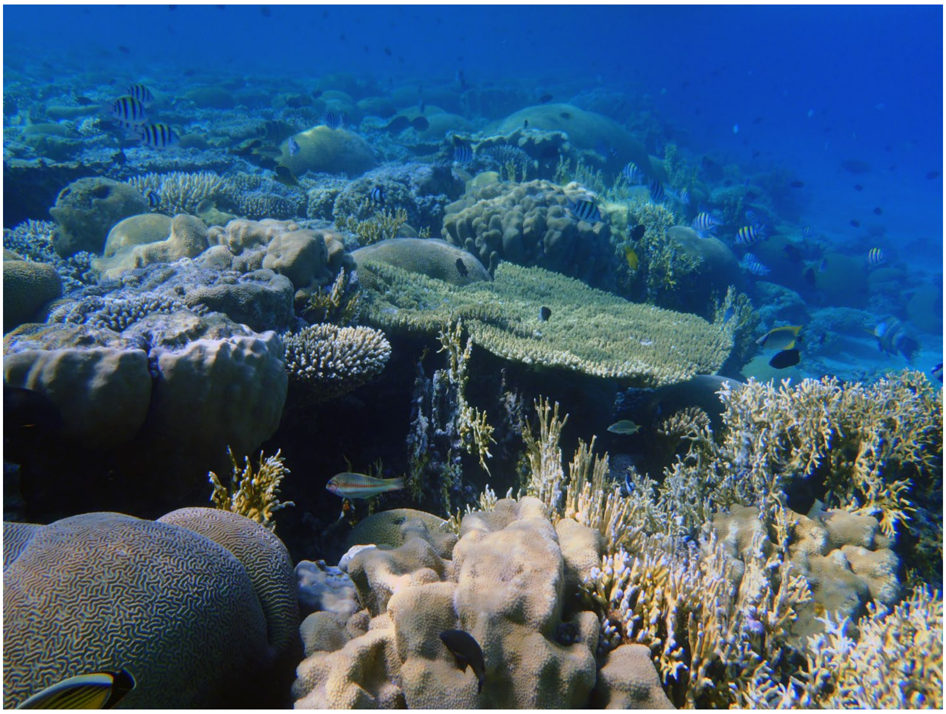
Initiative to Establish a Priority Programme

Tropical Climate Variability and Coral Reefs

A Past to Future Perspective on Current Rates of Change at Ultra-High Resolution



Programme committee

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1 Summary

Climate change, in particular the rise in tropical sea surface temperatures, is the greatest threat to coral reef ecosystems today and causes climatic extremes affecting the livelihood of tropical societies. Coral reefs provide ecosystem services that have the largest monetary values of all biomes. The interval between recurrent mass coral bleaching events driven by anomalously high water temperatures is becoming too short for a full recovery of mature coral reef assemblages and will have dramatic effects on future coral reef growth. The tropics are home to about 40 percent of the world's population and most vulnerable to the regional impacts of future climate change. Increasing tropical ocean temperatures may change the intensity and frequency of tropical climate modes potentially resulting in greater magnitude, pacing and duration of droughts, floods, heatwaves and cyclones than seen in the short instrumental observations. Assessing how future warming will change coral reef ecosystems and tropical climate variability is therefore of extreme urgency. It is critical time now that multiple research disciplines in Germany and elsewhere converge to tackle this challenge. ***Tropical Climate & Corals*** aims to fundamentally enhance our current understanding of tropical marine climate variability and its impact on coral reef ecosystems in a warming world, by quantifying climatic and environmental changes during both the ongoing warming and during past warm periods in order to serve future projections. ***Tropical Climate & Corals*** combines, for the first time, the monthly to weekly climatic and environmental information extracted from the skeletons of annually banded reef corals derived by novel geochemical and isotopic analysis tools with advanced statistical simulation methods, earth system modelling and observed ecosystem responses to quantify rates of change at ultra-high resolution, in order to project future changes in coral reef ecosystems and tropical marine climate variability at societally relevant timescales. This unique combination of disciplines is novel and the envisaged past to future perspective on current rates of change at ultra-high resolution involves an unprecedented time domain, representing cutting edge research that is of utmost relevance for assessing the future risks of climatic extremes and environmental stress on tropical societies and coral reef ecosystems in a warming world. The ultimate goal of ***Tropical Climate & Corals*** is to deliver estimates and projections of how tropical marine climate variability and coral reef ecosystems will change in a warming world with rising carbon dioxide levels, on timescales relevant for society.

2 State of the art and preliminary work

Early emergence of climate change in the tropics

Global warming continues unabated, with the recent four years each setting a new record (Haustein et al., 2017; Hartfield et al., 2018; Blunden et al., 2018; 2019; IPCC special report, 2018) (Figure 1). 2015 and 2016 were the warmest years ever recorded since 1850 with temperatures >1°C above pre-industrial levels (e.g., Hawkins et al., 2017). These two years saw a very strong El Niño event in the tropical Pacific. The El Niño-Southern Oscillation (ENSO) is the most powerful internal mode of interannual climate variability. ENSO modulates hydroclimatic extremes, marine heatwaves and cyclone activity throughout the tropics and beyond (e.g., Timmermann et al., 2018), with dramatic societal and ecological impacts. El Niño raises global mean temperatures, and with the current warming trend, El Niño years typically set new temperature records (Figure 1; Box 1). 2017 and 2018, however, were the warmest non-El Niño years ever recorded (Blunden et al., 2018, 2019), suggesting that the warming seen in 2017 and 2018 is driven by anthropogenic forcing, rather than by internal variability (e.g., Blunden et al., 2018, 2019). The tropical ocean is a key player in global climate dynamics on seasonal, interannual, and decadal timescales, and the years 2017 and 2018 have seen above-normal heavy rains, floods, and cyclone frequencies affecting countries throughout the tropical belt (Blunden et al., 2018, 2019). The combination of long-term global warming and El Niño-related warm events has severely affected corals and coral reefs throughout the tropical oceans. Mass coral bleaching, a result of large-scale temperature stress, was first observed during the 1982/83 El Niño, and followed by much more severe, global scale bleaching events, culminating in the most wide-spread and most destructive global bleaching episode to date, which lasted from 2014-2017 (Blunden et al., 2018) (Figure 1; Box 2). **Figure 1 demonstrates the disastrous interplay of anthropogenic warming and tropical climate variability, and the enormous threat this poses for tropical countries and coral reef ecosystems.**

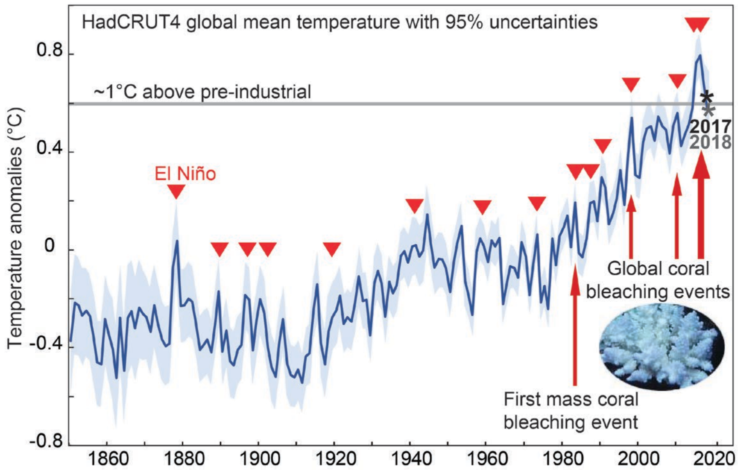

Figure 1: Global mean temperatures. HadCRUT4 annual global mean surface temperatures (anomalies relative to 1961-1990 mean) with 95% uncertainty (shading) (Morice et al., 2012). Red arrowheads: strong El Niño events. Major coral bleaching events occurred during years warmed by El Niño. 2015, 2016, and 2017 are the three warmest years on record. 2017 was the warmest year without El Niño influence, warmer than any El Niño year prior to 2015-2016. 2015 was the first year with global temperatures >1°C above pre-industrial (grey horizontal line) (Hawkins et al., 2017). The first mass coral bleaching was observed during the 1982/83 El Niño. Global bleaching events occurred during El Niño years of 1997/98, 2010 and, in so far unprecedented scale, from 2014-2017 (Blunden et al., 2018).

Coral reefs and global warming

Corals and coral reefs, also called the 'rainforests of the sea' have the largest monetary value of all biomes on Earth (de Groot et al., 2012) providing important ecosystem services that include fisheries, coastal protection and tourism. They are, like all tropical ecosystems, highly adapted to their specific environment and very sensitive to small external, physical or chemical changes in ambient seawater (DeCarlo et al., 2017; Camp et al., 2018). For example, small increases in local maximum summer temperatures may cause coral bleaching and death (Hughes et al., 2017, 2018) (Box 2). The persistent, large-scale warm sea surface temperature (SST) anomalies during recent El Niño events have caused re-current mass mortality events and destroyed many coral reefs (Hughes et al., 2017, 2018) (Figure 1). Current anthropogenic warming of the global tropics has already forced regional-scale climatic variables beyond the range of historical experience and has raised the possibilities for more frequent coral bleaching in the coming decades (e.g., Mora et al., 2013; Haustein et al., 2017; Hughes et al., 2017; Abram et al., 2016). **Tropical corals are at high risk already and are projected to transition to very high risk even if global warming is limited to 1.5°C** (e.g., Hughes et al; 2017; DeCarlo et al., 2017; IPCC, 2018, 2019). Almost all warm-water coral reefs are projected to suffer significant losses of area and local extinctions and the species composition and diversity of remaining reef communities is projected to differ from present-day reefs (IPCC, 2019). **No other marine ecosystem currently faces higher risks from climate change** (IPCC, 2019). Global databases of coral bleaching are available, but suffer from uneven sampling and poor maintenance (Hughes et al., 2018). Many coral reefs are in remote locations and cannot be monitored continuously. This important gap may be filled by the analysis of the carbonate skeletons of living corals. Coral growth structures and/or geochemical profiles provide distinct bleaching signatures that can be used to monitor current and past bleaching occurrences (e.g., Barkley and Cohen, 2016; Clarke et al., 2017; D'Olivo and McCulloch, 2017).

Assessing how current and future warming affects corals and coral reefs is of extreme urgency, but classical biological, census-based methods fail to capture the complex time-dependent response of corals to anthropogenic changes (e.g., Leupold et al., 2019). **Recent groundbreaking results suggest that geochemical data extracted from skeletons of living corals provide a key to unlock the complex interplay between coral physiology, calcification and ongoing environmental change (McCulloch et al., 2017).** These demonstrate a strong impact of external, physical and chemical environmental parameters on corals (Yamazaki et al., 2015; Duprey et al., 2017; D'Olivo & McCulloch, 2017). Placing these in the context of long-term climate change and natural climate variability is crucial to fully understand the impact of anthropogenic disturbances on coral reef ecosystems, and to develop models and projections that provide robust assessments of future changes. The likely future occurrence of temperature-driven regional- and global bleaching events can be investigated with state-of-the-art climate models (e.g., van Hooidonk et al., 2016; Langlais et al., 2017).

