TIPPING POINTS IN THE EARTH SYSTEM

# State dependence and spatial patterns of feedbacks

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# Summary for publication

This is a progress report on work undertaken as part of TiPES on some of the key indicators of climate change – namely climate response, feedbacks and sensitivity. These are metrics that quantify how much the climate is expected to change depending on how forcing such as atmospheric $CO_2$ changes in the future. More specifically, TiPES has been examining how these metrics may depend not just on forcing, but also on the state of the climate itself. Indeed, the current climate state may not be so obvious to observe: potentially, there may be more than one stable state and, one of the big challenges is to separate the internal variability from forced variability. In case of more than one stable climate states, transitions between different equilibria may appear as abrupt climate changes. Moreover, feedbacks may change their relative strength over time on a variety of timescales, such that the climate response changes underway during the transient towards a new equilibrium.

This work done in TiPES has has been looking at (a) better understanding of climate variability on a variety of time scales (b) improved methods of quantifying sensitivity and climate response with and without tipping points (c) improved methods of quantifying spatial and temporal patterns of climate feedbacks from transient simulations (d) exploring some of these methods against earth system models of varying complexity.

# Work carried out

This is deliverable D4.1 entitled *State dependence and spatial patterns of feedbacks,* which is part of the Tipping Points in the Earth System (TiPES) H2020 project. Specifically, this report is part of WP4: *From Climate Sensitivity to a general theory of Climate Response across scales* and is mainly related to Task 4.1 *Extending the concept of Climate Sensitivity.* In order to complete and structure the task T4.1, we present here an overview of feedbacks in the climate system that are relevant for the climate response and will be further addressed by TiPES. Subtask T4.1.1 relates to state-dependent (global) climate response and we focus therefore here on those feedbacks that might change in their strength over time. Subtask T4.1.2 in turn considers spatial and temporal patterns of feedbacks. In this report we focus on the variety temporal scales occurring in the climate response and indicate first steps towards spatial patterns of feedbacks.

The work presented here has crosscutting links to WP2 in the sense that it makes use of simulations also prepared for WP2 and links to WP5 by scientific exchange of mathematical tools to characterize the response of a system (e.g. early warning signals). In a broad sense, this task will contribute to TiPES Theme 2 (Climate Response Theory) and Theme 3 (Nonlinear and non-autonomous systems), and will directly contribute methodology, data and results to achieve Project Objectives 3 (O3) - to 'Characterise climate response in the presence of Tipping Points (TPs)'

**A. Introduction**

Climate sensitivity is a frequently used metric to understand global change and project future climate change. One of the most used variants is the equilibrium climate sensitivity (ECS), defined as the long-term (equilibrium) temperature increase resulting from instantaneous doubling of atmospheric $CO_2$. It was originally quantified in a climate model with land ice cover and vegetation fixed at present-day values [Charney1979] to be in a range of 1.5-4.5 K. Later, climate sensitivity was not only determined from climate models, but also from observations and palaeoclimate reconstructions. Despite enormous developments in climate modelling, data availability and analysis methods, the uncertainty remains largely unchanged with the 2013 report by the Intergovernmental Panel on Climate Change [IPCC, 2013] presenting the same range (1.5-4.5 K) with a >66% (termed "likely") probability and no best estimate. In the just released IPCC report 2021 [IPCC, 2021] the likely range is reduced to 2.5-4 K with a best estimate of 3 K. Much of this latter statement is based on the most recent assessment of the Earth's climate sensitivity [Sherwood2020], which has used three largely independent lines of evidence to constrain the range: feedback process understanding, the historical climate record, and the paleoclimate record. By using a Bayesian approach to combine all evidence into a probability density function (PDF) that study arrives at a >66% (likely) credible range of 2.3-4.5 K, in particular increasing the lower end of possible values. A climate sensitivity lower than 2 K becomes very unlikely in all three lines of evidence. However, the high (and most dangerous) end of the climate sensitivity range could not be constrained further, while events forming this 'warm tail' is potentially the result of abrupt transitions and tipping elements.

In order to further narrow down the range of climate sensitivity, in particular on the high end of values further research is necessary; for example, internal climate variability on a variety of time scales can potentially mask the equilibrium warming during the transient, and even when the system is already close to equilibrium (in the case of variability on long time scales), while it may be questionable whether a true equilibrium is ever reached. Similarly, clear relations between forcing and feedbacks are not well understood, in particular for longer time scales. Moreover, the focus has been very much on the global mean surface temperature response, while most processes in the climate system result in spatial patterns of surface warming, even under spatially uniform forcing. Finally, a number of feedback processes contributing to the climate sensitivity are known but difficult to quantify, as climate models have trouble capturing them completely (e.g. clouds).

The traditional forcing-feedback approach is inherently linear in many instances and while the climate system as such is clearly non-linear in many aspects, the range of validity of such linear approaches (e.g. linear response theory) remains largely unexplored. Another consequence of the nonlinear nature of the climate system in general is that it varies on a huge range of spatial and temporal scales, suggesting, e.g., that understanding forcing-feedback relations for short-term (internal) variability might not suffice to extrapolate to longer-term relations. Moreover, in particular when using information from past (warm) climates to constrain the present-day response to $CO_2$ forcing, the dependence of the climate sensitivity (or more general climate response) on the background state (on a number of time scales) remains a critical topic that requires further investigation including more observations, modelling with state-of-the-art climate models and theoretical development.

This report is structured as follows. In the next section we briefly review a few classical metrics of climate sensitivity and the forcing-feedback framework these are based on. In Section 3, we describe a few selected papers produced by the TiPES project, which address some of the shortcomings of the classical concepts. Moreover, we elaborate on first steps that have been taken towards a more generalized view of climate response.

