

Dust deposition and seawater fertilization in the Benguela current

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ABSTRACT

The atmospheric transport of windblown dust is a vital mechanism delivering essential nutrients to ecosystems, particularly influencing primary oceanic productivity through its impact on phytoplankton growth and the carbon cycle. The trace metal iron (Fe) is essential and plays a crucial role in the growth of oceanic biota. The scarcity of Fe has been linked to the limitation of phytoplankton growth in high-nutrient, low-chlorophyll (HNLC) regions. Eastern boundary upwelling systems, exemplified by the Benguela Upwelling System (BUS), are thought to share similarities with HNLC oceans and are suggested to face nutrient limitations, including Fe. Notably, desert dust, constituting approximately 95% of the global atmospheric budget, is a primary carrier of atmospheric Fe. However, given the frequency of dust-emitting sources surrounding the BUS, which are high in Fe, it's feasible to assume that the BUS is not Fe-limited. Previous remote sensing studies have highlighted the frequent dust emission from the southern African region, depositing in the adjacent BUS. Despite the potential significance of dust inputs to the BUS, the impact on phytoplankton biomass has only recently come under scrutiny. Recent research utilizing dust monitoring and chlorophyll a (Chl-a) remote sensing has observed increased chlorophyll concentrations in the BUS daily. Chl-a is commonly used as a proxy for phytoplankton changes in the ocean. While some research has examined the response of phytoplankton to individual nutrient treatments in the northern BUS, the reaction of BUS phytoplankton to a combined sample of Namib dust has not yet been explored. There is no existing long-term, high-resolution dust deposition modelling study for the BUS. It also remains unknown whether the seasonal dust deposition cycle potentially aligns with the seasonal phytoplankton changes in the region at the finer scale. In addition, a very recent dust emission event, visible on NASA satellite images, prompted the investigation of potentially new dust-emitting sources in the southwestern Angolan region. These limitations impede our understanding of dust deposition and seawater fertilization in the BUS. This study explores the dust problem over the western southern African coast by answering four key questions: 1) Is there a dust problem? 2) What are the sources of the dust? 3) Where is the dust being transported to? and 4) What are the effects of dust deposition on the BUS? In pursuit of these objectives, the study aims to i) Characterize high and low aerosol episodes over the Namibian coast through ambient monitoring; ii) Identify preliminary new southern African dust sources; iii) Investigate the relationship between ambient Fe concentrations over the Namibian coast and satellite Chl-a data; iv) Evaluate total dust deposition to the BUS using a Conformal Cubic

Atmospheric Model (CCAM) simulation; and v) Investigate the response of BUS phytoplankton to Namib desert dust addition in a land-based mesocosm experiment. During high aerosol episodes (HAEs), prevailing winds were southerly and south-westerly, originating from the adjacent BUS. Daytime Fe concentrations varied between 3.00 and 3687.00 ng/m³, averaging 351.67±496.58 ng/m³, while nighttime concentrations were typically lower, averaging 362.06±410.95 ng/m³. Monthly mean Fe concentrations showed variations, with the most extreme concentration events (ECEs) occurring in March. The locations of 47 new potential southern African dust sources were identified, and their landform types are suspected to be similar to the Namibian sources to the south. All detected plumes from the sources stretched over 100 km, suggesting a substantial potential for emission and deposition. Notably, the Benguela Low-Level Jet drove emissions from these sources. Two domains of high dust deposition were identified: one to the north adjacent to southwestern Angola and the other in the south surrounding Lüderitz. No seasonal correlation and agreement were found in comparing the CCAM dust deposition with the observed Chl-a concentrations separately for both identified domains. Namib desert dust addition resulted in a positive response from the BUS phytoplankton, given the higher Chl-a concentrations in the mesocosm subject to dust addition compared to the control mesocosm. The observation that adding dust from the Namib desert stimulated the dust mesocosm is both significant and surprising. Given that this experiment was conducted in an upwelling system near the continental shelf and within a region frequently exposed to substantial aeolian dust supply, it is plausible to expect that phytoplankton in the Benguela would be nutrient-replete. The Chl-a increase was unrelated to Fe, Si, PO₄³⁻, or light intensity, given weak correlation coefficients.

Key terms: dust, BUS, Fe, Chl-a, Namib desert, Benguela Low-Level Jet, CCAM

In loving memory of my mother,
Kathleen Belelie (1955-2021),
and my aunt,
Eliza October (1958-2022),
who always supported me tirelessly,
and loved me unconditionally.



PREFACE

From my hometown's rolling hills and Swartberg mountains to the sandy dunes of Henties Bay, I am sure I will never forget the Namibian coast! While travelling through Namibia for the first time in 2017, I thought the country was renowned only for the semi-permanent stratocumulus clouds along its coast and the Namib desert. But it's not; it is much more than that. Now, I consider it an area delineated by a dune landscape to the south, gravel plains, and the Skeleton coast to the north.

Despite its isolation, the area is filled with isolated shrubs and surprisingly mesmerizing gardens that the residents created. One of my most memorable experiences was driving through the Cape Cross Seal Colony. I travelled towards the Skeleton coast and explored the dustiest rivers and salt pans. It was an experience that I will never forget. As I gazed at the breathtaking sight of the lichen and rock cuddling in the cold Benguela current, I realized that life is present even in this landscape. It is like nature's way of saying, "Don't worry, it is not as dry as it looks!" I guess you could say I had a whale of a time!



Figure P.1: Myself preparing for the second mesocosm experiment undertaken at the Sam Nujoma campus, Henties Bay, Namibia, during September/October 2022.



Figure P.2: The green-hue Benguela in the background and the Omaruru ephemeral riverbed right next to it. The photo was taken from the east cliff of the Sam Nujoma Campus.

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This research is the author's original work and was not previously submitted for a degree at any university. I was engaged in the study presented in this document from January 2018 to November 2022 and was involved in formulating, conducting, and writing.

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LIST OF ABBREVIATIONS

AERONET	- AErosol RObotic NETwork
AOD	- Aerosol Optical Depth
AOI	- Area of Interest
AS	- Angola dust emitting Sources
BLLJ	- Benguela Low Level Jet
BUS	- Benguela Upwelling System
CCAM	- Conformal Cubic Atmosphere Model
CDO	- Climate Data Operators
Chl-a	- Chlorophyll <i>a</i>
CM	- Control Mesocosm
CSIRO	- Commonwealth Scientific and Industrial Research Organisation
DG	- Dust Group
DIP	- Dissolved Inorganic Phosphorous
DOP	- Dissolved Organic Phosphorous
EBUS	- Eastern Boundary Upwelling System
ECE	- Extreme Concentration Episode
ECMWF	- European Centre for Medium-Range Weather Forecasts
EOSDIS	- Earth Observing System Data and Information System
ERA5	- Fifth generation ECMWF reanalysis dataset
GDAS	- Global Data Assimilation System
GEOS-5	- Goddard Earth Observing System Model version 5
GIOVANNI	- Geospatial Interactive Online Visualization ANd aNalysis Infrastructure
GF/F	- Glass micro-Fiber Filters
HAE	- High Aerosol Episode

HBAO	- Henties Bay Aerosol Observatory
HCL	- Hydrochloric Acid
HDF	- Hierarchical Data Format
HDPE	- High Density Polyethylene
HgCl	- Mercuric Chloride
HNLC	- High Nutrient Low Chlorophyll
HTH	- Here to Help water care
HYSPLIT	- Hybrid Single-Particle Lagrangian Integrated Trajectory
IPP	- Inorganic Particulate Phosphorous
LAE	- Low Aerosol Episode
LNLC	- Low Nutrient Low Chlorophyll
MERIS	- Medium Resolution Imaging Spectrometer
MERRA-2	- Modern-Era Retrospective Analysis Version 2
MGC	- Micro-Glass Fiber Filters
MODIS	- Moderate Resolution Imaging Spectroradiometer
NASA	- National Aeronautics and Space Administration
NCEP	- National Centre for Environmental Prediction
NOAA	- National Oceanic and Atmospheric Administration
NCO	- NetCDF Operators
OPP	- Organic Particulate Phosphorous
PM	- Particulate Matter
PPM	- Parts Per Million
PTFE	- Poly Tetra Fluoro Ethylene
QGIS	- Quantum Geographic Information System
SASSCAL	- Southern African Science Service Centre for Climate Change and Adaptive Land Management

SeaWiFS	- Sea-viewing Wide Field-of-view Sensor
SST	- Sea Surface Temperature
TDS	- Total Dissolved Solids
UTC	- Universal Time Coordinated
VIIRS	- Visible Infrared Imaging Radiometer

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CHAPTER 1

To discuss dust-related impacts of deposition on the Benguela upwelling system requires a contextual setting that must surround both the sources and sinks of continentally derived aerosols. This chapter provides this setting by providing background on ocean fertilization and the importance of dust deposition. Next, a comprehensive literature review is provided on this study's essential components, including eastern boundary upwelling systems, windblown dust from continental sources such as deserts, and the micronutrient Fe importance.

INTRODUCTION AND LITERATURE REVIEW

1.1 Background

The Benguela upwelling system (BUS) is one of four eastern boundary upwelling systems (EBUS) that, despite covering only 1% of the Earth's ocean surface, are among the most productive regions in the world (Pauly & Christensen, 1995; Carr, 2001; Dansie et al., 2022). The BUS is located along the west coast of South Africa, Namibia, and Angola. It is known for its high production of diatoms, dinoflagellates, and small flagellates that support a thriving fishing industry (Louw et al., 2016). Unlike other EBUS, the BUS is surrounded by warmer waters on its northern and southern borders (Hutchings et al., 2009). These subsystems are separated by a significant upwelling cell located off the coast of Lüderitz (Duncombe Rae, 2005; Hutchings et al., 2009; Flohr et al., 2014). The northern BUS experiences constant upwelling, while the southern BUS has seasonal upwelling that peaks during spring and summer (Shannon and Nelson, 1996; Romero et al., 2003; Hutchings et al., 2009). During this time, the prevailing south-east trade winds cause nutrient-rich waters to be upwelled in the system, fueling phytoplankton productivity (Shannon, 1985; Lutjeharms & Meeuwis, 1987; Louw et al., 2016).

While productivity in EBUS is driven by nutrient-rich water, there is a notable difference in chlorophyll (Chl-a) concentrations between the EBUS (Carr & Kearns, 2003). It suggests that other factors, like dust deposition, may play an essential role in explaining productivity differences (Dansie et al., 2022). It is thought that these systems exhibit characteristics of high nutrient low chlorophyll (HNLC) ocean regions where iron (Fe) has been identified as a limiting factor for primary production (Capone & Hutchins, 2013; Mahowald et al., 2005; Messié & Chavez, 2015). However, given the frequency of dust-emitting sources surrounding the BUS (Vickery & Eckardt, 2013; von Holdt et al., 2017), which are high in Fe (Dansie et al., 2017), it's feasible to assume that the BUS is not Fe-limited. Dust is crucial in transporting macronutrients such as nitrogen (N) and phosphorous (P), as well as biologically essential Fe, to phytoplankton communities in the ocean (Baker et al., 2006; Okin et al., 2011). Silicon (Si) is also considered a vital driver of the biogeochemistry of marine biota, especially that of diatoms (Hawkings et al., 2017). These nutrients are critical drivers of primary oceanic productivity as they influence phytoplankton growth and, consequently, the carbon cycle (Jickels et al., 2005).

Fe is essential for the growth of oceanic biota (Mahowald et al., 2009), although prevalent uncertainties remain on its specific role in the biogeochemical cycle (Dansie et al., 2017b). Given the high insolubility of Fe in seawater, the element is readily removed from oceans via abiotic scavenging processes and biological uptake of dissolved Fe (Anderson et al., 2016). As a result, access to Fe by organisms such as phytoplankton in the remote open ocean depends mainly on the dominant continental mineral aerosol input as the primary source. At the same time, other regions may benefit from additional sources of Fe, such as hydrothermal vents, glaciers, coastal sediments, and biological processes. The atmospheric transport of Fe from soil dust sources is considered the most probable main input pathway of the nutrient to the remote deep ocean, as although inputs from riverine systems are significant, they are rapidly removed (Jickells et al., 2005). Mahowald et al. (2009) stated that an estimated 95% of the global atmospheric Fe budget originates from mineral aerosols/desert dust, in contrast to a 5% input from combustion aerosol sources.

