Paleoclimate and seasonality on Sumatra during the Late Glacial and Holocene

Insights from biomarkers and climate model simulations

Lars Petter Hällberg
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Academic dissertation for the Degree of Doctor of Philosophy in Geochemistry at Stockholm University to be publicly defended on Friday 3 May 2024 at 09.00 in William-Olssonsalen, Geovetenskapens hus, Svante Arrhenius väg 14.

Abstract

Deep atmospheric convection in the Indo-Pacific Warm Pool (IPWP) is a key driver of the Hadley and Walker Circulations that modulate the Asian-Australian monsoons and the El Niño Southern Oscillation (ENSO). Temperature and rainfall seasonality, i.e., the amount and timing of precipitation, impacts ecosystems, carbon content in soils and peats, and human livelihoods. Yet, past climate variability in the IPWP is poorly constrained. The Maritime Continent, located in the center of the IPWP remains a “quantification desert”, with a scarcity of terrestrial paleoenvironmental reconstructions.

This thesis investigates the evolution of temperature, precipitation amount and seasonality over the Late Glacial (14.7-11.7 ka BP) and the Holocene (last 11.7 ka). This is achieved by combining climate model simulations and lipid biomarker analyses of terrestrial peat archives from Sumatra. Temperature and seasonality were explored by analysis of climate model simulations for the Late Glacial and Holocene. Microbial membrane-derived glycerol dialkyl glycerol tetraethers (GDGTs) were investigated as temperature and hydro-environmental proxies. Using n-alkane distributions, the abundance of algae, aquatic and terrestrial plants was reconstructed and linked to past hydroclimate variability. The hydrogen isotopic composition (dD) of the n-alkanes was then used to disentangle seasonal and annual precipitation signals.

The analysis of Sumatran GDGTs revealed that bacterial community shifts of the GDGT producers had a strong impact on reconstructed temperatures, and that H-shaped branched GDGT isomers are good tracers of such community shifts. The branched GDGT temperature reconstruction indicates gradual warming over the Holocene, consistent with models and nearby marine records.

Rainfall seasonality has shifted drastically over the studied time frame, in particular during the end of the Late Glacial, and between 6-4.2 ka BP. The Late Glacial climate was characterized by a much stronger seasonality, with a cold and dry Asian winter monsoon suppressing atmospheric deep convection in the region. The resulting mean state conditions resembled the atmospheric circulation and sea surface temperature patterns during extreme El Niño events in the modern climate. The Mid-Holocene (6-4.2 ka BP) was characterized by increased seasonality, with alternating droughts and heavy rains due to strong monsoon precipitation and longer dry season.

The Early Holocene was relatively dry. Wetter conditions started around 7-6 ka BP, and peaked at 4.5-3 ka BP. This is consistent with a dD reconstruction on Sulawesi, but 1.5-2 ka later than indicated by speleothem oxygen isotopic (δ18O) records on Sumatra and Sulawesi. However, the speleothem records closely follow algal dD values, interpreted here as a seasonal monsoon signal, suggesting that speleothems in the region reflect monsoonal precipitation rather than an annual signal. Rapid drying was reconstructed for the Late Holocene, starting at 3 ka BP, co-occurring with the onset of strengthened ENSO variability. The Late Holocene drying caused drying out and decomposition of peat in one of the studied cores which resulted in a hiatus of 1700 years, highlighting the importance of hydroclimate for peat and carbon accumulation in tropical wetlands.

In conclusion, this dissertation enhances our understanding of past climatic conditions in the Maritime Continent and contributes toward constraining the evolution of temperature, precipitation, and monsoon-driven seasonality over the Late Glacial and Holocene in a region that has a scarce coverage of paleoclimate proxy information. Additionally, the methodological aspects of this thesis advance terrestrial paleoclimatological reconstructions by constraining source shifts of GDGTs and proposing a novel approach to disentangle seasonal and annual precipitation signals from dD.

Keywords: Holocene, Late Glacial, biomarkers, organic geochemistry, climate model, hydrogen isotopes, stable isotopes, paleoclimate, alkanes, GDGT, brGDGT, H-GDGT, bacterial community shifts, paleothermometry, precipitation reconstruction, peat.

Stockholm 2024
http://urn.kb.se/resolve?urn=urn:nbn:se:su:diva-227455


Department of Geological Sciences
Stockholm University, 106 91 Stockholm
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This thesis investigates the evolution of temperature, precipitation amount and seasonality over the Late Glacial (14.7-11.7 ka BP) and the Holocene (last 11.7 ka). This is achieved by combining climate model simulations and lipid biomarker analyses of terrestrial peat archives from Sumatra. Temperature and seasonality were explored by analysis of climate model simulations for the Late Glacial and Holocene. Microbial membrane-derived glycerol dialkyl glycerol tetraethers (GDGTs) were investigated as temperature and hydro-environmental proxies. Using n-alkane distributions, the abundance of algae, aquatic and terrestrial plants was reconstructed and linked to past hydroclimate variability. The hydrogen isotopic composition (δD) of the n-alkanes was then used to disentangle seasonal and annual precipitation signals.

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In conclusion, this dissertation enhances our understanding of past climatic conditions in the Maritime Continent and contributes toward constraining the evolution of temperature, precipitation, and monsoon-driven seasonality over the Late Glacial and Holocene in a region that has a scarce coverage of paleoclimate proxy information. Additionally, the methodological aspects of this thesis advance terrestrial paleoclimatological reconstructions by constraining source shifts of GDGTs and proposing a novel approach to disentangle seasonal and annual precipitation signals from δD.
Sammanfattning


Kunskap om förhistoriska klimatvariationer i IPWP är därför viktiga dels för att förbättra förståelsen för den globala klimatdynamiken, samt för att förbättra klimatmodellerna som används för att förutsäga framtida klimatförändringar. Nederbörd och, även variationer av säsongerna, särskilt mängden och tidpunkten för nederbörd har en stor påverkan på ekosystemen, kolinlagring i jordar samt människors levebröd. Trots det så är förhistoriska variationer i hydroklimat og säsongsvariation i IPWP otillräckligt utforskad. Den Maritima Kontinenten, öarna belägna in centrum av IPWP, är en "kvantifieringsöken" där det råder brist på terrestra paleomiljörekonstruktioner. Särskilt saknas förståelse av temperaturfluktuationer från land, och säsongsvariation i hydroklimat är en aspekt som har varit utmanande att kvantifiera i paleoklimatstudier.


Analyserna av GDGTs från Sumatra visade att variationer av den bakteriella sammansättningen hade en stark påverkan på den rekonsstruerade temperaturen, och en ny metod för att detektera skiften i den bakteriella sammansättningen baserat på H-formade GDGTs (H-GDGTs) presenteras. Den GDGT-baserade temperaturenrekonstruktionen visade att det sket en gradvis uppvärmning över holocen, i linje med modeller och närliggande marina rekonsstruktions. Denna uppvärmningstrend står i kontrast till de flesta rekonsstruktions i den östra delen av IPWP samt även globala temperaturtrenden, vilket indikerar förändringen IPWP havsyttetemperatur-mönster under tidiga och mitten av holocen jämliöf med idag.

Vad gäller hydroklimat indikerar derutande att variationer i nederbördssäsonger har förskiutits drastiskt under den studerade tidsläggen. Två perioder av intensiv nederbördssäsongsvariation noterades, under slutet av senglacial till början av tidig holocen och mellan 6–4.2 ka BP. Det senglaciala klimatet kännutecknades av en mycket starkare säsongssvariation, med en kall och torr asiatisk vintermonsun som undertryckte atmosfärisk djupkonvektion över den Maritima Kontinenten. De resultaterande förhållandena liknar atmosfärscirkulationer och havsyttetemperaturmönster under extrema El Niño-händelser i det moderna klimatet. De kräftiga säsongsväxterna mellan 6–4.2 ka BP rekonsstruerades från sammanställningen av biomassan, δD från alger och terrestra växter samt GDGTs, och kännutecknades av växtlande torka och kräftiga regn på grund av en stark monsun och lång torrperiod. Under dessa två perioder ökade även förekomsten av förbränningsrester i torvärven, som indikerar en ökning av skogsbränder, vilket ytterligare stöder att en intensifiering av säsongerna skett.

Den rekonsstruerade årliga nederbördindikerar att tidiga holocenen var relativt torr, och blötare förhållanden påbörjades mellan 7–6 ka BP, med nederbördssmaximum 4,5–3 ka BP. Det senare är en linje med en δD-rekonstruktion från Sulawesi, men 1,5–2 tusen år senare än vad som indikeras av syreisotoper (δ18O) i dropptenar från Sumatra och Sulawesi. Däremot följer dropptrens-rekonstruktionerna δD-värdet från alger, vilka här tolkats som en monsunsignal. Detta tyder på att rekonsstruktioner från dropptenar i regionen återspeglar monsun-nederbörd snarare än en årlig signal. Drastisk minska av nederbörde rekonsstruerades för senare delen av holocen, med start runt 3 ka BP, samtida med ökad ENSO-variation. Minskningen i nederbörd orsakade uttorkning och nedbrytning av torv i en av kärnorna,
vilket resulterade i en paus torvackumulation under 1700 år, vilket understryker vikten av hydroklimat i torvuppbynad och kol-lagring i tropikerna.

Sammanfattningsvis förbättrar denna avhandling vår förståelse av tidigare klimatförhållanden på den Maritima Kontinenten och bidrar till att kvantifiera utvecklingen av temperatur, nederbörd och monsun-driven säsongsvariation under senglacial tid och holocen. Avhandling bidrar med viktig temperatur- och nederbörsdata från en region som är understudad. Dessutom har projektet bidragit till att utveckla de metoder som används för att rekonstruera temperatur, hydroklimat samt variationer i säsonger vilket bidrar till att öka förståelse av tidigare klimatförhållanden.
List of papers

This thesis is based on three papers. The first paper was published in *Climate of the Past* and presents results from climate model simulations. The second paper, published in *Organic Geochemistry*, investigates paleo-temperature reconstructions using GDGTs. The third manuscript, focused on hydroclimate and seasonality reconstructions, is in a near-final state and will be submitted to *Quaternary Science Reviews*.


Author contributions

**Paper I:** PH and FS designed the study in detail with broad guidance by RS. FS conducted CESM1 climate model simulations. XK and PH analyzed the TraCE21ka data. PH created the figures and proxy compilation. PH led the data analysis and PH and FS wrote the manuscript with contributions from all authors.

**Paper II:** PH, RS and FS designed the study. PH analyzed the Diatas and Singgalang samples and supervised YS and GJB during their thesis work on Maninjau and Padang core materials. PH analyzed the model data together with QZ and FS. QZ ran the EC-Earth simulation. HR participated in all sampling, field planning and acquisition of field permits. MP did peat and lake coring. PH samples the Singgalang soil transect. All authors contributed to and commented on the final manuscript.

**Paper III:** PH: designed the study with broad guidance from supervisors MK, FS and RS. PH led the investigation and manuscript writing, with input from all authors, particularly from MK and RS. AH contributed to the biological interpretation. JS aided PH in constructing rbacon age models. GJB did lab work and analysis of GDGTs with guidance from PH. KY contributed via discussions of ideas and interpretation. HR participated in sampling, field planning and acquisition of field permits. All authors: feedback on the manuscript and actively participated in discussions of ideas.