Originally planned for project month 18, our work has suffered from substantial delay due to the Covid-19 pandemic. Some postdoc appointments have been delayed (UR) by 6 or more months. Moreover, collaboration between partners has been more difficult without physical meetings and due to additional (online) teaching duties of staff members. Nevertheless we have had regular contact online via individual meetings as well as formal and informal WP4&5 postdoc meetings.

## B. Metrics of climate sensitivity

Traditionally, climate sensivitity is measured as equilibrium warming per $CO_2$ doubling (termed equilibrium climate sensitivity ECS), but in practise a number of other measures are currently being used. For example, considering the warming per unit radiative forcing change is already more insightful because it can be applied to a wide range of $CO_2$ change scenarios and allows to vary with initial climate or $CO_2$ state. Its inverse – the increment of additional net power exported to space per unit warming – is termed the *feedback parameter* $\lambda$, which can be interpreted as an energetic spring constant of the system and contributions of individual physical feedback processes to $\lambda$ can be estimated. The feedback parameter also allows for a form of state-dependence, e.g. $\lambda$ could be temperature dependent, which appears as non-constant local slopes in the radiative forcing – temperature relationship [Heydt2014, Heydt2016].

The currently employed forcing-feedback framework involves the assumption that the net downward radiative imbalance at the top of the atmosphere $\Delta \mathrm{N}$ can be decomposed into three components, namely the radiative forcing $\Delta \mathrm{F}$, the radiative response related to the feedback $\Delta \mathrm{R}$ and climate variability $V$ unrelated to the forcing [Sherwood2020]:

$$\Delta \mathrm{N} = \Delta \mathrm{F} + \Delta \mathrm{R} + \mathrm{V} \qquad (1)$$

The main linearity assumption comes in when assuming that the radiative response is proportional to the change in global mean surface temperature to first order, i.e. $\Delta \mathrm{R} = \lambda \Delta \mathrm{T}$. In this framework, different time scales do not play a direct role, except for the equilibrium assumption: In the case of a stable climate ($\lambda < 0$) over sufficiently long time scales the system will be in equilibrium making both the radiative imbalance and unforced variability negligible, such that

$$\lambda = -\Delta \mathrm{F} / \Delta \mathrm{T}. \qquad (2)$$

The feedback parameter $\lambda$ reflects the total system feedback, which is assumed to consist of additive individual process feedbacks of strengths $\lambda_i$:

$$\lambda = \sum \lambda_i. \qquad (3)$$

The six (most important) feedback processes affecting the global mean surface temperature are estimated in [Sherwood2020]: (a) the Planck feedback, (b) combined water vapor and lapse rate feedback, (c) total cloud feedback, (d) surface albedo feedback, (e) stratospheric feedback, and (f) atmospheric composition feedback. Estimated values are summarized in Table 1.

**Table 1:** *Feedback processes affecting the global mean temperature and radiative balance. Estimates are according to the most recent assessment of climate sensitivity [Sherwood2020]. The estimates assume a Gaussian distribution for all feedbacks, given is the mean value ± standard deviation.*

| Feedback name | Contribution from physical quantities | Estimated value [$Wm^{-2}/K$] | Description |
|---|---|---|---|
| Planck | $\lambda_{Planck}=-4\varepsilon\sigma T^3$ | -3.2±0.1 | The Planck feedback represents the extra emission to space of LW radiation arising from a vertically uniform warming of the surface and the atmosphere with no change in composition. |
| Water vapour and lapse rate | Water vapour concentration, vertically non-uniform temperature changes. | +1.15±0.15 | The water vapor feedback quantifies the change in outgoing longwave and absorbed shortwave radiation at the top of the atmosphere due to changes in atmospheric water vapor concentration associated with a change in global mean surface temperature.<br>The lapse rate feedback is the change in outgoing longwave radiation resulting from vertically nonuniform changes in temperature.<br>The combined water vapour and lapse rate feedback enhances anthropogenic warming. |
| Clouds | | +0.45±0.33 | Diverse cloud formation processes add up the response to warming of all cloud types making a significant radiative contribution. Added together, the cloud feedback enhances anthropogenic warming. |
| Surface albedo | Snow cover, sea ice, land ice | +0.3±0.15 | The surface albedo feedback mostly arises from warming-induced shrinkage of the cryosphere, which exposes less reflective surfaces that absorb more sunlight. The albedo feedback enhances anthropogenic warming. |
| Stratosphere | | +0.0±0.1 | Changes in stratospheric temperature and water vapour. With the current estimate this feedback can either slightly enhance or dampen anthropogenic warming. |
| Atmospheric composition | Ozone, aerosols | +0.00±0.15 | Mostly indirect effects of ozone changes in the atmosphere; changes in production and lifetime of aerosols such as dust, sea salt and natural fires. With the current estimate this feedback can either enhance or dampen anthropogenic |

| | | | |
|---|---|---|---|
| | | | warming. |
| **Total feedback** | | **-1.3±0.44** | **Linear sum of all individual feedback factors. Note that the total feedback is negative, suggesting that a new (warmer) equilibrium can be reached. In case of a positive total feedback the earth would end up in a run-away climate.** |

Notable in Table 1 is the cloud feedback, which is inherently difficult to estimate, because different cloud types are generally not well represented in most general circulation models (GCMs). As an example, we consider high and low clouds in Figure 1, which via a number of physical processes result in either positive or negative feedback on the global mean surface temperature.

