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D8.3 Report on the existing information and possible data gaps for the definition of climate and climate change impact indicators

Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

• Deliverable number:	• D8.3
• Work package:	• WP8 – Virtual Research Environments and Cross-disciplinary Activities
• Intermediate Objective:	• IO8.3
• Deliverable type:	• X Document, report
•	• ☐ Websites, patent filings, videos, etc.
•	• ☐ Other: please specify ....
• Dissemination level:	• X Public
•	• ☐ Restricted
• Estimated delivery (bimester):	• B6
• Actual delivery date:	• 21.10.2023
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• Reviewed by:	• ITINERIS Executive Board
• Note:	•

IR0000032 – ITINERIS, Italian Integrated Environmental Research Infrastructures System - CUP B53C22002150006 (D.D. n. 130/2022)
Funded by EU - Next Generation EU
Mission 4 “Education and Research” - Component 2: “From research to business” -
Investment 3.1: “Fund for the realisation of an integrated system of research and innovation infrastructures”

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1. INTRODUCTION

The frameworks under which different climate and climate change impact indicators have been defined are manyfold. Chronologically, the first two are the Pressure-State-Response (PSR) and the Driver-Pressure-State-Impact-Response (DPSIR) frameworks, commonly used to assess, monitor and respond to environmental challenges. They both provide a structured approach to comprehend the cause-and-effect relationships within ecosystems.

Other frameworks have been developed within the meteorological community. The main one, also used in Deliverables 5.3 and 5.5 of the ITINERIS project, is due to the panel of experts of the Global Climate Observing System (GCOS) that has identified the so-called Essential Climate Variables (ECVs, e.g. Bojinski et al. 2014), i.e. the minimal group of “key variables” to be observed to understand the status and trends in climate variability. ECVs are also used for the negotiations under the United Nations Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC). Other meteorological frameworks include those that are respectively at the base of the State of the Climate Reports of the Bulletin of the American Meteorological Society (BAMS, e.g. Blunden et al. 2018), the State of the Global Climate Series of the World Meteorological Organization (WMO, e.g. WMO 2023a), the Assessment Reports of the same IPCC (e.g. IPCC 2021) and the European State of the Climate of the Copernicus Climate Change Service (C3S, e.g. C3S 2023). All different indicators of these reports are germane to provide an overview of changes in the climate system.

In the following paragraphs the above different frameworks are briefly described together with their similarities and differences.

<u>The Pressure-State-Response (PSR) framework</u>

The PSR framework (top panel of Figure 1) has been initially proposed by the Organization for Economic Co-operation and Development (OECD 1993). It is a conceptual model that delineates the causal relationships among human activities, environmental pressures, and the responses or measures taken to manage these pressures. The PSR framework is made up of three key components:

- <u>Pressure</u>: This component identifies the human activities that exert pressure on the environment, such as industrial emissions, deforestation, or agricultural practices. Pressures cause changes in the environment and are often the result of anthropogenic interventions. In Figure 1 the pressure exerted by human activities is, for example, the emission of greenhouse gases (GHG).
- <u>State</u>: The state component refers to the condition of the environment resulting from the pressures exerted upon it. It encompasses the physical, chemical, and biological aspects of ecosystems, providing a comprehensive picture of their health and functioning. In the example of Figure 1, the state of the environment is altered and measured by the change in the mean temperature or GHG concentration in the atmosphere.
- <u>Response</u>: Responses in the PSR framework are the actions or measures implemented to address the identified pressures and maintain or restore the desired state of the environment. These can include policy interventions, technological innovations, or changes in human behaviour to mitigate environmental impacts. In the example of Figure 1, the response may produce modifications to environmental policies, such as the introduction of taxes to discourage GHG emissions and/or favour the use of non-fossil energies.

Under the PSR framework the OECD defines an indicator as "a parameter, or a value derived from parameters, which points to/provides information about/describes the state of a phenomenon/environment/area with a significance extending beyond that directly associated with a parameter value" (cf. pag.6 in OECD 1993). According to this definition, the OECD has established a list of criteria for indicator selection (Table 1) and identified a core set of 33 indicators of environmental performance (Table 2).

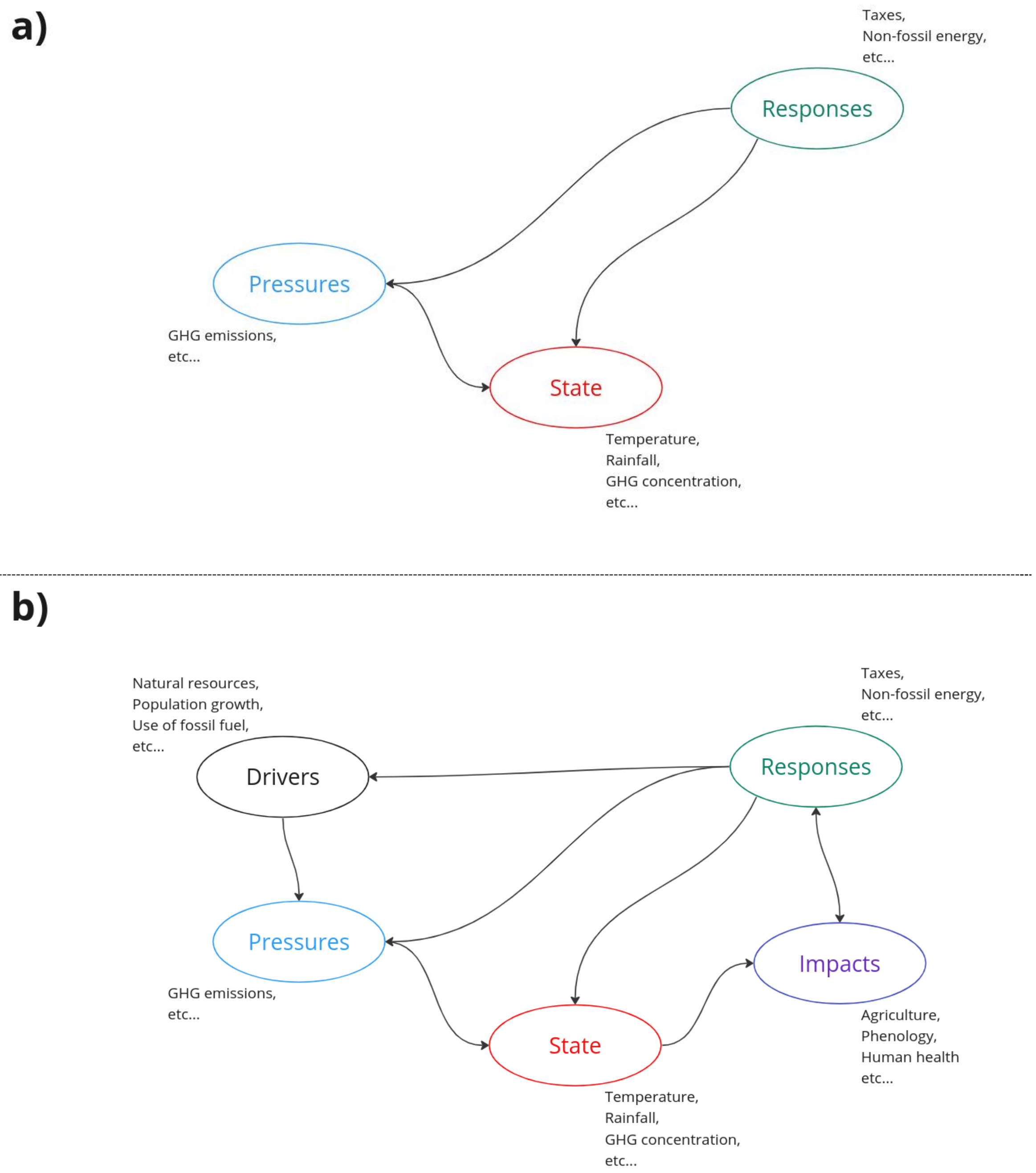

Figure 1: PSR (top panel a) and DPSIR (bottom panel b) frameworks as identified by OECD (1993) and EEA (1999) for reporting on environmental change. The acronym GHG stands for greenhouse gases.

Table 1 - Criteria established by the OECD for indicator selection (OECD 1993).

Policy relevance and utility for users
An environmental indicator should: • provide a representative picture of environmental conditions, pressures on the environment or society's responses; • be simple, easy to interpret and able to show trends over time; • be responsive to changes in the environment and related human activities; • provide a basis for international comparisons; • be either national in scope or applicable to regional environmental issues of national significance; • have a threshold or reference value against which to compare it so that users are able to assess the significance of the values associated with it.
Analytical soundness
An environmental indicator should: • be theoretically well founded in technical and scientific terms; • be based on international standards and international consensus about its validity; • lend itself to being linked to economic models, forecasting, and information systems.
Measurability
The data required to support the indicator should be: • readily available or made available at a reasonable cost/benefit ratio; • adequately documented and of known quality; • updated at regular intervals in accordance with reliable procedures.

With respect to climate change, Tables 1 and 2 underline how the identification of a set of indicators able to fulfill all criteria may result in a challenging task. The effects of climate and climate change on the environment are indeed complex and subject to great uncertainty often due to the scarcity of data. Moreover, the PSR approach focuses on anthropogenic pressures and responses neglecting the underlying reasons for the pressures and the motivations behind responses to changes in the state of the environment. These shortcomings are the primary motivations for the development of the DPSIR framework.

The Driver-Pressure-State-Impact-Response (DPSIR) framework

The DPSIR framework (bottom panel of Figure 1) has been developed by the European Environment Agency (EEA 1999) and built upon the PSR model. It incorporates two additional components with respect to the PSR framework: the driver and impact elements. By including the direct drivers and impacts of changes in the environment caused by human activities, the DPSIR framework provides a more detailed and comprehensive analysis of environmental issues. The DPSIR framework is thus made up of five key components:

Table 2 – Core set of indicators gathered by environmental issue as identified by the OECD according to the PSR framework (OECD 1993).

