



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. The chance of detecting abrupt changes and tipping points 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 that may be irreversible within human time frames. Here, we use well-documented abrupt changes of the past 30 kyr 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 palaeoclimate science to the understanding of abrupt changes in the Earth system.

There is increasing awareness and concern that human modification of the 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 use them for understanding possible consequences of future climate change, we must quantify the characteristics and timing of the initial abrupt change during these past events, the tipping points involved and the subsequent 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 concentrations (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 abate (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 may not generally have a strong effect on ecosystems adapted to such a climate state. However, if a drought persists over many years (megadroughts⁴),

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Box 1 | Terminology

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

Cascading impacts are 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) are quantitative indicators of the proximity of a system to a tipping point⁷⁴. EWS apply mathematical principles of dynamical systems to Earth system components. EWS could be measured in one-dimensional space (such as time series of dust deposition in a 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 are the atmosphere, ocean, cryosphere, biosphere and anthroposphere. These can be further divided into subcomponents such as monsoon systems, ocean circulation, sea ice, different ecosystems and human (social) systems.

Forcing refers to a factor that influences the system dynamics. For example, Earth system forcings include incoming solar radiation,

concentrations of greenhouse gases in the atmosphere and volcanic eruptions. For Earth system components and subcomponents, forcings could be changes in the other components leading to cascading impacts.

Irreversible change denotes a change that is irreversible if the recovery timescale to the state before change is substantially longer than the time it takes for the system to reach this state³.

State refers to 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) or societal variables (population density, income).

Tipping points are critical thresholds (in forcings 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 phenomenon 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 (for example, snowball and ice-free), with one state becoming unstable.

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

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 in the coming decades to centuries^{5,6}.

A rapidly growing archive of palaeoclimatic, palaeoecological 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 palaeo records alone, and the predictive power of past causalities for future events is limited by different timescales and forcings. However, we can infer causal interactions if there is sufficient evidence and consistency in the relative timing of changes, understanding of processes and, if available, support from Earth system model experiments.

Gleaning useful information from palaeo 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 this Review to consider causality generally flowing from climate to ecological and sometimes to social systems, focusing on the 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 palaeo records, and probably 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 bipolar seasaw¹⁰, including a southward shift of the Intertropical Convergence Zone, substantial cooling in the Northern Hemisphere centred in the North Atlantic region and general warming in the Southern Hemisphere. Palaeoclimate 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 (around 19–12 kyr ago (ka))¹⁰, and evidence from deep-sea sediments confirms that these abrupt climate changes were associated with substantial changes in the AMOC^{11,12}. The cause of these changes in the 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 and 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. The abrupt onsets of warming in these events on decadal timescales¹⁸ correspond to temperature increases that may have exceeded 15°C in Greenland and several degrees Celsius in Europe, and are 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 cycling^{20–22}, with evidence for crossing of 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, the extirpation of Holarctic megafaunal

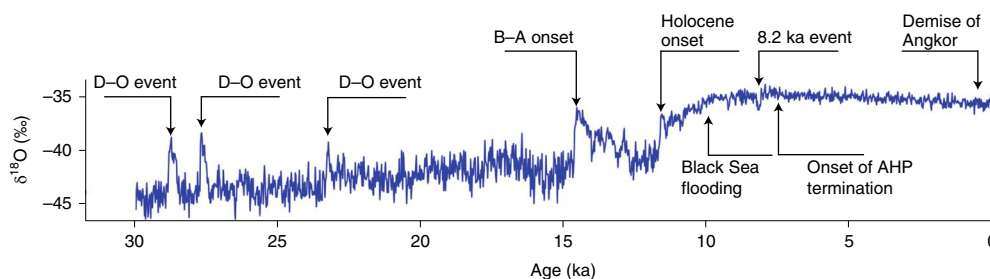


Fig. 1 | Timeline of abrupt events over the past 30 kyr overlaid on a $\delta^{18}\text{O}$ time series. The $\delta^{18}\text{O}$ time series is from North Greenland Ice Core Project⁴⁴. AHP, African Humid Period; D-O, Dansgaard-Oeschger event; B-A, Bølling-Allerød warm period.

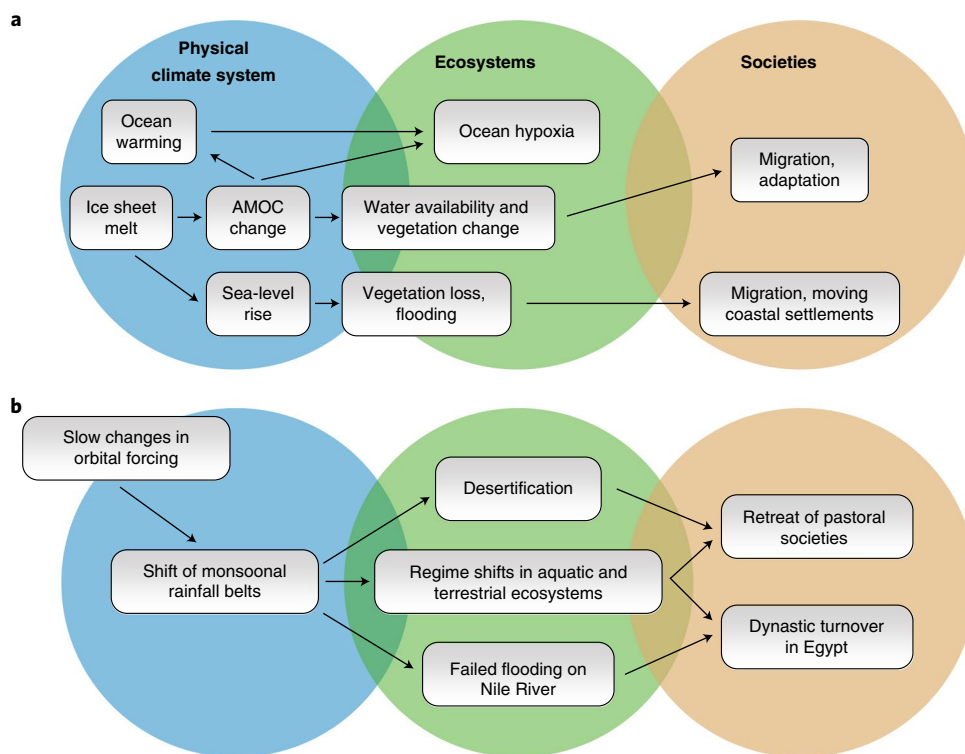


Fig. 2 | Cascades of abrupt changes in physical-ecological-societal components of the Earth system. a, Onset of the Bølling-Allerød warm period. **b,** Termination of the AHP.