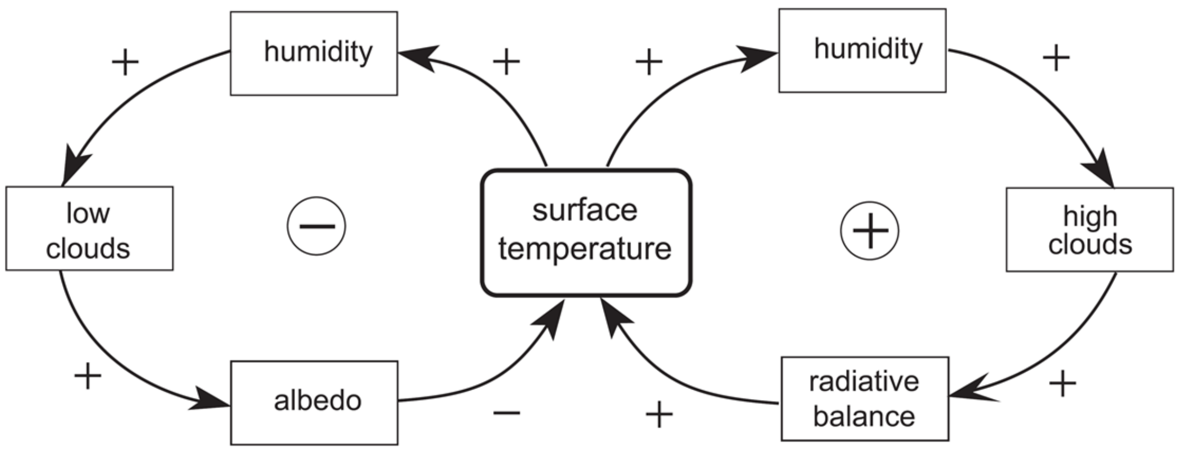


**Figure 1:** Example of positive and negative feedback chains associated with different cloud altitudes. The sign of correlation between subsequent boxes are indicated. The overall sign of the feedback results from the multiplication of all correlations and is indicated by circled signs.

The original definition of equilibrium climate sensitivity is in practice often replaced by the so-called *effective climate sensitivity*, which is an extrapolated model-determined quantity: The first 150 years of an experiment following an instantaneous quadrupling of $CO_2$ are considered and the global mean top-of-atmosphere energy imbalance is regressed onto global mean near-surface air temperature. This regression is then extrapolated to zero imbalance giving an estimate of the long-term warming valid under the assumption that all feedbacks contributing to the total system feedback stay active and constant until equilibrium is reached [Gregory2004]. In general, the effective climate sensitivity seems to correlate well with equilibrium climate sensitivity suggesting that the forcing-feedback framework as sketched above holds in this case as well. However, it should be kept in mind that the forcing-feedback framework is inherently linear and the assumption of all feedbacks remaining constant all the time may mask potential "surprises" in the climate system response.

The feedback scheme proposed above misses the time-dimension of the involved processes, and one sometimes need to separate heuristically fast from slow feedback mechanisms. The formalism of response theory allows to provide a rigorous link between the time scales of the feedbacks and the modes of relaxation of the climate system, as demonstrated in our following TiPES publications:[Lucarini2018, Tantet2018, Ghil2020] and the discussion revolving around [Bastiaansen2021], presented later in this report.

**C. Work done within TiPES: Time- and background state dependence**

The spectral view of variability is a compelling and adaptable tool for understanding variability of the climate. In his seminal paper [Mitchell1976] captured in one graph with log scales, a very wide range of climate variations from millions of years to days. The spectral approach is particularly useful for suggesting causal links between forcing variability and climate response variability. However, a substantial degree of variability is intrinsic, and the Earth system may respond to external forcing in a complex manner. There has been an enormous amount of work on understanding climate variability over the last decades. In the review paper [Heydt2021], we address the question: Can we (after 40 years) update the Mitchell (1976) diagram and provide it with a better interpretation? By reviewing both the extended observations available for such a diagram and new methodological developments in the study of the interaction between internal and forced variability over a wide range of timescales, we give a positive answer to this question. In addition, we review alternative approaches to the spectral decomposition and pose some challenges for a more detailed quantification of climate variability.
Our understanding of the climate variability spectrum that has evolved over the past 40 years is crucial for extending the general concept of climate sensitivity. In particular, given that the climate system varies on a huge range of time scales with some more preferred than others, the question arises on which time scales the variability V in equation (1) can be safely assumed to average to zero in a true equilibrium or on the trajectory to equilibrium by extrapolation techniques. This work therefore contributes to Task 4.1 by providing insights into specific time scales of the climate system.

A significant challenge for TiPES comes from the fact that ECS is an approximate linear response of a highly nonlinear, high dimensional turbulent forced system with multiple timescales. Stochastic energy balance models may still have highly nonlinear feedbacks but are not usually considered in terms of their ECS. In work completed during the TiPES project, [Ashwin2019] propose a geometric definition of ECS (`two-point sensitivity') that can be used to relate changes in global mean surface temperature to changes in forcing associated with GHG forcing without making any assumption of linearity. The two-point sensitivity compares climate and GHG forcing conditions at pairs of sample points of a palaeoclimate time series, independent of how much time has passed between the two points. This limits in some sense to the usual notion of linearized `instantaneous' ECS but allows for quantification of scenarios where there may be multiple equilibria with differing sensitivities. The paper [Ashwin2019] considers two example climate models (an energy balance and the multiple-box model by Gildor and Tziperman [Gildor2001]) that is able to reproduce ice-age cycles) to illustrate the utility of the two-point sensitivity and to relate it to climate regimes for models with multiple stable climate states.
More generally the paper [Ashwin2019] expands on an earlier paper [Heydt2016] and explores climate sensitivity in the context of a *climate attractor,* a geometric object in parameter space on which all allowed climate dynamics (i.e. past and future trajectories) take place. This work contributes to Task 4.1 and Task 4.2 providing means to characterize the (local) attractor of the climate system, where also tipping points might occur (T4.2). Moreover, it links to WP5 by applying their measures to the climate response.

