2025 IMEKO TC26 International Conference on
Metrology for Archaeology and Cultural Heritage
Bergamo, Italy, October 15-17, 2025

Earth Observation based products for risk assessment of cultural and natural heritage against climate and pollution impact

Alessandro Sardella[1], Ramiro Marco Figuera[2], Stefano Natali[2], Alessandra Bonazza[1]

[1] National Research Council of Italy, Institute of Atmospheric Sciences of Climate (CNR-ISAC), Via Gobetti 101, 40129, Bologna, a.sardella@isac.cnr.it; a.bonazza@isac.cnr.it
[2] SISTEMA Gmbh SISTEMA GmbH, Tiefer Graben 19 /2, A-1010 Wien, figuera@sistema.at; natali@sistema.at

Abstract – **Cultural and natural heritage faces increasing threats from climate change and pollution. To address this, the INACO project (*INnovative strategies for the Adoption of risk management plans to enhance the resilience of sensitive Cultural and natural heritage Objectives against climate hazards in river basin districts*) aims to develop and enhance innovative tools for safeguarding these valuable assets. Our research focuses on the Risk Mapping Tool for Cultural Heritage Protection, a powerful instrument that combines both Earth Observation-based data and outputs from climate models. This integrated approach provides a comprehensive view of current and future risks by incorporating satellite observations with predictive climate projections. The tool's primary objective is to integrate novel variables, such as extreme indices and air quality data, to provide more accurate risk assessments. This advanced capability will directly support policy and decision-makers in their efforts to effectively manage and preserve heritage by delivering concrete, data-driven strategies.**

Introduction.

Slow and extreme changes in climate pose risks to cultural and natural Heritage, with consequent impacts on the safety of occupants and users, and to the local economies. The inappropriateness of restoration and intervention works, as well as the lack of tailored risk management plans, highly affects the vulnerability of heritage assets [1].

Within this framework, the Interreg Central Europe Project INACO, coordinated by CNR-ISAC aims at improving the resilience of the Central European Regions in facing climate change impacts on cultural and natural resources in river basin districts, exposed to threats linked to hydro-meteorological hazards [2]. Built upon the experience gained in the previously funded Interreg Central Europe Projects ProteCHt2save [3] and STRENCH [4], INACO tackles the emerging needs at the territorial level by setting up tools for improved management and testing them at different pilot sites. The project's pilot sites were chosen across diverse geographical/environmental contexts to test the project's solutions and bridge the gap between theory and practice. Three distinct types of environments were selected:

- Coastal or river-mouth sites: These include natural reserves, historic villages, and gardens located in transitional zones between a river and the sea (such as the Po Delta River in Italy and the Dubrovnik River in Croatia).
- Lakeshore sites: This category features natural reserves, historic buildings, and archaeological sites situated on the banks of lakes (like Lake Neusiedl in Austria and the town of Fonyód in Hungary).
- Inland river basin sites: This group comprises monumental complexes, historic parks, and gardens found within inland river valleys (including the Valley of Wiesent and Rednitz in Germany, the Jelenia Góra Valley in Poland, the Kosice Region in Slovakia, and the Central Bohemia Vltava River Valley in the Czech Republic).

Among the innovative solutions under development in the project, the “Risk Mapping Tool for Cultural Heritage Protection” will be upgraded [5], thanks also to the synergies with the “Extraordinary National Plan for monitoring and conservation of Italian cultural heritage”, coordinated by the Italian Ministry of Culture [6].

Summarising, the final objectives of the INACO project are the following:

- Improve the resilience of Central European regions against the impacts of climate change on cultural and natural resources.
- Develop and test innovative tools for enhanced management of heritage assets, specifically those vulnerable to hydro-meteorological hazards.

- Upgrade the "Risk Mapping Tool for Cultural Heritage Protection" by leveraging Earth Observation-based products and services.
- Bridge the gap between theoretical research and practical application by testing solutions at various pilot sites across different environmental contexts.

