TIPPING POINTS IN THE EARTH SYSTEM

D1.3: Spatial patterns of the interrelations between different Tipping Elements

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Summary for publication

There is emerging concern that abrupt climate transitions may occur in response to ongoing anthropogenic warming. One crucial question in this context is if and in what way such abrupt transitions in one subsystem of the Earth could trigger transitions in another. A potential source of information regarding the interrelations between abrupt transitions in different subsystems is given by paleoclimate proxy records.

We have analyzed a large set of paleoclimate proxy archives, available publicly in the TiPES database on past abrupt transitions (https://paleojump.github.io). We considered different time scales, ranging from Pleistocene Glacial Cycles to the current Holocene. Upon a careful review of available proxy records, strongly building upon the TiPES proxy database published alongside deliverable D1.1, we focussed on the Dansgaard-Oeschger (DO) events during the last glacial interval, i.e. rapid Northern-Hemisphere warming transitions of regionally up to 15° within a few decades, which we consider the archetype of abrupt climate transitions evidenced in paleoclimate proxy records. In addition to their relevance, the data coverage is exceptionally high for these events, making them ideal for investigating to what extent reliable statements about spatial patterns of the causal interrelations between transition events in different subsystems of the Earth can be made.

The necessary first step in the analysis of interrelations between transitions in different subsystems was to quantify the uncertainties in the dating of the respective records, which propagate to the timing of abrupt transitions in a given subsystem. For this, a thorough statistical method was developed (Myrvoll-Nilsen et al., Climate of the Past 2022). We focussed on ice-core based paleoclimate proxy records, which are available at exceptional time resolution compared to other records such as speleothems.

It turned out that even for such records, if all uncertainties are thoroughly propagated, it is often difficult to derive significant lead-lag relationships between abrupt transition events in different subsystems. In principle, there are two different ways to assess temporal sequences of events, leading to abrupt change: First, proxies that represent different climate variables (different climate subsystems) recorded within the same archive (e.g. deep ice cores from Greenland?) can be compared. This approach comes at the cost that there are only a few proxies which represent different climatic signals (e.g. air temperature, winds, sea-ice, and precipitation for the case of Greenland ice cores) but it has the advantage that these proxies are given on the same chronology. However, even in this case, chronology within the firn diffusion horizon and the timescale of atmospheric air incapsulation in the firn can be uncertain, especially in Antarctica, where the snow accumulation rate is low. Second, records from different proxy-archives offer a greater variety of climate signals from different locations for investigation, however, with these proxies being dated independently, temporal comparison of abrupt changes suffers from dating uncertainties.
Following the first approach, the lead-lag relationship between abrupt transitions in proxy variables representing North Atlantic sea ice extent, Greenland air temperature, and atmospheric circulation, respectively, could not be settled in a statistically significant way (Riechers & Boers, Climate of the Past 2021). In this context, the main complication comes from the fact that determining the timing of transitions in time series from paleoclimate proxy data is subject to uncertainties (Riechers & Boers, Climate of the Past 2021; Bagniewski et al., CHAOS 2021). Our results imply that abrupt transition events, for which sub-decadal temporal lags between their expressions in different subsystems are

expected, it will be impossible to infer their causal relationships based on paleoclimate proxy data. This, in particular, also applies to the effect of the DO warmings and the associated sea-ice retreat on the tropical monsoon system. The fact that the signal's atmospheric propagation took place on time scales far below decadal implies that based on paleoclimate proxy records alone, an identification of causal relationships is not possible.

Following the second approach, Corrick et al. (2020) have carried out a comprehensive investigation of speleothem records from the Asian Summer Monsoon, the South American Monsoon and the Europe-Mediterranean region. Abrupt climate change in agreement with the DO variability seen in Greenland ice cores can be evidenced in all regions. Studying the temporal interrelation, Corrick et al. consistently found intra- and interregional synchrony for a large majority of the recorded abrupt changes. Supported by modelling results, they conclude that the atmospheric response to an AMOC reinvigoration causing the Greenland warming is immediate and that changes associated with DO events happened simultaneously in Greenland, and in the three aforementioned regions - at least within the limitations imposed by dating uncertainty and the uncertainty in the transition onset detection.

We also revealed an example for a different situation, where clear statements about the lead-lag relationships between different events are possible. This is given by the so-called bipolar seesaw, describing the fact that the Northern-Hemisphere abrupt warming transitions appear to be synchronous with temperature maxima in Antarctica. Here, it is thought that the signal is mainly transported via ocean circulation changes, which act on time scales long enough so that an uncertainty-aware determination of lead-lag relationship based on ice-core proxy data is possible. Indeed, it was found, using volcanic tracers that are present in both Greenland and Antarctic records, that the Antarctic temperature maxima follows the Greenland warming events by approximately 122 years (Svensson et al., Climate of the Past 2020). This result allows important conclusions regarding the role of the Atlantic Meridional Overturning Circulation as a global-scale conveyor belt transporting signals related to abrupt climate transitions.

Work carried out

The databases for the analysis of the spatial interrelations between different Tipping Elements was to a large degree provided by the Paleojump database published by the TiPES project and in particular the project beneficiary at the ENS Paris in the context of deliverable D1.1 (https://paleojump.github.io). The methodological tools for a thorough analysis of the different proxy time series from that database have been mainly developed at PIK in the context of the statistical toolbox of TiPES deliverable D1.2.

To establish the patterns of spatial interactions, the first step is to determine the causal relationship or at least the temporal order and synchronization patterns between any pair of tipping events. For a quantitative assessment there are two main constraints: (i) the paleoclimate episode in question must have experienced abrupt transition in some tipping element and (ii) the temporal resolution of corresponding proxy archives has to be sufficiently high to allow to determine the temporal order of events in different proxy archives, evidencing the dynamics of different tipping elements. Given these constraints, we had to mainly restrict our analyses to the last glacial cycle (approximately 130.000 years to 11.700 years before present (BP), see (Ditlevsen, 2022) and (Richers et al., 2022)); for earlier episodes, we had to conclude that the temporal resolution of available proxy archives is not sufficient to establish statistical sound statements on the temporal order of events, which is necessary to determine interaction patterns from data. For the more recent Holocene (from 11.700 years BP until today), large-scale tipping events are not evidenced, except potentially the so-called 8.2kyr-event which will be briefly discussed below. Moreover, we mainly had to restrict ourselves to the analysis of proxy records derived from Greenland and Antarctic ice cores, because their dating is based on (quasi-)annual layer counting and has hence substantially higher resolution, while still allowing for continuous records over long time intervals (the Greenland Ice Core Chronology GICC05 has almost annual resolution until 60.000 years BP).