The concept of ECS assumes we have access to (statistical) equilibrium climate states. However, since global climate models cannot be fully equilibrated in practice, extrapolation techniques are used to estimate the equilibrium state from transient warming simulations. These transient simulations are often relatively short; the common standard in e.g. the Coupled Model Intercomparison Project (CMIP) only requires 150 years to be simulated, while processes related to e.g. land ice dynamics act on much longer time scales. Because of the abundance of climate feedbacks—spanning a wide range of temporal scales— it is hard to extract the long-term behavior of the climate system from these short-time series. In particular, the predominantly used techniques, such as the previously described forcing-feedback framework, are only capable of detecting the single most dominant eigenmode; that is, these only find a constant feedback parameter $\lambda$ that is capturing only the dynamics on these short time scales of the transient simulations used; this thus hampers the ability to give accurate long-term estimates. In [Bastiaansen2021], we have presented an extension to those methods by incorporating data from multiple observables in a multicomponent linear regression model. This way, not only the dominant but also the next-dominant eigenmodes of the climate system are captured, essentially allowing us to track changes in the feedback parameter $\lambda$ over multiple time scales. This means transient state-dependencies are more accurately tracked, which leads to better long-term estimates from short, nonequilibrated time series.

When the climate system is forced, e.g. by emission of greenhouse gases, it responds on multiple time scales. As temperatures rise, feedback processes might intensify or weaken. Current methods to analyze feedback strengths, however, do not take such state dependency into account; they only consider changes in (global mean) temperature and assume all feedbacks are linearly related to that. That is, they assume, often implicitly, that the individual feedback parameters $\lambda_i$ are constant and do not change during the transient period. This makes (transient) changes in feedback strengths almost intangible and generally leads to underestimation of future warming. In [Bastiaansen2021b], we present a multivariate (and spatially explicit) climate feedback framework that allows for dissecting climate feedbacks over time scales. Using this framework information on the composition of projected (transient) future climates and feedback parameters $\lambda_i$ can be obtained, including how they change as time progresses. Moreover, the framework can be used to make projections for many emission scenarios through linear response theory. In [Bastiaansen2021b], the new framework is also illustrated using $CO_2$ forcing experiments with the Community Earth System Model v2 (CESM2). Here, it was shown, for example, that in an abrupt 4xCO2 experiment, the water vapour feedback strength would almost triple in a century and that the surface albedo feedback would become almost irrelevant in the same time span. Both of these works contribute to Task 4.1 by going beyond the linear concept of ECS and acknowledging multiple temporal and spatial scales as well as state dependence in the climate response.

Global Climate Models are key tools for predicting the future response of the climate system to a variety of natural and anthropogenic forcings. In the TiPES paper [Lembo2020] we show how to use statistical mechanics to construct operators able to flexibly predict climate change. We perform our study using a fully coupled model - MPI-ESM v.1.2 - and for the first time we prove the effectiveness of response theory in predicting future climate response to $CO_2$ increase on a vast range of temporal scales, from inter-annual to centennial, and for very diverse climatic variables. We investigate within a unified perspective the transient climate response and the equilibrium climate sensitivity, and assess the role of fast and slow processes. The prediction of the ocean heat uptake highlights the very slow relaxation to a newly established steady state. The changes in the Atlantic Meridional Overturning Circulation (AMOC) and the Antarctic Circumpolar Current (ACC) are accurately predicted when comparing model results with response-based projection. The AMOC strength is initially reduced and then undergoes a slow and partial recovery. The ACC strength initially increases due to changes in the wind stress, then undergoes a slowdown, followed by a recovery leading to an overshoot with respect to the initial value. Finally, we are able to predict accurately the temperature change in the North Atlantic. This work makes use of simulations also contributing to WP2 and WP3 and mainly contributes to Task 4.1 in anticipation of Task 4.2, where we intend to study the limits of this approach in the presence of tipping points.

Comprehensive models show that under a constant forcing, the global climate feedback becomes less negative (increasing) over time. This has been attributed to increases in cloud and lapse-rate feedbacks. However, out of eight Earth system models of intermediate complexity (EMICs) not featuring interactive clouds, two also simulate such a feedback increase: Bern3D-LPX and LOVECLIM. Using these two models, we investigate in [Pfister2020] the causes of the global-mean feedback increase in the absence of cloud feedbacks. In both models, the increase is predominantly driven by processes in the Southern Ocean region. In LOVECLIM, the global-mean increase is mainly due to a local longwave feedback increase in that region, which can be attributed to lapse-rate changes. It is enhanced by the slow atmospheric warming above the Southern Ocean, which is delayed due to regional ocean heat uptake. In Bern3D-LPX, this delayed regional warming is the main driver of the global-mean feedback increase. It acts on a near-constant local feedback pattern mainly determined by the sea ice–albedo feedback. The global-mean feedback increase is limited by the availability of sea ice: faster Southern Ocean sea ice melting due to either stronger forcing or higher equilibrium climate sensitivity (ECS) reduces the increase of the global mean feedback in Bern3D-LPX. In the highest-ECS simulation with $CO_2$ forcing, the feedback even becomes more negative (decreasing) over time. This reduced ice–albedo feedback due to sea ice depletion is a plausible mechanism for a decreasing feedback also in high-forcing simulations of other models. This work adds to the characterization of state- (or time-) dependent feedbacks in Task 4.1 and makes use of model simulations used in WP2 and WP3.

