Title of Proposal

Tipping points of the climate system: Early warning signals and likelihood estimates for the quantitative assessment of impacts and risk management for the Arctic, Europe, Mediterranean and Sahel.

[TipTop]

1. Excellence

1.1 Objectives

TipTop's overall aim is to quantitatively assess the likelihood, impact, and adaptation and mitigation pathways for key tipping points in the climate system.

- ***We will achieve this by identifying tipping points in the latest state-of-the-art climate model projections for the future, analysing the associated feedback-processes, and by determining the reliability of the model simulations through observational constraints from recent instrumental data and paleo-reconstructions.***
- ***We will focus on environmental and societal impacts of abrupt climate changes and change in frequency of extreme weather events in the Arctic, Sahel, Europe and Mediterranean area of the most prominent tipping points, as well as the potential of vulnerable societies to tip in response to gradually passing thresholds in food and water supply.***
- ***To avoid such impacts, we will assess the presence of early warning signals and quantify timely, adequate adaptation and mitigation pathways to stay within safe operating spaces for societies at risk.***

Background. There exists ample evidence from climate data, paleo records and earth system models that several elements of the climate system show highly non-linear responses to natural and anthropogenic climate forcing and have the ability to switch between different climate equilibria. These ***'tipping points'*** can be abrupt, and cascade to a range of environmental variables and have considerable impacts on human activities through a sudden step change in average climate and weather extremes. The term ''tipping point'' commonly refers to a critical threshold at which a tiny perturbation can qualitatively alter the state or development of a system[1]. The thresholds in greenhouse forcing where such switches occur for individual tipping elements are poorly constrained. Indeed, predicting the risk for passing such thresholds has remained elusive since most tipping points have been assessed subjectively by expert elicitation, so that objective risk assessment of crossing climate tipping points has not been realised. In addition, tipping points are still perceived as low probability events, but from an economic and humanitarian perspective, reaching a tipping point could be catastrophic. *Up to now, assessment of the likelihood of occurrence, impact and risks associated with passing climatic tipping points has been qualitative, because of lack of trust in models to simulate these events correctly, lack of a method to account for model biases, and lack of a methodology to find them in model simulations and describe and analyse the physical feedbacks that cause them.*

A new approach. TipTop proposes a new approach that makes objective, quantitative risk assessment possible for crossing climate thresholds and estimating likelihood of climate hazards, impact on societies vulnerable to these hazards, and adaptation and mitigations pathways to manage risks. This new approach has become possible by ***scaling up a research and classification method*** recently developed by TipTop members and combining this with a more ambitious, interdisciplinary program. The supporting analysis program will include examination of predictability of tipping points, early warning signals, physical precursors, constraints from instrumental and paleo observations, impact analysis, risk management and assessment of adaptation and mitigation pathways for abrupt climate change.

- TipTop will focus on the Arctic, Europe, the Mediterranean and the Sahel regions. This choice is motivated by their relevance for EU policy, notably safeguarding the Arctic, increasing resilience of European societies to climate change, and dealing with migration pressure from climate refugees. In addition, the search and classification method will be extended to include abrupt changes in the frequency of weather extremes, putting focus on tipping points in temperature, soil moisture and precipitation, that strongly affect society.
- TipTop will also assess societal tipping points associated with gradual change in climate variables, but which, after crossing a certain threshold, could have dramatic impact on societies by disrupting water and food supply.
- With this approach, TipTop will, for the first time, arrive at an evidence-based assessment of likelihood of tipping point occurrence. This will allow for identification of safe operating spaces for vulnerable societies, as well as long-term strategies for preventing or mitigating impacts of abrupt climate changes.

TipTop has 7 high-level objectives:

Obj 1. To identify objectively, abrupt changes in key climate variables, including changes in weather extremes, in the databases of future climate projections (Climate Model Intercomparison Project, CMIP5&6).

Obj 2. To identify the feedback processes that cause these abrupt changes and evaluate their predictability through the use of decadal prediction systems.

Obj 3. To estimate the reliability of the identified feedback processes by using recent observations and paleo-reconstructions and assess the influence of model biases on the modelled feedbacks.

Obj 4. To quantify the likelihood of crossing tipping thresholds, assess the potential for early warnings using timeseries analyses in combination with physical precursors, and estimate the associated uncertainties.

Obj 5. To evaluate the impacts of abrupt climate change on economy and welfare of regions and societies that are vulnerable to these particular tipping points, and develop case studies for the Sahel, the Mediterranean and the low-lying delta of the Netherlands, focusing on the elements that are most relevant for EU policy.

Obj 6. To identify societal tipping points in response to more gradual climate changes that cause step changes in food and water supply and to propose risk management scenarios and safe operating spaces for allowing these societies to cope with the identified abrupt changes.

Obj 7. To ensure knowledge transfer to European policymakers, third sector organisations, businesses and the general public and develop a program for societal engagement built on the above-mentioned case studies.

To achieve these objectives, TipTop has assembled an interdisciplinary consortium of experts on tipping points in climate and on the impact of climate change on vulnerable societies. This consortium is optimally placed to further develop an innovative approach linking the science part through objective risk assessment to adaptation and mitigation policy.

