local-scale research to devise suitable adaptation strategies, and may be restricted for fear of compromising each site's Outstanding Universal Value.

This session and its roundtable discussion are extremely valuable in emphasizing not just the importance for all policymakers to integrate adaptation into their strategies, but also to highlight some remaining uncertainties when deciding adaptation strategies in the region. Several research targets are identified to enable the impact of climate change to be better predicted and thus adaptation strategies to be more effective. Improved knowledge of the physical and oceanographic changes would also inform research into the biological impacts of salinity changes, acidification, water temperature and oxygen levels. The description of the MOSE barrier in Venice shows that engineering approaches could be effective in the short term, but there are signs that the current rate of sea level rise would soon require such frequent closure between the Adriatic Sea and the Venice Lagoon that water quality and the local ecosystem could be seriously degraded.

Case studies of concrete-based solutions need to be seen alongside natural solutions such as wetland and marsh restoration and ultimately retreat, as is taking place in many coastal locations in Europe. New infrastructure and build also need to factor in the combination of mean sea level rise, local variations and combine with extreme event scenarios to avoid investing in assets that will all too soon be at risk as the inexorable rise in sea level continues for centuries. With the inherent unpredictability of extreme weather events, physical adaptation needs to be combined with 'soft' adaptation of warning systems and relief resources.

Safeguarding the hundreds of cultural assets is a particular challenge. Many of these may be beyond the resources of the countries hosting them and of the international resources available. Moreover, there are many climate impacts which cannot be compensated through adaptation. Increasing dead zones in the sea, desertification of the surrounding lands, increased forest fires, crop losses through drought, and other ecological impacts have only limited adaptation potential. Where adaptation is an option, it may be just a matter of buying time to allow society to implement the only long-term solution, which is to abandon fossil fuels in their entirety, and transform society to one that does not depend on emitting gigatonnes of carbon dioxide and other greenhouse gases. And to restore the Planet's destroyed ecosystems (from forests to wetlands) so that they can play their natural role in mitigating climate change rather than exacerbating it.

**Michael NORTON**
*European Academies' Science Advisory Council (EASAC) Environment Program Director, Brussels, Belgium*

## HOW CAN WE ADAPT TO SEA LEVEL RISE IN THE MEDITERRANEAN SEA REGION?

**General context**

Sea level rise is a major consequence of present-day global warming. Being a slow but long-term process, sea level will continue to rise over the coming centuries at rates that will depend on future greenhouse gas emissions. Satellite-based monitoring reports a global mean sea level elevation of ~15 cm over the past three decades but also a substantial acceleration caused by accelerated land ice melt and ocean warming (IPCC, 2021). Observations also show that sea level rise is not uniform over the oceanic domain, with rates 2 to 3 times faster than the global mean in some regions, a result of non-uniform ocean heat storage. Figure 1 shows non uniform altimetry-based sea level trends in the Mediterranean Sea over 1993-2022.

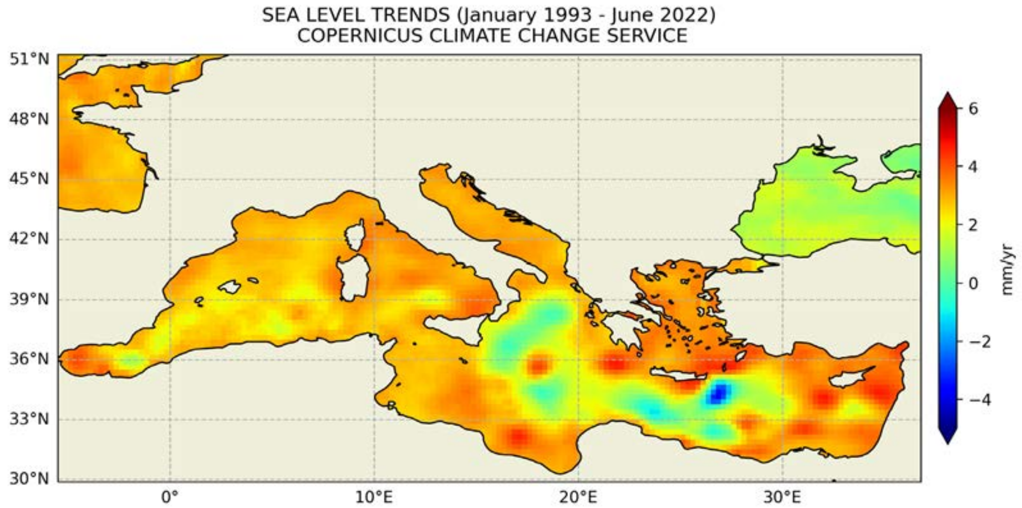


**Figure 1.** *Sea level trends over January 1993 to June 2022, based on satellite altimetry in the Mediterranean Sea (Source: Copernicus Climate Change Service, https://climate.copernicus.eu/).*

While still modest, present-day sea level rise has already significant effects on some low-lying coastal regions (in particular during extreme events, since the higher the sea level, the more devastating the temporary inundations). Moreover, at the coast, sea level results from the superposition of the global mean rise, large-scale regional changes and small-scale coastal processes (e.g., shelf currents, small-scale eddies, sea water density changes in river deltas and estuaries), with the regional and local factors possibly amplifying the global mean rise. How to adapt to such a still poorly quantified but inescapable threat is a complex problem faced by many countries which have important maritime facades. This is indeed the case of France.

**Different strategies of coastal adaptation**

Different strategies have been proposed to adapt to sea level rise. We briefly summarize them below (on the basis of the synthesis made by Bongarts Lebbe et al., 2021).
In coastal areas developing rapidly, avoiding to build new infrastructure in areas exposed to flooding and erosion reduces future lock-ins. For existing infrastructure, responses to sea level rise can be classified as follows (IPCC, 2022): (1) engineering protection, (2) soft protection, (3) accommodation (4) ecosystem-based adaptation, and (5) retreat.

Engineering protection consists of building coastal defenses such as dikes, seawalls and estuarine barriers to prevent from flooding, salinization and shoreline erosion. This strategy has been developed in Europe (e.g., in the Netherlands, United Kingdom, Venice) and in many Asian countries such as South Corea or Japan. Engineering protection can also result in land reclamation such as in Singapore or the Maldives, resulting in advances seaward. However, engineering protection has several drawbacks. It is costly and it is not always well accepted by coastal societies where coastal defenses prevent from accessing to the seashores. Besides, seawalls and dikes may degrade coastal ecosystems through habitat loss and reduced species, and may favor intrusion of non-native invasive species.

Soft protection is subject to growing interest worldwide because it produces less negative impacts than engineering protection. It mainly consists of sand-based nourishment of beaches and dunes. This practice is receiving increased interest in several coastal areas, e.g., in the Netherlands with the Sand Engine, a mega-nourishment project. It points out however the problem of sand availability in some regions and potential decrease of coastal ecosystem services depending on how sand nourishment is performed.

Accommodation is another strategy whose objective is to adapt existing infrastructures to climate change and natural hazards. These include interventions at the level of buildings to reduce damages in case of flooding (e.g., elevated electrical devices or waterproof doors) or to improve urban drainage or innovations such as floating housing in sheltered waters.

Ecosystem-based adaptation includes the restauration of salt marshes, mangroves and coral reefs where available, to create a buffer zone that naturally accumulates sediments between the sea and coastal infrastructures, or to reduce peak water levels during a storm as seawaters spill into wetlands. While limited in efficiency for high rates of sea-level rise, this approach is generally considered as very positive as it provides multiple benefits to coastal species while reducing coastal erosion and flooding.

Finally retreat consists of relocation of populations and infrastructures. Relocation clearly poses a broad range of social, cultural psychological and economic issues. It is deployed differently around the world, the largest project so far being the relocation of the capital of Indonesia from Java to Borneo due to a range of environmental and political issues, including sea-level rise and subsidence. While difficult to implement today due to a range of operational and social constraints, this option should receive more attention in the future as sea levels will continue to rise.

**The case of France**

Coastal management in France remains still largely dominated by engineering-based adaptation. The last major marine flooding event in mainland France (the Xynthia storm in 2010) also resulted in new investments in coastal defenses. However, environmental considerations and costs are motivating new approaches such as relocation and ecosystem-based management. This is supported by two distinct processes: the ongoing adaptation planning stimulated by climate change, and the regulations and strategies focused on coastal areas.

For more than a decade, France has established a national adaptation plan to climate change in order to implement concrete actions for adapting by 2050 the French territories (including overseas territories) to regional impacts caused by the changing climate. The plan addresses various impacts of climate change, including fires, water availability and resources, decrease of land and marine biodiversity and shoreline erosion & retreat. It proposes strategies to increase economic resilience in response to the changing environment. Importantly, the plan includes the consideration of sea-level rise scenario of 60 cm by 2100 for coastal risk prevention plans.

In addition to ongoing adaptation plans, France has developed over the last decade a strategy for integrated coastal management that considers coastal impacts of sea level and extreme events, shoreline evolution and many other coastal management issues. The French shoreline is 20 000 km long, of which 22% is eroding. 650 km of the shoreline is retreating, among which 270 km at a mean rate of 50 cm/year. This concerns 17% of the France main land coastlines, and 12% in overseas territories. As the population density at the coast is 2.5 times larger than the national average, this impacts a large amount of people. In case of 1 m elevation by 2100, several coastal areas of France main land will be permanently inundated.