	PRESSURE	***STATE***	***RESPONSE***
Issues	***Indicators of environmental pressures***	***Indicators of environmental conditions***	***Indicators of societal responses***
a) Climate change	1. Emissions of CO_2	2. Atmospheric concentrations of greenhouse gases 3. Global mean temperature	4. Energy intensity
b) Stratospheric ozone depletion	5. Apparent consumption of CFCs	6. Atmospheric concentration of CFCs	
c) Eutrophication	7. Apparent consumption of fertilizers measured in N and P	8. BOD, DO, N and P in selected rivers	9. % of population connected to waste water treatment plants
d) Acidification	10. Emissions of SOx and NOx	11. Concentrations in acid precipitations (pH, SO4, NO3)	12. Expenditure for air pollution abatement
e) Toxic contamination	13. Generation of hazardous waste	14. Concentration of lead, cadmium, chromium, copper in selected rivers	15. Market share of unleaded petrol
f) Urban environmental quality		16. Concentrations of SO_2 and NO_2 particulates in selected cities	
g) Biological diversity and landscape	17. Land use changes	18. Threatened or extinct species as % of known species	19. Protected areas as % of total area
h) Waste	20. Generation of municipal, industrial, nuclear, and hazardous waste	Not applicable	21. Expenditure on waste collection and treatment 22. Waste recycling rates (paper and glass)
i) Water resources	23. Intensity of use of water resources		
j) Forest resources		24. Area, volume, and distribution of forests	
k) Fish resources	25. Fish catches		
l) Soil degradation (desertification and erosion)	26. Land use changes		
m) General indicators not attributable to specific issues	27. Population growth and density 28. GDP growth 29. Industrial and agricultural production 30. Energy supply and structure 31. Road traffic and vehicle stock	Not applicable	32. Pollution abatement and control expenditure 33. Public opinion on the environment

- Driver: Like the pressure in the PSR framework, drivers in the DPSIR model represent the root causes or forces that initiate environmental change. Drivers encompass societal, economic, and demographic factors that contribute to the pressures on the environment. In the example of Figure 1, drivers leading to the emission of GHG may be the exploitation of natural resources, the population growth and/or the consumption of fossil fuels.
- Pressure: As in the PSR framework, this component identifies the specific activities that exert stress on the environment. In the example in Figure 1, the pressure is the emission of GHG.
- State: The state component remains consistent with the PSR framework, representing the condition of the environment resulting from the applied pressures. As above in the example of Figure 1, the state of the environment is altered and measured by the change in the mean temperature or GHG concentration in the atmosphere.
- Impact: The impact element introduces a crucial dimension to the DPSIR framework, emphasizing the direct consequences of environmental changes on ecosystems, human health, and socio-economic systems. In the example of Figure 1, this element results in a quantification of the impacts of the change in the mean temperature or GHG concentration in the atmosphere, like changes in the crop production in agriculture, or changes in animal and plant phenology (i.e. changes in the timing of recurring developmental stages in plants and animals such as the arrival date of migratory birds), or the increase of the number of skin cancers in human health.
- Response: Responses in the DPSIR framework are like those in the PSR framework, representing the measures taken to address the identified pressures and mitigate the impacts on the environment. As in the example of Figure 1, the response may produce modifications to environmental policies, such as the introduction of taxes to discourage GHG emissions and/or to favour the use of non-fossil energies.

The DPSIR framework allows the definition of indicators associated with the impact sector whose function is to quantify the impacts of climate change on the environment. The evaluation of impact indicators is of great importance as they regulate the societal response which in turn affects the drivers of climate change (Figure 1). Impact indicators may also reinforce public support for policy measures by raising public awareness on environmental problems. The challenge of using DPSIR is thus to identify which components of the framework can be robustly monitored using observational data.

The Essential Climate Variables framework

The main framework for determining key variables representing the state of the climate is the GCOS set of essential climate variables (ECVs, Bojinski et al. 2014) that has been selected by evaluating readiness, feasibility, and impact to address societal needs. ECVs provide the procedures needed to understand and predict climate evolution, guiding mitigation and adaptation measures. ECVs are defined as “physical, chemical, or biological variables or a group of linked variables that critically contribute to the characterization of Earth’s climate”. The ECVs can be used to calculate indicators of pressure and state elements and are useful to evaluate the impact component, establishing a direct link with the DPSIR framework (Masó et al. 2020).

ECVs are identified based on the following criteria:

- Relevance: The variable is critical for characterizing the climate system and its changes.
- Feasibility: Observing or deriving the variable on a global scale is technically feasible using proven, scientifically understood methods.
- Cost effectiveness: Generating and archiving data on the variable is affordable, mainly relying on coordinated observing systems using proven technology, taking advantage, where possible, of historical datasets.

The set of ECVs is periodically reviewed and updated to ensure that new variables may be added following technological innovations and development. The current set (Table 3) consists of 55 different variables (16 atmospheric, 19 oceanic, and 20 terrestrial) gathered in 10 different subcategories.

Table 3 – The current set of ECVs

Category	***Subcategory***	***ECVs***
Atmospheric	Surface	Precipitation; Pressure; Radiation budget Temperature; Water vapor; Wind speed and direction
	Upper-air	Earth radiation budget; Lightning; Temperature; Water vapor; Wind speed and direction; Clouds
	Atmospheric composition	Aerosols; Carbon dioxide, methane, and other greenhouse gases; Ozone; Precursors for aerosols and ozone
Oceanic	Physical	Ocean surface heat flux; Sea ice; Sea level; Sea state; Sea surface currents; Sea surface salinity; Sea surface stress; Sea surface temperature; Subsurface currents; Subsurface salinity; Subsurface temperature
	Biogeochemical	Inorganic carbon; Nitrous oxide; Nutrients; Ocean color; Oxygen; Transient tracers
	Biological/ecosystems	Marine habitats, Plankton
Terrestrial	Hydrosphere	Groundwater; Lakes; River discharge; Terrestrial water storage
	Cryosphere	Glaciers; Ice sheets and ice shelves; Permafrost; Snow
	Biosphere	Above-ground biomass; Albedo; Evaporation from land; Fire; Fraction of absorbed photosynthetically active radiation (FAPAR); Land cover; Land surface temperature; Leaf area index; Soil carbon; Soil moisture
	Antroposphere	Anthropogenic greenhouse gas fluxes; Anthropogenic water use

The BAMS State of Climate report indicators

The State of the Climate series is an annually peer-reviewed compilation report of scientific papers led by the scientists of the National Centers for Environmental Information (NCEI) from the U.S. National Oceanic and Atmospheric Administration (NOAA). The report is published as a supplement to the Bulletin of the American Meteorological Society (BAMS) with the aim of providing a comprehensive understanding of the Earth's climate system.

The ECVs represent the natural framework of reference for the BAMS State of the Climate report which directly covers most of the essential climate variables considering scientific research, observational and numerical data. Each annual report contains a specific introductory section where the list of fully monitored ECVs is explicitly provided together with those ECVs that are either partially monitored or not yet covered. The fully covered ECVs are those with sufficient spatial and temporal data and with peer-reviewed documentation for a global-scale characterization. The variables that are considered only partially monitored are those linked to systematic and rigorous measurements but lacking some coverage in time and space due to observing limitations or availability of data or authors. The remaining variables are declared as not yet covered or outside the scope of the report (Blunden et al. 2023).

The State of the Climate series also considers atmospheric circulation patterns, such as the El Niño-Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO). These large-scale climate modes significantly influence regional weather patterns, affecting different climatic variables from precipitation to hurricane activity. The series also integrates the contribution of climate models and numerical simulations. Numerical models, validated against observational data, facilitate the exploration of future climate scenarios, allowing for the assessment of uncertainties and the refinement of projections. This iterative process between modeling and observation enhances the precision of climate predictions, aiding policymakers and stakeholders in developing informed strategies for climate adaptation and mitigation.

The WMO State of Global Climate report indicators

The World Meteorological Organization issues annual reports on the status of the global climate to provide credible scientific information on climate and its variability. These reports are collected under the name of State of Global Climate Series.

The need to target a larger audience and the difficulties in defining indicators matching the selection criteria of the above-cited frameworks has pushed the WMO to select and focus on a new set of indicators named as "headline climate indicators" in the State of Global Climate reports. The idea is to consider a few numbers (between 5 and 10) of sufficiently simple indicators to foster communication with a larger and non-scientific public, particularly with policymakers. These indicators need to be scientifically robust and cover the land, atmosphere, ocean, and cryosphere.

The characteristics to ensure such a broader reporting of the State of Global Climate reports are indicated in Williams and Eggleston (2017) and are:

- Relevance: Each headline indicator should be a clear, understandable indicator of the state of the climate system, with broad relevance for a range of audiences, whose value can be expressed as a single number. Some such global indicators may also have value at the national and regional levels.

- Representativeness: The indicators as a package should provide a representative picture of a broad range of changes to the Earth system related to climate change.
- Traceability: Each indicator should be calculated using an internationally agreed upon (and published) method and accessible and verifiable data.
- Timeliness: Each indicator should be calculated regularly (at least annually), with the minimum possible time between the end of the period and publication of the data.
- Data adequacy: The available data needed for the indicator calculation must be sufficiently robust, reliable, and valid.

Based on these characteristics, seven headline indicators (Table 4) have been defined by the WMO's Commission for Climatology at its 2018 meeting (WMO 2018a). It must be noted that the above characteristics may vary a lot even between headline indicators. For example, some of these indicators, like temperature, are well supported by long-term time series with relative low uncertainty even at preindustrial levels. Other indicators, like sea ice extent, are instead largely dependent on satellite data and only available in the last 40 years. Others, like glacier mass balance, have data available only for the very last few years. Headline indicators share, however, the important characteristic of being expressed as a single number which is scientifically meaningful as an indicator of the state of the climate.

The 2017 State of the Climate (WMO 2018b) is the first document reporting numbers for five out of the seven selected indicators. At that time, the available data for 2017 has been judged to be sufficiently robust only for the following headline indicators:

- Global mean surface-temperature anomaly (1981–2010 baseline): 2017, annual mean.
- Global ocean heat content change, 0–700 metre layer: 2017, annual mean.
- Global mean CO_2 surface mole fraction: 2016, annual mean.
- Global mean sea-level change since 1993: 2017, December.
- Arctic sea-ice extent summer minimum: 2017, September.