It is estimated that around 477 Tons of dust are emitted from continental sources each year and transported to oceanic regions (Mahowald et al., 2010). The South Atlantic receives the sixth-highest amount at 17 Tg/yr, including approximately 0.11–0.32 Tg of soluble Fe (Jickells et al., 2005). While Fe may be supplied to the ocean through sediment discharge from the continental edge and the release of metal-rich fluids from hydrothermal vents, dust transport through the air provides about 95% of this nutrient (Jickells et al., 2005). This dust originates from anthropologically induced land surfaces, desert regions, and ephemeral dry lakes or riverbeds (Mahowald et al., 2009). Previous research identified Etosha Pan in Namibia and the Makgadikgadi Depression in Botswana as two of the southern hemisphere's largest southern African dust sources (Bryant, 2003; Washington et al., 2004). Later research identified Namibian coastal salt pans, dry valleys, and extensive dunes as a third primary dust emission source (Eckardt & Kuring, 2005; Vickery et al., 2013). Under Berg wind conditions, seasonal dust plumes may be transported as far as 100 km offshore from ephemeral riverbeds such as the Kuiseb, Huab, Tsauchab, and Omaruru (Vickery et al., 2013).

These riverbeds are rich in nitrogen, phosphorous, and especially bioavailable iron (Dansie et al., 2017b). It has been suggested that the iron sediments in these sources may play a significant role in fertilizing phytoplankton in the adjacent Benguela upwelling region (Dansie et al., 2017a). In addition, a study showed that the nutrient content in ephemeral riverbeds is significantly higher than in dust-emitting pans – sources previously thought to be the primary sources of Fe deposition in the adjacent Benguela. A recent correlation study between dust emitted from Namibian

ephemeral riverbeds and adjacent Benguela observed enhanced chlorophyll-a concentrations at a daily timeframe (Dansie et al., 2022). Mineral dust has also been established as the second primary source of aerosols over the coast at the Henties Bay Aerosol Observatory with a 14.7% contribution (Klopper et al., 2020), likely dominated by contributions from surrounding river valleys. These dust-emitting sources have been previously classified (Vickery & Eckardt, 2013; Vickery et al., 2013), but it is evident that there is a potentially important dust source to the Benguela on the coast of southwestern Angola. The BUS is adjacent to such sources and is impacted by periodic dust inputs from nearby upwind desert regions (Eckardt and Kuring, 2005; Vickery and Eckardt, 2013).

1.2 Literature Review

Despite the global warming trend observed in most oceanic regions, contrasting or mixed trends are observed for the main upwelling regions (Belkin, 2009). In these regions, cold, nutrient-rich water bubbles up from beneath the ocean surface to above and is supplied to oceanic biota. Other oceanic areas are characterized by lower biological productivity than what is commonly expected for common nutrient conditions at the surface (Fuji et al., 2005) and are referred to as high nutrient low chlorophyll (HNLC) zones. These zones cover about 30% (Pitchford & Brindley, 1999; De Baar & Boyd, 2000) of the Earth's ocean surface compared to a coverage of approximately 60% by low nutrient low chlorophyll (LNLC) regions (Longhurst et al., 1995). In recent years, dust deposition impacts on LNLC/oligotrophic zones have been increasingly subject to research (Astrahan et al., 2016; Guo et al., 2016; Herut et al., 2016; Krom et al., 2016; Lagaria et al., 2017; Meador et al., 2017; Pitta et al., 2017; Rahav et al., 2016; Tsagaraki et al., 2017; Tsiola et al., 2017) given that productivity in these regions is less understood.

The HNLC regions, formerly called 'Antarctic Paradox' regions, exhibit moderately low phytoplankton concentrations yet high macronutrient concentrations (Mock & Thomas, 2008). The major HNLC ocean regions are generally classified as the Southern Ocean, North Pacific and Eastern Equatorial Pacific (Figure 1-1). In these regions, nitrate (NO_3^-) and phosphorous-based compound concentrations are high throughout the year, but surprisingly, phytoplankton blooms are uncommon. As a result, concentrations of N and P are never entirely depleted. It has been suggested that this is due to the limit imposed on phytoplankton growth by insufficient bioavailable Fe (Pitchford & Brindley, 1999). The Southern Ocean is regarded as the region with the world's most noteworthy unutilised macronutrient supply (Smetacek, 1998). It is also considered the most significant source

of the exportation and burial of biogenic SiO_2 resulting from diatoms (Smetacek & Nicol, 2005). Given the distance, these ocean regions are located far from the primary mineral dust sources and are considered Fe-limited. The previous means that oceanic regions near mineral sources (like the Benguela Upwelling System) cannot be regarded as Fe-limited like the HNLC regions, given their frequent dust emission.

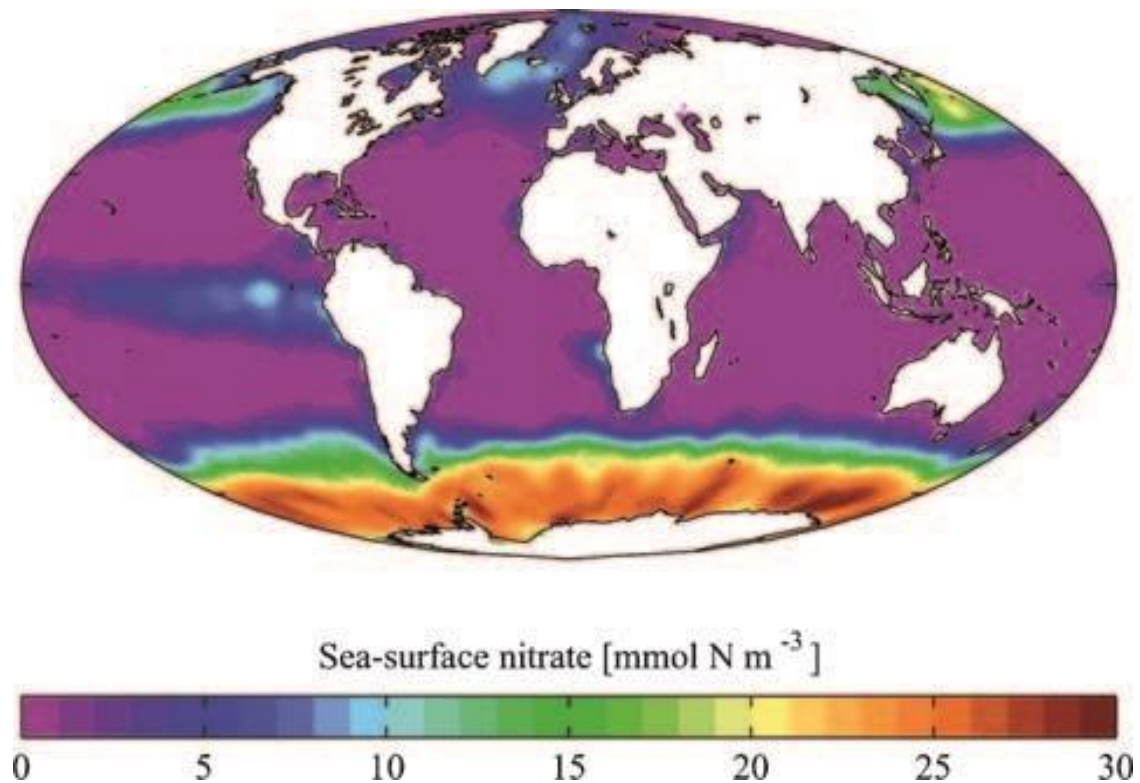


Figure 1-1: A map illustrating the world's HNLC, LNLC, and EBUS regions. The gradient represents concentrations of NO_3^- at the sea surface.

1.2.1 Coastal Upwelling of the Earth's Oceans

The ocean surface to the west of the African coast is dominated by the flow of the Benguela current in a northerly direction (Figure 1-3). Along with the current flow between 17-35°S is a series of circulatory cells that causes the intermittent upwelling from the depths to the surface of the BUS. Since the late Pliocene, this system has been displaced southward. Petrick et al. (2015) found this displacement consistent with weaker and expanded Hadley cell circulation over the region. For most of the year, Southern Africa is located directly beneath the Hadley cell's descending side (Piketh & Walton, 2004) – predominantly during winter (Tyson & Gatebe, 2001). The intensity of the upwelling process in such zones is highly dependent on the intensity of the south-eastern trade

winds (Zonneveld et al., 2001). These winds drive cold, nutrient-rich water from as deep as 300m (Shannon, 1985). The displacement of these winds to the south may be the cause of perennial upwelling in the southern Benguela area (Petrick et al., 2015), where the most vigorous and most frequent upwelling occurs close to Luderitz, Namibia (McKay et al., 2016). The enforcer behind the upwelling in the EBUS is the ‘tropical meridional overturning circulation’ (Demarcq, 2009) atmospheric forcing directly impacted by global heating (Quan et al., 2004). The BUS is extensively studied concerning its ecology, primary production and trophic levels (Ware, 1992; Zonneveld et al., 2001; McKay et al., 2016). Moreover, Messie & Chavez (2015) have shown that primary production in the EBUS varies with season, space, and between systems and that the supply of macronutrients is the main regulating factor. The EBUS is located west of South Africa/Namibia/Angola, California, Peru (Figure 1-2), and Mauritania. It was thought that these upwelling systems had either disappeared, had less intensity, or changed their mode of operation during the Pliocene (Petrick et al., 2015). The upwelling system flowing along the west coast of South Africa and Namibia is known as the Benguela upwelling system (BUS) (19-34°S) (Hutchings et al., 2009; McKay et al., 2016). In the past, the system was divided into two sections: the southern (west and south of South Africa) and the northern (Angola-Namibia) Benguela systems (Shannon, 1985). This initial division may have been due to the BUS bordering the Agulhas retroflexion to the south and the warm Angola-Benguela front to the north (McKay et al., 2016). A later study then divided the BUS into the perennial upwelling Benguela zone to the north and the southern Benguela that experiences seasonal upwelling of nutrients (Boebel et al., 2003; Hutchings et al., 2009). This seasonal upwelling reaches its peak concentrations during spring (September, October, November) and summer (December, January, February) (Shannon & Nelson, 1996; Romero et al., 2003). During the upwelling period, the predominant southeast trade winds and subsequent Ekman Spiral offshore cause the upwelling of nutrient-rich waters in the system (Lutheharms & Meeuwis, 1987). For example, intense seasonal dust events adjacent to the BUS (von Holdt et al., 2017) have not been observed off Peru (Böning et al., 2020).

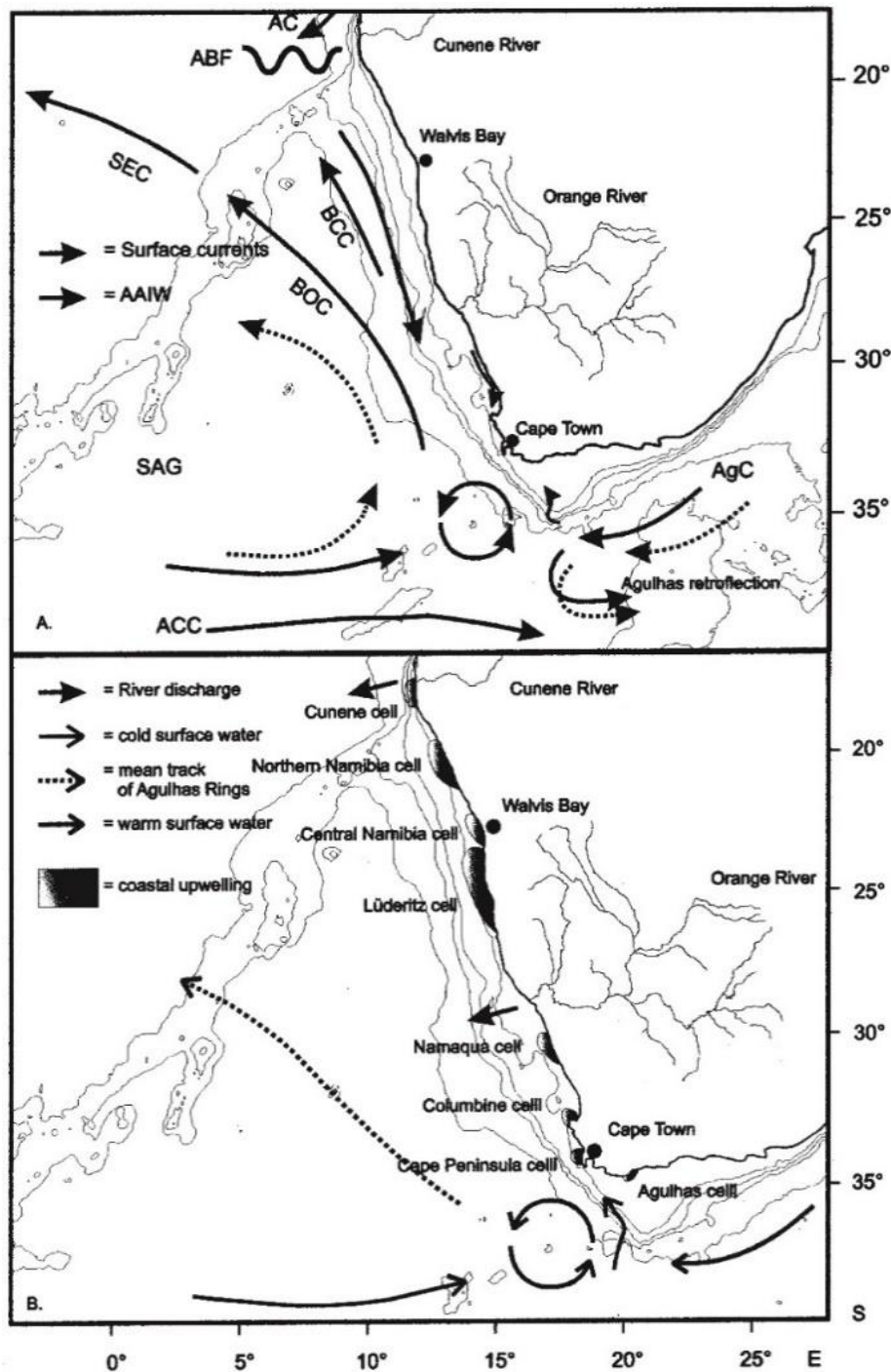


Figure 1-2: The Benguela region and its surface and sub-surface currents (A) and the locations of upwelling cells (B) (Zonneveld et al., 2001). AC = Angola Current; ABF = Angola Benguela Front; SEC = South Equatorial Current; BCC = Benguela Coastal Current; BOC = Benguela Oceanic Current; SAG = South Atlantic Gyre; ACC = Antarctic Circumpolar Currents; AgC = Agulhas Current.

