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National climate change scenarios in the context of EURO-CORDEX activity – potential for standardization across European Union

(Národní scénáře změny klimatu v kontextu aktivit EURO-CORDEX – standardizace v rámci EU)

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Abstract: This paper presents selected alternative approaches to climate change scenarios that may contribute to the standardization of methodological procedures within the European Union. As part of the EURO-CORDEX initiative, an extensive set of regional climate simulations is being developed, providing a significant basis for climate change scenario development and the assessment of related uncertainties. The paper summarizes the current progress of this initiative. It also presents an example of a national scenario for the Netherlands, which illustrates a possible physically consistent approach.

Keywords: climate change scenario – storylines – EURO-CORDEX – global warming levels

Abstrakt: Příspěvek představuje vybrané alternativní přístupy k tvorbě scénářů změny klimatu, které mohou přispět ke standardizaci metodických postupů v rámci Evropské unie. V rámci iniciativy EURO-CORDEX vzniká rozsáhlý soubor regionálních klimatických simulací, které poskytují významný podklad pro tvorbu scénářů změny klimatu a hodnocení souvisejících nejistot. V příspěvku je shrnut aktuální vývoj této aktivity. Současně je prezentován příklad tvorby národního scénáře pro Nizozemsko, který ilustruje možný přístup založený na fyzikálně konzistentních scénářích.

Klíčová slova: scénáře změny klimatu – "storylines" – EURO-CORDEX – "global warming levels"

Introduction

Within the European Union, the development of national climate change scenarios is currently underway in all member states, reflecting both shared scientific foundations and diverse national needs. A key motivation for standardization efforts is the growing demand for consistent and policy-relevant climate information to support climate risk management and adaptation planning. At the European level, there is an increasing emphasis on creating a coherent methodological framework, which would allow national scenarios to be comparable while still capturing regional specifics.

The importance of such harmonization stems from the increasing role of climate scenarios in policy and planning processes. National scenarios are used to guide long-term investments, infrastructure development, and sectoral adaptation strategies. However, their effective uptake is often hindered by their complexity. Establishing a common baseline – such as shared assumptions about global temperature development – can significantly improve their usability. It allows stakeholders to better

understand the need to prepare for a climate that differs substantially from historical conditions and supports more consistent decision-making across sectors and countries.

A central concept emerging in this context is the use of a reference global warming trajectory (see Section 2), which links global temperature increase to regional climate change. Rather than focusing solely on different emission scenarios or model outputs, this framework emphasizes global warming levels as a common reference metric, facilitating clearer communication and more robust decision-making (Wartenburger et al. 2017; Seneviratne et al. 2021; Evin et al. 2024).

Overall, the ongoing development of national climate scenarios within the EU can be seen as part of a broader effort to balance standardization and flexibility. While a common framework enhances comparability and policy relevance, individual member states must still tailor their scenarios to local conditions, vulnerabilities, and decision-making contexts.

Alternative approaches to climate change scenarios

In addition to the more traditional methods of climate scenario construction and uncertainty assessment (Holtanová and Belda 2026), several alternative approaches have emerged in recent years. These methods aim to address some limitations of classical techniques and to better capture the complexity and decision-relevant aspects of climate change. This section introduces two important alternative approaches: "global warming levels" and "storylines".

Global warming levels

Another increasingly important approach is based on global warming levels (GWLs). Instead of analyzing climate change at fixed future time periods (e.g., mid-century or end-of-century), this method examines regional climate responses corresponding to specific increases in global mean temperature, such as 1.5 °C or 2 °C above pre-industrial levels (Wartenburger et al. 2017; Seneviratne et al. 2021; Evin et al. 2024). This represents a conceptual shift from time-based projections to temperature-based thresholds, which are more directly linked to international climate targets. The GWL approach facilitates comparisons across scenarios and models, as different simulations may reach the same warming level at different times. However, several open questions remain, including the dependence of regional responses on the trajectory leading to a given warming level (e.g., whether warming occurs rather rapidly or gradually), which may influence the resulting climate conditions (Seneviratne et al. 2016; James et al. 2017; Seneviratne and Hauser 2020).

