



# Testing the Tropical Trigger Hypothesis of Abrupt Climate Variability

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Dansgaard-Oeschger oscillations (DOs) are abrupt shifts in climate, which are dramatic temperature fluctuations observed in Greenland and recorded globally. These abrupt changes are associated with the slowing and shutting down of the Atlantic Meridional Overturning Circulation (AMOC), but despite their importance the driving forces of DOs are not fully understood. Here we assess the role of the AMOC during DOs, the Northern vs Southern Hemisphere control on AMOC, and the possibility of neotropical moisture as a driver for abrupt climate variability. During DOs, South America has recorded a disparity between the degree of warming, and the change in precipitation at different sites. Based on our current understanding, we propose likely oceanic and continental changes in tropical South America that can help disentangle the triggers of these events. With the margins of error associated with dating sources of palaeo-data, the need for an independent chronology with multiple proxies recorded in the same record, could offer the information needed to understand the driving forces of DOs.

**Keywords:** Dansgaard-Oeschger, chronology, tropical trigger, South America, vegetation, marine records

## INTRODUCTION

Global climate change in the 21st century is the largest challenge humanity has faced (IPCC, 2014) and is already resulting in extreme weather, reduced food security, and threats to biodiversity (Ripple et al., 2017). In spite of this urgency, our ability to make reliable predictions for the future is still hampered by our limited understanding of the climate system. We need accurate knowledge on natural climate variability to comprehend how human activities impact climate. We are yet to understand the natural triggers of rapid climate variability and how regional abrupt climate shifts can modify the global climate (Hodell and Channell, 2016; Sánchez Goñi et al., 2018).

Abrupt climate fluctuations have interrupted the baseline climate conditions of the Quaternary and are termed Dansgaard-Oeschger oscillations (DOs). These abrupt events are global, being recorded in diverse locations across both hemispheres, from Greenland and the North Atlantic to South America and Antarctica (Blunier and Brook, 2001; Corregge et al., 2004; Harrison and Sanchez Goñi, 2010; Wolff et al., 2010; Zhang et al., 2015; Markle et al., 2017). DOs may induce glacial-interglacial transitions (Berger, 1992; Marino et al., 2015) and are linked to large fluctuations in global CO<sub>2</sub> (Staufer et al., 1998) and CH<sub>4</sub> (Wolff et al., 2010). Abrupt climate events are also of critical interest because their magnitude and speed (Wolff et al., 2010; Orsi et al., 2014) correspond to climate projections under anthropogenic forcing (IPCC, 2014). Understanding DOs is therefore essential to constrain climate sensitivity (Rohling et al., 2012), improve our ability to predict future

climate change (von Deimling et al., 2006; Collins et al., 2013), and to understand how climate perturbations in one region may affect climate in other parts of the world.

In this article we assess the potential of two main hypotheses for driving DOs: the changes to ocean circulation from the North Atlantic and the tropical moisture source from the equatorial Atlantic. South America has largely been understudied in research into DOs, resulting in a lack of data for the tropical moisture hypothesis. By looking at the modern South American climate, it is possible to explore how these climatic controls influence abrupt climate variability. Then we assess the critical knowledge gaps in our understanding of abrupt climate variability, and how the tropical trigger hypothesis could be tested using marine sediments from the tropical Atlantic.

## ABRUPT CLIMATE VARIABILITY

Dansgaard-Oeschger oscillations consist of rapid warming events followed by gradual cooling (**Figure 1A**) and occur during glacial and deglacial periods. In the Greenland ice core record, DOs are recorded as dramatic shifts of Northern Hemisphere temperatures (Wolff et al., 2010; **Figure 1A**). During the warming events, Greenland temperatures can increase by 7 to 16°C in a few decades (Wolff et al., 2010) and are linked to major changes in ocean circulation and the configuration of tropical rain belts and monsoon systems (Broccoli et al., 2006; Clement and Peterson, 2008; Cruz et al., 2009; Gottschalk et al., 2015). DOs have a global impact, but the magnitude and direction of change can be regionally variable (Sánchez Goñi and Harrison, 2010; Wolff et al., 2010). For example, more humid conditions are observed in the Mediterranean (Budsky et al., 2019), precipitation changes occur in South America (Zhang Y. et al., 2017) and East Africa (Brown et al., 2007), the monsoonal system intensifies in Asia (Li et al., 2017; Dong et al., 2018; Liang et al., 2019) and shifts in northwest Africa (Itambi et al., 2009), drying occurs in northern Australia (Muller et al., 2008) and Indonesia (Griffiths et al., 2013), and while other records suggest very little or no climatic fluctuations occurred during DOs (Mulitza et al., 2007; Hessler et al., 2010).

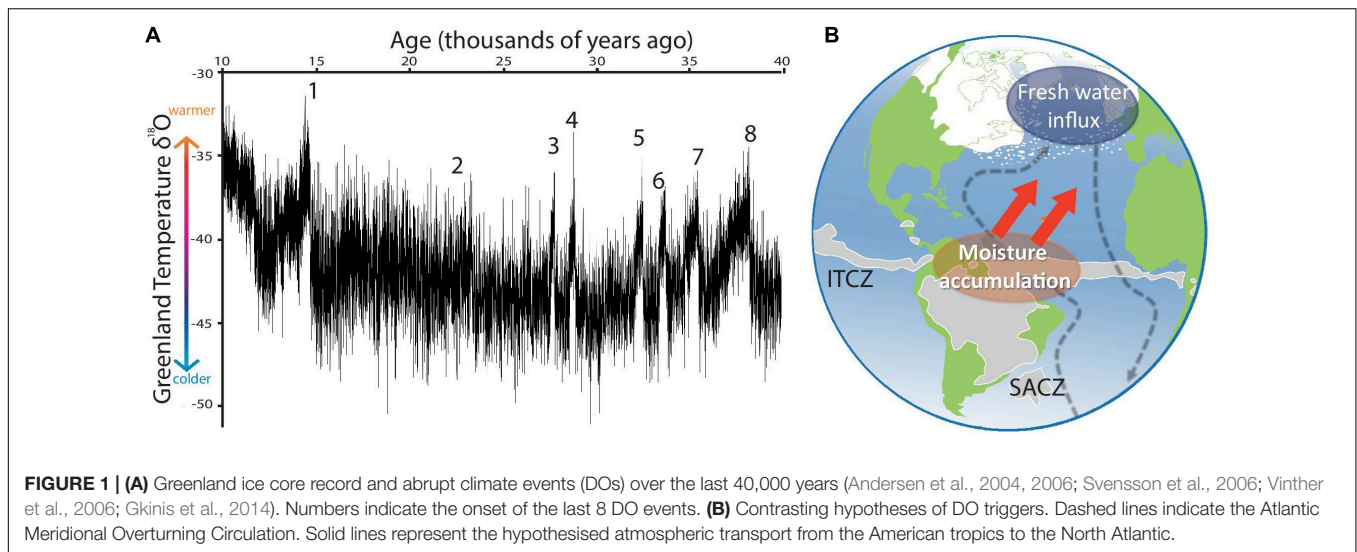
## TRIGGER HYPOTHESES OF ABRUPT CLIMATE EVENTS