While France is still largely implementing engineering coastal protection, other approaches are being experimented. For example, the Ministry in charge of Environment launched an experiment to consider relocation in several coastal zones covering a wide range of coastal contexts: cliffs in Guadeloupe and Northern France, high and low-energy beaches along the Mediterranean and southwest Atlantic coasts, including in areas that are already protected with coastal engineering infrastructures. Relocation is also considered, for example in the case of the village of Miquelon (St Pierre and Miquelon territory) which is highly exposed to flooding and where some inhabitants prefer to invest in higher locations that will remain unaffected by sea-level rise over decades, rather than in a low-lying flood plain that might be too costly to protect within decades (Philippenko et al., 2021).

Regarding ecosystem-based adaptation, an important experiment is being developed under the impulsion and leadership of the French Coastal Conservation Agency. In 10 coastal sites, the Conservation Agency is experimenting ecosystem-based approaches, consisting, for example, in removing the 1st rank of coastal defenses, building new defenses inland, thus saving land and restoring natural processes in wetlands (https://www.lifeadapto.eu/). These experiments could promote a larger implementation of nature-based solutions in coastal areas of France because the Conservation Agency is interacting with many stakeholders (e.g., elected representatives, communities at risks, farmers).

Like many countries in the world, France is just beginning to be affected by an unprecedented event in the human history: the onset of climate-induced sea-level rise and associated coastal changes. As noted in the latest IPCC report (IPCC 2022), the governance supporting coastal adaptation requires decades to be put in place. This is illustrated above for France, which is developing this governance and is implementing some experiments to explore the possibilities to escape from a response dominated by engineering solutions. Yet, the time available to discuss and plan adaptation is shrinking as adaptation requires time to be implemented, while at the same time sea level rise is accelerating. In this context, we argue that there is a need for a transparent public debate explaining options to deal with sea level rise over the coming decades, with associated economic, social and environmental impacts and co-benefits.

**Anny CAZENAVE**
*Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, Toulouse, France*

**Goneri LECOZANNET**
*Bureau de Recherches Géologiques et Minières, Orléans, France*

## LAND-SEA INTERACTIONS IN THE MEDITERRANEAN: HOW CAN WE TAKE ADVANTAGE OF MULTIPLE INFLUENCES ON THE MEDITERRANEAN BASIN CLIMATE, BIODIVERSITY, ENVIRONMENTS, CULTURES, PEOPLE, RELIGIONS, LANGUAGES...?

Mediterranean basin performs as a melting pot for people, cultures, and natural systems. How to benefit from such a diversity?

In the first place recognizing and acknowledging it. It implies exploring, understanding, viewing and incorporating social suggestions. It is not the case at present. We receive a wealth of information, suggestions and pressures, from entities, societies and people from outside the basin. What is more: we rarely tune on sources broadcasting from the other rim, from Africa and Near East. And yet, these E and S regions, treasure vigourous cultures and active societies. It might be that we turn our eyes to them as energy resources or tourist destinations, but we are not eager to learn from their lives or to share their mounting problems. When we receive an endless flow of courageous migrants aiming at European countries, we pretend it is unacceptable, responding with barriers, walls, or police squads to halt them. Med countries attempt to handle newcomers passing them to N European countries as if they never existed. Med countries fail to gain from their presence, culture, abilities, and interests and easily charge them with misbehavior or crime.

Blind to their culture, deaf to their demands, we overlook how their population is growing outnumbering the countries seated on the N rim.

On second place, is the benefit of culture. In history, cultural exchange has been the role, not the exception. In archaeological collections, there is a time when local pieces are joined by outside elements. Neighboring or distant artifacts are found, and at a later stage, the foreign design, symbols, and even gods are incorporated to the local population's religion and way of living. This fusion was always enriching local cultures, often leading to the most important discoveries. Ancient Greek incorporated the Phoenician alphabet, adding new signs for vowels and building up the foundation of classic culture. Greek literature, philosophy, and scientific legacies were brought to Europe through Arabic invaders which conquered Spain in the VIII century. From Arabic towns such as Cordoba, Zaragoza, and Murcia, Greek legacy, including numbers and mathematics, found its way to Europe in an exercise of Mediterranean enlightenment. When tourists visit Islamic countries in the S and E rims of the basin, they are surprised by the relaxed way of living, hospitality, and craftsmanship. And deep religious attitudes.

Aside from souvenirs and pictures, the busy societies in S rim deserve more interest, and a genuine desire for collaboration, education, and participation. Access to the local literature and arts. An equalitarian approach to help lay the basis for an easy understanding across the Sea.

A third family of elements entering the Mediterranean melting pot exhibits environmental roots. Species, phenomena, climate, or environments, have no political boundaries and they often occur all around the basin. This feature makes them most adequate for integrative research and the application of local results to many other problems. What is more, when a relevant result sheds new light on one process or feature, it serves to give light to common solutions to many points in the basin. There is a family of Med problems which demand joint research ventures: the regulation of sea level and salinity equilibrium from

E to W; the sensitivity to currents under a scenario of climate change; the unbalance of fish species under a growing fisheries exploitation; the effect of eutrophication due to river outflow with a high nutrient content; the fate of mercury contamination and the incorporation to fish captures; the spreading of introduced species from Red Sea, aquaculture and domestic aquaria. Some of above listed issues demand adequate management which needs common protocols to become effective. The basin provides a rich collection of islands where the local population has attained a sustainable equilibrium with natural resources, land, water, biota, and fisheries. Island cultures summarize the principles of the circular economy.

In a different direction, policies of freshwater use, of energy consumption and production, species protection and ecosystem restoration, tourism activities, resort building, and natural resource exploitation. All strongly demand collaboration among regions and countries to sustain common policies letting the Mediterranean basin be addressed in a common way. African migrants, in their trajectory to Europe, reach the sea border where they are abused by the local mafia and harassed by police. People suffering and the thousands of casualties caused by unsafe boats during navigation show a political and social dysfunction to be overcome without delay.
Population in S-rim countries rapidly grows, outnumbering N-rim countries. Large gas deposits, some oil, rich aquifers, valuable minerals such as phosphates, and endless possibilities of energy production from aeolian, or solar plants are highly appreciated assets to sustain economic development both in S and N countries, provided they are not turned into political weapons. A state of war persists in a few countries (Syria, Israel, Lebanon, Cyprus), making it even more difficult to progress to sustainable development.

The Mediterranean basin offers a long list of needs, demands, suggestions and problems to be heard and solved. Water is a distinct protagonist in many of them. A wide scenario remains open for collaboration, trial (and error), for engaging in new activities to overcome historical problems.

An example of relevant activities is this meeting on water issues entitled "The Mediterranean System: a hotspot for climate change and adaptation", set up by the Accademia Nazionale dei Lincei. I wish that during next year, a parallel venture will be held in one of the S rim countries, exhibiting how collaboration in Mediterranean countries was proceeding.

**Francisco GARCIA NOVO**
*Spanish Royal Academy of Science,*
*Madrid, Spain*

## CAN WE REDUCE DISASTER RISK IN A CHANGING CLIMATE?

Stretching from the Alps to the Mediterranean Sea, Italy has a long history of geophysical and meteorological hazards, a result of the subduction of the African plate under the Eurasian plate. Frequent and widespread damaging events affect an area of about 301,000 $km^2$, inhabited by 59 million people, with 31 million buildings and 180,000 km of roads and railways. Depending on the hazard, the number of people at risk ranges from millions to tens of millions and is expected to increase with projected climate change. In the coming decades, we will not be able to make our natural and built environments safe from these hazards. It will be too difficult and costly and, in places, socially unacceptable. Solutions to (at least) reduce the human toll will rely on soft measures, notably early warning systems based on sound science. For most hazards, existing knowledge and technology are sufficient to implement effective measures. As with climate adaptation (Stocker, 2013), the reasons for postponing decisions are political, not scientific. I argue that we should use existing knowledge and technologies before seeking new ones that may not come soon (Park et al., 2023). I further argue that to cope effectively with geophysical and meteorological hazards in the face of the changing climate, we need a "new science" able to consider the complex interactions between all the physical, environmental, economic, social, and human elements that characterize hazards and their consequences, adopting a convergent research approach (Sharp & Hockfield, 2017).

**Fausto GUZZETTI**
*Consiglio Nazionale delle Ricerche,*
*Rome, Italy*

## COULD HIATUSES INFLUENCE THE PERCEPTION OF CLIMATE CHANGE AGAIN?

The recent global warming does not represent a uniform increase of temperature. As could be seen in the Figure 1, the first part of which is based on the time series constructed by Hansen et al. (2010), there were intervals when the temperature increase slowed down or even temporarily changed to the decrease, obviously related to the multidecadal variability influencing the long term trend. It is of interest that the attention paid by the researchers and the general public to the global warming issue was to some extent influenced by the variability. In order to illustrate this, also shown in the figure are numbers indicating some influential publications on global warming. Although several factors influenced the scientific activity, as did, for example, the preoccupation of early researchers with the origin of ice ages or the decrease of research intensity during the wars, it is still obvious that the scientists tended to pay more attention to the global warming when the temperatures were increasing or were high. After the formation of the Intergovernmental Panel on Climate Change (IPCC) in 1988, the intensity of research increased irrespective of what was happening with the temperature. However, the slowing down of the temperature increase (so-called hiatus) in the beginning of the $21^{st}$ century affected the public interest. The latter could be illustrated by the number of articles in which the terms 'global warming/climate change', 'skeptic' or 'denier' were mentioned in the major world newspapers (Grundmann, 2015) or by the number of sentences devoted to climate change in the university-level biology textbooks published in the United States (Prillaman, 2023).