The global warming framework also acknowledges that timing matters. The impacts associated with a given level of warming (e.g., +2 °C) depend not only on the magnitude of change but also on when it occurs. For instance, reaching +2 °C by 2050 implies different adaptation requirements than reaching the same level by 2100, particularly given the varying lifespans of infrastructure and policy measures. Therefore, linking global warming levels with specific time horizons – forming a “trajectory” rather than a single value – is essential for practical planning.

Szabó et al. (2026) is an example of the global warming level (GWL) approach applied to Central Europe, focusing on projected changes in heat extremes. They investigate co-occurrences of hot days and warm nights using performance-based subsets of CMIP6 simulations. The study evaluates both Paris-agreement-aligned GWLs (1.5 °C, 2.0 °C) and policy-relevant warming (1.9 °C, 2.7 °C). The studied events were rare in the historical period but show a clear increase in both frequency and duration already between 1.5 °C and 1.9 °C, followed by strong intensification at higher warming levels. The study highlights the value of GWLs for evaluating high-impact climate extremes and for supporting region-specific adaptation planning.

Storylines

One increasingly prominent alternative to traditional probabilistic approaches is the concept of climate storylines (Shepherd et al. 2018). Rather than relying on statistical characteristics, they focus on a small number of carefully constructed “narratives” that represent distinct pathways of climate development.

This makes them particularly useful for decision-making contexts where clarity, interpretability, and relevance to specific risks are essential. Another key advantage of the storyline approach is that it allows the explicit exploration of causal mechanisms linking large-scale drivers to regional impacts. For example, storylines can be used to investigate how particular circulation patterns, soil moisture conditions, or ocean states may influence the occurrence of extreme events such as heatwaves, droughts, or intense precipitation. In this way, they provide insight not only into what changes might occur, but also why they occur (Zappa and Shepherd 2017). This process-oriented perspective is especially valuable for understanding compound or high-impact events that may be underrepresented in standard ensemble statistics.

Storylines have been applied, for instance, to assess flood risks under extreme precipitation scenarios, to explore the impacts of persistent heatwaves on agriculture and human health, or to evaluate the effectiveness of adaptation measures in urban environments (Shepherd 2019; Sillmann et al. 2021). This approach provides a structured way to examine high-impact, low-probability events and to better understand the physical consistency of projected changes. This makes them a valuable addition to the toolbox of climate scenario development, particularly in contexts where decision-making under uncertainty is critical.

Upcoming EURO-CORDEX generation: the new data source

The forthcoming generation of EURO-CORDEX simulations driven by state-of-the-art CMIP6 GCMs represents a significant step forward in regional climate modeling over Europe (Sobolowski et al. 2025). The preceding EURO-CORDEX multi-model ensemble has been criticized due to inconsistencies of projected changes between the nested and driving simulations (e.g., Bartok et al. 2017). The new simulations are expected to become fully available in the near future. They incorporate improved parameterization schemes and more consistent experimental design across modeling centers. The ensemble will combine six GCMs with seven RCMs, ensuring that each GCM drives multiple RCMs and vice versa, thereby improving the robustness of uncertainty estimates. Thereby, the ensemble will provide robust and spatially detailed projections of future climate change over Europe (Katragkou et al. 2024; Sobolowski et al. 2025).

In summary, the new EURO-CORDEX simulations will provide an essential foundation for impact studies, climate services, and adaptation planning, while also offering new opportunities to investigate uncertainties and refine scenario methodologies at the regional scale. Putting the PERUN scenarios based on ALADIN-CLIMATE/CZ into the context of these new scenarios is planned in due course.

An example of national scenarios: KNMI climate change scenarios

The KNMI'23 climate scenarios (van der Wiel et al. 2024) provide a representative example of national climate scenario development within Europe, illustrating a shift toward more physically grounded and application-oriented approaches. These scenarios are based on a storyline framework, which emphasizes a small set of internally consistent and physically plausible narratives of future climate change rather than relying solely on large probabilistic ensembles. This approach enables clearer interpretation of projected future conditions while still capturing key uncertainties relevant to decision-making.

