

Past abrupt changes, tipping points and cascading impacts in the Earth system

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The geological record shows that abrupt changes in the Earth system can occur on timescales short enough to challenge the capacity of human societies to adapt to environmental pressures. In many cases, abrupt changes arise from slow changes in one component of the Earth system that eventually pass a critical threshold, or tipping point, after which impacts cascade through coupled climate-ecological-social systems. Abrupt changes are rare events and their chance to occur increases with the length of observations. The geological record provides the only long-term information we have on the conditions and processes that can drive physical, ecological, and social systems into new states or organizational structures, which may be irreversible within human time frames. Here, we use well-documented abrupt changes of the past 30 thousand years to illustrate how their impacts cascade through the Earth System. We review useful indicators of upcoming abrupt changes, or early warning signals, and provide a perspective on the contributions of paleoclimate science to the understanding of abrupt changes in the Earth system.

There is increasing awareness and concern that human modification of environment runs the risk of inducing abrupt changes in a variety of Earth System components¹ (Box 1). Disintegration of ice sheets, permafrost thaw, slowdown of ocean circulation, tropical and boreal forest dieback, and ocean deoxygenation are examples of rapid changes with harmful societal consequences that might happen in the future due to ongoing anthropogenic climate change. Analogous events have occurred in the recent geological past² (Fig. 1). To be useful for understanding possible consequences of future climate change, these past events require quantifying the characteristics and timing of the initial abrupt change, the tipping points involved, and the following sequence of cascading consequences for other components (Box 1).

Here, we follow the Intergovernmental Panel on Climate Change Assessment Report 4 (IPCC AR4)³ definition of abrupt changes (events) as large-scale changes that are much faster than the change in the relevant forcing such as rising atmospheric CO₂ concentration (Box 1). In addition,

we assess evidence for past tipping points, or thresholds, beyond which components of the Earth system rapidly move to a new state, but take much longer to return to the original state even when forcings are ceased away (Box 1). Forcings evolve frequently in the Earth system, but do not always reach the tipping points that might lead to abrupt changes. For instance, regional droughts interspersed with occasional wet periods generally may not have a strong effect on ecosystems adapted to such a climate state. However, if a drought persists over many years (megadroughts⁴), the water available for plants could drop below a critical threshold, leading to a cascade of abrupt changes in vegetation cover, agriculture and societies that may be irreversible for decades to centuries^{5,6}.

A rapidly growing archive of paleoclimatic, paleoecological, and archaeological records is particularly useful for understanding the ways in which abrupt change emerges from the interaction among system components and can cascade across components and scales. Here, we consider cascading interactions where abrupt changes in one component have led to abrupt changes in other components⁷ (Box 1). Causality in such cascading interactions can be difficult to prove from paleorecords alone, and predictive power of past causalities for the future events is limited by different timescales and forcings. However, we can infer causal interactions if there is sufficient evidence and consistency in relative timing of changes, process understanding, and, if available, support from Earth system model experiments.

Gleaning useful information from paleo archives requires putting this evidence into consistent temporal, spatial and conceptual frameworks. It is especially hard to infer causality in interactions among Earth system components. Existing work on these interactions suggests that the majority of cascading changes proceed from larger to smaller spatial scales⁸. Hence, we structure the paper to consider causality generally flowing from climate to ecological and sometimes to social systems, focusing on cascading of abrupt changes from one component to another, with particular attention to cryosphere-ocean interactions and hydroclimate variability (Fig. 2). These two important classes of abrupt changes are the most prominent examples with the requisite

number or quality of paleo records, as well as they likely have important societal impacts in the near future.

Cascading Impacts of Cryosphere-Ocean Interactions

Interactions between the cryosphere and oceans have produced some of the most dramatic events in the geological record, including glacial outburst floods and repeated catastrophic iceberg discharges during past glaciations (Table 1). Model simulations of the ocean-atmosphere dynamics consistently show that the vertical convection in the North Atlantic, as well as the advective fluxes associated with the Atlantic meridional overturning circulation (AMOC), may be weakened or even stopped ('shut down') by pulses of freshwater into the surface ocean at high northern latitudes⁹. These circulation changes are associated with a specific spatial pattern, often referred to as a "bi-polar seasaw"¹⁰, including a southward shift of the Intertropical Convergence Zone, substantial cooling in the Northern Hemisphere centered in the North Atlantic region, and general warming in the Southern Hemisphere. Paleoclimate data from ice cores reveal the persistence of such a bipolar pattern of climate on millennial timescales during the last ice age and the deglaciation (ca. 19 to 12 thousand years ago)¹⁰, and evidence from deep-sea sediments confirms that these abrupt climate changes were associated with substantial changes in AMOC^{11,12}. The cause of these changes in AMOC is widely believed to be related to cryosphere-ocean interactions. The likely candidate mechanisms including surging ice sheets¹³, ice-shelf breakup¹⁴, a coupled ocean-ice "salt oscillator"¹⁵, catastrophic ice stream retreat¹⁶, deep ocean warming due to deglaciation¹⁷, are all considered to be threshold responses to slowly varying forcing (Fig. 2a).