In particular, the present contribution focuses on the presentation of the methodological approach, introducing possible applications of the Risk Mapping Tool for Cultural Heritage Protection based on the exploitation of Earth Observation-based products and services.

I. MATERIAL AND METHODS

The Risk Mapping Tool for Cultural Heritage Protection is a web-based platform designed and implemented to support managers and curators of cultural and natural heritage in evaluating potential exposure to specific climate hazards at the regional level and assessing the vulnerability of their heritage at the local scale. One of the tools of the platform is specifically set up to facilitate the investigation among a set of climate and air quality products, analysing and downloading maps and time series of specific parameters and functions, as follows:

- air quality parameters influencing the damage process in cultural heritage materials.
- climate data related to selected climate variables and climate extreme indices based on the change of temperature and precipitation, and linked to heavy rain, flooding, drought and extreme heating.
- damage functions for quantitative evaluation of the impact of climate and air quality parameters on heritage materials (surface recession, biomass accumulation) [1, 7].

In our approach, climate variables and extreme indices, as well as air quality parameters with a key role in causing damage and loss of cultural and natural resources, are elaborated by the exploitation of data and products available in the Earth observation domain.

A. Data and reference products

Satellite-based products

Precipitation is one of the most significant climate variables for assessing the impact on cultural and natural heritage. In our work, we utilize products from the NASA Global Precipitation Measurement (GPM) mission, which provides highly detailed precipitation data. Specifically, we have selected and used the Integrated Multi-satellitE Retrievals for GPM (IMERG) products [8]. IMERG, a flagship dataset of the GPM mission, combines data from a constellation of international satellites to provide global precipitation estimates with a high spatial resolution of 10 km and a temporal resolution of 30 minutes. While the GPM mission itself was launched in 2014, the IMERG product includes a reprocessed, long-term dataset that incorporates data from the preceding Tropical Rainfall Measuring Mission (TRMM), creating a consistent record extending back to 2000. Both liquid and solid precipitation layers from this dataset have been collected to derive the total precipitation and the climate extreme indices used in our tool (see section II of this contribution). Recent studies highlight the versatility and importance of IMERG and GPM data in environmental monitoring and hazard assessment. For example, the work by Ghaderpour et al. (2023) specifically uses GPM-IMERG data for the analysis and forecasting of precipitation time series in Italian regions [9]. Other research, such as that by Moreno et al. (2024), has demonstrated the use of these satellite products to assess and forecast rainfall-induced damage to historical fortifications, while Bonazza et al. (2022) have discussed the integration of Earth Observation data, including climate-related products, to support the management and protection of cultural and natural heritage [10, 11].

B. Numerical model-based products

Copernicus Climate Change Service (C3S).

Precipitation and temperature have also been extracted from C3S [12] and used to compute climate extreme indices (see section II of the present contribution). This approach, which leverages large-scale climate data for detailed risk assessment, is a recognized methodology in the field [13]. Moreover, precipitation and temperature have been used in combination with air quality information to compute damage functions for surface recession and biomass accumulation on cultural heritage assets [14]. Currently, C3S provide the ERA5 Land re-analysis [15] a dataset from which the following variables have been used in the Risk Mapping Tool for Cultural Heritage Protection:

- Air Temperature (2m) (°C)
- Daily accumulated precipitation (mm)
- Dew Point Temperature (2m) (°C)
- On-ground solar irradiance (J/m^2)
- Wind intensity and direction (10 m) (m/s)

These ERA5 Land products feature a spatial resolution of 9 Km and are available globally every hour from 1950, providing a robust, long-term dataset for detailed analysis.

Copernicus Atmosphere Monitoring Services (CAMS).