species²⁵ (Table 1) and abrupt increases in methane emissions from wetlands²⁶) (Fig. 3). The D-O events demonstrate that global-scale reorganization of the climate system can occur on decadal timescales²⁷, possibly triggered by abrupt changes in the AMOC. Although 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 and 3). The strengthening of the AMOC¹², rapid sea-level rise during the Meltwater Pulse 1 event²⁹ and an abrupt increase in atmospheric CO_2 and CH_4 concentrations²⁶ (Fig. 3) led to abrupt changes in the terrestrial climate, water availability³⁰ and vegetation composition in the Northern^{31–33} and Southern³⁴ hemispheres (Table 1 and Supplementary Information). In addition, marine records from low-oxygen regions document rapid shifts to sedimentary hypoxia (Fig. 3 and Supplementary

Information). These records include evidence for an expansion of the oxygen minimum zone 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 of circulation and productivity. In the North Pacific, the abrupt onset of hypoxia occurred in conjunction with rapid warming of surface waters by 4–5 °C (ref. ³⁷). Rates of onset of severe hypoxia were on century timescales or possibly faster³⁸ (Fig. 3 and Supplementary Information), while benthic faunal recovery lasted 1–2 kyr, representing recovery time periods that were at least ten times longer than the onsets³⁷.

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 m kyr⁻¹ (ref. ³⁹) (Figs. 2a and 3 and Supplementary Information). 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 m below sea level. As ice sheets melted, and sea level

Table 1 | Examples of abrupt events and tipping points in the past 30 kyr

Abrupt event/ tipping point	Date(s)	Rapidity of event	Effects in Earth system components	
			Climate, cryosphere and hydrosphere	Land and marine ecosystems; atmospheric CO ₂ and CH ₄ ; societies
Onset of D–O events	28.9, 27.7 and 23.3 ka (refs. 18,44)	<30 yr (ref. 19)	8–16 °C of warming in Greenland ¹⁹ ; intensification of the Asian summer monsoon ⁵¹ ; weakening of the South American summer monsoon ²¹	Afforestation from grasslands to wooded steppes in Europe ³¹ ; Holarctic megafauna extirpations ²⁵ ; expanded oxygen minimum zones (for example, Cariaco Basin) ²³ ; abrupt increase in atmospheric CH ₄ (ref. 22)
Onset of Bølling–Allerød warming	14.7 ka (ref. 19)	1–3 yr (refs. 18,44)	9–14 °C of warming in Greenland ¹⁹ ; 4–5 °C of sea surface temperature warming in the North Pacific ³⁷ ; rapid ice sheet melt, acceleration of sea-level rise (meltwater pulse) ^{29,39} ; drying in southwestern North America ³⁰ ; intensification of the West African ⁵³ and Asian summer monsoons ⁵¹ ; weakening of the South American summer monsoon ³⁴	Rapid afforestation of tundra (Scandinavia), expansion of species from glacial refugia ³² ; expansion of oxygen minimum zones and contraction of marine benthic diversity (North Pacific) ^{35,37} ; abrupt increase in atmospheric CH ₄ and CO ₂ ²⁶
Onset of the Holocene	11.7 ka (ref. 44)	<60 yr (refs. 18,44)	8–12 °C of warming in Greenland ¹⁹ , 4–6 °C of warming in western Europe; 4–5 °C increase in sea surface temperature in the northeast Pacific and 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	9.5–9.0 ka (ref. 41)	<40 yr (ref. 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, a shift from freshwater to saltwater ecosystems and anoxia in the deep basin ⁴¹
8.2 ka event	8.2 ka (ref. 44)	5 yr (refs. 18,44)	3–4 °C of cooling in Greenland ⁴⁸	Rapid plant community turnover, declines of thermophilous species ⁴⁹
Holocene aridification; end of the AHP	8–3 ka, timing varies regionally	100–1,000 yr (ref. 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} ; an eastward shift of prairie–forest ecotones, activation of dunes, C ₃ /C ₄ plant shifts and altered fire regimes in central North America ⁶⁹
Holocene megadroughts	High variability 5.4–4 ka; past 2 ka (ref. 47)	1–10 yr	Water shortage, extreme drought, decrease of groundwater levels ⁴⁷	Slowed tree growth rates, mortality of mesic tree species and abandonment of early agricultural sites ^{6,47,67}

gradually rose to the level of the Black Sea sill at approximately 9.5–9.0 ka, seawater spilled into the basin, raising sea level in the Black Sea by more than 10 m within a few decades^{40,41}. This flooding established a connection to the sea that includes saltwater inflow at depth and fresher outflow at the surface⁴¹, creating an anoxic and sulfate-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 palaeo-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 ka (ref. 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; ref. 44), represents the most vivid example of cascading abrupt changes relevant to the 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 scales^{46,47}. For example,

an abrupt climate event at about 8.2 ka, 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 and Supplementary Information). 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 probably responsible for abrupt cooling in the sixth 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) seem to represent unforced variability in the ocean–atmosphere system, such as the El Niño/Southern Oscillation⁴. Megadroughts during the Holocene were larger and more intense than any observed in twentieth- and twenty-first-century instrumental records. In North America, multiple episodes of droughts and abrupt ecosystem changes are identified from 10.7 to 0.6 ka (ref. 47), with the earliest abrupt moisture decrease at 9.4 ka probably linked to meltwater pulses into the North Atlantic. Widespread megadroughts and synchronous societal collapse and reorganization have been reported at

Table 2 | Precursors of past abrupt changes in climate–ecological–societal systems

Abrupt changes	Source and methods of detection	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 the 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
D–O 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 the 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 the AHP	Dust deposition record ⁵³ ; conceptual models	Inconclusive signals ^{50,74}	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 the 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

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^{16,58} is especially pronounced at the end of the AHP, which lasted from 15 ka to 5 ka (ref. 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 AHP at around 5 ka occurred on a centennial, rather than decadal, timescale, but at least an order of magnitude faster than the orbital forcing changes (Supplementary Information). The termination was amplified by vegetation feedbacks, the 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, the episodes of failed flooding on the Nile River and dynastic turnover from the 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 the rapid replacement of C₃ forest and grasslands with C₄ grasslands⁶⁷,

forest loss and eastward shifts of the prairie–forest ecotone⁶⁸ (Fig. 3 and Supplementary Information), 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 the 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 past agricultural societies. However, it should be viewed more as a trigger of societal collapse than the sole cause. Even where the subsistence economies depended on sophisticated water management systems that required extensive cooperation and organizational management, societal resilience and collapse also involve complex interactions between multiple natural and social factors⁵⁸. For example, periods of regional droughts during the past millennium⁶ are linked with the collapses of the Khmer Empire at Angkor between ~1300 and 1500 AD (ref. ⁴⁶) (Fig. 3 and Supplementary Information), the prehistorical Hohokam society in central Arizona⁷² in the fifteenth century and the Ming Dynasty in China approximately 1600 AD (ref. ⁶). All three of these example societies had weathered previous 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 the American