About twenty climate fluctuations known as Dansgaard-Oeschger (D-O) events occurred during the last glacial cycle. Their abrupt onsets of warming on decadal timescales¹⁸ correspond to temperature increases that may have exceeded 15°C in Greenland and several degrees in Europe, generally followed by a multi-century cooling trend and terminated by an abrupt return to

the glacial baseline¹⁹. These events caused major adjustments to hydroclimate and carbon cycling²⁰⁻²², with evidence for crossing regional thresholds in marine ecosystems, such as a change to anoxic deep water conditions in the Cariaco Basin²³, and terrestrial ecosystems, for example, forest expansion in western Mediterranean region²⁴, extinction of Holarctic megafaunal species²⁵ (Table 1), and abrupt increases in methane emissions from wetlands²⁶ (Figure 3). D-O events demonstrate that global-scale reorganization of the climate system can occur on decadal time scales²⁷, possibly triggered by abrupt changes in AMOC. While the focus is often on meltwater as the driver of AMOC reduction and Northern Hemisphere cooling, the onset of D-O warming is extremely abrupt and typically exceeds the rate of cooling into stadial events. These rapid fluctuations suggest that AMOC recovery can occur on even faster timescales than a 'shutdown'^{18,28}.

During the rapid deglacial transition into the Bølling-Allerød warm period (14.7-12.9 ka), abrupt changes cascaded through the whole Earth system (Figs. 1, 2a, 3). The strengthening of the AMOC¹², rapid sea level rise during Meltwater Pulse 1 event²⁹, and an abrupt increase in atmospheric CO₂ and CH₄ concentrations²⁶ (Fig. 3) led to abrupt changes in terrestrial climate, water availability³⁰ and vegetation composition in the Northern³¹⁻³³ and Southern Hemisphere³⁴ (Table 1, Annex 1). In addition, marine records from low-oxygen regions document rapid changes to sedimentary hypoxia (Fig. 3, Annex 1). These records include evidence for an expansion of the oxygen minimum zone (OMZ) across the North Pacific³⁵ as well as shifts to more severe hypoxia in the Cariaco Basin²³ and Arabian Sea³⁶, suggesting a persistent link between warming and ocean deoxygenation that transcends regional patterns in circulation and productivity. In the North Pacific, abrupt onset of hypoxia occurred in conjunction with rapid warming of surface waters by 4-5°C³⁷. Rates of onset of severe hypoxia were on century time scales or possibly faster³⁸ (Fig. 3, Annex 1), while benthic faunal recovery lasted 1,000-2,000 years, representing recovery time periods that were at least 10 times longer than the initial changes³⁷.

Past sea-level rises linked to ice-sheet collapses have sometimes caused abrupt flooding events with ecological and social consequences. The best-quantified rates during these rapid rises exceed 20 meters per thousand years³⁹ (Figs. 2a, 3, Annex 1). The flooding was more abrupt at local to regional scales. A particularly prominent example of abrupt flooding is the Black Sea (Table 1), which has a sill depth across the Strait of Bosphorus that today is 35 meters below sea level. As ice sheets melted, and sea level gradually rose to the level of the Black Sea sill at approximately 9.5 to 9.0 ka, seawater spilled into the basin, raising the Black sea level by more than 10 meters within few decades^{40,41}. This flooding established connection to the sea that includes saltwater inflow at depth and fresher outflow at the surface⁴¹ creating an anoxic and sulphate-reducing deep basin. Other examples of deglacial sea level flooding include Doggerland between the modern British Isles and mainland Europe, where the Channel River or Fleuve Manche paleo-river gave way to the repeated deglacial inundations that most recently resulted in the modern English Channel and North Sea⁴², and the broad Sunda Shelf with abrupt submergence period between 14.6 and 14.3 ka⁴³. In each of these cases, crossing regional-scale thresholds in response to a gradual rise of sea level resulted in new and dramatically different states that, in places, presumably altered the trajectories of early human societies.

Cascading Impacts of Hydroclimate Variability

Hydroclimate variability (changes in land climate and hydrology) in the current interglacial, the Holocene (started 11.7 ka⁴⁴), represents the most vivid examples of cascading abrupt changes relevant for present- day. The Holocene is often considered a period of relatively stable climate and a “safe operating space” for humankind⁴⁵. While this is true globally, geological records show a number of abrupt changes originating and cascading through coupled climate, ecological, and social systems on regional scale^{46,47}. For example, an abrupt climate event about 8200 years ago, caused by ice-sheet meltwater discharge into the North Atlantic, led to cold and dry conditions in the Northern Hemisphere⁴⁸ visible in rapid changes in vegetation composition in Europe⁴⁹ and North America (Table 1, Annex 1). Key characteristics of the current interglacial

include a warm and hydrologically variable atmosphere, a growing anthropogenic footprint⁵⁰, and multiple instances of abrupt change in hydroclimate⁵¹, vegetation⁵², and societies⁴⁶.