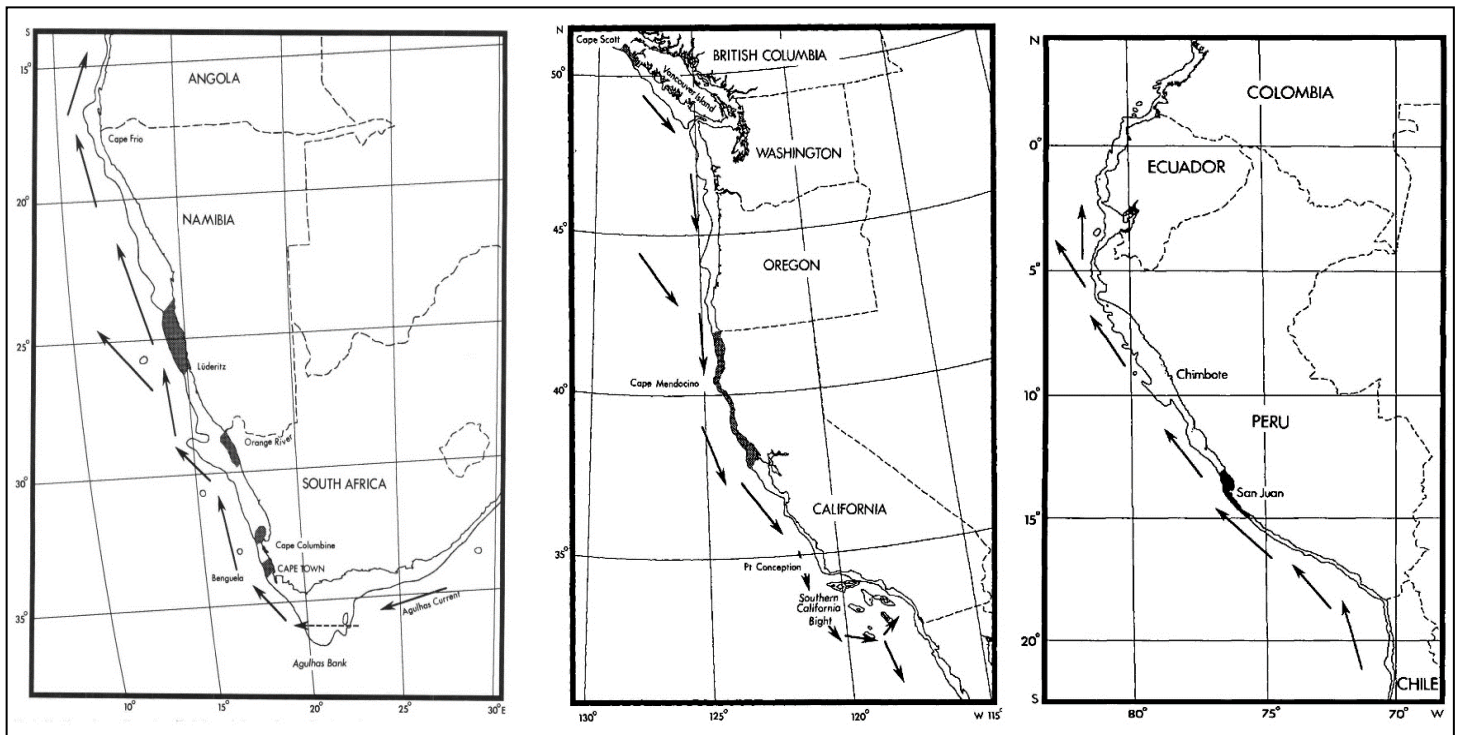


Figure 1-3: Three of the four EBUS of the ocean. To the left is the Benguela upwelling system; in the middle is the California upwelling system; and to the right is the Peru upwelling system. The Arrows indicate the direction of the predominant current (Ware 1992).

1.2.2 Dust Sources in the Southern Hemisphere

Fe is supplied to the ocean through various sources, including discharge from sediments on the edge of the continent (Elrod et al., 2004) and the release of metal-rich fluids from hydrothermal vents located on mid-oceanic ridges (Tagliabue, 2014). However, the aeolian dust transport supplies about 95% of this nutrient (Jickells et al., 2005). This dust originates from land surfaces altered due to human activities, desert regions, and ephemeral dry lakes or riverbeds (Mahowald et al., 2009). The primary continental sources of dust in the southern hemisphere that contribute mineral aerosols to the Southern Ocean are southern Africa, Patagonia and Australia (Li et al., 2008). However, the most significant annual contribution to the global atmosphere is from a source in the north (80-90%) (Figure 1-4) (Bhattachan et al., 2015). As illustrated by the modelling result, this dominant source is the Saharan desert, which is corroborated by observations from satellite imagery (Bhattachan & D'Odorico, 2014). The modelling study by Li et al. (2008), averaged over 20 years, inferred that of the southern hemisphere sources, Australia appears to be the significant emitter of dust (about 120 ± 8.4 Tg/yr) – a result supported by Albani et al. (2012). It is sequentially

followed by South America (about 50 ± 3.0 Tg/yr) and southern Africa (about 34 ± 2.1 Tg/yr). The leading active emitter in Australia is the Lake Eyre Basin (Mcgowan & Clark, 2008; Bhattachan & D’Odorico, 2014; Bhattachan et al., 2015), and according to Bhattachan & D’Odorico (2014), the main emitting area in South America is the Salar de Uyuni in Bolivia. The major dust-emitting regions in South America are the Bolivian Altiplano, the Atacama Desert, a small area in western Argentina, the Patagonian Desert (Li et al., 2008) and the southern Puna region (Gili et al., 2017). Some significant dust-emitting events, as captured by NASA satellites, are illustrated in Figure 1-5 with a recent prominent event in the Saharan Desert.

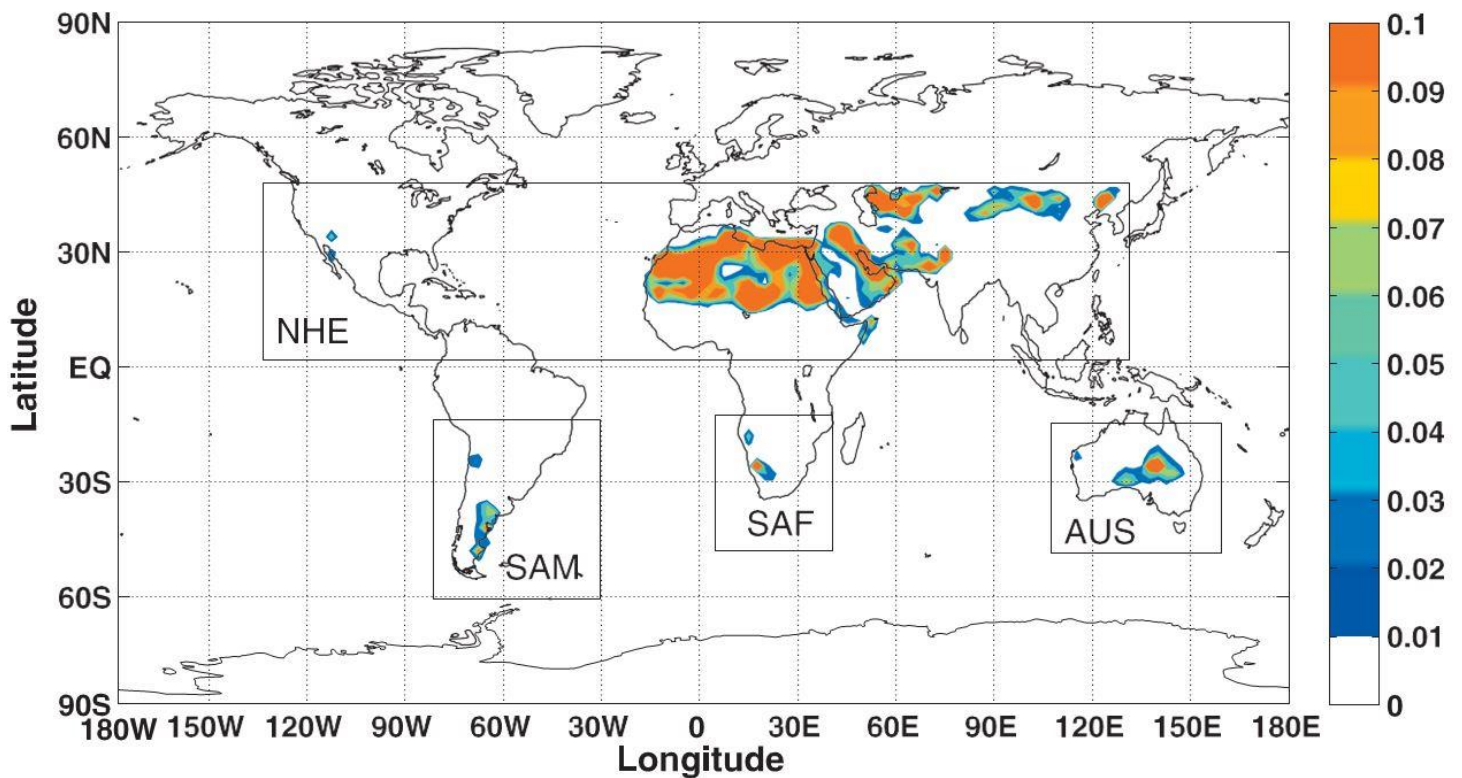


Figure 1-4: The primary continental dust sources in the southern and northern hemispheres as modelled by Li et al. (2008).