The global warming was accompanied by a number of other changes in the climate system. One of them is the global sea level rise (Church and White, 2011), which was likewise subjected to the multidecadal variability with the rise being relatively slow in the 1900s and 1960s. It appears, however, that the variability was not reflected in the interest of researchers (Barnett, 1990), probably due to the fact that the trends never changed sign. The warming hiatus observed during the past decades could be related to the present sea level rise that is fast but stable, which probably explains why the rise did not fuel imagination of skeptics and deniers.

When it comes to the Mediterranean and Adriatic Seas, both the regional temperature data (Hansen et al., 2010) and the regional sea level data (Orlić et al., 2018) reveal a considerable influence of the multidecadal variability, comparable to or even larger than the variability observed on the global scale. Consequently, the temperature trends were negative in the 1960s and the sea level trends were negative in the 1970s. It is not known whether the multidecadal variability influenced the activity of climatologists interested in atmospheric processes, but it did affect the publication record of oceanographers studying sea level trends: as is visible from the review published by Vilibić et al. (2017), the Adriatic sea level change was addressed in some early papers, published in 1938, 1947 and 1961, and, after a standstill, in the papers that appeared in the 1980s and afterwards.

How will the multidecadal variability influence the future temperatures and sea levels? In order to illustrate a possible sequence of events, projections of both the global and regional temperatures expected under the RCP4.5 scenario (Stocker et al., 2014) are used and are subjected to the multidecadal variability representing a simple extension of observed variability into the future. The global temperature values thus obtained and the related trends are shown in the Figure 1'. Moreover, a variant of the semi-empirical method (Orlić and Pasa-

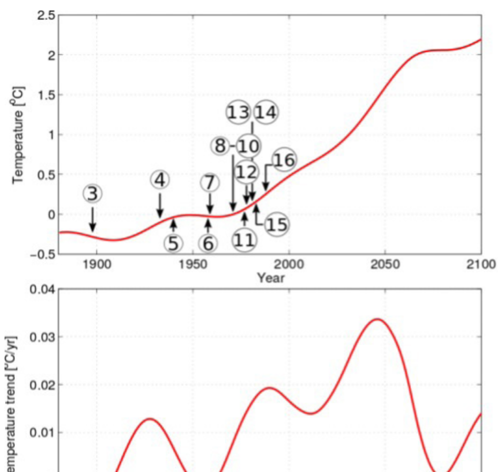


**Figure 1.** *Global temperatures (up) and global temperature trends (down), observed (Hansen et al., 2010) and projected until the end of the present century under the RCP4.5 scenario (Stocker et al., 2014), subjected to a low-pass filter in order to remove interannual and decadal-scale variability; projected temperatures include the multidecadal variability, which was obtained by simply extending the observed variability into the future. In the upper figure the numbers indicate some influential publications on global warming, which appeared before the IPCC era: (3) S. Arrhenius, 1896, (4) E. O. Hulburt, 1931, (5) G. S. Callendar, 1938, (6) G. N. Plass, 1956, (7) R. Revelle and H. E. Suess, 1957, (8) S. Manabe and K. Bryan, 1969, (9) M. I. Budyko, 1969, (10) W. D. Sellers, 1969, (11) W. S. Broecker, 1975, (12) C. D. Keeling et al., 1976, (13) K. Hasselmann, 1979, (14) J. Charney et al., 1979, (15) J. Hansen et al., 1981, (16) P. D. Jones et al., 1986. Two early studies (by J. B. J. Fourier, 1824, and J. Tyndall, 1859) were published before the time interval considered here.*

rić, 2013) is applied on the observed temperatures and sea levels and is then used to prepare projections of the global and regional sea levels on the basis of corresponding temperature projections. The results point to the global temperature and sea level accelerations lasting until the middle of this century and the subsequent decelerations leading to minimum trends late in the century. As for the regional temperatures and sea levels, the evolution is similar albeit shifted to earlier times and therefore characterized by minimum trends in the 2050s and 2060s (temperature) and 2070s (sea level).

Let us finally return to the question posed in the title. Assuming that the emission of greenhouse gases will follow the moderate scenario and that the future multidecadal variability will be similar to the observed one, the temperature and sea level hiatuses could be expected late in the present century on the global scale and in the mid-century on the regional scale. Because, however, the projections suggest that all the trends will stay positive, i.e., that the increases of temperature and sea level will slow down but will not reverse to the decreases, and that the dynamics will change when the temperatures and sea levels are already high, it is not likely that the forthcoming hiatuses will influence the perception of climate change. Consequently, it is unlikely that the future multidecadal variability will adversely influence the development of adaptation strategies.

**Mirko ORLIĆ**
*Croatian Academy of Sciences and Arts*

## WHICH ARE THE MOST VULNERABLE CULTURAL AND NATURAL UNESCO HERITAGE SITES IN THE MEDITERRANEAN?

The Mediterranean region, one of the cradles of global civilization, is included among the most vulnerable regions to climate change for the decades to come. Cultural and natural heritage in the Mediterranean, including 244 UNESCO heritage sites, is expected to be at risk from man-made climate change (Sesana et al., 2021). Heritage monuments can be vulnerable to climate change, considering their old age, the detrimental to their authenticity reparations with new and modern materials or replacement of some of their parts/structure that might be necessary to cope with the climate change induced hazards (Haugen & Mattsson, 2011; Berenfeld, 2008; Cassar, 2005). In addition, cultural landscapes and important plant or animal species may be lost. A multi hazard risk assessment for the design and optimized implementation of disaster risk reduction and resilience-enhancing strategies is necessary for the Mediterranean heritage sites, in which the incorporation of climate change is a challenge.

A methodology to assess the total hazard from the synergy of extreme weather in the future climate with the seismic activity at the cultural and natural heritage sites in the Mediterranean has been introduced by Kapsomenakis et al., 2022 (and references therein). Six climate indices were calculated throughout the period 1971-2100 at the locations of all the UNESCO sites in the Mediterranean. The indices represent estimates of the man-made climate change hazards and are described as it follows:

i. Number of days with maximum temperature higher than 37°C (Extreme heat),
ii. Number of days with Fire Weather Index higher than 45 (Wildfires) (Good et al., 2008),
iii. Number of days with precipitation higher than the 99th percentile of the reference period 1971-2000 (Heavy rainfall),
iv. Number of days with minimum temperature lower than 0°C (Frost),
v. Aridity (Aridity index) (Thornthwaite, 1948) and
vi. Changes in mean sea level (Sea level rise).

The indices were calculated from a large ensemble of high spatial resolution model results, under the RCP4.5 and RCP8.5 IPCC emission scenarios, based on 21 regional climate models applied in the framework of the EUROCORDEX program (https:// euro-cordex. net/). Sea level rise was calculated from the Extreme Sea Level dataset of the Large Scale Integrated Sea-level and Coastal Assessment Tool program developed by the Joint Research Center of the European Commission.

A synergistic-combined Heritage Hazard Index (HHI) was calculated to account for the synergy of all above mentioned climate change hazards with the local geophysical properties of the heritage sites, such as topography, proximity to forests and seas and earthquake probability. The latter has been estimated only at the locations of the south European heritage sites using the extracted intensity measure type of the maximum expected peak ground acceleration value from the most up to date European Seismic Hazard Model (Danciu et al., 2021).

Figure 1 presents the climate change total hazard (i.e. the sum of the six individual climate change hazards) and its synergy with the seismic hazard, under the two IPCC emission scenarios RCP4.5 and RCP8.5. In Figure 1, a four-class color scale is depicted, in parallel to the arithmetic scale, to characterize the following groups of hazard intensity: Low (L),

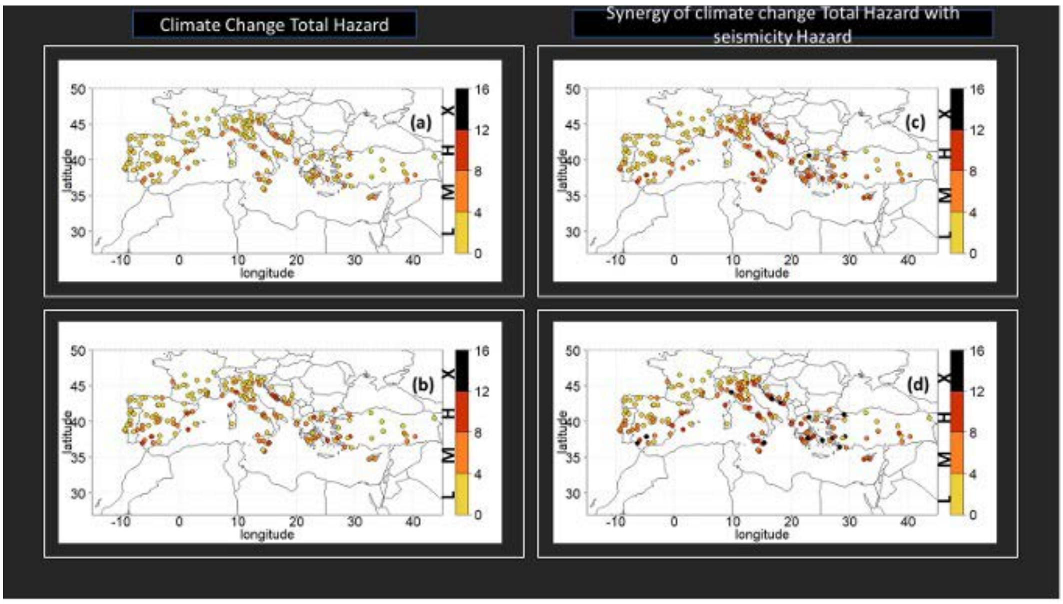


**Figure 1.** *The climate change total hazard (left) under the two IPCC emission scenarios RCP4.5 (a) and RCP8.5 (b). Figures 1 (c) and (d) show the synergy of climate change total hazard with the seismic hazard.*