For an in-depth investigation of the dependencies between different tipping elements from paleoclimate proxy data, we thus focussed on archives from Greenland and Antarctic Ice Cores, although we also considered some speleothem records for comparison. Several methodological challenges needed to be addressed first; the associated work was mainly carried out at PIK:

C1: Dating uncertainties in paleoclimate proxy archives
Paleoclimate proxy records are subject to qualitatively and quantitatively different kinds of age uncertainties. This is due to the fact that the age corresponding to a given value of the proxy variable in question has to be explicitly measured; for example, by counting annual deposition layers in ice cores, or by Uranium-Thorium-based dating methods in cave speleothems. These measurements come with different kinds of uncertainties. In order to associate the information available in such records to the dynamics of individual Tipping Elements, one first needs to quantify and propagate these uncertainties in order to be able to compare different proxy time series, encoding the behaviour and abrupt transitions of different Tipping Elements.

C2: Uncertainties in detecting abrupt transitions in time series
The timing of tipping events on paleoclimate time scales is likewise subject to pronounced dating uncertainties. Detecting a transition and determining its timing is subject to additional uncertainties because in practise the transition takes a finite number of time steps - determined by the discrete sampling frequency or natural temporal resolution in the record - and a quantification of the transition onset time as well as of the time when the transition terminated are typically not unique. The onsets of such events can thus only be determined probabilistically. A comprehensive survey of techniques for transition detection has first been performed, and we have adopted and further advanced a Bayesian approach in this regard.

After these challenges had been addressed (please see below for the corresponding results and progress beyond the state-of-the-art), several candidates for interrelations between different Tipping Elements have been investigated in detail; most of this work was carried out at PIK:

I1: Relationships between different proxy records in Greenland Ice Cores for the last glacial interval, such as d18O, Sodium, Calcium, and annual layer thickness.

The Dansgaard-Oeschger events, characterized by abrupt warming in Greenland and the Northern Hemisphere, occurred repeatedly during the last glacial interval. They are the archetype of past abrupt climate changes, and therefore extremely important to more generally understand the processes involved in abrupt climate transitions in the Earth system.

To date, the exact mechanistic interplay of ocean and atmospheric dynamics, but also sea ice and Northern Hemisphere Glaciers, to cause the abrupt DO events remains unclear (CITE). In Greenland Ice Cores, the DO transitions are evidenced in d18O as a proxy for local air temperature, sodium as a proxy for sea-ice extent, calcium as a proxy for atmospheric circulation changes, and the annual layer thickness as a proxy for precipitation amounts. To advance our understanding of the causal relationships between these different subsystems for which Greenland ice core proxy time series are available, we investigated their temporal succession in detail, keeping in mind the challenges imposed by the associated uncertainties (C1 and C2). While previous results (Erhardt et al., 2019) suggested a temporal lead of atmospheric changes with respect to changes in Greenland temperatures and changes in the sea ice cover at the onset of DO events, we have shown now, that no statistically significant inference on the temporal sequence of events can be drawn from the highest resolved data currently available (Riechers and Boers, 2021). This conclusion is in line with findings from Capron et al. (2021), who carried out a similar analysis as Erhardt et al. (2019) but using updated highly resolved data. See below for the corresponding results and progress beyond the state of the art.

I2. Relationship between abrupt Greenland warming events and Antarctic temperature maxima

It has been noted previously that the abrupt Greenland warming events termed DO events occur in phase with temperature maxima in Antarctica; the cold Greenland intervals prior to the DO events ('Greenland stadials') overlap with period of gradual warming in Antarctica, while the warmer Greenland intervals after DO events ('Greenland interstadials') overlap with episodes of gradual cooling in Antarctica. An average lag between 200 to 300 years between the abrupt DO events in Greenland and the Antarctic temperature maxima has recently been reported (Buizert et al., 2015). However, the synchronisation of the Greenland and Antarctic ice core records is far from trivial, and the existing, mainly Methane-based synchronisation efforts are subject to considerable uncertainties. Mainly at UCPH, a thorough refinement of the synchronization between Greenland and Antarctic ice core proxy records has been performed, based on the 'barcode' pattern given by the traces that different, globally synchronous volcanic eruptions leave in the respective ice cores. See below for the corresponding results and progress beyond the state of the art.

I3. Interaction identified from other records than ice cores.

Based on loess sequences from European terrestrial archives, we were able to estimate dust concentrations during the Last Glacial Maximum (Rousseau et al., 2021); changes in dust concentrations are related to large-scale reorganisation of atmospheric circulation patterns; unfortunately, however, the precise temporal order of changes cannot be determined based on loess sequences given the difficulties in precisely dating such records. We have also studied abrupt transition events in speleothems for the Last Glacial Maximum (LGM) but also the Holocene. For the LGM, we have also considered the radiocarbon variability / dead carbon fraction in speleothems from Socotra island, in the Indian Ocean close to Somalia (Therre et al., 2020).

I4. Interaction identified for other episodes than the last glacial interval.

We have also investigated DO-like events for the penultimate glacial cycle (Marine Isotope Stage 6); for this analysis, we revealed alternating loess intervals and paleosols with a focus on the European mainland (Rousseau et al., 2022). Due to the absence of a Greenland ice core record for this time interval, we had to use synthetic Greenland ice core records, reconstructed based on information provided from Antarctic ice core records and East-Asian speleothems (Barker et al., 2011). Given the involved uncertainties, the abrupt transitions in Greenland and Europe during the penultimate glacial cycle had to be concluded to have happened simultaneously. Moreover, we have used the Antarctic EPICA Dome C ice core to analyze millennial- to centennial-scale abrupt fluctuations in CH4 and N2O (Schmidely et al., 2021).

For an even earlier period, we investigated (mainly at University of Bern) sudden CO2 jumps during the period from 450.000 years to 330.000 years ago; these jumps could successfully be associated with disruptions of the Atlantic Meridional Overturning Circulation (AMOC) due to freshwater discharge from the Northern-Hemisphere ice sheets (Nehrbas-Ahles et al., 2020), which has important implications for future climate change, given the possibility of AMOC disruptions in the context of anthropogenic climate change.