# Main results achieved

As described above, the classical framework of characterizing the climate response to increasing greenhouse gas concentrations is based on a number of linear assumptions and disregards the multitude of temporal and spatial scales in the climate system. The work we have carried out in TiPES so far, provides first steps towards a more generalized view of the climate response. In particular we address the multitude of time scales in the climate system and the notion that feedbacks can vary over time (i.e. state dependence).

The publication [Heydt2021] summarizes our current understanding of the huge range of time scales in the climate system, where some may be more preferred than others due to internal generated and externally forced variability. The climate variability spectrum that has evolved over the past 40 years is crucial for extending the general concept of climate sensitivity. In the case of ECS, when using extrapolation techniques, it is important to determine whether the variability V in equation (1) averages (approximately) to zero in both a true equilibrium and on the trajectory to equilibrium.

The publication [Ashwin2019] demonstrates how disappearance of a stable regime through tipping can cause an increased tail in the distribution of ECS within an ensemble. It also proposes a notion of “tipping probability” that can be used to decompose the distribution of observed ECS conditional on whether tipping has been undergone. However [Ashwin2019] also notes that the converse is not necessarily the case – high sensitivities can be induced through temperature-driven variation of the feedbacks. This highlights the need for more work to be done to disentangle properties of ECS and/or to give improved metrics that give important information in climate states that may or may not undergo tipping.

The publications [Bastiaansen2021a] and [Bastiaansen2021b] describe novel numerical methods to extract and estimate more accurately the long-term behaviour of climate sensitivity and feedback parameters. In [Bastiaansen2021a], the focus is on equilibrium climate sensitivity estimates from relatively short transient simulations that do take the multiple time scale dynamics of the climate systems into account. In [Bastiaansen2021b], the focus is on the transient changes (i.e. the transient state-dependency) of individual climate feedback parameters $\lambda_i$ over time in various forcing scenarios.

The publication [Lembo2020] provides the first example of use of response theory for performing climate change projections on a CMIP6-class Earth system model. The study shows the great potential of such statistical mechanical approach for predicting accurately climate change both for fast variables associated with the atmosphere and slow variables associated with the ocean circulation. In particular, the nearing of the AMOC tipping point in future climate conditions where higher CO2 concentration is found emerges clearly in the response-based projection. Finally, one can better understand the peculiar properties of changes in the surface temperature in the so-called cold blob in the North Atlantic.

The publication [Pfister2020] points at the fact that Southern Ocean sea ice melting may constitute an important effect to modify the evolution of the climate feedback on time scales of centuries. While anthropogenic warming in the climate system mainly affects the Northern Hemisphere already now and over the next decade to century, processes in the high southern latitudes may have a longer-term effect.

These results provide an important step towards the overall objective O4, by characterizing the climate response on various spatial and temporal scales [Heydt2021, Bastiaansen2021a,b, Pfister2020] and providing tools to characterize the climate attractor [Ashwin2019] and applying Ruelle's response theory [Lembo2020], which will be useful for extending towards the response in the presence of tipping points (T4.2)

# Progress beyond the state of the art

The publication [Heydt2021] updates our view and understanding of the climate variability spectrum that was generated more than 40 years ago. It highlights in particular understanding of processes producing internal variability and (nonlinear) synchronization effects, where external forcing interacts with internal climate dynamics time scales. Moreover, alternative approaches to the spectral decomposition are presented.

The publication [AH2019] has furthered the debate on how the linear notion of climate response may be usefully interpreted in a climate with state-dependent feedbacks that give rise to tipping points and multiple equilibria. In particular it highlights the utility of quantifying ECS at the same time as estimating a regime tipping probability.

The publication [Bastiaansen2021a] has introduced a novel numerical method that is capable of extracting the evolution of climate variables over multiple time scales from short transient simulations, leading to more accurate estimates of equilibrium climate sensitivity.

The publication [Bastiaansen2021b] has introduced a numerical tool that allows for tracking of the transient state-dependency of individual feedback parameters in various forcing scenarios, enabling both better and more insightful projections of future climate states.

The publication [Lembo2020] contains a very ambitious use of response theory as the authors apply it to a numerical model that is far more complex than any previous attempts, in geosciences or otherwise. The efficiency of the proposed methodology over different time scale and climatic subsystems and its ability to indicate the nearing of tipping points is very promising.

Earth System Models of Intermediate Complexity play an important role in understanding the climate system on time scales of many centuries to millennia. Identifying processes that influence and modify the global-mean climate feedback are key to better understand tipping points in the climate system. By considering the role of Southern Ocean sea ice, the publications [Pfister2020] turns the attention to a climate system component that has not been in the focus of more complex models projecting anthropogenic climate change.

