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 components[1] (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 past[2] (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 CO_2 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 (megadroughts[4]), 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 components[7] (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 scales[8]. 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 latitudes[9]. 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 sheets[13], ice-shelf breakup[14], a coupled ocean-ice "salt oscillator"[15], catastrophic ice stream retreat[16], deep ocean warming due to deglaciation[17], 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 timescales[18] 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 baseline[19]. These events caused major adjustments to hydroclimate and carbon cycling[20-22], with evidence for crossing regional thresholds in marine ecosystems, such as a change to anoxic deep water conditions in the Cariaco Basin[23], and terrestrial ecosystems, for example, forest expansion in western Mediterranean region[24], extinction of Holarctic megafaunal species[25] (Table 1), and abrupt increases in methane emissions from wetlands[26] (Figure 3). D-O events demonstrate that global-scale reorganization of the climate system can occur on decadal time scales[27], 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 AMOC[12], rapid sea level rise during Meltwater Pulse 1 event[29], and an abrupt increase in atmospheric CO_2 and CH_4 concentrations[26] (Fig. 3) led to abrupt changes in terrestrial climate, water availability[30] and vegetation composition in the Northern[31-33] and Southern Hemisphere[34] (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 Pacific[35] as well as shifts to more severe hypoxia in the Cariaco Basin[23] and Arabian Sea[36], 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°C[37]. Rates of onset of severe hypoxia were on century time scales or possibly faster[38] (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 changes[37].

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 years[39] (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 Bosporus 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 surface[41] 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 Sea[42], and the broad Sunda Shelf with abrupt submergence period between 14.6 and 14.3 ka[43]. 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 ka[44]), 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 humankind[45]. 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 Hemisphere[48] visible in rapid changes in vegetation composition in Europe[49] and North America (Table 1, Annex 1). Key characteristics of the current interglacial include a warm and hydrologically variable atmosphere, a growing anthropogenic footprint[50], and multiple instances of abrupt change in hydroclimate[51], vegetation[52], and societies[46].

Hydroclimate variability during the Holocene was partially forced by slow variations in Earth's orbit on millennial timescales[53] and solar activity on centennial timescales[54]. 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 ka[47], 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 latitudes[56], 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 Atlantic[57].

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 ka[53] (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 emissions[61] (Fig. 2b). Some local aquatic and terrestrial ecosystems experienced a series of abrupt changes, as thresholds were passed for individual species and ecosystems[62]. 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 undercut[63]. It also includes the retreat of pastoral societies from North Africa[64] and the episodes of failed flooding on the Nile River and dynastic turnover from Old to New Kingdom in Egypt[58].

During the early Holocene, the Great Plains in North America were also marked by widespread regional drying on millennial timescales[65], producing abrupt biome-scale changes as individual species and ecosystems passed thresholds[66]. Examples include rapid replacement of C_3 forest and grasslands with C_4 grasslands[67], forest loss and eastward shift of the prairie-forest ecotone[68] (Fig. 3, Annex 1), altered fire regime[69] and lowered groundwater tables in the northern Great Plains[47]. 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 Atlantic[70]. 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 organizations[71].

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 factors[58]. For example, periods of regional droughts during the last millennium[6] are linked with the collapses of the Khmer Empire at Angkor between ca. 1300 and 1500 AD[46] (Fig. 3, Annex 1), prehistorical Hohokam society in central Arizona[72] in the 15th century, and the

Ming Dynasty in China ca. 1600 AD[6]. 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 impacts[7]. During the last 15 years, certain features of climate variability, in particular variance and autocorrelation, have become popular as "early-warning signals" of abrupt changes[73] (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 record[53] can be seen as an indicator of slowing down of hydroclimate-vegetation system approaching instability[74] 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 events[80], the termination of the African Humid Period[60,74], and shifts in east Asian monsoon activity[81] (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 detection[82].