Artificial intelligence tools were used for spell checking of the thesis with the software Grammarly, and generating the cover page image using Midjourney and the prompt ‘tropical ecosystem in the style of John Bauer’.
Publications not included in this thesis


5. Sechi D., Stevens T., Hällberg, P. L., Molnár M., Buylaert, J-P., Schneider, R., Edward, C., Smittenberg, R.H. Andreucci S, Pascucci., High-resolution luminescence and radiocarbon dating of Holocene aeolian silt (loess) accumulation in Greenland, *Quaternary Geochronology, under review*
Contents

Abstract ........................................................................................................................................ 1
Sammanfattning ............................................................................................................................ 2
List of papers ............................................................................................................................. 4
Author contributions ................................................................................................................... 5
Publications not included in this thesis ....................................................................................... 6
Introduction .................................................................................................................................. 8
Research objectives ..................................................................................................................... 11
Background .................................................................................................................................. 12
Peatlands – the paleoenvironmental archive .............................................................................. 12
Lipid biomarkers and their isotopic composition as climate proxies ........................................ 13
Glycerol Dialkyl Glycerol Tetaethers – GDGTs ........................................................................ 13
n-alkane distributions .............................................................................................................. 17
n-alkane hydrogen isotopic composition .................................................................................. 17
Climate model simulations ......................................................................................................... 18
Study area .................................................................................................................................... 19
Sites ............................................................................................................................................ 19
Climate ....................................................................................................................................... 20
Methods ...................................................................................................................................... 23
Climate model simulations ......................................................................................................... 23
Geochemistry ............................................................................................................................. 23
Extraction and fractionation ........................................................................................................ 24
GDGTs ...................................................................................................................................... 24
n-alkanes .................................................................................................................................. 24
Bulk elemental analysis: .......................................................................................................... 24
Age models ................................................................................................................................. 25
Summary of papers ...................................................................................................................... 26
Paper I ......................................................................................................................................... 26
Seasonal aridity in the Indo-Pacific Warm Pool during the Late Glacial driven by El Niño-like conditions ................................................................................................................... 26
Paper I - Contributions to the field ............................................................................................ 29
Paper II ....................................................................................................................................... 30
Branched GDGT source shift identification allows improved reconstruction of an 8,000-year warming trend on Sumatra ........................................................................ 30
Paper II - Contributions to the field ............................................................................................ 34
Paper III ...................................................................................................................................... 35
Disentangling seasonal and annual precipitation signals in the tropics over the Holocene: insights from δD, alkanes and GDGTs .................................................................................... 35
Paper III - Contributions to the field ............................................................................................ 38
Outlook and unpublished data ................................................................................................... 39
Paleoenvironmental reconstructions from the Diatas peatland ............................................... 39
Preliminary conclusions from Diatas ......................................................................................... 46
Conclusions ................................................................................................................................. 47
Acknowledgments ...................................................................................................................... 48
References ................................................................................................................................... 49
Introduction

Global warming poses an urgent need to reliably predict future climate change. A key aspect for understanding future changes is exploring past climate variability and its driving mechanisms. Knowledge about the climate prior to modern observations in the last decades to centuries is derived from climate model simulations and proxy reconstructions. Comparing climate model results against proxy data is also the only way of assessing their performance under boundary conditions different from the modern state, such as varied greenhouse gas concentrations, orbital forcing and ice sheet configurations.

The Indo-Pacific Warm Pool (IPWP; Fig. 1) climate and related monsoon systems directly affect more than half the global population, and knowing its past behavior is crucial for understanding the climate system and potential future change (Yamoah, 2016). The importance of the IPWP lies in its central role in affecting the global climate via teleconnections mainly governed by El Niño Southern Oscillation (ENSO) and the related atmospheric equatorial Walker Circulation, which influences Rossby waves on high latitudes and distributes heat and moisture over the globe (Yuan et al., 2018). The size and intensity of this climate hot spot, referred to as the ‘steam engine of the world’ vary on timescales ranging from intraannual (summer-winter seasonality), interannual (ENSO), to millennial (solar insolation variation due to orbital forcing) (DeDeckker, 2016).

Precipitation amount and its seasonal distribution, i.e., episodic drought and downpours versus stable ever-wet climate, is arguably one of the most important climate factors influencing ecosystems and biomes, weathering and erosion, and human livelihoods. Temperature is also a major driver of the hydrological cycle, determining evaporation rates and atmospheric convection and monsoon circulation (Mohtadi et al., 2016). Hydroclimatic variability, i.e., the variation in precipitation, evaporation and/or seasonality, is also a key factor for the tropical carbon cycle, affecting fire regime, peat accumulation and ecosystem development (Page et al., 2011).

However, proxy climate reconstructions are still scarce in the tropics, particularly for the Maritime Continent, located in the center of the IPWP. Major challenges consist of the fact that (a) terrestrial temperatures in the tropics are difficult to reconstruct, due to a (previous) lack of suitable methods, and that (b) the seasonality aspect of precipitation reconstructions has been difficult to tease out of most proxy records. Furthermore, current climate models disagree with proxies about the Holocene climate evolution. The Early-Mid Holocene (10-6 ka BP) experienced peak warmth according to global proxy reconstructions (Kaufman et al., 2020), while models show that the Early-Mid Holocene was a relatively cold period relative to the present peak warmth (Liu et al., 2014). This discrepancy is termed the “Holocene temperature conundrum” and suggests that there are still significant gaps in the understanding of the climate system – even for recent millennia – calling for further studies to increase knowledge of both proxies and models.
Figure 1. Sumatra and the Maritime Continent is located in the Indo-Pacific Warm Pool, defined as the region with surface water temperatures permanently >28 °C (encircled by the thick black line). The approximate location of the ITCZ in July and January (dashed lines) is based on Newton et al., (2006). Temperature data was derived from ERA5 1979-2020 annual average temperature (Hersbach et al., 2020).

Over the last decades, the number of temperature proxy reconstructions has increased considerably. However, very few are from the tropics, and nearly all of those are from marine sites (Kaufman et al., 2020). Although marine proxy records are crucial in understanding past climate states, they do not necessarily reflect land conditions and the oceans have a larger thermal inertia than the atmosphere and land (Sutton et al., 2007). Marine temperature proxy records usually reflect the euphotic zone (upper approx. 200m) but may be prone to seasonal and other effects such as influence by ocean currents, upwelling, shifts in productivity, etc. (Bova et al., 2021). Land-based temperature reconstructions remain rare and challenging to produce due to the lack of applicable and reliable methods. Currently, there are only around ten terrestrial temperature records for the entire tropics, and none from the tropical rainforest parts of Asia in the recent global Temperature12k database (Kaufman et al., 2020). To understand past and future climates, terrestrial records need to be considered, rather than only marine records, as the latter may be insensitive to rapid shifts, reflecting only longer timescale changes. Moreover, land ecosystems may respond differently to climate change, especially when it concerns hydroclimate, i.e., the intensity and seasonal distribution of precipitation.

In terrestrial settings, more proxy records of precipitation have been generated compared to temperature, as well as stable carbon isotopic composition ($\delta^{13}$C/$\delta^{12}$C ratio, expressed as $\delta^{13}$C in standard delta notation) of vegetation and pollen, reflecting precipitation and seasonality, but still with a low spatial resolution. Cave speleothem oxygen isotope ratios ($\delta^{18}$O/$\delta^{16}$O; expressed as $\delta^{18}$O) and leaf wax hydrogen isotope ratios (deuterium $\delta^2$H / hydrogen $\delta^1$H; expressed as $\delta^D$), reflecting past rainfall water isotopic composition, have been the main methods to estimate past precipitation. An increasing number of speleothem precipitation records have been constructed from the Maritime Continent: from Northern Borneo (Partin et al., 2007), Java (Ayliffe et al., 2013), Sulawesi (Krause et al., 2019; Yuan et al., 2023) and Sumatra (Wurtzel et al., 2018), as well as leaf wax records (Konecky et al., 2016; Niedermeyer et al., 2014; Tierney et al., 2012; Wicaksono et al., 2017). However, the seasonal component of the reconstructed convection on the Maritime Continent remains largely unexplored – i.e., to what extent the isotopes reflect seasonal or annual conditions is not yet constrained.

A regionally complex pattern of climate variability has emerged over the last decades from pollen, leaf wax $\delta^D$ and $\delta^{13}$C, and there is evidence, for example, of teleconnections between high latitude and IPWP climate in some records, but not in others (Huang et al., 2019; Partin et al., 2015), and cooling and drying during the glacial in most records (e.g., Konecky et al., 2016; Tierney et al., 2012). Notably, no significant change is observed in some records, even during the Last Glacial Maximum (LGM) (Chabangborn et al., 2018; Hu et al., 2002; Niedermeyer et al., 2014; Wang et al., 2007).

That the past temperature and precipitation evolution even during the relatively recent Late Glacial (~14.7–11.7 ka BP) and Holocene (past 11.7 ka) are poorly understood represents a major gap in the current knowledge. In this thesis, I contribute towards filling this gap in the IPWP region, by (a) climate model
simulations of Late Glacial/Early Holocene and pre-industrial climate and (b) climate reconstructions using lipid biomarker proxies on terrestrial archives from Sumatra. This interdisciplinary and multi-proxy approach is used to resolve sub-annual climate variability and study local vs. large-scale processes, and resolve the long-term climate evolution on Sumatra.
Research objectives

The overarching aim of this project is to understand how the climate has varied in the Maritime Continent over the Holocene and Late Glacial in terms of monsoons, Walker Circulation, temperature and precipitation. This is done by combining climate model simulations with proxy reconstructions from terrestrial peat archives located in Sumatra. Specifically, the aims are:

1. Use climate models (Paper I) to gain insights into the climate seasonality on interannual timescales, to further understand climate drivers on local versus large scales in the IPWP between the Late Glacial and pre-industrial climate.
2. Terrestrial temperature reconstructions (Paper II) over the Holocene, which will be among the first high-resolution terrestrial reconstructions of its kind from the IPWP.
3. Precipitation reconstructions over the Holocene, focused on rainfall seasonality and amount (Paper III and Outlook)
Background

Peatlands – the paleoenvironmental archive

Globally, around 530 GtC (Gigaton Carbon) is stored in peatlands, most of which is stored in high latitude cold and wet environments that favor slow decomposition (Hugelius et al., 2020, 2014). Some 105 GtC is stored in the tropics, of which 69 GtC is located in South East Asia and 57 GtC in Indonesia (Dargie et al., 2017; Page et al., 2011). Tropical peatlands thereby make up 20 % of global carbon storage in peats (Hugelius et al., 2020). Most Indonesian peatlands are located on Sumatra and Borneo (Page et al., 2011; Dommain et al., 2014; Fig. 2). Despite the high temperatures in the tropics, enabling fast decomposition of organic matter, peat accumulation is often faster in the tropics than in the high latitudes (Page et al., 2011). This relatively fast peat buildup at low latitudes has been suggested to be caused by a greater amount of aromatic and recalcitrant compounds and a lower fraction of carbohydrates in tropical peats compared to the high latitudes (Hodgkins et al., 2018).

Peat consists mostly of partially decomposed organic material and is defined as containing at least 65 % organic matter (Page et al., 2011). Peat accumulates when the rate of organic matter decomposition is slower than the production and deposition of biomass (Page et al., 2011). Slow decomposition in peatlands is tied to anoxia in waterlogged environments, prohibiting aerobic decomposition. Peat accumulation is thereby closely tied to hydroclimate variability and the balance between precipitation and evaporation, as well as being confined to locations with raised water tables, such as near the coast and in valley basins at highland sites (Dommain et al., 2014).

In Indonesia, peatland depths commonly reach 5-10 m or more, and mean accumulation rates in the region vary between 0.54 and 1.77 mm yr\(^{-1}\) (Dommain et al., 2011; Page et al., 2011). Most accumulation of peat in Indonesia occurred relatively recently, during the Holocene, after the sea level high stand at 6 ka BP (Dommain et al., 2014). This expansion of coastal peatlands in the Mid-Holocene was tied to the sea level transgression at the time, which resulted in a +5 m sea level relative to today (Hanebuth et al., 2011). The heightened sea level resulted in raised water table and waterlogging or even inundation of coastal areas, subsequently leading to peat formation (Dommain et al., 2014). During the LGM, the sea level was approximately 120 m lower than today, causing lowered water tables at today’s coastal peatland sites and a resulting absence of peat at the sites that currently harbor peat (Dommain et al., 2014). While Mid-Holocene sea level changes affected the coastal peatlands, highland sites were less affected, and started accumulating during the Late Glacial, but peatlands appear to be more or less absent from the region prior to 18 ka BP (Dommain et al., 2014).

The concentration of total organic carbon (TOC) is directly related to the amount of organic matter, approximately; TOC*2 = organic matter (%) (Page et al., 2011), giving information about the relative abundance of organics to inorganics (i.e., mineral particles) in sample material. The carbon to nitrogen ratio (C/N) can be used to imply the type of vegetation, since woody vegetation (rich in cellulose and lignin) contains relatively more C (C/N ratio of >20) than more proteinaceous vegetation (like grasses) and other biomass such as algal and microbial biomass with ratios of 6-10 (Ku et al., 2007; Xiao et al., 2019). The carbon isotopic composition of biomass depends on the metabolic pathway (e.g., C\(_3\) vs C\(_4\) plants), biomass type (algae, open C\(_3\) vegetation and C\(_3\) vegetation being increasingly more depleted in \(^{13}\)C (Aichner et al., 2010), water use efficiency of the plant (Hou et al., 2007) and the \(\delta^{13}\)C value of the atmospheric source carbon, which is relatively constant over the time period studied here (Diefendorf and Freimuth, 2017).