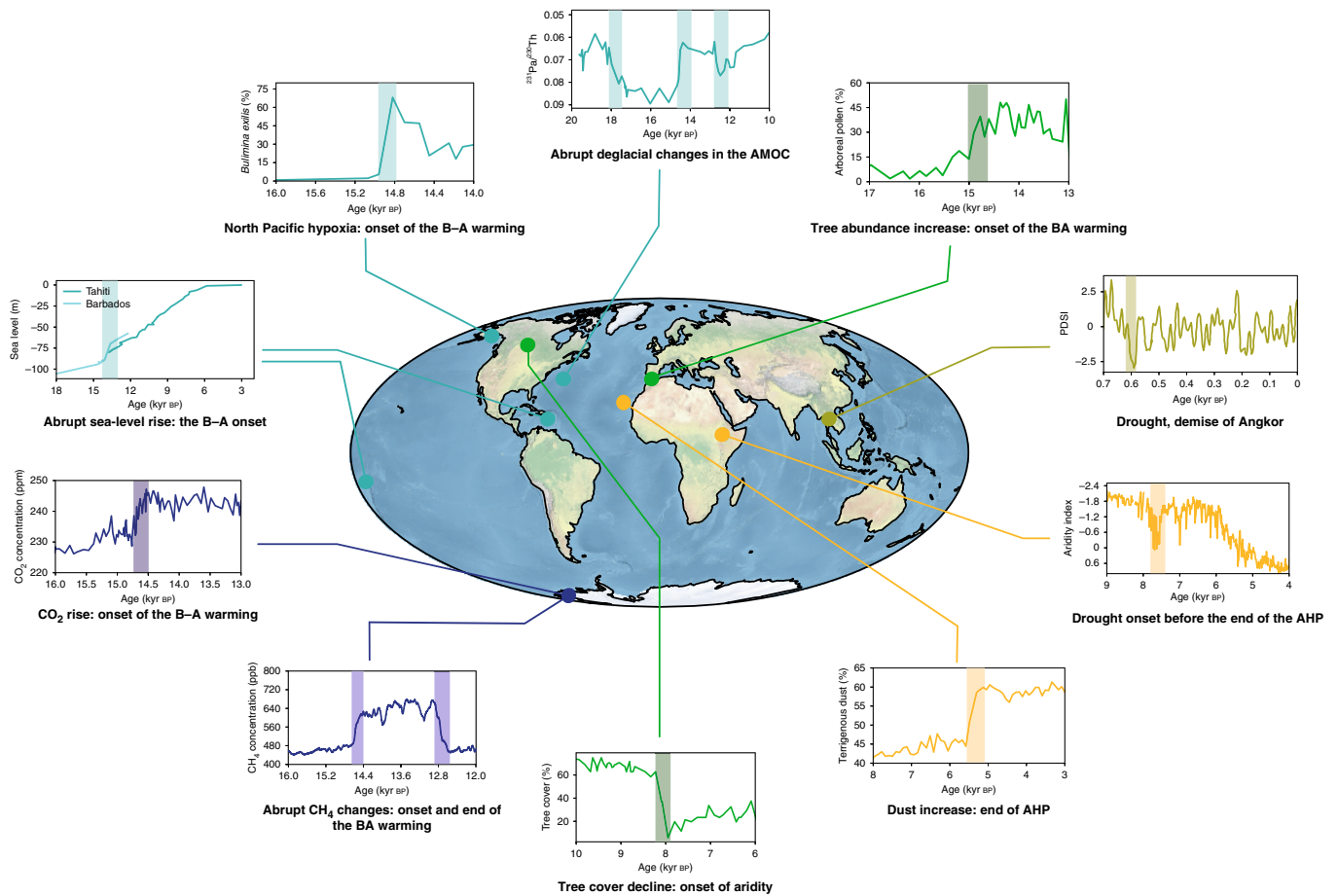


Fig. 3 | A map of selected atmospheric, oceanographic, ecosystem and societal records with abrupt changes or tipping points in the past 20 kyr. Dots are approximate record locations. Clockwise around the globe, the colours indicate the Earth system components: turquoise marks the ocean domain (sea-level change at Barbados³⁹ and Tahiti²⁹; hypoxia in the North Pacific³⁷ reflected in the relative abundance of low-oxygen benthic foraminifera *Bulimina exilis*; sedimentary Pa/Th in the deep western North Atlantic indicates the strength of AMOC¹²); light green is the societal domain (the Palmer drought severity index (PDSI) for the demise of the Angkor society⁴⁶); yellow marks environment-societal interfaces (drought index for the onset of the AHP end, marked by 14 short droughts including the most dramatic event from 7.9 to 7.7 kyr BP⁶⁰, and the dust fraction of deep-sea sediments showing a rise in Saharan dust at end of the AHP⁵³); bright green represents ecosystems (tree abundance increase in Western Europe during the onset of Bølling-Allerød warming^{24,33}, expressed as percentage of arboreal to total pollen grains; decline in tree cover estimated as percent of land area in the early Holocene^{66,69}, as local instances of broader regional to subcontinental trends) and blue marks the atmospheric domain (abrupt changes in CO₂ and CH₄ concentrations in Antarctic ice during the onset and end of Bølling-Allerød warming²⁶). Shaded bars indicate the periods of abrupt changes or tipping points. Time series of the data plotted on the figure are available as source data.

Southwest for the Hohokam and increasing political and social unrest when drought incited peasants to revolt against the Ming.

Palaeo records 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 past 15 years, certain features of climate variability, in particular variance and autocorrelation, have become popular as EWS of abrupt changes⁷³ (Box 1). These univariate precursors of abrupt changes have been analysed in many reconstructed and modelled time series in regions that were suspected to feature tipping points (univariate precursors in Table 2). Although the term ‘early warning’ sounds confusing for events that happened in the past, the palaeo archives are useful to test predictions of certain potential abrupt changes. For example, increased autocorrelation in the North African dust record⁵³ can be seen as an indicator of the slowing down of the hydroclimate-vegetation system, approaching instability⁷⁴ that is relevant for future changes.

The univariate framework is mostly based on simple, one-dimensional conceptual models. Owing to the complexity of

processes in the real world, the application of EWS 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, EWS are expected in a system that is in steady state with its environment and whose balance of feedbacks changes in a destabilizing way; that is, 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 of whether a reorganization of the AMOC is preceded by EWS, such as an 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 D-O events cast doubt on whether they meet the conditions to show EWS^{18,78,79} (Table 2). Abrupt changes caused by a sudden external forcing or the crossing of a spatial threshold (such as the Black Sea sill^{40,41}) do not carry such EWS.