Box 1: Modes of tropical climate variability

The term **Monsoon** refers to a seasonal reversing of surface winds, with distinct wet and dry seasons, driven by the asymmetric heating of land and ocean. The major monsoon systems of the world consist of the African, the Indian and the Asian-Australian monsoons. Monsoon precipitation is strongly influenced by interannual modes of tropical climate variability, such as El Niño and the Indian Ocean Dipole (e.g., Wang et al. 2012).

The **El Niño-Southern Oscillation (ENSO)** is the dominant interannual mode in global climate (e.g., Timmermann et al., 2018). ENSO is a coupled variation of sea-surface temperatures and surface winds across the equatorial Pacific. ENSO alternates between neutral, a warm phase (El Niño) and a cold phase (La Niña). The ENSO phases arise from disturbances of the equatorial Walker circulation. During neutral years, high (low) surface pressure over the eastern Pacific Ocean (Indonesia) drives the trade winds north and south of the equator, causing upwelling of cold water in the eastern Pacific. When the Walker circulation weakens or reverses, an El Niño results. Upwelling of cold water is reduced and the eastern Pacific warms. A strong Walker circulation, as seen during La Niña, increases upwelling and cooling. El Niño years are seen as warm years in the global mean temperature record (Figure 1), while La Niña causes global cooling.

The **Pacific Decadal Oscillation (PDO) / Interdecadal Pacific Oscillation (IPO)** is an interdecadal, El Niño-like pattern of climate variability, with a warm (cool) tropical Pacific and weakened (strengthened) trade winds during its positive (negative) phase (Mantua et al., 1997; Power et al., 1999). IPO phase changes strongly influence global mean temperatures: negative phases slow down the warming, as seen during the recent warming hiatus from 1998 to 2015 (e.g., England et al., 2015), while positive phases accelerate it (Meehl et al., 2016).

The **Indian Ocean Dipole (IOD)** is an interannual, aperiodic oscillation of sea surface temperatures (SSTs) in the equatorial Indian Ocean, with positive, neutral and negative phases (Saji et al., 1999). The IOD displays a strong asymmetry. The dominant, positive IOD events feature upwelling and cooling off Java/Sumatra, causing severe rainfall anomalies in the Indian Ocean region.

The **Atlantic Multidecadal Oscillation (AMO)** and **Hurricanes.** The AMO is a coherent, basin-wide pattern of North Atlantic SSTs, with a period of 60-80 years (Schlesinger and Ramankutty, 1994). During warm phases of the AMO, the number of severe hurricanes is much greater than during cool phases (e.g., Zhang et al., 2006). The AMO has a strong impact on rainfall in the countries surrounding the North Atlantic basin, particularly in the Sahel region (e.g., Zhang et al., 2006).

Tropical climate variability and global warming

Tropical marine climate variability on seasonal, interannual, and decadal timescales modulates weather, precipitation extremes, severe droughts, intense hurricane and cyclone activity, and marine heatwaves with dramatic societal and ecological impacts. **The tropics are home to 40% of the world's population and tropical societies are the most vulnerable to climate change** (IPCC special report, 2018). Climate shifts caused by interannual to decadal and multidecadal modes of climate variability (Box 1) lead to relatively small-magnitude ocean temperature changes (0.5 to 1°C) which strongly affect the unique socio-ecological systems in the tropics, and thus impact human societies (Schleussner et al., 2016). **Tropical SSTs determine the distribution and amount of rainfall, and small perturbations of the normal temperature pattern may cause severe droughts or flooding** (e.g., Vecchi et al., 2007; Funk et al., 2008). **Rising SSTs are thought to increase the intensity of tropical storms and cyclones** (Hetzinger et al., 2008; Emanuel & Sobel, 2013), and recent cyclones such as Dorian (Bahamas, 2019), Idai (Mozambique, 2019) and Haiyan (Philippines, 2013) were particularly severe. The negative impacts of these extreme events on tropical societies and coastal ecosystems last for decades (e.g., de Groot et al., 2012; Bell et al., 2014; Riegl et al., 2015; Lafratta et al., 2017). The displacement of millions of people due to climate change is not a future hypothetical; it is a current reality (UNHCR, 2018). In a warming climate, there is an increasing societal demand for an improved understanding of climate variability on seasonal, interannual, and decadal timescales, especially with respect to the tropical ocean, a key player in global climate dynamics. Improved knowledge on the range, anomalies and extremes associated with tropical marine climate variability on such timescales prior to the start of the short observational record can be obtained from the analysis of the carbonate skeletons of living and fossil corals. Coral geochemical and isotopic profiles provide proxy records for key parameters of the tropical ocean such as SST and salinity that can be used to study seasonal, interannual and decadal variability during the current and past warm periods.

Understanding how tropical marine climate variability on seasonal, interannual, and decadal timescales may change in a warming climate is of extreme urgency, but remains difficult because of the limited instrumental observations that only span parts of the 20th and 21st centuries, the chaotic nature of the climate system, and the poor reproducibility of variability on such timescales in model projections of future climate change. **Recent significant advances in analytical technology suggest that geochemical and isotopic data extracted from skeletons of living and fossil corals now provide a key to fully characterize the complex interactions of tropical marine climate and environmental variability on seasonal, interannual and decadal timescales during the current and past warm periods at monthly to weekly resolution.** Such information, combined with advanced statistical simulation methods and earth system modelling, will contribute towards efficient mitigation strategies and more reliable projections of regional climate change impacts on tropical societies and coral reef ecosystems that are thought to scale with increasing global temperature, by placing the ongoing rapid changes into the context of long-term variations and natural variability.

Coral as archives of climate variability and environmental stress

The geochemical and isotopic composition archived in the aragonite skeletons of tropical corals can provide large-scale ocean, climate and environmental reconstructions for recent and past warm periods, as well as documentations of coral and reef-scale responses to current environmental stress under ongoing global warming, which can be precisely dated and can achieve a monthly to near-weekly resolution. The high temporal resolution and good age control allows the application of statistical methods routinely applied in meteorology (e.g., Rimbu et al, 2001, 2003; Timm et al., 2005; Hetzinger et al., 2008; Laepple & Huybers, 2014; Zinke et al., 2015) and are ideal for comparisons with climate models outside the limited range of the instrumental record (Felis et al., 2004, 2012, 2015; Cobb et al., 2013; Zinke et al., 2014; Laepple & Huybers, 2014).

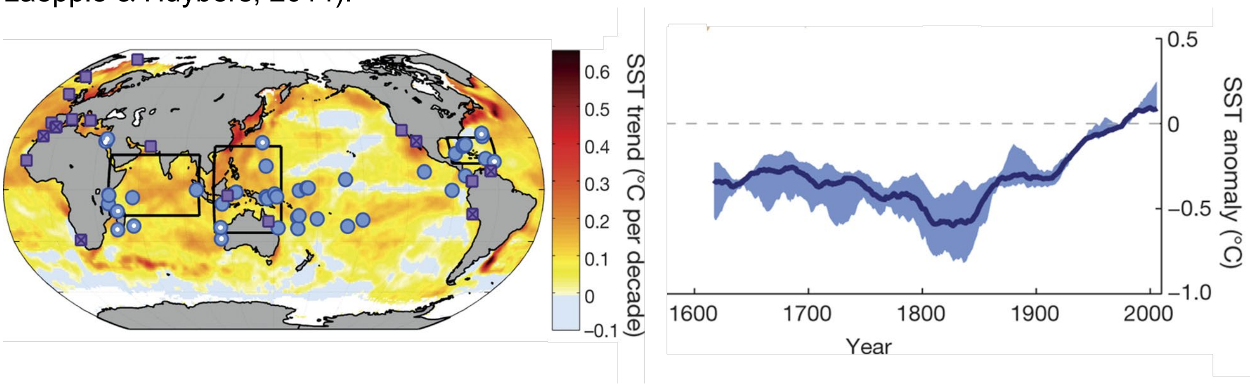

Figure 2: PAGES Ocean2k reconstruction. Left: Instrumental sea surface temperature (SST) trend for the period AD 1961-1990. Black boxes: *PAGES Ocean2k* reconstruction regions. Blue circles: Sites of coral records (white dots: records from German research groups). Purple rectangles: Low-resolution sediment records. **Right:** PAGES Ocean2k mean tropical SST reconstruction extending back into the 17th century (thick blue line: area-weighted mean). Minimum-maximum range across the Indian, western Pacific and western Atlantic reconstructions are indicated by shading. Anomalies relative to 1961-1990 mean (dashed line). From Abram et al. (2016).

Reconstructions from modern (living) corals extending back for centuries overlap with the observational period (e.g., Felis et al., 2000; Linsley et al., 2000; Pfeiffer et al., 2004; DeLong et al., 2012; Tierney et al., 2015), **and provide baselines of natural and current anthropogenic climate and environmental variability**. A synthesis of coral $\delta^{18}O$ and Sr/Ca records to estimate tropical SST trends for the last centuries has been achieved within the *Future Earth Past Global Changes* (*PAGES*) *2k network* (Tierney et al., 2015; Abram et al., 2016; Figure 2). The *PAGES Ocean2k* compilation shows that industrial-era warming of the tropical oceans commenced as early as the mid-nineteenth century, prior to the time covered by instrumental data, nearly synchronous with Northern Hemisphere continental warming (Tierney et al., 2015; Abram et al., 2016). Moreover, the reconstruction suggests an enhanced equatorial response mechanism to greenhouse gas forcing (Abram et al., 2016). However, long coral records that extend back into the Little Ice Age (~1450-1850) are still scarce, and the majority of records in the *Ocean2k* reconstruction are coral $\delta^{18}O$ records, a proxy that reflects both the temperature and the $\delta^{18}O$ of the seawater, the latter influenced by hydrological changes (e.g., Gagan et al., 1998; Cahyarini et al., 2008). Advances in analytical technology now allow the coral Sr/Ca temperature proxy to be routinely applied to century-long coral records at sub-seasonal resolution, and to disentangle the hydrological signal locked in coral $\delta^{18}O$. Such paired coral Sr/Ca and $\delta^{18}O$ records are necessary to obtain improved SST reconstructions, and to assess the interplay between SST and the hydrological cycle in the tropical ocean (e.g., Felis et al., 2009, 2018; Nurhati et al., 2011; Cahyarini et al., 2014; PAGES Hydro2k Consortium, 2017). Hydrology is a key parameter for tropical countries with significant socioeconomic impacts, and regional droughts and floods are driven by tropical SST anomalies. At present, there is large uncertainty how regional temperatures and rainfall will respond to any given scenario of future changes in atmospheric composition and land use (Braconnot et al., 2012).