Due to their gradual and often steady and continuous deposition over time, peatlands are excellent archives for paleoenvironmental reconstructions through time (e.g., Page et al., 2004). A major advantage of using peat relative to other archives, such as aeolian or lake sediments, when studying organic proxies is that the
provenance of the studied material is relatively well-known. For example, since most of the organic material can be assumed to have grown on or near the coring location, the dominant part of biomass remains can be assumed to have been produced on the peatland or in close vicinity, in particular for ombrotrophic (rainfed peatlands) where no soil material or nutrients have been washed into the peatland (Page et al., 2004). Lakes, on the other hand, may receive input from erosion and fluvial transport in its whole watershed, as well as having production of lipid biomarkers in the lake itself (Bertrand et al., 2024; Sheppard et al., 2019). This is, in particular, a complicating factor for glycerol dialkyl glycerol tetraether (GDGT) reconstructions, where microbial production occurs in surrounding soils, in surface waters, the water column, as well as in the bottom sediments (Baxter et al., 2021a, 2021b; Martin et al., 2019). Peat-based reconstructions may in this regard be preferred, as a mostly in situ origin of the GDGT signal may be assumed when ombrotrophic peatlands are utilized as paleoarchives.

Figure 2. Current peatland extent on Sumatra and Borneo. Peat is indicated by black. Shading of gray and blue indicates topography above and below sea level, respectively. Adapted from Dommain et al., 2014.

Lipid biomarkers and their isotopic composition as climate proxies

Lipid biomarker analysis is a field of research that has developed rapidly over the last decades. The following biomarkers were used in this thesis: (a) GDGTs as a proxy for temperature, but also for hydrology and ecosystem changes, (b) n-alkane distributions as a proxy for changes in the ecosystem, and (c) the hydrogen isotopic composition of these n-alkanes as hydroclimatic proxies.

Glycerol Dialkyl Glycerol Tetraethers – GDGTs

Temperature on land has been virtually impossible to reconstruct accurately in the tropics, due to a lack of suitable proxy methods, and most reconstructions have therefore been done on marine sediments. GDGTs are a family of microbial membrane lipids, and the relative abundance of specific GDGTs depends on environmental conditions. Isoprenoidal GDGTs (isoGDGTs), produced by archaea, are used in the marine realm to reconstruct temperature using the TEX$_{86}$ index based on the empirical discovery that GDGTs are produced in versions with more cyclic additions to the membrane lipids in colder environments (Schouten et al., 2002). Later, a similar temperature dependence was found for branched GDGTs (brGDGTs), produced by bacteria, but based on the degree of methylation rather than cyclization (Weijers et al., 2007) (Fig.
With the development of brGDGT analyses, a new field of research in terrestrial temperature reconstructions arose (Sinninghe Damste et al., 2000; Weijers et al., 2006). The methylation of brGDGTs (MBT) index now represents one of the few ways of reconstructing temperature on land, in particular in the low latitudes, and is therefore a promising avenue for achieving improved reconstructions of temperature variations of the Earth’s geological past (Raberg et al., 2022).

The cell membrane composition of brGDGT-producing bacteria is altered depending on environmental conditions, most importantly temperature and pH, to achieve optimal membrane fluidity and proton permeability (Schouten et al., 2013; Weijers et al., 2007). Generally, the colder it is, the higher the degree of methylation of the membrane lipid structure, while cyclopentane rings are mostly promoted by alkaline conditions (Fig. 3) (De Jonge et al., 2014). Based on empirical observations of correlations between brGDGT distributions and environmental parameters, transfer functions have been derived to calculate mean annual air temperature (MAAT) and pH from MBT and cyclization of branched tetrathers (CBT). brGDGTs are ubiquitous in the environment nearly everywhere on the planet (Raberg et al., 2022), but the exact producing organism has remained enigmatic. Earlier work pointed to the globally abundant acidophile bacterial phylum Acidobacteria as likely producers of brGDGTs (Sinninghe Damsté et al., 2018). Recently, a cultured acidobacteria species Candidatus Solibacter usitatus was found to produce a range of brGDGTs (Chen et al., 2022; Halamka et al., 2023), but this likely represent only one of many producers. Since brGDGTs are abundant in most soils, peats and lakes from polar to tropical environments, they are useful for terrestrial paleotemperature and environmental reconstructions.

![Temperature and pH adaptation of brGDGTs](image)

Figure 3. Schematic of brGDGT structures and their temperature and pH adaptation. Nomenclature and mass-over-charge (m/z) as in Fig. 4.
There are three main types of brGDGTs utilized in MBT and CBT quantifications, based on the number of methyl groups attached to the carbon structure (Fig. 4); four (tetramethylated, group I), five (pentamethylated, group II), or six (hexamethylated, group III). These can subsequently be divided based on the number of cyclopentane rings on the carbon structure: none (Ia, IIa, IIIa), one (Ib, IIb, IIIb), or two (Ic, IIc, IIIc). The methyl group in penta- and hexa-methylated groups (II and III) can also be at the sixth carbon atom (referred to as 6-methyl brGDGTs, 6me) instead of the fifth (5-methyl brGDGTs, 5me), and are then denoted with an apostrophe (IIa', IIb', etc.). Developments in liquid chromatography during the last decade have enabled separation of these 5me and 6me isomers (Hopmans et al., 2016). This has increased the accuracy of temperature calibrations by allowing the removal of the 6me isomers, which do not correlate as much to temperature as the 5me isomers. However, errors in temperature and pH reconstructions using brGDGTs remain relatively large at around 4.1 °C (Naafs et al., 2017a) or ~0.8 pH (De Jonge et al., 2014) on globally calibrated datasets.
Figure 4. Chemical structures of brGDGTs, H-shaped branched GDGTs (H-GDGTs), isoGDGTs and an example of an \( n \)-alkane with a chain length of 27 carbon atoms. Note that exact H-GDGT structures are only hypothesized, and the exact structures are not constrained. Figure adapted from Baxter et al. (2019) and Naafs et al. (2018).
Leaf epicuticular waxes are produced by plants as a protective film on their leaves against water loss, ultraviolet light and chemicals. The waxes are ubiquitous in the environment as they are formed by most vegetation types, are resistant to breakdown, and can be found deep down in the geological record. Leaf waxes are mid- to long-chain aliphatic hydrocarbons, alkanes (or n-alkane for normal alkane, indicating a straight-chain molecule), with 17-35 carbon atoms and the general formula \( C_nH_{2n+2} \). The number of carbon atoms in the alkane determines the length of the chain, and alkanes are often referred to as \( C_n \), i.e., an alkane with 27 carbon atoms (formula \( C_{27}H_{56} \); Fig. 4) is referred to as \( C_{27} \). Because of their acetogenic biosynthesis, plants produce predominantly odd-numbered homologs, with \( C_{27} \), \( C_{29} \) and \( C_{31} \) typically being the most abundant (Diefendorf and Freimuth, 2017). Leaf waxes are in solid form on the plants and are less volatile the longer the carbon chain, and have melting points at 22-82 °C and boiling points at ~300-500 °C in the \( C_{17}-C_{26} \) range. A few different chain lengths are produced by each organism, and there is much overlap between plant types, but generally this is relatively specific for each type of plant community; algae, fungi and photosynthesizing bacteria produce the shortest length n-alkanes (\( C_{15}-C_{21} \)), while macrophytes produce medium length n-alkanes (\( C_{21}-C_{25} \)), and forest vegetation (\( C_{25}-C_{31} \)) and open grassland vegetation (\( C_{29}-C_{33} \)) produce progressively longer n-alkanes (Aichner et al., 2010; Diefendorf and Freimuth, 2017; Ficken et al., 2000; Gelpi et al., 1970; Liu and Liu, 2019; Xu et al., 2017). Drawing on this characteristic of leaf wax production, (a) screening of alkane chain lengths can suggest what plant community produced the biomass, and (b) targeting specific chain lengths for isotope analysis can ensure that the compounds are sourced from the same type of producer, increasing data robustness.

The divergent alkane chain length production in different plant types has led to the construction of a wide range of n-alkane length indexes to reconstruct vegetation community shifts. Average chain length (ACL) is a concentration-weighted mean of long-chain n-alkane distribution and has been used to reconstruct vegetation regimes and their variability (Diefendorf and Freimuth, 2017). However, since there is considerable overlap in ACL between different plant communities, conclusions based on chain lengths need to be done with caution and supported by other evidence (Diefendorf and Freimuth, 2017), and more specific indicators of n-alkane distributions are used in this thesis. The \( P_{aq} \) index is a measure of the relative contribution of aquatic plants (macrophytes) in the sample total lipid extracts. Macrophytes predominantly produce \( C_{23} \) and \( C_{25} \), and the index is calculated as \( (C_{23}+C_{25})/(C_{25}+C_{27}+C_{29}+C_{31}) \) (Aichner et al., 2010; Xu et al., 2017). Algae and photosynthetic bacteria produce n-alkanes mainly in \( C_{15} \) to \( C_{21} \) lengths (Xu et al., 2017), and their relative abundance can be calculated as \( (C_{17}+C_{19})/(C_{17}+C_{19}+C_{23}+C_{25}+C_{27}+C_{29}+C_{31}) \). A range of other ratios can be constructed to measure the relative contribution from forest or open vegetation, for example \( (C_{25}+C_{31})/(C_{31}+C_{33}) \), drawing on the fact that open vegetation produces more of the longer alkanes than forests (Diefendorf and Freimuth, 2017).

**n-alkane hydrogen isotopic composition**

The stable hydrogen and oxygen isotope composition in precipitation are controlled by three main “effects” that have been observed in rainfall (Dansgaard, 1964): (1) the *amount effect*, an important control on \( \delta D \) and \( \delta^{18}O \) in the tropics, where precipitation amount has been observed to correlate with depletion of the heavier isotopes, (2) the *continentality effect* resulting in lower \( \delta D \) and \( \delta^{18}O \) the further away from the precipitation’s oceanic water source, and (3) the *temperature effect*, most important at higher latitudes, causing lowering of \( \delta D \) and \( \delta^{18}O \) at colder temperatures. The first two are caused by continuous preferential condensation and rainout of the heavier isotopes, causing the initial precipitation to be enriched in D and \( ^{18}O \) compared to the water vapor, and the remaining water vapor and subsequent precipitation getting progressively depleted the further away from the source, or the more precipitation has been rained out. The precipitated water further undergoes isotopic fractionation due to (a) evaporation in soils and lakes (causing residual enrichment of the heavy isotopes), (b) transpiration from leaves (enriching), and (c) biosynthesis of organic molecules (depleting), which is organism dependent (Sachse et al., 2012). In tropical South-East Asia, the amount effect is generally the most important factor in precipitation \( \delta D \) and \( \delta^{18}O \) and they thus reflect precipitation amount (Kurita et al., 2009; Partin et al., 2007; Wei et al., 2018; Wurtzel et al., 2018). However, moisture trajectories can have a large impact on the isotopic composition of precipitation. Konecky et al. (2016) measured the \( \delta D \) and \( \delta^{18}O \) of modern precipitation near the equator on Sulawesi, East Indonesia, combined with precipitation source trajectory modeling. They found a ~70 % range in \( \delta D \).
and 9 %δ18O, depending on whether the moisture source was from the northern or southern hemispheres. This seasonally bound isotopic difference was found to result in depleted deuterium during the LGM (indicating wetter conditions if the amount effect is dominant) despite a wealth of other proxy evidence indicating drier conditions (e.g., Konecky et al., 2016 and references therein; Partin et al., 2007; Wurtzel et al., 2018; Yuan et al., 2023). Changes in atmospheric circulation and moisture trajectories can thus be more important than the amount effect in some cases also in the tropics, but this has been found not to be the case on Sumatra which is mainly influenced by the Indian Ocean (Wurtzel et al., 2018).

Targeting specific chain lengths for isotope analyses avoids a significant problem of using bulk isotope values – the biomass source is much better constrained. The bulk isotopic signal (such as bulk δ13C measured by EA-IRMS) reflects the whole biomass community deposited in the sample material, meaning probably hundreds of different species contribute to the isotopic signal, with potentially different carbon sources and fractionation effects. Aquatic and terrestrial plants will, for example, produce different bulk δ13C signals, with less depletion in aquatic compared to terrestrial plants (Aichner et al., 2010), and a change in isotopic signal may thus be a shift in aquatic production rather than a shift between C3 and C4 vegetation of terrestrial plants. These effects can be partly constrained by analyzing specific lipids instead of bulk. This improved source constraint is important in hydrogen isotope analysis, where the source water δD is of interest, rather than the fractionation caused by plant metabolism. By analyzing the isotopes of a specific n-alkane chain length through a downcore record, i.e., from the same type of vegetation, it can be assumed that the fractionation effect in the vegetation has not varied significantly, and the isotopic effects are dependent on the source water. Furthermore, the δD of specific sources can be analyzed with the aim of investigating the differences in δD between organisms with various habitats and water sources (aquatic, terrestrial) or growth periods (during a specific season or over the entire year). This has previously been done using aquatic versus terrestrial plants (e.g., Thomas et al., 2020). Also, if all n-alkane homologs show the same trends in δD, it can be concluded that all vegetation is affected by changes in the source water isotope composition.

