Science for Public Policy

Risks and Hazards of Extreme Marine Events

Coordinated by:
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One of CSIC's functions is to inform, assist and advise public and private entities on science and technology, according to article 5 of its Articles of Association. As part of this function, the report *Risks and Hazards of Extreme Marine Events,* from the Science for Public Policy collection, is presented as a document aimed at public administrations and society in general. It explains the concept and characterisation of extreme marine events as exceptional fluctuations of natural phenomena of the climate system. The combination of anthropogenic factors and climate change projections predict an alarming increase in the impact of these events on marine ecosystems and coastal areas in the future. Three types of marine events are reviewed with the CSIC's active involvement, in collaboration with other national and international entities: marine heatwaves, coastal phenomena and harmful algal blooms. In all these cases, the lines of research primarily aim to understand the mechanisms that generate extreme marine events and to establish early warning systems and predictive models to advise public administrations on marine environment-related risk management.

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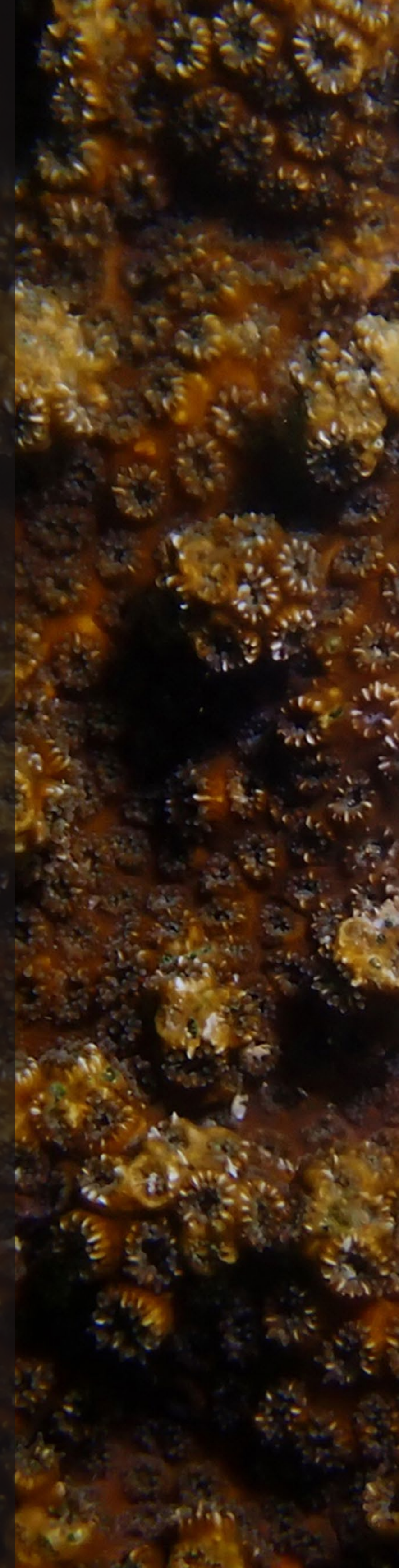


one

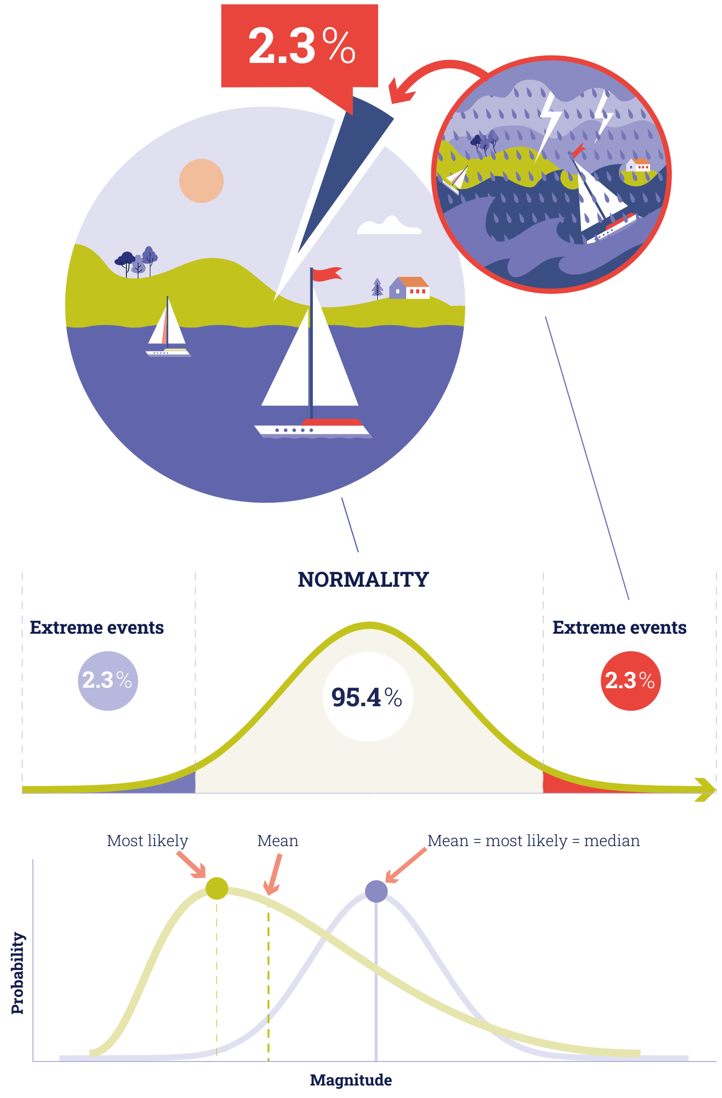
Introduction: Some Key Definitions and Concepts

1.1. Extreme events

Extreme events are often referred to as unusual or anomalous, semantically similar terms, chosen according to their negative implications. Basically, extreme events are those occurrences that deviate from the norm internalised by societies. However, from a scientific point of view, it is necessary to quantify and to refine the definition and, more specifically, to objectively separate an anomalous event from a non-anomalous event. This is not an easy or straightforward task and depends on the system under study. The most common criterion for defining an extreme event is the statistical approach, according to which it is an event "with a very low probability of occurrence". This definition includes two concepts: firstly, the characteristics of a normal state and, secondly, the degree of deviation from this normality.

To develop a quantitative statistical approach, we identify the statistical properties of the process and choose its characterising parameters. To illustrate this, let us suppose that we have established that the temperature in a given month follows a Gaussian statistical distribution with a mean value of 15.5 °C. In that case, the mean value and the most likely value of the temperature coincide and the standard deviation gives us an idea of how far the temperature value deviates from the mean temperature (let us assume it is 0.8 °C). This distribution indicates that 95 out of 100 times the temperature will be between 14.7 °C and 16.3 °C. This is what we would define as *normal*, while extreme events would be characterised by values above or below this range and are at the extremes or tails of the distribution. However, if the process were governed by another statistical distribution, we would have two effects. On the one hand, the mean value could differ from the most likely value, and on the other hand, the region of extreme values would be different, conditioning the probabilities of occurrence.

Figure 1



Top: definition of the normal state, extreme events and their probabilities of occurrence according to the probability distribution function of the data. Below: the parameters (mean, median...) according to the type of probability distribution that characterises the underlying dynamic processes.

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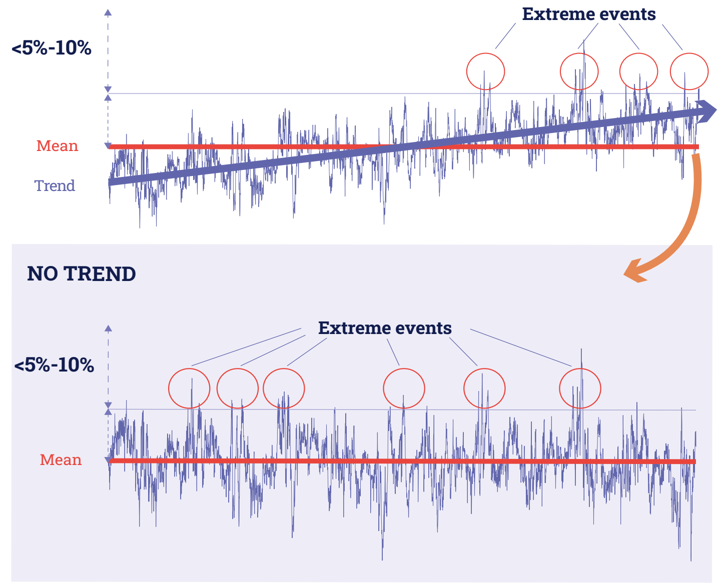
Another aspect to be taken into account in the statistical approach to extreme events has to do with the data source. In many cases, these sources are not, strictly speaking, the result of independent observations of a random process, but usually come from a series of time-sequenced observations that are usually correlated temporally and spatially at different scales. For example, when we roll a die several times in a row, the result of each roll does not depend on the order in which it was rolled. We say then that the events are independent and uncorrelated, i.e., the order in which they occur does not matter. In general, the time series of observations of the characteristic magnitudes of the atmosphere and the ocean are usually spatially and temporally correlated.

Finally, it is particularly relevant how to characterise the *normal* state used as basis to identify an event as extreme, especially when a time series of values is available. Thus, the World Meteorological Organisation defines climate as the reference state over a 30-year period. If the phenomenon we want to study oscillates during that period around a constant value (statistically stationary), then the reference state defined as *climatology* can be established by simply averaging over time. However, if the value of the magnitude we want to study oscillates while monotonically increasing (or decreasing) during the reference time period (such as global warming or sea level rise), simple time averaging does not allow us to characterise an unambiguous reference state. This can alter the way we detect and characterise events.

Figure 2



Identification of extreme events from time-series data (irregular curve). The thick blue line is the trend over time and the red line indicates the mean value over the period. The thin horizontal line indicates the level of variability, and extreme events are those data that appear above the level of variability. The long-term trend affects how marine events are detected.

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In summary, extreme events are those that are statistically characterised by a low or very low probability of occurrence and are located at the tails of the distributions that depend on the dynamic properties of the processes. The low probability of these events implies long recurrence intervals. A key element to understand the causes and consequences of these extreme events and to be able to predict them with increasing accuracy is the implementation of a multidisciplinary information system that allows us to know with sufficient spatial-temporal resolution the state of the system before, preferably during and after the impact produced by an event of these characteristics. In other words, we need a sustained monitoring system over time that allows us to construct historical series to be able to study and understand in detail the processes that produce these extreme events, and whether or not they are in fact extreme in comparison with the reference state, how often and with what intensity they occur, etc.

12.

Marine extreme events

ATMOSPHERIC and oceanic flows, the main components of the Earth's climate, are, together with continental plate movements, the processes whose extreme events have the greatest impact on human societies and ecosystems (the Indonesian tsunami in 2004 caused around 225 000 deaths in one day).

Those most familiar to us are probably hurricanes, torrential rains, volcanoes, tsunamis and, to a lesser extent, sea storms, which severely affect coastlines and compromise the safety of maritime navigation.

Marine events are of varied nature and causes and may have intertwined dynamics, forming what are known as compound *extreme events*. For example, extreme events related to abrupt variations in sea level, which seriously affect coastal areas and their infrastructure, may in turn be induced by different dynamic processes, such as extreme waves associated with unusual storms, or by tsunamis or meteotsunamis (tsunami-like ocean waves of atmospheric rather than seismic origin). Marine heatwaves are extreme sea temperature events that can cause severe mortality in many sea creatures, influence their migration patterns and, in turn, potentially feed back into the development of locally strong storms. In addition, they can also promote harmful algal blooms, ecological events with a major impact on commercial aquaculture farms or fisheries, which likewise constitute a risk to human and ecosystem health.

Some extreme events can be classified as natural, insofar as they may occur as a result of fluctuations in nature's own dynamics. In contrast to these are extreme events that are directly induced by human activity, such as an oil spill. Here we will focus on the former, natural extreme events, but bearing in mind that their potential impact is conditioned by climatic alterations, whether or not these are attributable to human action.