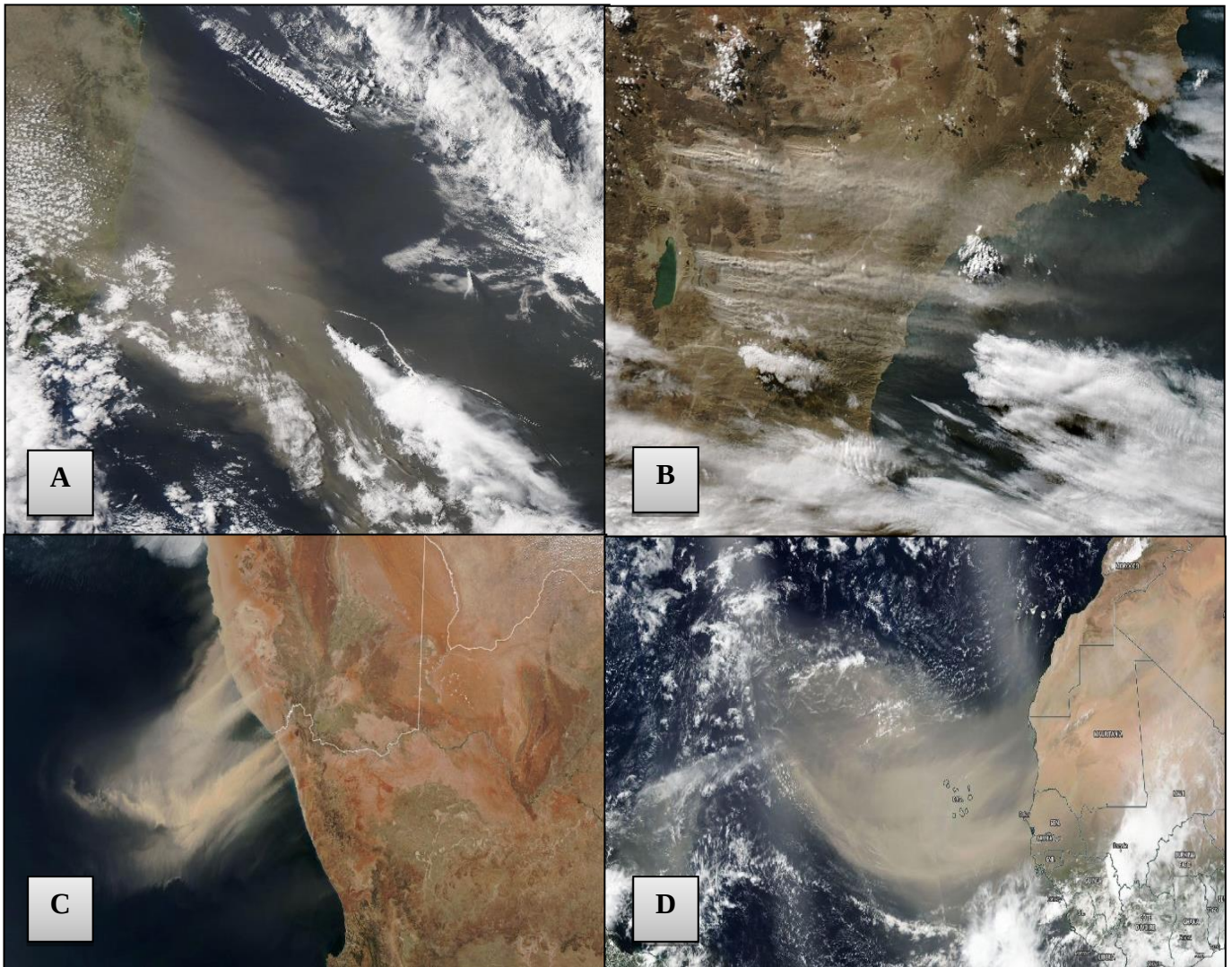


Figure 1-5: Emissions of dust from the significant dust southern hemisphere sources: (A) A dust emission event from the Australian continent as captured on 14 October 2009 by NASA's Aqua satellite; (B) A dust emission event from the Patagonian Desert as captured on 12 May 2013 by NASA's Aqua satellite; (C) A dust emission event from the Namib Desert region, off of the Namibian coastline as captured on 25 September 2019; and (D), a very recent dust plume is seen to be emitted from the dominant Saharan Desert in the north - captured by the NOAA-20 satellite on 18 June 2020 (NASA).

It has been shown that aeolian dust is the second largest contributor to the southern African coastal aerosol loading (Klopper et al., 2020), with BUS fertilization from southern African dust having been hypothesized (Piketh et al., 2000; Dansie et al., 2017a). Previous research identified Etosha Pan in Namibia and the Makgadikgadi Depression in Botswana as the major dust emitters in southern Africa (Bryant, 2003; Washington et al., 2003; Prospero et al., 2002; Li et al., 2008; Bhattachan & D'Odorico, 2014) (Figure 1-7). It may have been due to the coarser resolution Total Ozone

Mapping Spectrometer (TOMS) data that was used and partly why the sources received the most initial attention as regional dust sources (Prospero et al., 2002). Moreover, later research also identified them as the two leading sources of emission (Vickery et al., 2013), with evidence indicating that dust from these sources is deposited throughout southern Africa (Haywood et al., 2003; Resane et al., 2004; Dansie et al., 2017).

Previous studies have also investigated the potential of the southern Kalahari Desert as a third significant southern hemisphere dust source (Bhattachan et al., 2012; Bhattachan et al., 2013). Although infrequent, the source is an active dust emitter during the dry winter (Vickery et al., 2013). In addition, later studies showed that the source is enriched in N, P, and Fe (Bhattachan et al., 2015) and that dust may be deposited to the Benguela and as far as the southern ocean (Tesfaye et al., 2015; Tatlhego et al., 2020).

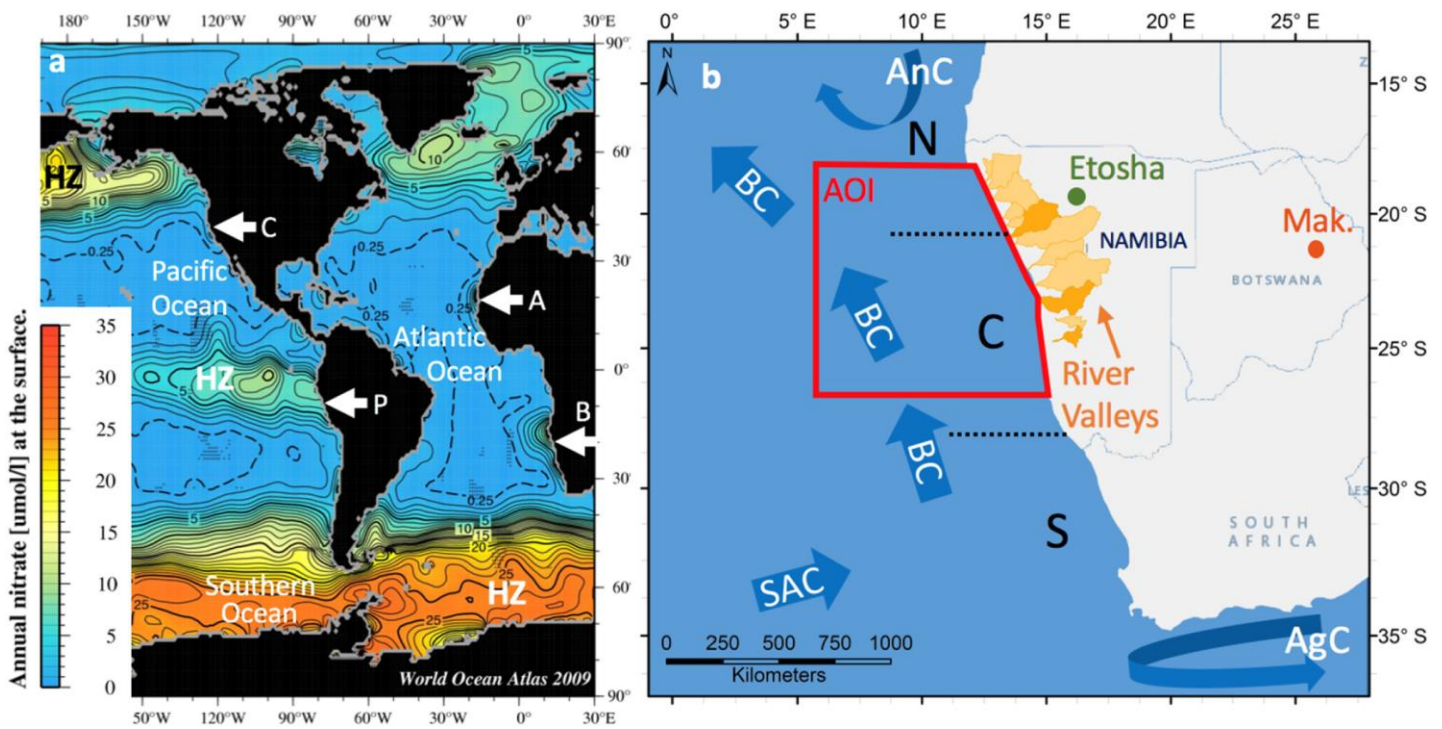


Figure 1-6: The oceanic EBUS (A, B, C, and P), Makgadikgadi and Etosha Pans, and the 12 Namibian ephemeral riverbeds (orange polygons) (Dansie et al., 2022).

The fourth crucial dust-emitting source is the Namibian ephemeral riverbeds (Figure 1-7), first identified and classified by Eckardt and Kuring (2005) between 1998 and 2001. Depending on the resolution, global dust models and satellite surveys often do not capture smaller dust-emitting sources (Vickery & Eckardt, 2013) and given the coarse resolution of the TOMS studies, these

sources were not detected (Dansie, 2017). Moreover, there was a lack of information on these small-scale sources despite the possibility of them contributing to a considerable fraction of global dust emissions (Ginoux et al., 2012). Subsequent remote sensing studies between

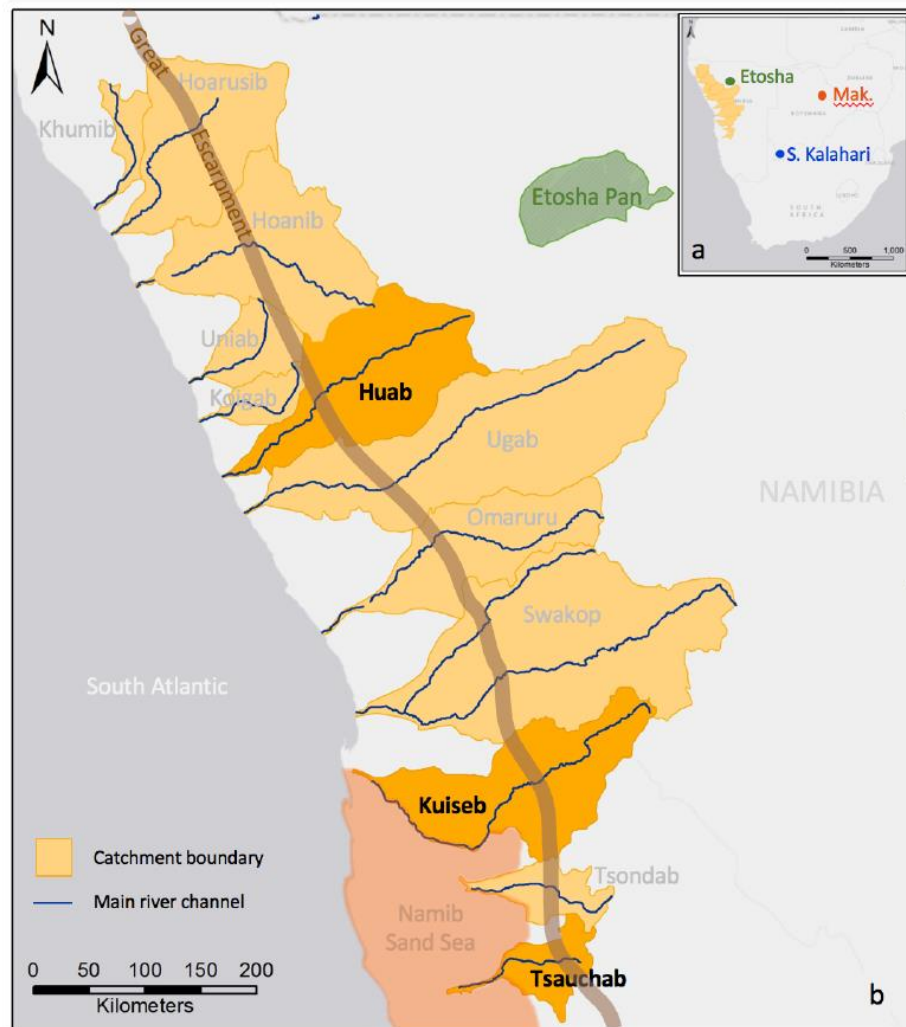


Figure 1-7: Namibia’s significant dust emitting sources (Dansie et al., 2017a).

2005-2008 using Moderate Resolution Imaging Spectroradiometer (MODIS) (Vickery et al., 2013) and 1989-2016 using Landsat imagery (von Holdt et al., 2017), identified high-resolution dust event inventories from these sources and the Namib gravel plain. The former identified 70/101 dust sources in the Namib desert, with 55% of events originating from the ephemeral riverbeds. Notably, the study showed that the Namibian coastline (comprising the riverbeds, pans, and wetlands) had a higher emission frequency (34%) than both Makgadikgadi (16%) and Etosha (11%). This finding triggered several subsequent studies, as for several years, it was believed that

Makgadikgadi and Etosha were considered the only persistent dust-emitting sources (Prospero et al., 2002; Bryant, 2003; Mahowald & Kiehl, 2003; Li et al., 2008). The studies that followed included research that found that the Kuiseb, Omaruru, and Huab riverbeds are the dustiest of all sources in the Namib Desert (Vickery & Eckardt, 2013; Vickery et al., 2013; von Holdt et al., 2017; von Holdt & Eckardt, 2018).