Climate model simulations

A key approach to getting deeper knowledge from the proxy signals measured in natural archives is to compare results with climate model simulations. While proxy reconstructions generate temporal variations at a single point in space through time, climate models can inform us of global patterns at high spatiotemporal resolution. Studying climate model output, therefore, yields understanding of the underlying mechanisms that are driving changes recorded by proxies. Importantly, climate models also resolve the variations over the entire year in detail, allowing a much deeper analysis of seasonal shifts than is usually possible using proxies. While it is usually practically feasible and/or meaningful to sample natural archives at resolutions representing decades to centuries of passed time per sample, climate models resolve monthly (or even hourly) temporal resolutions. Models can, therefore, also be used to shed light on seasonal variations that are impossible to derive solely from proxies. Modeling is thereby a powerful tool in exploring climate shifts recorded by proxy data over the Earth’s geological past. Vice versa, proxy reconstructions comprise an essential test case for models and their ability to reproduce past climate changes under varied forcing, which is fundamental in investigating how well the models can project future changes (IPCC, 2021). Apart from further reducing model-specific biases, it remains unclear how realistic climate models respond to climate forcing that is fundamentally different from today. This is already evident in long-term trends in global and hemispheric temperatures of the Holocene that are inconsistent with most proxy records (Liu et al., 2014). Several studies have proposed that either models or proxies might be seasonally biased and/or that important feedbacks might be missing in models (Bader et al., 2020; Bova et al., 2021; Kaufman and Broadman, 2023). Furthermore, significant uncertainties remain in the representation of ENSO in the current generation of climate models (Brown et al., 2020). It is hence important to evaluate both models and proxies in parallel to better understand the potential origins of discrepancies over time and space.
Study area

Sites
The proxy work in this thesis focuses on two peat cores from Sumatra: the Diatas peatland in West Sumatra (Paper II and Outlook section), and the Padang peatland in Jambi (Papers II and III), which are approximately 100 km from each other and just south of the equator (Fig. 5). The Diatas peatland is situated at 1529 m a.s.l., at 1.072 °S, 100.770 °E. The core is 709 cm long, with a basal age of 11 193 ± 368 calibrated years BP. The Padang peatland lies at 960 m a.s.l., at 2.206 °S, 101.526 °E. The core is 610 cm long, with a basal age of 7826 ± 195 calibrated years BP. The peat cores were collected in 2019 using a Russian D-corer with a diameter of 6 cm in 50 cm long sections from two holes approximately 2 m apart. Each core section was taken with a 10 cm overlap. The cores were stored at 4 °C and subsampled at 3 cm and 10 cm resolution for Diatas and Padang, respectively.

Two complimentary sample sets are used in Paper II as reference samples representing environments other than peats: a soil transect from Mount Singgalang and a short lake core from Danau Maninjau. The soil transect was collected between 0.39112 °S, 100.33256 °E at 2840 m a.s.l. near the top of Mount Singgalang, to sea level at the coast at 0.67374 °S, 100.16215 °E. The soils were collected from the surface from diverse types of environments. All samples from above 1600 m elevation were collected in the rainforest, and below 1600 m elevation from varied locations such as road cuts, forest, near farmland etc., but always away from obvious human impact. The 42 cm long lake core was collected using a Uwitec USC06000 gravity corer in 2019 from a water depth of 136 m. Lake Maninjau is a crater lake, further described by de Maisonneuve et al. (2019).
Climate

The current climate in the study area is ever-wet, with > 2000 mm mean annual precipitation (Maloney and McCormac, 1995), and 3100 mm according to the ERA5 reanalysis dataset averaged over 1979-2020 (Hersbach et al., 2020) (Fig. 5). Mean annual air temperatures at low elevations on Sumatra is approximately 27 °C (De Jonge et al., 2024), and 21.7 and 18.8 °C at Padang and Diatas, respectively, with cooler temperatures due to their high elevation (Climate-Data.org). The seasonal temperature variation is less than 1.5 °C. June is the driest month, and October-April are the wettest, in particular as the ITCZ passes the area in November and to a lesser extent in April (Fig. 5). The ITCZ occurs where the easterly trade winds from both hemispheres converge around the thermal equator, and represents the location with the strongest convection and precipitation (Schneider et al., 2014). The ITCZ migrates seasonally towards the warming hemisphere – from around 8 °S around Java and northern Australia in austral summer to around 20 °N over mainland Asia during boreal summer (Fig. 1).

Figure 5. Precipitation over the Maritime Continent and sketched atmospheric circulation of the low latitude Asian-Australian monsoons for winter (W) and summer (S) in their respective hemispheres. (a) Map of annual mean precipitation and (b) precipitation at the field sites. Data derived from ERA5 1979-2020 (Hersbach et al., 2020). Dashed lines show land-sea configuration, i.e., ancient coastlines at the LGM (grey) and 12 ka BP (black), based on modern topography from the ETOP01 dataset (Amante and Eakins, 2009). Field site locations are shown as circles for Diatas (green) and Padang (white). For a seasonal overview of precipitation, including primary wind directions, the reader is referred to Paper III.
Precipitation on Sumatra is sourced mainly from the relatively nearby Indian Ocean, with an influence from the South-China Sea during boreal winter and the Java Sea in boreal summer (Wurtzel et al., 2018). These seasonal water source changes are tied to the location of the ITCZ and the resulting Hadley cell atmospheric circulation (Fig. 6) (Djamil et al., 2023). The Hadley cells are composed of rising air at the ITCZ, and sinking air around 30 ° north and south, which gives rise to the monsoonal circulations on both hemispheres (Fiehn, 2017). The monsoon systems affecting the Maritime Continent are the Asian monsoon and the Indonesian-Australian monsoon. The Asian summer monsoon (ASM) exports heat and moisture from the IPWP to the Asian mainland during boreal summer, which results in dry conditions on Sumatra (Fig. 5). The Asian winter monsoon (AWM) is tied to dry conditions in mainland Asia and China due to cold and dry air originating from the high-pressure centers in continental Asia, but is associated with wet conditions on the Maritime Continent as the ITCZ passes the region causing northerly winds containing large amounts of moisture. The Indonesian-Australian summer monsoon (IASM) is the southern hemisphere part of the Asian-Australian monsoon system, and consequently occurs during austral summer (December, January, February DJF), and brings precipitation to the southern parts of the Maritime Continent and Australia. The Indonesian-Australian winter monsoon (IAWM) on the contrary exports dry air masses from Australia, causing seasonally dry conditions in Australia and Java and to a lesser extent on the rest of the Maritime Continent, tied to the northward export of heat and moisture of the ASM. The monsoons in their respective hemispheres and Hadley cells are thereby part of the same ITCZ-driven circulation system (Djamil et al., 2023; Fiehn, 2017; Schneider et al., 2014).

![Figure 6. Schematic of the meridional atmospheric circulation via the ITCZ and Hadley cells, which are driving the low latitude monsoons. Warm and moist air rises where the southern and northern hemispheres trade winds converge, giving rise to deep convection and Hadley cell circulation. Figure adapted from Fiehn (2017).](image-url)
On interannual timescales, perturbations in the Walker Circulation, i.e., the equatorial east-west atmospheric circulation (Fig. 7) (Walker, 1932), are the primary influence on hydroclimate variability (IPCC, 2021: Annex 4). The rising arm of the Walker Circulation in the Indo-Pacific is the convection center over the IPWP and the Maritime Continent, and its descending branch is located at the high-pressure system over the East Pacific and South America (IPCC, 2021: Annex 4). This zonal pressure difference causes easterly surface winds over the Pacific Ocean, which induce surface ocean currents in the same direction and warm water transport westward, leading to a feedback loop with warmer water in the IPWP and yet stronger Walker Circulation. This feedback is referred to as Bjerknes feedback (Bjerknes, 1966). Further strengthening the SST gradient over the Pacific Ocean is the southerly winds off South America, which drives oceanic upwelling via a net offshore surface water transport, i.e., Ekman transport (Fiehn, 2017; Price et al., 1987). This ocean-atmosphere circulation is perturbed in a ~2-7 yr cycle, which manifests as ENSO events – El Niños and La Niñas. Weakened Walker Circulation and SST gradients occur during El Niño events, leading to cooler and drier conditions in the IPWP. La Niñas are a strengthening of the neutral conditions of the Walker Circulation, making the IPWP warmer and wetter than usual (Fig. 7).

Figure 7. Walker Circulation over the Pacific Ocean, and the (a) neutral and (b) El Niño phases of the El Niño Southern Oscillation (ENSO). Figure from the European Space Agency.
Methods

Climate model simulations

In Paper I, The Community Earth System Model (CESM) version 1.0.5 was used to simulate the global climate at 13 ka BP, 12 ka BP and the pre-industrial (1850 C.E.). The model resolution was set to 0.9° x 1.25°, (~100 km). Each simulation was forced by orbital insolation, greenhouse gas concentrations, sea level rise through adjusted land-ocean masks, prescribed climatologies of monthly sea-surface temperatures and sea ice fraction from an earlier CCSM3 simulation (TraCE-21k) (He, 2011; Liu et al., 2009) and continental ice sheets (GLAC-IB) specific for each time period. The model consists of 26 vertical levels in the atmosphere and 15 levels for the land component down to a depth of 42 m. The model in its atmosphere-land-ice-ocean configuration was spun up for 50 years until reaching equilibrium in deep soil temperatures, and then subsequently ran for 100 years. The monthly and annual data reported here are the average values of the 100-year data if not otherwise stated. A more detailed description of the CESM1 setup can be found in Schenk et al. (2018).

A key advancement of the CESM1 simulations used compared to earlier studies consists in the high spatial resolution which is four times higher than the previous transient fully coupled CCSM3 simulation TraCE21ka which is widely used in the paleomodeling community (Liu et al. 2009, He 2011). However, the simulated ocean states from CCSM3 form the backbone of our high-resolution paleoclimate simulations. The CCSM3 ocean states are currently the most realistic simulations for Late Glacial conditions, which are here prescribed in CESM1 to reflect paleo-ocean and ice conditions in response to the drastic Atlantic Meridional Overturning Circulation (AMOC) and freshwater changes in response to melting ice sheets (He, 2011). The ocean states are not dynamically linked to the atmosphere in CESM1, which may reduce the variability in the high-resolution simulation. Fully-coupled models have been shown to show more extreme changes in SE Asia, since the atmosphere-ocean feedbacks can strengthen climate anomalies (DiNezio et al., 2016). However, the higher spatial resolution in CESM1 may in turn also increase feedback related to climate change and boundary conditions, including a more realistic representation of convection, near-surface winds and orographic interaction, which may be crucial for the complex topography of islands in SE Asia.

In Paper II, the brGDGT proxy reconstructions of temperature were compared to climate model data from three transient climate model simulations covering at least the past 8000 years: EC-Earth, MPI-ESM and iCESM. EC-Earth and MPI-ESM covers the past 8000 years, and iCESM covers the entire period from the LGM to the present. EC-Earth3-veg-LR (Döscher et al., 2022; Zhang et al., 2021) is a fully coupled atmosphere-ocean model with dynamic vegetation, forced by changes in greenhouse gas concentrations and orbital variations, with a resolution of 1.125° in the atmosphere and 1° in the ocean. MPI-ESM 1.2 (The Earth System Model of the Max Planck Institute for Meteorology) (Bader et al., 2020; Dallmeyer et al., 2021) is also a fully coupled model with dynamic vegetation, and was additionally forced by solar and volcanic activity as described by Dallmeyer et al. (2021), at a resolution of 1.875° in the atmosphere and 1.5° in the ocean. The iCESM1.2 (isotope-enabled Community Earth System Model) (Osman et al., 2021) is a ‘reanalysis’ climate model simulation, i.e., is constrained by proxy reconstructions, with a resolution of 1.9 x 2.5° in the atmosphere and 1° in the ocean. For detailed information about model setups, the reader is referred to each respective reference article (Bader et al., 2020; Dallmeyer et al., 2021; Döscher et al., 2022; He, 2011; Liu et al., 2009; Osman et al., 2021; Schenk et al., 2018; Zhang et al., 2021). In the proxy-model comparisons in this thesis, time series were calculated using a land-only box on Sumatra (1°S to 3°N, 100–104°E) presented as 200-year running means.
Geochemistry

In Papers II, III and the Outlook section, organic geochemical methods are applied to constrain the paleo-environment and -climate through time. Temperature and hydrological reconstructions were conducted via GDGTs. Precipitation variability and vegetation composition was reconstructed using leaf wax distributions and their stable hydrogen isotopes ($\delta^D$). Peat characteristics were constrained using bulk TOC and carbon stable isotopic composition ($\delta^{13}C$). Peat and carbon accumulation rates were established via density and radiocarbon analyses.