1.2 Relation to the work programme

TipTop responds to the call "LC-CLA-08-2018: addressing knowledge gaps in climate science, in support of IPCC reports", specifically sub-topic b) "tipping points".

Specific challenge #1: "Better understanding of the key processes controlling the climate-Earth system is fundamental in order to further improve climate projections, reduce uncertainty in climate sensitivity calculations, enhance understanding of frequency and strength of extreme weather events, and assess more accurately the impacts of climate change related to the proximity, rate, reversibility and tipping points of abrupt climate change, and the identification of safe operating spaces"

TIPTOP will take up this challenge by:

- Making for the first time an assessment of abrupt changes in frequency of extreme (hourly to daily) weather events in recent and new (CMIP5&6) climate change projections for the entire globe (*Objectives 1&2*).
- Making for the first time an in-depth analysis of the feedback processes leading to abrupt climate change as simulated in CMIP5&6 climate change projections, with a focus on the Arctic**,** and on droughts, floods and heat waves in Europe and the Sahel, and by using observational constraints to evaluate the impact of model biases on the relevant feedback processes as simulated in models (*Objectives 3&*4).
- Making for the first time an identification of the safe operating spaces that avoid tipping of climate systems in the Arctic, Europe and the Sahel as projected in CMIP5&6. For this purpose, new multi-model initialized ensemble runs will be performed with various greenhouse gas emission scenarios, to assess the predictability of crossing tipping thresholds by initialising with CMIP5&6 fields a few years prior to the tipping, and to identify the range of safe operating spaces in the coming century (*Objectives 2&6*).

Specific challenge #2: "future climate scenarios strongly benefit from the combined use of models and paleo-reconstructions conducted in Polar Regions as they allow a better understanding of how the climate system worked, both regionally and globally, during abrupt climatic transitions and under warmer or colder than present day conditions"

TIPTOP will address this challenge by: (1) synthesizing knowledge gained from ice core records and high-resolution sediment records for the process-based understanding of past abrupt changes during glacial and interglacial periods and use this knowledge to assess model reliability in simulating future climate tipping elements and constrain their likelihood; and (2) including assimilation of the newest paleo proxies into climate models for the last millennium to evaluate the potential for abrupt climate change during that period. By detailed comparison with the simulated abrupt changes in the newest future climate projections, this allows to assess the relevance of these past events for the future and further constrain the likelihood of future projected abrupt change (*Objective 3*).

Scope b) Tipping points: "Actions should result in better understanding of abrupt climate change, of climate-related Earth system tipping elements and their tipping points, and associated impacts; Actions should identify safe operating spaces, accompanied – where relevant – with long-term strategies for preventing or mitigating impacts; Actions should also advance the understanding of respective impacts and early warning indicators."

TipTop will deliver on Scope b) in the following way:

- TipTop will identify safe operating spaces by analysing global and regional warming levels at which the tipping occurs (*Objective 1*), by assessing the sensitivity to emission scenario in initialised decadal predictions (*Objective 2*), by estimating the likelihood of occurrence and associated uncertainty (*Objective 4*) and translating these results, in combination with a risk assessment associated with flooding, droughts, and heat waves (*Objective 5*) into risk management scenarios for vulnerable regions (*Objective 6*).
- TipTop will develop long-term strategies for preventing or mitigating impacts of climate change, based on tasks in which we identify predictability, sensitivity to emission scenarios, presence of physical precursors and early warning signals of tipping events (*Objective 4*); assess the impact of tipping points in temperature, soil moisture and precipitation on vulnerable societies in a few exemplarily case studies (*Objective 5*) and work together with policy makers and regional flood- and health-risks and food-security managers to identify adaptation pathways and risk management strategies (*Objective 6*).
- TipTop will further advance the understanding of respective impacts on society through evaluating the occurrence of societal tipping points in response to thresholds in food and water availability (*Objective 5*).

Together, these actions will allow for a step change in our understanding of climate-related tipping points in the coming centuries, the understanding of their impacts and the interpretation of early warning indicators.

- Thus, we will develop tools to better assess the potential impacts of the identified upcoming abrupt changes on society. Identifying promising risk management strategies, mitigation pathways and early warning signals to anticipate, prepare and timely adapt to the effects of abrupt climate change requires new decision-making approaches that better considers dynamics within and between the climate and human systems (*Objectives 5&7*).

Looking beyond the current call, TipTop's analysis of the impacts of abrupt climate changes and societal tipping points and its associated scientific and societal outcomes will be highly relevant to the forthcoming call LC-CLA-05-2019, related to climate-change-induced human migrations.