The effects of extreme marine events can be devastating from an ecological and socio-economic point of view. Global change is a key factor in understanding the impact of extreme marine events. Rising global temperatures lead to melting glaciers and thermal expansion of water, and contribute to an increase in average sea level. This, in turn, intensifies the vulnerability of coastal areas to both flooding and erosion. Both are linked to variations in weather patterns that determine storm regimes and average sea conditions (wave height, period and direction) affecting the coasts, as well as the climate extremes system. Available monitoring shows that sea level and temperature have been rising very rapidly since pre-industrial times in response to increasing concentrations of greenhouse gases in the atmosphere. This global change has repercussions on the dynamics of water masses and, through complex physical, chemical and biological interactions, contributes to extreme events in marine ecosystems, such as those discussed in this paper. Observations and future projections so far foresee an increase in frequency and intensity as a result of this climate scenario over the coming decades. Hence, there is growing interest and concern in understanding the causes and mechanisms that produce them, in order to be able to predict them and increase adaptability and resilience in the face of these events.

13.

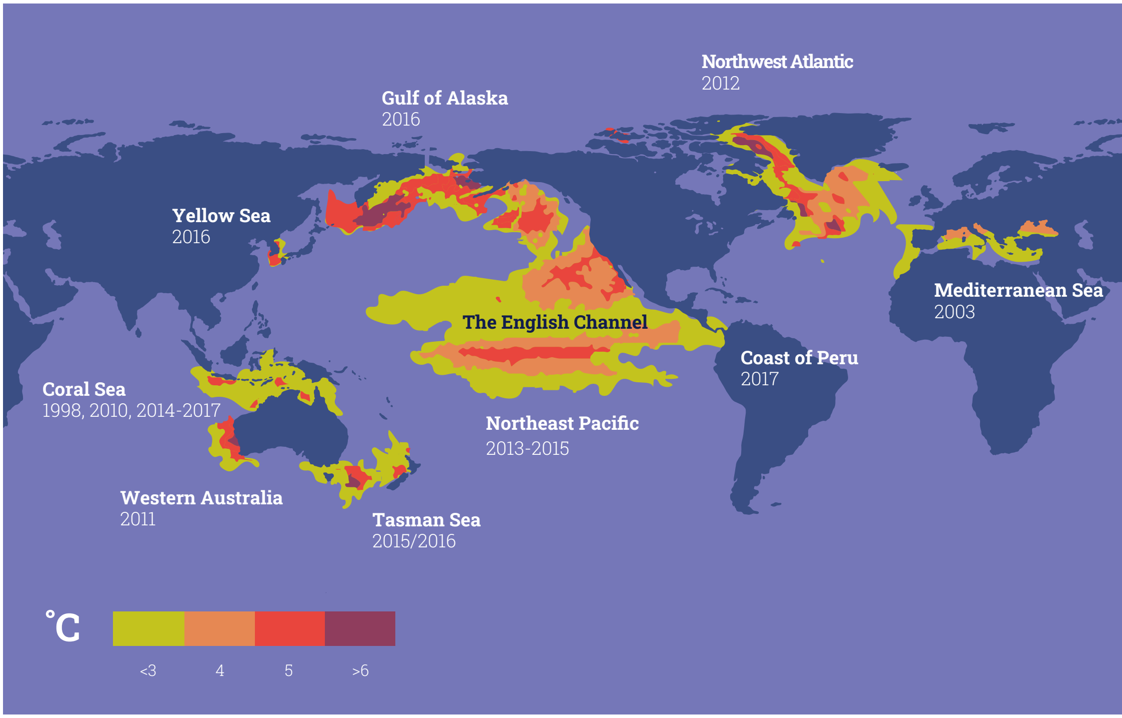
Marine heatwaves

Marine heatwaves are anomalous fluctuations in sea temperature. The term arises by analogy with atmospheric heatwaves and denotes similar fluctuations in air temperature. These events are not new. Temperature increases during El Niño can be characterised as marine heatwaves.

However, the concept of a marine heatwave was first coined in 2011, in a report by the Fisheries Service of the Western Australian Government Department of Environment and Conservation. It reported a severe mortality event on Australia's Great Barrier Reef in the summer of 2010. Observations showed mass coral bleaching associated with an unusual warm water invasion off the north-west Australian coast. Similar extreme variations in seawater temperature have been recorded in other parts of the world since this incident, with varying consequences for the ecosystem. Although they may occur in distant places simultaneously in certain years, they are not necessarily causally connected, and different mechanisms may be at work in different regions.

In recent years, these events have attracted scientific attention and have been considered one of the most serious threats to the future of marine ecosystems, aggravated by global warming. If warming continues at current levels, marine heatwaves would have a greater potential impact, according to analyses based on projections from the latest report of the Intergovernmental Panel on Climate Change (IPCC). The concurrence of several factors, such as atmosphere-ocean heat exchange processes and alterations in current patterns in response to wind changes, make their study and analysis very complex. We are now beginning to have some sufficiently extensive observational series, and sufficiently powerful computational capabilities, to begin to address the coupled atmosphere-ocean system on the typical oceanic scales needed to study the mechanisms involved in marine heatwaves.

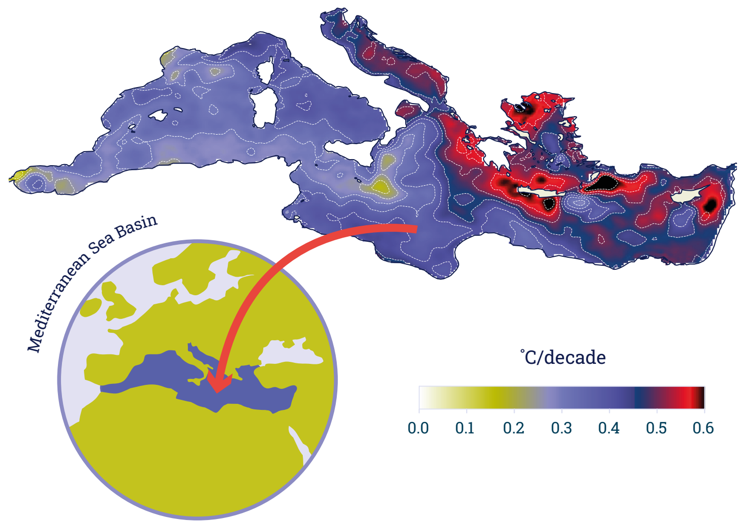
Figure 3 Exceptional heatwaves over the past two decades around the globe



Source: Frölicher & Lautfkotter, 2018.

The Mediterranean basin is particularly sensitive to global warming, as indicated by the rapid rate of warming over the last three decades. Over the last 40 years, the surface temperature of the Mediterranean has increased at a rate of between 0.2 °C and 0.6 °C every 10 years, with peaks of 0.68 °C in several areas of the eastern basin. This means that the same temperature anomaly could potentially have a greater impact in the coming decades.

Figure 4 Mediterranean Sea Basin surface warming in degrees per decade from satellite data from 1982-2022

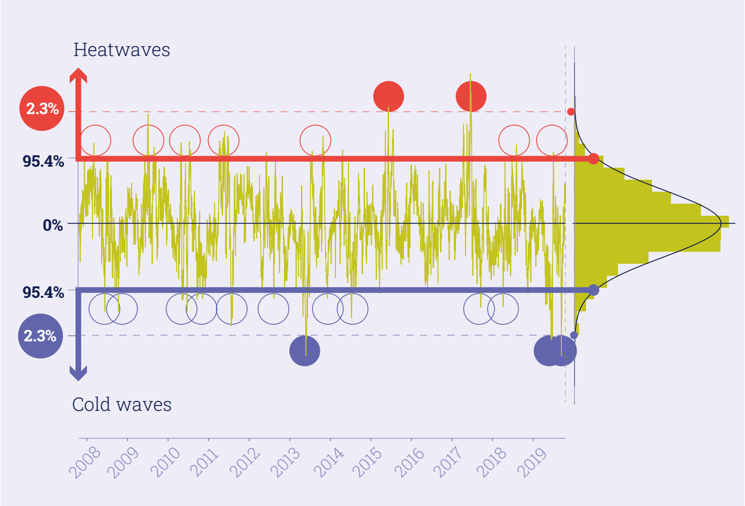


Source: Martinez *et al*., 2023.

The analysis and detection of marine heatwaves is conceptually very intuitive, but far from trivial for the following reasons:

- **Data availability.** The detection and characterisation of marine heatwaves (frequency, geographic extent, intensity, etc.) requires long and frequent time series of data that must adequately cover both the horizontal and the vertical dimension. This is extremely complicated and costly, even for a relatively small area such as the Mediterranean basin, where depths of hundreds of metres are quickly reached very close to the coast. The only observation system that can provide detailed information in time and space at present are satellites, but they only cover the surface of the planet, i.e., “the skin of the ocean”, and near the coast the data are often more uncertain due to interference with land (sediments, organic matter of terrestrial origin, etc.). To determine the vertical extent of marine heatwaves, data on the structure of the water column are also required, which, unfortunately, are very scarce.

Figure 5 Detection of marine heatwaves in the area of the Columbretes Islands from a time series of sea surface temperature (irregular curve)



Right, the probability distribution. The solid circles (in red and blue) indicate extremely hot and cold marine events that form the tail of the distribution.

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- **Mathematical definition.** For the sake of standardisation, different ways of detecting and characterising marine heatwaves have been proposed. The most common way to characterise a temperature fluctuation as a heatwave is if it meets a number of requirements:

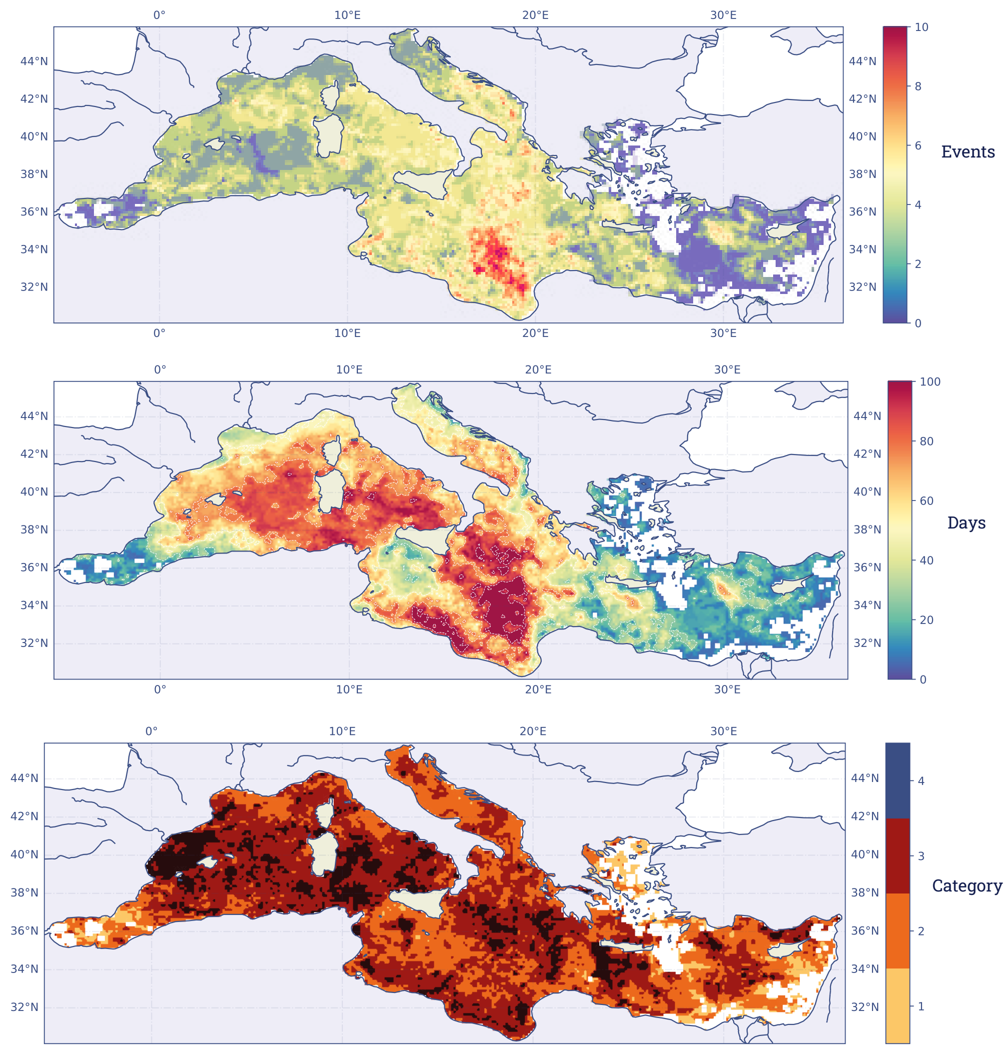
- **Persistence:** The fluctuation must persist for at least five days.