Besides climate, air quality information are useful to assess the amount of specific atmospheric components that can have effects on the cultural heritage materials. The most accurate air quality maps over Europe are generated by the CAMS [16]. The following datasets have been collected from CAMS:

- PM10 Surface Concentration (Particulate Matter) ($\mu g \cdot cm^{-3}$)
- PM2.5 Surface Concentration (Particulate Matter) ($\mu g \cdot cm^{-3}$)
- NO_2 Surface Concentration ($\mu g \cdot m^{-3}$)
- SO_2 Surface Concentration ($\mu g \cdot m^{-3}$)
- O_3 Surface Concentration ($\mu g \cdot m^{-3}$)

CAMS Regional European products feature a spatial resolution of 10 Km and are available over Europe every three hours starting from 2018.

C. Spatial extent and homogenization

To make the selected data and reference products usable for our tool, variables computation, spatial and temporal homogenization, and aggregation have been performed.

In Table 1, the spatial domain covered by different data is presented.

Table 1. Table reporting the spatial domain of the different products exploited

ERA5 Land and IMERG	CAMS
West=45.0° W, East=67.0° E	West=25.0° W, East=45.0° E
South=20.0° S, North=75.0° N	South=30.0° S, North=72.0° N

Since all data feature the same spatial resolution (~ 10km), there is no need to perform any spatial homogenization.

D. Temporal aggregation

Since the various products cover different time ranges, we decided to provide the data in the following time ranges:

- ERA5 Land and IMERG: from 2000
- CAMS products: from 2018

Within these periods, the following temporal aggregations are performed:

- Daily average
- Monthly average
- Quarterly average
- Yearly average

For all products and aggregations, both average and accumulated values are computed and provided

II. COMPUTATION OF SPECIFIC CLIMATE PARAMETERS AND CLIMATE EXTREME INDICES

D. Relative Humidity computation

As ERA5 Land products do not include the relative humidity (RH) variable, RH has been computed on an hourly basis using the following formula:

$$RH = 100 \times \left[\frac{e^{\frac{17.625 \times Dp}{243.04 + Dp}}}{e^{\frac{17.625 \times T}{243.04 + T}}} \right] \quad (1)$$

Where:

Dp is the 2m Dew Point Temperature in °C

T is the 2m Air Temperature in °C

E. Climate Extreme Indices computation

Climate indicators capture a specific weather and climate feature that can have more specific impacts on the ground. In the framework of the World Bank Climate Change Knowledge Portal (CCKP) [17], a selection of 39 indicators was chosen by the National Center for Atmospheric Research (NCAR) for the CCKP. They consist of a subset of the climate statistics indicators from the joint Expert Team on Climate Change Detection and Indices (ETCCDI) [18] and some others developed specifically to meet sectoral needs or requests (particularly the return intervals and the drought indicators). Specifically, the computation of the following selected climate extreme indices has been done with elaboration of data of total precipitation extracted from IMERG products: R20mm, R95pTOT, Rx5day, CWD, CDD, CDD5 (see definition of indices in Table 2 in Bonazza and Sardella 2023 [1]). Moreover, by elaborating precipitation and temperature extracted from C3S, the following climate extreme indices have been obtained: R20mm, R95pTOT, Rx5day, CWD, CDD, CDD5, Tx90p, SU, HWI, Tx99p, TR (see Table 2 in Bonazza and Sardella 2023 [1] for definition of the indices).

III. ELABORATION OF DAMAGE FUNCTION

Specific damage functions have been finally purposely computed. The damage functions presented here are selected among those available in the scientific literature [1,7].

F. Surface Recession of marble and compact limestone

The surface recession function is computed following the approach provided in [1,7] by using a revised version of the formula where the acid rain factor ($0.054 Rain \cdot [H^{+}]$) has been considered neglectable due to the increasing rain pH in the last decade [19].