Well-preserved fossil corals can provide subseasonal-resolution snapshots of tropical climate variability for key warm intervals in Earth's history. Improved radiometric dating methods of young subfossil corals allow the development of spliced chronologies of ENSO variability potentially extending over the last millennium (Cobb et al., 2003). Even older corals from the Holocene (e.g., Tudhope et al., 2001; Felis et al., 2004; Abram et al., 2007; Cobb et al., 2013; McGregor et al., 2013; Zinke et al., 2014) and, combined with improved radiometric dating methods (e.g., Obert et al., 2016), the last interglacial (e.g., Felis et al., 2004, 2015) can provide time windows of seasonal, interannual and decadal climate dynamics (e.g., ENSO, tropical Atlantic variability). These enable comparisons with climate model simulations to understand the processes driving the ocean-atmosphere system during past warm climates, and its response to different external forcings (e.g., Felis et al., 2004, 2015; Giry et al., 2012, 2013; Brocas et al., 2016, 2018) (Figure 3). Previous work has demonstrated the existence of pristine corals from deep geological time at sites of exceptional preservation, e.g., the Miocene and the Pliocene (e.g., Brachert et al., 2006; Watanabe et al., 2011), and the operation of interannual ENSO variability during the Pliocene warm period (Watanabe et al., 2011).

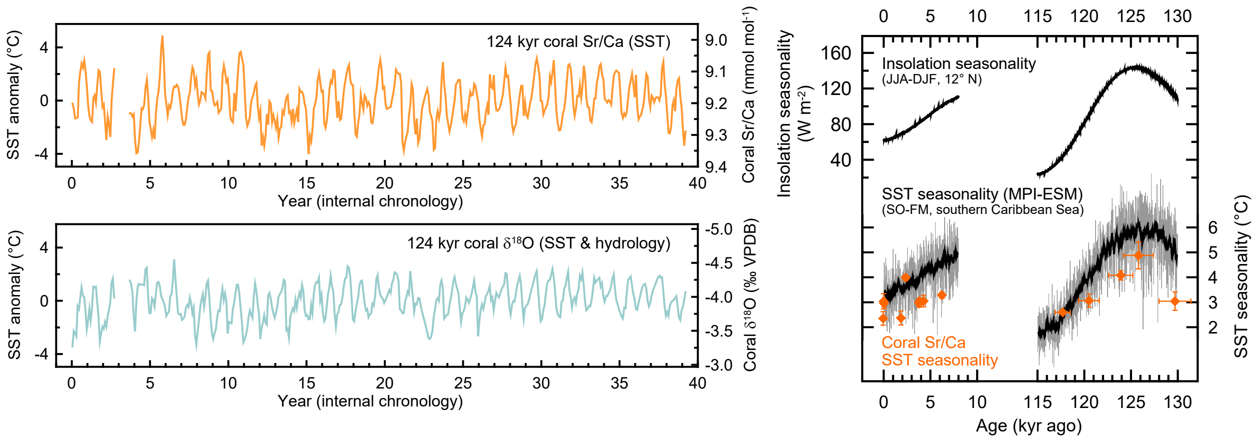

Figure 3: Monthly temperatures from last interglacial corals. Left: Monthly Sr/Ca-sea surface temperature (SST) proxy record from *Diploria strigosa* coral (southern Caribbean Sea) for ~40 years at 123.9±1.3 kyr ago. Deviations of corresponding monthly coral $\delta^{18}O$ from Sr/Ca-SST arise from seawater $\delta^{18}O$ effects. **Right:** Insolation seasonality (Berger, 1978) at this latitude (summer [Jun-Jul-Aug, JJA] minus winter [Dec-Jan-Feb, DJF]) and southern Caribbean SST seasonality simulated by MPI-ESM/COSMOS climate model (summer/autumn [Sep-Oct, SO] minus winter/spring [Feb-Mar, FM]). Bold line: 210-calendar year average. Orange rhombs: Coral Sr/Ca-SST seasonality (uncertainty: ±1SE) for time intervals of the Holocene and last interglacial ($^{230}Th/U$-age uncertainty: 2σ). Records ≤6-year length excluded. Coral-SST calculated after Hetzinger et al. (2006). Modified from Giry et al. (2012), Felis et al. (2015), Brocas et al. (2016, 2018).

Importantly, although past warm intervals such as the Holocene thermal maximum (~11,000–5,000 years ago), the last interglacial (~129,000–116,000 years ago), or Marine Isotope Stage 11.3 (~410,000–400,00 years ago) "are not strict analogues for future warming, **these past warm intervals do illustrate the regional climate and environmental response that may be**

triggered in the future, and thus remain useful as an observational constraint on projections of future impacts" (Fischer et al., 2018). "These times of peak warmth were associated with different orbital parameters, while their greenhouse concentrations were close to pre-industrial levels and their temperatures, although within the projected range of anthropogenic warming for the near future, have been controlled by a different blend of forcing mechanisms" (Fischer et al., 2018). "Past climates with greenhouse gas concentrations of >450 ppm include the mid-Pliocene warm period (3.3–3.0 million years ago) and the early Eocene climatic optimum (~53–51 million years ago), but these older warm intervals had continental configurations significantly different from today" (Fischer et al., 2018) and finding well-preserved corals is a challenge here.

Box 2: Coral bleaching

Coral bleaching involves the breakdown of the symbiosis between scleractinian corals and the zooxanthella living within their tissues (e.g., Hoegh-Guldberg et al., 2017). The zooxanthellae are single-celled dinoflagellates that provide the corals with nutrients through photosynthesis. Short periods of stress resulting from high temperature (or other physical stressors) can result in the loss of the symbionts. The corals lose their colour, revealing their white skeletons underneath (Figure 4). Bleached corals continue to live but starve. If stressful conditions persist, the corals die. Algae then overgrow the coral skeletons (Figure 4), and the reef structure is destroyed.

Mass bleaching is primarily driven by prolonged warm sea surface temperature (SST), exceeding the corals' physiological tolerances. The first mass bleaching occurred during the El Niño in 1983 and was followed by the global events in 1998 and 2010. The global bleaching event from 2014-2017 was the longest, most widespread, and most destructive on record (Blunden et al., 2018 and references therein). During global bleaching events, coral bleaching spans hundreds of kilometres in all three ocean basins (NOAA Coral Reef Watch: https://coralreefwatch.noaa.gov/satellite/index.php).

Smaller, regional-scale, heat induced bleaching events are also a modern phenomenon (e.g., Hughes et al., 2018). In the past decades, as global warming has progressed, many regional bleaching events have occurred (Hughes et al., 2018). These events now affect locations that were thought to provide spatial refuges for corals just a few years ago (Zinke et al., 2015; Hughes et al., 2018). The frequency and intensity of regional bleaching events increases with warming of tropical SST, and is currently approaching unsustainable levels (Hughes et al., 2018).

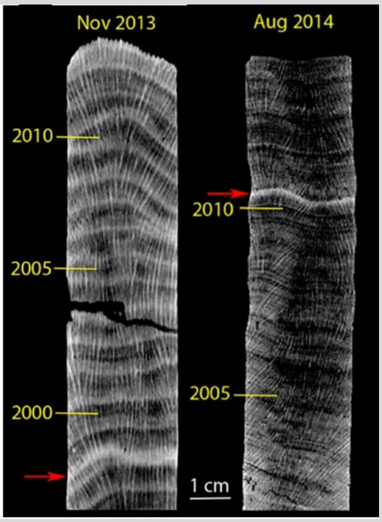

Figure 4: Coral bleaching. Left: Coral reef of American Samoa before, during and after the 2015 coral bleaching event (from left to right: healthy, Dec 2014; bleached, Feb 2015; dead and overgrown with algae, Aug 2015). Credit: The Ocean Agency/XL Catlin Seaview Survey. **Right:** CT scans of *Porites* spp. cores from Palau showing bright stress bands indicating past bleaching events (red arrows; left: 1998 El Niño, right: 2010 El Niño) and normal annual growth bands. From Barkley and Cohen (2016).

Recently, additional coral temperature proxies (U/Ca, Li/Ca, Li/Mg, Sr-U, clumped isotopes) have been successfully tested to independently constrain coral Sr/Ca through multi-element palaeothermometry, to improve reconstructions of tropical SST from corals (e.g., Felis et al., 2009; Hathorne et al., 2013a,b; Saenger et al., 2012; Montagna et al., 2014; Alpert et al., 2017; D'Olivo & McCulloch, 2017; D'Olivo et al., 2018). In addition to temperature and hydrology, corals provide a wealth of information on environmental conditions in the tropical ocean that can be simultaneously extracted to disentangle natural and human-driven changes over a broad range of temporal and spatial scales. A large number of proxies have been tested successfully over recent years. These include radiogenic tracers of ocean circulation and upwelling (e.g., Guilderson et al., 2009; Winkler et al., 2012), skeletal luminescence as proxies for organics/river runoff (Grove et al., 2010; Lough et al, 2014), Ba/Ca ratios and Ba-isotopes as proxies for river runoff and sediment load (McCulloch et al., 2003; Grove et al., 2013; Saha et al., 2016), Boron isotopes as recorders of ocean acidification (McCulloch et al., 2012, 2017; Wall et al., 2016; Wu et al., 2018), as well as stable nitrogen isotopes and P/Ca that are linked to global biogeochemical cycles or nutrient input from adjacent land areas (LaVigne et al., 2008, 2010; Yamazaki et al., 2015; Duprey et al., 2017).

Importantly, coral geochemistry now provides a tool to understand the response of corals and coral reefs to ongoing climate change and environmental stress. Boron isotope systematics suggest that corals can up-regulate the pH of their calcifying fluid to achieve oversaturation but stable levels of carbonate saturation, the key parameter controlling coral calcification (McCulloch et al., 2012, 2017). This would make them relatively insensitive to future ocean acidification. However, these studies also indicate that coral calcification is highly vulnerable to thermal stress from global warming. Coral bleaching disrupts the corals metabolism that up-regulates pH, thus effectively terminating calcification (McCulloch et al., 2017; D'Olivo & McCulloch, 2017) (Box 2; Figure 4). Boron isotope systematics coupled with high-resolution trace element analysis may show past bleaching events or periods of thermal stress (D'Olivo & McCulloch, 2017).