# Impact

## <u>How</u> has this work contributed to the expected impacts of TiPES?

We would like to highlight how the work outlined in the previous sections is expected to contribute to the four general areas where TiPES will have impacts (as stated in TiPES DoA, Part B, Section 2.1, table 4):

1. **“Supporting major international scientific assessments such as the IPCC”**: TiPES aims to develop an advanced theory of climate response that incorporates and extends the classical concept of climate sensitivity. The results described here focus on the issue of state-dependent sensitivity and have informed the chapter on ‘The Earth’s energy budget, climate feedbacks and climate sensitivity’ (AR6, Chapter 7), and in particular the most recent climate sensitivity assessment performed by the World Climate Research Programme [Sherwood2020]. Further results on climate response in the presence of TPs leading on from these results promise to influence the preparation of AR7.
2. **“Increase confidence in climate change projections”**: TiPES aims to develop a comprehensive climate response theory that allows one to perform climate projections for virtually any climate variable of interest for a continuum of time-dependent scenarios of forcing. The work outlined in this report are first steps to going beyond the current state-of-the-art, and a few scenarios are considered. In due course these results should contribute to increasing confidence (and understanding of uncertainty) in climate change projections as well as practical software tools to apply developments to climate models.
3. **“Providing added-value to decision and policy makers”**: TiPES will perform qualitative computations of safe operating spaces in order to achieve a target, minimizing dangerous and abrupt change in the control of a non-stationary system. The work outlined here contributes to a better understanding of the underlying metrics (climate sensitivity and response) that are essential to identify such safe operating spaces.
4. **“Sustaining Europe's leadership in climate science”**: TiPES integrates EU leading climate science with novel approaches from non-equilibrium statistical mechanics, stochastic processes, time-series analysis, and dynamical systems theory that will be relevant to a much wider class of complex multi-scale systems. The work outlined in this report strengthens the physico-mathematical understanding of the study of TPs. This work has been published in peer-review journals and already disseminated internationally in the climate science community, as highlighted in the section on dissemination and exploitation of TiPES results below.

### Impact on the business sector

Through the dialogue process established in WP7 (Amigo) the latest findings from theory and modelling of tipping points will be made available to the insurance and reinsurance sector.

## Lessons learned and Links built

The work in [Heydt2021] provides a long-needed overview of natural and forced climate variability to the general climate research community. It has arisen from collaboration of several TiPES partners (UU, UExe, UCPH, ULouvain) during a workshop in 2017 supported by the Past Earth Network and CliMathNet. The Past Earth Network is a EPSRC (UK) funded network with the aim to improve communication between palaeoclimate scientists and statisticians as to improve confidence in climate models for future projections by studying past climates. Similarly, CliMathNet is an initiative (EPSRC funded) aiming to bring together researchers in Mathematical Sciences and Climate Sciences.

The work in [Ashwin2019] is helping to motivate ongoing work in WP5 to better understand the nature of tipping beyond the “stochastic saddle-node" scenario, to highly turbulent systems. The latter work is looking at the effects of path dependence on the timing and indeed probability of tipping in systems undergoing changes in time-dependent forcing.

The work in [Bastiaansen2021] and [Bastiaansen2021b] forms extensions of the classic forcing-feedback framework that is used to analyze the output of global climate models, including those participating in model intercomparison projects such as CMIP. It is expected the newly introduced numerical tools will allow for more accurate analysis of these models, including especially (estimates of) their dynamics on longer time scales.

In the work in [Lembo2020], the tools from response theory have been applied for the first time to a reasonable state-of-the-art general circulation model, which provides the basis for developing this methodology further towards a software package (for deliverable D4.2).

The work in [Pfister2020] highlights the usefulness of intermediate complexity models in the search for state- and time dependence of various climate feedbacks. More of these models will be used in WP2 and contribute to further establishment of such state/time dependence in WP4. These type of models will be also used for past time periods where some comparison with (proxy) observations can be performed in collaboration with the PAGES network.

## Contribution to the top level objectives of TiPES

This report (D4.1) contributes mainly to TiPES objective O3, but also adds to the other TiPES objectives:

**Objective 3-Characterise climate response in the presence of Tipping Points (TPs)**
by elucidating state-of-the-art knowledge in climate feedbacks, climate response and climate sensitivity in the presence of tipping points, in particular examining cases where spatial-dependence of the feedback mechanism is important, and in helping to understand various aspects related to state dependence of climate feedbacks.

**Objective 1-Identify tipping elements (TEs) and their interactions in models and data**
by highlighting cases where regional tipping elements and state dependence of response are important for understanding climate feedbacks, climate response and climate sensitivity.

**Objective 2-Provide approaches for the identification and validation of Early Warning Signals**
by highlighting issues around the importance of tipping point prediction as well as climate response for understanding and predicting climate change under anthropogenic forcing.

**Objective 4-Define and identify safe operating spaces**
by highlighting areas where linear response theory may overestimate safe operating spaces in terms of climate response, due to the presence of tipping points.

**Objective 5-Bridge the gap between climate science and policy advice**
by highlighting challenges that tipping points pose to improving the predictability of climate response to changing anthropogenic greenhouse gas emissions using standard linearity-based tools.

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# Dissemination and exploitation of TiPES results