Ephemeral rivers, such as those in Namibia's ephemeral valleys, can replenish alluvial fine deposits (Dansie et al., 2017a). Rivers, especially those with naturally occurring flooding and drying, transport large sediment loads (Laronne & Reid, 1993) and nutrients in solution (Skoulidakis & Amaxidis, 2009). These ephemeral river systems are noteworthy sources of nutrient-rich wind-blown dust (Schepanski et al., 2013; Dansie et al., 2017a). Dansie et al. (2017a) suggested that these sources may be a significant source of nutrients to the BUS and that this necessitates investigations of phytoplankton responses to dust deposition. The riverbeds are rich in N and P, especially bioavailable Fe (Dansie et al., 2017b). Moreover, the nutrient content in the riverbeds is significantly higher than those in Makgadikgadi and Etosha Pans – sources previously thought to be the primary sources of Fe deposition to the adjacent Benguela (Dansie et al., 2017a). A recent study found a correlation between dust emitted from Namibian ephemeral riverbeds and enhanced Chl-a concentrations at a daily timeframe in adjacent Benguela (Dansie et al., 2022).

Mineral dust is the second primary source of aerosols over the coast at the Henties Bay Aerosol Observatory (HBAO), with a 14.7% contribution (Klopper et al., 2020). The previous is most likely due to a dominant contribution from the surrounding river valleys – a presumption given the proximity of the important sources to the coast and adjacent Benguela; ephemeral riverbeds (<100 km of the coast), Makgadikgadi Pan (1200 km), Etosha Pan (400 km), and the southern Kalahari (650 km).

1.2.3 Dust Transportation and Deposition

Dust emitted by continental sources and transported in atmospheric layers ultimately returns to earth – the more significant portion is estimated to return to the world's ocean bodies at an annual dust flux of about 477 Tg/yr (Mahowald et al., 2010). Per ocean region, the North Atlantic receives the most significant quantity of dust (202 Tg/yr), followed by the Indian Ocean (118 Tg/yr), the North Pacific (72 Tg/yr) (Jickells et al., 2005), the Mediterranean Sea (40 Tg/yr) (Guerzoni et

al.,1999), the South Pacific (29 Tg/yr), the South Atlantic (17 Tg/yr) (Jickells et al., 2005), and lastly the Arctic Ocean (5.7 Tg/yr) (Shevchenko & Lisitzin, 2004).

Given the importance of dust as a nutrient source to the ocean, it is essential to understand what changes the aerosol particles undergo during transport (Velasco-Merino et al., 2018). It has been well-established that enormous quantities of mineral aerosols may be mobilized by wind action in arid and semi-arid regions. Much of this can be transported over large atmospheric distances (Prospero, 1996; Prospero, 1999). Dust may also be mobilized after sediment erodes and scours from ephemeral riverbanks and beds (Dansie, 2017a). The subsequent long-range transport of mineral dust may then, for example, affect the air quality, radiative budget, and precipitation of faraway localities (Chouza et al., 2016; Dansie, 2017b; Schepanski, 2018; Banerjee et al., 2019) and significantly perturb the biogeochemistry of our oceans (Fung et al., 2000; Jickells et al., 2005).

Most southern African dust is emitted during winter, with a maximum in August and September (Vickery et al., 2013). It may be transported as far as 4000 km to the Atlantic ocean (Swap et al., 1996). A previous study suggested that these dust sources have a local rather than a global impact, given the smaller-scale sources and weaker winds (Li et al., 2008). Therefore, a substantial amount of dust, as much as 30 million tons per annum (Tyson et al., 1996), may be deposited to the adjacent BUS. In addition, it has been suggested that the oceans directly adjacent to mineral dust sources receive the more significant portion of emitted dust due to the gravitational settling thereof (Maring et al., 2003).

Due to southern Africa's location within the subtropical high-pressure belt most of the year, the average circulation over the area is 800 hPa, exceeding 70-80% during winter (Tyson et al., 1996; Tyson & Gatebe, 2001). Due to the frequency of subsidence over the southern African atmosphere, absolute stable layers form and are effective in trapping and influencing the distribution of aerosols (Tyson & Gatebe, 2001). South and southwesterly trade winds are prominent regional features (Lancaster, 1985). They result from the South Atlantic anti-cyclone and South African high-pressure system (Shannon, 1985) (Figure 1-8). These atmospheric circulation patterns influence the BUS's seasonal upwelling (Dansie, 2017). Another regional meteorological pattern observed is the strong east-to-northeasterly bergwind conditions during winter (Fryberger et al., 1979) when the dust emission season occurs (Eckardt & Kuring, 2005; Vickery et al., 2013). Under these conditions, seasonal dust plumes may be transported as far as 100 km offshore from ephemeral riverbeds such as the Kuiseb, Huab, Tsauchab, and Omaruru (Vickery et al., 2013). They typically occur

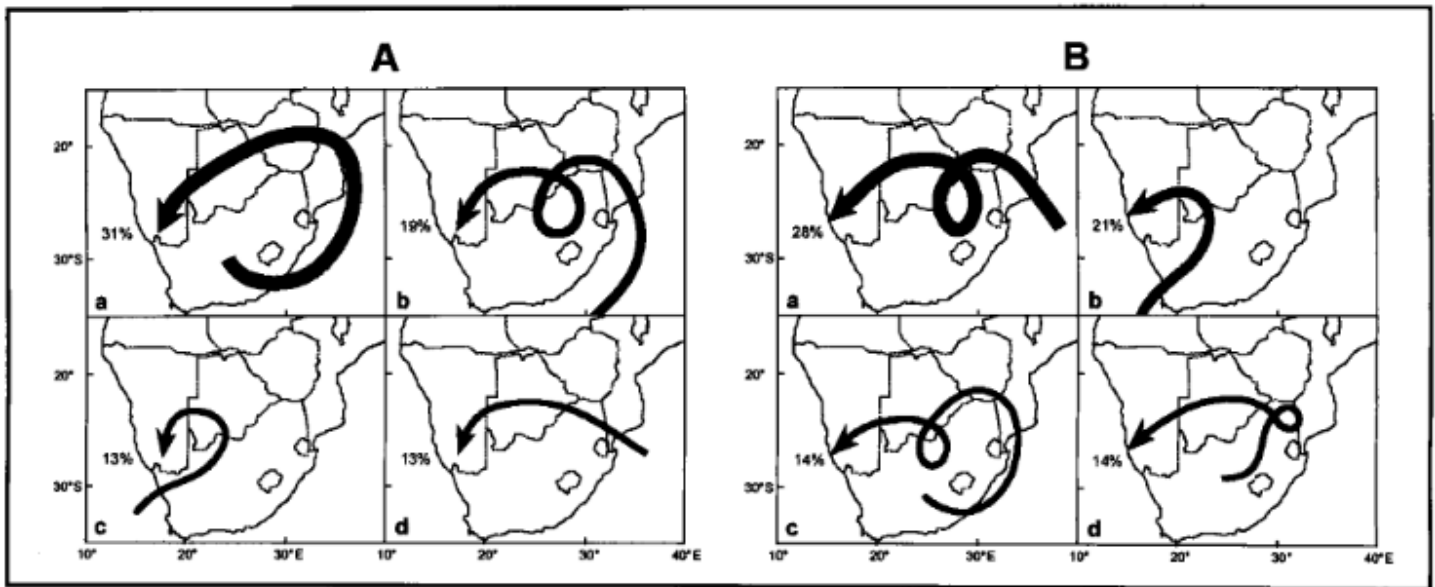


Figure 1-9: The eight major transport pathways of Bergwinds to Keetmanshoop (left) and Lüderitz (right) (Tlhalerwa et al., 2005).

1.2.4 Meteorological Conditions for Namibian Dust Generation

Dust generation in Namibia is a complex process influenced by various meteorological conditions. A recent study conducted at Etosha Pan, for instance, has identified strong E-ENE winds as a significant factor in dust events, which occur throughout the year and are not restricted to the austral winter (Wiggs et al., 2022) as previously thought from remote sensing research. In addition, their study showed that although the frequency of dust emission from the pan is low, it is of high magnitude. An earlier study established that mean particulate matter (PM) concentrations are higher over the coast than in the interior, such as Etosha Pan's location. PM is commonly divided by size into $PM_{2.5}$ (aerosols with an aerodynamic diameter of 2.5 μm or less) and PM_{10} (aerosols with an aerodynamic diameter of 10 μm or less) (Kastury et al., 2017; Kastury et al., 2018). Like Wiggs et al. (2022), Liebenberg-Enslin et al. (2020) observed that the highest measured PM_{10} concentrations were associated with easterly winds, but sea salt was the primary PM source over the coast.

1.2.5 Phytoplankton response to Dust Deposition

Several studies have been conducted globally, which investigate the relationship between dust deposition to the ocean and the response of phytoplankton (Figure 1-10). Some research has

suggested that the main input pathway of Fe is from island margins, the continental shelf, and ocean plateaus through lateral advection and upwelling of sediments (Meskhidze et al., 2007; Chever et al., 2010). According to Cassar et al. (2007), however, the aeolian supply of micronutrients to the ocean is predominant where the region is located downwind of the arid/semi-arid continental source. The mechanism controlling the input of Fe to ocean zones, especially HNLC areas, is described in detail by Martin (1991) – the Fe hypothesis.

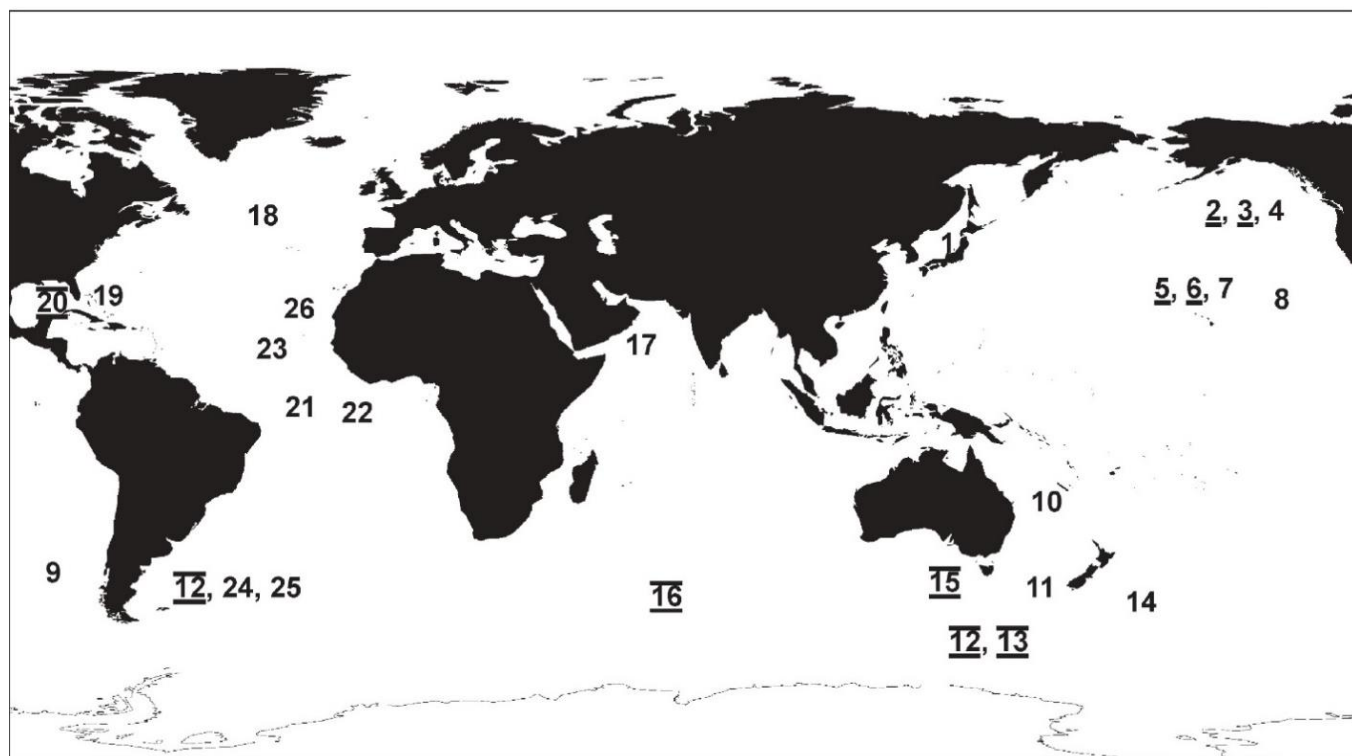


Figure 1-10: Regions across the earth where research has been conducted to establish the link between dust deposition and phytoplankton response (Boyd et al., 2010). (numerically ordered: Jo et al., 2007; Bishop et al., 2002; Boyd et al., 1998; Crispo et al., 2005; DiTullio & Laws, 1991; Young et al., 1991; Wilson, 2003; Johnson et al., 2003; Bonnet et al., 2008; Mackie et al., 2008; Boyd et al., 2004a & 2004b; Cassar et al., 2007; Brévière et al., 2006; Frew et al., 2006; Gabric et al., 2002; Ridgwell, 2002; Westberry & Siegel, 2006; Moore et al., 2006; Sedwick et al., 2005; Lenes et al., 2001; Baker et al., 2007; Tyrrell et al., 2003; Mills et al., 2004; Erickson et al., 2003; Meskhidze et al., 2007). The underlined numbers refer to the research successfully demonstrating a relationship between dust deposition and oceanic biota. Numbers that are not underlined refer to studies where no association could be found. Where numbers are both over- and underlined, re-analysis established that the research misattributed the reasons for the biological response of the biota to dust deposition (Boyd et al., 2010).

