Part A – Applicant

A.1 Main applicant

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Part B – Scientific proposal

B.1 Basic details

B.1.1 Title
Determination of the extent and strength of the Hadley cell over 5 glacial cycles off the coast of NW Africa

B.1.2 Abstract
This study is proposed to increase the understanding of the Hadley cell throughout the last 500 kyr based on multi proxy quantitative measurements. This research is important because there is a large research gap concerning the understanding of the Hadley cell in the paleoclimate record, more specifically, its variation over glacial cycles. This research is set up for two Ph.D. students. One Ph.D. student will focus on changes of the size of the Hadley cell and the other Ph.D. student will focus on changes of the strength of the Hadley cell. During a field campaign five piston cores will be taken from three selected areas. The cores will be analyzed by different proxies: grain size, XRF and foraminifera. All information combined will be used to observe the changes in the width and strength of the Hadley cell. The first area, cores 1, 2 and 3, will be taken at latitudes of approximately 33, 30 and 27°N. These cores will be used to observe variations in the northern extent/width of the Hadley cell. The second and third area will focus on the strength of the Hadley circulation. Area 2 will reconstruct this by counting multiple planktonic foraminifera species since upwelling strength can be used as an indicator of Hadley strength. The ratios between them can be used as a proxy for this strength. To do so, core 3 and 4 will be used that are located at 27 and 20°N, respectively. By covering a larger spatial region, possible conclusions about upwelling and Hadley cell strength variation are stronger. In Area 3, two cores, 4 and 5, will be taken at the same northern latitude, 850 km apart. Both will be analyzed on grain size as a stronger Hadley cell is capable of transporting larger, heavier grains. So, core 3 and 4 are analyzed on multiple proxies. On all cores, d18O will be computed at a 5 cm interval on calcareous foraminifera and is matched with d18O of the NGRIP and Antarctic ice cores. This will be used to create an age-depth model for the cores. The time period, the high resolution and the focus on the Hadley cell is what makes this research unique. This research is important, because it will fill a large research gap about the understanding of the Hadley cell and allows climate models to be evaluated, thereby giving more insight into climate change.

B.1.3 Summary
This study will increase the understanding of the Hadley cell throughout the last 500 kyr. The Hadley cell is the name of the continuous atmospheric circulation with rising air near the equator, called the Intertropical Convergence Zone and descending air over the subtropics, at about 30°N and S. This research has room for two Ph.D. students. One Ph.D. student will focus on changes of the size of the Hadley cell and one Ph.D. student will focus on changes of the strength of the Hadley cell. This research will concentrate on three different areas in the ocean of the northwest African coast where, during a 13 days field campaign, 5 sediment cores will be taken. In the first area, three cores will be taken (core 1,2 and 3) and analyzed on chemical elements. This analysis will be used to observe variations in the width of the Hadley cell. For area 2, core 3 and 4, will be analyzed on foraminifera species, because the ratio between them indicates oceanic upwelling strength. Upwelling strength can be used as an indicator for the strength of the Hadley circulation. Using two cores that are spatially apart, provides more insight about the upwelling strength along a larger region, which results in stronger conclusions about upwelling and Hadley cell strength. For the third area, core 4 and 5 will be used. Core 5 will be taken further away/westward from the coast, but at about the same latitude as core 4. The aim of the third area is to determine the strength of the Hadley cell. For these cores, grain size analysis will be used to indicate Hadley cell strength, because a stronger Hadley cell is able to transport heavier grains further away. For all cores, d18O will be computed on all cores to find the ages of the cores at different depths. This research is important, because it will fill a large research gap about the understanding of the Hadley cell and allows climate models to be evaluated, thereby giving more insight into climate change.

B.1.4 Keywords
Hadley cell; paleoclimatology; Sahara; marine sediments; dust; foraminifera; grain size analysis; XRF

B.2 Scientific proposal

B.2.1 Research topic

Climate models are increasingly being used to understand the effects of forcings on Earth's climate system and for making projections of future climate (Flato et al., 2014). These models are especially of importance in the light of human induced climate change. Since many climate models are developed to make projections for the 21st century, they are often calibrated based on the last decades (Braconnot et al., 2012). A large problem is that different models yield similar results for current climate, but show large differences for future projections (Knutti, Furrer, Tebaldi, Cermak & Meehl, 2010). A method to evaluate these models outside their calibration range is by using paleoclimatic data (Braconnot et al., 2012).