Extraction and fractionation

Lipid biomarkers were extracted from approximately 0.1-0.5 g freeze-dried and ground sediments using sonication in 20 ml Dichloromethane: Methanol (DCM: MeOH) 9:1 (v/v) for 15 min. This was repeated three times, and the extracts were combined into a total lipid extract. Total lipid extracts were fractionated using silica gel pipette columns using hexane to elute the non-polar and DCM: MeOH 1:1 to elute the polar fraction.

GDGTs

The polar fraction was dissolved in a mixture of hexane–isopropanol (99:1 v/v) and filtered using a 0.45 μm PTFE filter to remove poorly dissolved polar material. GDGTs distributions were analyzed using the method described in Hopmans et al. (2016), but with a 0.3 ml min$^{-1}$ instead of 0.2 ml min$^{-1}$ as described in detail in Paper II supplementary. A total of 333 samples were analyzed: 186 samples from Diatas, 60 samples from Padang, 38 samples from the Singgalang soil transect, and 49 samples from Lake Maninjau. The HPLC-MS system used was a Dionex/Thermo Scientific UltiMate3000 high-performance liquid chromatograph equipped with two Waters Acquity BEH HILIC columns (2.1 x 150 mm, 1.7μm) fitted with a pre-column (BEH HILIC 2.1 x 5 mm) connected to a TSQ Quantum Access Max Triple Quadrupole mass spectrometer with an APCI ion source. The brGDGT, isoGDGTs and H-GDGTs were quantified manually using the Xcalibur software with a limit of quantification signal-to-noise ratio of 3.

$n$-alkanes

Long chain $n$-alkanes present in the non-polar fraction were quantified by gas chromatography–mass spectrometry (GC–MS) on a Shimadzu GCMS-QP2010 Ultra, equipped with an AOC- 20i autosampler and a split-splitless injector operated in splitless mode. A Zebron ZB-5HT Inferno GC column (30 m x 0.25 mm x 0.25μm) was used for separation. The GC oven temperature was programmed from 60-180 °C at a rate of 20 °C min$^{-1}$ and then ramped to 320 °C at a rate of 4 °C min$^{-1}$ with a hold time of 20 min. MS operating conditions were set to an ion source temperature of 200 °C and 70eV ionization energy. Spectra were collected using GC solution Workstation software (v2). Quantification was performed using a calibration curve generated using a standard mixture with C$_{15}$-C$_{40}$ $n$-alkanes. $\delta^D$ values of the long chain $n$-alkanes were determined by gas chromatography–isotope ratio monitoring–mass spectrometry (GC-IRMS) with a Thermo Finnigan Delta V plus mass spectrometer interfaced with a Trace Ultra GC, GC Isolink and Conflo IV interface. A standard mixture of $n$-alkanes with known isotopic composition (reference mixture A6, provided by Arndt Schimmelmann, Indiana University, USA) was run several times daily to calibrate the reference gas against which the samples were measured. All analyses were performed at least in triplicate, and the results are reported as the mean. $\delta^D$ values are expressed relative to VSMOW. The hydrogen isotope measurements for Diatas (presented in the Outlook section) were run at ETH Zürich on a similar system.

Bulk elemental analysis:

Carbon and nitrogen contents and their stable isotopic compositions were measured at the Stable Isotope Laboratory at the Department of Geological Sciences at Stockholm University on 72 samples from the Diatas peat core on a Carlo Erba NC2500 elemental analyzer connected to a Thermo Scientific Delta V Advantage Isotope Ratio Mass Spectrometer (EA-IRMS). On the Padang core, 60 samples were analyzed...
at the Geological Institute, ETH Zürich, using a Flash-EA 1112 Elemental Analyzer (ThermoFisher Scientific) coupled to an isotope ratio mass spectrometer (IRMS, Delta V, ThermoFisher Scientific). Total organic carbon (TOC) is reported in percent (%) dry weight, and $\delta^{13}C$ is expressed in ‰ relative to VPDB. The measurement errors are approximately 1 % for TOC and <0.15 ‰ for $\delta^{13}C$.

Age models

Radiocarbon dating was conducted on 9 samples from Padang, and 34 samples from Diatas. At the time of publishing Paper II, only 16 had yet been dated from Diatas, and that age model is therefore based on a lower resolution radiocarbon analysis than the 34 radiocarbon dates that are presented in the Outlook section. Final age models were constructed using rbacoR version 3.1.1 (Blaauw and Christen, 2011), using the southern hemisphere radiocarbon calibration curve (Hogg et al., 2020).
Summary of papers

Paper I

Seasonal aridity in the Indo-Pacific Warm Pool during the Late Glacial driven by El Niño-like conditions

Tropical South East Asia is currently wet year-round and has the world’s highest density of tropical rainforests and peat swamp forests, storing 55% of global tropical peat (Dargie et al., 2017; Page et al., 2011). Surprisingly, however, few peatlands date back to older than 7000 years BP (Dommain et al., 2014). In an ever-wet tropical climate, peat swamp forests thrive, but for some reason, likely related to climate, this was not the case during the Late Glacial and the Early Holocene. Paper I investigates how the climate differed prior to the establishment of large peatlands in the region, in order to suppress peat formation. The time periods of focus were the last stages of the deglaciation (13 and 12 ka BP) compared to the pre-industrial (PI; 1850 C.E.), as well as the transient evolution of climate covering the entire deglacial and Holocene. Two climate model simulations were analyzed, with an emphasis on the climate seasonality in the IPWP and on the Maritime Continent.

The results suggest a dramatic shift in seasonality for the IPWP region during the Late Glacial compared to PI. The region was drier in general, but most of the change in precipitation was driven by droughts during the winters caused by a seasonal breakdown of the ITCZ, leading to a much more seasonal climate. Ocean temperatures were approximately 2 °C lower than the pre-industrial, and land areas, in particular exposed shelf areas, experienced a larger cooling of ~5 °C in winter. These changes in seasonality are attributed to four causes. (1) Insolation: The precessional cycle strongly influences tropical temperatures, and affect the annual timing of higher insolation due to the distance to the sun during a particular month. At 12 ka BP, the winter (January) incoming solar radiation was low, while at the same time, July insolation was very high. (2) Strong (dry) Asian winter monsoon: This led to strengthened seasonal cycles, in particular in the northern hemisphere, where winter monsoon was enhanced. The much colder Siberian/mainland Asian temperatures and relatively warm tropical temperatures during the Late Glacial led to a large meridional (north-south) temperature gradient. Furthermore, this led to an ITCZ shift southwards, and even a breakdown of deep convection over the Maritime Continent. (3) Sea level: ~60 m lower sea level at 12 ka BP exposed 1.6 million km² (the size of Mongolia) of the Sunda shelf that is today submerged by the ocean. DiNezio et al. (2018, 2011; DiNezio and Tierney, 2013; 2016) have made a series of modeling experiments showing that the larger land surface caused a significant change in atmospheric circulation in the IPWP, mainly by decreasing convection, cooling the surface via increasing albedo and decreasing moisture availability. Lower sea levels also affected oceanic currents and heat transport between the Pacific and Indian Oceans. These results are consistent with the changes in atmospheric circulation simulated by our model at 12 ka BP. (4) Walker Circulation: the conditions at 12 ka BP, with cold and dry South East Asia, coincides with a major reorganization of the Pacific (ENSO) and Indian Ocean Walker Circulation (Indian Ocean Dipole; IOD). Modern winter conditions are characterized by substantial atmospheric deep convection over South East Asia. This convection is part of the Walker Circulation, which drives Pacific and Indian Ocean wind patterns (Fig. 8b) and corresponds to neutral IOD and ENSO states. For 12 ka BP winter conditions, however, SE Asia experienced subsidence and no significant ITCZ convection. The convection was instead shifted to be over the Indian and Pacific oceans, and the mean state for 12 ka BP January is similar to IOD+ and El Niño states, with weakened Pacific Walker Circulation and reversed Indian Ocean Walker Circulation (Fig. 8d).
Paleo-environmental proxy records based on pollen and biomarkers indicate a shift towards open C₄ vegetation and drier/more seasonal conditions during the LGM and the deglacial period (~20-11.7 ka BP). This has sparked a debate about to what extent savanna expanded in the region, and a ‘Savanna Corridor’ hypothesis outlining a savanna biome across the exposed Sunda shelf has been suggested (Bird et al., 2005; Heaney, 1991; Wurster et al., 2019, 2010). While some proxy data support this hypothesis, evidence remains inconclusive for key regions because much of the proposed savanna areas were inundated during the deglacial 120 m rise in sea level (Hanebuth et al., 2011). Our modeling results show that nearly the whole region, except Borneo, was affected by several months of seasonal droughts annually (< 60 mm precipitation/month; Fig. 9), lending support to the ‘Savanna Corridor’ hypothesis. Our results are supported by most of the proxy records in the region, with ever-wet conditions and the earliest peat initiation date in the region on Borneo at 12 ka BP, and otherwise drier and higher influence of open C₄ vegetation (see Paper I for a table of proxies).
Figure 9. The number of simulated dry months per year at 12 ka BP and comparison of the regional annual temperature and precipitation cycles for 12 ka BP and PI. A dry month is defined as receiving < 60 mm of precipitation. Climate diagrams show the monthly average temperature and precipitation at key locations for PI (green) and 12 ka BP (black) CESM1 simulations. Central Borneo corresponds to the wettest area in the simulation, while Sumatra, North Borneo and Java approximately correspond to speleothem precipitation reconstructions (Ayliffe et al., 2013; Partin et al., 2007; Wurtzel et al., 2018). Figure from Hällberg et al. (2022).

These findings provide more information on the Late Glacial climate-environmental conditions. Another insight from this work is that very severe droughts and disrupted monsoon systems can occur under 12 ka BP forcings. The effects on ecosystems and the billions of people living around the IPWP are hard to imagine if even a small part of the simulated climate change would unfold due to anthropogenic forcing. While the 12 ka BP climate is a poor analog for the present (different orbital configuration, greenhouse gas concentrations, ice sheet configurations, etc.), an important part of the 12 ka BP climate is a relatively cold northern hemisphere due to meltwater flux in the Arctic and AMOC slowdown (He, 2011). AMOC slowdown has already been proposed to have started (Caesar et al., 2021) and has been projected for the future as freshwater runoff from precipitation and ice melt accelerates during warming (IPCC, 2021; Van Westen et al., 2024). While disputed (Chafik et al., 2020), AMOC shifts could have important implications for the tropics, which would last for centuries, as Partin et al. (2015) proposed.
Paper I - Contributions to the field

Paper I demonstrates why very few peatlands were established prior to the Mid-Holocene (Dommain et al., 2014). Seasonal droughts prevented wet enough conditions required for peat accumulation – until orbital forcing seasonality was less extreme, sea level increased, and the Indonesian Throughflow opened up during the Early-Mid Holocene. The LGM and Heinrich Stadial 1 (HS1 ~16.5 ka BP) were generally cooler and drier than the end of the Late Glacial (~12 ka BP), but due to increased seasonality, significant effects on ecosystems and wetlands remained until the Holocene. Additionally, the model data explain why the oldest peatlands are located on Borneo, in agreement with proxies (Dommain et al., 2014): the island’s high mountains caused local orographic precipitation, enough to sustain annually wet conditions and wetland buildup.

The ENSO and the ITCZ are the most important drivers of global interannual climate variability in the current climate, and large uncertainties exist for how they will respond to global warming (IPCC, 2021). Paper I contributes new information on their response to Late Glacial forcings and changes in AMOC. The Late Glacial simulations (13 and 12 ka BP) show permanent ‘El Niño-like’ winters, with Walker Circulation and SST patterns resembling extreme El Niño events in the modern climate. Furthermore, the model simulated ITCZ shifts and even the complete dissolution of boreal winter deep convection over the region that is usually associated with the ITCZ.

Further, the importance of AMOC changes during the Late Glacial was quantified and compared to other forcings. On millennial timescales during the Late Glacial (specifically, between 13 and 12 ka BP), the slowdown of AMOC caused a southward shift of the ITCZ and rearrangement of the Pacific Walker Circulation in terms of patterns of precipitation, atmospheric circulation and SSTs. These findings may be relevant in assessing the impact of a changing AMOC in the future. Over orbital timescales (several thousand years), at least for this time period, the importance of AMOC forcing was dwarfed compared to other forcings, i.e., orbital, sea level, greenhouse gas concentrations and ice sheet configuration.
Paper II

Branched GDGT source shift identification allows improved reconstruction of an 8,000-year warming trend on Sumatra

Paleotemperature reconstructions on land, particularly in the tropics, have remained challenging due to a lack of suitable paleotemperature proxies. Tropical temperatures, and the resulting heat gradients between the low and high latitudes, are key drivers in large-scale climate systems such as the monsoons. However, the past gradients are poorly understood, limiting our understanding of the fundamentals of the monsoonal systems, which affect some 70% of the global population (Mohtadi et al., 2016). Paper II contributes towards the goal of understanding past terrestrial temperatures by reconstructing equatorial temperatures of the Holocene. It also attempts to push the field of GDGT analyses and interpretations forward by evaluating uncertainties and shortcomings of the method, and suggests how they can be identified and/or avoided in future research.