Moderate (M), High (H) and Extreme (X) threat from the man-made climate change. Under the RCP4.5 scenario, the majority of heritage sites are under low or moderate climate change hazard (Figure 1a). The sites that are at higher hazard are mostly at coastal areas. The risk increases considerably under the RCP8.5 scenario at all heritage sites (Figure 1b). To the right of Figure 1, the amplification of climate hazard at places which are vulnerable also to seismic hazard is shown. These results are indicative of a comparatively higher total risk at the heritage sites located in countries at the center and east of southern Europe (Italy, Greece, Dalmatia, western Turkey and Cyprus). Based on the HHI and for the worst-case emission scenario (i.e. RCP8.5), 34 monument sites fall within the "High" hazard group. There are 13 heritage sites that fall under the category of "Extreme" hazard being the following:

i. Albania: Butrint
ii. Croatia: Stari Grad Plain; Old City of Dubrovnik
iii. Greece: Paleochristian and Byzantine Monuments of Thessalonika; Pythagoreion and Heraion of Samos; Archaeological Sites of Mycenae and Tiryns; Medieval City of Rhodes; Delos
iv. Italy: Portovenere, Cinque Terre and the Islands (Palmaria, Tino and Tinetto); Syracuse and the Rocky Necropolis of Pantalica
v. Spain: Doñana National Park
vi. Turkey: Hierapolis-Pamukkale; Historic Areas of Istanbul.

The previous discussion reveals that it is important to promote the adaptation of cultural and natural heritage sites to climate change, taking into consideration that the specific damage of climate change on heritage depends also on a variety of additional variables and parameters, e.g., the construction materials, state of conservation, surrounding landscape etc. Under this view, site specific multidisciplinary studies are necessary involving the earth science community, engineers, archaeologists, biodiversity experts etc., and the owners and/or managers, which can provide information about the criticalities and climate adaptation capacity of the heritage sites.

**Christos ZEREFOS**
*Academy of Athens, Greece*

# REFERENCES


**Ablain M., Legeais J.F., Prandi P., Fenoglio-Marc L., Marcos M., Benveniste J. and Cazenave A. 2017**. Altimetry-based sea level, global and regional, *Surveys in Geophysics*, 38: 7-31. DOI 10.1007/s10712-016-9389-8, 2017.

**Adloff F., Somot S., Sevault F., Jordà G., Aznar R., Déqué M., Herrmann M., Marcos M., Dubois C., Padorno E., Alvarez-Fanjul E., Gomis D. 2015**. Mediterranean Sea response to climate change in an ensemble of twenty first century scenarios, *Clim. Dyn.* 45: 2775-2802. DOI 10.1007/s00382-015-2507-3.

**Ali E., Cramer W. , Carnicer J., Georgopoulou E., Hilmi N.J.M., Le Cozannet G., Lionello P. 2022**. Cross-Chapter Paper 4. Mediterranean Region. In: *Climate Change* 2022: Impacts, Adaptation and Vulnerability. Contribution of WG II to AR6 of the Intergovernmental Panel on Climate Change [H.-O. Pörtner et al. (eds.)]. Cambridge University Press, Cambridge, UK and New York, USA, pp. 2233–2272. Doi:10.1017/9781009325844.021.

**Andersen O.B., Knudsen P., Kenyon S., Factor J.K., Holmes S. 2017**. Global Gravity Field From recent Satellites (DTU15) – Arctic improvements, *EAGE First Break*, vol. 35, no. 11.

**Anzidei M., Lambeck K., Antonioli F., Furlani S., Mastronuzzi G., Serpelloni E., Vannucci G. 2014.** Coastal structure, sea-level changes and vertical motion of the land in the Mediterranean, *Geol. Soc. Lond. Spec. Publ.*, 388: 453–479.

**Anzidei M., Bosman A., Carluccio R., Casalbore D., D'Ajello Caracciolo F., Esposito A., Nicolosi I., Pietrantonio G., Vecchio A., Carmisciano C. 2017**. Flooding scenarios due to land subsidence and sea-level rise: A case study for Lipari Island (Italy), *Terra Nova* 29: 44-51. http://dx.doi.org/10.1111/ter.12246.

**Anzidei M., Scicchitano G., Scardino G., Bignami C., Tolomei C., Vecchio A., Serpelloni E., De Santis V., Monaco C., Milella M., Piscitelli A., Mastronuzzi G. 2021**. Relative Sea-Level Rise Scenario for 2100 along the Coast of South Eastern Sicily (Italy) by InSAR Data, Satellite Images and High-Resolution Topography, *Remote Sens.* 13: 1108. https://doi.org/10.3390/rs13061108.

**Arrhenius S. 1896.** On the influence of carbonic acid in the air upon the temperature of the ground, The London, *Edinburgh and Dublin Philosophical Magazine and Journal of Science* 41: 237-276.

**Arias P., Bellouin N., Coppola E., Jones R., Krinner G., Marotzke J., ..., Zickfeld K. 2021**. In: *Climate Change 2021*: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change; Technical Summary.

**Ashkenazy Y., Stone P.H., Malanotte-Rizzoli P. 2012.** Box modeling of the Eastern Mediterranean sea, *Physica A*, 391: 1519-1531.

**Bakker A.M.R., Wong T.E., Ruckert K.L. et al. 2017.** Sea-level projections representing the deeply uncertain contribution of the West Antarctic ice sheet, *Sci Rep* 7: 3880. https://doi.org/10.1038/s41598-017-04134-5.

**Ballarotta M., Ubelmann C., Pujol M.-I., Taburet G., Fournier F., Legeais J.-F., Faugère Y., Delepoulle A., Chelton D., Dibarboure G., Picot N. 2019**. On the resolutions of ocean altimetry maps, *Ocean Sci.* 15: 1091-1109. https://doi.org/10.5194/os-15-1091-2019.

**Ban N., Caillaud C., Coppola E., Pichelli E., Sobolowski S., Adinolfi M., ... and Zander M.J. 2021**. The first multi-model ensemble of regional climate simulations at kilometer-scale resolution, part I: evaluation of precipitation, *Clim. Dyn.*: 1-28. https://doi.org/10.1007/s00382-021-05708-w.

**Barnett T.P. 1990**. Recent changes in sea level: a summary. In: Revelle R.R. (ed.), Sea-Level Change, National Academy Press, Washington, pp. 37-51.

**Barzaghi R. 2016**. The Remove-Restore Method. In: Grafarend E. (eds.), Encyclopedia of Geodesy. Springer, Cham. https://doi.org/10.1007/978-3-319-02370-0_19-1.

**Barzaghi R., Carrion D., Vergos G.S., Tziavos I.N., Gigoriadis V.N., Natsiopoulos D.A., Bruinsma S., Reinquin F., Seoane L., Bonvalot S., Lequentrec-Lalancette M.F., Salaun C., Andersen O., Knudsen P. 2018.** GEOMED2: high-resolution geoid of the Mediterranean. International Association of Geodesy Symposia. Springer, Berlin, Heidelberg, IAG, Kobe. DOI: https://doi.org/10.1007/1345_2018_33.

**Benjamin J., Rovere,A., Fontana A., Furlani S., Vacchi M., Inglis R.H., Galili E., Antonioli F., Sivan D., Miko S., Mourtzas N., Felja I., Meredith-Williams M., Goodman-Tchernov B., Kolaiti E., Anzidei M., Gehrels R. 2017.** Late Quaternary sea-level changes and early human societies in the central and eastern Mediterranean Basin: An interdisciplinary review, *Quaternary International* 449: 29-57. https://doi.org/10.1016/j.quaint.2017.06.025.

**Berenfeld M.L. 2008.** Climate change and cultural heritage: Local evidence, global responses, *The George Wright Forum* 25 (2): 66-82.

**Boers N. 2021.** Observation-based early-warning signals for a collapse of the Atlantic Meridional Overturning Circulation, *Nature Climate Change* 11: 680-688.

**Bongarts et al. 2021.** Designing Coastal Adaptation Strategies to Tackle Sea Level Rise, *Frontiers in Marine Sciences*, published online 03 Nov 2021. https://doi.org/10.3389/fmars.2021.740602.

**Bouda A. et al. 2017.** Conférence Méditerranéenne Côtière et Maritime. DOI: 10.5150/cmcm.2011.071.

**Broecker W.S. 1975.** Climatic change: Are we on the brink of a pronounced global warming? *Science* 189: 460-464.

**Bryden H.L. and Kinder T.H. 1991.** Steady two-layer exchange through the Strait of Gibraltar, *Deep-Sea Res.*, 38: S445-S463.

**Brogli R., Sørland S.L., Kröner N., Schär C. 2019**. Causes of future Mediterranean precipitation decline depend on the season, *Environ Res Lett.* 14: 114017. Doi:10.1088/1748-9326/ab4438.

**Budyko M.I. 1969.** The effect of solar radiation variations on the climate of the earth, *Tellus* 21: 611-619.

**Caesar L. et al. 2018.** Observed fingerprint of a weakening Atlantic Ocean overturning circulation, *Nature* 556: 191-196.

**Caesar L. et al. 2021.** Current Atlantic Meridional Overturning Circulation weakest in last millennium, *Nature Geoscience* 14: 118-120.