Table 1-2 provides a summary of incubation studies that investigated nutrient addition and phytoplankton relationship studies conducted around the world. Several studies have demonstrated that

adding dust can promote growth in various regions. For instance, incubation studies conducted in the Yellow Sea, eastern and northwestern Mediterranean, subtropical gyre, northwest Pacific, and western Tropical Atlantic Ocean have all reported positive growth responses (Liu et al., 2013; Zhang et al., 2018; Zhang et al., 2019; Herut et al., 2005; Krom et al., 2016; Bonnet et al., 2005; Giovagnetti et al., 2013; Chien et al., 2016). Mesocosm experiments in the eastern and northwestern Mediterranean have yielded similar results (Lagaria et al., 2014; Krom et al., 2016; Giovagnetti et al., 2013; Ridame et al., 2014).

However, a few studies have observed a negative relationship between dust addition and phytoplankton growth. Some research has shown that metals in aerosols can have a toxic effect on phytoplankton, resulting in negative growth responses (Paytan et al., 2009). This relationship appears species-specific, with *Prochlorococcus* particularly susceptible to Cu or Al toxicity. Declines in *Prochlorococcus* populations have been reported in the southeastern and western Mediterranean, northeast Atlantic, northwest Pacific, northern Red Sea, and western Atlantic (Herut et al., 2005; Jordi et al., 2012; Hill et al., 2010; Chung et al., 2011; Mescioglou et al., 2019; Borchardt et al., 2020).

Table 1-1: Summary of global nutrient addition and phytoplankton response-related research.

Main Ocean Region	Region	Study Type	Enrichment nutrient/s	Dust/Aerosol Source	Main Finding	Reference
Pacific Ocean	East China Sea	Mesocosm Experiment	Dissolved inorganic N, NH_4^+ , NO_3^- , SO_4^{2-} , Acetate	Huaniao Island	Chl-a concentrations were found to be highest after the addition of Fe and dissolved inorganic N-containing aerosols	(Meng et al., 2016)
	South China Sea	Microcosm Incubation Experiment	Fe, N, and P	Asian Dust	The addition of both N and P is urgently needed for phytoplankton growth. The addition of P or Fe alone does not affect growth	(Chu et al., 2018)
		Microcosm Incubation Experiment	Al	-	Al enhances the growth of only diatoms but inhibits the growth of dinoflagellates and <i>Synechococcus</i>	(Zhou et al., 2018)

	Northwest Pacific	Microcosm Incubation Experiment	Artificially modified dust and single N, P, and Fe treatments	Gobi Desert	The combination of nutrient addition is responsible for phytoplankton growth	(Zhang et al., 2018)
		Microcosm Incubation Experiment	-	Mu Us Sandland (Asian dust)	Chl-a concentration of nano- and micro-eukaryotic phytoplankton increased while that of pico-eukaryotic did not change significantly	(Wang et al., 2019)
		Microcosm Incubation Experiment	Leachable NH_4^+ , NO_3^- , NO_2^- , SiO_3^{2-} , and PO_4^{3-}	-	The addition of N stimulated phytoplankton growth	(Zhang et al., 2019)
		Microcosm Incubation Experiment	Single N and Fe treatments	Tengger Desert	Dust addition to seawater from different regions and different trophic statuses indicate a linear relationship between nutrient uptake and phytoplankton growth	(Zhang et al., 2020)
Mediterranean Sea	Corsica Island Elbo Bay	Mesocosm Experiment	< 20 μm fraction of alluvial soils (For elemental composition see citation)	Sahara Desert	Picophytoplankton respond to initial dust addition while both pico- and nano-/microphytoplankton respond to the second addition of nutrients	(Giovagnetti et al., 2012)
					The wet deposition has a much higher impact on phytoplankton growth than dry deposition	(Guieu et al., 2010) (Desboeufs et al., 2014) (Guieu et al., 2014b)
	Cretan Sea	Mesocosm Experiment	Actual single dust deposition event	Sahara Desert	Dust addition stimulated primary productivity	(Herut et al., 2016) (Pitta et al., 2017) (Tsagaraki et al., 2017)

	South-eastern Mediterranean	In situ	Dust deposition events	Sahara Desert, Eastern Europe, Iraq/Syria, and the Middle East	Moderate changes in Chl-a in response to dust addition	(Rahav et al., 2018)
		Land-based	NO ₃	-	The addition of N-rich well amelioration brines triggered a phytoplankton bloom – this resulted in increased algal biomass	(Raveh et al., 2019)
Atlantic Ocean	Caribbean Sea	Bioassay Incubation Experiment	Single N, P, Fe treatments and combination of N and P, and N and Fe	Aerosol samples collected on the east coast of Barbados	Phytoplankton growth is limited by P.	(Chien et al., 2016)
	North Atlantic	Microcosm incubation experiment	Dust samples	Sahara Desert	An observed initial increase in cell abundance followed by a decrease for both dry and wet deposition	(Korte et al., 2018)
	Subtropical western Atlantic	In-situ	Single dust deposition event simulation (NO ₃ , NO ₂ , and PO ₄)	Sahara Desert	Revealed rapid growth in autotrophic picoeukaryote and Synechococcus following dust deposition	(Borchardt et al., 2020)
Yellow Sea	Kuroshio Extension	Microcosm Incubation Experiment	Artificially modified dust and single N, P, and Fe treatments	Gobi Desert	The combination of nutrient addition is responsible for phytoplankton growth	(Zhang et al., 2018)
		Microcosm Incubation Experiment	Leachable NH ₄ ⁺ , NO ₃ ⁻ , NO ₂ ⁻ , SiO ₃ ²⁻ , and PO ₄ ³⁻	-	The addition of N stimulated phytoplankton growth	(Zhang et al., 2019)

Southern Ocean	Northern Benguela	Mesocosm Experiment	FeCl ₃ and K ₂ HPO ₄	-	Diatoms growth stimulated by P-addition The addition of Fe did not affect productivity	(Wasmund et al., 2014)
				-	Low N:P nutrient ratios do not stimulate phytoplankton growth of N-fixing organisms	(Wasmund et al., 2015)
	Australian Sector	Microcosm Incubation Experiment	Fe and CO ₂	-	Increased availability of Fe coinciding with CO ₂ stimulated growth	(Endo et al., 2017)

1.2.6 Solubility and Bioavailability of Nutrients

1.2.6.1 Nitrogen (N)

Initially, it was believed that N is the essential limiting nutrient in ocean regions (Howarth, 1988). Later, it was observed that productivity was limited by N and P (Vitousek & Howarth, 1991). However, it is still widely acknowledged as a nutrient with proximal limitation on global ocean surfaces (Howarth & Marino, 2006) and as an inorganic or organic species (Zubkov et al., 2008). Increases in N input to marine environments have been considered the driver of eutrophication in coastal regions as it accelerates the productivity of oceanic biota such as phytoplankton (Paerl, 1993; Nixon, 1995). Nitrogen availability for primary production in aquatic ecosystems is influenced by both the direct input of N from external sources and the indirect input of P and Fe, which can stimulate N-fixation by some cyanobacteria and other microbes (Figure 1-11) (Dansie, 2017). Following N-fixation, the bioavailable/fixed N forms (NO₂⁻, NO₃⁻ and NH₄⁺) are controlled by denitrification and N-fixation by diazotrophs. Ultimately, these are the species of N that phytoplankton use for primary productivity (Hutchins & Capone, 2022; Marshall et al., 2022). Probyn (1985) inferred that NO₃⁻ is the most essential N species for phytoplankton growth as it supplies about 71% of total assimilated N. It is vital, however, that phytoplankton receive an adequate supply of both N and P to facilitate this growth (Jickells et al., 2005).

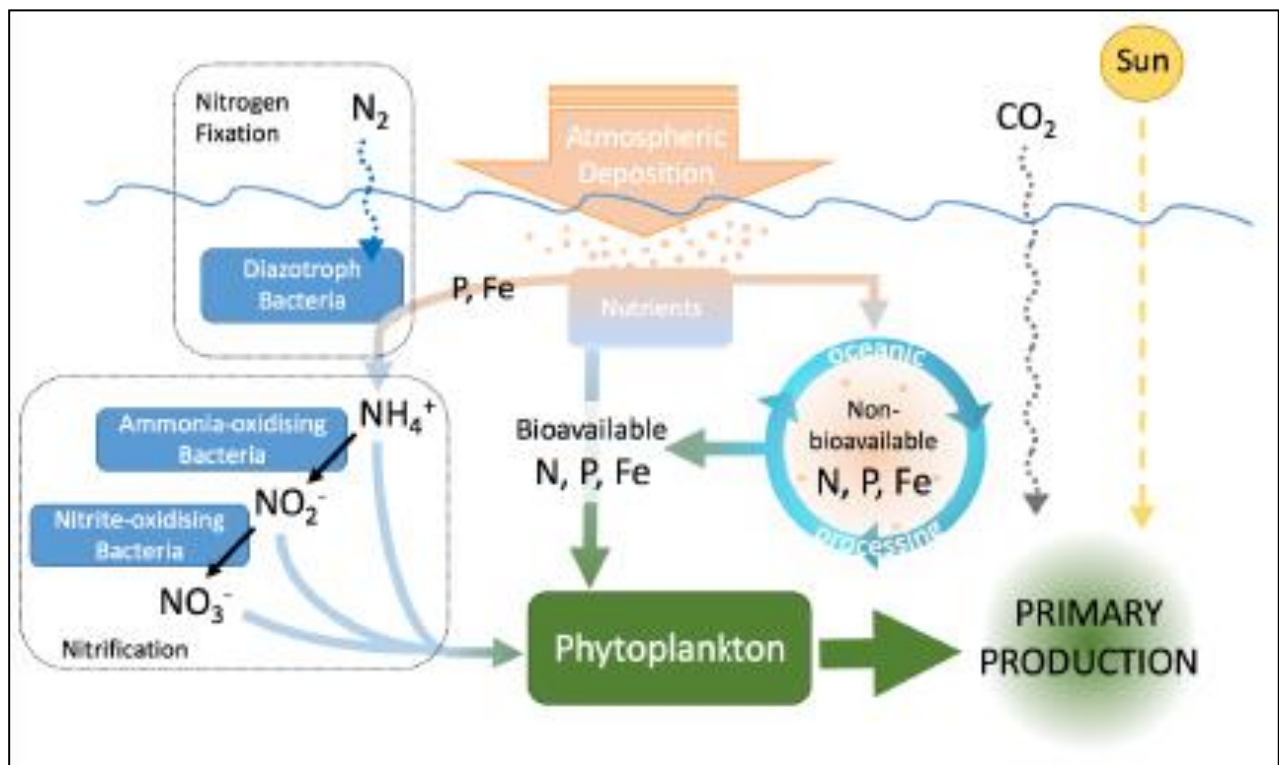


Figure 1-11: Potential N, P, and Fe uptake pathways following dust deposition (Dansie, 2017).

1.2.6.2 Phosphorus (P)

Atmospheric P has several natural and anthropogenic sources (Figure 1-12). Mineral dust is regarded as the most significant external source of P input to ocean regions (Stockdale et al., 2016), contributing about 1.15 Tg/a (83%) (Mahowald et al., 2008). The atmospheric deposition of P to oceanic regions has been reported as relatively small compared to N and Fe (Baker et al., 2003). However, it may still be vital for productivity as some oceans are co-limited by P (Mills et al., 2004). Myriokefalitakis et al. (2016) estimated a P deposition flux of about 0.45 Tg/a (40%). Two decades ago, very little was known about P solubility (Baker et al., 2006). Several studies have reported P solubility estimates between 10-36% (Graham & Duce, 1982; Herut et al., 1999; Ridame & Guieu, 2002; Baker et al., 2006) for Saharan and Algerian soil.