Table 4 – The seven headline climate indicators defined by the WMO

Variable	***Proposed headline indicator***
Temperature	Global mean surface temperature
Ocean heat content	Global ocean heat content anomaly
Sea level	Global mean sea level change from a reference benchmark
Sea ice extent	Sea ice extent for the Arctic and Antarctic
Glacier mass balance	Global mass change of glaciers outside the Greenland and Antarctic ice sheets
Ocean acidification	Global mean ocean pH
Greenhouse gas mole fractions	Mean global mole fraction of CO_2

In the WMO State of Climate Reports, the headline indicators are always complemented by other important and global indicators which were not selected as headline indicators because they are either not reducible to a single number or lack coverage to be considered representative. For example, the global averaged precipitation has not been selected as a headline indicator because of the strong regional variations in sign of the observed changes which make the global calculation less meaningful and important than the regional signal itself. In addition, precipitation over the ocean is only available in the period covered by satellites while precipitation over land is retrieved thanks to different datasets whose spread is large (Gehne et al. 2016).

Being mean variables calculated over a year or a season, headline indicators are also not representative of extreme events which however cause the most important impacts related to climate changes. For this reason, the WMO State of Climate reports also contain sections reporting indicators related to climate risks, extreme events, and socio-economic impacts.

The IPCC Assessment Reports

The Intergovernmental Panel on Climate Change (IPCC) Assessment Reports share important similarities with those of the WMO State of Global Climate Series, even if released at periodic intervals and not annually. The IPCC Assessment Reports incorporate observations, numerical models and analysis spanning the atmosphere, the cryosphere, the biosphere, and the oceans. The IPCC Assessment Reports are meant to provide a robust foundation for policymakers, governments, and the general public to understand, mitigate, and adapt to the complex climatic dynamics.

The reports are structured into several Working Groups, each focusing on different elements of climate science, impacts, and mitigation strategies. Working Group I assesses the physical science basis of climate change, considering factors such as greenhouse gas concentrations, temperature trends, and changes in extreme weather events. The findings of Working Group I are at the base of the understanding of the fundamental mechanisms driving climate change, providing a robust scientific structure for the subsequent assessments. The most recent contribution from Working Group I has been released in 2021 (IPCC 2021) and shows a selection of six “key indicators” which demonstrate the changes across the physical climate system (Figure 2). These six key indicators are:

- CO_2 concentration, global annual mean expressed in parts per million.
- Precipitation, mean anomaly in two latitude bands, expressed in millimeters per year.
- Glacier mass loss, global annual mean, expressed in gigatonnes per year.
- Surface temperature, global mean anomaly, expressed in degrees Celsius.
- Sea level, global mean anomaly, expressed in centimeters.
- Ocean heat content, global mean anomaly, expressed in zettajoules.

The datasets used for each key indicator are clearly indicated in the contribution document from Working Group I together with the baselines for the calculations of the anomalies. The key indicators share the same logic behind the headline indicators of the WMO State of Global Climate reports.

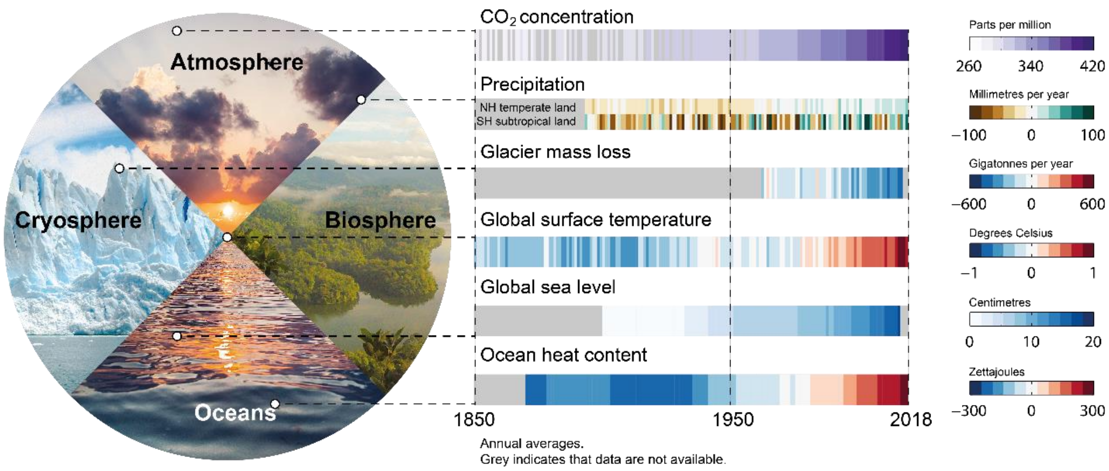

Figure 2: The six key indicators shown in Figure 1.4 of the contribution document from Working Group I to the last IPCC Assessment Report (IPCC 2021). The period considered for the indicators begins either from 1850 or the start of the observational or assessed record and ends in 2018. Each stripe indicates the global (except for precipitation which shows two latitude band means), annual mean anomaly for a single year, relative to a multi-year baseline (except for CO_2 concentration and glacier mass loss, which are absolute values). The grey colour indicates that data are not available.

Working Group II focuses on impacts, adaptation, and vulnerability. By examining how climate change affects ecosystems, human societies, and vulnerable populations, this group addresses the human dimensions of climate change, ranging from threats to food security and water resources to the intensification of existing social inequalities. Working Group III focuses on mitigation by addressing the causes and drivers of climate change and by proposing strategies for the reduction of greenhouse gas emissions and the transition to renewable energy sources. An additional publication, the Synthesis Report, puts together the findings of all three working groups, underlining the main point and messages of the entire assessment. This synthesis is crucial for communicating with policymakers and the general public.

As in the WMO State of Global Climate reports, The IPCC Assessment Reports consider many other indicators related to climate risks, extreme events, and socio-economic impacts.

The CS3 European State of the Climate indicators

The European State of the Climate is an annual report put forth by the Copernicus Climate Change Service (C3S) and implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF). The European State of the Climate report is typically released in April and is one of the products in the C3S portfolio of climate monitoring services. The report relies largely on datasets provided operationally and in near real-time by the Copernicus Services and includes a global analysis during the year, followed by a specific focus on the conditions in Europe and in the Arctic. The key findings of the report are condensed in the European State of the Climate Summary (e.g. CS3 2023) which is aimed at a non-specialist audience. The Summary outlines the latest updates in terms of the so-called “C3S Climate Indicators” which cover the whole globe, Europe, and the polar regions.

Previously, up to the European State of the Climate 2019, the CS3 Climate Indicators have been updated only once a year being part of the report. Since the European State of the Climate 2020, they are themselves considered as a standalone online product in the C3S portfolio and may be subjected to additional updates during the year, as new data become available. The date of the latest update is indicated in the sidebar of each online indicator page.

The last European State of the Climate 2022 reports twelve C3S Climate Indicators which are:

- Global Temperature – anomaly with respect to pre-industrial level and expressed in degrees Celsius
- European Temperature – anomaly with respect to pre-industrial level and expressed in degrees Celsius
- Arctic Temperature – anomaly with respect to pre-industrial level and expressed in degrees Celsius
- Carbon Dioxide (CO_2) – annual average level and expressed in parts per million
- Carbon Dioxide Increase (CO_2) – annual average increase since 2010 and expressed in parts per million per year
- Methane (CH_4) – annual average level and expressed in parts per billion
- Global Glaciers – ice loss since 1997 expressed in cubic kilometers
- European Glaciers – ice loss since 1997 expressed in cubic kilometers
- Greenland Ice Sheet – ice loss with respect to the 1992-2020 median expressed in cubic kilometers
- Global Sea Level – increase since 1993 expressed in cm
- Global Sea Surface Temperature – increase since 1980 expressed in degrees Celsius
- Arctic Sea Ice Extent – loss in the month of September between 1980s and 2010s expressed in million squared kilometers

The C3S Climate Indicators share the same characteristics of the indicators used in the WMO State of Climate Reports as discussed in Williams and Eggleston (2017) for better communication to policymakers and the public.

Scope and structure of the deliverable

This deliverable D8.3, together with deliverable D8.4, represents the ITINERIS Intermediate Objective IO8.3 and aims to provide information and possible data gaps for the definition of climate and climate change impact indicators. The deliverable must be seen as a first and necessary step for the creation of the Virtual Research Environment on indicators of climate change (CLIMA VRE) which represents a specific objective (OBJ7) of the WP8 "Virtual Research Environments and Cross-disciplinary Activities" of the ITINERIS project.

The discussion within this deliverable is limited to the most common sets of climate and climate change indicators and associated frameworks reported above, as it is impossible to cover all indices that have been developed in the literature. The description of many other less common indicators like the Saharan Oscillation and western Mediterranean Oscillation indices (Martin-Vide et al. 2006, Khomsi et al. 2020) or the redundant National Aeronautics and Space Administration (NASA) "Vital Signs of the Planet", are beyond the scope of this document.

In this deliverable D8.3 a list of recognized climate and climate change impact indicators is provided in Section 2 together with the available datasets associated with each indicator. The rationale is not limited to gathering information on existing indicators but also in providing specific data sources and datasets to be harvested in the creation of the CLIMA VRE for the potential creation of new indicators. The focus is above all on the indicators used in the CS3 European State of the Climate reports. This choice is justified by: a) the European focus of CS3 which needs to be taken into account in the strategies of the Research Infrastructures participating to the ITINERIS project; b) the tight link of the CS3 services with the Essential Climate Variables framework on which most of the ITINERIS observational effort is based upon (for example compare with Deliverables 5.3 and 5.5) and c) the consistency between the CS3 and WMO approaches. The description of some other relevant indicators is provided in Section 3 together with examples of combined indicators. Some examples of recognized gaps are provided in Section 4 while conclusions are drawn in Section 5 together with opportunities and indications to develop specific demonstrator services for the CLIMA VRE.