**Callendar G.S. 1938.** The artificial production of carbone dioxide and its influence on temperature, *Quarterly Journal of the Royal Meteorological Society* 64: 223-240.

**Caloi P. 1938**. Sesse dell'alto Adriatico con particolare riguardo al Golfo di Trieste, *Memorie*, R. Comitato Talassografico Italiano, 247: 1-39.

**Cassar M. 2005.** Climate change and the historic environment. University College London.

**Cavaleri L., Bajo M., Barbariol F., Bastianini M., Benetazzo A., Bertotti L., Chiggiato J., Ferrarin C., Trincardi F., Umgiesser G. 2020.** The 2019 flooding of Venice and its implications for future predictions, *Oceanography* 33: 42-49.

**Cazenave A., Gouzenes Y., Birol F., Leger F., Passaro M., Calafat F. M., Shaw A., Nino F., Legeais J.-F., Oelsmann J., Restano M., Benveniste J. 2022.** Sea level along the world's coastlines can be measured by a network of virtual altimetry stations. *Commun Earth Environ* 3, 117. https://doi.org/10.1038/s43247-022-00448-z.

**Charney J.G., Arakawa A., Baker J., Bolin B., Dickinson R. E., Goody R.M., Leith C.E., Stommel H.M., Wunsch C.I. 1979.** Carbon Dioxide and Climate: A Scientific Assesment, National Academy of Sciences, Washington.

**Cherif S., Doblas-Miranda E., Lionello P,. Borrego C., Giorgi F., Iglesias A., Jebari S., Mahmoudi E., Moriondo M., Pringault O., Rilov G., Somot S., Tsikliras A., Vila M., Zittis G. 2020.** Drivers of change. In: Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. MAR1 [Cramer W. et al. (eds.)] Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp. 59-180, doi:10.5281/zenodo.7100601.

**Church J.A., White N.J. 2011.** Sea-level rise from the late 19th to the early 21st century, *Surveys in Geophysics* 32: 585-602.

**Civitarese G., Gacic M., Batistic M., Bensi M., Cardin V., Dulcic J., Garic R. and Menna M. 2023.** The BIOS mechanism: history, theory, implications, *Progr.Oceanogr.*, in press.

**Copernicus Ocean State Report 2020.** *J. Oper. Oceanogr.*, 6, 220 pp.

**Coppola E., Dosio A., Otto F., Dereczynski C., Gomis M.I., Jones R.G. et al. 2021.** Cross-Chapter Box 10.3: Assessment of climate change information at the regional scale. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan and S. Berger (eds.), Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 1435-1438. Cambridge University Press. https://doi.org/10.1017/9781009157896.012.

**Cramer W., Guiot J., Fader M., Garrabou J., Gattuso J.-P., Iglesias A., Lange M.A., Lionello P., Llasat M.C., Paz S., Peñuelas J., Snoussi M., Toreti A., Tsimplis M.N., Xoplaki E. 2018.** Climate change and interconnected risks to sustainable development in the Mediterranean,- *Nat. Clim. Change* 8 (11): 972-980. Doi:10.1038/s41558-018-0299-2.

**D'Agostino R., Lionello P. 2020.** The atmospheric moisture budget in the Mediterranean: Mechanisms for seasonal changes in the Last Glacial Maximum and future warming scenario, *Quat. Sci. Rev.* 241: 106392. Doi: 10.1016/j.quascirev.2020.106392.

**Danciu L., Nandan S., Reyes C., Basili R., Weatherill G., Beauval C., Rovida A., Vilanova S., Sesetyan K., Bard P-Y., Cotton F., Wiemer S., Giardini D. 2021.** The 2020 update of the European Seismic Hazard Model: Model Overview. EFEHR Technical Report 001, v1.0.0.

**Dangendorf S., Hay C., Calafat F.M., Marcos M., Piecuch C.G., Berk K., Jensen J. 2019.** Persistent acceleration in global sea-level rise since the 1960s, *Nat. Clim. Change* 9: 705-710.

**Darmaraki S., Somot S., Sevault F., Nabat P., Cabos Narvaez W.D., Cavicchia L., Djurdjevic V., Li L., Sannino G., Sein D.V. 2019.** Future evolution of Marine Heatwaves in the Mediterranean Sea, *Clim. Dyn.* 53: 1371-1392. Doi:10.1007/s00382-019-04661-z.

**Davolio S., Della Fera S., Laviola S., Miglietta M.M., Levizzani V. 2020.** Heavy precipitation over Italy from the Mediterranean storm "Vaia" in October 2018: Assessing the role of an atmospheric river, *Mon. Wea. Rev*. 148: 3571-3588.

**DeConto R.M., Pollard D., Alley R.B. et al. 2021.** The Paris Climate Agreement and future sea-level rise from Antarctica, *Nature* 593: 83-89. https://www.nature.com/articles/s41586-021-03427-0.

**Dieng H.B., Cazenave A., Gouzenes Y. and Sow, A. 2021.** Trends and inter-annual variability of coastal sea level in the Mediterranean Sea: Validation of high-resolution altimetry using tide gauges and models, *Advances in Space Research* 68 (8): 3093-3520. https://doi.org/10.1016/j.asr.2021.06.022, 2021.

**Dinardo S., Scharroo R., Bonekamp H., ..., Loddo C., Benveniste J. 2016.** A preliminary assessment of the S-3A SRAL performances in SAR mode, European Space Agency, (Special Publication), ESA SP, SP-740.

**Doblas-Reyes F.J., Sörensson A.A., Almazroui M., Dosio A., Gutowski W.J., Haarsma R., Hamdi R., Hewitson B., Kwon W.-T., Lamptey B.L., Maraun D., Stephenson T.S., Takayabu I., Terray L., Turner A., Zuo Z. 2021.** Linking Global to Regional Climate Change. In *Climate Change* 2021: The Physical Science Basis. Contribution of WGI to AR6 of the Intergovernmental Panel on Climate Change [Masson-Delmotte V.P. et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1363-1512. Doi:10.1017/9781009157896.012.

**Douville H., Raghavan K., Renwick J., Allan R.P., Arias P.A., Barlow M., Cerezo-Mota R., Cherchi A., Gan T.Y., Gergis J., Jiang D., Khan A., Pokam Mba W., Rosenfeld D., J. Tierney, Zolina O. 2021.** Water Cycle Changes. In: *Climate Change* 2021: The Physical Science Basis. Contribution of WGI to AR6 of the Intergovernmental Panel on Climate Change [Masson-Delmotte V., P. et al. (eds.)] Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1055-1210. Doi:10.1017/9781009157896.010.

**Drinkwater M.R., Floberghagen R., Haagmans R., Muzi D., Popescu A. 2003.** GOCE: ESA's First Earth Explorer Core Mission, *Space Science Reviews, Kluwer Academic*, 108 (1-2): 419-432. Doi:10.1023/A:1026104216284.

**Drobinski P., Da Silva N., Bastin S., Mailler S., Muller C., Ahrens B., Christensen, O.B., Lionello P. 2020.** How warmer and drier will the Mediterranean region be at the end of the twenty-first century? *Reg. Environ Change* 20: 1-12. DOI: 10.1007/s10113-020-01659-w.

**Emery K.O., Aubrey D.G. 1991.** Sea Levels, Land Levels, and Tide Gauges, Springer-Verlag, New York.

**FAO 2022.** The State of the Mediterranean and Back Sea Fisheries. https://www.fao.org/3/cc3370en/cc3370en.pdf.

**Ferrarin C., Bajo M., Benetazzo A., Cavaleri L., Chiggiato J., Davison S., Davolio S., Lionello P., Orlić M., Umgiesser G. 2021.** Local and large-scale controls of the exceptional Venice floods of November 2019, *Progress in Oceanography* 197: 102628.

**Ferrarin C., Lionello P., Orlić M., Raicich F., Salvadori G. 2022.** Venice as a paradigm of coastal flooding under multiple compound drivers, *Scientific Reports* 12 (5754): 1-11.

**Flaounas E., Davolio S., Raveh-Rubin S., Pantillon F., Miglietta M. M., Gaertner M. A., Hatzaki M., Homar V., Khodayar S., Korres G., Kotroni V., Kushta J., Reale M., Ricard D. 2022.** Mediterranean cyclones: current knowledge and open questions on dynamics, prediction, climatology and impacts, *Weather and Clim. Dyn.* 3: 173-208. https://doi.org/10.5194/wcd-3-173-2022.

**Fourier J.B.J. 1824.** Remarques générales sur les températures du globe terrestre et des espaces planétaires, *Annales de Chimie et de Physique* 27: 136-167.

**Francis J.A., Vavrus S.J. 2012.** Evidence linking Arctic amplification to extreme weather in mid-latitudes, *Geophysical Research Letters* 39 (L06801): 1-6.

**Garola A., Lopez-Doriga U., Jiménez J.A. 2022.** Ocean and Coastal Management, 218, 1: 106034. https://doi.org/10.1016/j.ocecoaman.2022.106034.

**Genua-Olmedo A., Alcaraz C., Caiola N., Ibànez C. 2016.** Science of the Total Environment, 571: 1200-1210. https://doi.org/10.1016/j.scitotenv.2016.07.136.

**Good P., Moriondo M., Giannakopoulos C., Bindi M. 2008.** The meteorological conditions associated with extreme fire risk in Italy and Greece: Relevance to climate model studies, *International Journal of Wildland Fire* 17 (2): 155.

**Grundmann R. 2015.** Climate skepticism, in: Bäckstrand K., Lövbrand E. (eds.), Research Handbook on Climate Governance, Edwar Elgar Publishing, Cheltenham, pp. 175-187.