On the other hand, we have also considered the Holocene, although it is debatable if any actual global-scale climate tipping events have occurred in this period. The main event that could be considered an abrupt climate transition is the 8.2kyr event, characterized by a large melwater pulse into the North Atlantic resulting from the drainage of Lakes Agassiz and Ojibway after the collapse of the Laurentide ice dam separating them from the Labrador Sea, and some slowing down of the AMOC in response. Using three different speleothems from caves in Germany, we were able to reconstruct the impact of this North-Atlantic event on European climate (Waltgenbach et al., 2020). Pronounced negative d18O peaks could be discovered, which could be associated with significant changes in precipitation, while temperatures seem to have stayed relatively stable.

In addition, we have revealed characteristic warming events throughout the Holocene from the melt rates measured in the EastGRIP ice core record, and compared them - for the last 2.500 years - with corresponding data from tree ring composites, revealing that the Greenland warming events happened simultaneously with warm central-European summers; the results suggest that early-Holocene summers must have been roughly 3° warmer than present-day in Europe (Westhoff et al., 2022).

Main results achieved

Regarding the challenge **C1**, a comprehensive statistical approach was developed at PIK to thoroughly quantify these uncertainties (Myrvoll-Nilsen et al., 2022a). In particular, a probabilistic relationship between the depth in the proxy archive and the associated age is defined, where the number of layers accumulated per unit of depth is expressed as the sum of one deterministic and one stochastic component. The deterministic component can describe both natural processes, such as the ice core thinning, and potential systematic counting biases, and is expressed using a regression model. The remaining variation is modelled using a stochastic process. If the noise component is a Gaussian Markov process, e.g. white noise or an order-p autoregressive (AR(p)) process, then the model can be fitted using the INLA (Integrated Nested Laplace Approximations) framework (Rue et al., 2009, 2017), which produces the marginal posterior distributions in linear time. This allows for an efficient sampling scheme of plausible chronologies that retains the correlation structure of the joint age distribution. These samples can then be used in further analyses such that the propagation of the dating uncertainty is treated rigorously. The R code for fitting this model using a white noise, AR(1) or AR(2) stochastic component, and for simulating chronologies has been made into an R package which is included in the statistical toolbox of deliverable D1.2.

Potential unknown systematic biases in layer-counted proxy archives can be corrected by adjusting the chronology using knowledge obtained from other sources. This knowledge can be represented as tie-points with uncertainty expressed using a probability density function. In an upcoming paper (Myrvoll-Nilsen et al., 2022b) we show how tie-points and their associated uncertainty can be incorporated into the framework presented in (Myrvoll-Nilsen et al., 2022a). In short the joint age vector is split into two partitions, one representing the tie-points and one representing the remaining free variables. The synchronised age vector is then found by conditioning the free variables on the tie-points. This is made computationally feasible by taking advantage of the Markov property of the stochastic component of the age-depth relationship. The R code for efficient simulation of synchronised chronologies using an AR(1) model for the layer-increment noise has been built into the R package mentioned above.

Regarding the challenge **C2**, a Bayesian approach was adopted at PIK, which yields the probability distribution of the onset date of a given abrupt transition evidenced in the proxy archive in question (Riechers & Boers, 2021; Bagniewski et al., 2021; Myrvoll-Nilsen et al., 2022a). Originally, this approach was proposed by Erhardt et al. (2019). It builds on the assumption that the data can be described as an Ornstein-Uhlenbeck (AR1 in discrete time) process that fluctuates around a stable fixed point which in turn undergoes a (piecewise) linear ramp in time. A corresponding process model is fully determined by 6 parameters: t0 and dt describe the onset and the duration of the linear ramp, while y0 and dy indicate the fixed point before the ramp and the ramp amplitude, respectively. Finally, an autoregressive coefficient a1 and a noise amplitude specify the stochastic motion around the fixed point. Given a time series that comprises a single, apparently linear (abrupt) shift in its level of values, a posterior distribution of the six model parameters can be obtained upon specification of suitable prior distributions. The required likelihood distribution follows immediately from the model equations but since the parameter space is six-dimensional, its evaluation is not straightforward. While Erhardt et al. (2019) and Capron et al. (2021) used an MCMC algorithm to draw representative samples from the posterior distributions which result from multiplication of the priors and the likelihood-function, our statistical toolbox now comprises an INLA-based approach which allows for much faster inference. In short, INLA takes advantage of the Markov property of the AR(1) process and approximates the marginal posterior distributions numerically using the Laplace approximation among other techniques. By evading simulations, inference can be obtained in seconds as opposed to minutes/hours which is not uncommon when using MCMC. Importantly, integrating over the other parameters one obtains quantitative estimates of the transition onset and duration. The resulting marginal posterior distributions can be interpreted as an indication of how likely a certain value for the transitions onset (duration) is in view of the noisy proxy data. A generic version of the Baysian ramp-fit algorithm is provided in the statistical toolbox both with an INLA-based and an MCMC based sampling procedure.

In the example of Tipping Element interrelations **I1,** namely the relationship between regional air temperatures, sea ice, atmospheric circulation, and precipitation at the onset of the abrupt Greenland warming transitions called DO events, we focussed on the assessment of paleoclimate proxy variables from the same ice core. Dating uncertainties can thus be assumed to be shared among the different relevant proxy variables, but uncertainties in the actual transition onset detection remain.

Building on the detection approach as proposed by Erhardt et al. (2019), we tested if the suggested decadal lead of atmospheric changes over changes in the sea ice cover and local temperatures was statistically significant. Given a finite number of realisations of a random variable, statistical tests provide a tool to make statements about the underlying population which can in itself never be observed. In view of the similar expression in different proxy time series that is shared by all DO events it is reasonable to assume that all such events followed the same physical mechanism. Within such a 'one-mechanism' framework, if one TE was to trigger another — e.g. an abrupt change in the atmospheric could potentially entail a sudden change in the sea ice cover —, the temporal order of these two tippings should never be reversed. Yet, with DO events taking place in the presence of multiple stochastic influences the exact time lag between cause and consequence in this framework can reasonably be regarded as a random variable. The question, if there is a 'cause-consequence' relation between the abrupt transitions in two different proxy time series and, therewith, between the climate variables they represent, must thus be understood as a question of the distribution of the corresponding time lags.

A pair of proxy records from Greenland ice cores provides as many realisations of the random time lag as there are DO events falling into the recorded period. Given these realisations it is natural to use them for testing if the underlying population is in agreement with an hypothesised 'cause-consequence' relationship between the two proxies. The detection of transition onsets in the different proxy time series smears out the initial hypothesis distribution. We therefore argued that in order to evidence a causal and therefore an unambiguous lead-lag relationship between the DO related abrupt transitions of two Greenland ice core proxies, it is mandatory to be able to discriminate the mean of the distribution of lags from a mean equal to zero. Note that a lag distribution mean different from zero is not a proof for a 'cause-consequence' relation, but a necessary condition.