The two peat cores used for the paleoenvironmental reconstructions in this thesis are located only ~150 km from each other and should, therefore, have experienced approximately the same temperature trends in the past. However, results based on MBT$_{SME}$ showed contradictory temperature trends. (At least) one of the reconstructions must, therefore, be wrong. To understand what caused this discrepancy, an in-depth analysis of GDGT distributions on Sumatra was performed from a variety of terrestrial archives: the peat cores, a lake core and a soil transect. The focus was on brGDGTs, and isoGDGTs were used to evaluate the results, and the composition of H-GDGTs was explored as an indicator for bacterial community shifts. Further, the reconstructed temperature trends on Sumatra were compared to transient climate model simulations (EC-Earth, MPI-ESM and iCESM) and earlier marine and terrestrial reconstructions in the IPWP.

The results indicate that the source environment of the GDGT-producing microbes was a main driving factor in controlling the GDGT distribution, including MBT$_{SME}$, in the Sumatran sample set. Peat samples generally had a very low degree of cyclization (DC') and 6-methyl isomerization (IR$_{6me}$) (DC' and IR$_{6me}$ < 0.1), with a very close correlation between MBT' to MBT$_{SME}$ ($R^2 > 0.99$). BIT values were close to 1 due to low abundances of crenarchaeol due to anoxic waterlogged conditions. On the contrary, lake samples had much higher DC' and IR$_{6me}$, no correlation between MBT' and MBT$_{SME}$ and lower BIT (0.25 ± 0.21) values due to more oxygenated conditions and aquatic production of GDGTs. Soil samples had a wide range and variation of GDGT distributions.

For the peat samples, a strong effect on the GDGT distributions was also found from TOC content. In the context of peats, TOC is directly proportional to organic matter content, and thereby inversely proportional to the mineral content. Both the isomerization and cyclization of GDGTs were negatively correlated with TOC ($R^2 = 0.80$ and 0.78, respectively), and MBT$_{SME}$ was weakly positively correlated with TOC ($R^2 = 0.12$). This was likely caused by a pH effect due to increased cation input via minerogenic material when the TOC was lower, resulting in a less acidic environment. This environment favors an altered bacterial community composition, leading to shifting GDGT compositions.

Furthermore, major differences in H-shaped branched GDGT (H-GDGT) composition were found between different environments in the studied sample set (Fig. 10). Peats almost exclusively produced H-1020c, H-1034b and H-1048. The lake samples, and African lakes from literature data (Baxter et al. 2019), had a much larger range of H-GDGTs, also including H-1034a and H-1034c, and H-1020a and H-1020b. To investigate the applicability of H-GDGTs to distinguish marine from terrestrial source environments, a data comparison was conducted with the marine samples from the Indian Ocean (Kirkels et al., 2022). The marine samples almost exclusively produced H-1020a and H-1020b, i.e., highly distinct from the terrestrial samples. Based on these findings, the isomerization of H-GDGT index (IR$_H$) was introduced, calculated as the aquatic divided by aquatic and terrestrial H-GDGTs:

$$\text{IR}_H = \frac{\text{H}1020a + \text{H}1020b + \text{H}1034a + \text{H}1034c}{\text{H}1020a + \text{H}1020b + \text{H}1020c + \text{H}1034a + \text{H}1034b + \text{H}1034c}$$
Figure 10. Principal component analysis on normalized fractional abundances of the brGDGT and H-GDGT data from Sumatra, including soil, lake and peat samples. (a) and (b) show all brGDGT and H-GDGT data, while (c) and (d) only include H-GDGTs. (a and c) score plot of all samples, and (b and d) loadings of each compound. Indexes with blue labels in (b) are overlaid \textit{a posteriori}. Figure adapted from Hällberg et al. (2023).

By identifying down-core shifts in brGDGT distributions in the peat cores, and therefore potential GDGT-producing microbial community shifts based on the variables described above, the cause for the contradicting trends in the reconstructed temperature was pinpointed.

The Diatas peat core lithology changed over the depositional period. The basal parts of the core accumulated when the wetland was in contact with the adjacent lake, and likely had some standing water and had more inputs of mineral material. Accordingly, the GDGT composition was more similar to lake samples than other peat samples. When the middle section of the peat sequence accumulated, the lithology was almost purely organic, signifying a fully terrestrialized (overgrown) peatland without lake input. With this change in conditions, the GDGT distribution shifted dramatically towards higher MBT$^{\prime}$5ME and lower DC$^{\prime}$,
IR$_{6me}$, and IR$_H$. The upper parts of the core again shift towards lower TOC, due to increased mineral input following erosion from the surrounding soils. Since the GDGT distributions and MBT'都将correlate with TOC, these environmental changes led to lowered MBT'values and increased DC', IR$_{6me}$, and IR$_H$. Thereby, the GDGT distributions in the Diatas peatland were dominantly driven by lithological changes, which overrode any trends caused by temperature changes. The likely underlying drivers of these observed changes with lithology are pH and oxygenation-driven shifts in bacterial community shifts, in agreement with previous research on modern soils (Chen et al., 2022; De Jonge et al., 2021; Halamka et al., 2023, 2021).

The Padang peat core distinctly differed from the Diatas peat core in that the lithology was highly homogeneous throughout the sequence. Almost the entire core displayed a TOC $> 50 \%$, i.e., fully organic peat, with a brief exception around 4.3 ka BP, where the TOC decreased to 43%. As a consequence of the largely unchanging lithology, the GDGT distributions throughout the core changed little in most aspects, i.e., stable IR$_{6me}$, DC’ and BIT values, IR$_H$. These unchanging conditions were interpreted as a stable environment with no changes in the GDGT-producing bacterial community. MBT' was the only GDGT index that changed significantly through the core and was interpreted to be driven by temperature, i.e., the traditional interpretation (De Jonge et al., 2014).

The Padang record was thereby a good target for a temperature reconstruction, excluding the samples that were deposited during the minor mineral input at 4.3 ka BP. The resulting temperature trend shows gradual warming over the past 8000 years, consistent with transient climate model outputs used in our study, as well as global simulated trends (Fig. 11) (Liu et al., 2014). Likewise, proximal marine proxies off the west coast of Sumatra indicate similar results. However, a marine proxy temperature reconstruction compilation based on records from the relatively nearby eastern IPWP (i.e., westernmost Pacific, ~1600+ km east of Sumatra) shows the opposite trend over the studied period (Dang et al., 2020), in agreement with globally distributed tropical sites (Kaufman et al., 2020). These divergent trends may suggest altered IPWP dynamics over the Holocene, with a cool west IPWP and warm east IPWP in the Early and Mid-Holocene, and a smaller difference towards the Late Holocene and present day.
Figure 11. Reconstructed temperature anomalies compared with transient model simulations over Sumatra. Simulated temperatures (200 yr running means) from (a) iCESM, (b) EC-Earth, (c) MPI-ESM and (d) Sumatra MAAT (this study) with a 5-point moving mean (black) and all data points (grey). Marine SST reconstructions from (e) a nearby marine core (Mohr et al., 2010), and (f) eastern IPWP (Dang et al., 2020). Low latitude proxy compilations for marine (g) and terrestrial (h) reconstructions (Kaufman et al., 2020). For the Padang brGDGT record, samples around the 4.3 k event were excluded, due to mineral input which affected the brGDGT distribution. Anomalies in (a–e) are relative to the entire Holocene, while (f) is relative to 6–10 ka BP. (g) and (h) display z-scores calculated by Kaufman et al. (2020) to facilitate comparison across various proxies and thus indicate trends rather than absolute temperature changes. Note the different y-axes scales. Figure from Hällberg et al. (2023).
Paper II - Contributions to the field

A key issue with GDGT paleo-reconstructions is that it is challenging to constrain if MBT$^{\text{SME}}$ shifts reflect temperature or bacterial community changes (De Jonge et al., 2021; Halffman et al., 2022). This has led to likely over- or mis-interpretations of temperature variations in the literature. By examining several GDGT source indicators in the Sumatra lake, peat and soil dataset, and introducing a new source index based on H-GDGTs, IR$_H$, this research helps constrain and identify source shifts. A greater understanding of confounding factors of GDGT research will hopefully lead to more transparent reporting of uncertainties and increased consideration of changes in chemistry/environmental conditions in cores where temperature changes are co-occurring. This is important to avoid providing erroneous or uncertain data for climate researchers in other fields.

The results in Paper II further suggest that paleotemperature reconstructions need to be restricted to cores without large changes in lithology. The GDGT work here highlights the need to assess environmental shifts and shifts in provenance of the GDGTs, i.e., bacterial community shifts, prior to reconstructing paleotemperatures downcore. In case of large changes in paleoenvironments, via, for instance, mineral input and pH changes, or changes in waterlogging, the MBT$^{\text{SME}}$ index may be dominantly affected by microbial community shifts rather than temperature. Such shifts may be detectable by changes in independent geochemical proxies but also via a number of GDGT indexes, such as the degree of cyclization and isomerization, as well as the IR$_H$ index proposed here.

While not all cores are suitable for GDGT paleotemperature reconstructions (due to provenance or lithology-induced bacterial community shifts), the GDGTs in such cases instead may be useful as environmental proxies for other variables, as shown in here in Papers II, and also in Paper III and the Outlook section. In the Diatas peatland, changing isoprenoidal GDGT composition indicates variations in waterlogging and methanogens versus peat oxygenation. Likewise, pH changes can be reconstructed via brGDGTs. The IR$_H$ index informs about the influence from lakes and surrounding soils, i.e., changes in provenance. Branched and isoprenoidal GDGTs, therefore, hold great potential as terrestrial paleoenvironmental proxies even though they are not always applicable as temperature proxies. $P_{\text{GDGT}}$ index also appears to be a good qualitative proxy for precipitation amount (discussed further in Papers III and the Outlook section).

Based on the fact that the Padang reconstruction agrees with nearby marine cores and climate model simulations in terms of trends, the temperature reconstruction likely accurately reproduces the relatively small temperature changes seen over the Holocene. This shows that GDGTs provide a powerful method even for periods with relatively minor temperature changes from a geological perspective. brGDGTs temperature reconstructions are quantitative, i.e., the transfer functions from MBT$^{\text{SME}}$ to mean annual air temperature yield absolute values. However, this study, amongst others, shows that the specific numbers are inaccurate, either in terms of core top temperatures or, as in the case of Sumatran peats, in the magnitude of temperature shifts over time (Parish et al., 2023; Smittenberg et al., 2022; Zhao et al., 2022). The calibration datasets are based on global sample sets, and report relatively large RMSE $> 3.8^\circ$C (Dearing Crampton-Flood et al., 2021; Martínez-Sosa et al., 2021; Naafs et al., 2017b, 2017a). However, the uncertainties relevant for global sample sets, which cover completely different ecosystems and climate zones, may not be directly applicable for a smaller area or downcore records. For example, Russell et al. (2018) conducted a survey of African Lakes, and constructed a calibration with a much lower RMSE of 2.1 $^\circ$C. Similarly, tropical peat-specific calibrations may provide more robust absolute temperature estimates than is currently possible.
Disentangling seasonal and annual precipitation signals in the tropics over the Holocene: insights from $\delta$D, alkanes and GDGTs

Previous research in the IPWP has mainly utilized isotopic proxies from speleothems and leaf waxes interpreted as “precipitation amount” based on the ‘amount effect’ (Dansgaard, 1964; Niedermeyer et al., 2014; Wurtzel et al., 2018). However, whether this ‘amount’ reflects annually averaged conditions, i.e., mean annual precipitation, or a seasonal ‘monsoon’ signal, has previously not been fully explored. A potential reason for this incomplete interpretation of current methods may be that it is challenging to decipher specifically which season a proxy signal records.

Paper III focuses on hydroclimatological changes over the past 8000 years derived using a multiproxy approach on the Padang peat core. The goal of the paper was to do an in-depth analysis of hydrological proxies, and how they relate to (1) annually averaged precipitation and (2) seasonal precipitation.