The following formula is therefore used:

$$R=3.95+0.0059\cdot[SO_2]\cdot RH_{60}+0.078\cdot[HNO_3]\cdot RH_{60}+0.0258\cdot PM_{10} \quad (2)$$

Where:

R: Surface Recession per year ($\mu m \cdot year^{-1}$) (yearly average)

$[SO_2]$: SO_2 concentration ($\mu g \cdot m^{-3}$) (yearly average)

RH_{60}: relative humidity considered only when RH>60, otherwise 0 (%) (yearly average)

$[HNO_3]$: HNO_3 concentration ($\mu g \cdot m^{-3}$) (yearly average)

PM_{10}: PM_{10} concentration ($\mu g \cdot m^{-3}$) (yearly average)

All parameters, except HNO_3 are directly retrieved from IMERG, ERA5 Land and CAMS. $HN0_3$ can be computed using the following formula provided in [Bonazza et al., 2009, 20]:

$$HNO_3 = 516\cdot e^{-3400(T+273)}\cdot([NO_2]\cdot[O_3]\cdot RH)^{0.5} \quad (3)$$

The concentrations of NO_2 and O_3 have been retrieved from CAMS, while T has been collected from ERA5 Land and RH has been computed from climate variables collected from ERA5 Land.

F. Biodeterioration /Biomass accumulation on silicate stones

The function Biodeterioration /Biomass accumulation is computed using the formula provided in [1].

$$B = e^{(-0.964+0.003P-0.01T)} \quad (4)$$

where:

B is the accumulated biomass (mg·cm^{-2})

P is the yearly average amount of precipitation (mm)

T is the yearly average of Temperature (°C)

All variables necessary for the computation of the damage function have been collected from ERA Land.

IV. RESULTS.

Following the methodological approach mentioned above, the current version of the Risk Mapping Tool for Cultural Heritage Protection allows exploring selected air quality parameters, climate variables, and extreme indices re-computed following the full time series, the following products:

Concerning climate data

- Copernicus C3S ERA5 Land products (~10 km resolution, from 1981).
- NASA GPM IMERG products (10 Km resolution, from 2000)

Concerning air quality parameters

- Copernicus CAMS products (10 km resolution, from 1981).

As an example of the result obtained by the application of the tool, Figures 1 and 2 show two maps related to the distribution of NO_2 (Fig.1) and PM10 (Fig.2) concentration in Europe and the Mediterranean Basin. Figures 3 and 4 illustrate maps derived from the computation of the damage functions for surface recession and biomass accumulation, respectively.

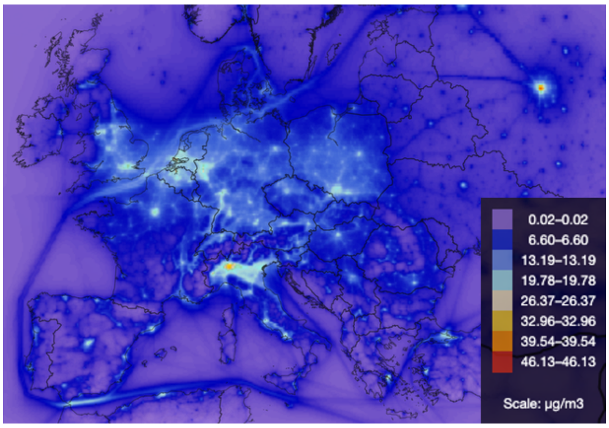

Fig. 1. Map of NO_2 concentration in 2019 (Data source CAMS, yearly average)

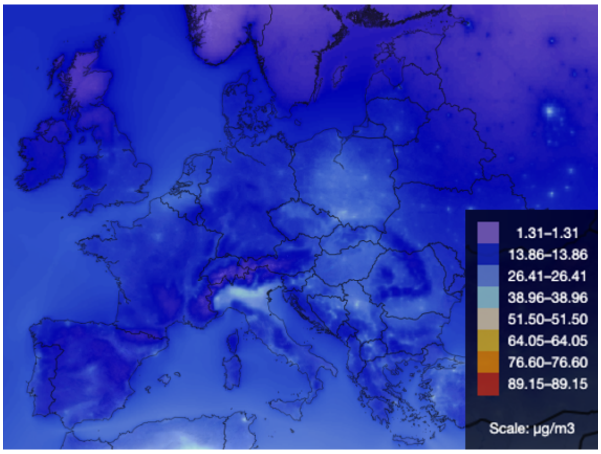

Fig. 2. Map of PM10 concentration in 2019 (Data source CAMS, yearly average)