Future perspective – Tropical climate variability and coral reefs

We are currently at the cusp of being able to realise the potential of tropical coral skeletons as ultra-high resolution archives of (1) coral and reef-scale response to current environmental stress and of (2) large-scale ocean, climate and environment reconstructions during recent and past warm periods of Earth's history. Latest developments in analytical technology (laser ablation, inductively coupled plasma spectrometry, accelerator mass spectrometry, radiochemical separation techniques, autodilution and autosampler systems) regarding instrument sensitivity and precision, sample size and sample throughput now allow a truly multi-proxy approach. Precisely dated, replicated, century-long monthly or higher resolved coral proxy reconstructions of climate and environmental change in the tropical oceans are now possible. Similarly, recent advances in transient simulations with fully coupled atmosphere-ocean general circulation models are remarkable. Important areas of progress include the models' spatial resolution, the inclusion of oxygen isotopes in the models' hydrological cycle, marine biogeochemistry models, pseudo proxy experiments, proxy system forward modelling and palaeoclimate data assimilation. It is now possible to compare coral proxy reconstructions and model estimates of climate and environmental variability and change at previously unprecedented levels. Moreover, recent developments in advanced statistical simulation methods (Bayesian tools, bootstrap resampling), noise filtering techniques, nonlinear statistical-dynamical analysis methods (graphical models, artificial neural networks, manifold learning techniques) and mathematical frameworks for detecting cross-frequency phase-amplitude dependencies in the climate system, now allow more reliable determinations of the uncertainties of statistical estimations derived from monthly resolved coral proxy records. It is now possible to preserve the full temporal variance in comparisons with earth system model estimates of climate variability. These techniques and methods will allow substantial improvements in linking observational records of climate and environmental variables and coral-based proxies towards a fundamental understanding of the long-term interactions between global climate change and modes of tropical climate variability, and their combined impact on coral reef ecosystems and tropical societies in a warming world.

Transient climate model simulations over the last millennium, the Holocene, the last interglacial and older interglacials of the Pleistocene offer new opportunities for the investigation of variability on timescales from interannual to decadal and multidecadal to centennial and for the assessment of their underlying mechanisms (e.g., Fischer and Jungclaus, 2011; Jungclaus et al., 2014; Segschneider et al., 2018) (Figure 3). In connection with isotope-enabled simulations of earth system models and activities in forward-modelling of specific proxies a comprehensive model-based data set is emerging that allows for dynamical interpretation of variability in coral proxy reconstructions of temperature, hydroclimate, and environment. Finally, the combination of climate models with marine biogeochemistry models allows further insights into changes in nutrient availability, calcification rates, and also water mass ages. Along with new coral reconstructions of climate and environmental variability, this will lead to significant progress in the mutual evaluation of climate model simulations and coral proxy-based reconstruction techniques and might contribute to decipher the mechanisms for the apparent mismatch between climate models and proxy data regarding the amplitude of decadal variability in tropical SST (Laepple & Huybers, 2014), the Holocene temperature evolution (Liu et al., 2014), and the link between interannual variability and annual cycle strength in the tropical Pacific Ocean during the Holocene (Emile-Geay et al., 2016).

Pseudo proxy experiments aim at testing climate reconstruction methods in the controlled environments of climate model simulations, providing an assessment of their strengths and deficiencies. Its application to corals offers new possibilities to reconstruct spatially consistent fields and investigating tropical climate and reef ecosystem dynamics using proxy system forward modelling. It also allows testing the ability of comprehensive climate models to realistically simulate past, present and potential future climatic changes. Proxy system forward modelling approaches have recently been applied to mimic and mechanistically simulate the δ^{18}O signatures of coral records (Thompson et al., 2011; Dee et al., 2015). A challenge would be to setup this kind of proxy system forward models for bleaching of corals. Along this avenue it allows to investigate the impact of environmental factors such as SST, salinity and pH on the physiological conditions of corals. A successful calibration and validation of those mechanistic forward models eventually allows to assess changes in the bleaching dynamics in the context of potential future climatic changes, including uncertainties in the evolution of oceanic pH (e.g., Kwiatkowski & Orr, 2018). This is of ultimate importance for projecting the future of coral reefs and for developing adaption and mitigation policies for tropical coastal communities.

Ultra-high resolution coral geochemistry now provides a tool to understand the **temporal response** of **corals** and **coral reefs** to **ongoing climate** and **environmental change**, to reconstruct **past tropical climate** and **environmental variability** and to use these data in conjunction with **advanced statistical methods** and **earth system modelling** for **improved projections** of **future** changes in **tropical climate** and **coral reef ecosystems**.

This **combination** of **topics** and **disciplines** is **unique** in the **German research environment** and represents an **emerging field** of **utmost urgency**.

Despite the **extreme vulnerability** of **tropical societies** and **coral reef ecosystems** to **ongoing rapid climate change**, **Germany** still **lacks** a **coordinated research programme** that addresses these challenging issues.

3 Project-related publications by members of the programme committee

3.1 Articles published by outlets with scientific quality assurance, book publications, and works accepted for publication but not yet published

Cahyarini, SY, **Pfeiffer, M**, Nurhati, IS, Aldrian, E, Dullo, W-Chr, Hetzinger, S [**2014**] Twentieth century sea surface temperature and salinity variations at Timor inferred from paired coral δ^{18}O and Sr/Ca measurements. ***Journal of Geophysical Research Oceans***, 119, 4593–4604. *doi:10.1002/2013JC009594*

Cahyarini, SY, **Pfeiffer, M**, Timm, O, Dullo, W-Chr, Garbe Schönberg, D [**2008**] Reconstructing seawater δ^{18}O from paired coral δ^{18}O and Sr/Ca ratios: Methods, error analysis and problems, with examples from Tahiti (French Polynesia) and Timor (Indonesia). ***Geochimica et Cosmochimica Acta***, 72, 2841–2853. *doi:10.1016/j.gca.2008.04.005*

Felis, T, Mudelsee, M [**2019**] Pacing of Red Sea deep water renewal during the last centuries. ***Geophysical Research Letters***, 46, 4413-4420. *doi:10.1029/2019GL082756*

Felis, T, Ionita, M, Rimbu, N, Lohmann, G, Kölling, M [**2018**] Mild and arid climate in the eastern Sahara-Arabian Desert during the late Little Ice Age. ***Geophysical Research Letters***, 45, 7112-7119. *doi:10.1029/2018GL078617*

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5 Merits of the proposal taking into account the objectives of the programme

5.1 Originality of research questions in terms of topic and/or methodology

The overall scientific objective of ***Tropical Climate & Corals*** is to understand the interaction between global climate change and modes of tropical climate variability, and their combined impact on coral reef ecosystems and tropical societies in a warming world. The focus is on seasonal, interannual, and decadal timescales, the timescales most relevant to humans and ecosystems today and currently the most unexplored. ***Tropical Climate & Corals*** aims to quantify climatic and environmental changes during both the ongoing warming and during past warm periods in order to serve future projections. ***Tropical Climate & Corals*** aims to provide a mechanistic framework towards efficient mitigation and management strategies and more reliable projections of regional climate change impacts on coral reef ecosystems and tropical societies that are thought to scale with increasing global temperature.

Because of the ever increasing societal need for reliable high-resolution climatic and environmental baseline information for the tropical oceans and coral reef ecosystems, in order to improve future projections in a warming climate, and because of substantial recent advances (1) in analytical technology to read such information in tropical coral skeletons, (2) in climate and proxy modelling, and (3) in advanced climate and proxy statistics, *Tropical Coral Archives* are currently maturing into a major internationally recognized research field that is of high relevance for global climate and environmental change.

For the first time, this research field will be addressed by a large coordinated multidisciplinary national research programme. This will have a lasting impact on the scientific landscape in Germany, Europe and beyond. The climatic, environmental and ecological information to be gained from ***Tropical Climate & Corals*** will no doubt improve fundamentally our knowledge on and change the way we think about tropical marine climate variability at seasonal, interannual, and decadal timescales, and their impacts on tropical societies and coral reef ecosystems.

Tropical Climate & Corals aims to bring together the German multidisciplinary expertise and analytical and computational infrastructure in this emerging field, in order to improve established and explore new and risky methods and approaches. We aim to establish new avenues of climate and ecosystem research, which will influence research areas such as palaeoclimatology and climatology, climate modelling and climate statistics, coral reef ecology, carbonate geochemistry and radiometric dating, and in particular climate risk management and coral reef management.

Originality and quality of *Tropical Climate & Corals*
in terms of topic and methodology

Tropical Climate & Corals **aims to provide an**
ultra-high resolution past to future perspective on current rates of change
to project how tropical marine climate variability and coral reef ecosystems
will change in a warming world

Tropical Climate & Corals combines, **for the first time**,

- the **climatic** and **environmental information** extracted from skeletons of **annually banded reef corals** by **novel geochemical** and **isotopic analysis tools** and
- the **stress response** of major **reef-building corals** in **today's coral reef ecosystems**
- with **advanced statistical simulation methods**, **earth and proxy system modelling** and **observed ecosystem responses**
- to **quantify rates of change** at **ultra-high resolution** (monthly to weekly),
- in order to project **future changes** in **coral reef ecosystems** and **tropical marine climate variability** at societally relevant timescales, and
- brings together **various German institutions** in an **interdisciplinary approach** that will have a **lasting impact** on the **scientific landscape** at the **national** and **international level**.

Tropical Climate & Corals deals with the topics of climate impacts and marine ecosystem feedbacks under future warming that are currently of paramount importance, as indicated by the latest "*State of the Climate in 2017*" and "*State of the Climate in 2018*" reports of *NOAA's Center for Weather and Climate* at the *National Centers for Environmental Information* of the United States. The ***NOAA* (*National Oceanic and Atmospheric Administration*) reports** provide an update on global climate, notable weather events, and other data collected by environmental monitoring stations and instruments located on land, water, ice, and in space (Blunden et al., 2018, 2019). The reports **underline once more the sensitivity of the tropics and coral reef ecosystems to global climate change**:

> *"In 2017, the dominant greenhouse gases released into Earth's atmosphere reached new record highs. The global temperature across land and ocean surfaces ranked as the second or third highest, depending on the dataset, since records began in the mid-to-late 1800s. Notably, it was the warmest non-El Niño year in the instrumental record. Across the global oceans, the overall long-term sea surface temperature warming trend remained strong. The years 2015, 2016, and 2017 produced the three highest annual values observed. These high anomalies have been associated with widespread coral bleaching. The most recent global coral bleaching lasted three full years, June 2014 to May 2017, and was the longest, most widespread, and almost certainly most destructive such event on record. Precipitation over global land areas in 2017 was clearly above the long-term average. Across India, heavy rain and flood-related incidents during the monsoon season claimed around 800 lives. Above-normal precipitation triggered the most devastating floods in more than a decade in areas of Venezuela. In Nigeria, heavy summer rain caused rivers to overflow, bringing floods that displaced more than 100 000 people. 95 tropical storms were observed during 2018, well above the 1981–2010 average. Eleven tropical cyclones reached category 5 intensity. North Atlantic major hurricane Michael's landfall intensity was the fourth strongest for any continental U.S. hurricane landfall in the 168-year record and caused US$25 billion in damages. In the western North Pacific, super typhoon Mangkhut led to US$6 billion in damages across the Philippines, China and Hong Kong."*
>
> Summarized from Blunden et al., "*State of the Climate in 2017*", Sxvi (2018), "*State of the Climate in 2018*", Sxvi (2019).