1.3 Concept and methodology

(a) Concept

Overall concept

Rationale. The potential for climate to change in very non-linear way, with large variations occurring within a few decades, has been highlighted in paleoclimate reconstructions[2,3] and climate model experiments[4]. These large variations have been associated with so-called tipping elements in the climate system, which are characterized by ***tipping points*** after which a ***switch to a different climate state*** occurs. These tipping points have become a subject of substantial interest in the last decades due to their potentially large impacts on human society and the difficulty to prepare and adapt for. The term tipping is used to describe various classes of transitions, bifurcations, and abrupt changes in climatic variables. Several tipping elements of the climate system have already been identified, including the Atlantic Meridional Overturning Circulation (AMOC), Arctic sea ice, the Indian and West-African monsoon systems. Among those, we will focus on the elements that are most relevant for EU policy, notably safeguarding the Arctic, making European societies more resilient to climate change and dealing with migration pressure from climate refugees. *TipTop will not only deliver new cutting-edge science, but also make impact assessments for better social resilience and planning purposes.*

State-of-the-art. Up till now, tipping point assessments have largely been based on ***expert elicitation*** (gathering best-guess estimates from experts) and on a very limited number of model simulations, hampering objective risk assessment. For some tipping elements, further analysis of both simplified climate models and (paleo) observations has been undertaken, but mostly in terms of physical feedbacks analysis. Economic and humanitarian impact models have been developed for some tipping points, but in each case based on probabilities grounded on best-guess estimates by experts. Recently, a ***new method to objectively identify abrupt changes*** in large climate model simulations (CMIP5) has been carried out under the FP7 EMBRACE programme, but this search was limited to annually averaged fields, and subsequently only tipping points of slow systems were found (ocean, cryosphere and vegetation). As a result, potentially important tipping elements like monsoon systems and tipping points associated with extreme weather were not addressed. Also, the identified tipping points were not evaluated with supporting analyses of the CMIP5 models themselves, nor with observations. *Most importantly, an integrative framework that links physical science with impact, risk assessment and risk management in an objective way is still lacking.*

Proof of concept. Within EMBRACE, members of this consortium developed ***search and classification criteria*** for ***abrupt changes*** in yearly mean outputs in the CMIP5 database and applied these criteria to the climate model simulations, subsequently identifying a large number of abrupt changes[5]. One of the robust and novel findings was the occurrence of abrupt cooling in the subpolar gyre (SPG) of the North Atlantic in various climate change projections. By comparing oceanic stratification, a key variable for the cessation of ocean deep convection which led to the abrupt climate change, between models and observations, a skill core was developed to test robustness of the simulated abrupt change and to adjust its likelihood of occurrence. It was found that models showing abrupt change were among the best for this metric, indicating that the probability, or the risk of encountering such abrupt change was much larger than previously thought[6]. In one climate model, it was found that including the effect of Greenland ice sheet melting in response to global warming led to substantial AMOC weakening. An investigation of the impact of a weakening AMOC on the Sahel region found a very large decrease in precipitation, due to a southward shift of the InterTropical Convergence Zone. The impact on sorghum and millet crops appeared substantial and analysis of the demography in this region led to estimate the potential impact on millions of people[7], which could severely influence migration pressure.

Approach. In TipTop, we will scale up the methods developed within EMBRACE to include ***faster, more policy relevant and higher-impact tipping elements*** and to allow for an integrative framework that links physical science with impact and risk management in an objective way. The mathematical and physical analysis will also include analysis of weather extremes based on ***metrics that define the tail of the probability distribution of these events***, like extremes with 1% or 5% probability. To this end, in TipTop we will define a catalogue of metrics that is suited for analysing abrupt changes in extremes, focusing on temperature, soil moisture and precipitation. In addition, TipTop will make use of new simulations and decadal predictions performed with our own models (IPSL-CM6, MPI-ESM, EC-EARTH, HadGEM3, CNRM-CM6). The goal is to assess whether different models can simulate the same tipping point when fed by initial conditions derived from the climate model a few years before the tipping in that model occurs. TipTop will also look for physical precursors of tipping in climate models (like changes in winds, currents, water masses, pressure systems, *etc.*), evaluate their importance in our decadal prediction system, and evaluate their behaviour in existing observation-based monitoring systems, allowing for recommendations for further monitoring. TipTop will apply various early warning analyses, using time-series analysis, network analysis and machine learning methods to assess these signals in relation to adaptation measures. Finally, using regional climate models for downscaling, TipTop will analyse selected case studies in vulnerable regions, to develop risk management and adaptation strategies. These case studies include droughts and food production failure in the Sahel and Mediterranean, heat waves in Central and Southern Europe, and coastal flood risk in the Netherlands.

Interdisciplinary considerations and use of stakeholder knowledge

Multi-disciplinary Expertise. TipTop includes experts on ocean circulation, sea ice, monsoon dynamics, and floods and droughts over the Euro-Mediterranean area and the Sahel region. To manage the associated risks, experts in hydrology and water management will examine abrupt changes in heat waves and floods in Central and Southern Europe, droughts frequency and subsequent food production failure in the Sahel, flood risk in the Netherlands, and the impact these events may have on societies. They will work in close collaboration with experts in downscaling that will transform large-scale climate projections to their regional aspects. Experts in crop management, notably in the Sahel region are included, allowing a refined picture of key impacts in that area. Social scientists from Red Cross / Red Crescent