The origin and distribution mechanisms of abrupt climate variability remains enigmatic despite their global importance. One hypothesis is that these events are triggered in high latitudes by interruptions to oceanic circulation. An influx of freshwater into the North Atlantic causes changes in the Atlantic Meridional Overturning Circulation (AMOC), which then distributes the climate perturbations to the rest of the planet (**Figure 1B**; Ganopolski and Rahmstorf, 2001; Clark et al., 2002; Kageyama et al., 2010). The AMOC is part of the temperature and salinity driven thermohaline circulation (Broecker, 1991). As warm surface waters migrate northwards, heat is released into the atmosphere, warming more northerly latitudes.

When freshwater, in the form of sea ice from ocean-cryosphere interactions, is injected into the North Atlantic, the density of the surface water is reduced, slowing downwelling, and slowing or shutting down the AMOC. With the AMOC slowed, global heat dispersal is reduced, and cooling at higher latitudes occurs (Heinrich, 1988; Bassis et al., 2017; Vettoretti and Peltier, 2018). An increase in freshwater release in the North Atlantic leading to a decrease in North Atlantic deep water formation is also captured by models (Ganopolski and Rahmstorf, 2001; Vettoretti and Peltier, 2018). The growth and collapse of an ice shelf could result in sea ice expansion, disturbing the AMOC and driving in the interstadial/stadial phases of the DOs cycles (Li et al., 2010; Li and Born, 2019; Petersen et al., 2013). Alternative drivers of AMOC instability have also been suggested. Ice surges from the Fennoscandian ice sheet may be a likely freshwater source (Dokken et al., 2013) during some DO cycles, while sea ice from Laurentide ice sheet may dominate others (Sánchez Goñi et al., 2020). Changes in the Southern Hemisphere have also been suggested to drive AMOC stability (Jaeschke et al., 2007; Buizert and Schmittner, 2015; Dima et al., 2018). Empirical data from obtained off the northeast Brazil coast coupled with model experiments also suggest that warming in the Southern Ocean and links with the South Atlantic western boundary current subsequently led to an abrupt restart of the AMOC during deglaciation (Jaeschke et al., 2007). The Southern Ocean can influence the AMOC by changes in the Antarctic Bottom Water formation, Atlantic density and pressure gradients, warm buoyant water entering the Southern Ocean and upwelling in the Southern Ocean (Buizert and Schmittner, 2015). Changes in these factors can lead to slowing down of the AMOC.

An alternative driver for DOs is a deep-decoupling oscillation within the North Atlantic (Schulz et al., 2002). Linked to surface water freshening, deep water formation fails to form and enters a deep-decoupled phase, with a reduced AMOC and less heat transfer. Import of heat and salt by advection and diffusion weakens and breaks down the halocline. This leads to convection and triggers a deep-coupled phase in the North Atlantic, resulting in deep water formation, and a strong AMOC and greater heat transfer (Schulz et al., 2002).

While shutting down of the AMOC is most accepted as the trigger of abrupt climate variability, discrepancies between model and proxy data suggest that our understanding of these events is still incomplete (Mecking et al., 2017; Goes et al., 2019; Gu et al., 2020). Some studies have shown disparate responses to different DOs, for example the Santos Basin shows DO signals during Marine Isotope Stage (MIS) 5 but absent or dampened millennial scale climate variability during MIS 3 (Santos et al., 2020). Modelling work also suggests that shutting down of AMOC and tropical SST changes and moisture accumulation are teleconnected (Lohmann, 2017; Zhang X. et al., 2017). In fact, some model simulations show that tropical climate perturbations could indeed precede, and potentially trigger, changes in the North Atlantic (Rodgers et al., 2003). Further understanding of these ocean-atmosphere teleconnections through combinations of empirical data and models could help in gaining a greater understanding of AMOC responses and the triggers of abrupt climate variability.



The propagation of abrupt climate events is another topic yet to be fully understood. Freshwater input into the North Atlantic can disturb the AMOC and produce climate shifts from cold to warm (Lippold et al., 2012) that then spread over the entire planet. However, it can take about 200 years for the oceans to redistribute heat from one hemisphere to the other (WAIS Divide Project Members, 2015), while the atmosphere (Markle et al., 2017) could allow for a quick transfer to distant parts of the world. This suggests that the AMOC might play a lesser role in transmitting DOs and that these events might originate outside the North Atlantic. Moreover, MIS 19 (800,000 years ago) is a period marked by abrupt climate shifts in the North Atlantic region, but these early shifts are not linked to AMOC perturbations (Sanchez Goñi et al., 2016). Instead, they may be explained by increased moisture transport from the tropical Atlantic to high latitudes (Sanchez Goñi et al., 2016), suggesting a low-latitude trigger. Remarkably, a tropical trigger for abrupt climate variability has hardly been explored (Arz et al., 1998; Cane and Clement, 1999; Clement and Peterson, 2008).