## Dissemination activities

| Type of dissemination activity | Name of the scientist (institution), title of the presentation, event | Place and date of the event | Estimated budget | Type of Audience | Estimated number of persons reached | Link to Zenodo upload |
|---|---|---|---|---|---|---|
| Participation to conference | Anna von der Heydt (UU), How does the geological record inform our quantification of climate sensitivity | Online, 26-27 May 2021, https://www.geolsoc.org.uk/05-GSL-Climate-Change | none | Scientific community, General Public | 300 | http://doi.org/10.5281/zenodo.4817435 https://www.youtube.com/watch?v=RTlOPdr2A9o |
| Organisation of a conference | Anna von der Heydt (UU), Peter Ashwin (UExe), Valerio Lucarini (UR), "Tipping points in the Earth System" session ITS3.1/NP1.2 at EGU General Assembly 2021 | Vienna, April 2021, online | | Scientific Community (Higher Education, Research) | 18.000 (online) ~ 200 in session | https://meetingorganizer.copernicus.org/EGU21/session/40422 |
| Organisation of a conference | Anna von der Heydt (UU), "Scaling, multifractals and nonlinear dynamics in the atmosphere, ocean, hydrosphere and solid earth" session NP3.1 at EGU General Assembly 2021 | April 2021, online | | Scientific Community (Higher Education, Research) | 18.000 (online) ~ 100 in session | https://meetingorganizer.copernicus.org/EGU21/session/39131 |
| Organisation of a conference | Valerio Lucarini (UR) "Statistical and Dynamical Methods for Geophysical Extremes " shourt course SC4.10 at EGU General Assembly 2021 | April 2021, online | | Scientific Community (Higher Education, Research) | 18.000 (online) | https://meetingorganizer.copernicus.org/EGU21/session/38987 |
| Participation to a conference | Valerio Lucarini: A New Mathematical Framework for Atmospheric Blocking Events, EGU General Assembly 2021 | 19–30 Apr 2021, online | | Scientific Community (Higher Education, Research) | 18.000 (online) | https://doi.org/10.5194/egusphere-egu21-1828, 2021 |
| Participation to a conference | Robbin Bastiaansen (UU), "Multivariate Estimations of Equilibrium Climate Sensitivity from Short Transient Warming Simulations", EGU General Assembly 2021 | 19-30 April 2021, online | | Scientific Community (Higher Education Research) | 18.000 (online) ~100 in session | https://doi.org/10.5194/egusphere-egu21-187 |
| Participation to an event other than a conference or workshop | Robbin Bastiaansen (UU), "Multivariate Climate Projections: More Accurate Equilibrium Estimations & Evolution of Climate Feedbacks", Minnesota Dynamical Systems Seminar | 13 April 2021, online/Minnesota | | Scientific Community (Higher Education Research) | 20 | |
| Participation to an event other than a conference or workshop | Robbin Bastiaansen (UU), "Multivariate Estimations of Equilibrium Climate Sensitivity from Short Transient Warming Wimulations", Nederlands Aardwetenschappelijk Congres (Dutch Earth Sciences Congress) | 9 April 2021, online | | Scientific Community (Higher Education Research) | ~60 in session | |
| Participation to an event other than a conference or workshop | Robbin Bastiaansen (UU), "Multivariate Estimations of Equilibrium Climate Sensitivity", Leiden's Informal Analysis Seminar | 20 January 2021, online/Leiden | | Scientific Community (Higher Education Research) | 15 | |
| Organisation of a workshop | Anna von der Heydt (UU) -TiPES WP4 and 5 postdoc meeting | 18th Nov 2020 | | Scientific Community (Higher Education, | 10 | |

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| | | | | Research) | | |
| Participation to a conference | Niklas Boers (PIK), Thomas Stocker (UBERN) | Online, 13th Oct 2020, Climate science2policy event | | Policy Makers | 80 | https://ec.europa.eu/easme/en/section/environment/climate-science2policy-workshop |
| Participation to an event other than a conference or workshop | Anna von der Heydt (UU), Palaeoclimate variability, Specialist lecture at MPE-CDT Summer School | Online, September/October 2020 | | Scientific Community (Higher Education, Research) | 50 | https://webspace.science.uu.nl/~dijks101/styled-6/ |
| Organisation of a workshop | Peter Ashwin (UNEXE), Theme 3 – Nonlinear and non-autonomous systems | 12th Oct 2020 | | Scientific Community (Higher Education, Research) | 50 | https://www.tipes.dk/event/tipes-online-meeting-theme-3-nonlinear-and-non-autonomous-systems-peter-ashwin/ |
| Press release | Henrik Prætorius (UCPH), “Climate will probably warm more than we’d hoped” | Online, Denmark 7th Aug 2020 | | Media | 40,000 | https://www.tipes.dk/climate-will-probably-warm-more-than-we-have-hoped/ |
| Participation to an Event other than a Conference or a Workshop, | TiPES webinar organized by AMIGO-talk by Robbin Bastiaansen | June 24 2020 | | Scientific Community (Higher Education, Research) | 50 | |
| Participation to a conference | Anna von der Heydt (UU), "Extreme sensitivity and climate tipping points", invited talk in session NP2.1 at EGU General assembly 2020 | Vienna, April 2020, online | Scientific Community (Higher Education, Research) | | 22.000 (online), ~150 in session | https://doi.org/10.5194/egusphere-egu2020-4671 |
| Participation to a conference | Anna von der Heydt (UU), "Uncertainty quantification of climate sensitivity: State-dependence, extreme values and the probability of tipping", EGU General Assembly 2020 | Vienna, April 2020, online | Scientific Community (Higher Education, Research) | | 22.000 (online), ~200 in session | https://doi.org/10.5194/egusphere-egu2020-4684 |
| Organisation of a conference | Anna von der Heydt (UU), "Tipping points in the Earth System" session ITS3.1/NP1.2 at EGU General Assembly 2020 | Vienna, April 2020, online | | Scientific Community (Higher Education, Research) | 22.000 (online) ~ 200 in session | https://meetingorganizer.copernicus.org/EGU2020/session/35744 |
| Organisation of a conference | Peter Ashwin (UExe), Valerio Lucarini (UR), "Mathematics of Planet Earth" session NP1.1 at EGU General Assembly 2020 | Vienna, April 2020, online | | Scientific Community (Higher Education, Research) | 22.000 (online) | https://meetingorganizer.copernicus.org/EGU2020/session/35967 |
| Participation to a Workshop | Thomas Stocker (UBERN): Podiumsdiskussion Nachhaltigkeit, Universität Bern | Switzerland, March 4, 2020 | | general public | 100 | |
| Participation to a conference | Thomas Stocker: Oeschger Centre Plenary Meeting, Bern: The Wyss Academy for Nature | Switzerland, February 13, 2020 | | Scientific Community (Higher Education, Research) | 80 | |
| Participation to an event other than a conference or workshop | Robbin Bastiaansen(UU), High school mathematics teachers organised by the Royal Dutch Mathematical Society. Topic: mathematics | 11th Jan 2020 | | General Public | 100 | |
| Participation to an event other than a conference or workshop | Anna von der Heydt (UU), Energy Days (TU Eindhoven), Series 5 (2017-20) DAY 7: CLIMATE CHANGE: CAPTURING THE ROLE OF CO2 | 31st Oct 2019 | | Scientific Community (Higher Education, Research) General Public | 100 | https://energydayscom.wordpress.com/previous-editions/ |
| other (civil defense) | Thomas Stocker (UBERN), Zivilschutz Eiken: Klimakrise: Was kommt auf uns zu? | Switzerland, October 29, 2019 | | Policy makers | 100 | |