Methodologically, KNMI'23 integrates multiple complementary data sources, including CMIP6 GCMs, EURO-CORDEX RCMs, and observational datasets used for evaluation and bias correction of model outputs (van der Wiel et al. 2024). Instead of directly presenting ensemble spreads, the process-based analysis allows for identifying the dominant drivers of regional climate variability and change. Large-scale atmospheric circulation patterns over Europe are recognized as a major source of uncertainty affecting temperature, precipitation, wind, and extremes in the Netherlands. By explicitly incorporating different plausible circulation responses into the scenario design, the framework ensures that the resulting storylines reflect physically meaningful mechanisms.

The scenarios are further structured around global warming levels (GWLs), linking regional climate changes to global mean temperature increases. This allows consistency with international mitigation targets. The KNMI'23 framework defines four main storylines, combining two key dimensions: the level of global warming (moderate versus high) and the strength of changes in atmospheric circulation (weak versus strong). This structure replaces traditional probability-based interpretations with a scenario space defined by physically interpretable drivers. Each storyline thus represents a consistent and plausible trajectory of climate evolution, facilitating targeted analyses of specific risks.

A key advantage of the KNMI'23 approach is its usability for decision-making. By providing a limited set of clearly defined and physically consistent scenarios, it improves communication with stakeholders and supports practical adaptation planning. Overall, these scenarios demonstrate how combining multiple data sources with a process-based, storyline-oriented framework can enhance both the scientific robustness and practical relevance of national climate projections.

Conclusion

Recent developments in the field of climate change scenarios are also strongly influenced by the concept of "seamless prediction", which seeks to bridge the traditional divide between weather forecasting and climate projection (Delgado-Torres et al. 2026; Hurrell et al. 2009). One practical outcome of this approach is the development of initialized climate simulations, which aim to produce skillful predictions on seasonal to decadal timescales by incorporating information about the current state of the climate system, particularly the ocean. An ambitious extension of the seamless prediction paradigm is the concept of "digital twins" of the Earth system. These are high-resolution, data-driven numerical representations of key components of the climate system, designed to simulate their evolution in near real time and under hypothetical scenarios. In Europe, a prominent example is the Destination Earth initiative, which aims to develop highly detailed digital models of the planet (Hoffmann et al. 2023). Such systems have the potential to significantly improve our understanding of climate processes and enhance scenario development, with many potential policy-relevant applications, including, for example, diverse storylines.

Overall, the emerging approaches described above complement traditional climate modeling by offering new perspectives on uncertainty, improving the relevance of climate information for decision-making, and enabling more flexible and physically grounded analyses of future climate change.

Regarding the concept of European climate trajectories, there is the need for a common, policy-relevant framework to guide climate risk assessment and adaptation across member states. Climate risk management is increasingly constrained not by a lack of scientific knowledge, but by the complexity and diversity of existing climate scenarios, which can hinder their practical use in policy and planning. To address this, a reference global warming trajectory is proposed as a unifying framework. This approach links global warming levels with specific time horizons (e.g. ~1.5 °C by 2030, ~2 °C by 2050, and ~2.6 °C by 2100 under current policies (CAT 2024)), providing a common baseline for all EU member states. Importantly, this framework does not eliminate regional diversity but rather provides a common reference point upon which region-specific analyses can be built.

Overall, the European approach emphasizes the need for scientifically robust yet operationally useful climate information, moving toward harmonized climate risk assessments and common adaptation reference scenarios that can support coherent and actionable adaptation strategies across the European Union (European Commission 2021; European Scientific Advisory Board on Climate Change 2026).

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Statement on use of AI

Generative AI was used to assist with English grammar and text clarity, but all conceptualization, design, and conclusions are original to the authors, who take full responsibility for the content's accuracy and academic integrity.

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