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 latitudes[78]. Second, one can explicitly analyze spatial-temporal statistics such as spatial variance[83] or cross-correlations[84] 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 age[87], 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 stability[84]. Past records provide evidence that increasing correlations between North Pacific and Greenland climates preceded the abrupt deglaciation at the end of the last ice age[87]. 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 another[84]; 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 scale[86]; iii) vice versa, the propagation from large to smaller scales, for example, during the D-O events[24]; 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 warnings[73], 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 physical[77], ecological [93-95], 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 changes[97] 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 systems[6]. 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 system[87]. 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 progress[100]; they are capable of simulating some abrupt changes, especially in cryosphere, during the last century and in the future projections[101]. However, they are challenged by attempts to reconstruct abrupt events that are well documented from the past, including meltwater pulses due to ice sheet collapses[29], rapid release of CO_2 during deglaciation[26], 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 thaw[103]. 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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The authors declare no competing interests.

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

Additional information

Supplementary information is available for this manuscript.

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Figure legends

Figure 1. A timeline of abrupt events over the last 30 thousand years overlaid on the $\delta^{18}O$ timeseries from North Greenland Ice Core Project[44].

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

Figure 3. A map of selected atmospheric, oceanographic, ecosystem, and societal records with abrupt changes or tipping points in the last 20 thousand years. Dots are approximate record locations. Colors clockwise around the globe indicates the Earth components: turquoise, ocean domain (sea level change at Barbados[39] and Tahiti[29], hypoxia in North Pacific[37], AMOC changes[12]); light green, societal domain (drought index for demise of Angkor society[46]); orange, environment-societal interface (drought index for the onset of the AHP end[60], dust record for the end of AHP[53]); bright green, ecosystems (tree cover increase in Western Europe during onset of Bølling-Allerød warming[24,33], decline in tree cover in the early Holocene[66,69] as local instances of broader regional to subcontinental trends); dark blue, atmospheric domain (abrupt changes in CO_2, CH_4 concentrations in Antarctic ice during onset and end of Bølling-Allerød warming[26]). Shaded bars indicate the periods of abrupt changes or tipping points. Time series of data plotted on the Figure are available as Supplementary Data 1.

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

Abrupt events / tipping point	**When?**	**Rapidity 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 varia-bility 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

Box 1. Terminology

Abrupt change – large-scale change that is much faster than the change in the relevant forcing[3]. 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.

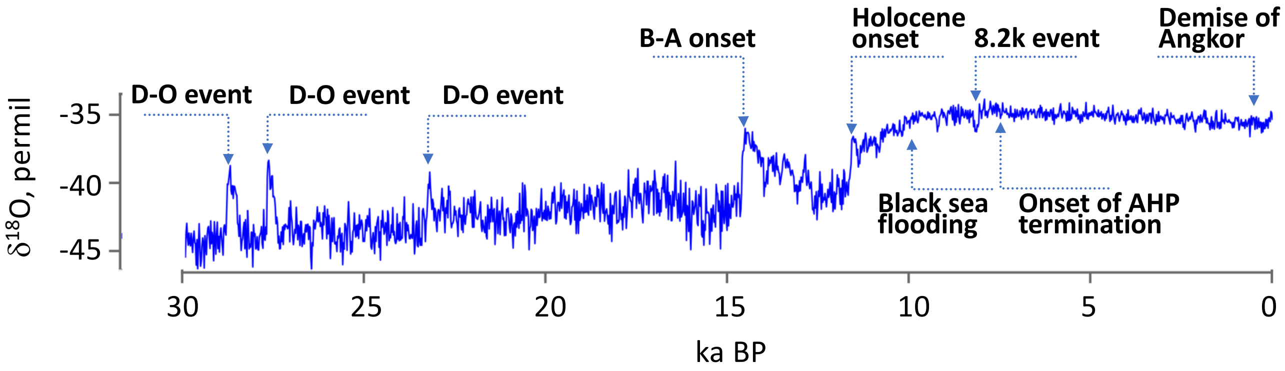
Irreversible change - a change is irreversible if the recovery timescale to the **state** before change is significantly longer than the time it takes for the system to reach this **state**[3].

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 system[1]. 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:

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


D-O event
D-O event
D-O event
B-A onset
Holocene onset
8.2k event
Demise of Angkor
Black sea flooding
Onset of AHP termination
δ18O, permil
-35
-40
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25
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Figure 1.