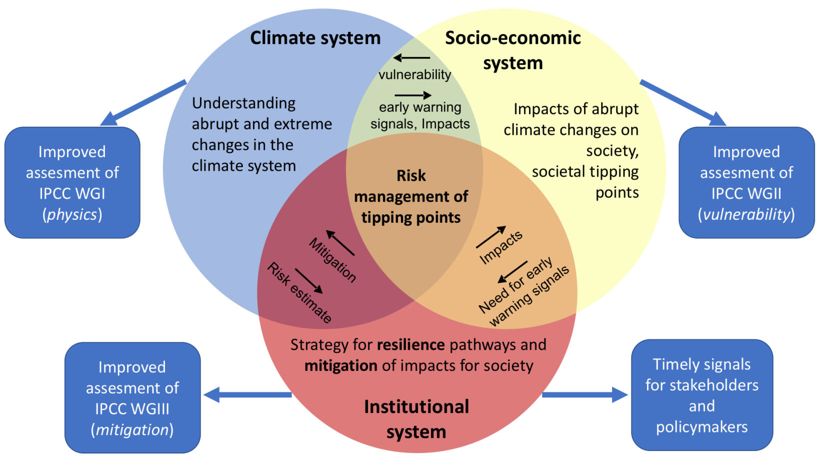

Figure 1: scheme of the general philosophy of the TipTop project. Each circle refers to one system, from climate to the socio-economic systems, with interaction with institutional system to disseminate our key results. The blue rectangles represent the main end users that will benefit from the TipTop project.

will evaluate, notably through field work, the vulnerability of populations in the Sahel and Mediterranean areas to droughts and heat waves, to estimate the potential for crossing societal thresholds due to slow and regular climate changes leading to failure in food and water availability, and to develop strategies for managing the risks (*cf.* Figure 1).

Stakeholder involvement. The consortium will incorporate stakeholder knowledge (national and regional policymakers and local and regional flood defence, health security and food production managers) from Europe, the Mediterranean and Sahel areas, by using the ***Dynamic Adaptive Policy Pathways*** approach[8]. This approach aims to support decision making under uncertain conditions by developing an adaptive plan, based on exploring alternative adaptation pathways for a range of potential futures, and allowing to switch between scenarios when uncertainty narrows down on the basis of new information. So far, this approach has been used in the UK[9], the Netherlands[8], and New Zealand. Here this approach will be applied for the first time to abrupt changes and the evaluation of early warning signals on criteria such as reliability, timeliness, and whether they are convincing for the stakeholders to act upon.

Positioning of the project

Technology readiness levels. TipTop is innovative across the range of technology readiness levels (TRL). **Workpackages (WP) 1-4** will provide the fundamental steps forward in scientific understanding of climate tipping points, which underpin the other WPs. **WP1-4** are mostly active at **TRL 1-3**, but the advances offered by a truly objective assessment of tipping points are ground-breaking. Building on these advances, TipTop offers new ways to integrate climate risks into global and regional risk management, and economic risk assessment. **WP6** will identify societal tipping points in response to climate change, which until now have not been thoroughly examined. Together, **WP5-7** will develop new services, tools, and communication formats for establishing and integrating this knowledge into tangible pathways for society response, representing innovation at **TRL 5-6**.

National or international research and innovation activities

Building on former EU projects. TipTop will use knowledge from and feedback knowledge to the BLUE-ACTION and APPLICATE EU projects (having partners from these projects). The analysis of climate predictability in the Arctic, focusing on near-term changes in these projects, helps constraining the abrupt changes we will find in climate model projections, while TipTop will encompass the longer time frame, up to the next century, and will also focus on teleconnections between the Arctic and the monsoon regions, putting the results of the two Arctic projects in a broader perspective. TipTop will use knowledge and outputs gained in the NACLIM and SPECS projects (having partners from those projects) dedicated to the understanding of, and predictability of the North Atlantic region, helping to constrain our findings on abrupt change in this area. It will collaborate with, and incorporate data from the PRIMAVERA project to analyse the role of model resolution in the representation of abrupt changes and feed this knowledge back to PRIMAVERA. Our results will strengthen the World Climate Research Program grand challenge of near-term decadal predictions, which TipTop will analyse in terms of the ability to predict abrupt changes. Finally, TipTop also builds on experience from the HELIX project (having partners from this project), where analysis on tipping points was carried out on a far more limited dataset.

Using observational monitoring systems. The observational constraints on simulated tipping elements and role of bias will be underpinned by ocean observations of national and international programmes, in particular the global Argo array and the science programmes that continuously measure the AMOC (RAPID-MOCHA at 26°N, OSNAP at 57°N, SAMOC at 34°S and the Greenland-Scotland Ridge arrays); the GO-SHIP programme of repeat hydrography; and observations coordinated under EU AtlantOS and GOOS. TipTop partners have strong links with these observation programmes and will communicate our new findings on physical precursors and early warning signals in ocean observations. Concerning paleoanalysis, TipTop will use results from the ERC synergy project ice2ice, focused on abrupt changes in ocean circulation and sea ice in the North Atlantic and Arctic for robustness and impact of model biases on simulating future abrupt changes, and similarly for the ACER INQUA project that has provided a compilation of abrupt changes in vegetation from paleodata.

Interacting with national efforts. At the national level, a few projects are very relevant concerning abrupt changes in the Sahel region, like the French ANR ACASIS and the AMMA-2050 in the UK, focusing on heat waves and extreme precipitation events respectively. It will also pursue efforts in decadal prediction analysis led in former national projects (*e.g.* French ANR MORDICUS, German MikLIP projects). The added value of TipTop is the analysis of abrupt changes in frequency for these events in future projections and association this with risk assessment and risk management.