Although 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 D–O events⁸⁰, the termination of the AHP^{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, the time resolution too low or the dating uncertainty too large. Such data limitations may be overcome with future palaeoclimate research, but the inherent properties of many palaeo 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 EWS with a spatial component (spatially explicit precursors in Table 2). First, changes in the univariate signals discussed above can have different detectability at different places. For example, models show that the EWS in the advective water flux of the AMOC differ between latitudes⁷⁸. Second, one can explicitly analyse spatio-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 AHP have 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 the climates of the North Pacific and Greenland 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: (1) a spatial propagation of an abrupt change from one location to another⁸⁴; (2) 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; (3) vice versa, the propagation from large to smaller scales, for example, during the D–O events²⁴; and (4) the propagation from one component of the Earth system to another (Fig. 2)⁹⁰. As well as the climate system, ecological systems can show early warnings⁷³, and some studies claim to have identified them before changes in human societies^{91,92}. These examples support the view that EWS can potentially occur in any component of the Earth system, whether physical⁷⁷, ecological^{93–95} or societal^{91,92}. This makes them highly relevant for a transdisciplinary approach to the coupled physical–ecological–social system. The dynamics of abrupt changes and EWS propagating through such coupled systems are explored in a conceptual way at present^{90,96}, but more tools are becoming available that allow for an automated detection of abrupt changes⁹⁷ and their precursors^{98,99}.

Future work

How can the palaeo community further contribute to our understanding of abrupt changes? For palaeoclimatologists, palaeoecologists and archaeologists, the main task is twofold. First, the precision, resolution, spatial coverage and reproducibility of palaeo-environmental records must be quantitatively improved. This is necessary for identifying EWS^{73,95}, which remains difficult due to

low-density data networks and the insufficient resolution and/or precision of the records (Table 2). The potential to test precursors of abrupt changes using palaeo records is not yet fully exploited. Second, 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 reconstructing the propagation of the signal, such as AMOC disruption, to the other domains of the Earth system⁸⁷. For Earth system modellers, the main task is the further improvement of their models of coupled atmosphere–ocean–biosphere–cryosphere processes. Good progress is being made with Earth system models¹⁰⁰; they are capable of simulating some abrupt changes, especially in the cryosphere, during the past century and in 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, the rapid release of CO₂ during deglaciation²⁶ and abrupt climate and vegetation changes in North Africa during the termination of the AHP^{53,102}. An important 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 to simulating gradual, rather than abrupt, changes—as shown, for example, for permafrost thaw¹⁰³. Increasing model resolution and improving sub-grid-scale parameterizations are therefore promising avenues.

Humans will always strive 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. Constraining Earth system models to better simulate past abrupt changes is a joint task for modellers and data-gatherers. If we cannot model abrupt changes in the past, we cannot hope to predict them in the future.

Data availability

Source data are provided with this paper.

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Author contributions

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

Competing interests

The authors declare no competing interests.

Additional information

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Supplementary information

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

In the format provided by the authors and unedited

Annex 1. Calculation of abruptness rates

Our approach to calculate abruptness of changes during abrupt event follows the recent method¹: we compare the rate of changes before the event and during the event. We calculate a ratio of these rates for the variable under consideration, such as atmospheric CO₂ concentration, and compare it with the ratio for the orbital forcing. The procedure is as follows. We define the abrupt event period T_{ab} , t_1 to t_2 , and calculate rate of changes in variable under consideration, $V(t)$, during abrupt period. Because of interannual variability in $V(t)$, we use an average of variable of up to 200 years before and after the change to calculate the rate

$$R_{ab} = (\bar{V}(t_2) - \bar{V}(t_1)) / (t_2 - t_1) \quad (A1)$$

For the reference period, T_{ref} , t_0 to t_1 , which is taken much longer than the period of abrupt changes, the rate of V changes, R_{ref} , is calculated as a slope of linear interpolation using Python package *lmfit*. The abruptness of changes relative to the reference period, A_{ab} , is calculated as a ratio R_{ab} / R_{ref} . The higher the value of A_{ab} , the more abrupt are changes relative to the reference period. Let us note that abruptness A_{ab} calculated in this way is not limited to time scale of changes, e.g. decadal or centennial, but is defined relative to the changes during the reference period.

To compare with the abruptness of the orbital forcing $F(t)$, we do the same procedure with the orbital forcing as above using a computational algorithm of long-term variations of insolation². We use the same reference and abrupt change periods T_{ref} and T_{ab} , respectively. Because interannual variability in orbital forcing is negligible, we skip averaging of forcing before and after change and calculate the rate of changes in orbital forcing during the abrupt change period, O_{ab} , as

$$O_{ab} = (F(t_2) - F(t_1)) / (t_2 - t_1) \quad (A2)$$

For the reference period, T_{ref} , t_0 to t_1 , the rate of orbital forcing changes, O_{ref} , is calculated as a slope of linear interpolation using Python package *lmfit*. The abruptness of changes relative to the reference period, A_{orb} , is calculated as a ratio O_{ab} / O_{ref} .

Finally, we calculate abruptness of changes in the variable relative to changes in the orbital forcing, A , as a ratio A_{ab} / A_{orb} . The values of intermediate variables and final rates are provided in Table A1 and illustrated in the Figure A1. To explain the procedure, let us follow an example of the Case 1 in the Table A1. The variable is atmospheric CO₂ concentration from the West Antarctic ice core³. The steps of calculating abruptness A are as follows:

- Firstly, from the CO₂ record, we visually defined an abrupt change period, 14.8 to 14.6 ka BP. Calculating average values in CO₂ during 200 years before the abrupt change, i.e. during 15.0 to 14.8 ka BP, and after the change, i.e. 14.6 to 14.4 kyr BP, we find an increase of 11.1 ppm during the abrupt change period. The rate of change R_{ab} is therefore 11.1 ppm/0.2 kyr, or 56 ppm kyr⁻¹. The average concentrations before and after the change are shown as black horizontal lines in Fig. 1 (left), while the black line connecting them indicate a slope of change.

- Secondly, we linearly interpolate CO₂ concentrations during the reference period which we define as 16.0 to 14.8 ka BP. The rate of increase during the reference period, R_{ref} , is 5.9 ppm kyr⁻¹, while a total change during the reference period is 7.1 ppm. The interpolation is shown as a blue line on Fig. 1, left. Consequently, $A_{ab} = R_{ab} / R_{ref} = 56 \text{ ppm kyr}^{-1} / 5.9 \text{ ppm kyr}^{-1} = 9.5$. For the orbital forcing, we assume that the relevant characteristic is an incoming solar radiation averaged over July at 65°N. Results of calculated changes during the abrupt change period and reference period are shown on Fig. 1 (right). The abruptness of orbital forcing, A_{orb} , is calculated as 1.08.
- Finally, an abruptness of changes in CO₂ concentration relative to the changes in orbital forcing, A , is $A_{ab} / A_{orb} = 9.5 / 1.08$, or 8.8.