2. CLIMATE INDICATORS AND ASSOCIATED AVALAIBLE DATASETS

Temperature indicators

The temperature indicators are the most reliable metrics to monitor the state of the climate. They are generally expressed as an anomaly from a baseline period which may be varying according to the specific indicator and the associated datasets.

In the case of the 2022 CS3 European State of the Climate reports, the temperature indicator is based on six different datasets. The first two are two reanalysis products: ERA5 (Hersbach et al 2020), produced by C3S (ECMWF) and available in the CS3 Climate Data Store and JRA-55 produced by the Japan Meteorological Agency (JMA). The other four products are gridded datasets based on observations: GISTEMPv4 produced by the US National Aeronautics and Space Administration (NASA), HadCRUT5 produced by the Met Office Hadley Centre in collaboration with the Climatic Research Unit of the University of East Anglia, NOAAGlobalTempv5 produced by the US National Oceanic and Atmospheric Administration (NOAA) and Berkeley Earth, produced by the organization of the same name.

The above six datasets have been assessed in terms of their quality and homogeneity. Their largest differences are related to the interpolation in areas such as the polar regions, where data are sparse (Simmons et al. 2017). For example, reanalysis products are more spatially complete in the Arctic region and show stronger recent warming trends than those with limited Arctic representation.

The six datasets above are the same considered in the last WMO State of the Global Climate 2022 while the last IPCC Assessment Report by Working Group I has adopted the 1850-1900 period as a working definition of preindustrial-equivalent baseline. Only HadCRUT5 and Berkeley Earth products cover the full 1850-1900 period and are used together in the IPCC report with two additional datasets: NOAA GlobalTemp Interim and Kadow et al. (2020). The latter is an Artificial-Intelligence (AI) based reconstructed dataset where AI methods are shown to fill observational gaps when combined with numerical climate models.

Table 5 – Dataset information for the indicators associated with the temperature variable reported in CS3 and IPCC

Dataset	***Reference***	***Link to data***
ERA5 (European Centre for Medium-Range Weather Forecasts) (1979–present)	Hersbach et al. (2020)	https://cds.climate.copernicus.eu/cdsapp#!/data-set/reanalysis-era5-single-levels-monthly-means?tab=form
JRA-55 (Japan Meteorological Agency) (1955–present)	Kobayashi et al. (2015)	https://jra.kishou.go.jp/JRA-55/index_en.html
GISTEMPv4 (U.S. National Aeronautics and Space Administration) (1880–present)	Lenssen et al. (2019)	https://data.giss.nasa.gov/gistemp
HadCRUT5 (Met Office Hadley Centre/University of East Anglia Climatic Research Unit) (1850–present)	Morice et al. (2021)	https://www.metoffice.gov.uk/hadobs/hadcrut5/data/cur-rent/download.html
NOAA GlobalTempv5 (U.S. National Oceanic and Atmospheric Administration) (1880–present)	Huang et al. (2020)	https://www.ncei.noaa.gov/data/noaa-global-surface-temperature/v5.1/access/gridded
Berkeley Earth (1850–present)	Rohde and Hausfather (2020)	http://berkeleyearth.org/data-new
NOAA GlobalTemp Interim (1850–present)	Vose et al (2021)	Not available
Kadow et al (1850–present)	Kadow et al (2020)	https://doi.org/10.5281/zenodo.3766741 https://github.com/FREVA-CLINT/climatereconstructionAI

The methodology to calculate CS3 and WMO temperature indicators is different even if they both start from the same datasets and use the same 1991-2020 reference period. For the current CS3 indicators, each dataset is aligned to have the same average temperature as ERA5 for the 1991–2020 period. For JRA-55, this involves an adjustment that reduces global averages by 0.13°C and European averages by 0.03°C. Uncertainty is larger for the all-land averages due to the polar regions. The average temperature over all land points from JRA-55 is about 0.4°C higher than that from ERA5.

Sea surface temperature indicators

The sea surface temperature (SST) is an essential climate variable as it affects the atmospheric circulation, the precipitation field and tropical cyclones. The SST datasets are also important for the estimations of the global temperature field. In CS3, SST anomalies are calculated relative to the 1991-2020 average considering both satellite and in situ datesets.

Table 6 – Dataset information for the indicators associated with the sea surface temperature variable reported in CS3

Dataset	***Reference***	***Link to data***
ESA CCI/C3S SST Climate Data Record v3.0 (1981–present)	Merchant et al. (2019)	https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-sea-surface-temperature?tab=form
NOAA ERSSTv5 (U.S. National Oceanic and Atmospheric Administration) (1854–present)	Huang et al. (2017)	https://www.ncei.noaa.gov/products/extended-reconstructed-sst
HadSST.4.0.1.0 (Met Office Hadley Centre)(1850–present)	Kennedy et al. (2019)	https://www.metoffice.gov.uk/hadobs/had-sst4/data/download.html
HadISST1 (Met Office Hadley Centre)(1870–present)	Rayner et al. (2003)	https://www.metoffice.gov.uk/hadobs/hadi-sst/data/download.html

The SST indicators are calculated in CS3 for the whole Europe and for the Baltic, Black, Mediterranean and North Sea areas. The satellite data starts in 1981 while the in situ ERSSTv5 and HadSST4 dataset extends back to 1854 and 1850, respectively. For the satellite data, the anomalies are calculated daily based on a daily climatology computed from a five-day average centred on each day. For the in situ datasets, anomalies are calculated on a monthly basis by subtracting the 1991–2020 mean anomaly (relative to the original baseline used by the dataset) for each month. Daily anomalies are aggregated to monthly anomalies, and the monthly anomalies are aggregated to annual anomalies.

The ESA CCI/C3S SST Climate Data Record v3 dataset provides daily estimates of global sea surface temperature (SST) based on observations from multiple satellite sensors since September 1981. The products are available as Climate Data Records (CDRs), which have sufficient length, consistency, and continuity to be used to assess climate variability and changes. These SST CDRs are identical to those produced as part of the European Space Agency (ESA) SST Climate Change Initiative (CCI) project.

The Extended Reconstructed Sea Surface Temperature (ERSSTv5) dataset is a global monthly analysis of SST data derived from the International Comprehensive Ocean–Atmosphere Dataset (ICOADS). The dataset can be used for long-term global and basin-wide studies and incorporates smoothed local and short-term variations.

The Met Office Hadley Centre's sea surface temperature dataset, HadSST.4.0.1.0, is a monthly global field of SST on a 5° latitude by 5° longitude grid from 1850 to date. HadSST.4.0.1.0 is produced by taking in situ measurements of SST from ships and buoys and calculating a robust average of the resulting anomalies on a 5° by 5° degree monthly grid. After gridding the anomalies, bias adjustments are applied to reduce the effects of changes in SST measuring practices. The SST data are taken from release 3.0.0 of the International Comprehensive Ocean-Atmosphere Data Set, ICOADS, from 1850 to 2014 and from ICOADS release 3.0.1 from 2015 onwards. From January 2016, these are supplemented by drifting buoy observations from the Copernicus Marine Environment Monitoring Service (CMEMS).

The Met Office Hadley Centre's sea ice and sea surface temperature dataset, HadISST1, has replaced the Global sea Ice and Sea Surface Temperature (GISST) datasets, and is a unique combination of monthly globally-complete fields of SST and sea ice concentration on a 1 degree latitude-longitude grid from 1870 to date. The SST data are taken from the Met Office Marine Data Bank (MDB), which from 1982 onwards also includes data received through the Global Telecommunications System (GTS). The sea ice data are taken from a variety of sources including digitized sea ice charts and passive microwave retrievals. The sea ice fields are made more homogeneous by compensating satellite microwave-based sea ice concentrations for the impact of surface melt effects on retrievals in the Arctic and for algorithm deficiencies in the Antarctic, and by making the historical in situ concentrations consistent with the satellite data. SSTs near sea ice are estimated using statistical relationships between SST and sea ice concentration.

Glacier indicators

The annual mass balance of a glacier is calculated as the difference between snow accumulation (mass gain) and melt of ice and snow (mass loss) over a year and is affected by the prevalent atmospheric conditions. Long-term cumulative glacier mass changes are thus a valuable indicator integrating the effects of various components of the global climate system on snow and ice. The global net loss of glacier mass contributes to sea level rise (Zemp et al. 2019), whereas seasonal melting of ice and snow contributes to runoff.

Data on glacier mass balance are collected through the worldwide network of the World Glacier Monitoring Service (WGMS). The WGMS has identified some “reference glaciers”, i.e. glaciers that have more than 30 years of continuous glaciological mass-balance measurements. They are selected as their fluctuations are mainly driven by climatic factors and are not subject to other major factors such as avalanches, calving or surge dynamics, heavy debris cover, artificial snow production or melt protection.

Table 7 – Dataset information for the indicators associated with the glacier mass balance variable reported in CS3 and WMO

Dataset	***Reference***	***Link to data***
World Glacier Monitoring Service Glacier mass change	WGMS (2023)	https://wgms.ch/data_databaseversions
Composite data of WGMS in situ and geodetic mass balance	Zemp et al. (2019)	https://zenodo.org/records/1492141
GRACE (US National Aeronautics and Space Administration)	Wouters et al. (2019)	https://svs.gsfc.nasa.gov/3910

In CS3 the mass balance estimates are based on a subset of global and European WGMS reference glaciers within the time period from 1957 to 2022. The reference year is 1997. In the WMO State of the Global Climate reports, two additional datasets have been considered: the first one is based in the comparison of repeated digital elevation models of the ice surface, referred to as the geodetic method, and it allows assessing the volume change of large glacier samples at time intervals of a few years to decades (Zemp et al. 2019). The second dataset is based on the Gravity Recovery and Climate Experiment (GRACE) and has provided direct observations of glacier mass changes from space, only at a spatial resolution of 100 km or more, until its cessation in 2017.