The low latitudes could trigger abrupt climate events because the tropics receive maximum solar irradiation and can become hotspots of heat accumulation due to orbital fluctuations (Berger et al., 2006). Precession and eccentricity are the primary orbital parameters modulating insolation or the amount of solar energy reaching the top of the atmosphere at the low latitudes (Laskar, 1990; Ruddiman, 2006). Phase coupling between precession, semiprecession and eccentricity, which originates in the tropics, have been essential in maintaining the ice sheet oscillations for the past 1.5 million years (Hagelberg et al., 1994; Rutherford and D'Hondt, 2000). Insolation changes linked to eccentricity and the precession harmonics can cause a decrease in the seasonal variations of equatorial insolation (McIntyre and Molino, 1996; Berger et al., 2006). This may induce heat accumulation in the tropical regions and result in potential moisture build-up. Previous work has linked insolation and moisture availability in western Amazonia (Urrego et al., 2010), however, the paucity of other regional records has hindered the identification of

a moisture source. A solar cycle combined with two much shorter freshwater cycles, has been modelled to produce the response observed in DOs (Braun et al., 2005). Coupled atmospheric-ocean models have shown that gradual increases in tropical CO<sub>2</sub> can trigger abrupt warming and cooling events (Zhang X. et al., 2017), also supporting a tropical origin for these abrupt events.

Extra warmth in the tropics relative to the high latitudes may also enhance the latitudinal thermal gradient, strengthening, and shifting the westerlies northwards (Sanchez Goñi et al., 2016; Markle et al., 2017). Abrupt climate events have also been linked to the strength and latitudinal reach of tropical winds and the direct advection of low-latitude surface water heat to the North Atlantic (McIntyre and Molino, 1996; Venancio et al., 2018). Reduced insolation seasonality and increased heat accumulation in the American tropics could therefore trigger abrupt climate events through (i) moisture accumulation from an enlarged land-sea thermal contrast, and (ii) increased moisture transport toward the North Atlantic from an amplified latitudinal thermal gradient and northward penetration of latent heat (**Figure 1B**).

An alternative scenario where abrupt climate changes are triggered by heat and moisture build-up in the understudied tropical regions and where both the ocean and atmosphere propagate these climate disruptions to the high latitudes is therefore likely (Arz et al., 1998; Cane and Clement, 1999; Jennerjahn et al., 2004; Berger et al., 2006; Clement and Peterson, 2008; **Figure 1B**). In fact, freshwater input in the North Atlantic is linked to iceberg discharges and ice growth (Ruddiman, 2006), but ice sheets necessitate moisture to grow. Moisture increases are recorded in Greenland preceding ice sheet growth (Steffensen et al., 2008; Sánchez Goñi et al., 2018), with suggestions that this is sourced from the North Atlantic (Nusbaumer et al., 2019). The tropical regions could be an alternative source for that moisture. The western tropical Atlantic is an important hot water reservoir of the global ocean conveyor (Wang and Enfield, 2001); and maximum solar irradiance linked to insolation cyclicity (Berger et al., 2006; Sánchez Goñi et al., 2018) make

the American tropics a likely location for moisture build-up. Indeed, cooling in the high latitudes is suggested to be reinforced by tropical Atlantic warming and redistribution of heat in the surface of the oceans during the Cenozoic (Tremblin et al., 2016). Model studies have shown that SST changes in the tropical oceans can be linked to temperature changes in the Northern Hemisphere via atmospheric teleconnections (Rodgers et al., 2003; Lohmann, 2017; Zhang X. et al., 2017). Increases in tropical SST results in warming of Canada during the Boreal Summer and melting of the Laurentide Ice Sheet (Rodgers et al., 2003). Orbitally-driven heat accumulation and moisture build up in the tropics may therefore cause rapid global redistributions of warm waters and moisture, potentially triggering these rapid and large climate shifts.

One key area of research which could help understand whether tropical moisture injection or changes in ocean circulation can drive abrupt climate change, is to look at the timing of events. In the tropical moisture hypothesis, ice sheet formation would occur and, as the ice sheet grew, cooling would follow. Alternatively, if changes in ocean circulation are the driving forces, cooling would precede ice sheet growth. In support of the tropical moisture hypothesis, dust studies in the Greenland ice core suggest that changes to the low latitude atmospheric circulation precede the Greenland temperature change (Steffensen et al., 2008).

The Paleoclimate Modelling Intercomparison Project (PMIP) has explored various possible drivers for DOs. Some results suggest North Atlantic sea ice anomalies are important for creating the climate signal associated with DOs (Knorr et al., 2009; Li et al., 2010; Li and Born, 2019). Other results suggest North Atlantic sea ice brine rejection is a driving force on the stability of AMOC and DOs (Wang and Mysak, 2006). However, ocean temperatures likely influence the sea ice dynamics, and thus are the driving forces of DOs (Alvarez-Solas et al., 2010; Barker et al., 2015). Gradual oceanic cooling results in a non-linear climatic response, with sea ice acting as a positive feedback mechanism (Barker et al., 2015). Alternatively, the North Pacific has been suggested as a driver for ice sheet growth during DOs (Kiefer et al., 2002). Warm SST in the North Pacific provide moisture to East Greenland, replenishing ice sheets associated with DOs (Kiefer et al., 2002).

A tropical source for DOs has also been modelled by PMIP. Warming of tropical SST from boundary glacial conditions could result in changes to extratropical moisture and temperature. These changes in temperature and precipitation could result in the melting of ice sheets (Rodgers et al., 2003). The suggestion of a tropical methane source for driving DOs is unsupported by PMIP modelling. Simulations with two wetland models of different complexity show that tropical methane from wetlands alone is not enough to drive DOs, and that either missing wetland processes in the models are required, other methane sources are needed, or an alternative mechanism unrelated to methane release is required to explain DOs (Ringeval et al., 2013).

There is some uncertainty on whether current models can effectively represent the pathways driving DOs, as there is currently no PMIP common guidance for investigating DOs (Sime et al., 2021). Further developments into models for DOs

and similar climatic events would provide further insights into this climate variability. Overall, we are yet to fully understand to what extent ocean-atmosphere interactions in the tropics can induce global climate shifts and whether they precede a fresh water influx in the North Atlantic.