**Guerou A., Meyssignac B., Prandi P., Ablain M., Ribes A. and Bignalet-Cazalet 2023.** Current observed global mean sea level rise and acceleration estimated from satellite altimetry and the associated uncertainty, *Ocean Sciences*. https://doi.org/10.5194/egusphere-2022-330.

**Gutiérrez J.M., Jones R.G., Narisma G.T., Alves L.M., Amjad M., Gorodetskaya I.V., Grose M., Klutse N.A.B., Krakovska S., Li J., Martínez-Castro D., Mearns L.O., Mernild S.H., Ngo-Duc T., van den Hurk B., Yoon J.-H. 2021.** Linking Global to Regional Climate Change. In: *Climate Change* 2021: The Physical Science Basis. Contribution of WGI to AR6 of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1927-2058. Doi:10.1017/9781009157896.021.

**Haasnoot M., Kwakkel J., Walker W., Ter Maat J. 2013.** Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world, *Global Environmental Change* 23/2. Doi: 10.1016/j.gloenvcha.2012.12.006.

**Hansen J. , Johnson D., Lacis A., Lebedeff S., Lee P., Rind D., Russell G. 1981.** Climate impact of increasing atmospheric carbon dioxide, *Science* 213: 957-966.

**Hansen J., Ruedy R., Sato M., Lo K. 2010.** Global surface temperature change, *Reviews in Geophysics* 48 (RG4004): 1-29.

**Hasselmann K. 1979.** On the signal-to-noise problem in atmospheric response studies, in: Shaw D. B. (Ed.) Meteorology Over the Tropical Oceans, Royal Meteorological Society, London, 251-259.

**Haugen A., Mattsson J. 2011.** Preparations for climate change's influences on cultural heritage, *International Journal of Climate Change Strategies and Management* 3 (4): 386–401.

**Hawkins, Edward & Sutton, Rowan 2009.** The Potential to Narrow Uncertainty in Regional Climate Predictions, *Bulletin of the American Meteorological Society* 90. 10.1175/2009BAMS2607.1.

**Hinkel J., Aerts C.J.H., Brown S., Jimenez J.A., Lincke D., Nicholis R.J., Scussolini P., Sanchez-Arcilla A., Vafeidis A., Addo K.A. 2018.** The abilities of Societes to Adapt to Twentyfirst Century Sea-Level Rise, *Nat. Clim. Change* 8.7: 570-578. Doi:10.1038/s41358-018-0176-z.

**Horwath M., Gutknecht B.D., Cazenave A., Palanisamy H.K., Marti F., Marzeion B., Paul F., Le Bris R., Hogg A.E., Otosaka I., Shepherd A., Döll P., Cáceres D., Müller Schmied H., Johannessen J.A., Nilsen J.E.Ø., Raj R.P., Forsberg R., Sandberg Sørensen L., Barletta V.R., Simonsen S.B., Knudsen P., Andersen O.B., Ranndal H., Rose S.K., Merchant C.J., Macintosh C.R., von Schuckmann K., Novotny K., Groh A., Restano M. and Benveniste J. 2022.** Global sea-level budget and ocean-mass budget, with a focus on advanced data products and uncertainty characterisation, *Earth System Science Data* 14: 411-447. https://doi.org/10.5194/essd-14-411-2022.

**Houma F., Bachari N.E.I., Bachouche S., Kassar A., Belkess R. 2017**. Contribution à l'évaluation de la pollution des eaux marines sur la côte Ouest d'Alger en utilisant l'imagerie satellitale, Conférence Méditerranéenne Côtière et Maritime. DOI: 10.5150/ cmcm.2011.071.

**Iles C.E., Vautard R., Strachan J., Joussaume S., Eggen B.R., Hewitt C. D. 2020.** The benefits of increasing resolution in global and regional climate simulations for European climate extremes, *Geosci. Model Dev.* 13: 5583-5607, https://doi.org/10.5194/gmd-13-5583-2020.

**Hulburt E.O. 1931.** The temperature of the lower atmosphere of the earth, *Physical Review* 38: 1876-1890.

**IPCC 2021**. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press. Doi:10.1017/9781009157896.

**IPCC 2021.** Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of WGI to AR6 of the Intergovernmental Panel on Climate Change [Masson-Delmotte V., P. et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3-32. Doi:10.1017/9781009157896.001.

**IPCC 2022.** Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp. Doi:10.1017/9781009325844.

**Jones P.D., Wigley T.M.L., Wright P.B. 1986.** Global temperature variations between 1861 and 1984, *Nature* 322: 430-434.

**Jousset S., Aydogdu A., Ciliberti S., Clementi E., Escudier R., Jansen E., Lima L., Menna M., Mulet S., Nigam T., Sánchez A., Tarry D. R., Pascual A., Peneva E., Poulain P.-M., Taupier-Letage I. 2022.** New Mean Dynamic Topography of the Mediterranean Sea from altimetry, gravity and in-situ data. In preparation.

**Kapsomenakis J., Douvis C., Poupkou A., Zerefos S., Solomos S., Stavraka T., Melis N., Kyriakidis E., Kremlis G. and Zerefos C. 2022.** Climate Change Threats to Cultural and Natural Heritage UNESCO Sites in the Mediterranean, *Environment, Development and Sustainability*. https://doi.org/10.1007/s10668-022-02677-w.

**Karagiannis G.M. 2017.** Joint Research Centre (European Commission). https://publications.jrc.ec.europa.eu/repository/bitstream/JRC109015/$oods_ci_eur28855en_new_edition_!nal.pdf.

**Keeling C.D., Bacastow R.B., Bainbridge A.E., Ekdahl C.A., Gunether P.R., Waterman L.S., Chin J.F.S. 1976.** Atmospheric carbone dioxide variations at Mauna Loa Observatory, Hawaii, *Tellus* 28: 538-551.

**Kesslitz W. 1911.** Die Sturmflut am 15. und 16. November 1910 in Pola, *Mitteilungen aus dem Gebiete des Seewesens* 39: 157-163.

**Khodayar S., Davolio S., Di Girolamo P., Lebeaupin Brossier C., Flaounas E., Fourrie N., Lee K.-O., Ricard D., Vie B., Bouttier F., Caldas-Alvarez A., Ducrocq V. 2021.** Overview towards improved understanding of the mechanisms leading to heavy precipitation in the western Mediterranean: lessons learned from HyMeX, *Atmos. Chem. Phys.* 21, 17051-17078. https://doi.org/10.5194/acp-21-17051-2021.

**Kopp R.E., De Conto R.M., Bader D.A., Hay C.C., Horton R.M., Kulp S., Oppenheimer M., Pollard D., Strauss B.H. 2017.** Earth's Future 5 (12): 1217-1233. https://doi.org/10.1002/2017EF000663.

**Lambeck K., Woodroffe C., Antonioli F., Anzidei M., Gehrels W., Laborel J., Wright A. 2010.** Paleoenvironmental Records, Geophysical Modeling, and Reconstruction of Sea-Level Trends and Variability on Centennial and Longer Timescales, *Fac. Sci. Pap. Arch.* c04: 61-121.

**Legeais J.F., Ablain M., Zawadzki L., Zuo H., Johannessen J.A., Scharffenberg M.G., Fenoglio-Marc L., Fernandes J., Andersen O.B., Rudenko S.., Cipollini P., Quartly G.D., Passaro M., Cazenave A., Benveniste J. 2018.** An improved and homogeneous altimeter sea level record from the ESA Climate Change Initiative, *Earth Syst. Sci. Data* 10, 281-301, https://doi.org/10.5194/essd-10-281-2018.

**Lionello P., Barriopedro D., Ferrarin C., Nicholls R.J., Orlić M., Raicich F., Reale M., Umgiesser G., Vousdoukas M., Zanchettin D. 2021.** Extreme floods of Venice: characteristics, dynamics, past and future evolution (review article), *Natural Hazards and Earth System Sciences* 21: 2705-2731.

**Lionello P., Giorgi F. 2007.** Winter precipitation and cyclones in the Mediterranean region: future climate scenarios in a regional simulation, *Adv Geosci* 12: 153-158. DOI: 10.5194/adgeo-12-153-2007.

**Lionello P., Giorgi F., Rohling E., Seager R. 2023.** Mediterranean climate: past, present and future. In: Oceanography of the Mediterranean Sea (pp. 41-91). Elsevier, DOI: 10.1016/B978-0-12-823692-5.00011-X.

**Lionello P., Scarascia L. 2018.** The relation between climate change in the Mediterranean region and global warming, *Reg Environ Change* 18: 1481-1493. DOI: 10.1007/s10113-018-1290-1.

**Lionello P., Scarascia L. 2020.** The relation of climate extremes with global warming in the Mediterranean region and its north versus south contrast, *Reg Environ Change* 20: 31, DOI: 10.1007/s10113-020-01610-z.

**Lionello P., Abrantes F., Congedi L., Dulac F., Gacic M., Gomis D., Goodess C., Hoff H., Kutiel H., Luterbacher J., Planton S., Reale M., Schröder K., Struglia M.V., Toreti A., Tsimplis M., Ulbrich U., Xoplaki E. 2012.** Introduction: Mediterranean climate-background information. In: The climate of the Mediterranean region: From the past to the future (pp. xxxv-xc). Elsevier Inc. DOI:10.1016/B978-0-12-416042-2.00012-4.

**Lionello P. et al. 2023.** Mediterranean climate: past, present and future. In Oceanography of the Mediterranean Sea (pp. 41-91). Elsevier, DOI: 10.1016/B978-0-12-823692-5.00011-X
Loizidou X.I. et al. (2023). Environment Systems and Decisions (submitted, 01/2023).