Timeliness of *Tropical Climate & Corals*

***Tropical Climate & Corals* addresses topics currently of paramount importance identified by the**
IPCC Special Report on the Ocean and Cryosphere in a Changing Climate"
(*published 24th September 2019*)

- Almost all warm-water **coral reefs** are projected to suffer **significant losses** of **area** and **local extinctions**, even if global warming is limited to 1.5°C (high confidence). The **species composition** and **diversity** of remaining reef communities is **projected to differ from present-day reefs** (very high confidence).
- **Coastal communities** are exposed to **multiple climate-related hazards**, including tropical cyclones, extreme sea levels and flooding and marine heatwaves (high confidence). Extreme sea levels and coastal hazards will be exacerbated by **projected increases** in **tropical cyclone intensity** and **precipitation** (high confidence).
- Over the 21st century, the **ocean** is **projected** to transition to **unprecedented conditions** with **increased temperatures** (virtually certain), greater upper ocean stratification (very likely), **further acidification** (virtually certain), oxygen decline (medium confidence), and **altered net primary production** (low confidence). **Marine heatwaves** (very high confidence) and **extreme El Niño** and **La Niña** events (medium confidence) are projected to become **more frequent** and to likely **intensify existing hazards** with drier or wetter responses in several regions across the globe. Projections indicate that **extreme Indian Ocean Dipole** events also **increase** in **frequency** (low confidence).

Tropical Climate & Corals will monitor the transition of today's coral reef ecosystems and tropical climate variability, i.e. during the current onset of anthropogenic warming, using the powerful tool of coral biogeochemistry. Today's changes will be placed in the context of past climate variability (last millennium and past warm periods), and the latter will be used to improve regional-scale projections of future climate and environmental change using a combination of advanced statistical simulation methods and earth system models.

The overall scientific questions of ***Tropical Climate & Corals*** are summarized here:

Overall scientific questions of *Tropical Climate & Corals*

Can we understand the interaction between global climate change and modes of tropical climate variability, and their combined impact on coral reef ecosystems and tropical societies in a warming world?

- Can we **identify** and **understand rapid changes** and **transitions,** their **precursors**, and **thresholds** on **seasonal, interannual** and **decadal timescales** during the **current** and **past warm climates** - in **coral proxy records** of **climate** and **environment, coral reef ecosystems,** and **earth system model simulations?**
- Can **monthly climatic** and **environmental information** extracted from **coral skeletons** by **novel geochemical** and **isotopic analysis tools,** combined with **advanced statistical methods, earth system modelling** and **observed ecosystem responses** quantify rates of change to **project future coral reef ecosystem** and **tropical marine climate change?**
- What are the **future risks** associated with the impact of **increasing tropical sea surface temperature** on dominant **tropical climate modes, regional climate extremes, long-term precipitation trends, tropical societies** and in particular, **coral reef ecosystems?**

5.2 Delimitation of scope taking into account the duration of a Priority Programme

Study area:	***Global tropical to subtropical oceans***
Timescales of interest:	***Seasonal, interannual and decadal variability***
Time intervals of interest:	***Current anthropogenic changes, Last centuries & millennium, Holocene, last interglacial(s), Pliocene, Eocene***
Methods:	***Coral proxy reconstructions of climate & environment, Coral response to stress events (geochemistry, calcification), Earth system models, advanced statistical methods***

Tropical Climate & Corals aims to read the unique climatic, environmental and ecological information documented and archived in massive skeletons of annually banded reef corals during both the current warming and during past warm periods, prior to the start of instrumental observations of climate and establishment of reef monitoring programmes, in order to serve future projections. ***Tropical Climate & Corals*** intends to work globally throughout the tropical oceans and up and down to the subtropical limits of coral growth to exploit the full range of coral reef ecosystems. ***Tropical Climate & Corals*** aims to provide both documentations of the coral and reef-scale response to current environmental stress and large-scale ocean, climate and environment reconstructions, precisely dated and with monthly or even near-weekly resolution. ***Tropical Climate & Corals*** aims to provide actual and retrospective views on tropical marine climate variability on seasonal, interannual, and decadal timescales and their impact on coral reef ecosystems and tropical regions, by combining information from coral archives with climate, reef & proxy modelling and climate & proxy advanced statistics. ***Tropical Climate & Corals*** aims at documentations during the last decades using modern corals and at reconstructions for the last centuries and time intervals during the Holocene (the last ~11,700 years) and last interglacial (~125,000 years ago) warm periods using modern and fossil corals, and to compare the results with current coral reef ecosystem responses and instrumental observations of climate and reef monitoring. Reconstructions for time intervals during older Pleistocene interglacials or warm intervals of the Pliocene or Eocene are possible from well-preserved fossil corals. ***Tropical Climate & Corals*** will contribute towards concerted efforts to increase policy relevant empirical evidence for improved management actions with respect to climatic risks and environmental stress affecting tropical societies and coral reef ecosystems in a warming climate. ***Tropical Climate & Corals*** addresses this challenge in an interdisciplinary way that opens up unprecedented synergies between palaeoclimatology, climate modelling, climate statistics, coral reef ecology, carbonate geochemistry and radiometric dating to fundamentally improve our understanding of tropical marine climate variability and its impact on coral reef ecosystems on societally relevant timescales in present, past and future climate scenarios.

Tropical Climate & Corals **is organised around three major research topics in order** to fuel interdisciplinary collaboration among various disciplines and **to successfully address the overall scientific objectives within six years of programme duration (2 x 3 years)**. The organisational structure reflects the results of multidisciplinary discussions at the *DFG Rundgespräch* (*DFG Round Table*) *“Tropical Coral Archives”* (29-30 January 2018, 35 participants from 19 German institutions) and corresponding workshops with international (28 September 2017, 38 participants from 8 countries) and national scope (15-16 November 2016, 26 participants from 12 German institutions) held in Bremen (*MARUM*), Germany over the last years, which were initiated and organised by *T. Felis*, *M. Pfeiffer*, and *J. Zinke*.

The three major research topics of *Tropical Climate & Corals* are described here:

Topic A: Large-scale ocean, climate & environment reconstructions aims to fully characterize tropical marine climate and environmental variability on seasonal, interannual and decadal timescales, the timescales most relevant to human societies and coral reef ecosystems, during warm climates beyond the start of instrumental observations. Recent progress in analytical technology now allows precisely dated century-long coral proxy reconstructions of numerous oceanographic, climatic and environmental parameters of the tropical ocean at monthly resolution, during the ongoing and during past warm periods. Reconstructions of temperature and salinity near the sea surface at monthly to weekly resolution will allow to assess and quantify large-scale tropical ocean-atmosphere interactions and associated climate modes (monsoon, ENSO, IPO, IOD), and the related regional impacts of climatic extremes (droughts, floods, heatwaves, cyclones) on tropical islands, coastal regions of adjacent continents and coral reef ecosystems, as well as remote climatic interactions with the extratropics via global atmospheric teleconnections. Reconstructions of biogeochemical parameters of the tropical surface ocean such as pH, nitrogen and barium isotopic composition and of radiocarbon and anthropogenic radionuclides at annual to monthly resolution will allow to assess and quantify basin-scale trends in ocean acidification and productivity, the oceanic nitrogen and nutrient cycles, and changes in large-scale ocean circulation and oceanic upwelling. The regional- to basin-scale reconstructions will provide essential baselines of natural and current anthropogenic climate and environmental variability (frequency and intensity of extreme events, seasonality, interannual to decadal variability) to serve **Topic B** and **Topic C**.

Overarching research questions (Topic A)

- **Can we fully characterize tropical sea surface temperature, hydroclimate and biogeochemical variability? Can we separate internal variability from natural external forcing and anthropogenic forcing?**
- **How do modes of tropical climate variability respond to changes in background conditions, external forcing and anthropogenic forcing?**
- **Can we understand the linkage between tropical climate (mean state, seasonal cycle) and its variability (extreme events, interannual/decadal variability)? What are the implications for tropical societies and coral reefs?**

Key variables and methods (Topic A)

Multi-century monthly-resolved paired Sr/Ca (temperature) and $\delta^{18}O$ (hydrology, salinity) records from modern (living) and fossil corals (last centuries & millennia, Holocene, last interglacial(s), Pliocene, Eocene), coupled with boron, nitrogen and barium isotopes (ocean acidification, productivity, & nutrient cycles), multi-proxy palaeothermometry (Sr/Ca, Li/Mg, Li/Ca, U/Ca, Sr-U, clumped isotopes); radiogenic tracers (ocean circulation & ventilation); higher temporal resolution (weekly or higher); improved radiometric dating (higher precision & spatial resolution). From **Topic B**: Effects of biomineralization on coral proxies. From **Topic C**: Advanced statistical methods and earth system modelling.

Topic B: Coral & reef-scale response to current environmental stress aims to understand how corals and coral reef ecosystems respond to the current rise in the frequency of stress events. Recent progress in coral geochemistry allows, for the first time, to fully characterize the biogeochemical processes during coral calcification and its response to environmental stressors such as temperature and ocean acidification. Moreover, geochemical data extracted from coral skeletons provide a temporal perspective on the frequency of stress events and their impact on coral growth and calcification. These novel methodologies have been applied primarily to massive corals, as these are used for climate reconstructions. To understand how coral reef ecosystems will change with future warming and acidification, these novel methodologies must now be applied to other major reef-building corals, as different genera have different sensitivities to anthropogenic stressors. This will provide a dynamic picture of the ongoing changes in present-day coral reef ecosystems. Reconstructions of stress events related to marine heatwaves, pH, nutrient loading, river sediment discharge, light levels and pollution in reef waters at monthly resolution, together with coral growth and calcification rates allows identifying the most prevalent stressors on corals. This is crucial to identify potential mitigation measures, and to predict possible shifts in the dominance of major reef-building coral genera. Achieving these goals also requires knowledge of regional and basin scale temperature and biogeochemical trends and variability (**Topic A**), and likely future pathways of warming, ocean acidification and the nutrient cycle (**Topic C**). 20th century warming and internal variability differs markedly between tropical seas. These background conditions likely impact coral reef ecosystems in different ways.

Overarching research questions (Topic B)

- **What can we learn from geochemical proxies regarding coral calcification processes? Are coral calcification rates already declining? If so, what genera/species are most vulnerable?**
- **How do large-scale stressors such as rising temperatures and ocean acidification interact with local stressors (river runoff, nutrient loads, pollution) over time? Can we improve coral resilience by limiting the latter?**
- **How do corals of various genera/species respond to rising temperatures and environmental stress events, and how will this affect coral reef ecosystems in the near future?**

Key variables and methods (Topic B)

Multi-proxy geochemical data from modern (living) corals (boron isotopes and B/Ca ratios, Li/Mg, Li/Ca, U/Ca and Sr/Ca ratios) to assess calcification processes; nitrogen isotopes, Ba/Ca and Cd/Ca ratios (nutrient loading, river runoff, eutrophication); estimates of coral calcification (densitometry, computer tomography); genus and species-specific studies. From **Topic A** and **Topic C**: Regional-scale projections of past natural, current and future sea surface temperatures, frequency of extreme events (marine heatwaves, cyclones) and ocean acidification.