Hydroclimate variability during the Holocene was partially forced by slow variations in Earth's orbit on millennial timescales⁵³ and solar activity on centennial timescales⁵⁴. Decadal-scale clusters of volcanic eruptions were likely responsible for abrupt cooling in the 6th century that led to famine and societal reorganization in Europe (transformation of the eastern Roman Empire) and Asia (a rise of the Arabic Empire)⁵⁵. Many of the most severe megadroughts (decadal-scale droughts) appear to represent unforced variability in the ocean-atmosphere system, such as the El Niño–Southern Oscillation (ENSO)⁴. Megadroughts during the Holocene were larger and more intense than any observed in the 20th and 21st-century instrumental records. In North America, multiple episodes of droughts and abrupt ecosystem changes are identified from 10.7 to 0.6 ka⁴⁷, with the earliest abrupt moisture decrease at 9.4 ka likely linked to meltwater pulses into the North Atlantic. Widespread megadroughts, synchronous societal collapse and reorganization have been reported at 4.2 ka, especially in mid- and low latitudes⁵⁶, which is the basis for proposed Megahalayan stage of the Holocene. However, the cause of the 4.2 ka event remains unclear and its signal is weak in some regions such as the northern North Atlantic⁵⁷.

The propagation of abrupt change from the hydroclimate to collapses in ecological and social systems well-documented in regions around the world^{6,58} is especially pronounced at the end of the African Humid Period (AHP) lasted from 15 ka to 5 ka⁵³ (Fig. 2b). The southward retreat of monsoonal rainfall belts in North Africa - driven by changes in the summer insolation mainly related to the climatic precession of the Earth's orbit - was frequently marked by abrupt, local-scale declines in rainfall that progressed spatially from north to south^{59,60}. The termination of the African Humid Period at around 5 ka occurred on centennial rather than decadal timescale, but at least an order of magnitude faster than the orbital forcing changes (Annex 1). The termination was amplified by vegetation feedbacks, desiccation of lakes, soil erosion and dust emissions⁶¹ (Fig. 2b). Some local aquatic and terrestrial ecosystems experienced a series of abrupt changes,

as thresholds were passed for individual species and ecosystems⁶². North African drying and vegetation changes led to a cascade of other abrupt changes. These include the collapse of complex networks of terrestrial vertebrate herbivores and carnivores, as their resource base of primary productivity was undercut⁶³. It also includes the retreat of pastoral societies from North Africa⁶⁴ and the episodes of failed flooding on the Nile River and dynastic turnover from Old to New Kingdom in Egypt⁵⁸.

During the early Holocene, the Great Plains in North America were also marked by widespread regional drying on millennial timescales⁶⁵, producing abrupt biome-scale changes as individual species and ecosystems passed thresholds⁶⁶. Examples include rapid replacement of C₃ forest and grasslands with C₄ grasslands⁶⁷, forest loss and eastward shift of the prairie-forest ecotone⁶⁸ (Fig. 3, Annex 1), altered fire regime⁶⁹ and lowered groundwater tables in the northern Great Plains⁴⁷. In the mesic forests of eastern North America and Europe, trees such as oak and hemlock experienced major decline in abundance that have been linked to droughts and climate variability in the North Atlantic⁷⁰. In southwestern North America farming settlements experienced repeated cycles of growth in the number and size, followed by abandonment and population dispersal. These cycles were intimately linked to expansion and contraction of maize production, which were tied to drought events whose impacts were amplified during periods of maximal growth by higher populations and more complex societal organizations⁷¹.

Hydroclimate variability, such as megadrought, is often associated with destabilization of other past agricultural societies. However, it should be viewed more as a trigger of societal collapse than sole cause. Even where the subsistence economies depended on sophisticated water management systems that required extensive cooperation and organizational management, societal resilience and collapse breakdown also involve complex interactions between multiple natural and social factors⁵⁸. For example, periods of regional droughts during the last millennium⁶ are linked with the collapses of the Khmer Empire at Angkor between ca. 1300 and 1500 AD⁴⁶ (Fig. 3, Annex 1), prehistorical Hohokam society in central Arizona⁷² in the 15th century, and the

Ming Dynasty in China ca. 1600 AD⁶. All three of these example societies had weathered prior hydroclimatic changes. The environmental tipping points that triggered societal breakdowns occurred in the context of pre-existing vulnerabilities created by societal dynamics: an overextended human-built hydrology system in the Khmer capital of Angkor, an increasingly hierarchical social order coupled with immigration from elsewhere in American Southwest for the Hohokam, and increasing political and social unrest in which drought incited peasants to revolt against the Ming.

Palaeorecords as a testbed for early warning approaches

There is growing interest in anticipating abrupt changes in coupled social and ecological systems, because of their impacts⁷. During the last 15 years, certain features of climate variability, in particular variance and autocorrelation, have become popular as “early-warning signals” of abrupt changes⁷³ (Box 1). These univariate precursors of abrupt changes have been analyzed in many reconstructed and modelled timeseries in regions that were suspected to feature tipping points (Table 2, column “univariate precursors”). While a term “early warning” sounds confusing for events happened in the past, the palaeo archives are useful to test prediction of certain potential abrupt changes. For example, increased autocorrelation in North African dust record⁵³ can be seen as an indicator of slowing down of hydroclimate-vegetation system approaching instability⁷⁴ relevant for future changes.