One effect of climate change that has been modeled by several researchers is widening and weakening of the Hadley cell (HC) (D'Agostino, Lionello, Adam & Schneider, 2017; Lu, Vecchi & Reichler, 2007; Frierson, Lu & Chen, 2007, Otto-Bliesner & Clement, 2004). The HC is the continuous atmospheric circulation with rising air over the equator (Intertropical Convergence Zone, ITCZ) and sinking air over the subtropics, at roughly 30°N and S (Dima & Wallace, 2003). The two regions are linked by poleward mass transport in the upper troposphere and stable, continuous trade winds in the lower troposphere (Quan, Diaz & Hoerling, 2004). The HC is vital in Earth's climate system by transporting energy and angular momentum poleward (Lu et al., 2007). In addition, the HC largely determines the high precipitation region around the equator and the subtropical dry zones (Larrasoaña, Roberts & Rohling, 2013; Lu et al., 2007). The climate models help to understand the processes and responses to forcings of the HC. However, as pointed out by Son, Kim and Min (2018), the Hadley circulation in the paleoclimate is not well documented. So, it is unclear how the HC differs during glacials and interglacials in terms of size and strength. This complicates the evaluation of the models. Therefore, this research is proposed to obtain the necessary paleoclimatic data which eventually can benefit the climate models.

Model results suggest that the HC was narrower and stronger on both hemispheres during the Last Glacial Maximum (LGM) (D'Agostino et al., 2017; Son et al., 2018). Yet, the strength signal is much less pronounced on the Southern Hemisphere than on the Northern Hemisphere (NH). Thus, investigating whether the size and strength signal indeed can be found in the paleoclimate record has probably the highest chance of success in the NH. Therefore, the proposed research will concentrate on the NH. As dust has shown to be a valuable proxy for climate reconstruction (Does, Korte, Munday, Brummer & Stuut, 2016) and North Africa contributes to 50-58% of the global dust load, this study will focus on the North African region (Kok et al., 2021; Tanaka & Chiba, 2006). The following section discusses the regional setting of this area.

In the North African region (0-32°N) different vegetation bands can be distinguished: forest – woodland – wooded grassland – grassland – desert – (sub-)Mediterranean (Larrasoaña et al., 2013). The desert part, the Saharan region, ranges from about 17 to 31°N. The vegetation zones are mostly determined by the amount of precipitation, which is affected by the seasonal meridionally moving ITCZ (Larrasoaña et al., 2013). Large convection at the ITCZ results in more than 2000 mm precipitation each year. The North African region is dominated by the West African Monsoon system (WAM) with increased rainfall in the months April, May, June and July (Pausata et al., 2020; Gu & Adler, 2004). The WAM can have an influence up to 25°N (Gasse, 2000), but is generally confined to 15°N (Gu & Adler, 2004). Yearly precipitation decreases with increasing latitude, with the Sahara desert receiving less than 100 mm/year (Larrasoaña et al., 2013) caused by the year-round anticyclones resulting from the descending air of the HC (Gasse, 2000).

Another characteristic of the North African region is, as mentioned, its contribution to the global dust cycle. The trade winds in the HC transport the dust westward to the Atlantic (Prospero et al., 2002). The effect is that, on an annual basis, the dust column in the atmosphere over the Northern Atlantic originates almost solely from the Saharan desert. Dust deposition over the Atlantic is estimated to be 170 Tg/year (Prospero, 1996) thereby being an important supplier of nutrients to marine systems (Baker, Kelly, Biswas, Witt & Jickells, 2003). Chiapello et al. (1997) identified three regions within the Saharan region (north/west Sahara, central/south Sahara and the Sahel region) that have distinguishable elemental ratios. The ratios are Si/Al, Ca/Al, Fe/Ca, K/Ca and can be used as geochemical fingerprints to trace back from which region the dust originates.

Along the coast of Saharan Africa, another source of nutrients results from upwelling (Chavez & Messié, 2009). Trade winds are the driving force of the subtropical gyre which results in the southward Canary current. The combined effect of the African coast being located east of the current and the Coriolis force, produces Ekman flow. Thus, surface water moves away from the coast. In turn, this water is replaced by cool and nutrient-rich deep water which decreases sea surface temperature (SST) and increases primary production (Chavez & Messié, 2009). This distinct upwelling zone results in unique living conditions for specific planktonic foraminifera species. Characteristic upwelling species are *Globigerina quinqueloba*, *Globoquadrina duterei*, *Globorotalia inflata and Globigerina bulloides* (Thiede, 1975). On the other hand, *Globigerinoides ruber* and *Globigerinoides sacculifer* are characteristic tropical warm water species and can be found mostly further away from the African coast where SST is higher. The specific living conditions make these species exceptionally useful as indicators for the amount of upwelling.