- **Intensity:** The temperature anomaly with respect to the climatological values at the same place and time in the seasonal cycle must be greater than 90%.

- **Discrete:** A marine heatwave is considered to be temporarily isolated if more than two days with temperatures below the 90th percentile have been recorded at the same location before and after the heatwave. Based on these criteria, the properties of marine heatwaves can be established and quantified.

Ultimately, the identification and characteristics of marine heatwaves are a combination of temporal and spatial properties of the observed temperature values. To analyse their impact, the most appropriate way to represent their properties is on the basis of geographical maps of each of these aspects.

Figure 6 Characteristics of the marine heatwave in the Mediterranean basin in the summer of 2003



The maps depict the total number of days with marine heatwave events (top), the distribution of the total number of events (centre) and the maximum attained category (bottom). The heatwave categorised as severe resulted in high species mortality in regions affected by more than 100 days of heatwave.

Source: Martínez *et al.*, 2023.

14.

Coastal phenomena

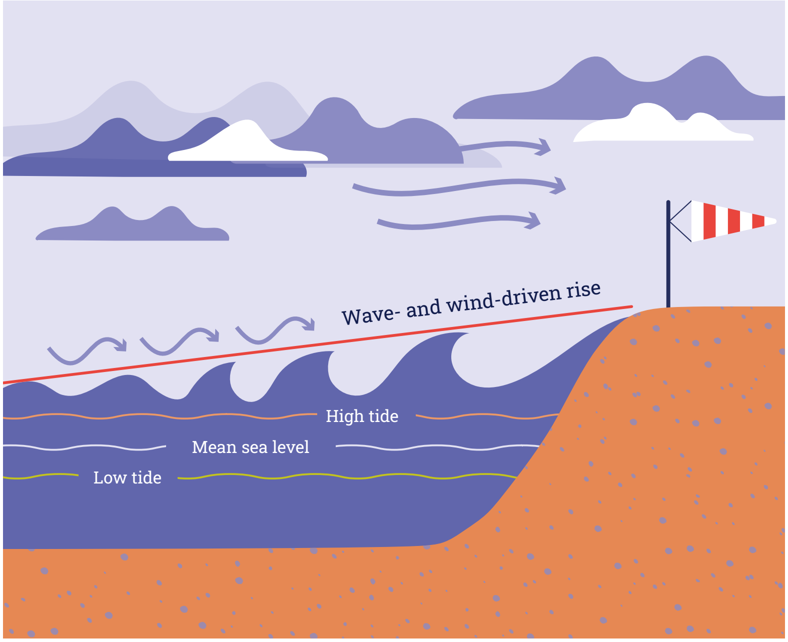
A coastal zone is defined as the geographical region where the transition between land and ocean, sea or any large body of water occurs. This area ranges from the emerged zone, eventually affected by marine processes, to the submerged area beneath the waves. Coastal areas highly complex, where human activities interact with a variety of ecosystems such as beaches, estuaries, mangroves, salt marshes, dunes, coral reefs and submerged grasslands. Coastal zones represent one of the most dynamic and vulnerable environments on the planet. They are home to unique biodiversity and are fundamental to the global economy because of their role in trade, tourism and fisheries. Currently, half of the world's population lives within 100 kilometres of the coast and much of the world's marine resources are essential for approximately 37% of humanity, meaning that pressures and impacts on coastal zones represent a very high risk for society. However, these areas are also highly exposed to extreme natural phenomena such as hurricanes, tsunamis, flooding and sea level rise, leading to inundation, erosion, loss of functionality and threats to valuable ecosystems such as beaches or underwater plant meadows.

Coastal flooding is a natural phenomenon that affects areas bordering oceans and seas. These floods can be caused by a variety of factors, such as storms, high tides, tsunamis and, in the longer term, sea level rise due to climate change. We can classify floods as permanent (associated with sea-level rise due to global change) or periodic (associated with extreme events). There is a consensus in the scientific community that coastal areas and communities will be increasingly threatened by sea level change, especially in those areas characterised by a flat, low sea level morphology of emerged coastline, such as deltas and estuaries.

Changes in storm frequency, alterations in wind and current patterns and various human activities are accelerating sediment loss and beach degradation. It should be noted that, according to the scenarios reported by the Intergovernmental Panel on Climate Change, inundation events with 100-year recurrences at present will tend to occur annually within a few decades, due to the progressive rise in sea level. Beach erosion in this context represents a significant challenge for coasts all over the world. The constant action of waves and storms erodes beaches and cliffs, displacing sediments and reducing the available land area. The loss of beaches negatively affects tourism and biodiversity, with impacts feeding back into coastal erosion and coastal retreat, along with flooding, saltwater intrusion into aquifers and surface waters, and a decline in coastal wetlands.

The impact of extreme events depends on the intensity and characteristics of the waves, the sea level during the storm and coast morphology. Sediment management and the morphology of coastal littoral systems, such as deltas and beaches, are crucial factors in understanding and mitigating flood impacts. The relationship between these elements can be approached from various angles, such as sediment dynamics, the formation of coastal structures and how these influence the frequency and severity of flooding. Tackling this problem requires a holistic approach that combines the construction of coastal barriers, restoration of natural ecosystems, sand replenishment, appropriate urban planning and community education. Effective sediment management (including inland water management, whose use and retention in reservoirs leads to reduced inputs to the coast) as essential elements of coastal management and an understanding of coastal morphology are essential to reduce flood risks. Implementing nature- and science-based strategies can help mitigate these risks and promote coastal resilience.

Figure 7 Components contributing to sea level variations during a coastal storm



Source: adapted from Melet *et al.*, 2018.

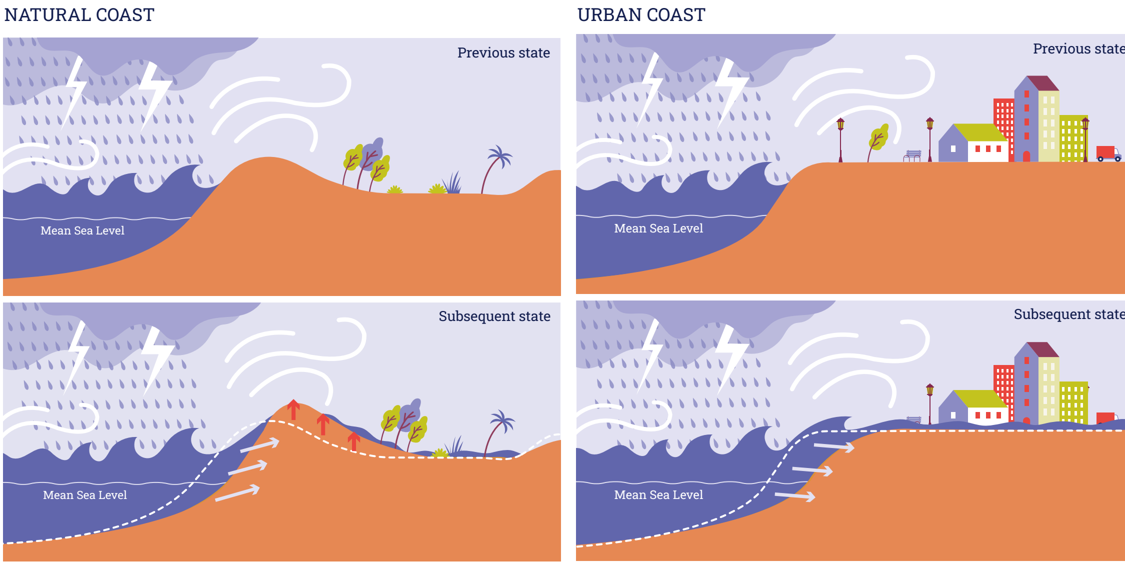
Changes in sea level in a given coastal area are the result of the overlap of average sea level changes and localized sea level changes produced by the combination of wind, meteorological and astronomical tides and waves. The flood level is determined by the interaction between coastal morphology and the sum of different contributions to mean sea level. These are the tide level, composed of the astronomical tide and the meteorological tide, and the effects of the waves, which propagate towards the coast, finally breaking and causing the water mass to rise.

Some of the factors involved in coastal flooding are random variables and therefore their occurrence is subject to a certain probability, with 1% or 2% percentiles of occurrence being commonly used. Obviously, sea level rise is exacerbating many of the coastal flood risks. In this sense, permanent inundation is the result of flooding at all elevations below mean sea level. The variation in sea level rise is one of the aspects systematically analysed in the IPCC's future projections of human activity and greenhouse gas emissions (Representative Concentration Pathways, RCPs).

Figure 8 Examples of the effects of erosion and flooding during storm events

Left: urbanised coastline. Right: natural coastline / J. GUILLÉN.

Figure 9 Impact of storms on natural (left) and urban (right) coasts



Natural coasts have a greater capacity for adaptation and resilience than urban areas, where part of the beach has rigid structures and has no capacity for adaptation.

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Coastal behaviour in the face of these extreme events depends on its adaptive capacity and resilience, which may differ significantly depending on whether it is natural or urban. Extreme marine events that can potentially affect coastal areas particularly include the following:

1. Hurricanes, tropical storms and extra-tropical cyclones are meteorological phenomena that significantly affect coastal areas and other regions of the world. Each of these phenomena has specific characteristics in terms of their formation, structure and effects. Hurricanes are low- pressure systems that form over warm tropical and subtropical waters.

2. A hurricane occurs when sustained winds reach or exceed 119 kilometres per hour. Hurricane formation requires a high ocean temperature (at least 26.5 °C), high humidity in the mid-troposphere and favourable winds for storm organisation. Hurricanes cause tidal surges, i.e., a rise in sea level, torrential rainfall and coastal flooding with a combination of winds and associated swell that can damage infrastructure, erode beaches and displace entire populations. Tropical storms are low atmospheric pressure systems with sustained winds between 63 and 118 kilometres per hour and form under hurricane-like conditions. Extra-tropical cyclones form outside tropical regions, typically in mid-latitudes, and develop along fronts, where warm and cold air masses collide. In Europe, one of the largest storm disasters of the 20th century occurred in the North Sea in the winter of 1953, when large waves accompanied by high sea levels flooded large parts of the Netherlands, Belgium and the United Kingdom, killing more than 2,500 people.

3. Tsunamis, usually generated by submarine earthquakes, can rapidly inundate coastal areas and destroy structures, taking human lives. Tsunamis are extremely destructive when they reach coastal areas without early prediction. On 1 November 1755, a devastating earthquake followed by a tsunami hit the city of Lisbon in Portugal and had catastrophic effects in several regions of the Atlantic, including the southwest coast of Spain. Cadiz was one of the Spanish cities most affected by this event, known as the *Great Lisbon Earthquake*. The first wave of the tsunami reached Cadiz at around 10 a.m. and was followed by several additional waves that exceeded ten metres in height, flooded much of the city and the port, destroyed buildings and washed away coastal infrastructure. It is estimated that hundreds of peopledied as a result of the tsunami and subsequent flooding. A particular case refers to meteotsunamis, also known as *meteorological tsunamis*, which are long waves generated by atmospheric

disturbances that are amplified at the surface by certain atmospheric conditions, a phenomenon called *Proudman resonance*. Waves from meteotsunamis can travel at speeds comparable to those of seismic tsunamis, but generally have lower heights, however, in confined areas, such as bays and estuaries, waves can be amplified if the harbour geometry is suitable and reach dangerous levels. Although they can occur in any body of water, meteotsunamis are more common in enclosed and semi-enclosed seas, such as the Mediterranean, Adriatic and Black Seas. A meteotsunami in the port of Ciutadella on the island of Menorca in the western Mediterranean generated waves up to four metres high on 15 June 2006, damaging ships and port infrastructure. The event was caused by a rapid atmospheric disturbance that generated pressure waves, which were amplified when they reached the bay.