**Loizidou X.I., Orthodoxou D., Loizides M., Petsa D., Anzidei M. 2023.** Adapting to sea level rise: participatory, solution-oriented Policy Tools in vulnerable Mediterranean areas, Submitted to Environment Systems and Decisions.

**Lorenz R., Argüeso D., Donat M.G., Pitman A.J., van den Hurk B., Berg A., Lawrence D.M., Chéruy F., Ducharne A., Hagemann S., Meier A., Milly P.C.D., Seneviratne S. I 016.** Influence of land-atmosphere feedbacks on temperature and precipitation extremes in the GLACE-CMIP5 ensemble. *J. Geophys. Res Atmo.* 121: 607-623. Doi: 10.1002/2015jd024053.

**Lozier M.S., Owens W.B., Curry R.G. 1995.** The climatology of the north Atlantic, *Progr. Oceanogr.* 36, 1.

**Malanotte-Rizzoli P., Eremeev V.N. 1999.** The Eastern Mediterranean as a Laboratory Basin for the Assessment of Contrasting Ecosystems, *NATO Science Partnership*, 521 pp.

**Malanotte-Rizzoli P., Manca B.B., Ribera d'Alcalà M., Theocharis A., Brenner S., Budillon G. and Ozsoy E. 1999.** The Eastern Mediterranean in the 80s and in the 90s: the big transition in the Intermediate and deep circulations, *Dynam. Atmos. Oceans* 29: 365-395.

**Malanotte-Rizzoli P., Robinson A.R. 1993.** Ocean Processes in Climate Dynamics: Global and Mediterranean Examples, *NATO-ASI Series* 419: 437 pp.

**Manabe S., Bryan K. 1969.** Climate calculations with a combined ocean-atmosphere model, *Journal of the Atmospheric Sciences* 26: 786-789.

**Marcos M., Tsimplis M.N. 2008a.** Comparisons of results of AOGCMs in the Mediterranean Sea during the 21st century, *J. Geophys. Res.* 113: C12028.

**Marcos M., Tsimplis M.N. 2008b.** Coastal sea level trends in Southern Europe, *Geophysical Journal International* 175: 70-82.

**Mariotti A., Dell'Aquila A. 2012.** Decadal climate variability in the Mediterranean region: roles of large-scale forcings and regional processes, *Clim. Dyn.* 38: 1129-1145. Doi: 10.1007/s00382-011-1056-7.

**Millot C., Taupier-Letage I. 2005.** Circulation in the Mediterranean Sea. In: Saliot A. (eds.) The Mediterranean Sea. Handbook of Environmental Chemistry, vol 5K. Springer, Berlin, Heidelberg.

**Mosetti F. 1961.** Sulla tendenza secolare del livello medio marino a Trieste, Atti dell'Istituto Veneto di Scienze, Lettere ed Arti, Classe di Scienze Matematiche e Naturali 119: 425-434.

**Mulet S., Rio M.-H. end Bruinsma S. 2012a.** Accuracy of the preliminary GOCE GEOID models from an oceanographic perspective, *Marine Geodesy* 35: 314-336. DOI: 10.1080/01490419.2012.718230.

**Mulet S., Rio, M.-H., Mignot A., Guinehut S. and Morrow R. 2012b.** A new estimate of the global 3D geostrophic ocean circulation based on satellite data and in-situ measurements, *Deep-Sea Res. II.*, 77-80, 70-81. Doi:10.1016/j.dsr2.2012.04.012.

**Nabat P., Somot S., Mallet M., Sanchez-Lorenzo A., Wild M. 2014.** Contribution of anthropogenic sulfate aerosols to the changing Euro-Mediterranean climate since 1980, *Geophys Res Lett* 41: 5605–5611. Doi: 10.1002/2014gl060798.

**Oppenheimer M., Glavovic B.C., Hinkel J., van de Wal R., Magnan A.K., Abd-Elgawad A., Cai R., Cifuentes-Jara M., DeConto R.M., Ghosh T., Hay J., Isla F., Marzeion B., Meyssignac B., Sebesvari Z. 2019.** Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities, in IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 321-445. https://doi.org/10.1017/9781009157964.006.

**Orlić M. 1980.** About a possible occurrence of the Proudman resonance in the Adriatic, T*halassia Jugoslavica* 16: 79-88.

**Orlić M., Pasarić M. 2013.** Is the Mediterranean sea level rising again?, *Rapports et procès-verbaux des réunions CIESMM*, 40: 205.

**Orlić M., Pasarić M., Pasarić Z. 2018.** Mediterranean sea-level variability in the second half of the twentieth century: a Bayesian approach to closing the budget, P*ure and Applied Geophysics* 175, 3973-3988.

**Orlić M., Pasarić Z. 2013.** Semi-empirical versus process-based sea-level projections for the twenty-first century, *Nature Climate Change* 3, 735-738.

**Palmer M.D., Domingues C.M., Slangen A.B.A., Boeira Dias F. 2021.** Environ. Res. Lett. 16 044043. DOI 10.1088/1748-9326/abdaec.

**Park M., Leahey E., Funk R.J. 2023.** Papers and patents are becoming less disruptive over time, *Nature* 613: 138-144, https://doi.org/10.1038/s41586-022-05543-x.

**Penzar B., Orlić M., Penzar I. 1980.** Sea-level changes in the Adriatic as a consequence of some wave occurrences in the atmosphere, *Thalassia Jugoslavica* 16: 51-77.

**Pfahl S., O'Gorman P. A., Fischer E.M. 2017.** Understanding the regional pattern of projected future changes in extreme precipitation, *Nature Climate Change* 7: 423-427.

**Pfeifroth U., Sanchez-Lorenzo A., Manara V., Trentmann J., Hollmann R. 2018.** Satellite-based trends of solar radiation and cloud parameters in Europe, *Adv. Sci. Res.* 15: 31-37. Doi: 10.5194/asr-15-31-2018.

**Philippenko X., Goeldner-Gianella L., Le Cozannet G., Grancher D., De La Torre Y., 2021.** Perceptions of climate change and adaptation: A subarctic archipelago perspective (Saint-Pierre-and-Miquelon, North America), *Ocean & Coastal Management* 215: 105924.

**Pichelli E., Coppola E., Sobolowski S., Ban N., Giorgi F., Stocchi P., ... and Vergara-Temprado J. 2021.** The first multi-model ensemble of regional climate simulations at kilometer-scale resolution part 2: historical and future simulations of precipitation, *Climate Dynamics* 56(11): 3581-3602. https://doi.org/10.1007/s00382-021-05657-4.

**Pirazzoli P.A. 1981.** Bora e acqua alta, *Acqua-Aria* 10: 1115-1118.

**Pisano A., Marullo S., Artale V., Falcini F., Yang C., Leonelli F.E., Santoleri R., Buongiorno Nardelli B. 2020.** New evidence of Mediterranean climate change and variability from sea surface temperature observations, *Remote Sens.* 12: 132. Doi: 10.3390/rs12010132.

**Plass G.N. 1956.** The carbon dioxide theory of climatic changes, *Tellus* 8: 140-154.

**Polli S. 1938.** Livelli medi, capisaldi di livellazione e ampiezze della marea nel porto di Trieste, *Memorie*, *R. Comitato Talassografico Italiano*, 253: 1-27.

**Poulain P.-M.,Bussani A., Gerin R., Jungwirth R., Mauri E., Menna M., Notarstefano G. 2013.** Mediterranean surface currents measured with drifters: From basin to subinertial scales, *Oceanography* 26 (1): 38–47, http://dx.doi.org/10.5670/oceanog.2013.03.

**Prillaman M. 2023.** Climate-change content shrinks in US university textbooks, *Nature* 613: 228.

**Rahmstorf S. 1998.** Influence of Mediterranean outflow on Climate, *EOS* 79: 24.

**Rahmstorf S. 2002.** Ocean circulation and climate during the past 120,000 years, *Nature* 419: 207-214.

**Rahmstorf S. et al. 2015.** Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation, *Nat. Clim. Change* 5: 475-480.

**Ralph F.M. et al. 2018.** Defining "atmospheric river": How the glossary of meteorology helped resolve a debate, *Bull. Am. Meteorol. Soc.* 99: 837-839.

**Ranger N., Reeder T., Lowe J. 2013.** Addressing "deep" uncertainty over long-term climate in major infrastructure projects: four innovations of theThames Estuary 2100 project, *EURO Journal on Decision Processes* 3-4: 233-262.

**Reale M., Salon S., Crise A., Farneti R., Mosetti R. and Sannino G. 2017.** Unexpected Covariant Behavior of the Aegean and Ionian Seas in the Period 1987-2008 by Means of a Nondimensional Sea Surface Height Index, *J. Geophys. R.* 122, 10: 8020-8033.

**Reale M., Cabos Narvaez W.D., Cavicchia L., Conte D., Coppola E., Flaounas E., Giorgi F., Gualdi S., Hochman A., Li L., Lionello P., Podrascanin Z., Salon S., Sanchez-Gomez E., Scoccimarro E., Sein D.V., Somot S. 2022.** Future projections of Mediterranean cyclone characteristics using the Med-CORDEX ensemble of coupled regional climate system models, *Clim. Dyn.*, 1-24. DOI: 10.1007/s00382-021-06018-x.

**Reid J. 1979.** On the contributionof the Mediterranean Sea outflow to the Norwegian-Greenland Sea, *Deep Sea-Res* 26: 1199.