(b) Methodology

The organisation of TipTop is illustrated in Figure 2. Below we give a synopsis of the WPs.

WP1: Search engine for abrupt changes

Objective: *To develop a catalogue of abrupt climate changes including weather extremes.*

Approach: The new CMIP6 database will be scanned, searching for abrupt changes in monthly-mean surface variables from ocean, sea ice, land and atmosphere. Existing classification methods will be extended and improved, including a new search algorithm that allows identification of abrupt changes in the extremes in daily to hourly temperature, soil moisture and precipitation fields in climate model projections.

WP1 Outcomes: A new collection of simulated abrupt climate changes for monthly and yearly mean fields in CMIP6 and a first catalogue ever of abrupt changes in extreme weather events from CMIP5 and 6.

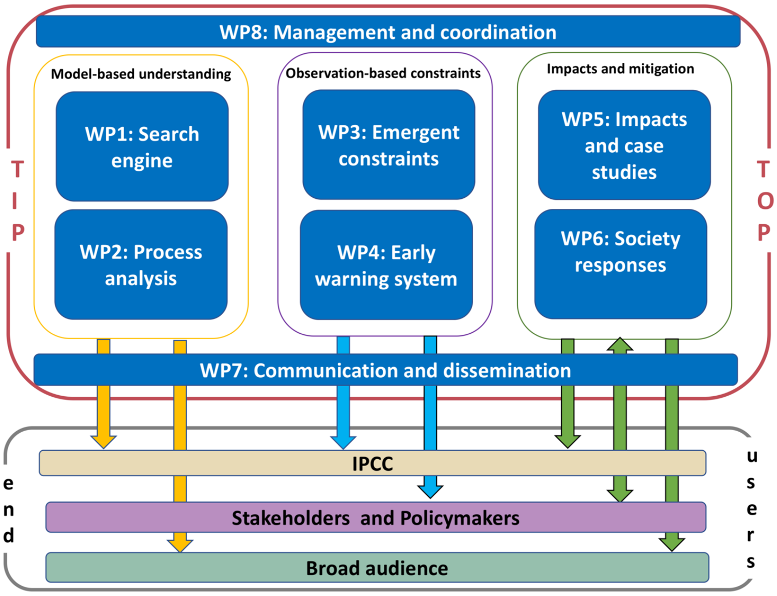

Figure 2: WPs structure and interactions with end users.

WP2: Process analysis, feedbacks and predictability

Objectives: *(1) To identify the chain of events leading to tipping in climate models; (2) to quantify how these mechanisms change under different boundary conditions; (3) to document the skill of decadal prediction systems to forecast imminent abrupt changes; (4) to develop conceptual models for a robust understanding of the underlying nonlinearities and bifurcations.*

Approach: We will perform a detailed analysis of individual tipping events in multiple models of the CMIP5&6 model pool. Efforts will be concentrated in four key regions prone to abrupt change and of high societal relevance: The North Atlantic circulation system including the AMOC and the SPG, the Arctic Ocean and sea ice, and the Mediterranean and the Sahel due to their sensitivity to changes in the hydrological cycle. The robustness of these mechanisms will be tested for different boundary conditions such as higher CO_2 levels. We will also coordinate a series of well-defined sensitivity simulations to be carried out at various partner institutes. There are two ways in which these findings will be employed: (1) A number of tipping events will be selected and tested for whether they can be reproduced in initialized simulations. This will provide crucial information on the performance of decadal prediction systems to act as early warning systems and guide their future improvement. (2) The selective application of initialization fields and the inclusion or omission of key regions will allow us to corroborate the mechanisms leading to tipping points as well as to define physical precursors as potential targets of operational observation systems. Lastly, the key mechanisms will be formulated into simplified mathematical models.

WP2 Outcomes: An assessment of feedback processes associated with tipping points; an assessment of their sensitivity to forcing and background climate; an assessment of the predictability of tipping points; a conceptual model synthesis of the tipping points.

WP3: Observation-based metrics for use as observational emergent constraints

Objectives: *(1) To comprehensively investigate which metrics are suitable as constraints for tipping points from WP1, taking into account the findings on processes from WP2; (2) to compile recent observation-based values for constraints; (3) to compile values for constraints during past warmer and colder conditions from paleodata.*

Approach: We will evaluate the reliability of simulated tipping points by using the observational constraints based on data sets and reanalyses from the instrumental period, with initial focus on global air-sea fluxes, Atlantic Ocean heat and freshwater transport, sea-ice cover, monsoonal rainfall and the continental hydrological cycle. We will improve the statistical robustness of the observational constraints by examining new paleo-reconstructions of the past 1000 years generated through assimilation of proxy data into climate models, as well as by investigating the stability of climate models through comparison of abrupt events in free runs and assimilation runs. Then, we will examine constraints from a new synthesis of multi-proxy paleo-reconstructions of rapid climate change in the last glacial and interglacial periods, thereby extending the usability of constraints to past warmer and colder conditions. These constraints will be used, together with the results of **WP2** on the sensitivity of feedback processes to the background climate, to evaluate the impact of model bias on the simulation of tipping points

WP3 Outcomes: A set of observational constraints used to quantify reliability in simulated tipping points; an assessment of proximity to tipping points; an assessment of the impact of model bias on simulating tipping points.