The univariate framework is mostly based on simple, one-dimensional conceptual models. Due to the complexity of processes in the real world, the application of early warning faces challenges because climate variability can change due to many reasons unrelated to changes in stability^{75,76}, a caveat that affects many of the examples in Table 2. In a nutshell, early warning signals are expected in a system that is in steady state with its environment and whose balance of feedbacks changes in a destabilizing way, i.e., where negative (dampening) feedbacks are weakened and / or positive (destabilizing) feedbacks are strengthened. However, it is often unclear whether this

shift in feedbacks dominates a system's variability. For example, the question whether a reorganization of the AMOC is preceded by early warnings such as increase in autocorrelation and variance^{77,78} (Table 2), depends on the contribution of the various mechanisms discussed above. Similarly, the uncertainties in the nature of Dansgaard-Oeschger events cast doubt on whether they meet the conditions to show early warning signals^{18,78,79} (Table 2). Abrupt changes caused by a sudden external forcing or crossing of a spatial threshold (such as the Black Sea sill^{40,41}) do not carry such early warning signals.

While such process complexity limits the predictability of future abrupt changes, early warning approaches can be used to make inferences about the mechanisms behind past abrupt changes in the climate record. Previous studies have addressed univariate precursors of abrupt changes such as the rapid onset of Dansgaard-Oeschger events⁸⁰, the termination of the African Humid Period^{60,74}, and shifts in east Asian monsoon activity⁸¹ (Table 2). The available palaeo records are often insufficient to confirm inferred mechanisms, because the time series are too short, time resolution too low, or dating uncertainty too large. Such data limitations may be overcome with future paleoclimate research, but the inherent properties of many paleo- time series, such as irregularly spaced samples and imperfect proxy representation of a state-variable, must be carefully considered to avoid errors in early warning detection⁸².

Another important difference between the real world and the framework of early warnings is spatial complexity: the Earth's surface is heterogeneous and different locations are connected via atmospheric dynamics. This fact has inspired the search for early warning signals with a spatial component (Table 2, "spatially explicit precursors"). First, changes in the univariate signals discussed above can have different detectability at different places. For example, models show that the early warning signs in the advective water flux of the AMOC differ between latitudes⁷⁸. Second, one can explicitly analyze spatial-temporal statistics such as spatial variance⁸³ or cross-correlations⁸⁴ between an area that has been destabilized and another location to infer the likelihood of instability approaching the second area. Collecting records from different but

climatically coupled locations may therefore reveal more about the stability of the climate system.

Model results indicate where one should look for early warnings, or how one should combine the information from several locations^{77,85,86}. For example, past records provide evidence that increasing correlations between North Pacific and Greenland climates preceded the abrupt deglaciation at the end of the last ice age⁸⁷, and case studies about the end of the African Humid Period has shown that information from single locations at the Earth's surface is not necessarily conclusive on a regional scale, but that increasing cross-correlations among different locations can help identify the next region that loses stability⁸⁴. Past records provide evidence that increasing correlations between North Pacific and Greenland climates preceded the abrupt deglaciation at the end of the last ice age⁸⁷. There is also evidence that terrestrial ecosystems feature spatial correlations and patterns that are indicative of their proximity to thresholds^{88,89}.

Spatial complexity is also related to the cascading of changes. A cascade of abrupt changes can have several manifestations: i) a spatial propagation of an abrupt change from one location to another⁸⁴; ii) the propagation from small to larger scales, for example, when the collapse of an ice sheet affects the AMOC and, hence, the climate on an almost global scale⁸⁶; iii) vice versa, the propagation from large to smaller scales, for example, during the D-O events²⁴; iv) the propagation from one component of the Earth system to another (Fig. 2)⁹⁰. Apart from the climate system, ecological systems can also show early warnings⁷³, and some studies claim to have identified them before changes in human societies^{91,92}. These examples support the view that early warning signals can potentially occur in any component of the Earth system, whether physical⁷⁷, ecological⁹³⁻⁹⁵, or societal^{91,92}. This makes them also highly relevant for a transdisciplinary approach to the coupled physical-ecological-social system. The dynamics of abrupt changes and early warning signals propagating through such coupled systems are currently explored in a conceptual way^{90,96}. At the same time, more tools are becoming available that allow for an automated detection of abrupt changes⁹⁷ and their precursors^{98,99}.