Topic C: Climate, reef & proxy modelling - Climate & proxy advanced statistics aims to apply advanced statistical methods to coral proxy records and instrumental datasets of ocean and atmosphere variability, and to provide and study simulations by coupled atmosphere-ocean general circulation models in comparison with coral estimates of climate and environmental variability derived from **Topic A** and **Topic B** and public databases. Simulations by earth system models will allow for dynamical interpretation of the variability observed in coral records. Pseudo proxy experiments, proxy system forward modelling and palaeoclimate data assimilation will allow progress in mutual evaluation of climate models and proxy-based reconstruction techniques towards a comprehensive understanding of tropical marine climate variability on seasonal, interannual and decadal timescales, and the development of environmental stress related metrics of coral reef ecosystem resilience. Advanced statistical simulation methods, nonlinear statistical-dynamical analysis, and mathematical frameworks for cross-frequency phase-amplitude dependencies in the climate system will allow for substantial improvements in linking observational records of climate and environmental variables and coral-based proxies including their uncertainties. This will contribute towards a fundamental understanding of the long-term interactions between different modes of tropical climate variability and related climate extremes during warm climates. Together with the information provided by **Topic A** and **Topic B**, this will ultimately lead to improved regional-scale estimates and projections of the climatic and environmental effects of rising tropical sea surface temperatures on tropical societies and coral reef ecosystems in a warming world.

Overarching research questions (Topic C)

- **Can we investigate tropical climate and reef ecosystem dynamics using pseudo proxy experiments, proxy system forward modelling and cross-scale dependencies?**
- **Can we improve coral proxy data assimilation for climate field reconstruction, mathematical descriptions of proxy response functions to temperature, and objective error estimates?**
- **What are the causes for apparent mismatches between climate model and coral proxy estimates of tropical sea surface temperature variability?**
- **Can we project coral bleaching dynamics and coral reef ecosystem changes with improved regional projections of tropical climate trends, modes of variability and extreme events?**

Key variables and methods (Topic C)

Advanced statistical methods (pseudo proxy experiments, proxy system forward modelling, nonlinear statistical-dynamical analysis, mathematical frameworks for cross-frequency phase-amplitude dependencies, statistical estimates of trends & extreme event frequency); climate & ocean field reconstructions; coral proxy data assimilation; earth system model simulations (incl. transient & isotope enabled simulations) and biogeochemical modelling (last centuries & millennia, Holocene, last interglacial(s), Pliocene, Eocene); regional-scale projections of future tropical climate and coral reef ecosystem change. From **Topic A**: Multi-century records of climate and environmental variability, trends, and frequency of extreme events during the current and past warm periods. From **Topic B**: Genus- and species-specific coral response to environmental stress events.

5.3 Coherence of planned research activities

The research activities in ***Tropical Climate & Corals*** occur along three major research topics (section 5.2). During previous meetings of the ***Tropical Climate & Corals*** network the study area, timescales and time intervals of interest, and the research output of each topic have been specified that need to be addressed in order to achieve the common goals (Figure 5). The basis of the research activities in the ***Tropical Climate & Corals*** network is the generation new coral-based proxy reconstructions of climate and environment, including estimates of their uncertainties (**Topic A**), as well as a synthesis of these records to develop reliable regional-scale composites. These data will provide baselines of natural and anthropogenic climate variability needed by **Topic B** and **C**. **Topic B** will focus on determining the thresholds beyond which changes in physical and (bio-)geochemical environmental conditions impact corals and coral reef ecosystems. Their frequency of occurrence will be determined with data from **Topic A** (past and current) and **Topic C** (likely future occurrences). Climate modelling & statistics (**Topic C**) will significantly contribute to uncertainty assessments of proxy reconstructions, and in addition provide a framework for a dynamical understanding of the climatic and environmental processes recorded by the corals. **Topic C** will also benefit from studying and assessing the increasing number of coral reconstructions available from public databases (Figure 2). The strategical balance between the different sub-disciplines of ***Tropical Climate & Corals*** should be reflected in the final array of active projects within the Priority Programme.

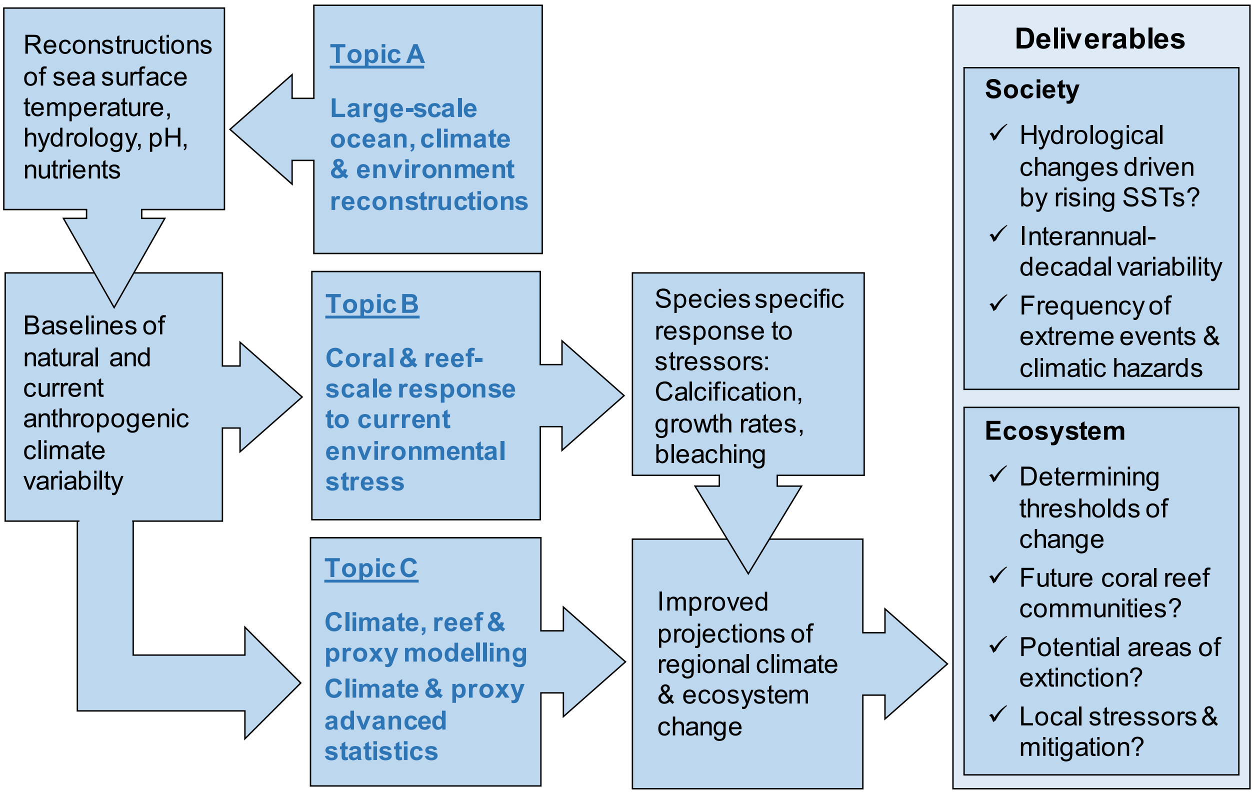

Figure 5: Schematic of the organisational structure of the Priority Programme *Tropical Climate & Corals* with its three major research topics (second column from left), expected research outputs per topic (arrows) and deliverables to be achieved within this collaborative research network. Topic A: Large-scale ocean, climate & environment reconstructions. Topic B: Coral & reef-scale response to current environmental stress. Topic C: Climate, reef & proxy modelling - Climate & proxy advanced statistics. See section 5.2 for detailed descriptions of the research topics.

The close interaction between individual projects and between topics within the ***Tropical Climate & Corals*** network is facilitated by the strong external, physical and chemical control on corals, their growth and their ecosystem structure, and the fact that corals themselves archive these changes in the geochemistry of their skeletons. Climate models can simulate the same variables – at the same temporal resolution as provided by the coral archives. For example, summer SST extremes accumulating over a 3-month period are arguably the most serious thread to corals today, and monthly mean water temperatures can be reconstructed from corals over the past centuries or past warm periods. These data can then be used to assess the frequency of extreme events in a certain region/scenario. In addition, monthly temperatures are a key climatic parameter provided by climate models, and future projections are available.

Similarly, the corals' response to ocean acidification and changes in biogeochemical cycles can be inferred from living coral samples, reconstructed over past centuries and past warm periods from modern and fossil coral cores, while advanced statistical simulation methods and earth system models provide future projections. In addition, corals are ideal archives to infer changes in hydrology, a key parameter determining the impact of future warming on tropical societies that is difficult to project in current climate models. Moreover, the magnitude of decadal and multidecadal climate variability inferred from corals can be compared with decadal and multidecadal variability indicated by climate models, as the latter still tend to underestimate low-frequency variability in tropical sea surface temperatures.

To foster cooperation between **Topic A**, **B**, and **C**, ***Tropical Climate & Corals*** is open for ***Joint Projects*** of two to three principal investigators, which should pursue an interdisciplinary approach. ***Joint Projects*** will provide a bridge between the various disciplines of ***Tropical Climate & Corals,*** and promote interdisciplinary collaboration. For example, ***Joint projects*** can combine past climate reconstructions and climate modelling to improve regional-scale projections of temperature and hydrology. Climate statistics, past climate reconstructions and current ecosystem response can be combined to determine species-specific bleaching thresholds and their frequency of occurrence in the past (for example by applying Bayesian statistics to the proxy data) and in the future (by analysing regional-scale model results). While we cannot provide details on ***Joint Projects*** given that Priority Programs are open calls, successful ***Joint Projects*** should focus on one common goal that is crucial for the overall objectives of ***Tropical Climate & Corals*** and that can only be achieved by synergies of the proponents involved. In addition, ***Focus Projects*** with single principal investigators are invited, which concentrate on one topic (e.g., last centuries' calcification or SST changes at a certain reef site) or provide specific expertise or service (e.g., climate modelling, climate statistics, or improved radiometric dating methods). ***Focus Projects*** will allow in-depth study of a key topic, and provide essential baseline information for other ***Focus Projects*** and especially the ***Joint Projects***. In this way, ***Tropical Climate & Corals'*** concept of ***Joint Projects*** and ***Focus Projects*** will stimulate interdisciplinary collaboration and joint writing of articles for international scientific journals. ***Tropical Climate & Corals*** also encourages sample and data sharing between research groups, for multi-proxy studies, advanced statistical analysis and climate model intercomparisons (section 5.4).

5.4 Strategies for collaborating / networking across disciplines and locations

A successful collaboration within the Priority Programme ***Tropical Climate & Corals*** is fostered by its clear focus on the physical and (bio-)geochemical environmental parameters that are (1) archived in coral skeletons at monthly and higher temporal resolution, (2) govern coral calcification and growth, and (3) are provided by earth system models at the same monthly resolution as the coral archive, allowing model-data comparisons as well as future projections.