WP4: Novel early warning indicators and physical precursors of climate tipping elements

Objectives: *(1) To uncover early warning signals for the abrupt changes identified in WP1 by developing novel techniques of time series analysis for detection and forecast of tipping; (2) to identify the main physical precursors of these transitions in line with WP2 analysis; (3) to identify any cascading effects and develop early warning indicators for such transitions; (4) to investigate the suitability of current monitoring and observation systems to detect early warning signals; (5) to investigate reversibility of the identified transitions and bifurcations.*

Approach: We will establish new time-series analysis techniques for early warning of transitions, notably based on machine learning, and compare those with existing techniques**.** These will be applied to timeseries of the tipping elements found in **WP1**. We will also analyse physical precursors in observation systems, guided by the predictability results from **WP2** and further model analysis of the climate models showing tipping in **WP1**. We will evaluate their plausibility from climate models and estimate their observed state and recent evolution. We will evaluate critical thresholds for tipping within different climate models and estimate our proximity to these thresholds from observations in collaboration with **WP2**. Thereafter, we will produce every year new decadal forecasts for near-term variations, based on two climate prediction systems, using large ensembles to correctly evaluate the potential risk of crossing thresholds in the near future. These predictions complement the predictability analysis from **WP2** but applied here for the near-term. Finally, we will analyse the potential for cascading effects, *i.e.* tipping points that can make other potentially unstable systems tip and develop statistical tools to derive early warning signals for such cascades.

WP4 Outcomes: An assessment of early warning signals for individual tipping points and cascading effects between various tipping points; an assessment of the use of physical precursors as additional early warning signal; an assessment of near-term likelihood of tipping

WP5: Impacts of abrupt climate change on society for specific case studies

Objective: *(1) To evaluate impact of tipping points in a few key regions and sectors; (2) to identify adaptation options and pathways together with stakeholders; (3) to assess potential societal vulnerabilities to climate tipping points.*

Approach: The case studies will include droughts and food production failure in the Sahel and Mediterranean, heat waves and flash floods in Europe, and coastal flood risk in the Netherlands. For each case, we will assess the impact of abrupt changes on the frequency of weather extremes (based on **WP1&2**). For example, we will evaluate the potential for storm surges and urban flooding due to an increase in precipitation extremes. Adaptation options and pathways to cope with abrupt changes will be assessed. Timeliness of early warning signals (link with **WP4**) will be evaluated based on the lead-time for implementation of the adaptation options. Stakeholders (national and regional policymakers and local and regional flood defence, health security and food production managers) will be involved to define the best adaptation options.

WP5 Outcomes: Assessment of impact (economic, environmental and humanitarian damage on health and welfare) for a few selected case studies of abrupt change; risk management and adaptation strategies for these cases to cope with abrupt changes in a few key regions, following the Adaptive Policy pathway approach.

WP6: Synthesis and implication for society and its responses

Objective: *(1) To synthesize the key findings of the other WPs; (2) to project current and future society in line with vulnerability and exposure; (3) to identify (even slow) climate changes that can cause tipping points in society.*

Approach: We will synthesize key findings from **WP1-4**. Then, we will engage in a two-way discussion with **WP1** and **WP5** to assess underlying characteristics that can cause societal tipping points in a few target regions by identifying thresholds for water and food availability (*e.g.* number of days the temperature above a certain threshold). Based on this analysis, we will elaborate potential pathways for policy makers and key stakeholders to maintain society within a safe operating space, mitigating both physical and societal tipping points.

WP6 Outcomes: Synthesis of knowledge gained in **WP1-4**, illustrated by case studies of **WP5**; an assessment of societal tipping points and their likelihood; a report dedicated to key policymakers and stakeholders on the pathway to remain in safe operating space.

WP7: Communication and dissemination

Objective: *(1) To facilitate effective communication and knowledge exchange between WPs and project partners; (2) to promote the project and disseminate its findings; (3) to engage policymakers, third sector organisations, businesses, and the general public; (4) to improve the science engagement skills of project partners.*

Approach: We will organise workshops, guest speakers, and interactive sessions at consortium meetings, concerning the language of communicating climate change, and public response to climate information and impacts. We will organise policy events notably in Brussels to disseminate the findings of the project. We will engage with artists to develop new tools to enhance public engagement building on the case studies of **WP5**.

WP7 Outcomes: A visible project with external impact and smooth internal communication. Specifics include: project website and newsletters, WP infographics, web-based 'explainer' films, policy briefings, a school educational toolkit.

WP8: Management and coordination

Objective: *To ensure pro-active management and facilitate interactions between the different WPs.*

Approach: A steering committee will be installed and will meet regularly. Annual general assemblies and dedicated workshops will be organized throughout the project. An external advisory board will be constituted to ensure that the high-level of our research is maintained and to guarantee excellence. A special care will be dedicated to ensure gender dimensions are correctly accounted for during hiring procedures and to adopt family-friendly policies. We anticipate that at least 6 of the 7 other WPs have a female lead or co-lead.