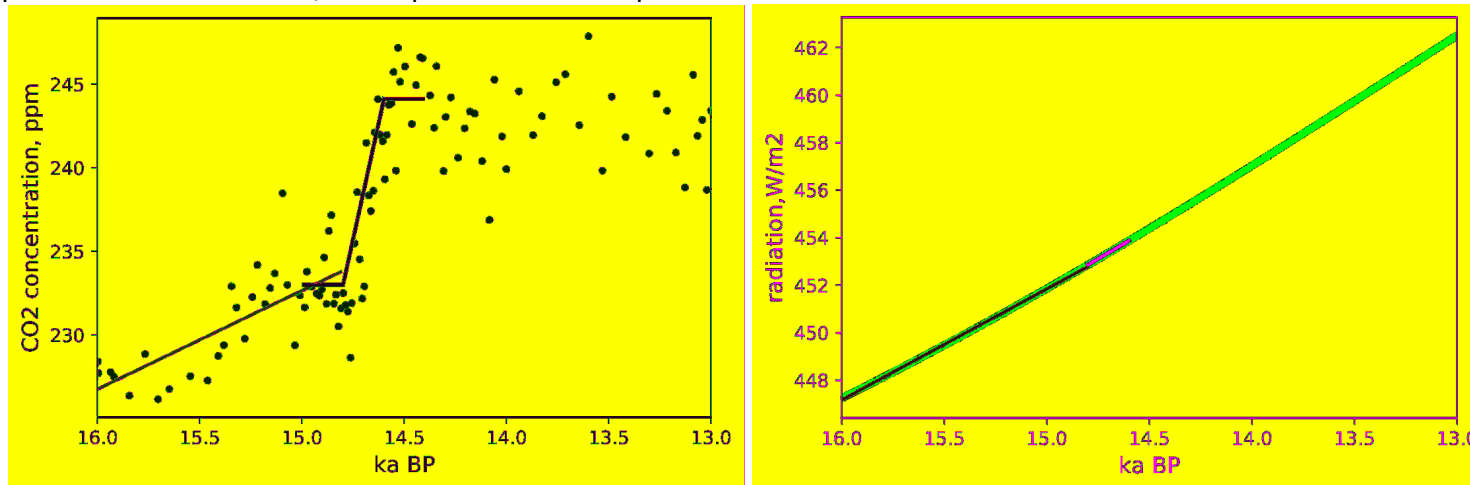
The abruptness of orbital forcing, A_{orb} is small (0.96-1.32), unless the reference period insolation change is small as for the case 7 of tree cover change in the Steel Lake record (2.45). Comparison of A_{ab} and A_{orb} shows that the change during the selected abrupt period is always substantially faster (3.4 to 89 times) than the change in orbital forcing. The abruptness A values in the Table A1 are in the range from 8 to 98, which we consider as significantly abrupt.

Table A1. Abruptness of changes for records shown in the Figure 3.

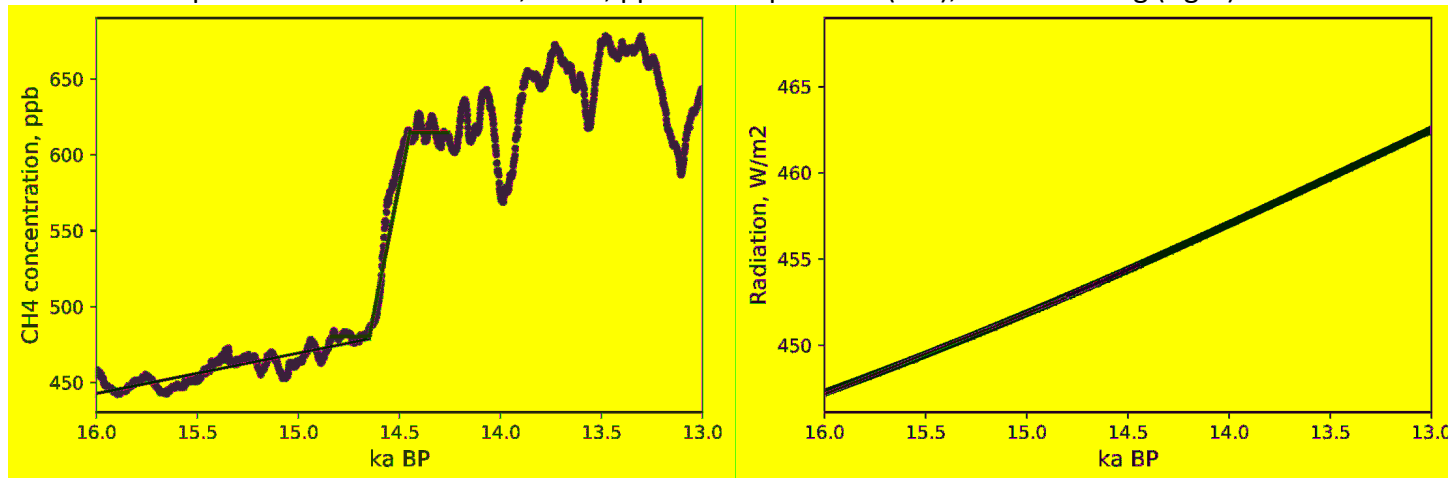
- The column “abrupt change period” shows: (i) the period with most abrupt changes, T_{ab} ; (ii) the amplitude of changes during this period calculated as a difference between averages of periods before-and after change (shown as horizontal black lines on the Fig. A1); (iii) the rate of changes during abrupt period, R_{ab} ;
- The column “reference period” shows characteristics as above, but for the reference period T_{ref} , including rates of changes R_{ref} ;
- “Abruptness relative to the reference period”, A_{ab} is calculated as a ratio R_{ab}/R_{ref} ;
- “Abruptness of orbital forcing (latitude)”: A_{ref} , the ratio of rate of changes in the orbital forcing during the abrupt change period (black lines on Fig. A1 plots) to the rate of change in orbital forcing during the reference period (blue lines). In parentheses, a latitude used in calculation of the orbital forcing.
- “Abruptness relative to the orbital forcing”: A , or ratio A_{ab}/A_{ref} .