A close interaction between the three major topics of ***Tropical Climate & Corals*** will significantly advance our understanding of global climate change and its interaction with modes of tropical climate variability, the impact this has on tropical countries and coral reef ecosystems today, and likely future changes.

Tropical Climate & Corals will benefit from participation of researchers from various institutions (Universities, Helmholtz Centres, Max-Planck Institutes, Leibniz Centres and Institutions) throughout Germany, representing a variety of disciplines such as palaeoclimatology and climatology, climate modelling and climate statistics, coral geochemistry and calcification, coral reef ecology and radiometric dating.

The strong interest to actively contribute to the emerging field of ***Tropical Climate & Corals*** is demonstrated by the large number of scientists who participated in the multidisciplinary discussions at the *DFG Rundgespräch* (*DFG Round Table*) *Tropical Coral Archives* (29-30 January 2018, 35 participants from 19 German institutions) and corresponding workshops with international (28 September 2017, 38 participants from 8 countries) and national scope (15-16 November 2016, 26 participants from 12 German institutions) held in Bremen (*MARUM*), Germany over the last years, initiated and organised by *T. Felis*, *M. Pfeiffer*, and *J. Zinke*.

Tropical Climate & Corals intends to go beyond the usual annual status seminars of Priority Programmes to foster interdisciplinary research. ***Tropical Climate & Corals*** intends to establish efficient strategies for data and sample sharing, as well as collaborating and networking across the various disciplines and locations involved from the very beginning and throughout the six years duration of the programme. ***Tropical Climate & Corals*** aims to synthesize the German multidisciplinary expertise and analytical and computational infrastructure in this field.

Once funded, ***Tropical Climate & Corals*** will start with a **kick-off seminar mandatory** for all principal investigators and project scientists that discusses our current level of understanding in all three research topics, the burning questions of each field and the physical and geochemical parameters that will help to address them. Major environmental parameters needed by various research groups will be identified and their required forms (temporal resolution, age control, uncertainty estimates) and formats will be discussed. For **Topic A, B** and **C**, **topic leaders** will be elected by participants of the kick-off meeting, who will ensure a continuous exchange between (1) members of their research topic analogous to *PAGES* working groups, and (2) between topics via regular teleconferences. They will also help the **coordinators** of ***Tropical***

Climate & Corals to prepare **annual status seminars** and identify burning questions that need to be discussed during **topical meetings** (see below).

Tropical Climate & Corals encourages the sharing of sample material and proxy data between research groups. Following the kick-off meeting, effective data management and sample sharing strategies will be implemented in order to ensure a smooth cooperation between projects. ***Tropical Climate & Corals*** will develop a meta-database of sample material and proxy data available within the network. To access the unpublished proxy data, a password-protected database will be created at the information system *PANGAEA* (*www.pangaea.de*) that facilitates easy data sharing between members of the ***Tropical Climate & Corals*** network. This will promote the generation of multi-proxy reconstructions, and research groups that focus on novel, time-consuming proxies such as nitrogen and boron isotopes will benefit from prior identification of change points or extreme events, for example in high-resolution coral Sr/Ca records. Climate modellers and statisticians will benefit from early access to unpublished data.

The **kick-off seminar** will be followed by **two annual meetings (2-3 days each)** in Germany of the entire network, **mandatory** for all principal investigators and project scientists. The **first annual meeting** will be a **conventional status seminar**, where the progress in individual projects will be presented in talks and posters under the overall umbrella of the multidisciplinary scope of ***Tropical Climate & Corals***, with time for interdisciplinary discussions and the identification of new synergies among individual projects to further strengthen collaboration. At each annual status seminar, the sample/data sharing and management strategies will be reviewed and, where necessary, improved.

The **second meeting of a year** will always be a **topical meeting**, dedicated to a burning question in one of the three major research topics, aiming at interdisciplinary discussions and the **writing** of **multi-author review** or **perspective articles** for international peer-reviewed scientific journals. Participation in the topical meetings will open the way for active input and co-authorships on these articles. In this way, ***Tropical Climate & Corals*** builds on the overall success of the workshops in Bremen in 2016, 2017 and 2018, and aims to establish an interdisciplinary collaboration of the *German* ***Tropical Climate & Corals*** network throughout the duration of the Priority Programme and beyond.

5.5 Early career support, promotion of female researchers, family-friendly policies

Tropical Climate & Corals will actively promote young scientists at various stages in their careers, including PhD students, postdocs and junior principal investigators on temporary positions. We explicitly welcome independent contributions from outstanding young scientists eligible for funding by the *DFG*. Suitable programmes include temporary positions for principal investigators ("Eigene Stelle"). Enthusiastic postdocs and junior principal investigators are encouraged to volunteer as **topic leaders**, to gain valuable experience with collaborative research programmes, with support and guidance from the **coordinators** of ***Tropical Climate & Corals***. All postdoc and PhD student positions will be announced internationally through various channels. We offer a multi-disciplinary research environment with state-of-the-art expertise in specialized fields, and an active and challenging interaction between various disciplines that will help young earth scientists to develop the skills needed to play decisive roles in future geopolitical, global environmental, and ecosystem management challenges. Quite a number of senior researchers in ***Tropical Climate & Corals*** are actually "relatively" young and will share their experience related to the various career opportunities available in the modern research environment, e.g. as mentors for enthusiastic young scientists.

Tropical Climate & Corals will implement specific measures to promote the careers of young researchers: a three-levelled mentoring programme which addresses the specific needs of the three main groups of early career researchers (junior principal investigators on temporary positions, postdocs and PhD students). The mentoring programme will include a series of workshops on relevant topics, such as funding opportunities, proposal writing, career planning and leadership skills. Structured graduate programs for PhD students are available at the participating institutions, e.g. the Integrated School of Ocean Sciences at Kiel University, the Max Planck Graduate Center in Mainz and the graduate school GLOMAR at MARUM/University of Bremen. In addition, all PhD students will be advised by a panel selected from members of

Tropical Climate & Corals, comprising researchers from the relevant major research topics, plus at least one independent researcher from a different field. Annual summer schools will be organized for students and postdocs, and include lectures and courses from internationally renowned experts in relevant fields. A young scientist mobility scholarship will be available to support research initiatives developed by PhD students and postdocs that are not covered by individual research projects of ***Tropical Climate & Corals***. These scholarships may fund visits to other national and international laboratories, sampling campaigns or extended research visits to collaborating institutions abroad. In addition, postdocs and PhD students are encouraged to join existing networks of young scientists, such as the *Future Earth PAGES Early-Career Network* (*ECN*) and *YESS* (*Young Earth System Scientists community*), and to attend conferences for young marine researchers (*YOUMARES*, *ICYMARE*, *Young Reef Scientists Meeting*).

Tropical Climate & Corals is dedicated to the promotion of female scientists and to family friendly policies for both men and women. The participating institutions are fully compliant with the gender equality concepts of the DFG. All participating institutions provide family support offices that offer counselling on family affairs and work-life balance, and provide regular and short-term childcare facilities. ***Tropical Climate & Corals*** will receive support from these family support services, for example by providing childcare for employees and in the form of flexible on-site childcare during workshops and summer schools.

Tropical Climate & Corals aims to increase the number of female scientists at the PhD and postdoc level above the current average following the “cascade” model. Open positions will be advertised on female scientists networks (e.g., The Earth Science Jobs Network sponsored by the Earth Science Women’s Network). Gender-balanced commissions will ensure a fair selection process. ***Tropical Climate & Corals*** supports flexible working hours for all its employees. Since the number of women in Geosciences decreases significantly with academic level, ***Tropical Climate & Corals*** will implement additional measures to encourage women to pursue an academic career. For example, ***Tropical Climate & Corals*** will invite world leading female scientists to annual workshops as “role models” (e.g., *Janice Lough* [*AIMS*], *Kim Cobb* [*Georgia Tech*], *Nerilie Abram* [*ANU*], *Helen McGregor* [*Univ. Wollongong*], *Bette Otto-Bliesner* [*NCAR*], *Kristine DeLong* [*Louisiana State*], *Nathalie Goodkin* [*EOS*]). The mentoring program for female young scientists will offer career counselling tailored to their needs. The accompanying workshops will contain modules that focus on the challenges of balancing family life and a scientific career. While these modules will specifically address the needs of female scientists (based on our current role models), they are open to all young scientists, as the number of dual career couples, were both partners are actively involved in family care, is currently increasing. ***Tropical Climate & Corals*** would like to encourage this trend. Topics covered will range from legal matters (DFG projects: parental leave, project extensions, and possible compensations for project leaders; parental leave in the “Wissenschaftszeitvertragsgesetz”) to practical information, for example on the various forms of childcare available in Germany or how to balance dual careers in academia. Regular meetings of female scientists from all levels (including senior researchers) will help young female scientist to develop their own network. During the previous three meetings of the ***Tropical Climate & Corals*** network (*National Kick-Off Workshop* 2016, *International Workshop* and *session* at *GeoBremen 2017*, and *DFG Rundgespräch/DFG Round Table* 2018) the percentage of female participants was on average 25%.

5.6 Networking of planned research activities within the international research system

The planned research activities of ***Tropical Climate & Corals*** are of high relevance for global climate and environmental change, and will be integrated into the international research system by various networking activities. These include the organisation of and contribution to scientific sessions at prominent international conferences (*European Union General Assembly*, *American Geophysical Union Fall Meeting & Ocean Sciences Meeting*, *International Coral Reef Symposium*, *International Conference on Paleoceanography*), and the organisation of splinter meetings and pre- or post-conference workshops on ***Tropical Climate & Corals*** at these conferences open to the international scientific community. Examples for pre-conference workshops are the *Future Earth Past Global Changes* (*PAGES*) *CoralHydro2k meeting* at the

13th International Conference on Paleoceanography in Sydney (2019) organised by *T Felis*, (*MARUM*), *N. Abram* (*ANU*), & *K. Cobb* (*Georgia Tech*), and workshops at the *14th International Coral Reef Symposium 2020* (Bremen) where *T. Felis* is organising committee member.

Tropical Climate & Corals will invite outstanding international scientists (preferentially female) to its annual meetings and topical workshops in Germany for keynote lectures, and will also encourage remote participation to reduce the CO_2 footprint. This will fuel mutual exchange of expertise and joint multi-author publications to further increase the international awareness of the Priority Programme and its integration within the international research system. Early career scientists will greatly benefit from the presence of outstanding international scientists at annual meetings and workshops, and opportunities may arise for research visits and jobs at international laboratories during the duration of ***Tropical Climate & Corals*** and beyond.

Tropical Climate & Corals will integrate its research activities into ongoing *Future Earth Past Global Changes* (*PAGES*) initiatives such as *Warmer Worlds*, the *PAGES-PMIP Working Group on Quaternary Interglacials*, or the *2k Network* including the *CoralHydro2k* project. Members of ***Tropical Climate & Corals*** are leading and/or actively involved in the *PAGES CoralHydro2k* initiative launched in 2017. *PAGES* is a *Global Research Project* of *Future Earth* and a scientific partner of the *World Climate Research Programme* (*WCRP*).