## OCEAN-ATMOSPHERE INTERACTIONS IN TROPICAL SOUTH AMERICA

Understanding the current and past configuration of atmospheric and oceanic interactions in tropical South America is crucial to assess a tropical trigger for DOs. Several atmospheric mechanisms dominate and could influence moisture build up in this region. The Intertropical Convergence Zone (ITCZ) is a belt of warm, moist air that sits on the thermal equator, shifting seasonally to the warmer hemisphere (Nobre et al., 2012; Schneider et al., 2014). Similarly, the South Atlantic Convergence Zone (SACZ) is a precipitation band located over eastern Brazil and the South Atlantic which shifts with changes in sea surface temperature (SST; Chaves and Nobre, 2004; Cruz et al., 2005; Jorgetti et al., 2014). Warm South Atlantic SST cause the SACZ to intensify and migrate to a more northerly position (Chaves and Nobre, 2004; De Almeida et al., 2007). However, SACZ is further influenced by interactions between solar radiation (Nobre et al., 2012) and intraseasonal anomalies in outgoing longwave radiation within the American tropics (Carvalho et al., 2004). The SACZ can result in a negative feedback response, as increased cloud cover dampens the initial SST warming by decreasing incoming solar radiation (Venancio et al., 2020). The South American Monsoon System (SAMS) controls where precipitation occurs on the South American continent, influenced largely by the ITCZ and the SACZ but also influenced by Atlantic SST (Mechoso et al., 1990; Garreaud et al., 2009), trade winds (Garreaud et al., 2009), and Amazonian evapotranspiration (Trenberth, 1999). These ocean-atmosphere systems have been suggested to shift during the Quaternary due to interhemispheric temperature fluctuations (Peterson et al., 1991; Broccoli et al., 2006; Correa-Metrio et al., 2012; McGee et al., 2014). As atmospheric mechanisms respond to abrupt climate shifts in the Northern Hemisphere and oceans, the location of tropical precipitation bands would rearrange. If cooling occurs in the Northern Hemisphere, the ITCZ would move southward, and areas in the north of the current ITCZ location will receive less precipitation while areas to the south would receive more (Behling et al., 2000). Additionally, during Northern Hemisphere cold periods, the South Atlantic would warm and SACZ intensify (Strikis et al., 2015). The intensified SACZ and more southerly ITCZ results in the intensification of the SAMS (Strikis et al., 2015).

If tropical moisture accumulation was a trigger for abrupt warming and cooling events in the Northern Hemisphere, changes in precipitation patterns could result in negative feedback loops. Warming would intensify the SACZ and the more northerly position of the ITCZ would result in increased moisture accumulation in the tropical Atlantic. This in turn

could result in more moisture being transported northward to the colder Northern Hemisphere where ice sheets would grow due to increased precipitation. Northern Hemisphere cooling would then occur, followed by changes to the AMOC. As the interhemispheric temperature differences increased, the ITCZ would then move southward again, resulting in less precipitation in the equatorial Atlantic. This reduction of moisture accumulation would result in less moisture reaching the ice sheets, halting ice growth.

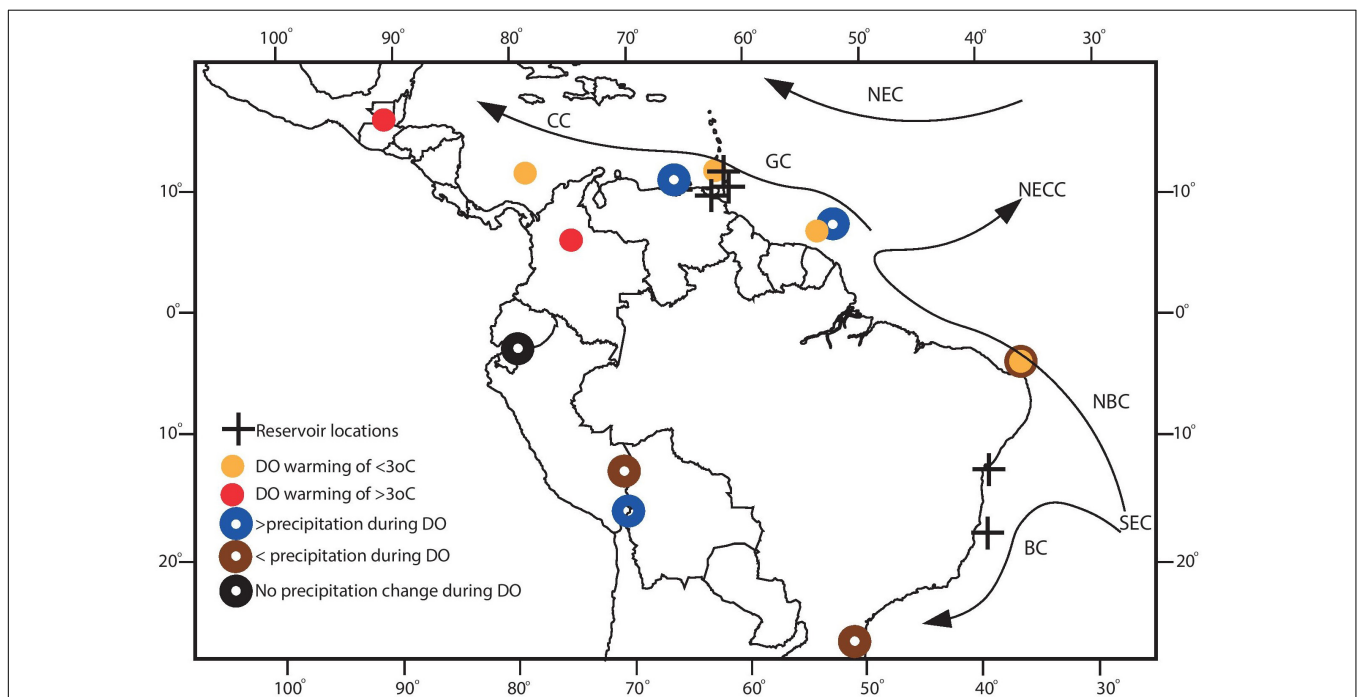
## AN UNCLEAR PICTURE OF ABRUPT CLIMATE VARIABILITY IN THE AMERICAN TROPICS

Existing empirical data (Figure 2) show a range of environmental fluctuations in the American tropics during DOs, but integrating these into a consistent regional interpretation of abrupt climate variability remains notoriously difficult (Urrego et al., 2014). For moisture availability, studies have shown that some DOs are associated with decreased precipitation in western Amazonia (Urrego et al., 2010), while increased humidity is recorded in the Bolivian Altiplano (Baker et al., 2001; Paduano et al., 2003), and in offshore French Guyana (Zhang Y. et al., 2017). Speleothem records suggest a weakened South American monsoon and reduced precipitation during some DOs in subtropical Brazil (Cruz et al., 2005), but record no change during others in lowland Ecuador (Mosblech et al., 2012). DOs are also linked

to increased precipitation and continental run-off in the Cariaco Basin (Peterson and Haug, 2006), and with decreased run-off in NE Brazil (Arz et al., 1998).