WP8 Outcomes: Efficient flow of the work programmes and easy interactions between partners and WPs.

1.4 Ambition

Going beyond the state-of-the-art

- **TipTop will allow for the first time an objective assessment (going beyond expert elicitation) of abrupt climatic changes and abrupt shifts in extremes, which constitutes a conceptual change in the way climatic tipping points are analysed.** The observational constraints that we will develop will reduce uncertainty and provide estimates of the likelihood of abrupt changes at the regional scale. This is a step change improvement in how climate risks can be integrated in global and regional risk management by providing likelihood estimates for abrupt change allowing for cost-benefit analyses of those risks against adaptation and mitigation measures.
- **The assessment of climate models in their ability to simulate and forecast tipping points is another major advance beyond the state-of-the-art.** TipTop will provide for the first time a quantitative estimate of biases in key processes of the climate system associated with tipping and abrupt changes and the way to improve them.
- **TipTop will provide the first analysis of specific case studies related to large-scale tipping points.** For instance, droughts and food production failure in the Sahel and Mediterranean, heat waves in Europe, and coastal flood risk in the Netherlands. Furthermore, we will identify, for the first time, societal tipping points associated with climate-induced failure in water and food supply to improve the resilience potential of vulnerable societies.

Innovation potential

Social science partnerships. TipTop's ability to achieve its ambitious and ground-breaking objectives is very much enhanced through its strategy of linking climate researchers with the social sciences and expert stakeholder partners. For example, by improving how we identify and predict abrupt changes in key climate variables (*Objective 1&2*), TipTop will not only quantitatively assess the likelihood of crossing tipping thresholds, but will also, for the first time, quantitatively assess the predictability and reliability of these tipping points and evaluate the potential for early warning signals (*Objective 3&4*). To generate societal impact from these objectives, our partners ***Red Cross/ Red Crescent*** and ***Deltares*** will work with stakeholders at risk from climate tipping points to co-develop new climate services and adaptation options. The ***Climate Data Factory*** will make these services available to a wide network of adaptation consultants, and will implement our tipping points search engine as a new product, including our results in the metadata of their products

Society-based metrics. Evaluating the timeliness of early warning signals using ***society-based metrics*** such as the lead time for implementation of adaptation options (**WP5**) is a new approach which promotes further integration of climate science and society. Similarly, our evaluation of ***the vulnerability of specific populations to abrupt climate changes*** (*via* case studies in **WP5**) will enable communities and governments to avoid potential humanitarian catastrophies. TipTop builds on this by introducing the new concept of ***thresholds for societal tipping points***, which complement climate tipping points. The evaluation reports developed in **WP6** represent a crucial new tool for policymakers, as they identify society as a volatile system that can tip in relation to climate change, leading to societal instabilities and conflicts. *We anticipate that the new services and tools developed in TipTop may enable new organisational models which encourage multi-level dialogue between the users of climate information, decision makers, and communities who will be most affected by climate and societal tipping points.*

Public engagement. In TipTop, we will interact with artists to develop new communication tools to widen public engagement. These tools will be tailored to the express needs of vulnerable societies by enhancing public awareness of the dangers that threaten these societies, consisting of performances at festivals, a series of web-based 'explainer' films, and other means. The case studies developed in **WP5** will serve as a basis for these communication tools.

2. Impact

2.1 Expected impacts

Supporting major international scientific assessments such as the IPCC

IPCC AR6. In previous IPCC assessments, regional aspects of climate change did not receive much attention, partly because of the larger uncertainty associated with climate change at regional scales, and partly because the global attribution and detection aspects still needed emphasis. As a result, the link between Working Group (WG) I, WGII and WGIII reports remained relatively weak. In the new AR6 structure these links are enhanced and regional climate change, and changes in weather extremes receive much more attention. TipTop will deliver products aligned with this new focus. By devoting a large part of our work to abrupt shifts in weather extremes (floods and droughts), the Arctic and North Atlantic, and monsoonal systems, we will contribute to, and strongly support this new emphasis in WGI of AR6. Moreover, by linking the scientific results to impact studies and risk management strategies TipTop will provide direct input for WGII, and by evaluating safe operating spaces, direct input for WGIII.

TipTop will: (1) assess the potential of abrupt shifts and tipping points in new observations and new CMIP6 model projections; and (2) evaluate how well the current generation of climate models simulates these events. Both aspects will make a unique contribution to the IPCC assessment cycle. As a result, TipTop will identify areas for improving climate models, by highlighting key processes and their evaluation in present-day climate models, and by identifying model biases. TipTop will also evaluate the ability of decadal prediction systems, developed within numerous EU projects, to estimate the risk of crossing thresholds, which will also feed the IPCC reports.

IPCC Experts. TipTop includes several partners that are active in the present IPCC cycle, for instance in the special report on the ocean and the cryosphere in a changing climate (Swingedouw, Bouwers, chapter 6 "Extreme, abrupt changes and managing risks"). Some partners were involved in the AR6 scoping meeting and are invited to take part in WGI and WGII reports as (coordinating) lead authors (Drijfhout, Braconnot, Sanchez-Goñi, Thorne, Coughlan de Perez). TipTop is also including a co-chair of CLIVAR DCVP (Cassou), which will allow further dissemination of our results at the international scale.