To sum up, the HC is responsible for multiple processes within the tropical and subtropical region. However, the Saharan region has seen large climate shifts over millions of years and thus, the strength of these processes might have varied (Le Houérou, 1997). Over the last 8 million years, the Sahara has had a much more humid climate for more than 230 times (Larrasoaña et al., 2013). These periods are called Green Sahara Periods (GSP). For example, these occurred during the Eemian between 128-122 kyr BP and during the Holocene between 10-6 kyr BP. During these humid periods, paleo-lakes formed, caused by rainfall intensities reaching 400 to 1500 mm/year between 19 to 31°N (Pausata et al., 2020). Currently, these paleo-lakes are large dust producers, an example being the Bodele Depression in the Lake Chad basin (Prospero et al., 2002). In turn, this dust results in less warming over the Sahara in the months preceding the monsoon, thereby weakening the WAM (Pausata

et al., 2020). Less precipitation is brought to the Sahara desert, thereby allowing less vegetation growth. As the WAM is part of the HC, this is a clear example of dynamic processes interacting within the cell.
Combining that (1) there is a large research gap concerning the understanding of the HC in the paleoclimate record, (2) the results of climate models indicate size and strength variation during glacial cycles, (3) the currently lacking paleoclimate data would allow for evaluation of these models, (4) this region has the potential to use both dust and foraminifera proxies and (5) the HC creates a dynamic environment in terms of atmosphere, ocean and vegetation leads to the following aim: Investigate the size and strength of the HC throughout the last 500 kyr based on quantitative measurements which increases the overall understanding of the HC. Objectives to fulfill this aim are: (1) Perform literature research into the HC, dust and foraminifera, (2) learn to use the laser particle device for grain size-analysis, the XRF core scanner and about foraminifera counting, (3) find undisturbed sediments off the northwest African coast useful as climate archive, (4) date the sediment cores using d18O to create an age-depth model, (5) sample the sediment cores to analyze grain size distributions, elemental ratios and foraminifera species ratios, (6) use these climate proxies to infer conclusions about the strength and size of the HC over 500 kyr. The choice for 500 kyr is based on the fact that this timespan covers five glacial cycles, which is assumed to be a reasonable amount of time to make conclusions about the size and strength of the HC in a warm and cold climate (Lisiecki & Raymo, 2005). The research will create two Ph.D. positions of which one will focus on the size and one will focus on the strength. Both will learn to use different laboratory and research vessel instruments which could be of great importance for their future scientific career. Innovative aspects of this research are its focus on quantitative determination of glacial-interglacial HC variation, the use of multiple climate proxies, core sites over multiple spatial locations and high-resolution sampling.

B.2.2 Approach

As described above, the atmospheric circumstances have changed through time and in order to improve the understanding about the HC over the last 500 kyr the following approach is proposed. Three areas will be differentiated at which different proxies will be analyzed to observe and explain changes in size and strength of the HC. A field campaign that uses a research vessel will be set up to take five piston cores in the three different areas. The next paragraph discusses and explains the reasoning behind the core locations and sampling techniques.
In the first area, core 1- 3 will be taken at latitudes of approximately 33-30-27°N (figure 1). These latitudes are chosen based on simulations by D'Agostino et al., 2017) that show that the northern extent of the HC seems to vary around these latitudes during the LGM, Mid-Holocene and pre-industrial. So, these cores will be used to observe variations in the northern extent/width of the HC. It is expected that core 1 will receive less aeolian sediment originating from the northern Sahara during glacials since the HC is more confined (D'Agostino et al., 2017). Thus, less dust from the northern Saharan region would be transported towards the Atlantic Ocean. Core 3, the southern core, would still have received the Saharan sediments. During interglacials, all cores will receive sediments. All three cores will be scanned by the XRF scanner. The ratios of Si/Al, Ca/Al, Fe/Ca, K/Ca will be used as geochemical fingerprints to verify that the dust originates from the northwestern Sahara (Chiapello et al., 1997).