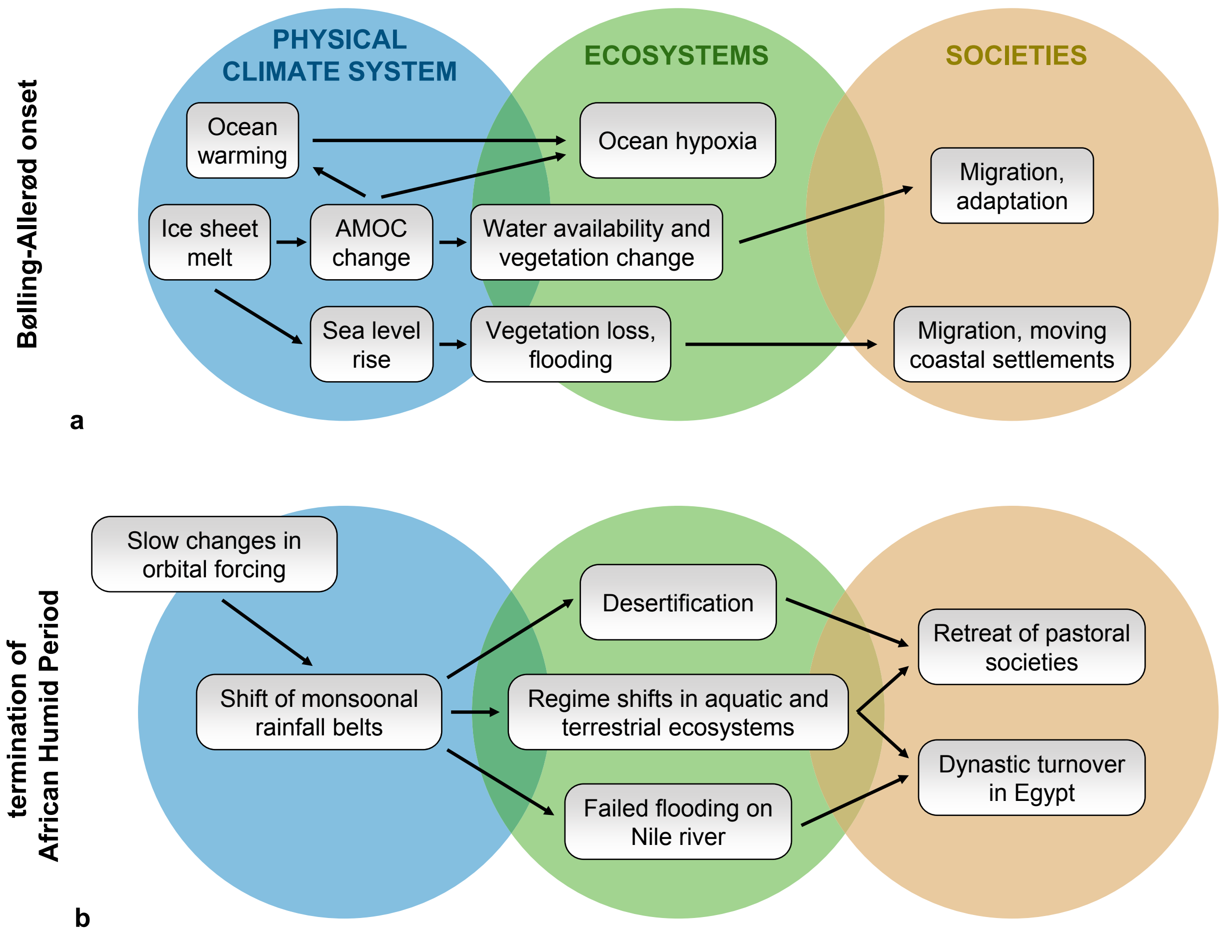
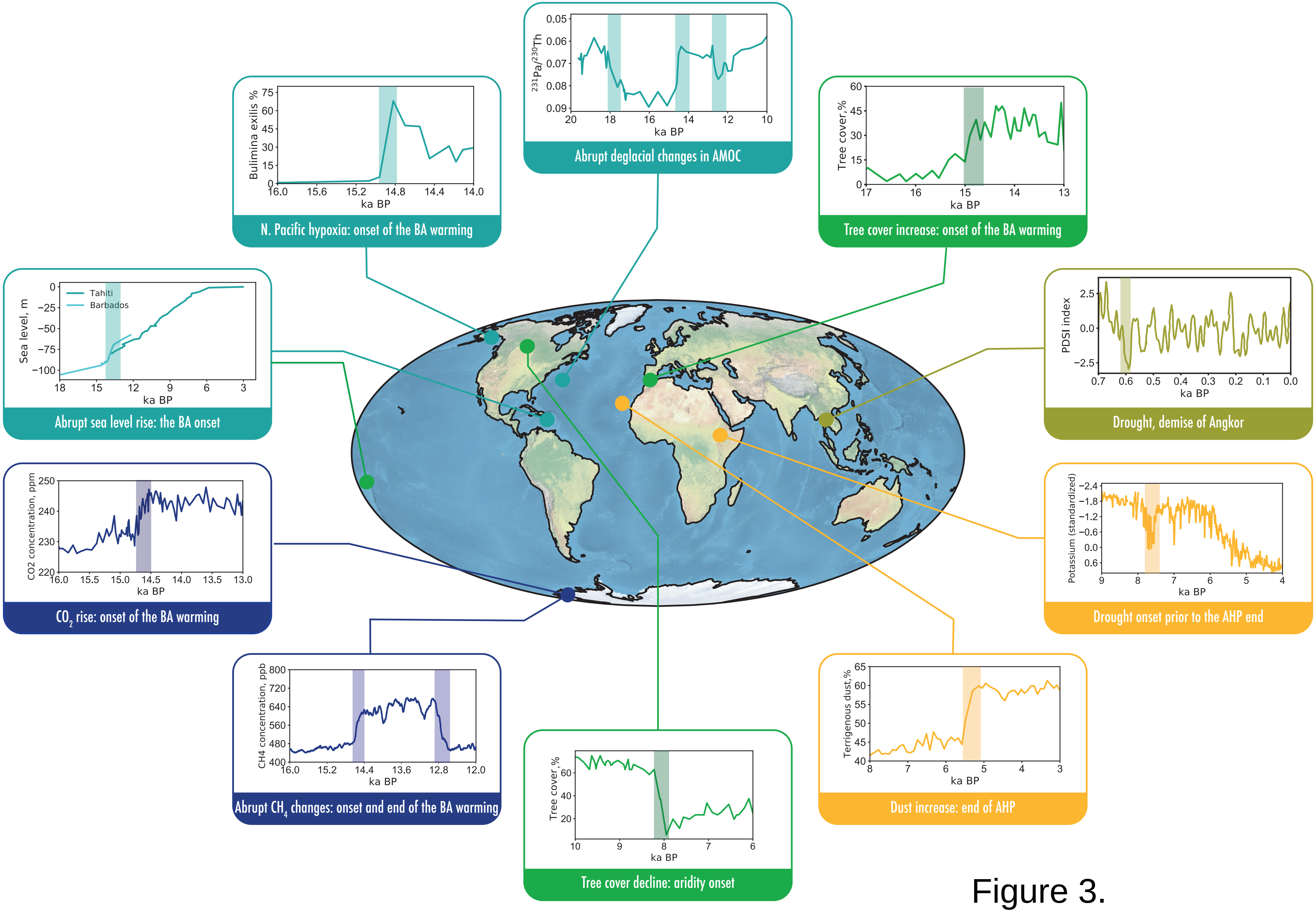