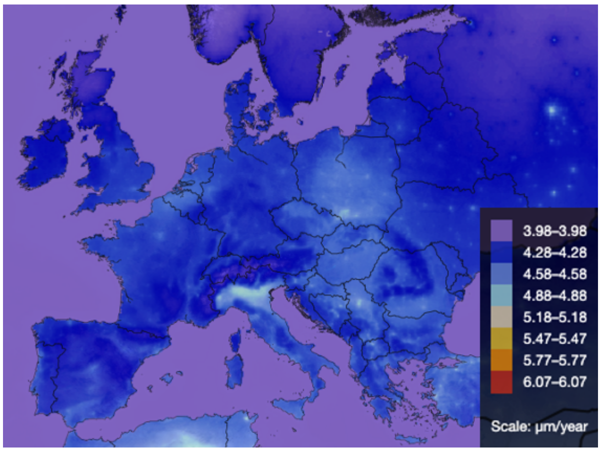

Fig. 3. Map of surface recession at European and Mediterranean level for the year 2019 (Data source

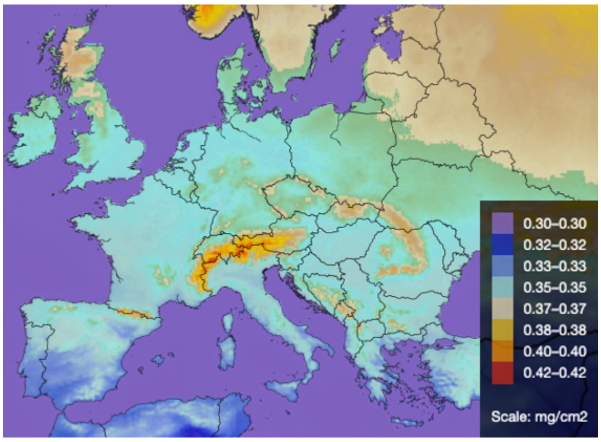

Fig. 4. Map of biomass accumulation at European and Mediterranean level for the year 2019 (Data source ERA5Land)

The maps reported in the Figures above (Fig. 1-4) highlight how the distribution of the different parameters varies across different geographical regions of Europe and the Mediterranean. Specifically, hotspots with high NO_2 concentration (up to 26 µg/m³) were identified in the Emilia-Romagna Region and in major cities of Central Europe (Fig. 1). Similarly, the 2019 maps for surface recession and biomass accumulation highlight the areas with the highest values. For surface recession, the highest values (4.88 $\mu m \cdot year^{-1}$) were found in the Emilia-Romagna Region in Italy and in a large part of Eastern Europe.

V. DISCUSSION

The INACO project is currently undergoing further development to broaden the platform's utility for a diverse range of end-users. This update will provide essential tools for evaluating the historical, current, and future impacts of both hydrometeorological extremes and slow cumulative damage within a climate change context. Our specific focus is on how pollution parameters, in combination with climate variables, drive the deterioration of cultural heritage building materials. We apply specific dose-response functions tailored to different materials. In this paper, we consider two primary damage functions: one for limestone, which models surface recession, and another for silicate stone, which assesses biomass accumulation.

VI. CONCLUSION

As part of the ongoing INACO project, we will expand the spatial domain of the ERA5 Land reanalysis to a global level and implement new risk indices to assess the threat of fires and landslides. The next step involves testing the Risk Mapping Tool for Cultural Heritage Protection with pilot site managers, whose feedback will be crucial for its finalization.

A current limitation in applying damage functions for long-term risk assessment is that they are specific to a single building material. Therefore, further laboratory testing is required to create functions that cover the full range of materials found in cultural heritage assets.