Figure 10 Sequence of a meteotsunami (A to D), locally called *rissaga*, which occurred on 15 June 2006 in the port of Ciutadella (Menorca).

Source: Montserrat *et al.* 2006.

15.

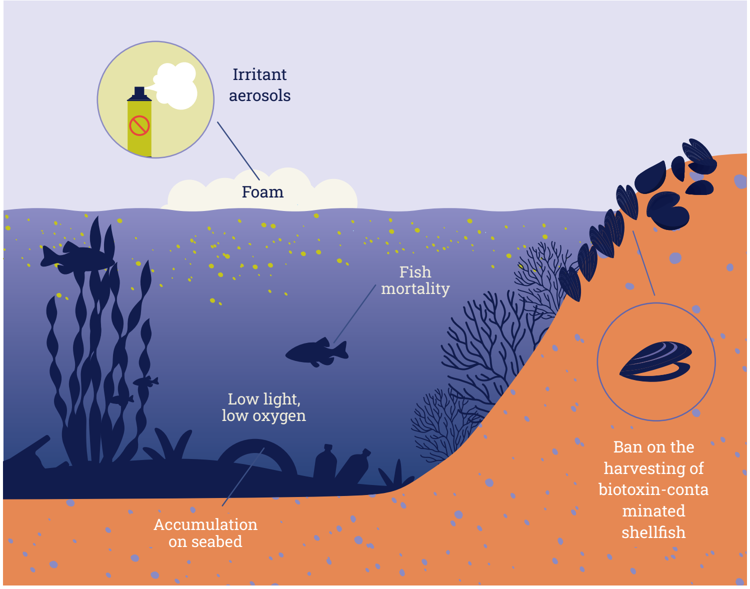
Harmful algal blooms

HARMFUL algal blooms are defined as those events in which are defined as events in which the concentrations of certain harmful or toxic aquatic photosynthetic organisms (unicellular microalgae, macroalgae, cyanobacteria and certain ciliates) increase above the range considered normal for each species. Their presence can have negative effects on ecosystems, on human health and well-being and on the economy of the affected areas.

Among the several thousand microalgae species described, about 300 are involved in harmful algal blooms, but only about 100 produce toxins or are involved in different harmful events. Harmful algal blooms associated with toxin-producing species are dangerous to human health above a certain threshold, as they are transmitted through food webs and contaminate food (such as fish and shellfish), and can cause food poisoning (amnesic, diarrhoeal, paralytic or ciguatera poisoning) if ingested. Other toxins contaminate drinking water (microcystins), are transferred in aerosols (ovatoxins and brevetoxins) and cause respiratory irritation, or effects on the skin by direct contact with water (in this case the toxic agent is not well determined). In addition to affecting humans, these toxins can cause the death of fish and other organisms. Some algal blooms are also non-toxic in nature, and their harmfulness is due to a significant accumulation of biomass. Often, this excess algal biomass cannot be efficiently consumed by the relevant components of food webs (microzooplankton, fish larvae, small crustaceans, etc.) and its degradation by bacteria reduces oxygen levels in the water (essential for marine organisms to breathe) and leads to a deterioration of the overall quality of the ecosystem.

Harmful algal blooms are natural phenomena that are also promoted by anthropogenic pressures, such as eutrophication, habitat modification and destruction, and the introduction of exogenous organisms into an ecosystem. Theseevents generally occur in summer under certain conditions favoured by a combination

Figure 11 Diagram of the impacts of different harmful algal blooms



Algal blooms are sometimes harmful due to the high concentration of biomass which, as it degrades, consumes oxygen in the water column, thus deteriorating the state of the ecosystem. Toxin-producing microalgae can cause mass mortality in fish farms or wild populations and can produce toxic substances that vaporise, causing respiratory irritation in humans. Toxins are transmitted through food webs to humans (detail on the right).

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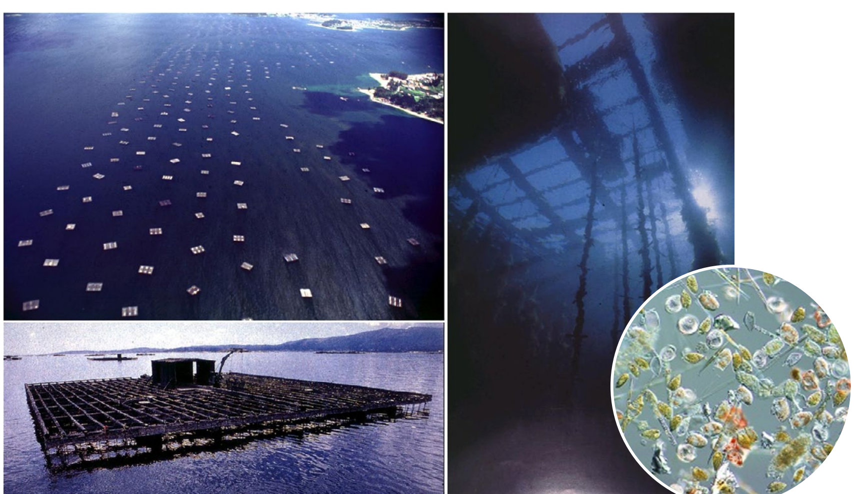
of high nutrient availability — of natural or anthropogenic origin — and low hydrodynamics (relatively calm or low-inflow water). Species that give rise to these proliferations often accumulate resistance cysts that constitute a reservoir of cells that can potentially germinate and proliferate under the right conditions. In these situations, a few species reach concentrations in the water above a level considered normal for each specific organism.

Algal blooms can cause the water to change colour, turning the colour of the pigment of the blooming organism (green, blue, yellow, brown or red), but this does not necessarily mean that it is harmful. In fact, only in a few cases does water colouring imply harmfulness. Blue-green cyanobacteria are often abundant in brackish or fresh waters. The term *red tides* has traditionally been used to refer to blooms of the dinoflagellate group.

Globally, some extreme harmful algal bloom events have been described, usually as part of compound events and associated with anomalous environmental conditions. This is the case of the *Pseudo-nitzschia* bloom with high concentrations of domoic acid toxin that occurred in late spring 2015 along the west coast of North America as a consequence of the marine heatwave known as *The Blob*. This extreme event disrupted important fisheries in the area, with the resulting economic losses, as well as the death of marine mammals and birds.

In Spain, especially in Galicia, episodes of harmful algal blooms disrupting extractive activities are not uncommon and usually occur every year, mostly caused by species of the genus *Dinophysis*. In recent years, there have been exceptionally intense harmful algal blooms caused by toxic species, such as *Alexandrium minutum* in 2018 and 2023 in the Vigo and Pontevedra estuaries. The last harmful algal bloom event of this toxic species was in the Ares estuary in 1984, but in 2018 it spread from its usual place (inside bays, ports, etc.) to all the Vigo and Pontevedra estuaries. The conditions related to this toxic event were characterised by a high stratification caused by a positive anomaly in rainfall and river discharge, high temperatures and alternating retention and dispersion processes caused by wind patterns. In 2023 a massive reproduction of this species was recorded again under similar conditions, but this time in the interior of the Pontevedra estuary.

Blooms of Ostreopsis cf. ovata, on the Mediterranean coast. This microalgae (detail of microscopic cell) produces toxic aerosols associated with mild respiratory irritation in exposed individuals. / E. BERDALET (PAISAJE) AND R. DURO (MICROSCÓPIO), @SCIENCEINTOIMAGES.



Mussel rafts in the Rias Baixas, Galicia and phytoplankton sample obtained in the Vigo estuary. Molluscs bioaccumulate toxins produced by various phytoplankton species. Although in many cases the proliferation does not lead to changes in the colour of the water, the high toxicity of the cells determines the disruption of product extraction, preventing its commercialisation (sometimes for long periods).
/ INTECMAR, YOLANDA PAZOS (BATEAS) Y IEO, S. GONZÁLEZ-GIL (MICROSCOPIO).

Harmful algal blooms entail economic costs, such as medical care for affected people and investment in the monitoring and control of toxic microalgae and their toxins to prevent health impacts. Some microalgae (*Chattonella antiqua, Fibrocapsa japonica, Chryso-chromulina* spp., *Cochlodinium* spp. *and Karlodinium* spp.) specifically kill fish in natural habitats or in aquaculture areas. In shellfish production areas, the prohibition of harvesting and sale of shellfish due to the presence of potentially toxic algae (e.g., *Dinophysis acuta* and *acuminata*, *Alexandrium minutum and Gymnodinium catenatum*) leads to large economic losses. Tourism is also affected, mainly due to the decomposition of dead algae which reduces the quality of the beach water and causes health problems. In this respect, the massive accumulation of Sargassum macroalgae on the beaches of the Caribbean and West African coast has been an emerging case of harmful algal blooms for the last ten years.

Harmful algal blooms are a complex global problem that appears to be increasing in severity and frequency and, in the case of certain species, their biogeographical range is increasing, partly due to global climate change. As a result, this issue has gained prominence worldwide over the last forty years. Anthropogenic pressures on coasts and oceans (habitat destruction and loss of biodiversity, eutrophication and urbanisation), and global warming are believed to be favouring an increase in harmful algal blooms in certain areas. The protection and sustainable use of the environment is essential to reduce this trend and ensure a healthy and resilient ocean.

two

CSIC's Contribution to the Understanding and Prediction of Extreme Marine Events

2.1.