For different pairs of NGRIP proxies and one pair of NEEM proxies we therefore aimed at rejecting the null hypothesis that the pairwise time lags, detected by means of the Bayesian ramp fit algorithm, were drawn from a distribution with zero mean. Due to the uncertainties in the transition onset detection we did not succeed in rejecting this null hypothesis and thus we could not evidence any systematic temporal lead-lag relationship.

We identified three different statistical tests, which all target the distribution mean, but rely on slightly different assumptions regarding distribution's shape. While in general the application of statistical tests is straightforward, we had to overcome the difficulty that in our setting the individual realisations of time lag were uncertain and quantified in terms of Bayesian posterior distributions. We showed that if these uncertainties were rigorously propagated, the sample of transition onset lags does not contradict the null hypothesis of a distribution mean equal to zero in a statistically significant manner. In other words, we found that the apparent tendency of transitions in proxies representing atmospheric dynamics to lead corresponding transitions in other proxies could have arisen by chance and cannot be classified as a systematic feature. The contrary, however, is true if the uncertainties are averaged out prior to the application of the tests. The qualitative difference in the overall assessment between a uncertainty sensitive and an averaging approach underpins once more the need for proper treatment of quantitative uncertainties related to paleoclimate proxy records.
We conclude that in multi-proxy records from Greenland ice cores systematic time lags between the different proxy's abrupt transitions associated with DO events, cannot be evidenced with certainty. This may either be due to the uncertain transition onset detection in the noisy time series, or due to the absence of such a systematic lag between the investigated proxies. Causal interrelation between the atmospheric changes, sea ice changes and Greenland warming can therefore not be deduced.

In the example of Tipping Element interrelations **I2,** namely the relationship between abrupt Greenland warming events and associated Antarctic temperature maxima, we have focussed on a situation where the same kind of proxy variable is investigated, but stemming from different archives; in this case ice cores from Greenland and Antarctica, respectively, with shared volcanic peaks in the chemostratigraphy used to allow for a very detailed synchronization of the different records (Svensson et al., 2020; Lin et al., 2022). The synchronisation between Greenland and Antarctic ice cores is essential for deducing the mechanisms governing the significant abrupt climate events / tipping points occurring during the last glacial period. Ice cores from the two poles have mainly been synchronized by matching up records of methane concentrations that share a common global signal as well as by identifying global geomagnetic events such as the Laschamp event in cosmogenic isotope records. The gas synchronization method suffers from limited precision as it builds on certain assumptions regarding the age difference between the age of the ice and that of the enclosed air bubbles in the ice cores, the so-called delta-gas-age. The cosmogenic linking technique is limited by the number of significant geomagnetic events and by costly and sample consuming experimental methods. Recently, it has been possible to advance the linking of ice cores from the two hemispheres by identification of large global volcanic eruptions that can be identified as strong acidity markers in the ice cores globally. For large volcanic eruptions the sulfuric acid is injected into the stratosphere where it is distributed globally before being deposited. Building on the existing methane and cosmogenic synchronization, the volcanic bipolar ice-core matching now allows for decadal scale bipolar synchronization. So far, we have synchronized the climate of the last half of the last glacial period using this method (Svensson et al., 2020) and quantified the major volcanic events of the same period (Lin et al., 2022). The improved timing of the relative inter-hemispheric climate phasing is strongly constraining the sequence of events and the role of the ocean and atmosphere in the transfer of the abrupt climate change events globally (see below).

Furthermore, geochemically unique volcanic ash (tephra) deposits found in the Greenland ice cores have been used as a direct synchronisation tool, linking ice cores, and thus provide an independent method to verify the timescale transfer between NGRIP, NEEM, GRIP, EGRIP. Cook et al., (2022) have constructed a detailed framework for the last glacial-interglacial transition that provides new ice-ice synchronisation points. This matching has been particularly valuable refining the synchronisation in intervals where ice cores lack chemostratigraphic match points, and have relied on interpolation between points e.g. in Greenland Stadial 2. Many of the tephras in the framework fall directly on climate transitions (Cook et al, in prep), including the GS2/GI-1 boundary and Holocene transition, thus providing essential constraints to assess leads-lags between ocean/atmosphere if found in North Atlantic marine cores with well resolved marine sediments. Ongoing work with marine sediments will start at UCPH in 2022, in collaboration with University of Iceland (north Iceland Shelf cores) and GEUS (Baffin bay cores). The framework provides a better record of volcanism, particularly the role of northern hemisphere eruptions in Japan and Kamchatka. We find the largest eruptions from these centres have a global signature (recorded in ice chemistry from both hemispheres), and inferences of temperature from stacked Greenland d18O records have shown decadal cooling of around 1.5C.

We note that comparisons between archives at different locations and of different kinds of proxy sources, e.g. between ice cores and cave speleothems, are substantially more difficult to handle in a statistically rigorous manner. The main reasons for the underlying difficulties are the different kinds of proxies and their interpretation in terms of climate variables themselves, but also their completely different dating methods (counting annual layers vs., e.g., Uranium-Thorium dating). For the example of comparing tipping events in Greenland ice core proxy data with corresponding events on globally distributed cave speleothems archiving past precipitation patterns, we had unfortunately to conclude that given the mechanistically expected temporal lags, no information on their actual causal relationships can be inferred from the proxy data alone, given the associated uncertainties and their propagation across the different types of archives and different kinds of dating them.

Progress beyond the state of the art

Regarding the challenges **C1** and **C2**, we have been able to advance the scientific state of the art substantially. With the methodological framework developed to address **C1** and **C2**, we have provided a sound statistical basis to quantify interrelations between different Tipping Elements from paleoclimate proxy data (as collected in the TiPES Paleojump database). Our addressing of these challenges will also help other scientists to address similar questions, using other archives that will be published in the future; they will be able to adopt and further advance our developed methods; in this way, the work related to reaching deliverable D1.3 will have a lasting and sustained impact. We hope that even higher-resolution data with narrower (dating) uncertainty ranges will become available in the near future, based on which one might be able to indeed draw statistically significant conclusions regarding the interrelation between the different climate subsystems relevant in the emergence of the DO cycles and their global-scale impacts.