REFERENCES

[1] Bonazza & Sardella. Climate Change and Cultural Heritage: Methods and Approaches for Damage and Risk Assessment Addressed to a Practical Application. Heritage 2023, 6, 3578–3589. https://doi.org/10.3390/heritage6040190

[2] Interreg Central Europe Project INACO. https://www.interreg-central.eu/projects/inaco/

[3] Interreg Central Europe Project ProteCHt2save. https://programme2014-20.interreg-central.eu/Content.Node/ProteCHt2save.html

[4] Interreg Central Europe Project STRENCH web page. https://programme2014-20.interreg-central.eu/Content.Node/STRENCH.html

[5] Risk Mapping Tool for Cultural Heritage Protection web page. https://www.protecht2save-wgt.eu/

[6] https://dgspatrimonioculturale.beniculturali.it/attivita-direzione-generale-sicurezza-del-patrimonio-culturale/bozza-automaticapiano-straordinario-di-monitoraggio-e-conservazione-dei-beni-culturali-immobili/

[7] Kucera, V.; Tidblad, J.; Kreislova, K.; Knotkova, D.; Faller, M.; Reiss, D.; Snethlage, R.; Yates, T.; Henriksen, J.; Schreiner, M.; et al. UN/ECE ICP materials dose-response functions for the multi-pollutant situation. Water Air Soil Pollut. Focus 2007, 7, 249–258.

[8] Global Precipitation Mission (GPM) IMERGE product. https://gpm.nasa.gov/data/imerg

[9] Ghaderpour, E.; Dadkhah, H.; Dabiri, H.; Bozzano, F.; Scarascia Mugnozza, G.; Mazzanti, P. Precipitation Time Series Analysis and Forecasting for Italian Regions. *Eng. Proc.* **2023**, *39*, 23. https://doi.org/10.3390/engproc2023039023

[10] Mónica Moreno, Rocío Ortiz, Pilar Ortiz; Remote sensing to assess the risk for cultural heritage: forecasting potential collapses due to rainfall in historic fortifications. *International Journal of Building Pathology and Adaptation* 14 March 2024; 42 (1): 92–113. https://doi.org/10.1108/IJBPA-03-2022-0040

[11] Bonazza, A.; Bonora, N.; Duke, B.; Spizzichino, D.; Recchia, A.P.; Taramelli, A. Copernicus in Support of Monitoring, Protection, and Management of Cultural and Natural Heritage. *Sustainability* **2022**, *14*, 2501. https://doi.org/10.3390/su14052501

[12] Copernicus Climate Change Service (C3S) web page. https://climate.copernicus.eu/

[13] Kotova, L., Leissner, J., Winkler, M. *et al.* Making use of climate information for sustainable preservation of cultural heritage: applications to the KERES project. *Herit Sci* **11**, 18 (2023). https://doi.org/10.1186/s40494-022-00853-9.

[14] Sabbioni, C., Bonazza, A., Gualdi, S., & Bonini, F. (2020). Climate change impact on cultural heritage: A damage function approach for stone monuments. *Environmental Research Letters, 15*(8), 084025.

[15] Copernicus Climate Change Service (C3S) ERA5 Land data web page. https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land?tab=overview

[16] Copernicus Atmospheric Monitoring Service (CAMS). https://atmosphere.copernicus.eu/air-quality

[17] Climate Knowledge Portal web page. https://climateknowledgeportal.worldbank.org/

[18] Expert Team on Climate Change Detection Indices. http://etccdi.pacificclimate.org/list_27_indices.shtml

[19] Spezzano, P. Mapping the susceptibility of UNESCO World Cultural Heritage sites in Europe to ambient (outdoor) air pollution. Sci. Total Environ. 2021, 754, 142345

[20] Bonazza, A.; Messina, P.; Sabbioni, C.; Grossi, C.M.; Brimblecombe, P. Mapping the impact of climate change on surface recession of carbonate buildings in Europe. Sci. Total Environ. 2009, 407, 2039–2050