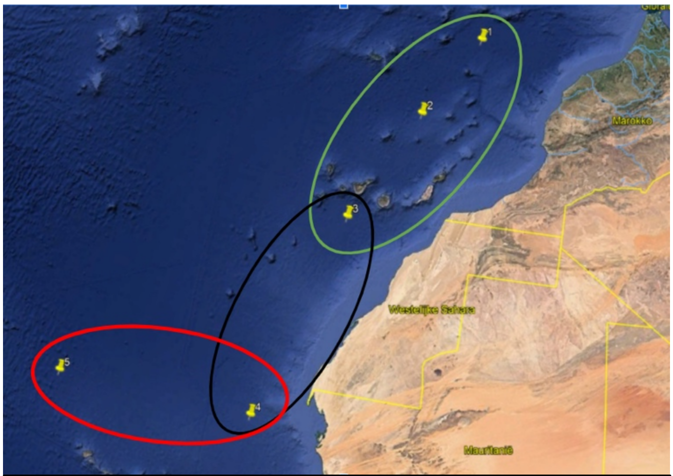

Figure 1. Location of core sites 1-5 off the coast of NW Africa. Green - Area 1: core 1-3 for elemental ratios; Black - Area 2: core 3,4 for foraminifera counting; Red - Area 3: core 4,5 for grainsize analysis (Google Earth Pro, 2022).

The second area will focus on the strength of the Hadley circulation. A reconstruction of the strength will be made, based on a reduction of upwelling. As described in Section B.2.1, the Canary current is a wind driven current. A weaker HC will reduce the amount of upwelling, which will result in a warmer SST. This alternation in SST will affect the planktonic foraminifera living in this area. The ratio between the upwelling, cool water species and the tropical, warm water species acts as a proxy for the strength of upwelling and therefore, as the strength of the HC. Core 3 will be used again and a new core (4) will be taken more southward, at about 20°N. So, both are located within the HC, the upwelling zone (Chavez & Messié, 2009) and the habitat of the foraminifera species (Thiede, 1975). This comparison between the two core sites is necessary, because core 4 is located fully within the habitat of the species, while core 3 is at the margin. This gives insights into the upwelling strength along a larger region, thereby strengthening possible conclusions about changes in the strength of upwelling and the HC.
The third area has the same aim as area two, determining the strength of the HC. However, grain size will be used as a proxy. If the strength of the HC increases, which is thought to happen during glacials (D'Agostino et al., 2017), the westward trade winds are better able to transport larger particles. To observe this effect, two piston cores at the same northern latitude will be taken. Core 4 will be used again and a new core (5) will be taken about 850 km west of core 4, at about 27°W. Both cores are needed, because this provides information about the downwind fining across the North Atlantic (Does et al., 2016). The latitude of 20°N has been shown to give excellent dust records to reconstruct paleoclimate (Does et al., 2016). For both cores, grain size-analysis will be executed which gives insight into the grain size distributions over time.
Cores 1-4 will be set at around the same distance from the coast, approximately 400 km. This will reduce the chance of turbidites disturbing the sediment layers, hence continuous sedimentation is assumed. In addition, the cores are not too far

from the coast to guarantee a relatively high sedimentation rate, which helps to sample the core at a high-resolution. Despite the reduced chance of turbidites, it is important to use combined multibeam and seismic investigation on the research vessel to guarantee the recovery of high-quality marine paleoclimate archives. This precludes disturbances in the records by turbidites and contourites, caused by deep water currents, that are both able to rework sediments. This is necessary for all five core sites as they are located between 2000-3000 m depth (Rona, 1971).

Based on the thick sediment layer in this region, for all core sites, a sediment core of more than 10 m is expected (Divins, 2003). However, cores of 5-8 m seem to be sufficient to cover the last 500 kyr based on the sedimentation rate of 1-1.5 cm/kyr (Ewing, Carpenter, Windisch & Ewing, 1973). To verify whether this assumption is valid, the first analyzed core will be sampled and dated up to 10 m. Following Does et al., (2016) for all cores, dating will be done by computing d18O at a 5 cm interval on calcareous foraminifera and is matched with d18O of the NGRIP for the first 120 kyr. In addition, Antarctic ice cores (Vostok and Dome C) will be used for comparison up to 500 kyr (Petit, 1999; Lüthi et al., 2008). Then, this can be used to create an age-depth model for the cores. Due to the long time interval of 500 kyr, carbon will not be used as a dating method since its maximum usability is up to 60 kyr (Christopherson & Birkeland, 2015). Subsequently, all cores will be sampled up to this depth with the age of about 500 kyr. This method prevents oversampling. In order to obtain a high-resolution signal, foraminifera counting and grain size-analysis will be sampled every 3 cm which corresponds to a 3.0-4.5 kyr resolution.