The migration of Andean vegetation during DOs has been shown to translate into air temperature changes which are consistent with ice-core records from tropical glaciers and tropical Atlantic surface water temperatures (Urrego et al., 2016), but the magnitude of temperature change in the atmosphere differs from that of the tropical Atlantic. Air temperature change from pollen records in the Central American lowlands (Correa-Metrio et al., 2012) and the Colombian Andes (Bogota-a et al., 2011; Groot et al., 2011) indicates warming between 3 and 13°C during DOs (Figure 2). Contrastingly, the magnitude of tropical Atlantic surface water warming remains minor compared to temperature change estimates over land, with a SST rise of 1°C recorded in the Tobago Basin (Rühlemann et al., 1999), 2°C in the Colombian Basin (Schmidt et al., 2004), and 2.6°C in the Guyana Basin (Rama-Corredor et al., 2015).

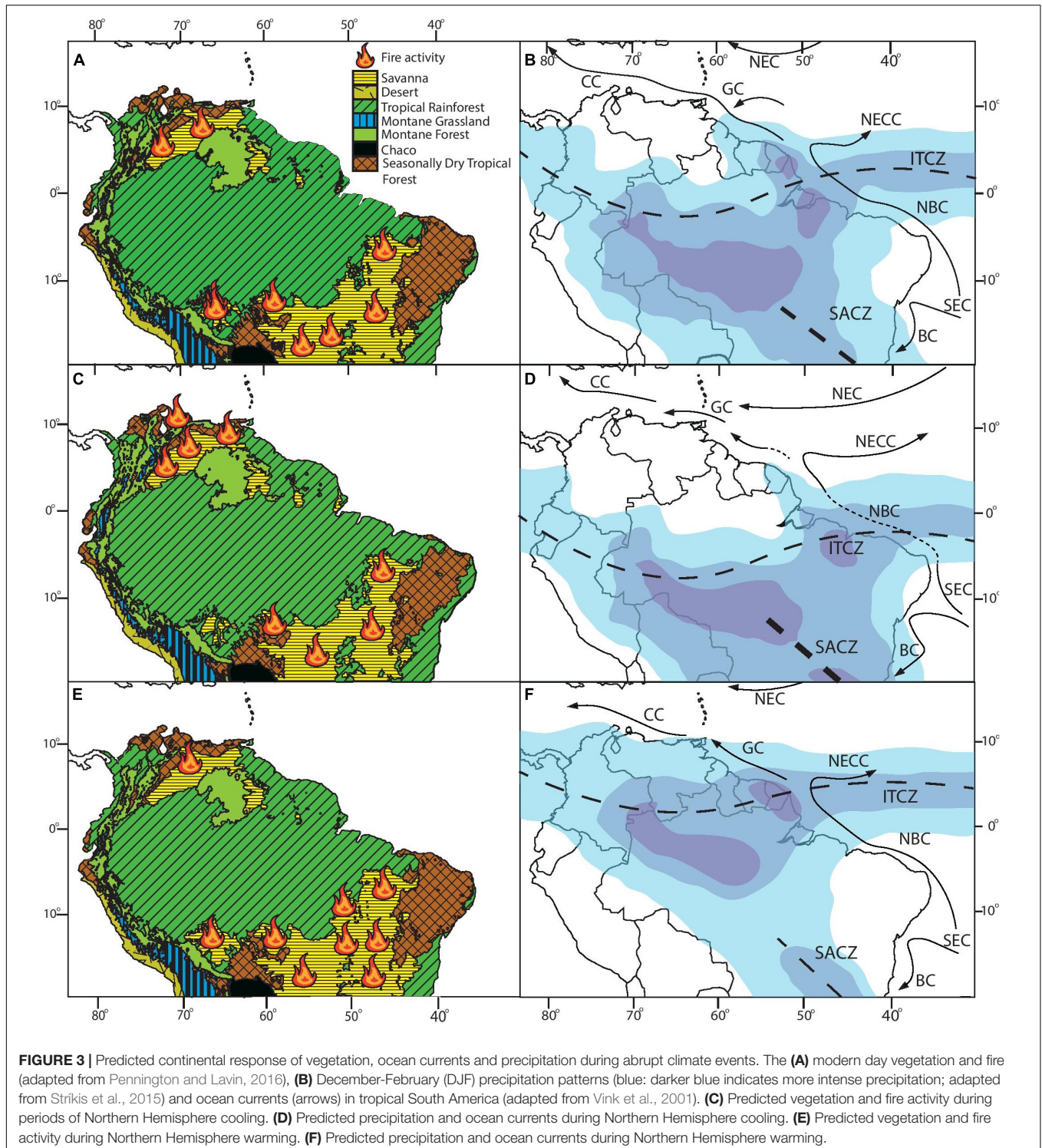
Overall, available palaeoclimate estimates for the American tropics are scarce (Hessler et al., 2010) but suggest significant land-sea temperature contrasts and atmospheric reorganisations that could result in moisture build-up. However, atmospheric reconstructions from speleothems and lakes are not directly comparable to oceanic changes measured in marine sediments because each relies on a different chronology with varying age uncertainties. This hinders simultaneous comparisons of air and sea temperatures to quantify land-sea thermal contrasts and identify moisture build-ups.



**FIGURE 2 |** Warming and precipitation changes in South America during DOs showing the continental masses warming considerably more than the oceans. The location of ages used for regional reservoir corrections referred in Table 1. Precipitation shows contrasting responses across the continent. Modern currents have been added (CC, Caribbean Current; GC, Guyana Current; NEC, North Equatorial Current; NECC, North Equatorial Counter-current; NBC, North Brazil Current; and SEC, South Equatorial Current).

Ocean circulation also shifts during abrupt climate events. During periods of Northern Hemisphere cooling, the North Brazil Current will weaken during the initial cooling, continuously weakening as the ITCZ migrates southward (Arz et al., 1999; Bahr et al., 2018). Synchronously, the North Equatorial Countercurrent will intensify with southward

migrations of the ITCZ (Wilson et al., 2011). These changes in the North Brazil Current and the North Equatorial Countercurrent, alongside the southward displacement of the ITCZ, result in the southward migration of the North Equatorial Current (Vink et al., 2001). An intensified North Equatorial Countercurrent will also decrease Guyana Current flow (Richardson et al., 1994).