Future Work

How can the paleo-community further contribute to the understanding of abrupt changes? For paleoclimatologists, paleoecologists, and archeologists, the main task is twofold. Firstly, precision, resolution, spatial coverage and reproducibility of paleoenvironmental records need a quantitative improvement. This is necessary for identifying early warning signals^{73,95}, which remains difficult due to low-density data networks and insufficient resolution and/or precision of the records (Table 2). A potential to test precursors of abrupt changes using paleo records is not yet fully exploited. Secondly, the complex picture of feedbacks and linkages between Earth system components calls for a synthesis of data during periods of abrupt changes, including connections between natural and social systems⁶. The synthesis of spatial and temporal patterns of past abrupt changes is crucial to reconstruct propagation of the signal, such as the AMOC disruption, to the other domains of the Earth system⁸⁷. For Earth system modelers, the main task is further improvement of their models of coupled atmosphere-ocean-biosphere-cryosphere processes. Earth system models are making good progress¹⁰⁰; they are capable of simulating some abrupt changes, especially in cryosphere, during the last century and in the future projections¹⁰¹. However, they are challenged by attempts to reconstruct abrupt events that are well documented from the past, including meltwater pulses due to ice sheet collapses²⁹, rapid release of CO₂ during deglaciation²⁶, and abrupt climate and vegetation changes in North Africa during the termination of the African Humid Period^{53,102}. A main limitation to overcome is the ability to simulate abrupt processes on a coarse grid. Current sub-grid scale parameterizations in Earth System models are better suited for simulating gradual rather than abrupt changes, as shown, for example, for permafrost thaw¹⁰³. Increasing model resolution and improving sub-grid scale parameterizations is the promising way to go.

As humans we try to anticipate the future. We are now well aware that complex systems, including the coupled social and ecological systems that now dominate our planet, can undergo abrupt changes. It is a joint task of modelers and data-gatherers to constrain Earth system

models in order to better simulate past abrupt changes. If we cannot model abrupt change in the past, we cannot hope to predict them in the future.

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Author Contributions

All authors contributed to the literature assessment. V.B., S.B., J.W., E.B. and T.L. developed the concept of the paper and compiled the paper with support by all coauthors. All co-authors contributed to the discussion of the manuscript.

Competing Interests statement

The authors declare no competing interests.

340 Data Availability Statement

341 Time series of data plotted in the manuscript (Fig. 3) are available as Supplementary Data 1.

342 Additional information

343 Supplementary information is available for this manuscript.

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623

624 Figure legends

625

626 Figure 1. A timeline of abrupt events over the last 30 thousand years overlaid on the $\delta^{18}\text{O}$
627 timeseries from North Greenland Ice Core Project⁴⁴.

628

629 Figure 2. Cascades of abrupt changes in physical-ecological-societal components of the Earth
630 system in the cases of onset of Bølling-Allerød (a) and termination of the African Humid Period
631 (b).

632

633 Figure 3. A map of selected atmospheric, oceanographic, ecosystem, and societal records with
634 abrupt changes or tipping points in the last 20 thousand years. Dots are approximate record
635 locations. Colors clockwise around the globe indicates the Earth components: turquoise, ocean
636 domain (sea level change at Barbados³⁹ and Tahiti²⁹, hypoxia in North Pacific³⁷, AMOC
637 changes¹²); light green, societal domain (drought index for demise of Angkor society⁴⁶); orange,
638 environment-societal interface (drought index for the onset of the AHP end⁶⁰, dust record for the
639 end of AHP⁵³); bright green, ecosystems (tree cover increase in Western Europe during onset of
640 Bølling-Allerød warming^{24,33}, decline in tree cover in the early Holocene^{66,69} as local instances of
641 broader regional to subcontinental trends); dark blue, atmospheric domain (abrupt changes in
642 CO_2 , CH_4 concentrations in Antarctic ice during onset and end of Bølling-Allerød warming²⁶).
643 Shaded bars indicate the periods of abrupt changes or tipping points. Time series of data plotted
644 on the Figure are available as Supplementary Data 1.

645 Table 1. Examples of abrupt events and tipping points in the last 30 thousand years

646

Abrupt events / tipping point	When?	Rapidly of event, years	What happened?	
			Climate, cryosphere and hydrosphere	Land and marine ecosystems; atmospheric CO ₂ and CH ₄ ; societies
Onset of Dansgaard- Oeschger events	28.9, 27.7, and 23.3 ka ^{18,44}	<30 ¹⁹	8 to 16°C warming in Greenland ¹⁹ ; intensification of Asian summer monsoon ⁵¹ ; weakening of South American summer monsoon ²¹	Afforestation from grasslands to wooded steppe in Europe ³¹ ; Holarctic megafauna extinctions ²⁵ ; expanded oxygen minimum zones (eg, Cariaco Basin) ²³ ; abrupt increase in atmospheric CH ₄ ²²
Onset of Bølling-Allerød warming	14.7 ka ¹⁹	1–3 ^{18,44}	9–14°C warming in Greenland ¹⁹ ; 4–5°C SST warming North Pacific ³⁷ ; rapid ice sheet melt, acceleration of sea level rise (meltwater pulse) ^{29,39} ; drying in southwestern North America ³⁰ ; intensification of West African ⁵³ and Asian summer monsoon ⁵¹ ; weakening of South American summer monsoon ³⁴	Rapid afforestation of tundra (Scandinavia), expansion of species from glacial refugia ³² ; expansion of oxygen minimum zones, contraction of marine benthic diversity (North Pacific) ^{35,37} ; abrupt increase in atmospheric CH ₄ and CO ₂ ²⁶
Onset of Holocene	11.7 ka ⁴⁴	<60 ^{18,44}	8–12°C warming in Greenland ¹⁹ , 4–6°C warming in western Europe; 4–5°C SST increase in NE Pacific & North Atlantic; monsoon impacts similar to Bølling-Allerød warming ⁵¹	Similar to the impacts of Bølling-Allerød warming (except atmospheric CO ₂) ³²