## Peer reviewed articles

| Title | Authors | Publication | DOI | Is TiPES correctly acknowledged? | How much did you pay for the publication? | Status? | Open Access granted | Comments on embargo time imposed by the publisher | If in Green OA, provide the link where this publication can be found |
|---|---|---|---|---|---|---|---|---|---|
| [Ashwin2019] Extreme Sensitivity and Climate Tipping Points. | Ashwin, P., & Heydt, von der, A. S. | Journal of Statistical Physics, 370(1962), 1166–24 (2019) | http://doi.org/10.1007/s10955-019-02425-x | YES | | Published | Yes | | https://arxiv.org/abs/1905.12070 |
| [Bastiaansen2021a]: Multivariate Estimations of Equilibrium Climate Sensitivity From Short Transient Warming Simulations. | Bastiaansen, R., Dijkstra, H. A., & Heydt, von der, A. S. | *Geophysical Research Letters*, *48*(1), e2020GL091090 (2021) | http://doi.org/10.1029/2020GL091090 | YES | | Published | Yes | | https://arxiv.org/abs/2010.00845 |
| [Bastiaansen2021b]: Projections of the Transient State-Dependency of Climate Feedbacks | Bastiaansen, R., Dijkstra, H. A., & Heydt, von der, A. S. | Submitted, arxiv 2106.01692 | https://arxiv.org/abs/2106.01692 | YES | | submitted | Yes | | https://arxiv.org/abs/2106.01692 |
| [Ghil2020]: The Physics of Climate Variability and Climate | Ghil, M. & Lucarini, V. | Rev. Modern Physics, 92, 035002 (2020) | http://doi.org/10.1103/revmodphys.92.035002 | YES | | Published | Yes | | |
| [Heydt2021]: Quantification and interpretation of the climate variability record. | Heydt, von der, A. S., Ashwin, P., Camp, C. D., Crucifix, M., Dijkstra, H. A., Ditlevsen, P. D., & Lenton, T. M. | *Global and Planetary Change*, *197*(6063), 103399 (2021). | http://doi.org/10.1016/j.gloplacha.2020.103399 | Yes | | Published | Yes | | https://arxiv.org/abs/2101.08050 |
| [Lembo2020] Beyond Forcing Scenarios: Predicting Climate Change through Response Operators in a Coupled General Circulation Model. | Lembo, V., Lucarini, V., & Ragone, F. | *Scientific Reports*, *10*(1), 8668 (2020) | https://doi.org/10.1038/s41598-020-65297-2 | Yes | | Published | Yes | | |
| [Pfister2020]: Changes in Local and Global Climate Feedbacks in the Absence of Interactive Clouds: Southern Ocean–Climate Interactions in Two Intermediate-Complexity Models | Pfister, P. L. and Stocker, T. F. | *Journal of Climate* 34, 755–772 (2020) | https://doi.org/10.1175/jcli-d-20-0113.1 | Yes | | Published | Yes | | |

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**Uptake by the targeted audiences**

As indicated in the Description of the Action, the audience for this deliverable is (marked with an X here below):

| | |
|---|---|
| **x** | The general public (PU) is and is made available to the world via CORDIS. |
| | The project partners, including the Commission services (PP) |
| | A group specified by the consortium, including the Commission services (RE) |
| | This reports is confidential, only for members of the consortium, including the Commission services (CO) |

**This is how we are going to ensure the uptake of the deliverables by the targeted audiences:**
TiPES adheres to the FAIR data principles (Findable, Acsessible, Interoperable and Reusable), meaning all publications within this deliverable have been made open access and code provided via github. Data are also available via the Zenodo through the TiPES community. This repository is open access and the data produced are discoverable with metadata and identifiable and locatable by means of a standard identification mechanism (e.g. unique identifiers such as Digital Object Identifiers linked to authors' ORCID accounts). We are currently working towards deliverable D4.2, where we are preparing a software package for linear response operators in climate models. Our results so far have been presented at various conferences and we are actively disseminating methods developed by TiPES within our institutes and scientific community. Also disseminating our results to the general public is actively pursued by outreach activities (public lectures, press releases, discussion with policy makers). All publications are listed with links to Open Access, downloadable copies on the TiPES project website www.tipes.dk. Publications are linked to the TiPES project via OpenAIRE.