Regarding the situation of interrelations between different Tipping Elements evidenced in the same proxy archive (**I1**), we have been able to advance the scientific state of the art by challenging previous conclusions that the atmospheric circulation acted first, before ocean and sea ice, in the context of the abrupt Greenland warming events of the last glacial interval (Erhardt et al., 2019); taking into account the full range of underlying uncertainties, even for this case where the relevant data is available within the same proxy archives - and thus no synchronisation across archives is needed - we had to conclude that the lead or lag between tipping events for the different elements in question is not statistically significant on one direction or the other (Riechers & Boers, 2021). More technically, we have established a statistical framework that treats quantities measured from different DO events as realisations of a random variable that is characterised by an underlying population. This perspective should form the basis for future statistical assessments of statements made on DO events.

Regarding the case where proxy variables of the same type, but from different, geographically distant records are compared (**I2**), we have been able to refine previous estimated of the lag at which Antarctic temperature maxima occurred with respect to the rapid Greenland warming events (Svensson et al., 2020) The so-called bipolar seesaw is quantified in terms of a data-derived Greenland-Antarctic synchronization, obtained by identifying the same patterns of large volcanic eruptions in both Greenland and Antarctic ice cores close to the onset of the Greenland DO warming events. The precision of the synchronization is decadal and thus better than the conventional bipolar ice-core synchronization that is based mostly on matching of methane concentration records. It is found that when the Antarctic temperature response to the abrupt Greenland DO warmings is averaged over several DO events and over several Antarctic ice cores there is an Antarctic time lag of some 122+-24 years (i.e., the DO events in Greenland happen on average 122 years prior to the temperature maxima in Antarctica). The duration/magnitude of this lag suggests an oceanic transfer of the abrupt signal from north to south, supporting previous assumptions from marine cores (Henry et al., 2016). However, when individual DO warmings are investigated in individual ice cores, it is seen that besides the 122 yr time lag, there is often also an immediate Antarctic response to the Greenland warming (occurring within decades) suggesting a direct atmospheric response to the abrupt change. Furthermore, it is seen that ice cores from different locations within Antarctica respond differently to the Greenland warming events, suggesting a geographical diversity in the response; see especially Fig. 3b and the supplementary material in (Svensson et al., 2020).

Impact

The work performed in the context of TiPES deliverable D1.3 has contributed to the following of the expected impacts of TiPES:

1. **“Supporting major international scientific assessments such as the IPCC”**
   In order to assess the possibility and likelihood of abrupt climate changes in response to anthropogenic climate change in the future, paleoclimate proxy evidence plays a vital role. In fact, the only empirical evidence for abrupt transitions in the climate system stems from paleoclimate proxy records.
2. **“Providing added-value to decision and policy makers”**
   One might see some of the results associated with TiPES deliverable D1.3 as negative, in the sense that in several instances, we had to conclude that - given the inherent uncertainties in paleoclimate records, no clear inferences about the causal relationships between different Tipping Elements could be drawn in a statistically sound manner. In fact, we put a lot of effort into developing the statistical framework and took into account the associated uncertainties at a level of completeness that is unprecedented in this context. We believe that such “negative” results are equally important scientifically, but also in terms of what information is communicated, it is important to clearly say what we can, but also what we **cannot** say reliably; in particular when it comes to possibly high-impact events such as abrupt climate changes.
3. **“Sustaining Europe’s leadership in climate science”**
   By providing a comprehensive analysis of interactions between Tipping Elements as evidenced in paleoclimate proxy data mainly from the last glacial interval, for which that databasis was most promising, we have substantially advanced the scientific understanding concerning reliable paleoclimate information on Tipping Element interactions.

Impact on the business sector

The work carried out has a rather fundamental scientific character and therefore does not have any direct impacts in the business sector.

Lessons learned and Links built

A key lesson learned in the context of deliverable D1.3 is that age and dating uncertainties make it extremely challenging to infer reliable information about interrelations of Tipping Elements from paleoclimate proxy data alone. The associated results emphasize how easy it is to derive spurious or biased results if the uncertainties are not fully taken into account in a quantitative manner.

Even in proxy archives with comparably very high-resolution, like the Greenland ice cores, and in situations where proxy measurements from the same ice cores are compared, we found that inferences about the temporal order of abrupt transition events in different proxy archives cannot be drawn beyond statistical doubt, given the uncertainties and the close succession in which the events seem to have played out.

For the case of comparing proxy archives of the same type, but from different archives, we have focussed on the comparison between Greenland and Antarctic Ice Core data of d18O, as a proxy of atmospheric temperatures. In this case, advancing previous Methane-based synchronization of the different records by taking into account volcanic layers successfully narrowed down the uncertainties in the estimated lags between the abrupt Greenland warming events and associated Antarctic temperature maxima. The main reason a systematic lead-lag analysis yielded unique results in this case is that the signal from Greenland to Antarctica is mainly transported by oceanic processes operating on comparably slow time scales.

In the course of the work toward reaching TiPES deliverable D1.3, we have built strong links between scientists working on the retrieval and initial analysis of paleoclimate proxy data with a focus on ice cores, we have eg. strengthened our collaborations with the East GRIP ice core community (EGRIP, including scientists from 14 countries), The RICE community (3 countries) and the MBS ice core community (3 countries) , and with statisticians in order to jointly develop a practically useful, yet still statistically rigorous framework, and to apply in together to the examples of proxy records that evidence interrelations between different Tipping Elements.

Relations to the TiPES cross-cutting themes

Theme 1. Tipping Elements in data and models

By investigating the interrelations between different Tipping Elements based on how their dynamics is evidenced in paleoclimate proxy data, the deliverable D1.3 directly contributes to the overarching TiPES Theme 1. Based on deliverables D1.1 and D1.2, it provides the synthesis of what we can reliably - and in a statistically sound manner - infer regarding interdependencies between tipping events of different tipping elements during past climates.

Theme 2. Climate response and Early Warning Signals

The deliverable D1.3 yields important information regarding what can be said about Tipping Element interactions in a statistically sound manner, based on paleoclimate proxy records. Since such interactions are relevant for both overall climate response, and the way how Early Warning Signals develop, the deliverable delivers potentially important information for the overarching TiPES Theme2.

Theme 4. Data and decisions

The deliverable D1.3 contributes to overarching TiPES Theme 4 in that it provides a comprehensive summary of what we can say - fully taking into account the relevant uncertainties - about the paleoclimate proxy data regarding interactions between different Tipping Elements. In particular for abrupt climate transitions that occurred further back in time, purely based on available data alone it is extremely challenging to determine causal relationships, because the temporal order of tipping events cannot be revealed given the substantial dating uncertainties in the different proxy archives. To understand how future tipping cascades could unfold, we therefore have to rely strongly on modelling experiments, although even state-of-the-art models continue to have problems in representing tipping elements and their interactions.