Tropical Climate & Corals will also provide a palaeo-perspective on ongoing activities in *CLIVAR* (*Climate and Ocean: Variability, Predictability and Change*). *CLIVAR* is a core project of the *World Climate Research Programme* (*WCRP*) and aims to describe and understand the dynamics of the coupled ocean-atmosphere system and to identify processes responsible for climate variability, change and predictability on seasonal, interannual, and decadal timescales. The new proxy data generated in ***Tropical Climate & Corals*** will directly contribute to these goals.

Tropical Climate & Corals, with its focus on recent and past warm periods of Earth's history, will define a baseline for the interpretation of climate and environmental variability derived from corals of glacial periods of the Pleistocene drilled by the *International Ocean Discovery Program* (*IODP*), for example, the postponed *IODP Expedition 389* (*Hawaiian Drowned Reefs*).

Tropical Climate & Corals will integrate its research activities into the international *Marine Annually Resolved Proxy Archives* (*MARPA*) initiative, a scientific community effort to build consensus on coral data and sample archiving procedures. ***Tropical Climate & Corals*** will make it mandatory to make all data generated within the Priority Programme freely available to the international research community and the general public through archiving at the information system *PANGAEA* (*www.pangaea.de*). *PANGAEA* is an Open Access library aimed at archiving georeferenced data from earth system research, guaranteeing long-term availability through commitment of the hosting institutions *Alfred Wegener Institute*, *Helmholtz Center for Polar and Marine Research* (*AWI*) and *Center for Marine Environmental Sciences*, *University of Bremen* (*MARUM*). Datasets can be identified, shared, published and cited using a Digital Object Identifier (DOI). *PANGAEA* is member of the *World Data System* (*WDS*) of the *International Council for Science* (*ICSU*). Data archiving follows *European Commission Guidelines on Open Access to Scientific Publications and Research Data in Horizon 2020* and *DFG recommendations for safeguarding good scientific practice*. *PANGAEA* is aligned with *OECD Principles and Guidelines for Access to Research Data from Public Funding*, and *FAIR Guiding Principles for scientific data management and stewardship*. ***Tropical Climate & Corals*** will also provide data through *NOAA's National Centers for Environmental Information* (*NCEI*) *World Data Service for Paleoclimatology*, and will support innovative data archiving formats such as *LiPD* (*Linked Paleo Data*) within *LinkedEarth* and *PaCTS1.0: A Crowdsourced Reporting Standard for Paleoclimate Data*.

6 Differentiation from other on-going programmes on related topics, e.g. Collaborative Research Centres, Research Units, programmes by other funding agencies

Tropical Climate & Corals limits its scope to modern scleractinian reef corals as they exist today, with a focus on the last centuries and past warm periods (Holocene, last interglacial(s), Pliocene, Eocene), and has a strong focus on recent, ongoing tropical climate variability and environmental changes with the aim of improving future projections at societally relevant timescales. In Germany, some larger projects with different research foci have potential for interaction with ***Tropical Climate & Corals***:

CHARON: "*Marine carbonate archives: controls on carbonate precipitation and pathways of diagenetic alteration*" is a *DFG Research Unit* (*FOR 1644*, since 2013) that investigates geochemical, physical and micro-biological parameters of Phanerozoic (the last 541 million years) marine environments that control inorganic and microbially-induced carbonate precipitation and diagenesis. Members of CHARON are part of ***Tropical Climate & Corals***, providing state-of-the-art expertise on the influence of biomineralisation and carbonate diagenesis on coral proxies.

PALMOD: The German Climate Modelling initiative "*From the Last Interglacial to the Anthropocene - Modeling a Complete Glacial Cycle*" (funded by German BMBF since 2015) aims at transient simulations of the last glacial-interglacial cycle using earth system models and covering climate dynamics on seasonal to multi-millennial timescales. These global simulations form a valuable basis to test the hypotheses proposed within ***Tropical Climate & Corals***.

SeaLevel: "*Regional Sea Level Change and Society*" is a *DFG Priority Programme* (SPP 1889, since 2016) that aims at understanding regional sea level change and its impacts on societies in the North and Baltic Seas and South-East Asia. ***Tropical Climate & Corals*** will not study climate-related sea level change, but important synergies with the SPP SeaLevel are possible.

TERSANE: "*Temperature – related stresses as a unifying principle in ancient extinctions*" is a *DFG Research Unit* (*FOR 2332*, since 2016) that focuses on biodiversity, mass extinctions and reef crisis in the Phanerozoic. The focus is on Paleozoic and Mesozoic times (541-66 million years ago), which will provide useful background information for ***Tropical Climate & Corals***.

7 Qualification of coordinator to manage a research network

Tropical Climate & Corals will be **coordinated by *T. Felis* (Year 1-3)** and ***M. Pfeiffer* (Year 4-6)**. ***Tropical Climate & Corals*** is a community-based effort originally initiated by *T. Felis*, *M. Pfeiffer* and *J. Zinke* (now at Leicester University, UK). **The shared coordination underlines the commitment of the *Tropical Climate & Corals* network to a close cooperation between various universities and research institutions across Germany** during the 6 years (2 x 3 years) duration of the Priority Programme and beyond.

…[…]

8 List of potential applicants

This list includes colleagues who have expressed their interest to participate in a *Priority Programme* on ***Tropical Climate & Corals*** by submitting research ideas (*), and/or by attending the *DFG Rundgespräch* (*DFG Round Table*) "*Tropical Coral Archives*" (29-30 January 2018, Bremen), the corresponding *International Workshop & Session* at *GeoBremen 2017 International Conference*, or the *National Kick-Off Workshop* (15-16 November 2016, Bremen) that were initiated and organised by *T. Felis*, *M. Pfeiffer*, and *J. Zinke*.

Coral palaeoclimatology

1. Dr Eleni Anagnostou*, *GEOMAR Kiel*
2. Prof Dr Thomas Brachert*, *U Leipzig*
3. Dr Nicolas Duprey*, *MPI-C Mainz*
4. Dr Thomas Felis*, *MARUM U Bremen*
5. Prof Dr Eberhard Gischler*, *U Frankfurt*
6. PD Dr Nikolaus Gussone, *U Münster*
7. Dr Edmund C Hathorne*, *GEOMAR Kiel*
8. Dr Steffen Hetzinger*, *U Hamburg*
9. Dr Henning Kuhnert, *MARUM U Bremen*
10. Dr Jürgen Pätzold, *MARUM U Bremen*
11. Prof Dr Miriam Pfeiffer*, *U Kiel*
12. Dr Henry C Wu*, *Leibniz ZMT Bremen*
13. *Prof Dr Jens Zinke*, U Leicester (United Kingdom)*

Coral proxies

14. Dr Michael Deveaux, *U Frankfurt*
15. Prof Dr Martin Frank, *GEOMAR Kiel*
16. Dr Dieter Garbe-Schönberg, *U Kiel*
17. Prof Dr Gerald Haug*, *MPI-C Mainz*
18. Prof Dr Adrian Immenhauser, *U Bochum*
19. Dr Tobias Kluge, *U Heidelberg*
20. Dr Martin Kölling, *MARUM U Bremen*
21. Dr Stefan Krause*, *GEOMAR Kiel*
22. Dr Volker Liebetrau*, *GEOMAR Kiel*
23. Dr Alfredo Martínez-García*, *MPI-C Mainz*

24. Dr Daniela Ransby*, *AWI Bremerhaven*
25. Dr Lars Reuning, *U Kiel*
26. *Dr Elias Samankassou*, U Geneva (Switzerland)*
27. Prof Dr Ulrich Struck, *Leibniz MfN & FU Berlin*

Coral dating

28. Prof Dr Anton Eisenhauer*, *GEOMAR Kiel*
29. Prof Dr Norbert Frank*, *U Heidelberg*
30. Prof Dr Janet Rethemeyer*, *CologneAMS U Cologne*
31. Prof Dr Denis Scholz*, *U Mainz*
32. Dr Andrea Schröder-Ritzrau, *U Heidelberg*

Coral reef systems

33. Dr Sonia Bejarano, *Leibniz ZMT Bremen*
34. Prof Dr Reinhold Leinfelder, *FU Berlin*
35. PD Dr Markus Reuter*, *U Leipzig*
36. Prof Dr Claudio Richter*, *AWI Bremerhaven*
37. Dr Alessio Rovere, *MARUM U Bremen*
38. Dr Gertraud M Schmidt*, *AWI Bremerhaven*
39. Dr Marlene Wall*, *GEOMAR Kiel*
40. Prof Dr Hildegard Westphal*, *Leibniz ZMT Bremen*
41. Prof Dr Christian Wild, *U Bremen*
42. *Prof Dr Martin Zuschin*, U Vienna (Austria)*

Climate modelling

43. Dr Jürgen Bader*, *MPI-M Hamburg*
44. Dr Bijan Fallah, *FU Berlin*
45. Dr Javier García-Pintado*, *MARUM U Bremen*
46. Dr Johann Jungclaus*, *MPI-M Hamburg*
47. Prof Dr Gerrit Lohmann*, *AWI Bremerhaven*
48. Dr Stephan Lorenz*, *MPI-M Hamburg*
49. Dr Ute Merkel*, *MARUM U Bremen*
50. Dr Wonsun Park, *GEOMAR Kiel*
51. Dr André Paul, *MARUM U Bremen*
52. Prof Dr Birgit Schneider*, *U Kiel*
53. Dr Joachim Segschneider*, *U Kiel*
54. Dr Martin Werner*, *AWI Bremerhaven*

Climate & proxy advanced statistics

55. Prof Dr Reik Donner*, *U Magdeburg-Stendal & PIK Potsdam*
56. Dr Monica Ionita*, *AWI Bremerhaven*
57. Dr Thomas Laepple*, *AWI Potsdam*
58. Dr Manfred Mudelsee*, *CRA company Bad Gandersheim* & *AWI Bremerhaven*
59. Dr Kira Rehfeld, *U Heidelberg*
60. Dr Norel Rimbu*, *AWI Bremerhaven*
61. Dr Sebastian Wagner*, *HZG Geesthacht*
62. Dr Eduardo Zorita*, *HZG Geesthacht*

9 Justification of requested annual funding amount for the first funding period of one, two or three years

In order to realise a DFG Priority Programme on ***Tropical Climate & Corals***, we plan 2 funding periods of 3 years each.

Based on the number of potential applicants and research groups and institutions involved, and of colleagues who provided research summaries, **we plan with about 23 funded projects**. Each project will have 1 project scientist (PhD student or Postdoctoral researcher) funded by the Priority Programme. **We plan with a total of 15 PhD students and 8 Postdoctoral researchers**. In addition, each project will have funding for student assistants, consumables (analytical and laboratory expenses), software and light equipment, travel expenses (conferences, field trips), and publication expenses.

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