Table 8 – Dataset information for the indicators associated with the ice sheet variable reported in CS3

Dataset	***Reference***	***Link to data***
Ice sheet Mass Balance Inter-comparison Exercise (IMBIE)	IMBIE (2018, 2020)	http://imbie.org/data-downloads

Ice sheet indicators

Ice sheets cover most of Greenland and Antarctica, and store about 68% of the planet's freshwater resources. Ice sheets gain mass through snowfall accumulation at the surface, and lose mass through surface meltwater runoff, sublimation, evaporation, and snow erosion by the wind as a result of interactions with the atmosphere, and via solid ice discharge to the ocean. As for glaciers, long-term cumulative ice sheet mass changes contribute to sea level rise and are a valuable climate indicator.

The mass balance of the ice sheets can be estimated from satellite data by measuring changes in the volume of the ice sheets, by measuring fluctuations in Earth's gravity field to assess any redistribution of mass caused by changes. In CS3 the cumulative mass balance estimates come from the Ice Sheet Mass Balance Inter-comparison Exercise (IMBIE). The IMBIE dataset combines mass balance estimates from three independent satellite techniques – gravimetry, altimetry and input-output method – and their associated uncertainty. For Greenland, 26 different surveys were used to produce this single community estimate; 24 were used for Antarctica.

Table 9 – Dataset information for the indicators associated with the sea ice variable reported in CS3 and WMO

Dataset	***Reference***	***Link to data***
OSI-SAF version 3 (EUMETSAT Ocean and Sea Ice Satellite Application Facility) (1978–present)	OSI-SAF (2022)	https://navigator.eumetsat.int/product/EO:EUM:DAT:0645
C3S Sea Ice Edge and Type CDR v3.0	Aaboe et al. (2021)	https://cds.climate.copernicus.eu/cdsapp#!/data-set/10.24381/cds.29c46d83?tab=form
Sea Ice Index, Version 3 (National Snow and Ice Data Center)(1978–present)	Fetterer et al. (2017)	https://doi.org/10.7265/N5K072F8

Sea ice indicators

Sea ice in both polar regions plays an important role in the climate system as it is influenced by the temperature of the air and of the water, as well as by surface winds and ocean currents. The presence or absence of sea ice has a profound impact on the water below it and the air above it: a reduction in sea ice cover allows more solar energy to be absorbed by the ocean (because of reduced albedo), and more heat to be released from the ocean into the atmosphere, which can then lead to further sea ice loss. This feedback loop has been one of the main drivers of Arctic amplification (Serreze and Barry 2011), the phenomenon describing the more rapid warming of the northern polar region relative to the rest of the world.

The gridded sea ice datasets in CS3 come from the EUMETSAT Ocean and Sea Ice Satellite Application Facility (OSI SAF) Global Sea Ice Concentration Climate Data Record v3.0. Sea ice concentration, edge and type datasets are daily products derived from satellite passive microwave observations and covering the period from October 1978 to present. For the type product, ocean grid points are classified as open water, first-year ice, or multiyear ice.

To generate monthly mean sea ice concentrations, the gridded data are first linearly interpolated in time. This gap filling procedure is only applied to the months of March and September for the Northern Hemisphere (of February and September for the Southern Hemisphere). The median sea ice edge is defined as the contour line along which grid cells have a 50% probability of being classified as open water or open ice in the daily gridded sea ice edge product. Note that this product uses a threshold of 30% ice concentration to distinguish between open water and open ice. For the time series of Arctic average sea ice types, the total daily sea ice area associated with each sea ice type is first calculated and then used to compute monthly averages and 3-month averages for January–March.

In the WMO State of the Global Climate reports the sea ice indicator is the “sea ice extent” defined as the area covered by ice concentrations greater than 15%. As in CS3 the sea ice extent is derived from passive microwave satellite measurements and the additional dataset from the National Snow and Ice Data Center, the Sea Ice Index, Version 3, is considered.

Table 10 – Dataset information for the indicators associated with the GHG concentration variable reported in CS3 and WMO

Dataset	***Reference***	***Link to data***
C3S climate data record XCO_2	Buchwitz et al (2023)	https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-carbon-dioxide?tab=overview
C3S climate data record XCH_4	Buchwitz et al (2023)	https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-methane?tab=overview
CAMS near real-time data record XCO_2	Heymann et al (2015)	http://www.iup.uni-bremen.de/~ghguser/
CAMS near real-time data record XCH_4	Butz et al (2011)	ftp://ftp.sron.nl/PROXY_NRT_L1X
WMO Greenhouse Gas Bulletin	WMO (2023b)	https://community.wmo.int/en/wmo-greenhouse-gas-bulletins

<u>Greenhouse gas concentrations indicators</u>

Among the greenhouse gases that are emitted by human activities, the ones that have the largest climate impact are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). In CS3 satellite data are used to monitor the atmospheric concentrations of carbon dioxide (CO_2) and methane (CH_4), but not of nitrous oxide (N_2O) as they are judged to be non accurate enough.

The C3S XCO_2 and XCH_4 satellite-derived data products are available from the Climate Data Store and they have been generated using retrieval algorithms using radiance spectra as measured by the satellite instruments SCIAMACHY on Envisat, TANSO-FTS onboard the Japanese GOSAT satellite and NASA's OCO-2 satellite mission. The CAMS XCO_2 data product has been retrieved in near real-time (NRT) from radiances as measured by the GOSAT satellite using the BESD algorithm (Heymann et al. 2015). The CAMS XCH_4 data product has also been retrieved from GOSAT radiances but using the RemoTeC algorithm (Butz et al. 2011) developed at SRON.

In the WMO State of the Global Climate reports the reference dataset is the WMO Greenhouse Gas Bulletin where all greenhouse gas observations are performed following the recommendation for quality assurance. The preindustrial levels of CO_2 are estimated with the same techniques as are used for modern in situ measurements but using analysis of the air trapped in ice cores.

Table 11 – Dataset information for the indicators associated with the sea level variable reported in CS3

Dataset	***Reference***	***Link to data***
CS3 Ssalto/Duacs Multimission Altimeter Products	Taburet et al. (2023)	https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-sea-level-global?tab=form

Sea level indicator

The changes in mean sea level are affected by both the thermal expansion of the ocean in response to its warming and by the increase in ocean mass due to the melting of ice sheets and glaciers. Long-term and interannual variations in sea level are observed at both global and regional scales. These variations can seriously impact coastal communities, where sea level variations are superimposed on local effects.

The sea level dataset used in CS3 is based on the sea level Ocean Monitoring Indicators produced by the Copernicus Marine Environment Monitoring Service (CMEMS). These datasets are derived from the Data Unification and Altimeter Combination System (DUACS) delayed-time altimeter gridded maps of sea level anomalies and are climate-oriented, that is, dedicated to the monitoring of the long-term evolution of sea level and the analysis of the ocean/climate indicators, both requiring a homogeneous and stable sea level record. To achieve this, a steady two-satellite merged constellation is used at all time steps in the production system: one satellite serves as reference and ensures the long-term stability of the data record; the other satellite (which varies across the record) is used to improve accuracy, sample mesoscale processes and provide coverage at high latitudes. The sea level anomalies are computed with respect to the 1993–2012 reference period. A convention is then applied for the whole time series so that the averaged global mean sea level during the year 1993 is set to zero.

3. OTHER RELEVANT CLIMATE INDICATORS

El Niño/Southern Oscillation (ENSO)

El Niño and the Southern Oscillation (ENSO) is a periodic climatic recurrent pattern across the equatorial Pacific Ocean registered both in terms of sea surface temperature (SST) and sea level pressure anomalies. Statistically its frequency can vary from three to seven years. Like many other climatic patterns, ENSO is characterized by positive and negative phases, which have distinctive effects on the distribution of rainfall, temperature and other meteorological and oceanographic conditions on specific areas of the globe.

ENSO onset is due to the peculiar equatorial coupled dynamics taking place between the Pacific Ocean and the above atmospheric circulation. The Southern Oscillation Index (SOI) is defined as a standardized difference between the sea level pressure measurements registered in the cities of Darwin and Tahiti. Lower pressure over Darwin and higher pressure over Tahiti favour easterly winds, forcing warm surface water westward and more precipitations to Australia and to the western Pacific. During El Niño conditions, the pressure difference between Darwin and Tahiti weakens: Australia may then experience severe droughts, while heavy precipitations can bring floodings to the west coast of the equatorial South America.

SST anomalies are generally used to monitor ENSO evolution. The Oceanic Niño Index (ONI) is defined as the SST anomaly running mean over three months in the so-called Niño 3.4 region, i.e. the portion of equatorial Pacific Ocean from 170°W to 120°W longitude. Warm and cold ENSO phases are defined as a minimum of five consecutive 3-month running averages of SST anomalies in the Niño 3.4 region surpassing a threshold of +/- 0.5°C.

The SOI dataset can be found either at http://www.bom.gov.au/climate/enso/soi or at https://psl.noaa.gov/gcos_wgsp/Timeseries/SOI .

The ONI dataset can be found at https://psl.noaa.gov/data/correlation/oni.data .

North Atlantic Oscillation (NAO)

The North Atlantic Oscillation (NAO) is a periodic climatic recurrent pattern in the northern hemisphere. Unlike ENSO, the NAO is a largely atmospheric mode and it is registered in terms of sea level pressure (SLP) anomalies between the Azores (high pressure) and Iceland (low pressure). Positive NAO phases are associated with an increase in the sea level pressure over most parts of continental Europe and the Mediterranean Sea and below-normal temperatures in Greenland. With a positive NAO, both poles, the Azores high and the Iceland low, are intensified, modifying the direction of the westerlies and associated storm tracks, thus leading to a decrease in the precipitation over the Mediterranean and Southern Europe and an increase over Northern Europe. On the other hand, negative NAO phases generate opposite patterns with negative SLP anomalies in Southern Europe and the Mediterranean basin, increasing the precipitation in these regions.

The NAO oscillation period is not regular as it may reverse within 10-20 days and also seasonally throughout the year thus showing some meteorological variability.

The NAO dataset can be found at https://psl.noaa.gov/data/20thC_Rean/timeseries/monthly/NAO .