Contribution to the top level objectives of TiPES

This deliverable contributes to different extent to the achievement of the objectives indicated in the Description of the Action, part B, Section 1.1, as follows:

Objective 1 - Identify tipping elements (TEs) and their interactions in models and data

The deliverable D1.3 contributes directly and in several ways to Objective 1. With deliverable D1.3, we have established the comprehensive scientific basis regarding uncertainty-aware statements about Tipping Element interactions based on paleoclimate proxy records. D1.3 draws on the complete collection of paleoclimate proxy records evidencing abrupt transitions as collected in the TiPES database “Paleojump” and uses the through methodology developed in the context of the statistical TiPES toolbox published in the context of deliverable D1.2, to draw conclusions of what can be said on the basis of paleoclimate proxy data - given the underlying, highly non-trivial uncertainties - about interrelations between different tipping elements, as summarized above.

Objective 2 - Provide approaches for the identification and validation of Early Warning Signals

The deliverable D1.3 contributes to Objective 3 by advancing our understanding of what insights can be drawn from paleoclimate proxy variables regarding the interconnectedness of tipping events in different paleoclimate archives. This is important information for the identification of suitable Early Warning Signals because the way such precursor signals unfold depends strongly on the way how the different Tipping Elements interact, and how these interactions are encoded in paleoclimate proxy data. Hence, with the results obtained toward Deliverable D1.3, we provide the synthesis of data-based information regarding tipping events in past climates, and thereby contribute to a better understanding of which kind of Early Warning Signals should be search for, given the constraints imposed by the uncertainties regarding the temporal order of events and how they affect potential precursor signals for cascades of transitions.

References (Bibliography)

See “Peer-reviewed articles” below.

Cook, E., Svensson, A., Rasmussen, S.O., *et al.* Volcanism and the Greenland ice cores: A new tephrochronological framework for the last glacial-interglacial transition (LGIT) based on cryptotephra deposits in three ice cores. *Quat. Sci. Rev* (in press). doi: 10.1016/j.quascirev.2022.107596

Corrick, E. C. *et al.* Synchronous timing of abrupt climate changes during the last glacial period. *Science (80-.).* **369**, 963–969 (2020).

Erhardt, T. *et al.* Decadal-scale progression of the onset of Dansgaard-Oeschger warming events. *Clim. Past* **15**, 811–825 (2019).

Riechers, K. & Boers, N. Significance of uncertain phasing between the onsets of stadial-interstadial transitions in different Greenland ice core proxies. *Clim. Past* **17**, 1751–1775 (2021).

Capron, E. *et al.* The anatomy of past abrupt warmings recorded in Greenland ice. *Nat. Commun.* **12**, 1–12 (2021).

Feliks, Y., J. Small and M. Ghil: Global oscillatory modes in high-end climate modeling and reanalyses, *Clim. Dyn*., **57**(11), 3385-3411 (2021), doi: 10.1007/s00382-021-05872-z, open access https://rdcu.be/cxwSM .

Myrvoll-Nilsen et al.: Comprehensive uncertainty estimation of the timing of Greenland warmings in the Greenland ice core records, *Clim. Past* **18**, 1275-1294 (2022)

Ditlevsen, P., The Pleistocene Glacial Cycles and Millennial-Scale Climate Variability, *Atmosphere-Ocean* (2022)

Riechers, K., T. Mitsui, N. Boers, M. Ghil: Orbital Insolation Variations, Intrinsic Climate Variabilty, and Quaternary Glaciations, *Clim. Past* **18**, 863-893 (2022)

Schmidely et al.,: CH4 and N2O fluctuations during the penultimate deglaciation, *Clim. Past* **17**, 1627-1643 (2021)

Nehrbass-Ahles et al.: Abrupt CO2 release to the atmosphere under glacial and early interglacial climate conditions, *Science* **369**,6505, 1000-1005 (2020)

Rousseau, D., P. Antoine, Y. Sun: How dusty was the last glacial maximum over Europe? *Quaternary Science Reviews* **254** (2021)

There et al.: Climate-induced speleothem radiocarbon variability on Socotra Island from the Last Glacial Maximum to the Younger Dryas, *Clim. Past* **16**, 409-421 (2020)

Waltgenbach et al., Climate and structure of the 8.2 ka event reconstructed from three speleothems from Germany, *Global and Planetary Change* **193,** 103266 (2022)

Westhoff et al., Melt in the Greenland EastGRIP ice core reveals Holocene warm events, *Clim. Past* **18**, 1011-1034 (2022)

Lin, Jiamei, et al. "Magnitude, frequency and climate forcing of global volcanism during the last glacial period as seen in Greenland and Antarctic ice cores (60–9 ka)." *Climate of the Past* 18.3 (2022): 485-506.

Dissemination and exploitation of TiPES results

Dissemination activities

The TiPES disseminations that relate to delivery D1.3 can be found in the below Table.

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 if available	Theme		Objectives	
Training	Sune Olander Rasmussen (NBI, UCPH), "Abrupt climate change from ice cores", PhD school: "Bornö Summer School 2021: The Role of Shelves for the Last Glacial Maximum Carbon Cycle"	Bornö Marine Research Station (58°22'48"N 11°34'48"E). 8-14 August 2021	N/A	Scientific Community (higher education, Research)	15		1		1	
Training	Sune Olander Rasmussen (NBI, UCPH), "Ice-core science and abrupt climate change", theme day at Falkonergaarden high school	Frederiksberg, Denmark, 9 March 2022	N/A	Civil Society	400		1		1	
Participation to a workshop	Sune Olander Rasmussen (NBI, UCPH), "The Greenland ice-core records as the basis of the INTIMATE event stratigraphy", online talk	Online, March 10. 2022	N/A	Scientific Community (higher education, Research)	100		1		1	