## PREDICTED RESPONSE TO ABRUPT CLIMATE CHANGE IN TROPICAL SOUTH AMERICA

We summarise here the expected changes in vegetation, fire regimes, ocean currents and atmospheric systems in tropical South America during abrupt climate events (**Figure 3**). During periods of Northern Hemisphere cooling, a southward position of the ITCZ and intensified SACZ would result in decreased precipitation within northernmost South America (**Figure 3D**). This would result in the expansion of dry forests and savannas, and increased precipitation in Brazil and Bolivia. Due to the cooling experienced in northernmost South America, montane forests would migrate downslope. Predicted fire activity will reflect changes in precipitation and vegetation. Due to the change in fuel and precipitation intensity, fire activity would increase in northern South America, and decrease in Brazil and Bolivia (**Figure 3C**). Within the oceans, the North Brazil Current will weaken and the North Equatorial Countercurrent will intensify. The decreased water supply from the North Brazil Current to the Guyana Current will be replaced by the North Equatorial Current, which is displaced southward (**Figure 3D**).

In contrast, during Northern Hemisphere warming, a more northward ITCZ and weakened SACZ would result in increased precipitation in northern South America (**Figure 3F**). This would result in the contraction of dry forests and savannas, and decreased precipitation in Brazil and Bolivia. Due to the warming experienced in northernmost South America, Andean forests will migrate upslope. Fire activity will decrease in northern South America due to changes in precipitation and fuel, and increase in the savannas of Brazil (**Figure 3E**). In the oceans, the North Brazil Current will intensify during Northern hemisphere warming, while the North Equatorial Countercurrent will weaken (**Figure 3F**).

## CHRONOLOGICAL EFFECTS

A consistent identification of DOs outside the North Atlantic is still hampered by low-resolution chronologies, a lack of

well-fingerprinted tephra for instantaneous dating, and poorly-constrained reservoir effects in marine records. The most updated regional reservoir corrections (Heaton et al., 2020) or  $\Delta R$  (Stuiver and Braziunas, 1993; Reimer and Reimer, 2017) still rely on limited data points in the American tropics, including updated locations in the Caribbean (DiNapoli et al., 2021), and the west Atlantic off the Brazilian Coast (Alves et al., 2015; Oliveira et al., 2019). The weighted mean of regional differences in marine reservoir error can vary from  $-229$  years using Caribbean ages to  $-128$  years using ages off the Brazilian coast, while the uncertainty varies from 165 to 111 (**Table 1**). Even though these regional differences fall well within global ranges of  $-500$  and  $500$   $\Delta R$  (Stuiver et al., 2021), they highlight regional variations in reservoir effects that can introduce further uncertainty to the chronology of short climate events such as DOs. Inconsistent chronologies between vegetation, speleothem, ice and marine records also hinder comparisons between records in the American tropics (Urrego et al., 2016; Adolphi et al., 2018). Recent studies on South American Uranium-Thorium (U/Th) dated speleothem records compared to the Greenland ice core record showed that South American abrupt events occur within the uncertainties of the Greenland core, though for some events dated shifts in speleothem records are at the limit of Greenland layer counting uncertainties (Adolphi et al., 2018). In the North Atlantic, unlike the American tropics, the chronology of DOs are well defined by layer counting in Greenland ice cores (Wolff et al., 2010), dating of loess records from western Europe (Moine et al., 2017), and direct dating of ice-rafted debris layers (Sánchez Goñi and Harrison, 2010).

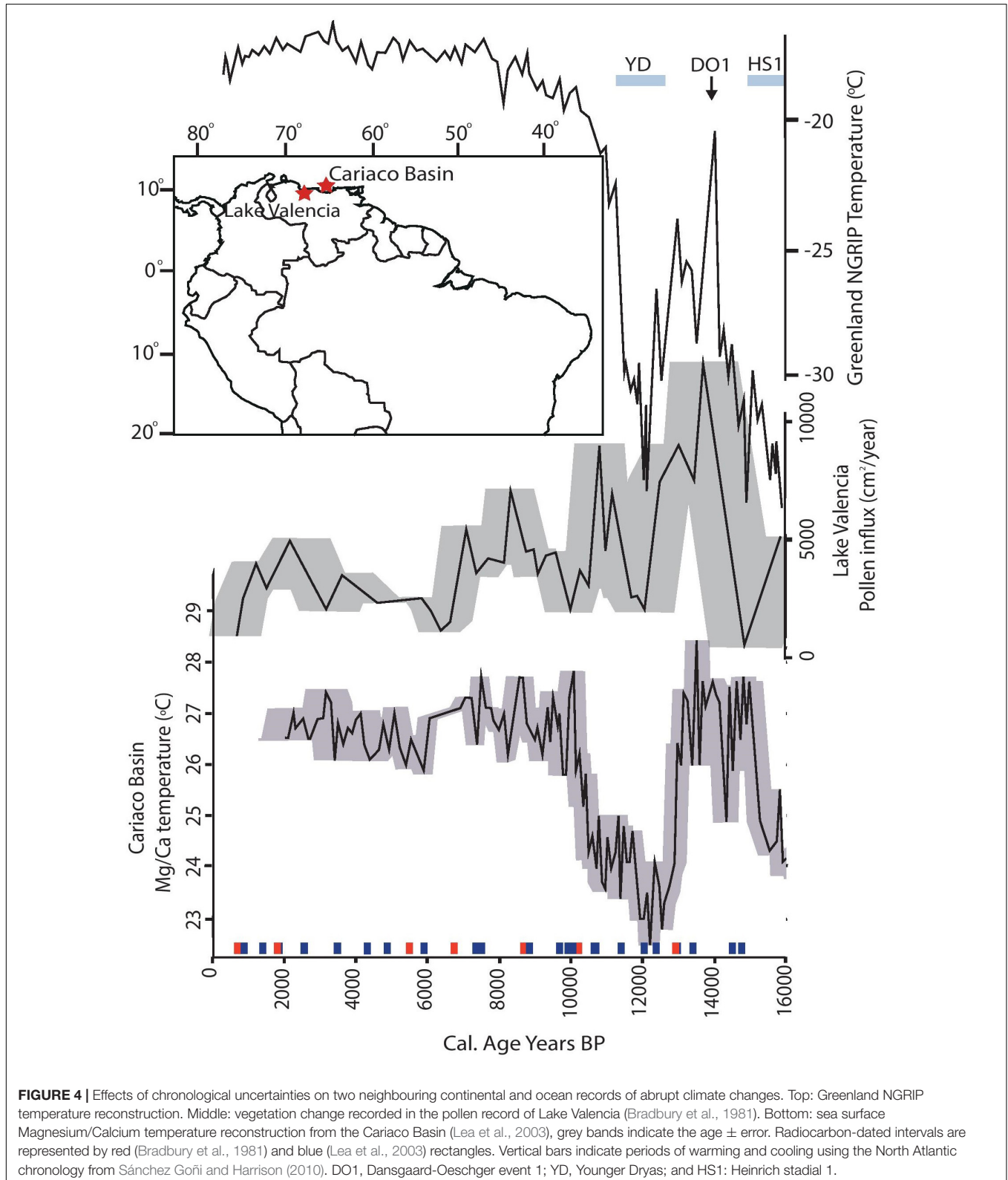
The absence of such stratigraphic layers challenges the definition of a DO chronology for the American tropics (Urrego et al., 2014), and as a result available records adopt different chronologies and are not comparable. DO timing is correlated to the chronostratigraphy of the North Atlantic (McManus et al., 2004; Chiessi et al., 2009), the Iberian Peninsula chronology (Bard et al., 2000; Martrat et al., 2007; Sánchez Goñi and Harrison, 2010; Mollier-Vogel et al., 2013), and the Greenland chronology (Martrat et al., 2007; Correa-Metrio et al., 2012; Mosblech et al., 2012). In speleothem records, DO timing is