**Reimann L. et al. 2018.** Mediterranean UNESCO World Heritage at risk from coastal flooding and erosion due to sea-level rise. Nature Communications. DOI: 10.1038/s41467-018-06645-9.

**Revelle R., Suess H.E. 1957.** Carbon dioxide exchange between atmosphere and ocean and the question of an increase of atmospheric CO2 during the past decades, *Tellus* 9: 18-27.

**Rio M.-H., Mulet S., Picot N. 2014a.** Beyond GOCE for the ocean circulation estimate: Synergetic use of altimetry, gravimetry, and in situ data provides new insight into geostrophic and Ekman currents, *Geophys. Res. Lett.* 41. Doi:10.1002/2014GL061773.

**Rio M.-H., Pascual A., Poulain P.-M., Menna M., Barceló B., Tintoré J. 2014b.** Computation of a new Mean Dynamic Topography for the Mediterranean Sea from model outputs, altimeter measurements and oceanographic in-situ data, *Ocean Sci.* 10: 731-744. www.ocean-sci.net/10/731/2014/ doi:10.5194/os-10-731-2014.

**Rodwell M.J., Hoskins B.J. 1996.** Monsoons and the dynamics of deserts. *Q. J. R. Meteorol. Soc.* 122: 1385-1404. DOI: 10.1002/qj.49712253408.

**Roether W., Manca B.B., Klein B., Bregant D., Georgopoulos D., Beitzel V., Kovacevic V., Luchetta A. 1996.** Recent changes in eastern Mediterranean deep waters, *Science* 271: 333-335.

**Rowell D.P. and Jones R.G. 2006.** Causes and uncertainty of future summer drying over Europe, *Clim. Dyn.* 27: 281-299. DOI: 10.1007/s00382-006-0125-9.

**Ruane A.C., Vautard R., Ranasinghe R., Sillmann J., Coppola E., Arnell N. et al. 2022.** The Climatic Impact-Driver Framework for assessment of risk-relevant climate information. *Earth's Future* 10: e2022EF002803.

**Rummel R., Sansò S. (eds.) (1993).** Satellite Altimetry in Geodesy and Oceanography, Lecture Notes in Earth Sciences, Springer-Verlag. ISBN 3-540-56818-2.

**Rus M., Fettich A., Kristan M., Ličer M. 2023.** HIDRA2: deep-learning ensemble sea level and storm tide forecasting in the presence of seiches – the case of the northern Adriatic, *Geoscientific Model Development* 16: 271-288.

**Samaniego L., Thober S., Kumar R., Wanders N., Rakovec O., Pan M., Zink M., Sheffield J., Wood E.F., Marx A. 2018.** Anthropogenic warming exacerbates European soil moisture droughts, *Nat. Clim. Change.* 8: 421-426. DOI: 10.1038/s41558-018-0138-5.

**Sansò F., Sideris M.G (eds.).** Geoid Determination: theory and methods, Lecture Notes in Earth System Sciences, Springer, ISBN 978-3-540-74699-7.

**Sellers W.D. 1969.** A global climatic model based on the energy balance of the earth-atmosphere system, *Journal of Applied Meteorology* 8: 392-400.

**Sesana E., Gagnon A.S., Ciantelli C., Cassar J., Hughes J. J. 2021.** Climate change impacts on cultural heritage: A literature review, *Wiley Interdisciplinary Reviews: Climate Change* 12 (4): e710.

**Sharp P., Hockfield S. 2017.** Convergence: The future of health, *Science* 355: 589.1-589, https://doi.org/10.1126/science.aam8563.

**Soto-Navarro J., Jorda G., Amores A., Cabos W., Somot S., Sevault F., Maclas D., Djurdjevic V., Sannino G., Li L., Sein D. 2020.** Evolution of Mediterranean Sea water properties under climate change scenarios in the Med-CORDEX Ensemble. https://doi.org/10.1007/s00382-019-05105-4.

**Stocker T.F. et. al. (eds.) 2014.** Climate Change 2013 – The Physical Science Basis, Cambridge University Press, Cambridge.

**Stocker T.F. 2013.** The Closing Door of Climate Targets, *Science* 339, 280-282, https://doi.org/10.1126/science.1232468.

**Sutton, R.T., Dong B. 2012.** Atlantic Ocean influence on a shift in European climate in the 1990s, *Nat Geosci* 5: 788-792. DOI: 10.1038/ngeo1595.

**Thornthwaite C.W. 1948.** An approach toward a rational classification of climate, *Geographical Review* 38 (1): 55-94.

**Tramblay Y., Somot S. 2018.** Future evolution of extreme precipitation in the Mediterranean, *Climatic Change* 151: 289-302.

**Tramblay Y., Koutroulis A., Samaniego L., Vicente-Serrano S.M., Volaire F., Boone A., Le Page M., Llasat M.C., Albergel C., Burak S., Cailleret M., Kalin K.C., Davi H., Dupuy J.-L., Greve P., Grillakis M., Hanich L., Jarlan L., Martin-StPaul N., Martínez-Vilalta J., Mouillot F., Pulido-Velazquez D., Quintana-Seguí P., Renard D., Turco M., Türkeş M., TrigoR., Vidal J-P., Vilagrosa A., Zribi M., Polcher J. 2020.** Challenges for drought assessment in the Mediterranean region under future climate scenarios, *Earth Sci. Rev.* 210: 103348. DOI:10.1016/j.earscirev.2020.103348.

**Tyndall J. 1859.** Note on the transmission of heat through gaseous bodies, Proceedings of the Royal Society of London 10/37: 155-158.

**Vecchio A., Anzidei M., Serpelloni E., Florindo F. 2019.** Natural Variability and Vertical Land Motion Contributions in the Mediterranean Sea-Level Records over the Last Two Centuries and Projections for 2100, *Water* 11: 1480. https://doi.org/10.3390/w11071480.

**Vilibić I., Šepić J., Pasarić M., Orlić M. 2017.** The Adriatic Sea: a long-standing laboratory for sea level studies, *Pure and Applied Geophysics* 174: 3765-3811.

**Wang Y.M., Sánchez L., Ågren J., Huang J., Forsberg R., Abd-Elmotaal H.A., Ahlgren K., Barzaghi R., Bašic T., Carrion D., Claessens S., Erol B., Erol S., Filmer M., Grigoriadis V.N., Isik M.S., Jiang T., Koç Ö., Krcmaric J., Li X., Liu Q., Matsuo K., Natsiopoulos D.A., Novák P., Pail R., Pitonák M., Schmidt M., Varga M., Vergos G.S., Véronneau M., Willberg M., Zingerle P. 2021.** Colorado geoid computation experiment – Overview and Summary, *Journal of Geodesy* 95: 127. https://doi.org/10.1007/s00190-021-01567-9.

**Zampieri M., D'andrea F., Vautard R., Ciais P., de Noblet-Ducoudré N., Yiou P. 2009.** Hot European summers and the role of soil moisture in the propagation of Mediterranean drought, *J. Clim.* 22: 4747-4758. DOI: 10.1175/2009JCLI2568.1.

**Zanchettin D., Rubinetti S., Rubino A. 2022.** Is the Atlantic a source for decadal predictability of sea-level rise in Venice?, *Earth and Space Science* 9: e2022EA002494.

**Zappa G., Hawcroft M.K., Shaffrey L., Black E., Brayshaw D.J. 2015.** Extratropical cyclones and the projected decline of winter Mediterranean precipitation in the CMIP5 models, *Clim. Dyn.* 45: 1727-1738. DOI: 10.1007/s00382-014-2426-8.

# LIST OF AUTHORS


| | |
|---|---|
| **Marco ANZIDEI** | *Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy* |
| **Riccardo BARZAGHI** | *DICA-Politecnico di Milano, Italy* |
| **Jérôme BENVENISTE** | *European Space Agency, ESA-ESRIN, Frascati, Italy* |
| **Bruno CARLI** | *Accademia Nazionale dei Lincei, Rome, Italy* |
| **Anny CAZENAVE** | *Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, Toulouse, France* |
| **Erica COPPOLA** | *The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy* |
| **Sofia DARMARAKI** | *University of Athens, Greece* |
| **Silvio DAVOLIO** | *Institute of Atmospheric Sciences and Climate (CNR-ISAC), Bologna, Italy* |
| **Fausto GUZZETTI** | *Consiglio Nazionale delle Ricerche, Italy* |
| **Francisco GARCIA NOVO** | *Spanish Royal Academy of Science, Madrid, Spain* |
| **Klaus HASSELMANN** | *Nobel Laureate for Physics 2021* |
| **Goneri LECOZANNET** | *Bureau de Recherches Géologiques et Minières, Orléans, France* |
| **Piero LIONELLO** | *University of Salento, Lecce, Italy* |
| **Paola MALANOTTE-RIZZOLI** | *Massachusetts Institute of Technology, USA* |
| **Marco MARANI** | *Università di Padova, Italy and Duke University, Durham, USA* |
| **Michael NORTON** | *EASAC Environment Program Director* |
| **Mirko ORLIĆ** | *Croatian Academy of Sciences and Arts, Zagreb, Croazia* |
| **Stefan RAHMSTORF** | *Potsdam Institute for Climate Impact Research, Germany* |
| **Marie-Hélène RIO** | *European Space Agency, ESA-ESRIN, Frascati, Italy* |
| **Fernando SANSÒ** | *Accademia Nazionale dei Lincei, Rome, Italy* |
| **Pier VELLINGA** | *Vrije Universiteit Amsterdam, Netherlands* |
| **Christos ZEREFOS** | *Academy of Athens, Greece* |