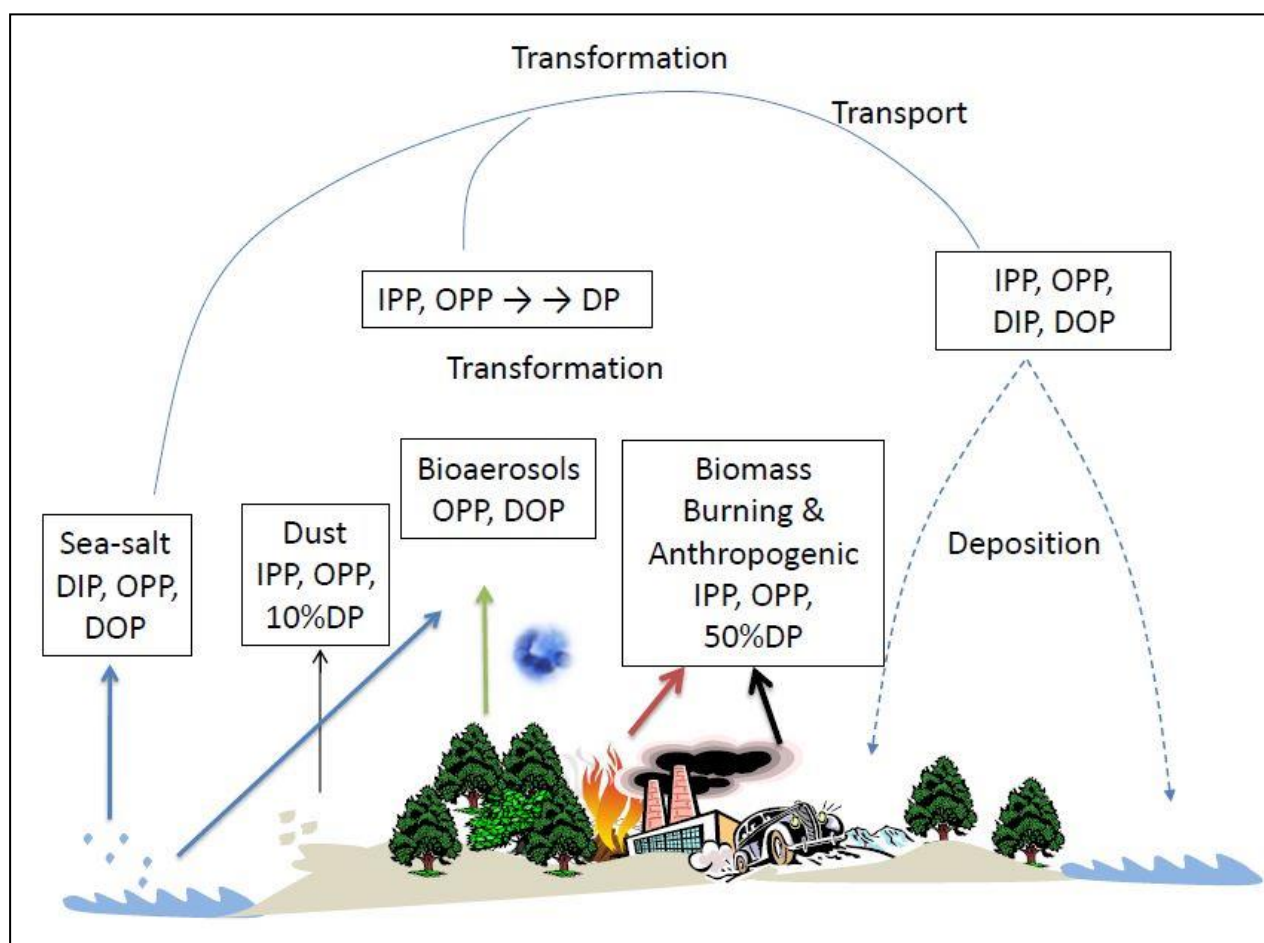


Figure 1-12: The atmospheric cycle of P illustrating its different natural and anthropogenic sources. Also shown are its forms: inorganic particulate P (IPP), organic particulate P (OPP), and soluble DIP and DOP (Myriokefalitakis et al., 2016).

The key sources of P for oceanic productivity are dissolved inorganic P (DIP) and dissolved organic P (DOP) (Nausch & Nausch, 2006; Duhamel et al., 2017). It is believed that most P exists as minerals that are not directly soluble and, consequently, not bioavailable to biota (Shi et al., 2012). Past research based on stoichiometry showed that organic P is remineralized proportional to organic C and N, which implies that P is largely bioavailable (Karl et al., 2001; Kolowitz et al., 2001). Moreover, a recent study reported that the bioavailability of the nutrient is considerably enhanced by acidification processes (Stockdale et al., 2016).

1.2.6.3 Iron (Fe)

It is widely known that atmospheric deposition is an essential component in the biogeochemical processes of remote ocean regions (Fung et al., 2000; Jickells et al., 2005; Jickells et al., 2016) as

it supplies crucial bioavailable nutrients to oceanic biota (Heimbürger et al., 2013). Data from several studies have demonstrated the importance of atmospheric deposition for trace elements to marine productivity (Jickells et al., 2016). The deposition of trace elements from the atmosphere to the ocean is a complex process involving many factors and conditions that are poorly understood (Shi et al., 2010; Chance et al., 2015). However, it is commonly assumed that dissolved trace elements are directly bioavailable to phytoplankton, as quantifying this process is complex (Shi et al., 2012). The bioavailability of these elements depends on several factors, such as physicochemical speciation and the soluble fraction thereof (Boyd et al., 2010).

Studies have reported Fe solubility estimates between 0.001 and 80% (Baker et al., 2006), and many factors have been reported for controlling its potential solubility rates. Its solubility is dependent on cloud microphysical and photochemical processes and the complexation of trace elements by organic ligands (Desboeufs et al., 2001; Desboeufs et al., 2005; Kieber et al., 2003; Gledhill & Buck, 2012) mineralogical composition of the dust source (Journet et al., 2008), and the element's enrichment factor relative to its natural crustal abundance (Heimbürger et al., 2013) (Figure 1-9). Organic ligands may significantly enhance their solubility by as much as a factor of ten (Gledhill & Buck, 2012), subsequently increasing their bioavailability (Ebling & Landing, 2017).

A recent study showed that the bioavailability of Fe from the Huab and Tsauchab ephemeral river valleys to be 5.1 ppm in deflated dust and 7.1-7.5 ppm in sediments at the surface (Dansie et al., 2017b). The same study inferred that the other Namibian ephemeral river valleys might have similar bioavailable Fe. However, Fe's bioavailability after deposition is poorly understood (Mahowald et al., 2009). The fraction of Fe that may be bioavailable is commonly considered Fe^{2+} (the labile Fe fraction) (Mahowald et al., 2005). However, the bioavailable fraction may also be Fe^{3+} (Barbeau et al., 2001; Barbeau, 2006). The previous is because the bioavailability of Fe^{2+} to biota depends on its chemical speciation, pH and redox conditions, competition and inhibition by other metals, and biological factors (Visser et al., 2003). Fe is converted from its primary Fe^{3+} to Fe^{2+} during atmospheric and oceanic transport (Figure 1-13). Given the difficulty in quantifying the bioavailable fraction, 'soluble Fe' is often used as a proxy for bioavailable Fe (Kangueehi, 2017). Recent modelling research hypothesizes that Fe species become increasingly bioavailable based on their interaction with acids emitted from anthropogenic sources, as pollutants such as SO_2 dissolve Fe species in aerosols (Baker & Croot, 2010; Li et al., 2017). The solubility of the element

is also dependent on the size as the larger particles are removed during atmospheric transport (Baker & Jickells, 2006) through gravitational settling.

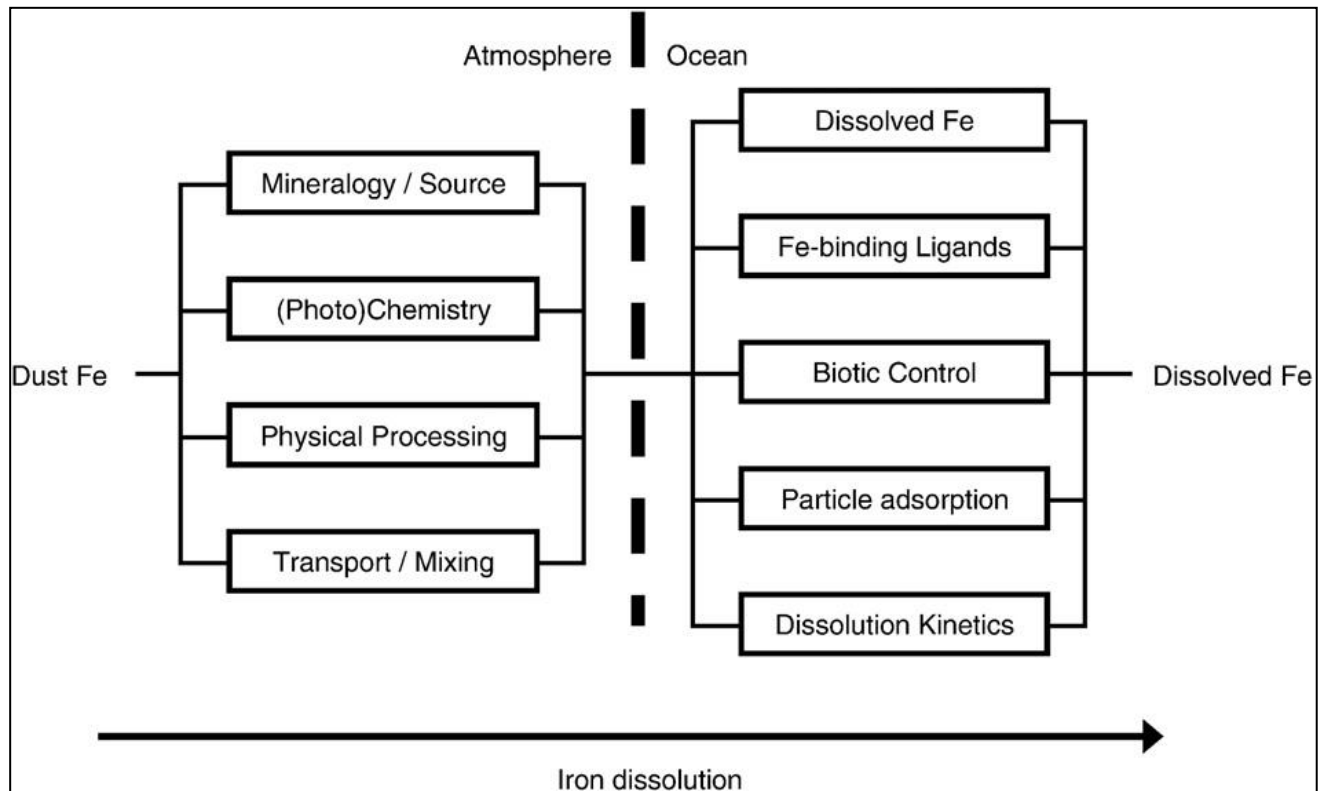


Figure 1-13: Conceptual model depicting the atmosphere-ocean cycle of Fe (Baker & Croot, 2010).

1.2.6.4 Silicon (Si)

Silicon (Si), although not as significant or extensively studied, plays a vital role in the biogeochemistry of oceanic biota, especially diatoms (Hawkings et al., 2016) – the dominant phytoplankton species in several marine ecosystems (Capellacci et al., 2013). Capellacci et al. (2013) investigated the bioavailability of different chemical forms of dissolved Si, mimicking various Si sources, to *Chaetoceros*, a common marine diatom. Recently, it was estimated that approximately 70% of dissolved silica input to oceanic regions originates from ephemeral riverine systems. The other vital mineral sources are Aeolian dust, input from hydrothermal sources, groundwater, and the upwelling from the ocean floor (Treguer & De La Rocha, 2013). The biogeochemistry cycle of silica is driven by the production and consequent dissolution rate of biogenic Si in the Southern Ocean (Nelson et al., 1996). The previous statement holds importance given that EBUS are directly influenced by the nutrient-rich water of the Southern Ocean (Hendry et al., 2021). However,

Capellacci et al. (2013) demonstrated that the soluble Si species (predominant in the dissolution products of SiO_2) are much more bioavailable to phytoplankton than biogenic and amorphous Si compounds. Although the roles of trace elements have been extensively studied, very little is known about the biological uptake of nutrients by photosynthetic oceanic biota, such as phytoplankton in the BUS (Kumar Das et al., 2017).