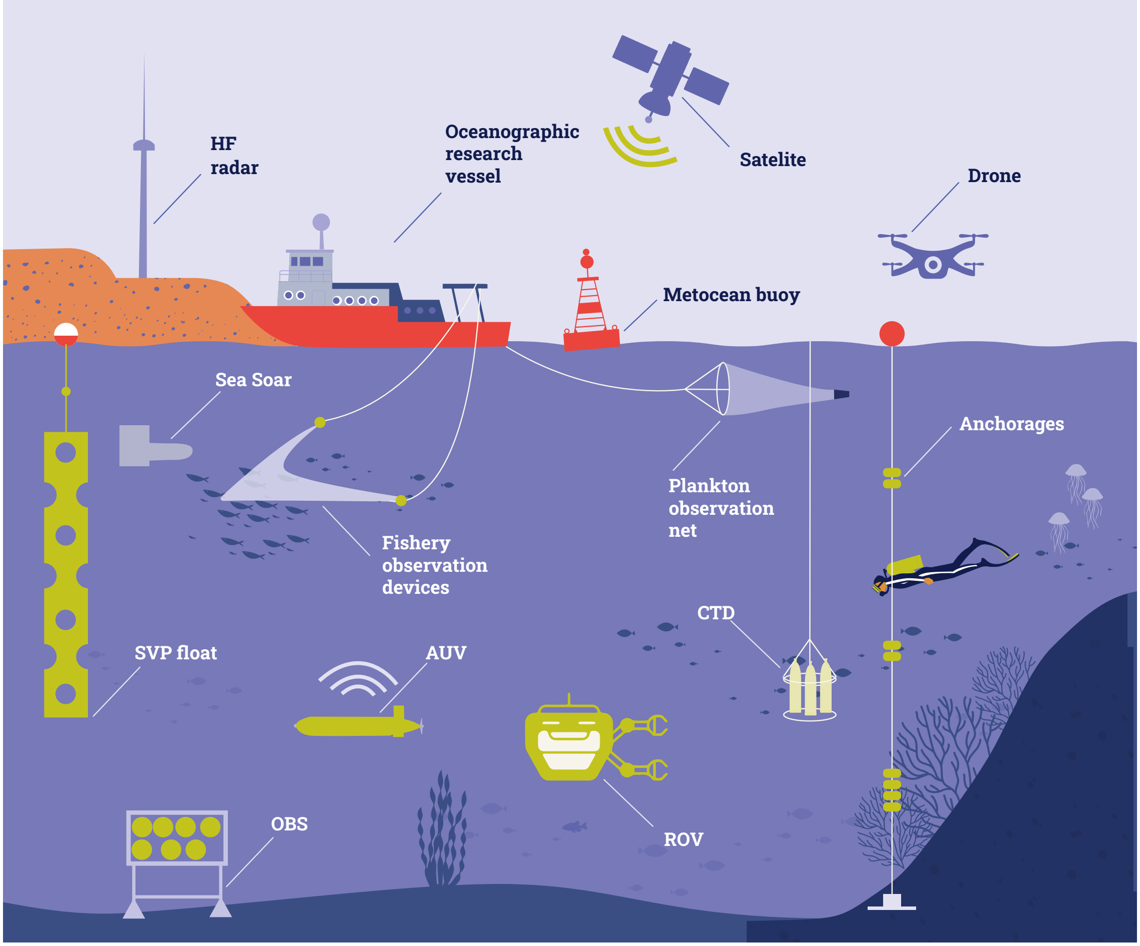
Observation systems and main results

EXTREME marine events are almost always associated with a negative impact, not only in socio-economic terms, but also in terms of human lives. Any progress that we can make in understanding and predicting these events will facilitate the way in which society must address the planning and management of maritime activities in an environmentally-friendly manner. At the same time, it will help to mitigate or minimise the associated potential risks for the benefit of mankind (blue economy). While the need for this anticipation is more than evident for extreme events in coastal phenomena or harmful algal blooms, in other cases, such as marine heat waves, society may not perceive the urgency, as the impact, sometimes irreversible, is mostly on marine ecosystems.

Extreme marine events are often a combination of multiple processes and factors. Given their complexity, understanding and describing all the causes involved and how they interrelate requires the combined use of observation systems and simulations of the underlying processes. In oceanographic research, as in meteorological or climate research, observations are essential. In these systems, it is very unlikely that two extreme events spaced apart in time will be identical, and this is why observation systems are particularly relevant. A suitable observation system for extreme marine events must pay attention to several aspects. Firstly, it must be sustained over time, i.e., due to the low probability of such events, the time series must be long enough (approximately thirty to forty years) to characterise them statistically. In addition, having information before, during and after the extreme event will allow not only to determine its characteristics and help to predict it, but also to know its consequences on the system. Secondly, it must have sufficient spatial resolution to capture phenomena that occur at different scales. And lastly, it must be multidisciplinary, i.e., it must collect information on the different essential variables in such a way that it can be integrated to carry out an effective prediction of the impacts. For example, in order to study the consequences of marine heat waves on fishery resources, we must have information on climate and meteorology (winds, relative humidity, air temperature, pressure, etc.), oceanography (sea surface temperature, salinity, stratification, nutrients, dissolved oxygen, chlorophyll, etc.), the ecology of fishery resources (plankton, invertebrates, fish, etc.), as well as the interaction between all these elements.

At present, some observing systems only partially meet these requirements, i.e., they only provide data on a few magnitudes and in many cases only account for a part of the ocean system, such as a specific station, a vertical section or the sea surface. However, for a complete reconstruction of the state of the ocean, simulation models are used to interpolate and reconstruct the necessary variables. The combination and improvement of observational systems has allowed this reconstruction using models, technically known as *reanalysis*, to be increasingly adjusted to the real evolution. From here we can make predictions or study possible present or future scenarios, and have early warning systems that allow us to anticipate the occurrence of an extreme event with a certain degree of probability. This is the final step in order to be able to recommend and establish actions to help mitigate the impact of extreme events. Several CSIC groups have been, and still are, actively involved in these tasks from different approaches through national and international research programmes. Let us summarise this work for the extreme marine events discussed herein.

Figure 12 Diagram of a multi-parametric oceanographic observing system with the different types of instruments and sampling strategies



Source: adapted from https://www.soos.aq/about-us.

22.

Marine heatwaves

The Mediterranean basin is a hotspot for climate change impact in terms of global warming. This is why long observational series of temperature and other hydrological parameters (salinity, currents and oxygen) gain relevance over time in order to characterise marine heatwaves. The CSIC is currently involved in several initiatives for the on-site monitoring of temperature variation in the Mediterranean basin, some of which are part of international initiatives and others of a more domestic nature. Among the longest series, the L'Estartit (Costa Brava) series, maintained for about 45 years by Josep Pascual, a volunteer observer, with support from CSIC institutes, is worth mentioning. This is the longest uninterrupted oceanographic observation series in the Mediterranean, which includes several depth levels (from the surface to 80 metres deep) and has made it possible to establish climatic trends in the warming of coastal surface waters.

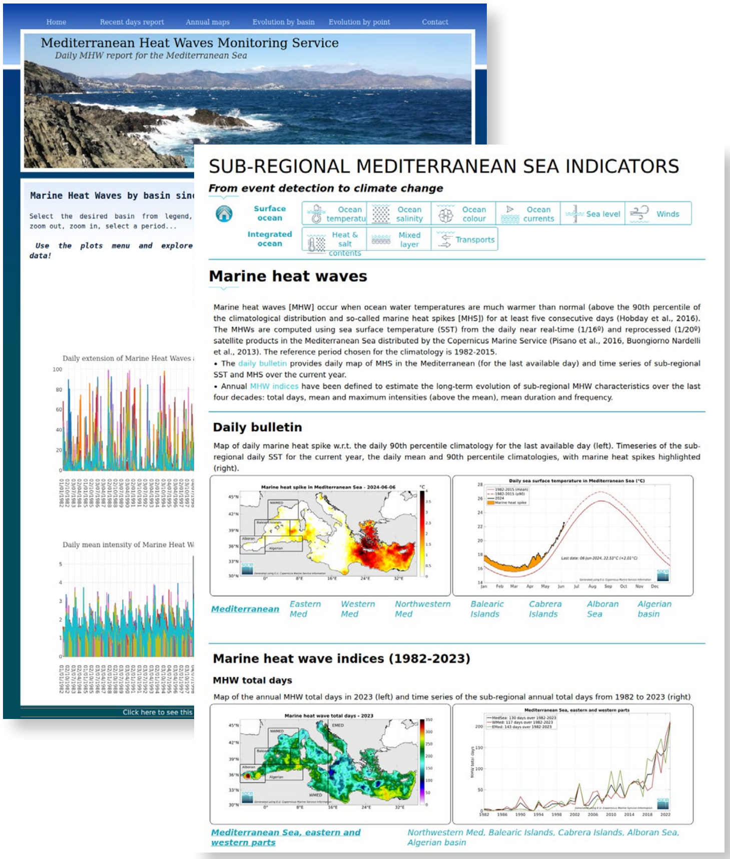
In the same line, the CSIC coordinates the TMEDNET network, an observational network of water temperature sensors in coastal areas from the surface down to 50 metres in marine protected areas in the Mediterranean basin. This network obtains high-resolution time series of temperature together with samplings of the evolution of marine communities, some with observation periods recorded since 1997. In addition, they have made it possible to identify the connection between episodes of mass mortality concurrent with marine heatwaves. Finally, the CSIC also coordinates and has contributed to several stations of the HYDROCHANGES network, which focuses on long-term changes in Mediterranean circulation and, since 2003, has maintained an anchorage at 1890 metres to record changes in the deep circulation.

These efforts are undoubtedly relevant for documenting singular extreme heatwave events. However, in order to establish their characteristics, longer series with more spatial-temporal resolution are needed, beyond those of the vast majority of these initiatives. Even the L'Estartit series, which in terms of length is

adequate, has a weekly resolution that is unable to resolve the evolution details of this type of exceptional phenomena. Persistent events of more than one month are detectable, but the systems cannot identify if it is a single event or a sequence of short events. In this scenario, an alternative is to use satellite information, which, as far as temperature observation is concerned, is one of the oldest systems in terms of temporal coverage from space. Forty years of data is already available enabling analysis of the evolution of large areas (e.g., the entire Mediterranean basin) with spatial resolutions of between 1.5 and 2 kilometres, and a daily temporal resolution.

Placement of temperature sensors attached to the substratum at regular 5-metre intervals between the surface and a depth of 50 metres, carried out in the framework of the TMEDNET network. / ALEXIS ROSENFIELD EN LA RÉSERVE NATURELLE DE SCANDOLA (CORSICA, FRANCE)

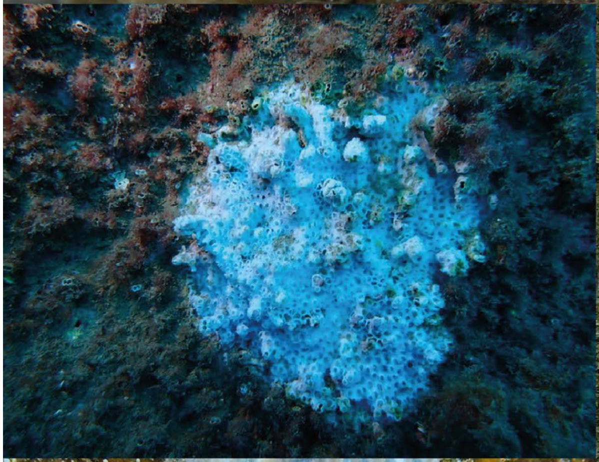
Several initiatives by CSIC groups are developing marine heatwave detection systems to obtain statistical properties based on satellite observations. These systems help to identify the evolution of temperature in near-real time on the scale of the Mediterranean basin and sub-basins, and make it possible to monitor the evolution of temperature anomalies.