Organization of a webinar	Denis-Didier Rousseau, Cascade of abrupt transitions in past climates	online, April 13th, 2022		Scientific Community (higher education, Research)	45		1		1	
Organization of a webinar	Keno Riechers, Changes in stability and jumps in Dansgaard–Oeschger events: a data analysis aided by the Kramers–Moyal equation	online, June 15th, 2022		Scientific Community (higher education, Research)	35		1	3	1	
Organisation of a scientific session	Denis-Didier Rousseau (CNRS): "Tipping Points in the Earth System: Different perspectives of all the relevant disciplines)" with Helle Astrid Kjaer, Niklas Boers and Pete Ditelvsen	AGU Fall Meeting 2021, New Orleans, 15 December 2021 (hybrid format)	N/A	Scientific Community (higher education, Research)	30	https://agu.confex.com/agu/fm21/meetingapp.cgi/Session/118397	1		1	
Participation to a scientific session	Denis-Didier Rousseau (CNRS): "Cascade of abrupt transitions in past climates" with v. Lucarini, W Bagniewski, M Ghil	EGU General Assembly, 27 April 2022	N/A	Scientific Community (higher education, Research)	100	https://doi.org/10.5194/egusphere-egu22-2396	1		1	
Participation to a scientific session	Witold Bagniewski (ENS): "Tipping points and abrupt climate change: A comparison of advanced analysis methods for paleoclimate records" with M. Ghil and D.D. Rousseau	AGU Fall Meeting 2021, New Orleans, 15 December 2021		Scientific Community (higher education, Research)	30	https://agu.confex.com/agu/fm21/meetingapp.cgi/Paper/838171	1		1	

Participation to a scientific session	Witold Bagniewski (ENS): "Paleoclimatic tipping points and abrupt transitions: An application of advanced time series analysis methods" with M. Ghil and D.D. Rousseau	EGU General Assembly, 27 April 2022		Scientific Community (higher education, Research)	100	https://doi.org/10.5194/egusphere-egu22-12501	1		1	
Participation to an Event other than a Conference or a Workshop	Keno Riechers (PIK)	online, July 1,2021	n/a	scientific community	20	10.5281/zenodo.6779650	1		1	
Participation to a conference	Keno Riechers (PIK)	online, April 19-30,2021	125€	scientific community	~80	https://doi.org/10.5194/egusphere-egu21-9733	1	3	1	3
Participation to a conference	Keno Riechers (PIK)	online, December 13-17, 2021	356,62€	scientific community	~30	agu2021fallmeeting-agu.ipostersessions.com/Default.aspx?s=A0-E4-D5-5F-74-20-B7-32-ED-44-65-3C-C3-6C-0D-9D	1	3	1	3

Participation to a conference	Keno Riechers (PIK)	online, May 23-27,2022	179,95€	scientific community	~100	https://doi.org/10.5194/egusphere-egu22-13023	1	3	1	
Podcast	Sune Olander Rasmussen (UCPH), Henrik Prætorius (UCPH)	Aug-20	none	Civil Society		The TiPES Podcast - Tipping points change Earth and climate- Confirmed: Sudden climate changes during ice ages influenced whole planet	1		1	
Participation to an event other than a conference or workshop	Helle Kjær (UCPH)-Talks in connection with Copenhagen DOX (documentary film festival)	25/3 and 28/3-2022	none	General Public	600		1		1	
Participation to an event other than a conference or workshop	Helle Kjær (UCPH)-Talk at danish society for analytical chemistry (SAK)	27/10-2021	none	Scientific Community	30	http://analytiskkemi.dk/wordpress/wp-content/uploads/2021/10/Generalforsamling-indkaldelse-2021.pdf	1		1	

Participation to a conference	Keno Riechers (PIK)	01/10-2020, Potsdam	50 €	scientific community	50	http://doi.org/10.5281/zenodo.4557650	1	3	1	
Seminar	Keno Riechers (PIK)	3/11-2020, Potsdam	none	scientific community	40	http://doi.org/10.5281/zenodo.4557650	1	3	1	
Seminar	Keno Riechers (PIK)	1/7-2021, online	none	scientific community	20	10.5281/zenodo.6779650	1	3	1	
Seminar	Eliza Cook (UCPH, PAGES ICYS: contructing a tephra framewrk for the LGIT	12/5/2021-online	none	Scientific Community (higher education, Research)	70	PAGES Ice Core Young Scientists (ICYS) seminar series: https://www.youtube.com/watch?v=D1nNDwKjnEA	1		1	
Seminar	Eliza Cook (UCPH), VICS Pages: origins of tephra in Greenland ice cores Eliza Cook on tephras in Greenland ice-cores	24/06/2021Online	none	Scientific Community (higher education, Research)	100	PAGES Volcanic Impacts on Climate & Society (VICS) https://pastglobalchanges.org/science/wg/vics/intro	1		1	

Seminar	Eliza Cook (UCPH), Intimate: volcanic constras over key events: LGIT to the Holocene	10/3/2022	none	scientific Community (higher education, Research)	100	Integrating Ice, Marine and Terrestrial Cores (INTIMATE) netwoek seminar:	1		1	

Peer reviewed articles

Title	Authors	Title of the Journal/ Proc./ Book	Number, date or freq. of the Journal/ Proc./ Book	Is Peer-reviewed?	Is Open Access ?	DOI	Repository Link	Comment
Volcanism and the Greenland ice cores: A new tephrochronological framework for the last glacial-interglacial transition (LGIT) based on cryptotephra deposits in three ice cores	Cook, E., Svensson, A., Rasmussen, S.O., et al.	Quat. Sci. Rev		yes		10.1016/j.quascirev.2022.107596		in press
Orbital insolation variations, intrinsic climate variability, and Quaternary glaciations	Keno Riechers, Takahito Mitsui, Niklas Boers, and Michael Ghil	Climate of the Past	18	Yes	Green	[10.5194/cp-18-863-2022](10.5194/cp-18-863-2022)	https://climatehomes.unibe.ch/~stocker/papers/poeppelmeier22qsr.pdf	

Automatic detection of abrupt transitions in paleoclimate records	W. Bagniewski, M. Ghil, D. D. Rousseau	AIP-Chaos	31 (11)	Yes	Green	10.1063/5.0062543	https://pubmed.ncbi.nlm.nih.gov/34881579/	
Significance of uncertain phasing between the onsets of stadial–interstadial transitions in different Greenland ice core proxies	Keno Riechers, Niklas Boers	Climate of the past		Yes	1600 Euro	10.5194/cp-17-1751-2021	https://publications.pik-potsdam.de/pubman/faces/ViewItemOverviewPage.jsp?itemId=item_25927	
Global oscillatory modes in high-end climate modeling and reanalyses	Yizhak Feliks, Justin Small, Michael Ghil	Climate Dynamics	57	Yes	Green	10.1007/s00382-021-05872-z		
Comprehensive uncertainty estimation of the timing of Greenland warmings in the Greenland ice core records	Eirik Myrvoll-Nilsen, Keno Riechers, Martin Wibe Rypdal, and Niklas Boers	Climate of the Past	18	yes	green	0.5194/cp-18-1275-2022		
The Pleistocene glacial cycles and millennial scale climate variability	Ditlevsen, P.,	Atmosphere-Ocean (TATO)		yes	green	10.1080/07055900.2022.2077172		