Attempts to resolve seasonality using speleothem records have, for example, been to analyze the $\delta^{13}$C signal, prior-calcite-precipitation and trace elements, next to $\delta^{18}$O which records water isotopes (Wolf et al., 2023). These methods can yield information on surface vegetation/biomass and cave ventilation (Wolf et al., 2023), which can be affected by seasonality, but no additional information specifically on the $\delta^{18}$O signal is achieved. In the case of leaf wax records, usually based on n-alkanes or n-alkanoic acids, the long chain compounds exclusively from terrestrial plants are commonly used (approx. C$_{27}$ to C$_{31}$) (e.g., Sachse et al., 2012; Konecky et al., 2016; Niedermeyer et al., 2014). However, these lipids are produced in a much wider range by different producers (approx. C$_{17}$ to C$_{35}$), and the currently dominant approach, therefore, utilizes only a fraction of the isotopic data available from the same measurement. A likely reason for this underutilization of the full range of wax lipids is that terrestrial lipids (C$_{27}$-$C_{31}$) are often much more abundant than aquatic (C$_{21}$-$C_{25}$) and algal (C$_{17}$-$C_{19}$) (Aichner et al., 2010) lipids and the shorter chains are therefore more challenging to measure.

In the Padang peatland, n-alkanes sourced from terrestrial plants (C$_{29}$-$C_{33}$) have the highest abundance, but large quantities of aquatic (C$_{21}$-$C_{27}$) and algal (C$_{19}$) sourced n-alkanes are also present in the core (Fig. 12). This allowed robust $\delta$D measurements from these three distinct sources. Thus, taking advantage of the full spectrum of n-alkanes from C$_{19}$-$C_{33}$, the differences in the isotopic signals derived from algae, as well as aquatic and terrestrial plants, were investigated. Since algae grow during the wet season (during flooding and potentially nutrient inputs), algae reflect the $\delta$D$_{precip}$ from the monsoon season. Terrestrial plants, on the other hand, grow throughout the year in the tropics (Malhi et al., 2014b, 2014a) and, therefore, reflect an integrated $\delta$D$_{precip}$ over more or less the whole year. Thus, $\delta$D measured on both algae and terrestrial plants in the same sample enables disentanglement of seasonal and annual precipitation signals.
The isotopic results indeed show that the $\delta D_{\text{terr}}$ and algal $\delta D_{C19}$ signals are divergent (Fig. 13). Annual precipitation, as reflected by $\delta D_{\text{terr}}$, increased from $\sim 7.1$ ka BP, with peaking precipitation around 4.5-3 ka BP and rapid drying from around 2.8 ka BP. $\delta D_{C19}$, interpreted to reflect monsoonal strength, displays more depleted deuterium ratios compared to $\delta D_{\text{terr}}$ between $\sim 8$-4 ka BP and more similar values during the Late Holocene. This difference between $\delta D_{C19}$ and $\delta D_{\text{terr}}$ in the older parts of the record is interpreted to indicate a larger seasonality, i.e., stronger monsoon (causing lower $\delta D_{C19}$) and drier dry season (causing higher $\delta D_{\text{terr}}$ via evaporative enrichment in terrestrial plants). To quantify the relative variations in $\delta D_{C19}$ and $\delta D_{\text{terr}}$, their difference is calculated in the $\Delta \delta D_{\text{terr}-C19}$ index (Fig. 14d).

The isotopic results form the foundation of Paper III and allow disentanglement of seasonal and annual precipitation signals. Since this is a novel approach, these results are validated using independent proxies for annual as well as seasonal conditions. Independently reconstructions of peat annual wetness were conducted by (1) utilizing vegetation/biomass composition derived from a PCA based on $n$-alkane distributions, which reflect aquatic and algal plants relative to terrestrial plants (PC1 alkanes; Figs. 14h), and (2) the
newly proposed \( P_{\text{GDGT}} \) index (Fig. 14i) (De Jonge et al., 2024). The reconstructed annual precipitation/humidity follows seasonal insolation during the wettest month, consistent with previous findings on Borneo and models (Fig. 14i) (Dang et al., 2020; Partin et al., 2007). In terms of independently reconstructing the seasonality in the Padang peatland, (a) crenarchaeol was used as a drought proxy (Fig. 14a), (b) the relative abundance of algae versus aquatic plants as a seasonal flood index (Fig. 14c), and (c) levoglucosan as a tracer of biomass burning (Fig. 14b). All proxies indicate the wettest overall conditions between approximately 4.5-3 ka BP, and the highest seasonality in the older parts of the records, particularly between 6-4.2 ka BP. The latter period was characterized by seasonal floods, droughts and wildfires, corroborating the isotopic results pointing towards severe seasonality. The more seasonal conditions in the Mid-Holocene relative to the Late Holocene are attributed to more intense autumn insolation (driving stronger monsoons) and weaker spring insolation (driving lengthened dry season with less precipitation) (Fig. 14e; Laskar et al., 2004).

Figure 14. Synthesis of the hydroclimatological data from the Padang wetland and insolation at 2 °S. Indicators for seasonality in a-e: (a) crenarchaeol (Cren) fractional abundance, (b) levoglucosan concentration, (c) algae/aquatic \( n \)-alkane ratio, (d) \( \Delta \delta^{18}O_{\text{terr}-C_{19}} \), (e) insolation difference between September to December and January to April at 2 °S (Laskar et al., 2004). Indicators for more annually integrated precipitation or humidity in f-i: (f) \( \delta^{18}O_{\text{terr}} \), (g) October to November insolation at 2 °S, (h) PC1 reflecting aquatic \( n \)-alkanes, and (i) \( P_{\text{GDGT}} \), precipitation proxy based on GDGTs. A three-point smoothing is applied to the isotopic records (\( \Delta \delta^{18}O_{\text{terr}-C_{19}}, \delta^{18}O_{\text{terr}} \)) and a five-point smoothing is applied to crenarchaeol, algae/aq, leading PC1 and \( P_{\text{GDGT}} \). Figure from Hällberg et al. (2024).
Paper III - Contributions to the field

In Paper III, a novel approach was applied in reconstructing hydroclimate variability using the full range of n-alkanes and their stable hydrogen isotopes. This method enables disentanglement of seasonal and annual precipitation, and appears robust because the conclusions are corroborated by other independent proxies.

Peaking precipitation was reconstructed between 4.5-3 ka BP using δDwax, reflecting annual conditions. This was ~1500-2000 years later compared to previous research in the area based on speleothem δ18O (Wurtzel et al., 2018). This offset is also observed between speleothem δ18O and δDwax on Sulawesi, also located at 2°S (Konecky et al., 2016; Krause et al., 2019; Yuan et al., 2023). The speleothem records rather follow the Padang proxy for seasonal monsoon rainfall amounts, δDC19, which indicates maximum monsoonal precipitation around 6 ka BP, rather than the annual precipitation. This indicates that speleothem data from the Maritime Continent may reflect seasonal rather than annual precipitation, and thereby challenges the conventional interpretation of these speleothem δ18O records (Wurtzel et al., 2018; Yuan et al., 2023). Thereby, δD based on various sources can be informative for how isotopic proxies are best interpreted. Lipid biomarkers thereby provide important complementary information to speleothem precipitation reconstructions.

The findings in this paper suggest that it would be beneficial to measure, discuss, and report as much source-specific δD data as possible in precipitation reconstructions. The current literature usually reports the isotopic composition of only one or a few chain lengths. It may be advantageous to target ‘wet’ sites (peats, lakes) that contain more short n-alkanes than drier archives, and also to extract large enough samples that there is enough material to conduct δD quantifications on all n-alkanes C17-C33, where feasible.
Outlook and unpublished data

Paleoenvironmental reconstructions from the Diatas peatland

This thesis is based on paleoclimatological and paleoenvironmental reconstructions using two peat cores from the Padang and Diatas peatlands. In Paper II, both peat cores were discussed together with other sample sets, in the context of GDGT source and temperature indicators. Paper III focuses on the hydrological data from the Padang peatland. In this section, I outline the main findings from the Diatas peatland, which focuses on local hydroenvironmental conditions, and forms an outlook on ongoing and future work. The unpublished work from Diatas focuses on biomarkers, similar to Papers II and III. Additionally, inorganic geochemistry is also investigated. The chemical composition in the Diatas peatland is tied to mineral grain size variations, which is interpreted to have been driven by changes in ENSO strength over the Mid-Late Holocene.

Initial radiocarbon dating of the core indicated a period of low accumulation rate during the Mid-Holocene, according to the age-depth model based on 16 radiocarbon samples for Diatas published in Paper II. To narrow down uncertainties and establish if the accumulation was continuous over the Holocene, 21 more samples were radiocarbon dated. The new age data revealed a hiatus at 350 cm depth, between 4.8-3.1 ka BP (Fig. 15). The hiatus may either be caused by halted peat growth or removal of peat following remineralization of organic matter due to decomposition or burning under oxygenated conditions. Assuming the latter, and an accumulation rate similar to the millennia preceding and following the hiatus, the remineralized material corresponded to approximately 1.07 m of peat. Since precipitation on Sumatra peaked between around 4.5-3 ka BP (Paper II), it is unlikely that biomass growth would have decreased at Diatas during the period of the hiatus. Therefore, the hiatus is attributed to increased peat decomposition rate. The end of the hiatus is similar in timing to rapid drying in the region (Paper II), and consequently, the hiatus is hypothesized to be caused by the Late Holocene climate shift. In line with this, the peat accumulation rate at Padang also decreased at this time, and peat accumulation rate in the whole region slowed down (Dommain et al., 2014). Alternatively, the increased seasonality between 6-4 ka BP (Paper II) may have caused faster peat decomposition at Diatas during dry season water table lowering, leading to interrupted peat buildup.
Figure 15. Lithology, age-depth model, TOC and accumulation rate from the Diatas peat core. (a) Munsell colors of the core, (b) age-depth model and inset age model statistics generated using rbacon. (c) TOC and (d) peat accumulation rate. Note the hiatus between 4.8-3.1 ka BP.

The n-alkane distributions and their sources in the Diatas core appear similar to Padang (Fig. 16). A PCA on the n-alkane distributions reveals that terrestrial long chain n-alkanes are highest in abundance and form two distinct groups: C_{29} and C_{31} in one group, and C_{33} and C_{35} in the other group, likely reflecting forest and open vegetation, respectively. C_{21} to C_{27} groups closely on the PCA, suggesting a similar macrophyte source (Aichner et al., 2010). As was the case in Padang, C_{19} plots similarly to the macrophytes on PC1, but separately on PC2. Almost no C_{17} was found in Diatas, similar to Padang, suggesting that C_{17} is not abundantly produced in Sumatran peatlands. A major difference between Padang and Diatas is that C_{19}, likely sourced from algae or bacteria (Aichner et al., 2010), is very low in concentrations in Diatas relative to the mid-length n-alkanes (C_{21}-C_{25}), suggesting generally drier conditions, likely with less standing water.
Figure 16. Diatas peat core average n-alkane distribution (a) and PCA loadings based on the n-alkane distributions of all samples (b). Black labels in (b) are PCA loadings for each n-alkane and blue labels are interpreted sources.

$\delta D_{\text{wax}}$ was measured on C$_{25}$-C$_{31}$ from the Diatas peatland (Fig. 17a). The trends in isotopic composition for C$_{27}$-C$_{31}$ were similar, revealing the following: dry conditions (high values) during the Early Holocene, wet (low values) Mid-Holocene and a drier Late Holocene. The trends agree with the total precipitation reconstructed at Padang, but due to the hiatus 4.8-3.1 ka BP, the timing of the wettest period according to Diatas isotopic data could not be constrained. Not enough lipid extract remained during GC-IRMS analysis to conduct measurements on the shorter, low abundance n-alkanes (C$_{19}$-C$_{23}$), which would have allowed a more direct comparison with the approach used on the Padang dataset.

The findings from $\delta D_{\text{wax}}$ of wetter conditions during the Mid-Holocene, and drier Early and Late Holocene are corroborated by independent multiproxy data. The biomass composition based on n-alkanes sourced from macrophytes, algae and terrestrial vegetation shows higher macrophyte and algal abundances in the Mid-Holocene, consistent with wetter conditions (Fig. 17b and c), $\delta^{13}$C show less depleted values both close to the base of the core and during the Mid-Holocene (Fig. 17e), interpreted to indicate aquatic biomass near the base, and a higher proportion of grasses in the Mid-Holocene, which is corroborated by the n-alkane distributions and the ‘Grassy/Woody’ index (C$_{29}$+C$_{31}$/C$_{33}$+C$_{35}$) (Fig. 17d). These findings are also supported by pollen data reconstructed by collaborator Anggi Hapsari at the University of Göttingen (not shown, personal communication, manuscript in preparation).