Arctic Oscillation (AO)

The Arctic Oscillation (AO) is the dominant periodic climatic recurrent pattern in the northern hemisphere at high latitudes, i.e. north of 20°N. It is a largely atmospheric pattern linked to the North Atlantic Oscillation and characterized by the SLP anomalies between the Arctic (low pressure) and the mid-low latitudes, i.e. the area centered about 37-45°N (high pressure). The AO index varies over time with no particular periodicity.

The AO is defined so that the positive phase corresponds to periods when the Arctic SLP is lower normality, the Arctic polar vortex is stronger and enhanced surface westerlies in the North Atlantic are registered. This is the "warm phase" as warmer and wetter than normal conditions take place in northern Europe. In the negative or "cool" phase the pattern is opposite with a weaker Arctic polar vortex, weaker westerlies and with a colder northern Europe as it gets hit with Arctic cold air.

The AO is important for the surface circulation and for the ice residence times within the Arctic Ocean. With positive AO indices the Beaufort Gyre is weakened and the Transpolar Drift can export more sea ice out of the Arctic Ocean. With negative AO indices the Beaufort Gyre is strengthened, the Transpolar Drift is weaker and more sea ice can recirculate within the Arctic Ocean.

The AO dataset can be found either at https://psl.noaa.gov/data/20thC_Rean/timeseries/monthly/AO or https://web.archive.org/web/20130518050021/http://jisao.washington.edu/data/aots .

The Mediterranean Oscillation (MO)

The Mediterranean Oscillation (MO) is a periodic climatic pattern between the western and eastern parts of the Mediterranean region. It has been firstly proposed by Conte et al. (1989) as the normalized 500-hPa height difference anomalies between the cities of Algiers and Cairo. Alternative definitions have estimated the MO index as the difference in the normalized SLP between the Strait of Gibraltar and the Lod Airport in Israel (Palutikof 2003) or between Marseille and Jerusalem (Brunetti et al. 2002). Using the latter definition, good (anti-)correlation values have been found between the MO index and the precipitation and the number of wet days in Italy.

In both MO phases, the SLP pattern induces wind trajectories that are closely related to the evaporation and net heat flux variability: warmer and moister air masses are transported to the central and western Mediterranean in the MO positive phase, as a consequence of the positive SLP anomaly dipole structure between north Africa and central Europe, resulting in milder winters and the subsequent decrease in evaporation and heat loss. Conversely, negative MO phases are characterized by a dipole of low SLP anomalies between Turkey and Central Europe, enhancing the flow of cold and dry air masses from continental regions to the Mediterranean. This results in severe winters in the Aegean and Levantine basins that increase evaporation and heat losses, favoring the convective processes that generate the Levantine Intermediate Waters (Criado-Aldeanueva et al. 2014).

The MO dataset can be found at https://crudata.uea.ac.uk/cru/data/moi .

Extreme events indicators

The impacts of weather and climate are most clearly felt during extreme events like, for example, heavy rain and snow, droughts and heatwaves. It has always been important to define indicators of extremes characterizing episodic events as these meteorological and climatological extremes, individually or in combination and in conjunction with other factors, can lead to other events such as flooding, landslides and wildfires. Statistical methods that do not rely on assumptions that the data are drawn from a given probability distribution (non-parametric approaches) can be used for extreme events with short return periods. One of the first effort using a non-parametric approach is due to the Expert Team on Climate Change Detection and Indices (ETCCDI) that has defined indices to characterize different temperature and precipitation extremes, also used in the IPCC Assessment reports. Similar indices to those proposed by ETCCDI have been used also to characterize droughts in the last IPCC Assessment Reports even though ETCCDI activities have been discontinued since 2018. For events with longer return periods (e.g., events that occur once in 20 years or even more rarely), the parametric approach based on Extreme Value Theory (EVT; Coles 2001) is used and adopted in the literature. Table 12 reports both non-parametric and parametric indices used in the last IPCC Report for extreme events in temperature, precipitation, and drought.

The same last IPCC Report introduces the term "Climatic impact-drivers" (CIDs) to describe changes in physical systems rather than "hazards", because the term hazard already assumes an adverse consequence. The terminology of CID allows to provide a more value-neutral characterization of climatic changes that may be relevant for understanding potential impacts, without pre-judging whether specific climatic changes necessarily lead to adverse consequences, as some could also result in beneficial outcomes depending on the specific system and associated values. "Extremes" are a category of CID, corresponding to unusual events with respect to the range of observed values of the variable.

At the same time, the last IPCC Report proposes the definition of the so-called "Climatic Impact-Driver indices" as as "numerically computable indices using one or a combination of climate variables designed to measure the intensity of the climatic impact-driver, or the probability of exceedance of a threshold. For instance, an index of heat inducing human health stress is the Heat Index (HI) that combines temperature and relative humidity (e.g., Burkart et al. 2011; Lin et al. 2012; Kent et al. 2014) and is used by the US National Oceanic and Atmospheric Administration (NOAA) for issuing heat warnings". The IPCC Report has decided to select a limited number of indices as it would have been impossible to cover all those developed in the literature and related to CDIs. The selection has been based on expert judgement using the following guiding principles. The set of indices should:

- describe the evolution of a manageable and illustrative number of indices;
- cover these categories, while giving more weight to those with a higher number of potential impacts as described in the literature;
- be used broadly in the literature;
- allow easy computation from publicly available model outputs and observations, or be accessible from published material through contact with the authors;
- be well evaluated in model simulations, or based on ECVs that are well evaluated in model simulations;
- represent CIDs of interest to regional impacts and risk assessments.

The selection has resulted in 13 regional indices that are reported in Table 13.

Table 12 – Extreme indices used and reported in the last IPCC Assessment Report (IPCC 2021)

Extreme	*Label*	*Index Name*	*Units*	*Variable*
Temperature	TXx	Monthly maximum value of daily maximum temperature	°C	Maximum temperature
	TXn	Monthly minimum value of daily maximum temperature	°C	Maximum temperature
	TNn	Monthly minimum value of daily minimum temperature	°C	Minimum temperature
	TNx	Monthly maximum value of daily minimum temperature	°C	Minimum temperature
	TX90p	Percentage of days when daily maximum temperature is greater than the 90th percentile	%	Maximum temperature
	TX10p	Percentage of days when daily maximum temperature is less than the 10th percentile	%	Maximum temperature
	TN90p	Percentage of days when daily minimum temperature is greater than the 90th percentile	%	Minimum temperature
	TN10p	Percentage of days when daily minimum temperature is less than the 10th percentile	%	Minimum temperature
	ID	Number of icing days: annual count of days when TX (daily maximum temperature) <0°C	Days	Maximum temperature
	FD	Number of frost days: annual count of days when TN (daily minimum temperature) <0°C	Days	Minimum temperature
	WSDI	Warm spell duration index: annual count of days with at least six consecutive days when TX >90th percentile	Days	Maximum temperature
	CSDI	Cold spell duration index: annual count of days with at least six consecutive days when TN <10th percentile	Days	Minimum temperature
	SU	Number of summer days: annual count of days when TX (daily maximum temperature) >25°C	Days	Maximum temperature
	TR	Number of tropical nights: annual count of days when TN (daily minimum temperature) >20°C	Days	Minimum temperature
	DTR	Daily temperature range: monthly mean difference between TX and TN	°C	Maximum and minimum temperature
	GSL	Growing season length: annual (1 Jan to 31 Dec in Northern Hemisphere (NH), 1 July to 30 June in Southern Hemisphere (SH)) count between first span of at least six days with daily mean temperature TG >5°C and first span after July 1 (Jan 1 in SH) of six days with TG <5°C	Days	Mean temperature
	20TXx	One-in-20 year return value of monthly maximum value of daily maximum temperature	°C	Maximum temperature
	20TXn	One-in-20 year return value of monthly minimum value of daily maximum temperature	°C	Maximum temperature
	20TNn	One-in-20 year return value of monthly minimum value of daily minimum temperature	°C	Minimum temperature
	20TNx	One-in-20 year return value of monthly maximum value of daily minimum temperature	°C	Minimum temperature
Precipitation	Rx1day	Maximum one-day precipitation	mm	Precipitation
	Rx5day	Maximum five-day precipitation	mm	Precipitation
	R5mm	Annual count of days when precipitation is greater than or equal to 5 mm	Days	Precipitation
	R10mm	Annual count of days when precipitation is greater than or equal to 10 mm	Days	Precipitation
	R20mm	Annual count of days when precipitation is greater than or equal to 20 mm	Days	Precipitation
	R50mm	Annual count of days when precipitation is greater than or equal to 50 mm	Days	Precipitation
	CDD	Maximum number of consecutive days with less than 1 mm of precipitation per day	Days	Precipitation
	CWD	Maximum number of consecutive days with more than or equal to 1 mm of precipitation per day	Days	Precipitation
	R95p	Annual total precipitation when the daily precipitation exceeds the 95th percentile of the wet-day (>1 mm) precipitation	mm	Precipitation
	R99p	Annual precipitation amount when the daily precipitation exceeds the 99th percentile of the wet-day precipitation	mm	Precipitation
	SDII	Simple precipitation intensity index	mm day^{-1}	Precipitation
	20Rx1day	One-in-20 year return value of maximum one-day precipitation	mm day^{-1}	Precipitation
	20Rx5day	One-in-20 year return value of maximum five-day precipitation	mm day^{-1}	Precipitation
Drought	SPI	Standardized precipitation index	Months	Precipitation
	EDDI	Potential evaporation, evaporative demand drought index	Months	Evaporation
	SMA	Soil moisture anomalies	Months	Soil moisture
	SSMI	Standardized soil moisture index	Months	Soil moisture
	SRI	Standardized runoff index	Months	Streamflow
	SSI	Standardized streamflow index	Months	Streamflow
	PDSI	Palmer drought severity index	Months	Precipitation, evaporation
	SPEI	Standardized precipitation evapotranspiration index	Months	Precipitation, evaporation, temperature

Table 13 – Regional CID indices as reported in the last IPCC Assessment Report (IPCC 2021)