Black Sea flooding	9.5 to 9.0 ka ⁴¹	<40 ⁴¹	Rapid flooding of surrounding shelves and subsequent salinification of the Black Sea basin, sea level rise of > 10 m ⁴¹	Drowning of land ecosystems and settlements on the shelf, coastal erosion, shift from freshwater to saltwater ecosystems, anoxia in deep basin ⁴¹
8.2ka Event	8.2 ka ⁴⁴	5 ^{18,44}	3-4°C cooling in Greenland ⁴⁸	Rapid plant community turnover, declines of thermophilous species ⁴⁹
Holocene aridification; end of AHP	8 to 3 ka, timing varies regionally	100-1000 ⁵³	Waning of monsoon rainfall in North Africa ^{53,60} ; drying in southwestern and midcontinental North America ⁶⁵	Regionally rapid southward shift of North African grasslands ^{53,59,64} , in central North America, eastward shift of prairie-forest ecotones, activation of dunes, C ₃ /C ₄ plant shifts, altered fire regimes ⁶⁹
Holocene mega-droughts	high variability 5.4 to 4 ka; last 2 ka ⁴⁷	1–10	Water shortage, extreme drought, decrease of groundwater levels ⁴⁷	Slowed tree growth rates, mortality of mesic tree species, abandonment of early agricultural sites ^{6,47,67}

648 Table 2. Precursors of past abrupt changes in climate-ecological-societal systems

Abrupt changes	Source, methods	Univariate precursors	Spatially explicit precursors
AMOC collapse	modelled and reconstructed changes ⁹⁻¹²	Observations too short and reconstructions too uncertain for meaningful analysis; models of different complexity suggest existence of precursors ^{77,78}	Autocorrelation of critical spatial pattern increases in a model ⁷⁷ ; increased autocorrelation and variance with latitude-dependent signal-to-noise ratio ⁷⁸
Dansgaard-Oeschger events	Greenland isotope record ⁴⁴	Shifts argued to be noise-induced ⁷⁹ ; increase in autocorrelation and variance in the ensemble of events, but not individual events ⁸⁰ ; increase in autocorrelation and variance on decadal timescales preceding events ¹⁸	No literature
Onset of Holocene	Greyscale sediment record from the Cariaco Basin ⁷⁴	Increased autocorrelation with signal at the edge of significance ⁷⁴	Synchronization of North Pacific and North Atlantic climates during recent deglaciation and Younger Dryas ⁸⁷
End of African Humid Period	Dust deposition record ⁵³ ; conceptual models	Inconclusive signals ^{60,74}	Pattern formation in several stages before complete desertification is observed ⁸⁹ ; increasing spatial variance and skewness in simple models ⁸⁸
Monsoon changes	Reconstruction of rainfall during the Pleistocene from Chinese caves ⁸¹	No consistent signals before abrupt changes in East Asian summer monsoon ⁸¹	No literature

Changes in aquatic and marine ecosystems	Reconstructions ³⁵ , contemporary observations	Increasing variance in fish populations after fishing ⁹³ , critical slowing down before extinctions of planktonic crustaceans ⁹⁵	Observed indications of increasing spatial variance before changes in shelf ecosystems ⁸³
Societal collapses and transformations	Reconstructions of past societal changes ⁷²	Increasing variance and autocorrelation before human population collapse during the European Neolithic ⁹¹ ; increasing variance before two cases of social transformation in the pre-Hispanic US Southwest ⁹²	No literature

649

650

Box 1. Terminology

Abrupt change – large-scale change that is much faster than the change in the relevant forcing³. Both, amplitude (scale) and relative rates of **forcing** and response changes are important. In the paleo context, the relevant **forcing** is usually the Earth orbital forcing with multimillennial timescale (the fastest component of the orbital forcing, precessional cycle, has a periodicity of 19,000 years).

Cascading impacts – a sequence of events where **abrupt changes** in one component lead to **abrupt changes** in other components. These changes could also interact with each other and propagate from larger to smaller spatial scales or vice versa (Fig. 2).

Early Warning Signals (EWS) – quantitative indicators of the proximity of a system to a **tipping point**⁷⁴. EWS apply mathematical principles of dynamical systems to **Earth System components**. EWS could be measured in one-dimensional space (such as timeseries of dust deposition in the marine core) using univariate precursors (for example, increasing temporal autocorrelation) or in multi-dimensional space (such as spatial patterns of vegetation cover) applying spatially explicit precursors (Table 2).

Earth System components – atmosphere, ocean, cryosphere, biosphere, and anthroposphere. These can be further divided into sub-components such as monsoon systems, ocean circulation, sea ice, different ecosystems, and human (social) systems.

Forcing – a factor that influence the system dynamics. For example, for Earth system forcings are incoming solar radiation, concentrations of greenhouse gases in the atmosphere, and volcanic eruptions. For **Earth System components** and sub-components, forcings could be changes in the other components leading to cascading impacts.