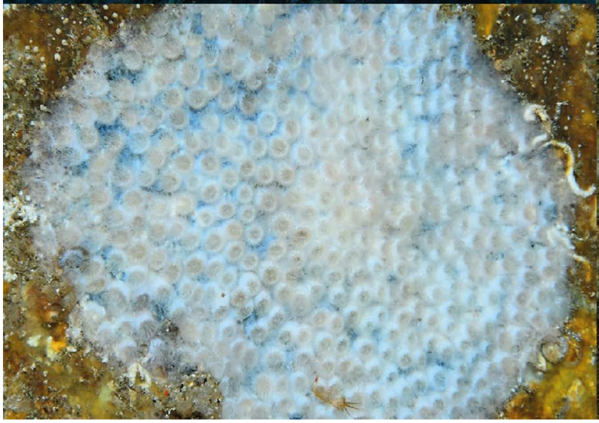


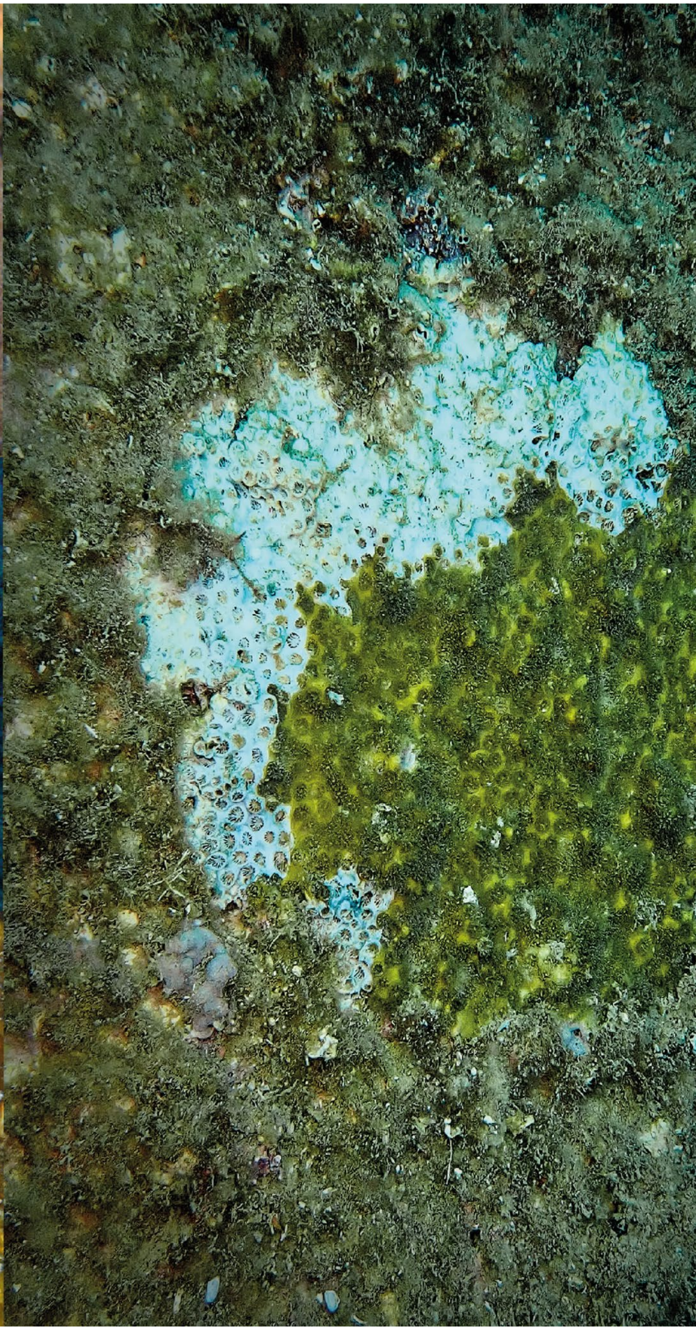
Marine heatwave monitoring systems deployed by the CSIC for the Mediterranean basin and sub-basins using satellite imagery.

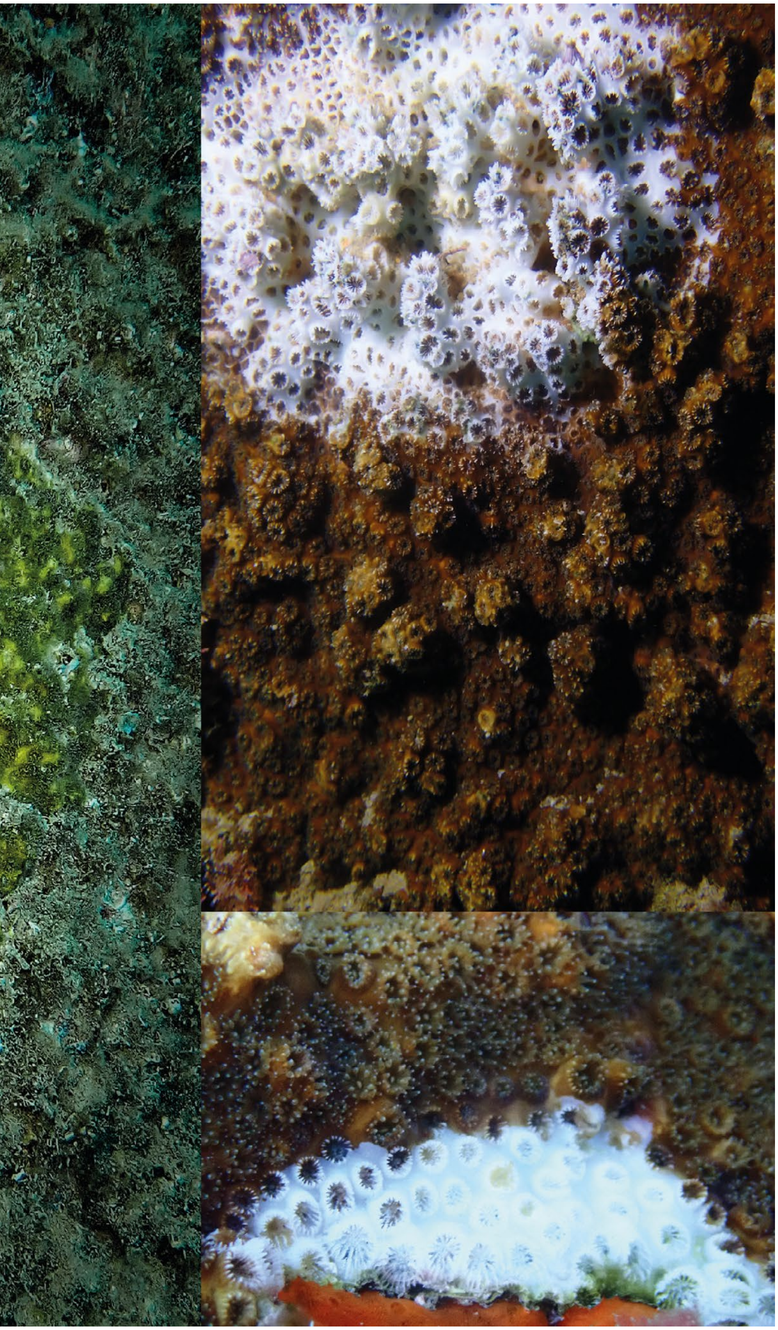
It is largely the existence of these series that makes it possible to delve deeper into the causes and characteristics of marine heatwaves. Recent work by several CSIC groups has yielded an analysis of marine heat waves on the ocean surface between 1982 and 2022. Some significant results have been obtained, firstly, on the impact of the methodology in terms of characterising marine heat waves in the Mediterranean basin. It should be noted that no statistically significant increase in the number or intensity of heatwaves over the past forty years could be established. In addition, a list of heatwaves has been compiled and a total of 20 severe and extreme events have been identified, and among the latter, specifically 5 (1989-1990, 1993-1994, 1999, 2001, 2007). This classification is based on a combination of heatwave properties (duration, area affected, intensity, etc.), but not in relation to their impact on the ecosystem, which may depend on additional environmental and biological factors, such as time of year, geographical location, heat stress and pathogen proliferation, among others. Thus, in terms of biological impact, some heatwaves — such as the 1999 extreme heatwave — were particularly damaging, affecting around 30 benthic species. Other heatwaves, such as those of 2003 and 2022, without reaching the maximum category, have had a notable and well-documented ecological impact.

Finally, given the limitations of systematic sampling in the marine environment, both in terms of costs and operations, the records generated by citizen science platforms in the marine environment are a complementary source of additional information for cataloguing marine biodiversity and estimating the impact of extreme events on marine ecosystems. The CSIC leads two citizen science platforms: Observadores del Mar, specialised in the marine environment, and MINKA, which is more general, as it includes the marine and terrestrial environment, and organises intensive observation campaigns (*biomarathons*) for intensive data collection.









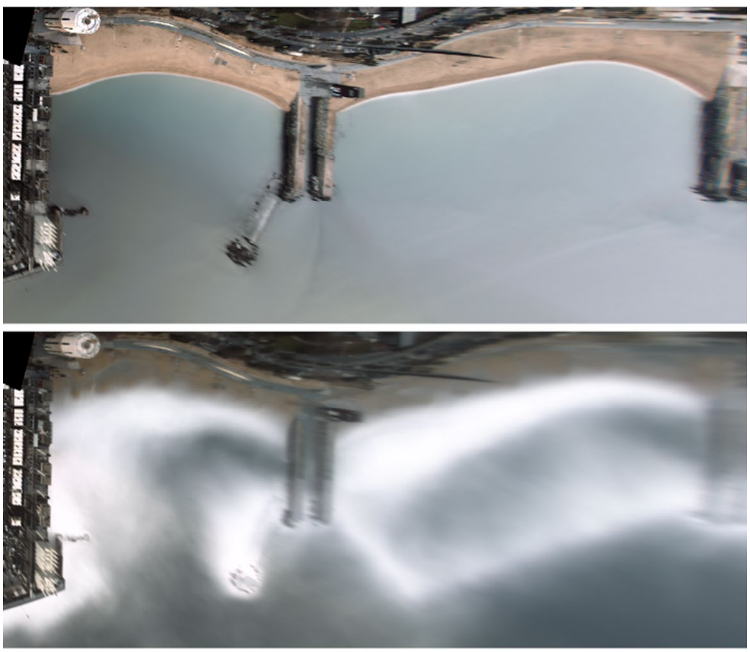
Observations of bleaching in *Oculina patagonica* by citizen volunteers and obtained along different points of the Catalan coastline. / PHOTOS (FROM TOP TO BOTTOM AND FROM LEFT TO RIGHT): JAUME PIERA, @JALABALL, XAVI SALVADOR COSTA, MANUEL MESA, BERTA COMPANYS OLIVA, BERTA COMPANYS OLIVA

2.3.

Coastal phenomena

Observing systems and forecasting models are the main tools used in coastal area, making it possible to anticipate the occurrence and effects of extreme marine events. Extreme event monitoring systems for observing coastal phenomena are more mature given the social impact they have had historically. These measurement systems are made up of a wide variety of oceanographic instrumentation whose particular feature is that they measure one or several environmental variables at a given point. This is the case of metocean buoys, which measure meteorological and oceanographic parameters such as water temperature, wave height, direction and period, wind speed and direction, and atmospheric pressure. In connection with the Spanish coast, the wave measurement network of the public organisation Puertos del Estado (OPPE) is noteworthy. On the other hand, sea level measurements are provided by the OPPE and IGME (CSIC) network of tide gauges along the entire coastline of the Iberian Peninsula, the Balearic and Canary Islands, as well as Ceuta and Melilla. Historical series are a fundamental tool for analysing the rise in mean sea level.

The CSIC has pioneered the use of video monitoring systems to assess the impacts caused by extreme weather events and the resilience of different coastal systems. Since 2001, it has developed and implemented this type of observation system to obtain information on the morphodynamic evolution of beaches and maritime climate conditions in an operational manner. In addition, new remote monitoring techniques are being developed for the study of underwater morphology. Parameters such as wave height, direction and period, position and variation of submerged sandbars and shoreline, as well as bathymetry of the shallow beach area are obtained from a series of products derived from video camera images. Additionally, the use of aerial photographs or satellite imagery is also a routine tool for the determination of the impact of extreme events on the coast. Also, the Spanish Meteorological Agency (AEMET) has created the Sistema de Notificación de Observaciones Atmosféricas Singulares [Singular Atmospheric Observations Reporting System] (SINOBAS) to collect and make available to the public information on the occurrence of certain phenomena that have been labelled as *singular*, characterised by being local, infrequent, of significant intensity and capable of causing a high social impact. In particular, SINOBAS provides coastal warnings of extreme waves, intense storms, wind or tornadoes that can cause damage in coastal areas.