Climatic Impact-driver Category	Climatic Impact-driver and Potential Affected Sectors	Index	Required ECVs	References
Heat	Change in cooling demand for energy demand and building consumption	Cooling degree days above 22°C	Tas, tasmin, tasmax	Spinoni et al. (2015, 2018)
	Heat, with thresholds important for agriculture	Number of days with Tmax >35°C or 40°C (TX35, TX40)	Tasmax	Hatfield and Prueger (2015); Hatfield et al., (2015); Grotjahn (2021)
	Heat stress index combining humidity used in occupational and industrial health	NOAA heat index (HI): number of days above 41°C threshold	Tasmax, huss, ps	Burkart et al. (2011); Lin et al. (2012); Kent et al. (2014)
Cold	Heating degree day for energy consumption	Heating degree days below 15.5°C	Tas, tasmin, tasmax	Spinoni et al. (2015, 2018)
	Frost	Number of frost days below 0°C (FD)	Tasmin	Barlow et al. (2015); Rawlins et al. (2016)
Wet	River flooding	Flood index (FI)	srroff/mrro	Forzieri et al. (2016); Alfieri et al. (2017)
Drought	Aridity	Soil moisture (SM)	mrso	Cook et al. (2020)
	Droughts	Standardized Precipitation Index accumulated over 6 months (SPI-6)	Pr	Naumann et al. (2018)
Wind & storm	Mean wind speed	Annual mean wind speed	sfcWind	Karnauskas et al. (2018); Li et al. (2018)
Snow/ice	Snow season length	Number of days with snow water equivalent >100 mm (SWE100) over the snow season (Nov–Mar for NH)	Snw	Damm et al. (2017); Wobus et al. (2017)
Coastal	Extreme sea level (ETWL) inducing storm surges	1-in-100-year return period level (ETWL)		Vousdoukas et al. (2018)
	Coastal erosion	Shoreline retreat by mid-and end of century		Vousdoukas et al. (2020)

Combining different variables and/or parameters: composite indicators

One of the first examples of combination of climate indicators is the obsolete IGBP Climate-Change Index (Noone et al. 2011). The idea behind the IGBP Climate Change Index is to mimic the Dow Jones Index used in the stock market by considering only the incremental contribution of the top parameter changes in a complex system. The IGBP Index calculation is based on four climate observed variables, namely: CO_2 concentration in the atmosphere, global mean sea-level, Arctic sea-ice minimum, and global average temperature. The annual change of each variable is normalized with respect to the average of the period considered before the combination. The value of the index for each year is then added to that of the previous year to show the cumulative effect of the changes. A positive rising index means moving away from the reference 1980 year, i.e. a shift away from a relatively stable climate. A negative dropping index means moving back towards the reference, i.e. moving toward a relatively stable climate. The index has been basically abandoned after the announcement of the termination of IGBP activities at the end of 2015.

The Community Temperature Index (CTI) is another composite indicator used in ecology to monitor species response to climate change, particularly to the increase of ambient temperatures. The index uses the species' thermal traits: warm-adapted species are expected to be favored with respect to cool-adapted ones with increasing temperatures. The CTI calculation is a weighted mean of the temperature preferences of species in a community, in which each species' temperature preference is weighted by its observed abundance, namely:

$$CTI = \sum_{s=1}^{n} TP_s \times RA_s$$

where the number of species in the community is *n* and each species *s* has a temperature preference (*TP*) and a relative abundance (*RA*, the species' abundance divided by the abundances of all species) in the community. This change in community composition can be used as a generalized indicator of the realized impacts of temperature change on communities. The CTI has been adopted as an indicator of climate change impact on biodiversity by the pan-European framework supporting the Convention on Biological Diversity. A temporal increase in CTI means that the site's community is increasingly composed of individuals belonging to warm-adapted species. Using the CTI, Devictor et al. (2012) have characterized bird and butterfly communities for each year from 1990 to 2008. They have showed that changes in community composition are rapid but different and equivalent to a 37 and 114 km northward shift in bird and butterfly communities, respectively. More recently, Arriaga et al. (2023) has used the CTI to show that macroalgal communities in the Southern Bay of Biscay have responded quickly to global warming with an increasing predominance of warm-temperature kelps during the years and suggesting an east-west meridionalisation of the region.

Another example of variable combination is the one put forth by Cyr and Galbraith (2021) to propose a new climate indicator for the Newfoundland and Labrador (NL) area. The NL climate index combines ten normalized anomalies derived annually by the following physical variables:

1. winter North Atlantic Oscillation;
2. air temperature;
3. sea ice season severity;
4. iceberg count;
5. seasonal sea surface temperature;
6. vertically averaged temperature at a specific mooring station (Station 27 of the Atlantic Zone Monitoring Program, AZMP);
7. vertically averaged salinity at the same station;
8. summer cold intermediate layer (CIL) at the same station;
9. summer CIL area on three AZMP hydrographic sections;

10. bottom temperature on the NL shelf.

The NL index starts from 1951 and is updated annually. It clearly resolves (Figure 3) the period in the early 1990s, characterized by anomalously cold and potentially unfavourable environmental conditions for fish stocks, which arguably led to the collapse of the Atlantic zone groundfish fisheries (de Young and Rose 1993). It is thus expected to be used for ecosystem studies, stock assessments and models of marine resources.

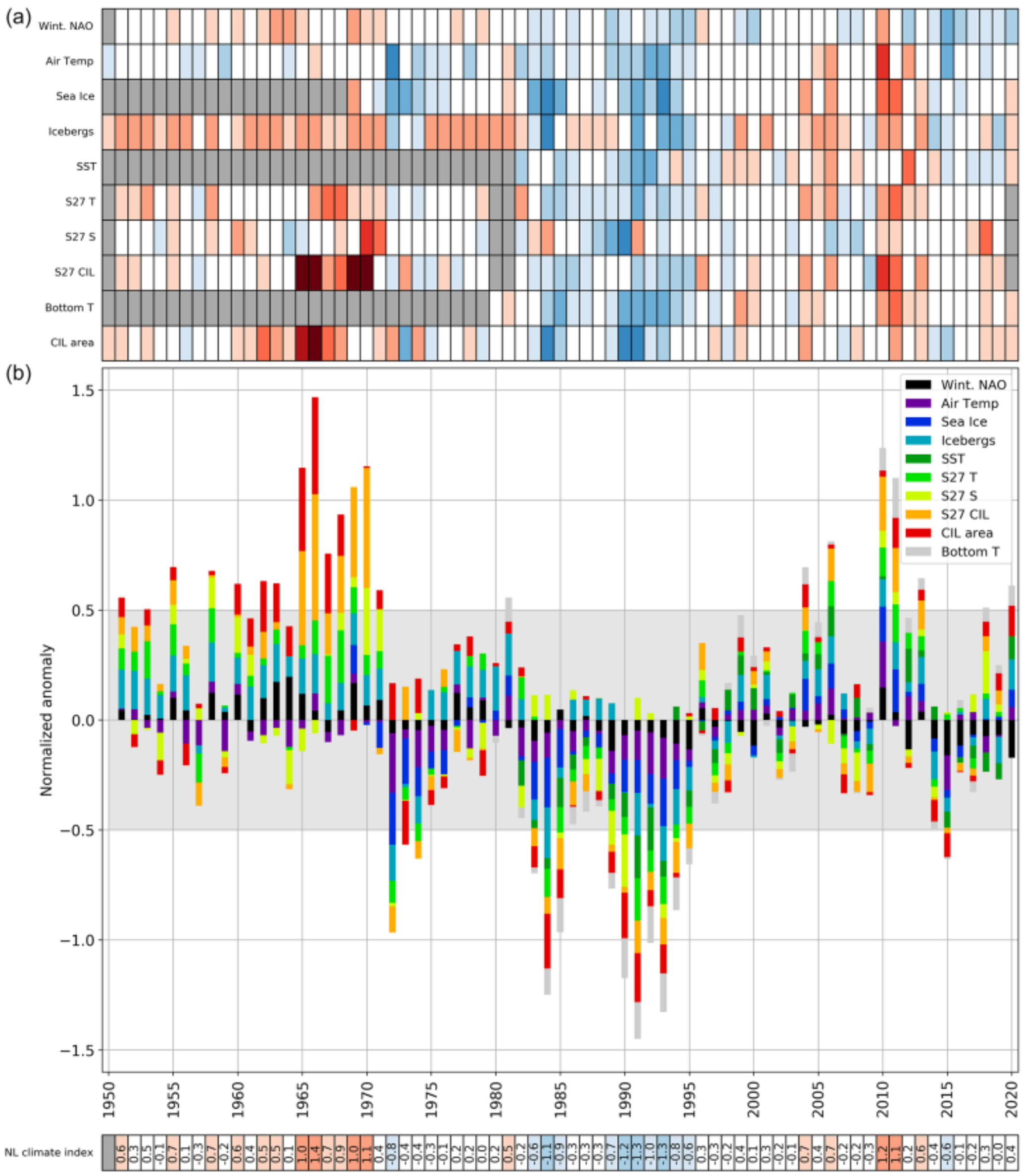

Figure 3: The NL climate index as described by Cyr and Galbraith (2021). Top panel a) represents the 10 variables or indices used to construct the climate index, colour coded according to their value (blue negative, red positive, white neutral). The sign of some variables or indices (NAO, ice, icebergs, salinity and CIL volume) has been reversed when positive anomalies are generally indicative of colder conditions. Grey cells indicate the absence of data. Bottom panel b) represents the climate index with all contributions of the variables or indices.