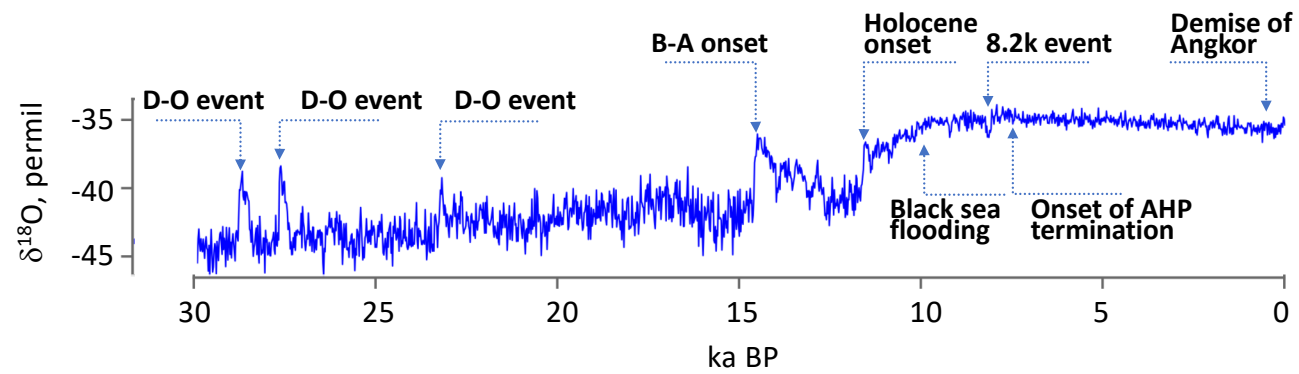
Irreversible change - a change is irreversible if the recovery timescale to the **state** before change is significantly longer than the time it takes for the system to reach this **state**³.

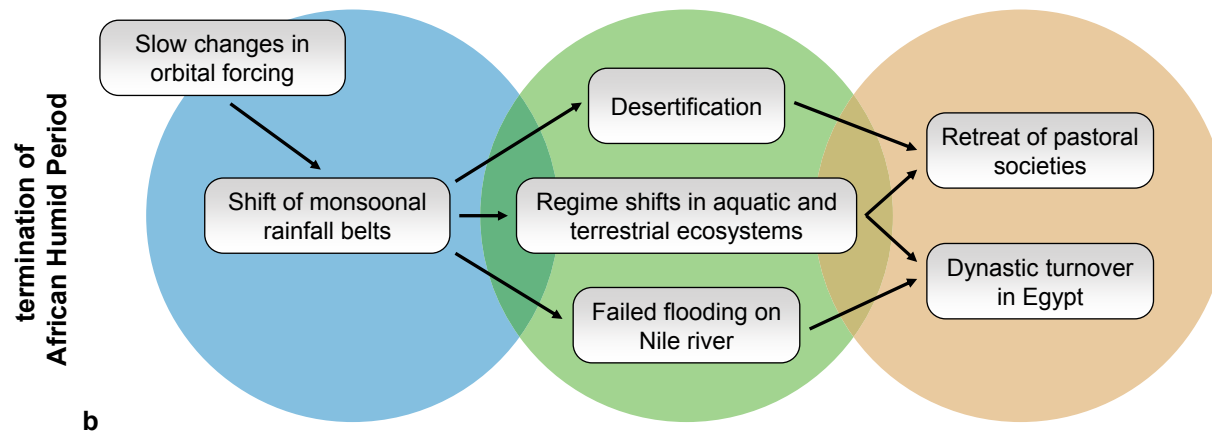
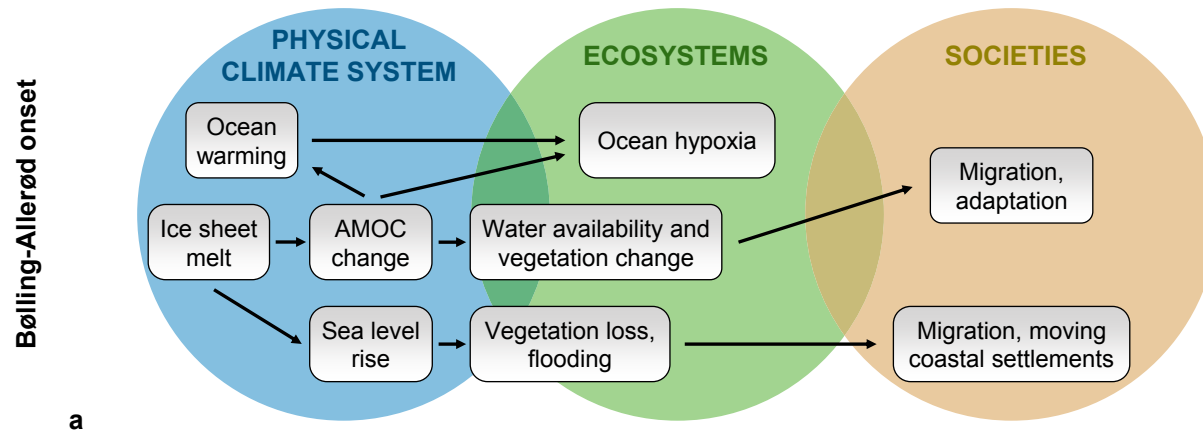
State – A set of variables that describes the state of a dynamical system. These could be climate variables (air temperature, stream velocity in the ocean), ecological variables (number of species, plant biomass), societal variables (population density, income).