Bølling-Allerød onset
PHYSICAL CLIMATE SYSTEM
ECOSYSTEMS
SOCIETIES
Ocean warming
Ocean hypoxia
Ice sheet melt
AMOC change
Water availability and vegetation change
Migration, adaptation
Sea level rise
Vegetation loss, flooding
Migration, moving coastal settlements
a
termination of African Humid Period
Slow changes in orbital forcing
Desertification
Retreat of pastoral societies
Shift of monsoonal rainfall belts
Regime shifts in aquatic and terrestrial ecosystems
Dynastic turnover in Egypt
Failed flooding on Nile river
b

Figure 2.



Abrupt deglacial changes in AMOC
ka BP
N. Pacific hypoxia: onset of the BA warming
Bulimina exilis %
Tree cover increase: onset of the BA warming
Tree cover, %
Abrupt sea level rise: the BA onset
Sea level, m
Tahiti
Barbados
Drought, demise of Angkor
PDSI index
CO2 concentration, ppm
CO2 rise: onset of the BA warming
Drought onset prior to the AHP end
Potassium (standardized)
Abrupt CH4 changes: onset and end of the BA warming
CH4 concentration, ppb
Tree cover decline: aridity onset
Dust increase: end of AHP
Terrigenous dust,%

Figure 3.