**TABLE 1** | Regional reservoir ages and corrections from the Caribbean and western tropical Atlantic extracted from the Marine20 database (Stuiver et al., 2021).

Latitude	Longitude	Reservoir Age	$\Delta R$	$\Delta R$ error ( $\sigma$ )	Subregion	References	Weighted mean $\Delta R$	Uncertainty	Number of points
13.2143	-59.525	401	-43	22	Barbados	DiNapoli et al., 2021	-229	165	7
13.0787	-59.6122	308	-165	25	Barbados	DiNapoli et al., 2021			
11.2507	-60.6987	177	-303	31	Tobago	DiNapoli et al., 2021			
11.2507	-60.6987	-16	-496	26	Tobago	DiNapoli et al., 2021			
10.4934	-61.0438	321	-122	23	Trinidad	DiNapoli et al., 2021			
10.4934	-61.0438	167	-276	34	Trinidad	DiNapoli et al., 2021			
10.4455	-61.2584	75	-374	29	Trinidad	DiNapoli et al., 2021			
-12.867	-38.517	207	-236	62	SW Atlantic	Oliveira et al., 2019	-128	111	3
-12.8833	-38.6667	332	-76	26	Brazil Coast	Alves et al., 2015			
-17.95	-37.367	124	-319	62	SW Atlantic	Oliveira et al., 2019			
Using all subregional reservoir ages available in Marine20 database							-212	158	10

defined as abrupt shifts in the oxygen isotope record (Cruz et al., 2005), which often involves large uncertainties from U/Th dating. Differences in chronological approaches result in age differences

of up to 800 years for the timing of DOs and hinder any meaningful comparisons between records (Blaauw et al., 2010; Urrego et al., 2014).





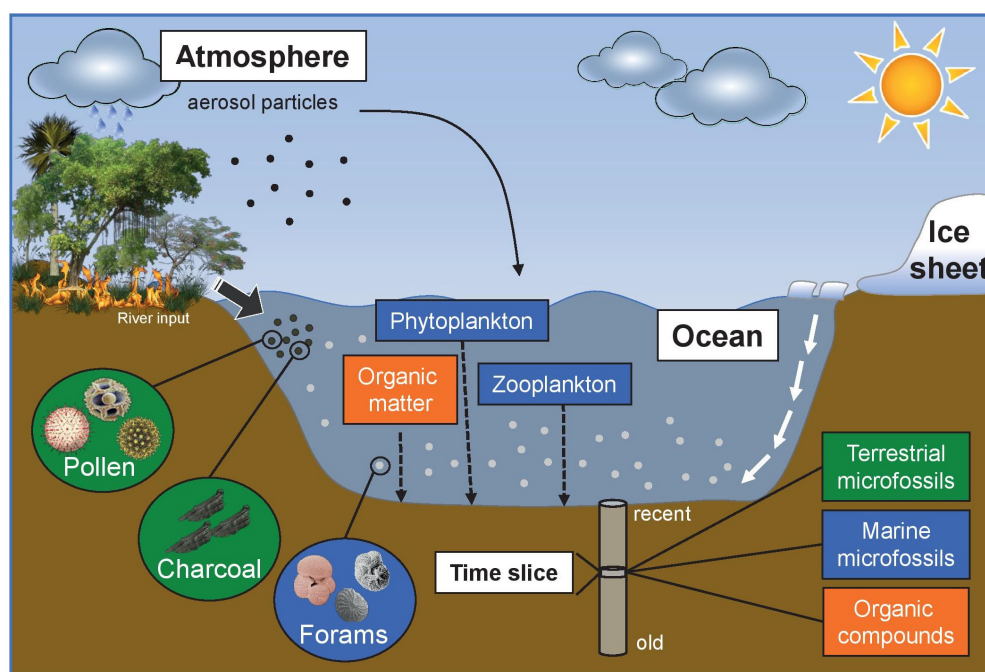
The chronology of tropical records is sometimes tuned to Northern Hemisphere records eliminating the opportunity for analyses of synchronicity and asynchronicity (Figure 4). For instance, the Cariaco Basin sediments (Peterson and Haug, 2006) provide a unique tropical counterpart to high-latitude ice core records for rapid climate variability, however, their chronology is tuned to that of Greenland. This assumption of synchronicity between North Atlantic and tropical records invalidates any analysis of leads and lags (Urrego et al., 2014) and does not allow for hypothesis testing of the origin of DOs. Furthermore, the timing of oceanic changes cannot be assumed to apply to atmospheric change if the aim is to disentangle the role of the oceans vs the atmosphere in propagating abrupt climate events. A chronology that is independent of Greenland and North Atlantic records is therefore crucial to identify the trigger of abrupt climate events.