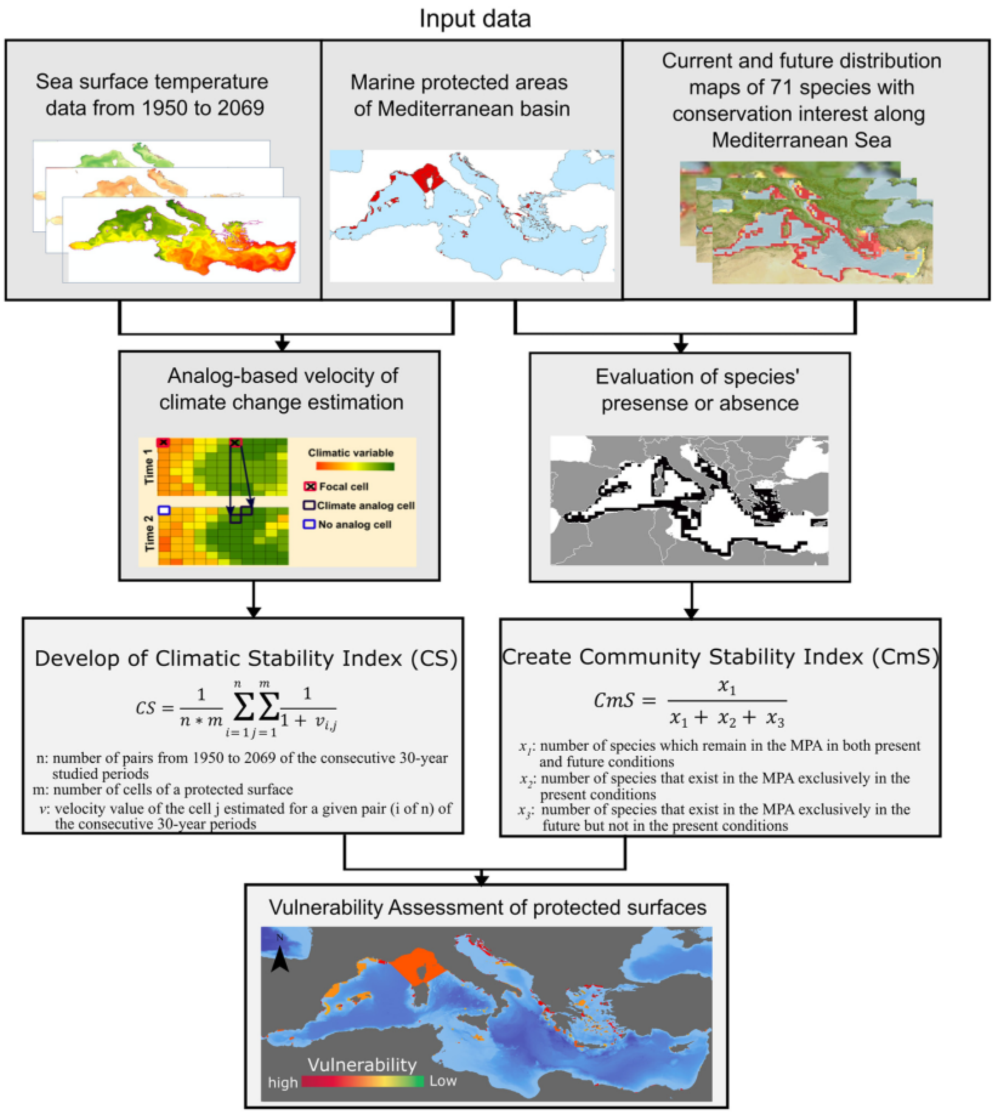

Figure 4: The methodology used in Kyprioti et al. (2021) to assess vulnerability of Mediterranenan Marine Protected Areas to climate changes.

In Kyprioti et al. (2021), a Climatic Stability (CS) index is built using spatial information on Mediterranean Marine Protected Areas (MPAs) and high-resolution sea surface temperature data in the period 1950-2069, coming from both historical simulations and future projections. The CS index is then combined with a Community Stability (CmS) index to assess vulnerability of MPAs to climate changes (Figure 4). The CmS index considers both the number of species which would remain in an MPA site in the future, but also the new species which would be added due to climate changes. It uses maps of current and future distribution of species from the Aquamaps dataset (Kaschner et al. 2019) which provides predictions on marine species distribution based on ecological niche models, built on environmental variables such as temperature, primary production, and salinity. It is found that about 70% of the Mediterranean MPAs are highly vulnerable to climate change and that climatic considerations cannot be neglected and must be taken into account in systematic conservation plans.

4. RECOGNIZED GAPS

The last BAMS 2022 State of the Climate report (Blunden et al. 2023) clearly recognizes gaps in terms of the Essential Climate Variables framework. According to the report, the following variables are considered partially monitored due to observing limitations or availability of data:

- Atmospheric composition: aerosols properties, cloud properties, precursors of aerosol and ozone
- Ocean physics: subsurface currents
- Ocean biogeochemistry: inorganic carbon
- Land: above-ground biomass, anthropogenic greenhouse gas fluxes, fire, fraction of absorbed photo-synthetically active radiation, glaciers, groundwater, ice sheets and ice shelves, lakes, permafrost, soil moisture
- Surface atmosphere: surface radiation budget.

At the same time the following variables are not yet covered in the report, or judged to be outside its scope:

- Ocean physics: sea state
- Ocean biogeochemistry: nitrous oxide, nutrients, oxygen, transient tracers
- Ocean biogeosystems: marine habitat properties
- Land: anthropogenic water use, land cover, land surface temperature, latent and sensible heat fluxes, leaf area index, soil carbon.

The atmospheric variables are the best represented especially for the upper atmosphere ECV sub-category and have the only exceptions in a few ECVs only partially covered for the surface atmosphere and the atmospheric composition. The ITINERIS activities inside the WP4 - Atmosperic domain represent an important opportunity to contribute filling this gap especially to study aerosol size distribution and chemical properties, aerosol vertical transport and new aerosol formation in particular in the Mediterranean basin and Po Valley, hot spot areas for air quality and climate in Europe. The development of the AERO VRE in the ITINERIS WP8 will also produce climatological charts of the aerosol types occurred at the different sites together with indicators of the occurrence of the desert dust presence and validation activities of satellite observations.

The BAMS 2022 State of the Climate report suggests that the main gaps are in the ocean and land categories, especially with respect to the biological component. In ITINERIS, the WP6 – Terrestrial Biosphere has a specific objective (OBJ1) to integrate and harmonize data from the different RIs and to fill gaps in the key observations needed on land to ensure the provision of a complete and exhaustive view of the terrestrial ecosystems. Furthermore, more Virtual Research Environments in the ITINERIS WP8 are dedicated to terrestrial ecosystems. The WP6 results will be gathered in the Essential Variables VRE producing services and tool for data analysis, data visualization, and collaboration among researchers, focused on the global frameworks provided by the Essential Variables. The Critical Zone VRE will consider both purely terrestrial and freshwater systems such as lakes, ponds, streams, and aquifers. The BIOMASS VRE will focus on biomass responses to climate change in aquatic ecosystems by integrating data resources, services, and modelling tools of different RIs. The Crop, Plants and Pests VRE will look at process-based models for crop production, water use, plant phenology, pest and disease spread, pathogen dynamics and impacts.

The considerations for the ocean are more critical: deliverable D5.5 has already pointed out that only 17% of the ITINERIS marine facilities measure at least one marine essential biological variable (EBV) or bio-eco essential ocean variable (bio-eco EOV). Most marine EBVs (i.e. 10 on the total number of 18) are currently nowhere observed by any RI participating in the ITINERIS project. Activities inside the WP5 – Marine domain, will start filling this gap by increasing the number of autonomous sensors, floats, vehicles, and smart devices able to measure bio-eco EOVs and EBVs. Following this direction, specific activities will be aimed to increase nutrient measurements at depth via gliders, surface velocity profilers and Argo floats.

5. CONCLUSIONS AND SUGGESTIONS FOR THE CLIMA VRE

Two main suggestions may be put forth for the CLIMA VRE following the existing information and data gaps reported in this deliverable.

The first suggestion is to focus on the marine domain while structuring the CLIMA VRE inside a cluster where datasets, modelling and visualization tools may be shared among the different ITINERIS VREs. This approach will favour the cross-domain VRE interactions optimizing the general WP8 effort in filling the gaps on climate-related activities. The considerations raised in the previous section suggest that the CLIMA VRE needs to tighten the important points of contact with the AERO, Essential Variables, Critical Zone, BIOMASS and Crop, Plants and Pests VREs. For example, datasets of interest or created in these other VREs may be then used in the CLIMA VRE to combine and create a new indicator and viceversa. This same suggestion has also two practical implications on the technical implementation of the CLIMA VRE. The first implication is that a proper and common Data Infrastructure must be selected in agreement with the other VREs of interest to ease the sharing processes. The second is that a special CLIMA VRE software tool must be implemented to get direct access to the other VRE variables and datasets.

The second suggestion is to discuss the preparation of a specific set of demonstration tools for the CLIMA VRE which will be used to showcase the capabilities and potentialities of the virtual environment. Three initial demonstration tools may be envisioned:

1. Having in mind the specific target of a non-specialist audience, the first demonstration tool could calculate, as key Italian climate indicators, the sea surface temperature anomalies for the five Italian Seas, namely the Adriatic, Ionian, Ligurian, Sardinian and Tyrrhenian Seas. The idea is to combine satellite data with the in-situ sea surface temperature ITINERIS observations and use the same procedure used in CS3, starting from the same CS3 datasets, and using the same 1991-2000 reference period for the average.
2. The second demonstration tool could fill the gap of not using the “Ocean state” ECV measurements and leverage on the distribution of wave buoys along the whole Italian coasts mainly due to the GeoScience research infrastructure (see deliverable D5.3). The idea is to integrate wave buoy measurements with those for the same variable coming from HF radar systems and with satellite and modelling products (e.g. Korres et al. 2021). As in Gramcianinov et al. (2023), extreme wave indicators could be calculated using the averaged monthly 95th percentile of significant wave height to provide an overview of the wave climate along Italy. These indicators are especially useful for coastal risk analysis and for subsequent socio-economic indicators of impacts of extreme wave events.

3. The third demonstration tool could use the new nutrient measurements at depth foreseen with the new ITINERIS marine instruments. The idea in this case is to provide a virtual lab where nutrients measured by several types of platforms could be integrated at different depths to provide a new three-dimensional observational dataset to calibrate and validate the biogeochemical models used by the climate community.

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