Case Nr.	Variable	Abrupt change period, amplitude of changes, rate of changes	Reference period, amplitude of changes, rate of changes	Abruptness relative to the reference period	Abruptness of orbital forcing (latitude)	Abruptness relative to the orbital forcing
1	Atmospheric CO ₂ concentration, WAIS, ppm ³	14.8 to 14.6 ka BP, 11.1 ppm, 56 ppm kyr ⁻¹	16.0 to 14.8 ka BP, 7.1 ppm, 5.9 ppm kyr ⁻¹	9.5	1.08 (65°N)	8.8
2	Atmospheric CH ₄ concentration, WAIS, ppb ³	14.65 to 14.45 ka BP, 134 ppb, 672 ppb kyr ⁻¹	16.0 to 14.65 ka BP, 36 ppb, 27 ppb kyr ⁻¹	25	1.09 (65°N)	23
3	AMOC strength, ²³¹ Pa/ ²³⁰ Th ratio, ppt ⁴	14.65 to 14.45 ka BP, 22 ppt, 107 ppt kyr ⁻¹	16.0 to 14.65 ka BP, 1.5 ppt, 1.1 ppt kyr ⁻¹	98	1.09 (65°N)	89
4	N. Pacific hypoxia, Bulimina exilis, % ⁵	14.9 to 14.7 ka BP, 43%, 216% kyr ⁻¹	16.0 to 14.9 ka BP, 3.7%, 3.4% kyr ⁻¹	64	1.06 (55°N)	58
5	Sea level, Barbados, m ⁶	14.4 to 13.6 ka BP, 23 m, 29 m kyr ⁻¹	18.2 to 14.4 ka BP, 14 m, 3.7 m kyr ⁻¹	7.8	1.35 (65°N)	5.8
6	Tree cover, Iberian margin, % ⁷	15.0 to 14.5 ka BP, 27%, 54% kyr ⁻¹	17.0 to 15.0 ka BP, 11%, 5.3% kyr ⁻¹	10	1.1 (35°N)	9
7	Tree cover, Steel Lake, % ⁸	8.3 to 7.9 ka BP, -41%, -103% kyr ⁻¹	9.0 to 8.3 ka BP, -8.4%, -12% kyr ⁻¹	8.6	2.45 (45°N)	3.4
8	Drought index, Chew Bahir basin, Africa ⁹	7.9 to 7.7 ka BP, 1.11, 5.6 kyr ⁻¹	9.0 to 7.9 ka BP, 0.41, 0.37 kyr ⁻¹	15	1.32 (5°N)	11
9	Dust increase, ODP 658C, % ¹⁰	5.6 to 5.3 ka BP, 13.5%, 45% kyr ⁻¹	7.0 to 5.6 ka BP, 2.7%, 1.9% kyr ⁻¹	24	1.10 (25°N)	22
10	Drought index (PDSI), Angkor ¹¹	0.63 to 0.6 ka BP, -3.6, -120 kyr ⁻¹	0.7 to 0.63 ka BP, -0.87, -12.4 kyr ⁻¹	9.7	0.96 (15°N)	10

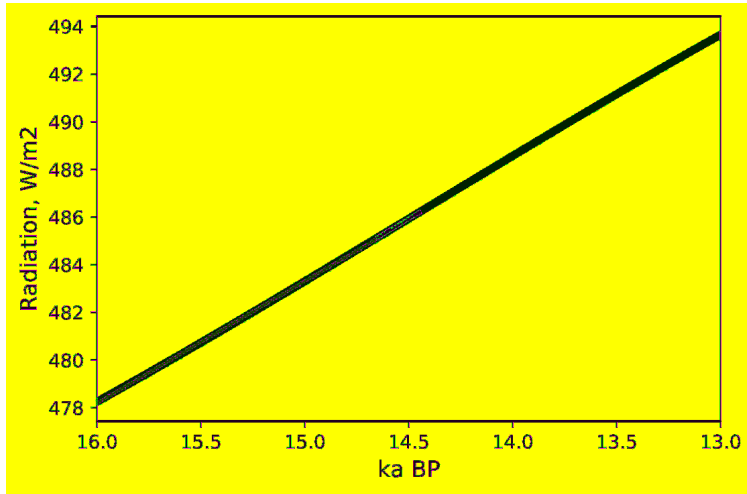
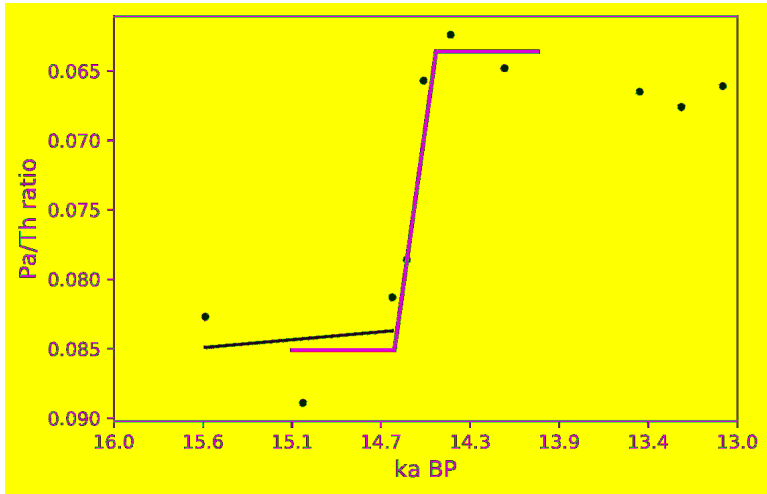
Figure A1. Graphical illustration of calculation of abruptness of changes in variables (left) and orbital forcing (right) for cases in Table A1. Red dots and lines are for variable and orbital forcing values, respectively. Blue line, trend in the reference period; black line – in the abrupt change period. For more details, see explanation of abruptness calculation above.



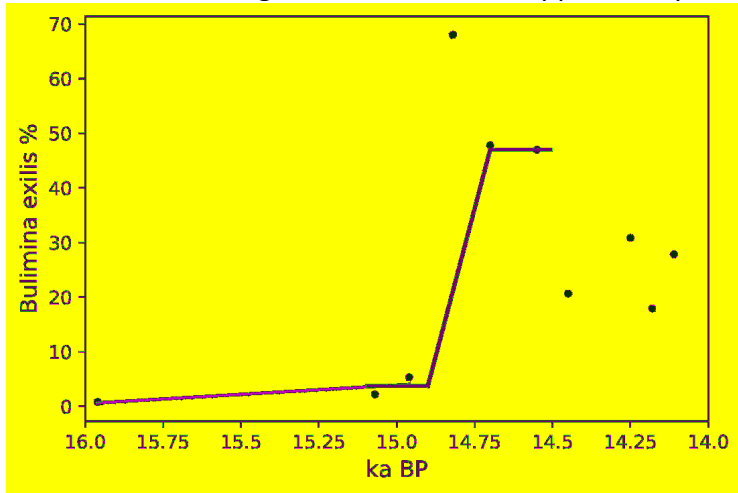
Case 1. Atmospheric CO₂ concentration, WAIS, ppm³. Abrupt series (left); orbital forcing (right).