Tipping point – a critical threshold (in **forcing** or in a system) at which a small perturbation can nonlinearly alter the **state** or development of a system¹. Tipping points combine different types of phenomena inasmuch as thresholds could be explicit (for example, 0°C for ice) or hidden (such as small reduction in insolation leading to a snowball Earth). The latter can indicate a co-existence of two stable states (eg, snowball and ice-free) with one state becoming unstable.

Statistical terms:

- 684 • Autocorrelation – a correlation between an observational timeseries and its copy shifted by a
685 certain time lag.
- 686 • Skewness – a measure of asymmetry of the data distribution.
- 687 • Univariate precursor – a function of one variable.
- 688 • Variance – a measure how far a dataset is spread out from its average.





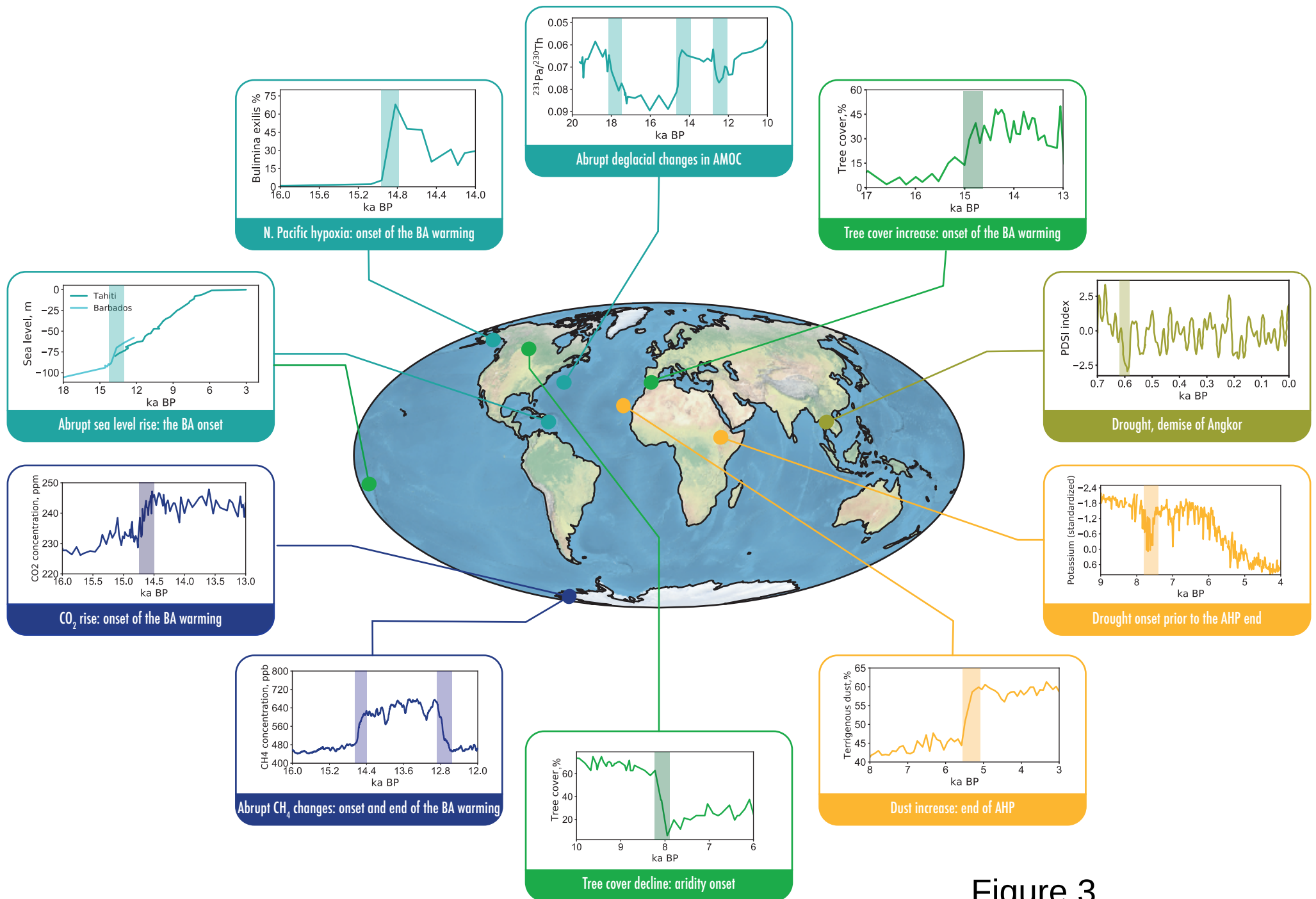


Figure 3.