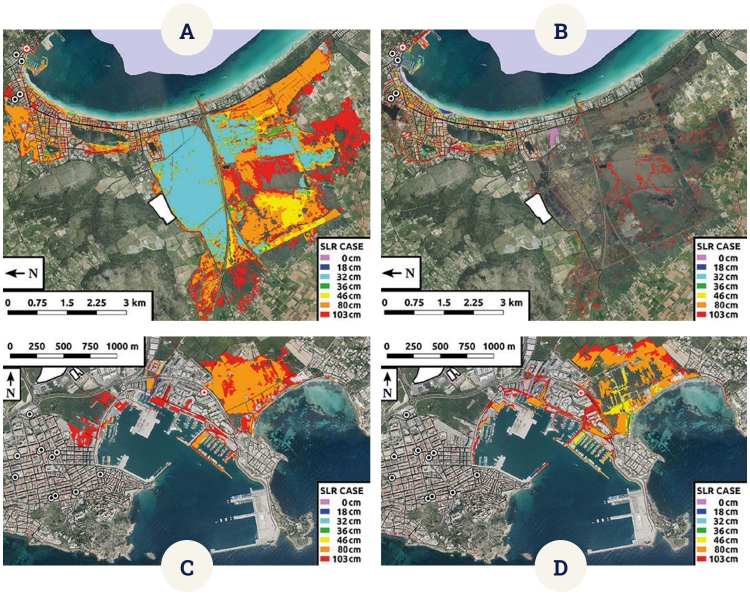
Example of the beaches of Barceloneta and Somorrostro (Barcelona) before (top) and during the Gloria storm (bottom); this was the most severe storm ever recorded, affecting the Mediterranean coast in January 2020. Video monitoring makes it possible to accurately assess the impacts of extreme storms on the coast. / J. GUILLEN

Advances in numerical prediction of the atmosphere and the ocean are making it possible to refine forecasts of the future evolution of coastal phenomena. For short-term predictions (less than three days), models use observational data to simulate and predict the evolution of extreme events such as storms and tsunamis. OPPE and AEMET produce and distribute a twice-daily wind and wave forecast for the North Atlantic and the western Mediterranean Sea basin. The forecast system consists of a series of applications, based on a wave generation model, which use the wind fields predicted by the HARMONIE-AROME limited area meteorological model provided by AEMET. The horizon of this forecast is 72 hours and provides hourly predicted fields. These short- and long-term forecasts are incorporated into morphodynamic models to determine the coastal evolution and to estimate the specific impact of extreme events.

In the longer term (years and decades), changes induced on the coast by regular and predictable processes and occasional extreme events can modify the morphology both in terms of land area and coastline profile. The equilibrium beach profile is determined by the average wave regime in the area. Understanding how extreme storms or hurricanes modify the profile, which determines the beach's wave-energy dissipation capacity, is of crucial importance to establish correct management strategies and is one of the relevant aspects of research work being carried out at the CSIC. In the long term, these morphodynamic models simulate the effects of erosion, flooding and other geomorphological processes on the coast.

Also, sea level rise in the long term is associated with a permanent loss of emerged coastal areas with widespread ecological and economic impacts. The receding coastline and rising sea levels will cause cyclonic storms to inflict greater damage to the Spanish coastline as a whole, with widespread erosion and the expansion of flood zones. These effects, which these changes will bring about over the coming decades, have been assessed at the CSIC using predictive numerical models of flood propagation. These models take into account the impact of extreme tidal surge and wave events (defined by 100-year return periods) together with sea level rise forced by climate

Figure 13 Extent of permanent and extreme flooding, based on different estimates of sea level rise, over the Alcúdia wetland, Mallorca (A, B) and the port of Ibiza (C, D)



Roads and streets are marked with black lines. Educational facilities are indicated with black dots, healthcare buildings with red crosses and energy production plants with white polygons.

Source: Luque *et al.*, 2021.

scenarios under different greenhouse gas emission conditions. Sea level rise projections for the year 2100 range from 32 cm in a mid-range emissions scenario to 82 cm in a severe emissions scenario. In the case of the Balearic Islands, the loss of emerged beach surface was quantified at between 7.8 km^2 and 27.7 km^2 in the mid-range emissions scenario and between 10.9 km^2 and 36.5 km^2 in the severe emissions scenario. This decrease in land area, which for some beaches represents the loss of more than 50% of their surface area by the end of the century, leads to a loss of recreational tourism services that could represent a decrease in gross domestic product (GDP) of up to 7.2% compared to GDP in 2019.

The detection of tsunamis on the Spanish coast is undertaken by the Sistema Nacional de Alerta por Maremotos [National Tsunami Warning System] (SINAM), a coordinated system for the detection of tsunami-generating earthquakes. SINAM uses the information gathered by the National Seismic Network, the OPPE's REDMAR tide gauge network, the detection systems of the IEO (CSIC), as well as the other marine detection systems of the various public administrations. The CSIC also carries out the risk assessment in the coastal zone in connection with extreme events based on the identification of exceptional phenomena that have occurred in the past, both at historical and geological scales, and the mapping of potentially dangerous areas. For example, studies address the identification of sedimentary deposits generated by severe storms, the evaluation of geomorphological impacts caused by tsunamis and the interpretation of the driving mechanisms (earthquakes, landslides or volcanic activity), as well as the location of active fault zones that can potentially cause earthquakes and pose a risk to the coastal zone. All this information contributes to enhancing the detection of recurring extreme events and their intensity, and optimising the prediction of vulnerability. As for meteotsunamis, the CSIC is working with the AEMET on the early detection of conditions likely to generate this type of phenomena using numerical models of long-wave propagation, especially along the coast of Ciutadella, in Menorca.

24.

Harmful algal blooms

Since the 1976 incident of mass poisoning across Europe after consuming mussels from Galician estuaries, the urgent need to establish a programme to monitor harmful algal blooms became apparent.

In Spain, the monitoring and control of these events in accordance with European regulations are carried out by the autonomous communities, which implement these measures according to the economic sector (aquaculture, tourism, etc.) or the environment that may be affected. In Galicia, a weekly monitoring system in the Galician estuaries was first implemented by the IEO (Spanish Institute of Oceanography) and then powers were transferred to the Xunta de Galicia in the 1990s. It is currently managed by the Instituto Tecnológico del Control del Mar [Technological Institute for Sea Control] (INTECMAR). Every week it provides information from different stations in the Galician estuaries on the counts of potentially toxic phytoplankton (such as *Dinophysis acuminata, D. acuta, D. caudata, Amphidomataceae, Pseudo-nitzschia* spp, *Alexandrium* spp., *Gymnodinium catenatum*, etc.) and biotoxins (paralytic, amnesic or lipophilic biotoxins, such as okadaic acid, diarrhoeic toxins, yessotoxins and azaspiracids). Depending on whether these values exceed certain thresholds, the closure or opening of aquaculture production areas in the estuaries is decreed. In addition, an oceanographic observation network, in collaboration with CSIC centres in Galicia, collects data to characterise environmental conditions, such as temperature, salinity, pH, oxygen and chlorophyll in the water column. The oceanographic observation network is assisted by a coastal network for the discrete measurement of these parameters by means of portable meters, or with continuous recording systems using automated instruments.

IEO centres in Galicia also monitor stations of the multidisciplinary observation system in the Vigo and A Coruña estuaries within the RADIALES time series programme. These time series collect information on physical, biogeochemical and plankton conditions going back more than thirty years, with a temporal resolution that has gone from monthly to weekly in recent years. These .oceanographic data, together with other sources of information from regional agencies (Augas de Galicia, with information on river flows and water quality, and Meteogalicia, with meteorological information, among others) and national agencies (AEMET and Puertos del Estado), have made it possible to improve the characterisation of the oceanographic conditions underlying these harmful algal blooms and to advance towards prediction, a fundamental tool for the prevention of the impacts from these events.

In Catalonia, exhaustive monitoring is carried out to ensure that water quality throughout the region complies with the standards established by the European Water Framework Directive (WFD. This monitoring applies to natural aquatic ecosystems as well as aquaculture facilities and recreational areas. WFD implementation involves the monitoring of microalgae in the water column. However, in recent years, a proliferation of microalgae growing on seabed substrates (e.g., macrophytes or rocks) has been found, which requires a different sampling protocol for their study and detection. Such sampling is being implemented in Catalonia through the Agència Catalana de l'Aigua in collaboration with the CSIC, with the aim of preventing the effects caused by the proliferation of the microalgae genus *Ostreopsis* on certain beaches in summer, closing the beaches if necessary. The spreading of this species along the Mediterranean coast and on Atlantic beaches in France is motivating the implementation of the benthic sampling protocol. As this is an emerging phenomenon, researchers from the CSIC and other public bodies are now collaborating to build a database in order to identify the trend in microalgae proliferation.

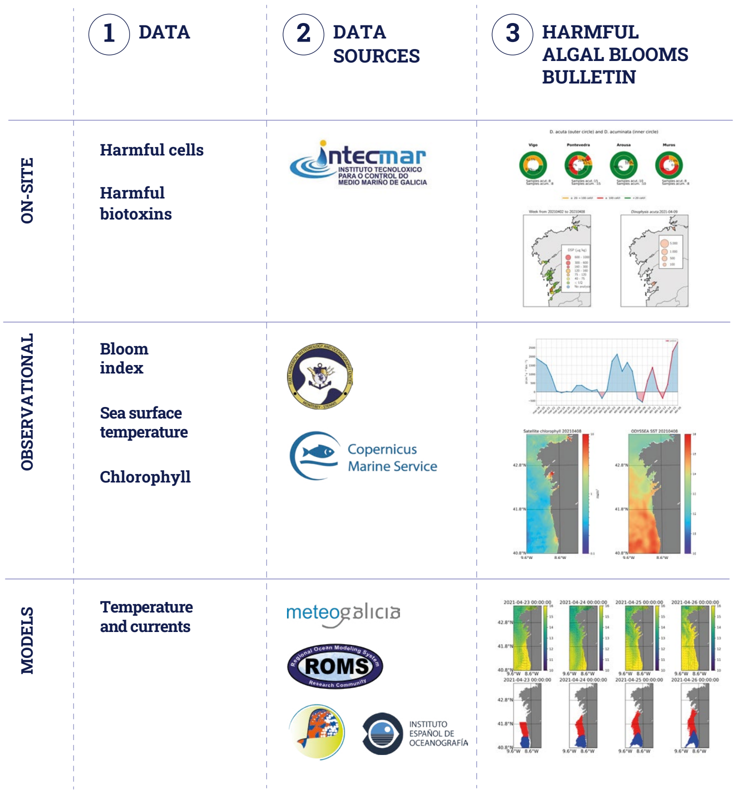
In addition to and in combination with on-site observation, new methods developed collaboratively by several CSIC institutes are proving useful for the detection of algal blooms that alter the colour of waters (toxic or not) using high-resolution satellites with colour sensors, such as Sentinel 2A/B.

The CSIC is using coupled hydrodynamic (currents, temperature and salinity) and marine biogeochemistry (nutrients and plankton) models to simulate in an integrated manner all processes related to harmful algal blooms in specific events. The models have also been used to predict advection transport of toxic cells, once they have been detected by the monitoring system, as part of an early warning system initiated with the European ASIMUTH project and continued with the MarRISK and PRIMROSE projects.

The potential for an early warning system for harmful algal blooms providing sufficient knowledge in advance of the likelihood of when and where they may occur would be an important step forward for the aquaculture sector. In this way, decisions could be taken that would significantly reduce economic impact. On the other hand, in case of closed production areas, this system could also indicate when conditions have improved sufficiently to allow for their reopening.

As in the case of Galicia, such an early warning system is only possible through a combination of observations (on-site and satellite) and modelling, in a multi-stakeholder effort. The availability of data in real (or near-real) time is a key element in an early warning system. To this end, data must be shared and provided in standard and interoperable formats. Overall, data on harmful and toxic events are shared internationally, with specific countries with which Spain has established collaborations, and with the platforms and working groups of UNESCO's Intergovernmental Oceanography Committee.