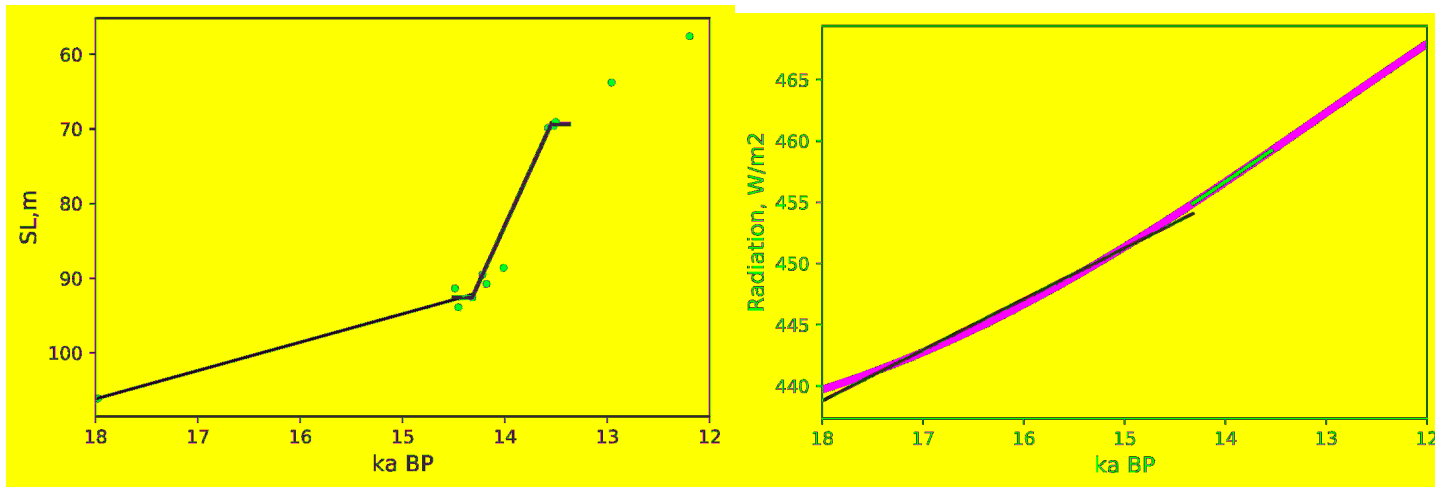
Case 2. Atmospheric CH₄ concentration, WAIS, ppb³. Abrupt series (left); orbital forcing (right)



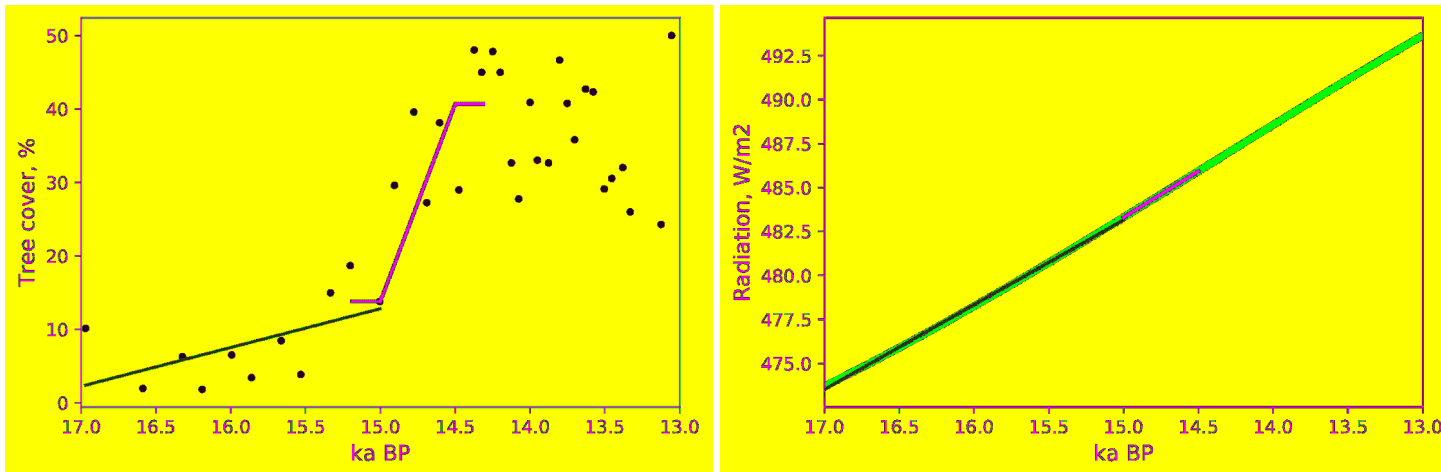
Case 3. AMOC strength, $^{231}\text{Pa}/^{230}\text{Th}$ ratio, ppt⁴. Abrupt series (left); orbital forcing (right)



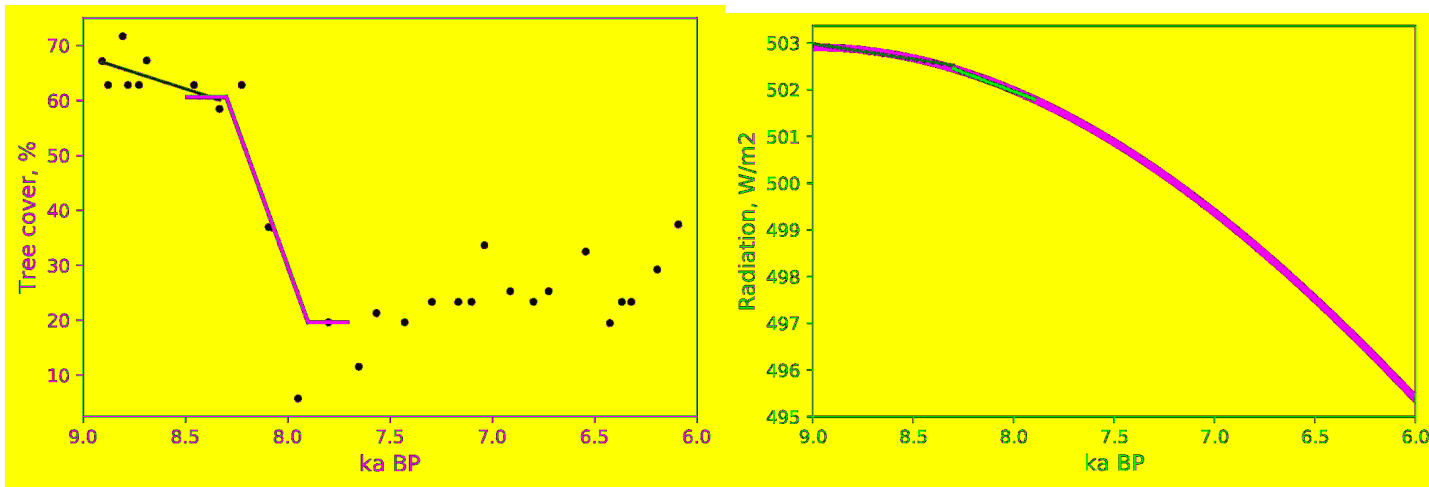
Case 4. N. Pacific hypoxia, *Bulimina exilis*, %⁵. Abrupt series (left); orbital forcing (right)