CH4 and N2O fluctuations during the penultimate deglaciation	Loïc Schmidely, Christoph Nehrbass-Ahles, Jochen Schmitt, Juhyeong Han,Lucas Silva, Jinwha Shin, Fortunat Joos, Jérôme Chappellaz, Hubertus Fischer, Thomas Stocker	Climate of the Past	17(4)	Yes	Green	[10.5194/cp-17-1627-2021](https://doi.org/10.5194/cp-17-1627-2021)	https://hal.archives-ouvertes.fr/hal-03418313/document	
Abrupt CO2 release to the atmosphere under glacial and early interglacial climate conditions	C. Nehrbass-Ahles, J. Shin, J. Schmitt, B.Bereiter, F. Joos, A. Schilt, L. Schmidely, L. Silva, G. Teste, R. Grilli, J. Chappellaz, D. Hodell, H. Fischer, T. F. Stocker	Science		Yes	Gold	[10.1126/science.aay8178](https://doi.org/10.1126/science.aay8178)	https://syndication.highwire.org/content/doi/10.1126/science.aay8178	
How dusty was the last glacial maximum over Europe?	Denis-Didier Rousseau, Pierre Antoine, Youbin Sun	Quaternary Science Reviews	254	Yes	Green	[10.1016/j.quascirev.2020.106775](https://doi.org/10.1016/j.quascirev.2020.106775)	https://academiccommons.columbia.edu/doi/10.7916/d8-zkpr-fb37	
Climate and structure of the 8.2 ka event reconstructed from three speleothems from Germany	Sarah Waltgenbach, Denis Scholz, Christoph Spötl, Dana F.C. Riechelmann, Klaus P. Jochum, Jens Fohlmeister, Andrea Schröder-Ritzrau	Global and Planetary Change	193	Yes	Green	[10.1016/j.gloplacha.2020.103266](https://doi.org/10.1016/j.gloplacha.2020.103266)	https://gfzpublic.gfz-potsdam.de/pubman/item/item_5002551	

Melt in the Greenland EastGRIP ice core reveals Holocene warm events	Julien Westhoff, Giulia Sinnl, Anders Svensson, Johannes Freitag, Helle Astrid Kjær, Paul Vallelonga, Bo Vinther, Sepp Kipfstuhl, Dorthe Dahl-Jensen and Ilka Weikusat	Climate of the past	18	Yes	Green	10.5194/cp-18-1011-2022	https://cp.copernicus.org/articles/18/1011/2022/	
Bipolar volcanic synchronization of abrupt climate change in Greenland and Antarctic ice cores during the last glacial period	Anders Svensson, Dorthe Dahl-Jensen, Jørgen Peder Steffensen, Thomas Blunier, Sune O. Rasmussen, Bo M. Vinther, Paul Vallelonga, Emilie Capron, Vasileios Gkinis, Eliza Cook, Helle Astrid Kjær, Raimund Muscheler, Sepp Kipfstuhl, Frank Wilhelms, Thomas F. Stocker, Hubertus Fischer, Florian Adolphi, Tobias Erhardt, Michael Sigl, Amaelle Landais, Frédéric Parrenin, Christo Buizert, Joseph R. McConnell, Mirko Severi, Robert Mulvaney, Matthias Bigler	Climate of the Past	16/4	Yes	Green	10.5194/cp-16-1565-2020	https://zenodo.org/record/4585864#.YEXV52hKhPY	

East Greenland ice core dust record reveals timing of Greenland ice sheet advance and retreat	Paul Vallelonga; Aslak Grinsted; Alejandra Borunda; Alejandra Borunda; Steven L. Goldstein; Steven L. Goldstein; Thomas Blunier; Marius Simonsen; Mai Winstrup; Diana Vladimirova; Helle Astrid Kjær; Bo M Vinther; Gisela Winckler; Gisela Winckler; Barbara Delmonte; Robert Frei; Anders Svensson; Giovanni Baccolo; Todd Sowers	Nature communications	30	Yes	Gold	10.1038/s41467-019-12546-2	http://europepmc.org/articles/PMC6776541	
Role of mineral dust in the nitrate preservation during the glacial period: Insights from the RICE ice core	Abhijith U.Venugopala Nancy A.N.Bertler Rebecca L.Pyne Helle A.Kjær V. Holly L.Winton Paul A.Mayewski Giuseppe Cortesea	Global and Planetary change		Yes	Green	10.1016/j.gloplacha.2022.103745		

A portable Lightweight In Situ Analysis (LISA) box for ice and snow analysis	Kjær, Helle Astrid Lisa Lolk Hauge Marius Simonsen Yoldi, Zuriñe Iben Koldtoft Maria Hörholdt Johannes Freitag Sepp Kipfstuhl Svensson, Anders Paul Vallelonga	The Cryospher e	15	Yes	Green	10.5194/tc-15-3719-2021	https://nbi.ku.dk/english/staff/?pure=en%2Fpublications%2Fa-portable-lightweight-in-situ-analysis-lisa-box-for-ice-and-snow-analysis(beda9fb0-6625-4bf8-bdd5-e862336bd5ff).html	

Role of mineral dust in the nitrate preservation during the glacial period: Insights from the RICE ice core	Abhijith U.Venugopala Nancy A.N.Bertler Rebecca L.Pyne Helle A.Kjær V. Holly L.Winton Paul A.Mayewski Giuseppe Cortesea	Global and Planetary change	Yes	Green	10.1016/j.gloplacha.2022.103745	

Uptake by the targeted audiences

As indicated in the Description of the Action, the audience for this deliverable is *(mark 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:

The results associated with this report have been disseminated intensively to the scientific community beyond the TiPES consortium by 1) publishing the associated work in relevant high-level Open-Access journals such as Climate of the Past, 2) presenting the associated work at scientific workshops both organized by TiPES and by other communities, and 3) presenting the work at high-level international conferences such as the General Assembly of European Geoscience Union. Via the usual routes to disseminate scientific results (such as news releases on the TiPES website, radio and newspaper interviews), we have also made sure that the gained results are - to the degree that they are directly relevant - communicated to the general public.