Increasing confidence in climate change projections

TipTop contributes to increasing confidence in the ability of climate change projections to include tipping events by:

- Explicitly evaluating the models' capacity in simulating potential past and future abrupt changes (**WP1&2**)
- Ground-truthing these with emergent constraints from paleo and recent instrumental observations (**WP2&3**)
- Assessing reliability and predictability of the simulated climate tipping points (**WP2-4**)

By assessing tipping events, which often appear as outliers present in only a few model realisations, TipTop goes beyond the analysis of the multi-model ensemble mean response to climate change and more properly evaluates the range of possible future scenarios. It will also evaluate the sensitivity of specific tipping elements to greenhouse gas concentration pathways, in order to precisely quantify the optimal pathway that avoids tipping and remains in a safe operating space. In particular, we will evaluate if the 1.5°C or 2°C global warming target allow this (**WP2&6**). Adding these new elements to climate change projections increases confidence in the projections. TipTop will also strengthen interactions between paleo-data scientists, *in situ* observationalists, mathematicians and climate modellers (**WP1-4**), who will provide richer interpretation of climate change projections by crossing different areas of evidence, increasing consensus across different disciplines.

Providing added-value to decision and policy makers

Linking with EU and national policy makers. The policy community is a key stakeholder group for TipTop, as understanding the impact of tipping points on the environment and society is a high priority for policymakers. We will organize a meeting in Brussels with well-identified people from the European Commission (**WP7**), using the network from the CNRS lobby group based in Brussels, to disseminate our main findings, and to integrate our risk management analysis within European policymaking. We will make use of our project partners and their strong links with European Commission organizations (*e.g.* JPI Climate, DG Climate), international organizations (UN and IPCC), NGOs (Red Cross), and national networks to communicate our messages and project outcomes and to provide training on tipping points, in order to support evidence-based policy making.

Improving national climate services. We will integrate the results of this project with national climate change assessments and scenarios. For example, we will build on existing interactions with the French Ministries of Environment and Defence (Swingedouw) and the climate change assessment of the Netherlands Meteorological Institute (Drijfhout). The project will provide climate services (**WP5&6**) with assessments on abrupt changes and decision-making services on how to deal with these changes through *The Climate Data Factory* and *Deltares*. The risk assessment of abrupt climate change would be added to climate metrics, which are now developed within different ministries or companies. We will also work with the Copernicus Climate Change Services (C3S), the Society for Decision Making under Deep Uncertainty, providing climate changes services to decision makers on the national level (**WP5&6**).

Developing disaster management. TipTop will improve climate change adaptation strategies by providing assessments of abrupt changes in the higher percentiles of the probability distribution of extreme weather to (governmental) organisations responsible for climate adaptation[8,10]. This is key to improve the resilience of communities to extreme climatic events and abrupt changes unprecedented since the last Ice Age. It will allow economies to prepare to such eventualities, notably the insurance companies, the agricultural sector or urban development. One of the key points we want to emphasize in our interaction with policy makers is that adaptation strategies should be flexible and keep options open to adapt to abrupt changes when early warning signals indicate increasing risks and when rare (for instance one in every hundred year) events increase their frequency in the future. For example, the case study on coastal flood risk in the Netherlands (**WP5**) will be done with participation of the Dutch Delta programme, which recently identified potential acceleration of sea-level rise as a signal that requires further investigation into consequences for their adaptive plan. Concerning the Sahel region, we will engage with stakeholders notably from Senegal (**WP5**) through Regional Climate Change Committees (COMRECC) and National Climate Change Committees (COMNACC) thanks to the network from IRD experts (Sultan, Mignot). The outcomes of TipTop will have implications for pressing international issues such as migration and the provision of food and water, which will be communicated to, for instance, the GFDRR (global facility for disaster reduction and recovery) initiative.

Sustain Europe's leadership in climate science

TipTop builds on a novel method to search, find and classify abrupt changes in CMIP databases. This method was first developed in a previous European project (EMBRACE) and led to two highly cited high-impact papers that also drew a lot of attention outside the climate science community. It is here widened in scope by integrating new knowledge gained in other EU projects (NACLIM, SPECS, HELIX) such as linking physical precursors to early warning systems using decadal climate predictions.

- Through an integral assessment of climate tipping points, with leading experts in time-series statistical analysis, network analysis and machine-learning methods, we will be the first to properly link climate tipping points with early warning indicators on an unprecedented scale.
- By using constraints from instrumental and paleo observations, and decadal prediction systems, we will be the first to provide an objective risk assessment of tipping events, which previously depended on expert judgment.
- The association and integration between assessment of tipping points in the physical climate system with impact, adaptation policy and social sciences is novel and unique, including the development of narratives for selected case studies, dynamical downscaling with regional climate models, and the use of impact models and social science tools to assess societal vulnerability and hazard risks.
- Together with predictability assessment of the pertinent hazards, such an integrated assessment implies an almost discontinuous step-change in interdisciplinary research on climate tipping points, risk, and impact, keeping Europe at the very forefront of climate science.

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