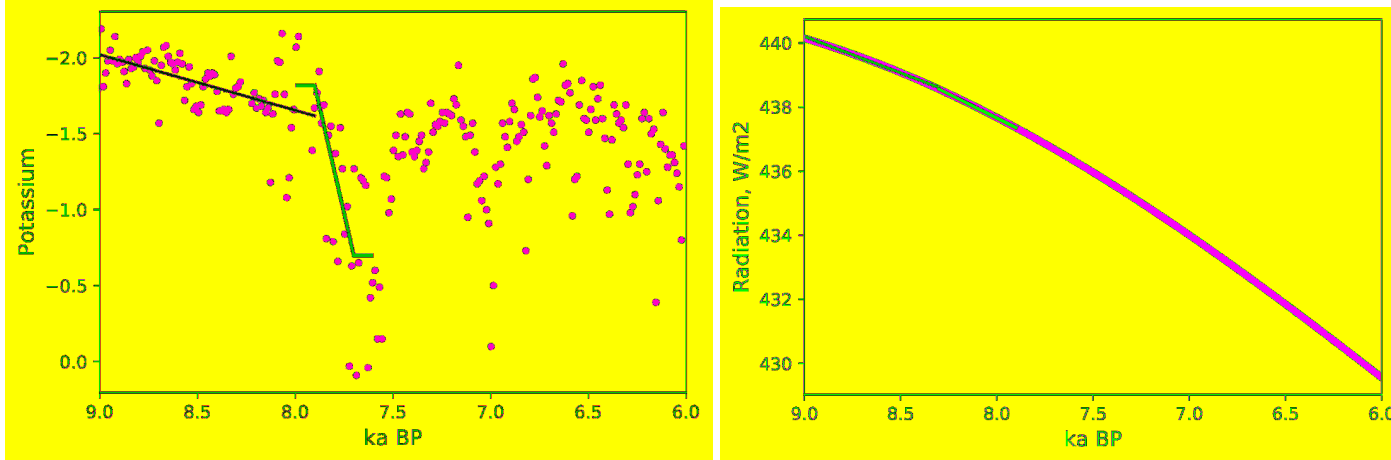
Case 5. Sea level, Barbados, m⁶. Abrupt series (left); orbital forcing (right)



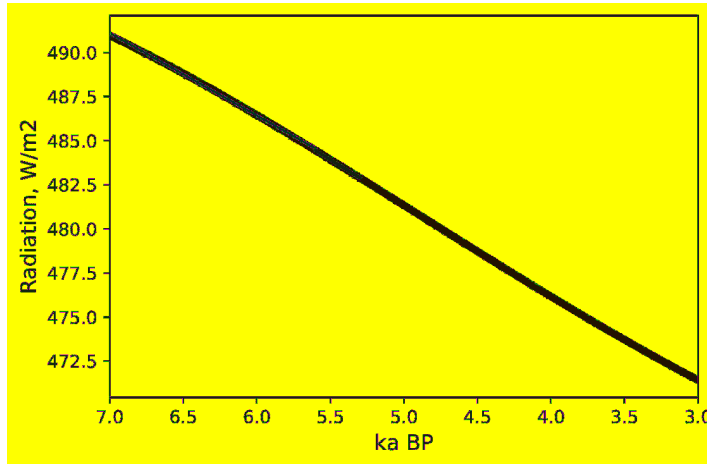
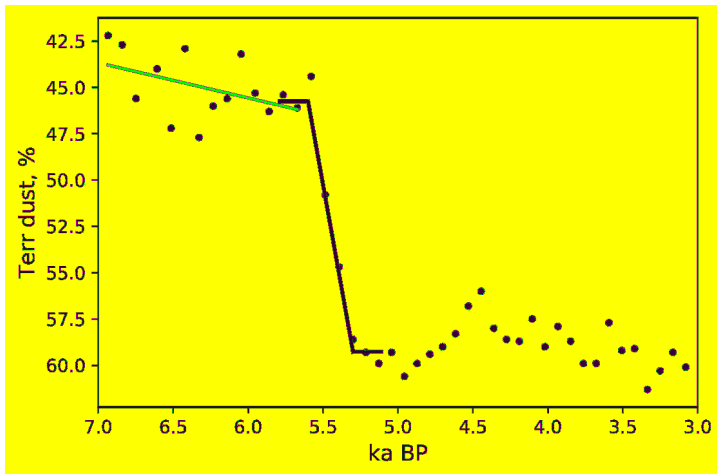
Case 6. Tree cover, Iberian margin, %⁷. Abrupt series (left); orbital forcing (right)



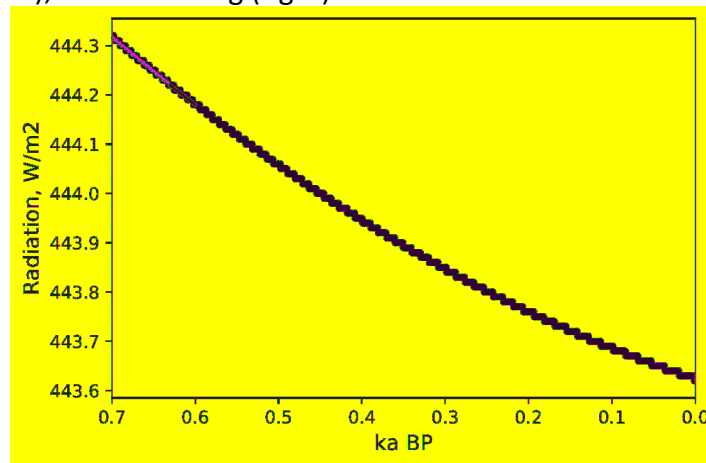
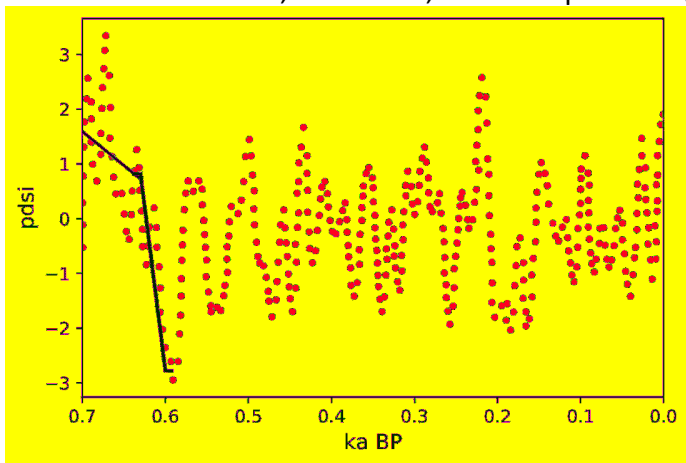
Case 7. Tree cover, Steel Lake, %⁸. Abrupt series (left); orbital forcing (right)



Case 8. Drought index, Chew Bahir basin, Africa⁹. Abrupt series (left); orbital forcing (right)



Case 9. Dust increase, ODP 658C, %¹⁰. Abrupt series (left); orbital forcing (right)



Case 10. Drought index (PDSI), Angkor¹¹. Abrupt series (left); orbital forcing (right)

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