A comparison between the Cariaco Basin and Lake Valencia records illustrates how different chronologies hinder the reconstruction of DOs signals in the American tropics (Figure 4). The Cariaco Basin provides a reconstruction of SST in the tropical Atlantic (Lea et al., 2003), while the pollen concentration from Lake Valencia (Bradbury et al., 1981) shows productivity on the vegetation linked to continental warming. The chronologies are derived from radiocarbon dating the two cores independently. The combined age uncertainty of the two records can lead to differences in interpretations of the DO signal. In the above example, the rise in pollen ~14,000 years BP could be linked to a warming (BA), stable, or cooling climate, depending where you base data points within the margin of error. If using the

median point for both, the rise in pollen concentration occurred with a 2°C rise in SST. If using the minimum point for both datasets, the increase in pollen occurs with a small rise of 0.5°C in SST. If using the maximum point for both, the pollen rise occurs with an increase in 3°C. This shows that by using two proxies from two different cores, interpretation of continental and oceanic responses may be inconclusive. In this example, a maximum in productivity of continental vegetation may be linked to a significant range of SST warming in the tropical Atlantic that derives only from the chronological uncertainties. These differences illustrate the challenges of reconstructing a coherent picture of DO signals in the tropics and the obstacles of identifying land-sea correlations that allow testing of alternative DO trigger hypotheses.

## TESTING THE TROPICAL TRIGGER HYPOTHESIS

To understand to what extent heat and moisture accumulation in the American tropics may trigger abrupt climate events and how the ocean and the atmosphere may transmit perturbations to the rest of the globe, we need to (i) quantify vegetation changes on land and across biomes to uncover fluctuations in the major atmospheric systems and potential moisture build-up, and (ii) quantify variations in surface water temperature and salinity along the Atlantic coast of South America to find potential evaporation sources, and to link surface water heat transport to major oceanic currents. Tropical vegetation records are ideal



**FIGURE 5 |** Integrated approach using marine sedimentary sequences to unravel terrestrial and oceanic changes during abrupt climate events and pathways of terrestrial and marine microfossil deposition. Forams: foraminifera. Modified from Center for Advanced Marine Core Research, Kochi University. (2020) <https://www.kochi-u.ac.jp/marine-core/research/>.

for tracking atmospheric change and moisture build-up because plants are highly sensitive to moisture availability (Phillips et al., 2009), and tropical biome boundaries (i.e., ecotones) are largely determined by precipitation (Ratter, 1992; Da Silveira and Lobo Sternberg, 2001). Atmospheric and oceanic records need to be high resolution to allow close investigation of these rapid and short climate events. A chronology that is independent from Greenland and North Atlantic records (Blaauw, 2012; Urrego et al., 2014) is also crucial to determine if climate changes in the American tropics precede climate perturbations in the North Atlantic region and are the likely triggers of abrupt climate events.

Integrated climate reconstructions from marine sedimentary sequences is therefore the best way to unravel terrestrial and oceanic changes in the American tropics during abrupt climate events (Figure 5). High-resolution terrestrial and marine tracers from the same sedimentary sequence can provide unique information to identify tropical moisture accumulation during DOs. Marine sediment sequences can be used to quantify land-sea climate contrasts and identify moisture build-ups. Marine sediments collected near continents are ideal as they provide high-quality records documenting past changes in the vegetation of the adjacent landmasses. They also contain marine indicators that can provide reconstructions of oceanic change (Sánchez Goñi et al., 2018). Terrestrial tracers include pollen and microcharcoal particles. Pollen documents vegetation changes that can be translated into air temperature, precipitation and rainfall seasonality. Charcoal particles document fluctuations in fire activity linked to vegetation type and precipitation. Marine tracers such as oxygen isotopes from benthic and planktonic foraminifera assemblages allow reconstructions of global ice volume and sea surface salinity (SSS), respectively. Additionally, organic compounds such as alkenones can be used to reconstruct SST and stratigraphic and sedimentological changes can be used to estimate changes in river runoff and wind intensity. All these marine and terrestrial tracers can be analysed from the same sample and thus same time slice (Figure 5) to achieve integrated ocean and atmospheric datasets. By quantifying terrestrial and marine indicators from the same sample, the reliance on external chronologies to determine leads and lags is minimised. Such an approach has proven invaluable to understand air and sea temperature coupling-decoupling in western Europe (Sanchez Goñi et al., 2013), the potential role of continental climates in the glacial inception (Desprat et al., 2005), orbital and millennial-scale changes in continental fires in western Europe (Daniau et al., 2007) and Southern Africa (Daniau et al., 2013), and Holocene land and ocean climates in the tropical Pacific (Seillès et al., 2016).

## CONCLUSION

Despite abrupt climate events such as DOs being a global phenomenon, they are still poorly understood, especially how they are triggered. Several hypotheses have been suggested on what is driving changes in the ice sheets, and how changes outside the North Atlantic could trigger or propagate these events. The

main two hypotheses for driving causes of DOs are changes to the AMOC in the North Atlantic and changes in tropical moisture accumulation and export. Modelling work suggests that these two mechanisms are linked and that tropical climate perturbations could indeed precede, and potentially trigger, changes in the North Atlantic.

Our projections of changes in vegetation and fire activity predict drying and fire increases in northernmost South America during Northern Hemisphere cooling, along with downslope migration of montane taxa. During Northern Hemisphere warming increased precipitation is projected to result in reduced fire activity and spread of rainforests.

The lack of a consistent and constant chronology for DOs outside the North Atlantic is one reason why the source of these changes is not fully understood. Due to the margin of error surrounding chronologies, it is challenging to reliably compare two different sites as the error can be larger than the duration of these abrupt events. To gain further insights into understanding the possible drivers of abrupt climate events such as Dansgaard-Oeschger cycles, multi-proxy approaches should be used on high resolution marine sequences. Marine sequences from the tropical Atlantic will produce integrated datasets of oceanic and terrestrial change that permit to explore the tropical trigger hypothesis of DOs.

A greater understanding of past abrupt climate events is crucial to better predict how the climate system may be responding to anthropogenic forcing in the 21st century and how it may respond in the future. By understanding the driving forces and responses of natural climate variability, we can mitigate and prepare for anthropogenic climate change. A better understanding of the climate system would provide the opportunity to manage current and future climate crises and their effects in food security, natural disasters and biodiversity loss.

## AUTHOR CONTRIBUTIONS

JO and DU conceived and developed the ideas in the manuscript. JO and DU wrote the manuscript and created the figures for the manuscript. Both authors contributed to the article and approved the submitted version.

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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