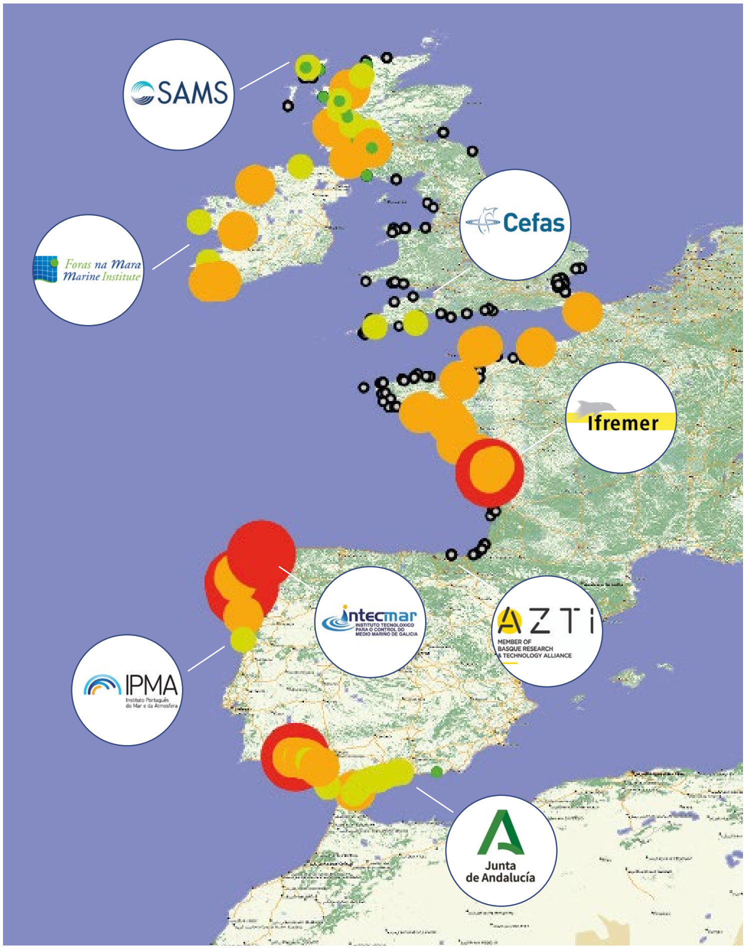
Figure 14 Elements of the Harmful Algal Bloom Early Warning System Pilot Bulletin in Galicia developed during the ASIMUTH and PRIMROSE projects



The data obtained from the different sources shown in the figure are processed using programming languages (Python) and stored in databases (PostgreSQL).

Going a step further, the CSIC, in the framework of the European PRIMROSE project, has developed web services that have improved the visualisation and analysis of count and toxin data of species potentially responsible for harmful algal blooms, making the data available to the end user in a more efficient, transparent and simple way. This collaboration can help the development of transboundary early warning systems, as well as increase our knowledge of the dynamics of these species beyond the regional level. The existence of such monitoring programmes is effective in preventing contaminated seafood from reaching consumers. In the case of emerging blooms such as *Ostreopsis*, the knowledge gained in other cases of harmful algal overabundance is enabling coordinated monitoring to establish a baseline for these events and to characterise and predict their future evolution.

Figure 15 Map of harmful algal blooms of the species *Dinophysis acuminata* (diarrhoeal toxin-producing) in Europe during September 2020



More vibrant colours and larger sizes refer to a higher number of harmful phytoplankton cells. Map retrieved from the web service developed in the framework of the PRIMROSE project to share data in standardised and interoperable formats.

three

Conclusions and Recommendations

Conclusions

The most severe extreme marine events often appear as compound events, i.e., where several extreme anomalies of different nature are combined in a cause-effect manner (e.g., a marine heatwave induces mortality in a coral population and facilitates an algal bloom that may be harmful). These events are statistically characterised as low-probability events based on time series of observations.

Understanding extreme marine events, predicting them and potentially mitigating their impacts requires multidisciplinary observational systems featuring high spatial and temporal resolution. At present, however, there are few observation systems that provide sufficiently long time series to adequately quantify the characteristics of extreme events.

Marine heatwaves, coastal phenomena and harmful algal blooms are natural fluctuations in the marine environment involving biogeochemical and physical processes of atmosphere-ocean interaction. They are classified as extreme according to the degree with which their characteristic values of magnitude (such as sea temperature, wave height or phytoplankton concentration) deviate from reference values. Their impact on society is increasing, mainly due to climate change and the human factor.

Through observation, data analysis and modelling, early warning systems can be designed and implemented to prevent and mitigate the impacts of extreme marine events on human societies and economic resources from the sea. The CSIC has been and continues to be actively involved in the development and implementation of various regional, national, and international initiatives to detect, monitor and predict extreme marine events such as those discussed herein. This strategy is in line with the goals of the UN Decade of Ocean Science for Sustainable Development, set to achieve an ocean and coasts where human communities and infrastructure are safer from the hazards of extreme marine events.

Marine heatwaves can have major impacts on the structure and evolution of marine ecosystems. It has been shown that extreme heatwaves are generally associated with mass mortality events of marine species. In the Mediterranean, despite global warming (up to 0.06 °C per decade), analyses of sea surface temperature over the last 40 years (over the period 1982-2022) do not indicate a statistically significant increase in marine heatwave characteristics. This may demonstrate some resilience of the Mediterranean ecosystem in general, although it does not guarantee that it can be sustained in the future if global warming continues.

Monitoring systems for extreme events of coastal phenomena are more mature due to their social impact throughout history. The observation networks (managed by the public entity Puertos del Estado and the CSIC) provide measurements of sea level variations along the entire coastline. The CSIC has pioneered the implementation of complementary video-monitoring systems for the study of beach dynamics and underwater morphology, necessary to analyse and quantify the impact of extreme marine events.

As far as harmful algal blooms are concerned, the main risk to human health is poisoning from eating shellfish contaminated with biotoxins produced by microalgae. In Spain, following European regulations, there is a rigorous system for monitoring and controlling these events in production areas, which includes taking biological samples in the water column and analysing toxins in seafood products. The CSIC is involved in various studies that have contributed to the understanding of the recurrent or exceptional dynamics of these events (which can lead to a ban on shellfish harvesting for several months each year), working with health authorities to prevent impacts on health and the economy.

Advances in numerical prediction of the atmosphere-ocean system are leading to improved forecasts of coastal phenomena.

In the short-term forecasts (e.g., less than three days), it is possible to anticipate the development of storms, tsunamis, wind and waves, to issue warnings to the public and estimate the specific impact of extreme events.

In the long term, existing information and future projections of different climate change scenarios allow probabilistic ranges of values to be established for the future evolution of the coast, due to occasional and extreme processes as well as to regular and progressive ones (e.g., gradual sea level rise). These ranges are necessary for the development of flood management and coastal management policies.

The combination of on-site and satellite observations with coupled hydrodynamic and marine biogeochemical models makes it possible to develop early warning systems. In the case of harmful algal blooms, the dissemination of information from the early warning system through bulletins can help prevent food poisoning from consumption of seafood contaminated with toxins produced by phytoplankton. These information bulletins are also useful for seafood producers and traders in planning their activity and reducing the economic impact of production closure. The experience gained over more than forty years allows new emerging harmful algal blooms and extreme events to be addressed in coordination with other countries that are similarly affected.

Recommendations

For policy management:

In order to understand the causes and consequences of extreme marine events and to be able to predict them with increasing accuracy, a multidisciplinary information system is needed to collect meteorological, oceanographic and biogeochemical data.

Extreme events can exceed the usual monitoring periods. In this regard, the combined availability of geological and historical data on these extreme events can provide a more robust view to both characterise and better understand them.

Currently, there is a mixture of institutions, departments and agencies at all government levels (local, regional, state and European) managing, sometimes in duplicate, observation systems in the maritime domain. A centralised information system, along the lines of the US NOAA (National Oceanic and Atmospheric Administration), could be an example to follow. However, a decentralised model would be valid and effective as long as it ensures that intra-institutional coordination structures are in place to achieve optimal coverage, following multidisciplinary information exchange standards in line with the European Union's FAIR (*findable, accessible, interoperable and reusable*) principles.

Early warning systems are required to improve the management and protection of the marine environment and its resources, in analogy to terrestrial management. In the case of coastal phenomena, early warning systems are well developed and their responsibility lies with the meteorological agencies and are managed by meteorological agencies (AEMET, METEOCAT, METEOGALICIA, EUSKALMET), with the collaboration of other institutions (such as Civil Protection and SASEMAR, among others).

The same is true for harmful algal blooms, which are under the responsibility of the regional administrations. However, with respect to marine heatwaves, there are no such systems, beyond the monitoring efforts made by CSIC research groups. Importantly, these warning systems should also be implemented in marine protected areas, being indicators of the general health of marine ecosystems, in order to mitigate the impact of extreme events. Short-, medium- and long-term management of potential changes caused by these extreme events should be envisaged, with measures to protect and adapt land use in these areas.

A key and decisive element in a widely decentralised multilevel-government system as is Spain's is the development of effective coordination and cooperation mechanisms between the different administrations (local, autonomous, regional, state and European).

These coordination mechanisms must carry out policy integration and organisational and institutional dialogue between departments and agencies. In other words, they should seek to optimise regulations that harmonise policies aimed at preserving and improving the resilience of ecosystems to the impact of extreme marine events.

The combination of extreme marine events, the human factor and long-term climate change is a growing threat to our coasts. Stable, knowledge-based policy consensus and decision-making based on (or at least informed by) scientific evidence is needed to develop resilient management of the coastal environment and its ecosystems.

The transfer to society of the knowledge acquired, observations and early warning systems to reduce the impacts of extreme events must account for aspects such as the use of new technologies and education; complex elements with considerable room for improvement in terms of increasing their efficiency, and in which the CSIC has also expressed the need to become involved in various areas.

For companies:

New technologies (including low-cost sensors) and sampling strategies need to be included and developed to massively collect new information. The collection of data from opportunity platforms or marketplaces should be encouraged, taking advantage of the work carried out by companies exploiting marine resources, a sector known as the blue economy (such as fishing fleets, aquaculture and recreational tourism), and offshore infrastructures such as offshore wind farms.

R&D&I investment is required to overcome technical limitations. For example, for the use of non-invasive methods that avoid the harvesting of living organisms, through robotic underwater systems, a technological sector on the rise thanks to the incorporation of artificial intelligence techniques.

It is urgent to prioritise measures and resources to develop and implement methods for the recovery and restoration of marine ecosystems (such as micro-restoration, closures and the extension of protected areas), promoting a more sustainable use that contributes to greater resilience to these events. The participation and involvement of blue economy companies in decision-making is essential to ensure the health of the oceans.

For society:

Today, we can and must encourage citizen science in the marine environment. Retrieving data on the various components of the marine ecosystem is one of the main constraints to understanding impacts. It is economically and humanly unfeasible for the Government to provide observation systems covering all of its territorial waters at the necessary scales. The contribution of citizen volunteers to marine observation can help to fill the gaps and complement existing systems.

Promoting initiatives for co-management of the maritime space to address and mitigate the risks posed by extreme marine events and climate change in a concerted manner. This involves organising discussion spaces where all levels of society, public administrations, academia, companies and citizens are represented in a non-hierarchical way. Such initiatives are being successfully applied at regional level in Catalonia in connection with the sustainability of fishing (both commercial and recreational) and have been approved by the European Parliament ("Report on co-management of fisheries in the EU and the contribution of the fisheries sector for the implementation of management measures"). Such initiatives could be extrapolated to other areas, such as coastal management and the regulation of recreational activities, among others.

Extreme marine events are natural phenomena that are aggravated by climate change and other anthropogenic factors. It is on this human component that we must act. We need to promote and prioritise the education of citizens in awareness, respect and protection of the marine environment, given its vital importance for climate and as a primary source of marine resources.

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List of Centres

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Centro de Estudios Avanzados de Blanes (CEAB, CSIC)	www.ceab.csic.es	direccion.ceab@csic.es
Instituto de Ciencias del Mar (ICM, CSIC)	www.icm.csic.es	direccion.icm@csic.es
Instituto de Ciencias Marinas de Andalucía (ICMAN, CSIC)	www.icman.csic.es	direccion.icman@csic.es
Instituto de Diagnóstico Ambiental y Estudios del Agua (IDAEA, CSIC)	idaea.csic.es	direccion.idaea@csic.es
Instituto Español de Oceanografía (IEO, CSIC)	www.ieo.es	webmaster@ieo.csic.es
Instituto Geológico y Minero de España (IGME, CSIC)	www.igme.es	sec.dg@igme.es
Instituto de Investigaciones Marinas (IIM, CSIC)	www.iim.csic.es	direccion.iim@csic.es
Instituto Mediterráneo de Estudios Avanzados (IMEDEA, CSIC-UIB)	imedea.uib-csic.es	direccion.imedea@csic.es
Unidad de Tecnología Marina (UTM, CSIC)	www.utm.csic.es	direccion.utm@csic.es

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Further Information

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