The GDGT dataset for Diatas is indicative of local chemistry and hydrology changes rather than temperature (Paper II). The findings here add support for the hydrological conditions indicated by the previously mentioned proxies. pH reconstruction based on the CBTpeat index (Fig. 17j) (Naafs et al., 2017b) indicates that the peat was more acidic during the wettest period, consistent with waterlogging and buildup of organic acids. Crenarchaeol and BIT (Fig. 17g), which can be used as a proxy for peat oxygenation (Hällberg et al., 2023, and references therein), similarly indicates waterlogging during the Mid-Holocene, and oxygenation of the peat during the Late Holocene. Higher values of crenarchaeol during the Early Holocene are likely related to the input of aquatically produced GDGTs. Notably, the P$_{\text{GDGT}}$ proxy (De Jonge et al., 2024; Paper II) closely follows the isotopic reconstruction of precipitation (Fig. 17i). Thereby, P$_{\text{GDGT}}$ follows precipitation on Sumatra in our Singgalang soil transect (De Jonge et al., 2024), the Padang peatland (Paper II) as well as the Diatas peatland – lending support for further use of GDGT composition as a qualitative precipitation proxy.

Microcharcoal quantification on the Diatas core was also done by Anggi Hapsari at the University of Göttingen, and that data is presented in Fig. 17f. Large amounts of charcoal were deposited during the Early Holocene when the climate was drier and potentially more seasonal, with peaks around 11 and 8.2 ka BP. During the Mid-Holocene, peaks in charcoal provide evidence for a large fire at 6.2 ka BP and a smaller fire at 5.5 ka BP. These dates are consistent with the period of high seasonality reconstructed from Padang.
(Paper III). Radiocarbon dating revealed that the hiatus occurs at a depth of 350 cm. Charcoal analyses were conducted on samples from depths of 342 and 352 cm. The sample below the hiatus had very low charcoal concentration, and the sample above the hiatus had just a slight increase (Fig. 17f). Thereby, it appears that the hiatus was not caused by biomass burning, but this remains to be confirmed by analyzing more samples surrounding the hiatus. Charcoal concentrations gradually increased over the last millennia, which may be related to intensified human activity and biomass burning in the area.
Figure 17. Hydrological and ecological proxies from the Diatas peat core. (a) $\delta D_{wax}$ from $n$-alkanes C$_{25}$-C$_{31}$, and the average of C$_{27}$-C$_{31}$ as a thick black line. (b) $f(C_{21}-C_{27})$, indicative of macrophytes, (c) $f(C_{17}-C_{19})$, likely sourced from algae, (d) grassy/woody vegetation index, (e) bulk $\delta^{13}C$, interpreted to reflect grass and aquatic vegetation relative to forest or terrestrial biomass, (f) microcharcoal concentration, (g) BIT index, indicative of the fractional abundance of crenarchaeol which requires oxygenated conditions, (h) the IRH index (Paper II), indicating GDGT sources, (i) the precipitation proxy $P_{GDGT}$, and (j) peat pH inferred from CBTpeat.
The organic geochemical data show that the peatland underwent large shifts in paleoenvironment and chemistry. In line with this, inorganic geochemical data (X-Ray Fluorescence: XRF, measured by Steffen Wiers and collaborators at Nanyang Technical University, Singapore, using an Avaatech core scanner) show substantial changes in chemical composition in the peat core.

The Ti/Si ratio, log normalized as log(Ti/Si), has been reported in the literature to reflect grain size, with a larger proportion of Ti in the coarse fraction and Si in the finer fraction (Bertrand et al., 2024; Löwemark et al., 2011). Silica can also have a biological source, produced by diatoms and in leaf phytoliths (Bertrand et al., 2024). The Ti/Si ratio at Diatas was high during the Early Holocene, when the wetland was connected to the nearby lake (Fig. 18), suggesting coarse grain size particles being deposited. During the Mid-Holocene, very low Ti/Si ratios indicate small grain sizes, i.e., low energy available for soil transport into the wetland. The Late Holocene was then characterized by much higher Ti/Si values and coarser grain sizes.

To evaluate if the findings from Ti/Si data indeed reflect grain size in the Diatas core, a PCA was additionally conducted on elemental center log ratio normalized compositional data (Fig. 18) (Bertrand et al., 2024). The elemental data show clear grouping on PC1, which explains 45.2% of the dataset variability. Elements associated with the lithogenic fraction and coarse particles (Al, Ti, Zr) display negative PC1 loadings. Elements that are more easily weatherable and can be associated with organic matter or are often found in the finer fraction plot positively on PC1. Ti/Si and PC1 show a strong correlation ($R^2 = 0.76$), and we, therefore, interpret them both to reflect grain size variations through the core, in line with previous research (Bertrand et al., 2024; Löwemark et al., 2011). To ground-truth this interpretation, the grain size was measured using a Malvern Mastersizer 2000 on a small subset of samples and found a strong correlation to PC1 ($R^2 = 0.73$) and a moderate correlation to log(Ti/Si) ($R^2 = 0.50$). The elemental data is, therefore, a robust and high-resolution (2 mm scan interval) indicator of grain size throughout the Diatas peat core. The input of minerals and their grain size variations at the Diatas peatland between the Mid-Holocene (small amount of fine minerals) and Late Holocene (larger amounts of coarse minerals) is likely tied to climate and environmental changes between the two periods, i.e., intensified transport of soil particulates during the Late Holocene.
A potential mechanism for coarser mineral erosion from the soils surrounding the Diatas peatland, and subsequent deposition in the peatland, during the Late Holocene is increased hydroclimate variability. A transition from wet and relatively stable conditions during the Mid-Holocene, into a highly variable and drier Late Holocene with increased ENSO activity, was likely responsible for the increased input of coarse material into the peatland. Since ENSO is composed of alternating periods of dry (El Niño) and wet (La Niña) conditions, their increased activity provides a likely mechanism for increased erosion. Downpours during La Niñas would generate high energy conditions to mobilize soil material in the Diatas valley, leading to larger amounts of minerals and larger grain sizes to be deposited on the peatland. Droughts during El Niños may also have decreased soil stability due to changes in slope vegetation cover. A combination of a generally dry climate with ENSO-induced climate variability, therefore, seems like a likely driver of grain size variation in the Diatas peatland. This interpretation is supported by climate model data, which shows increased hydroclimate variability in the Late Holocene (based on own analyses of EC-Earth and MPI-ESM and literature data, e.g., Carré et al. (2021)) and proxy reconstructions from the Pacific Ocean (Emile-Geay et al., 2016).

No interpretation was made of the elemental data during the Early Holocene, in the basal Early Holocene part of the core. These grain size variations are probably more related to the peatland succession from a wetland connected to the adjacent lake into a raised peat bog and are, therefore, not interpreted as a signal of climate change.
Preliminary conclusions from Diatas

The Diatas peat core extends the Holocene work of this thesis from the past 8000 years (Padang: Papers II and III) to the past 11 000 years. The precipitation reconstruction based on δDmax shows that the Mid-Holocene was much wetter than the Early and Late Holocene, in line with results from Paper II and a Borneo speleothem δ18O reconstruction (Partin et al., 2007), and shows more pronounced changes than the nearby speleothem on Sumatra (Wurtzel et al., 2018). The precipitation reconstruction is corroborated by GDGT and biomass-type reconstructions. A 1700-year-long hiatus in the core hints toward a large ecological effect of the sudden drying in the Late Holocene, with implications for carbon storage in the region (Dommain et al., 2014). The grain size record is interpreted as a proxy for erosion from the surrounding soils. Surprisingly, erosion was low when precipitation amounts were highest in the Mid-Holocene. Instead, erosion intensified in the dry Late Holocene due to strengthened ENSO variability.

The conventional application of brGDGTs as a paleotemperature proxy was not applicable to the Diatas peat core due to variations in the brGDGT-producing bacterial community. This issue with the temperature reconstruction, and the hiatus, which was accurately constrained only after a very large effort of radiocarbon dating, highlights the limitations in age models and the challenges and uncertainties in GDGT proxy reconstructions. Additionally, multiple cores and sites have to be considered to generate robust paleoclimate data.
Conclusions

The seasonal component of paleoclimatological studies has been emphasized in this thesis. Paper I shows that the Late Glacial climate was much more seasonal than the LGM and most of the Holocene. The Maritime Continent experienced cool and extremely dry winter conditions during the Late Glacial, resembling extreme El Niño conditions in the modern climate. Orbital forcing, sea level transgression, opening of the Indonesian Throughflow and warmer SSTs caused a decrease in seasonality in the Early to Mid-Holocene, according to our model results. Paper III reconstructs total precipitation over the past 8000 years on Sumatra, and further shows from a proxy perspective that seasonality has changed drastically also over the Holocene. The Mid-Holocene, particularly 6-4.2 ka BP, was much more seasonal than the Late Holocene. The impact on the studied site during the most seasonal period was alternating droughts, flooding and wildfires, i.e., more frequent extremes, reminiscent of current changes seen in many locations globally under recent rapid warming.

Paper II presented a reconstruction of the temperature evolution on Sumatra over the past 8000 years. The Sumatran climate has warmed over this time period, agreeing with nearby marine reconstructions and annual mean global temperatures from climate models. However, gradual warming is in contrast to global reconstructions which show cooling over the time period. Hypothetically, the absence of significant temperature seasonality on Sumatra may be an explanation for the reconstructed gradual warming which is different to the Holocene temperature trends reconstructed elsewhere.

The hydrological reconstructions (Papers III and Outlook) show that the wettest conditions started to occur around 6.5 ka BP and peaked around 4.5-3 ka BP. This is 1.5-2 ka later than indicated by previous reconstructions from the regions based on speleothems. The findings here suggest that the speleothem reconstructions should be interpreted as monsoonal rather than annually averaged signals. This is an important distinction, particularly for ecosystems, and when it comes to providing accurate proxy data that can be used to validate climate model simulations that are used to predict future climate.

The Late Holocene was characterized by rapid drying, even causing peat remineralization, and a transition towards higher impact of El Niño and La Niña climate variability on Sumatra, resulting in increased soil erosion.

This thesis highlights the importance of considering the isotopic values of the full range of \textit{n}-alkane chain lengths in order to gain an expanded understanding of the hydrological cycle in precipitation reconstructions. The \textit{n}-alkane distributional data is a powerful tool in reconstructing biomass types, from algae, macrophytes, woody plants and open vegetation, further strengthening paleoclimate reconstructions. The findings in this thesis also show that the impact of environmental changes on GDGT distributions must be analyzed prior to attempting brGDGT paleotemperature reconstructions, and a novel approach to identify down-core bacterial community changes was presented.
Acknowledgments

I am profoundly grateful for the group of people who have been around me during my PhD days at Stockholm University. Malin Kylander has helped tremendously over the past two years. Her help was invaluable to get me back on track after some personal hardships, and Malin’s ‘Dirt-people’ (Terrestrial Paleoclimate Group) research group has been a highly enjoyable research environment and a source of open scientific discussions, inspiration, and fun. Thank you for everything, Malin! A heartfelt thanks to Rienk Smit-tenberg for training me as an organic geochemist, and for being open to all possible research directions, and always providing plenty of support. Frederik Schenk was very important throughout the project, and has been my main pillar of support for everything related to climate model simulations. A huge thanks goes out to Viktoria Arvinge, who has given me incredible support that I am endlessly thankful for. Magnus Mörth is also thanked for continuous support. I have had many interesting discussions with Kweku Yamoah over the years – thank you for the ideas and inspiration. Julia Steinbach has been great support in the lab. Thank you, Klara Hajnal, for showing me the ropes in the lab during my initial year, with your four-decade long experience at Stockholm University – and for your friendship. Caroline Bouvet de la Maisonneuve is thanked for inviting me to NTU Singapore and field work on Sumatra, as well as sharing of core material that has laid the foundation for this thesis. Steffen Wiers and Francesca Forni who also were at NTU are thanked for making my visit in Singapore a great experience and their scientific contributions towards the work in this thesis. Hamdi Rifai is thanked for organizing and assisting during my visit to Sumatra. Thanks to Riyan Fadila and Prima for joining the adventure on Mount Singgalang. Thank you Guillermo Jarne-Bueno, Voula Paraskevi and Yolanda Schankat, for contributing to the project during your theses – I really enjoyed working with you. Thanks to the whole PhD group at IGV for the supportive community and all the laughs and fikas, and extra thanks to Jenny Sjöström and my fellow geochemists: Tzu-Hao Huang, Sophie ten Hietbrink, Jonas Fredriksson and Emelie Stähl. Last but certainly not least, I want to thank my partner Linnea Sandberg and my family.

The Swedish Research Council is thanked for providing the main sources of funding for this PhD project, and the Bolin Centre for Climate Research is thanked for providing funding for research visits and conferences.
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