For this field campaign, it is proposed to collaborate with the Royal Netherlands Institute for Sea Research (NIOZ). They have more than 140 years of experience in this research field (Royal Netherlands Institute for Sea Research, n.d.). Moreover, they do a lot of joint research projects (Royal Netherlands Institute for Sea Research, n.d.). They also have laboratory facilities and a research vessel called RV Pelagia available. So, this ensures the applicability and accessibility of the proposed techniques.

The duration of the research is four years. Year 1 focuses on literature research and gaining experience with measurement devices in the laboratory and the boat. Year 2 continues this learning process and includes taking and analyzing the cores. Year 3 continues with core analysis and also includes the start of Ph.D. thesis writing. Year 4 is used for finishing the thesis, presentations and bringing the results to the general public. For more detailed information, there is referred to figure 2.

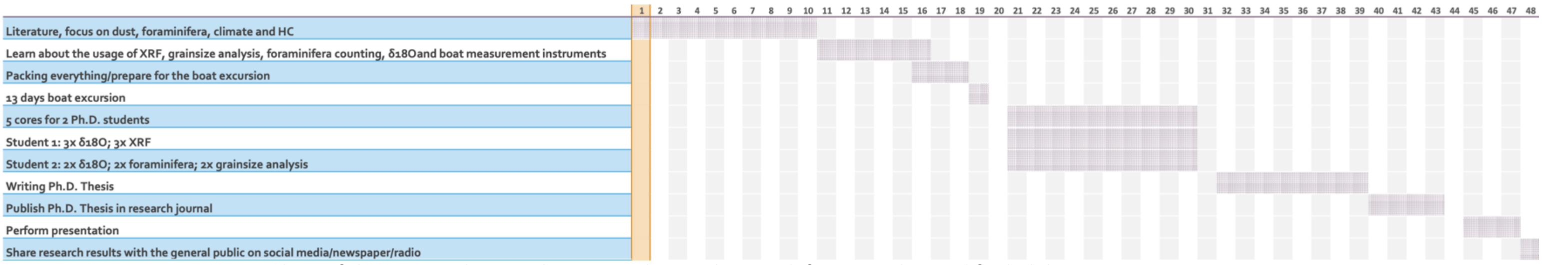

Figure 2. Gantt chart of the proposed research. Gaps in the timeline are left open to be used for holidays.

B.2.3 Justification

The total costs of the research will be around 770 k€ (table 1). More than half of this amount will be spent on two Ph.D. positions over a four-year period. The second largest part of the budget will be used on a 2-week research campaign where the data will be collected. The total distance between Casablanca (departure port), all core sites and Cape Verde (arrival port) is about 3340 km. Assuming a cruising speed of 8 knots, this takes about 10 days. Per core site four hours can be spent on taking the core and 10 hours on multibeam and seismic investigation and interpretation of those results. This makes a total of 13 days. A strict schedule is followed, to limit costs. The rest of the budget will be used for laboratory analysis and travel costs. Moreover, the Ph.D. students will fly by plane to the departure port and back to Amsterdam, because this is much cheaper than using the research vessel. Costs will also be limited by using cores for multiple purposes. As explained, core 3 will be used for both XRF scanning and foraminifera counting. Core 4 will be used for both foraminifera counting and grain size-analysis.

Despite the high costs of this campaign, we assume that this field campaign is of large importance because of multiple reasons. First, for the two Ph.D. positions it will be a lifetime experience, which will expand their scientific experience for both setting up a field campaign, to be on a research vessel as well as gaining hands-on experience with different measurement techniques and proxies. Secondly, their social network will expand which is of importance in the field of science. Also, piston cores can be taken from accurately chosen locations, which will be beneficial to obtain the right signal of the different proxies within the sediment cores. Furthermore, the schedule of the research allows for time to be spent on sharing the research results with the general public on social media, with the newspapers and on the radio. In addition, as mentioned earlier, the data created by this study will be beneficial for evaluating climate models. Thus, the knowledge utilization is assumed to justify the costs.

Table 1. Costs of the proposed research study.

Category	Clarification	Costs (EUR)
Personnel	2 Ph.D. positions, 48 months (2x €245 000)	490 000
Travel	Research vessel, 13 days (13x €20 000)	260 000
	Flight tickets Amsterdam-Casablanca; Cape Verde-Amsterdam	2 000
Lab experiments	XRF core scanner (3x max. 8 m)	4 800
	Grain size-analysis (Laser Particle) (517 samples)	5 170
	D18O analysis (5x 160 samples)	8 000
Total		**769 970**

B.2.4 Literature/references (in this proposal)

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