1.2.7 Phytoplankton Groups

During the first-ever survey of phytoplankton in the BUS, it was observed that the abundance of phytoplankton in the BUS is most prominent in spring and summer between 0-20 m deep (Brown, 1981). Diatoms throughout the northern BUS upwelling cycle between March and November typically dominate the phytoplankton community structure (Pitcher, 1986; Mitchell-Innes & Winter, 1987; Louw et al., 2017) mostly the *Chaetoceros* species (Burger et al., 2020). They commonly dominate newly upwelled nutrient-rich water, while micro flagellates, dinoflagellates, and coccolithophores are predominant later in calm nutrient-depleted waters (Mitchell-Innes & Winter, 1987; Giraudeau et al., 1993; Fawcett et al., 2007) during the latter stage of the process. Phytoplankton blooms form once the water wells up from the colder layer below the thermocline into the euphotic zone (Mitchell-Innes & Walker, 1991). Depending on factors (like light intensity and nutrients), diatoms typically prefer cooler while dinoflagellates prefer warmer waters (Finkel et al., 2010).

1.3 Motivation for this research

Previous research has characterized the soluble Fe fraction in Namibian sediments and soils (Dansie et al., 2017a; Dansie et al., 2017b) and in southern African dust aerosols (Desboeufs et al., 2024). However, ambient Fe concentrations over the Namibian coast are still not characterized. The most critical dust emitters for the BUS are Makgadikgadi and Etosha pans (Mahowald et al., 2005) and Kuiseb, Huab, Tsauchab, and Omaruru ephemeral riverbeds, which are rich in Fe, N, and P (Dansie et al., 2017). However, recent NASA MODIS images during July 2023 revealed a third potential source over the southwestern Angolan region (hereafter AS). It prompted an update on the current source inventory of significant dust emitters to the adjacent BUS. It is not an entirely novel study, as we know that the dust extends to the AS (Chappell et al., 2023). However, the surface characteristics have not been looked at in much detail. The frequency of dust emission from the region also remains unclassified.

The two predominant sources of particulate matter (PM) in coastal Namibia are sea salt and dust (Klopper et al., 2020). Dust is frequently emitted from sources surrounding the site and transported to the adjacent ocean (Vickery & Eckardt, 2013). Despite the potential importance of dust inputs from these sources to the BUS, relatively little was known about the effects of this dust on phytoplankton biomass until recently. A dust monitoring and Chl-a remote sensing study (Dansie et al., 2022) observed enhanced chlorophyll concentrations at the daily timeframe. While some studies have also investigated the response of phytoplankton to single nutrient treatments in the northern BUS (Wasmund et al., 2014; Wasmund et al., 2015), the reaction of BUS phytoplankton to a composite sample of Namib dust addition is yet to be investigated. To address this knowledge gap, we conducted the first mesocosm study to explore the impacts of Kuiseb riverbed dust on phytoplankton biomass in the BUS. During this mesocosm campaign, ambient PM concentrations were sampled to determine high and low-concentration PM events and under what meteorological conditions they occurred. In addition, we used a similar method to Dansie et al. (2022) through remote sensing data. However, with a slight modification, we use ambient Fe concentrations measured at a coastal site and investigate correlations with Chl-a concentrations in a region of interest over the BUS. There is no long-term and high-resolution dust deposition modelling study for the BUS. Therefore, we also evaluated total dust deposition in the system from a conformal cubic atmospheric model (CCAM) simulation.

1.4 Aim and objectives

This study aims to determine whether windblown dust from the Namib Desert consists of sufficient Fe to create a fertilisation response within the Benguela current. Southern African remote sensing studies have identified sources of significant plumes originating from the Namib Desert. How these dust plumes from the Namib Desert influence the adjacent BUS is yet to be fully understood.

The main objectives of this study are to:

- I. Analyse particulate matter concentrations at Henties Bay by:
 - a. Identifying episodes of high and low particulate matter concentrations;
 - b. Identifying the atmospheric conditions conducive to high and low particulate matter episodes; and
 - c. Identifying the dominant transport patterns of particulate matter.
- II. Investigate southern African dust sources located in Angola:

- a. Identifying potential dust-emitting source locations for the region; and
 - b. Investigating the atmospheric conditions conducive to their dust emission.
- III. Investigate the relationship between ambient Fe concentrations measured over the Namibian west coast and satellite Chl-a by:
 - a. Characterising ambient Fe concentrations;
 - b. Correlating measured Fe with satellite-retrieved Chl-a, AOD, and SST; and
 - c. Identifying the synoptic circulation favouring anomaly occurrence.
- IV. Evaluate a long-term dust deposition simulation to the BUS by:
 - a. Analysing a CCAM-modelled total dust deposition to the Benguela current;
 - b. Evaluating the model's performance by comparing it to MERRA-2 dust deposition; and
 - c. Investigating whether the CCAM dust deposition simulation aligns with the seasonal cycle of Chl-a in the BUS.
- V. Investigate the response of phytoplankton to dust addition in a mesocosm experiment by:
 - a. Measuring and analysing the nutrient conditions conducive to Chl-a concentration changes.

1.5 Study design and thesis outline

This thesis is presented in the traditional format and comprises the following chapters:

Chapter 1 – Background and literature review: provides a background and detailed literature review that explores the state and knowledge of ocean upwelling dynamics, significant dust emitting sources, their transport and deposition, and the importance of this dust deposition for phytoplankton growth. Also outlined are the research's motivation, aim, objectives, and thesis outline.

Chapter 2 – Data and Methods: outlines the central area of interest and smaller regions relevant to each objective. It also provides a detailed description of the various datasets and methodologies used for each objective. Furthermore, the chapter elaborates on the assumptions and considerations taken.

*Chapter 3 – Particulate matter episodes at Henties Bay (**Objective I**):* presents the results of a detailed analysis of daily particulate matter concentrations measured between 15 and 29 July 2019 at Henties Bay, Namibia. Also included is a characterisation and classification of the observed

concentrations into high and low aerosol episodes. In addition, the episodes are explored by investigating the atmospheric conditions favouring their occurrence.

*Chapter 4 – Angolan dust sources (**Objective II**):* identifies the locations of new potential Southern African dust sources from a multi-sensor method. It also analyses the meteorology present during dust emission days from these sources.

*Chapter 5 – Coastal ambient Fe and Benguela Chlorophyll-a (**Objective III**):* presents an analysis of the correlation between ambient Fe concentrations measured at a coastal Namibian site and chlorophyllic responses in the adjacent BUS. In addition, correlations between Chl-a, aerosol optical depth (AOD) and sea surface temperature (SST) are presented.

*Chapter 6 – A long-term CCAM dust deposition simulation to the Benguela (**Objective IV**):* evaluates a long-term CCAM dust deposition simulation to the BUS between 1979 and 2013. The results are evaluated against those from a MERRA-2 dataset. The seasonality of the simulated dust deposition is compared to the seasonal BUS Chl-a cycle.

*Chapter 7 – The response of Benguela current phytoplankton to Namib desert dust addition (**Objective V**):* reports findings from the first-ever mesocosm study that investigated the response of BUS phytoplankton to the addition of Namib desert dust obtained from the dusty Kuiseb riverbed.

Chapter 8 – Summary and conclusions: encapsulates the main findings of each research objective outlined in Chapter 1. It also provides the overall conclusions of the study.

CHAPTER 2

The following chapter outlines the research design, research methodologies followed, and datasets used. These are discussed in detail in the sequence of the study objectives. A detailed description of the study area, experimental methods, and statistical analysis procedures and tools are provided for each objective. In some cases, limitations imposed on the study are given where applicable.

DATA AND METHODS

2.1 Analyse Particulate Matter Concentrations at Henties Bay

2.1.1 Aerosol Sampling

Concentrations of particulate matter (PM) were sampled at the University of 'Namibia's Sam Nujoma campus (S22°5'43.944"; E14°15'9.552") between 15 and 29 July 2019 (Figure 2-1) (Figure 2-2). The campus is next to the Omaruru riverbed, southwest of the Etosha Pan and Huab riverbed and northwest of the Kuiseb- and Tsauchab riverbeds. The sampling was done by concurrently operating two E-samplers mounted on tripods (Met One Instrument, 2011). It has a particle size range of 0.1–100 μm and a measurement range between 0 and 65 mg/m^3 with a precision of 2%. The measurements were converted from mg/m^3 to $\mu\text{g}/\text{m}^3$ by multiplying each value by 1000. One sampler continuously measured $\text{PM}_{2.5}$, and the other measured PM_{10} (Figure 2-2). Measurements were taken in 15-minute intervals at a flow rate of 2 L/min.

Unfortunately, the meteorology during the sampling period was not measured at the site. However, the Wlotzkasbaken weather station from the “Southern African Science Service Centre for Climate Change and Adaptive Land Management” (SASSCAL) is about 32 km southeast of the monitoring site (Kaspar et al., 2015). An hourly wind speed and wind direction dataset for the weather station was obtained from the SASSCAL website (www.sasscal.org), given its proximity to Henties Bay. This dataset created daily and hourly wind roses for the sampling period.

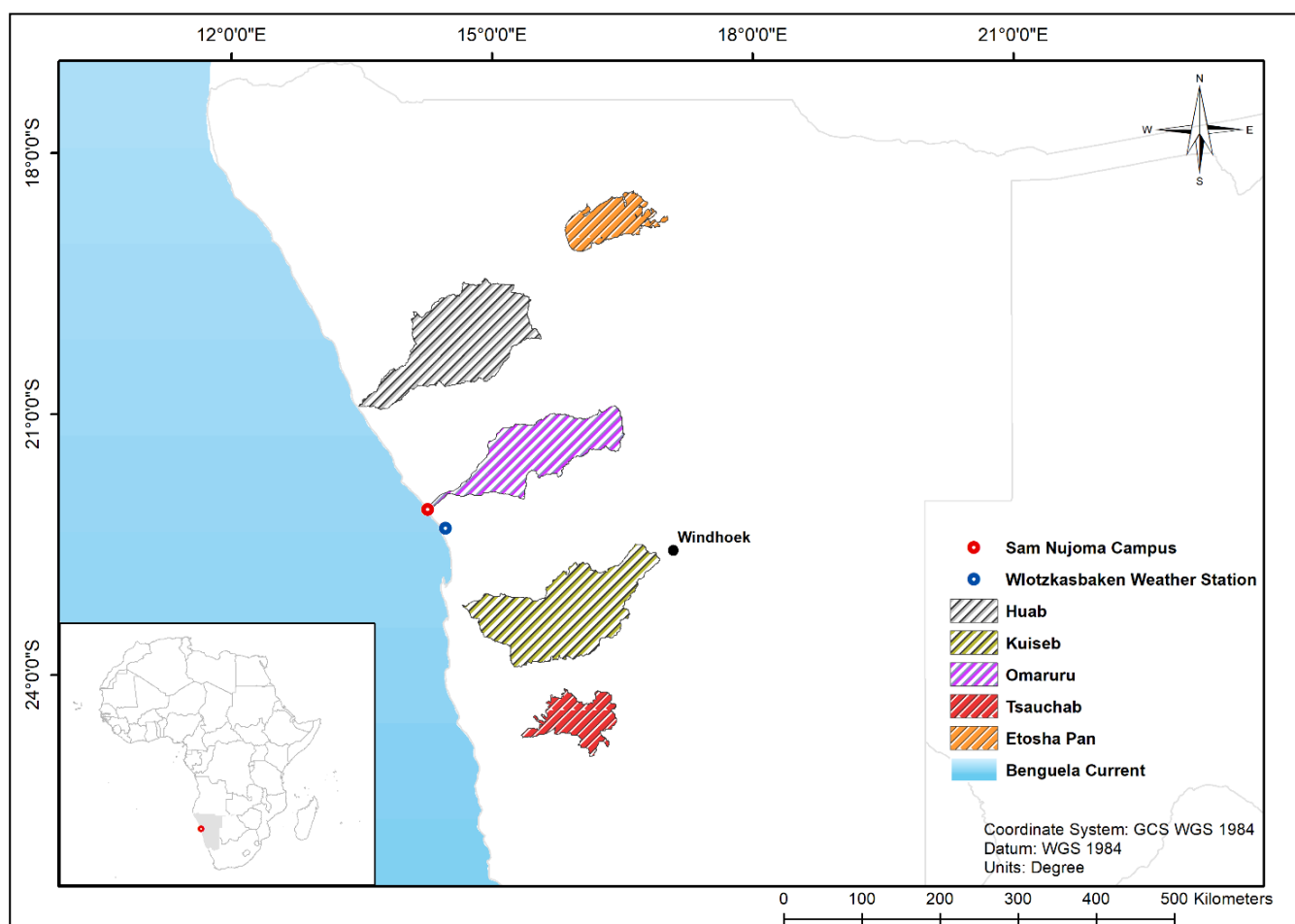


Figure 2-1: Location of the University of Namibia's Sam Nujoma campus, the Wlotzkasbaken weather station, and 5 of the 12 identified primary Namibian dust sources.



Figure 2-2: E-samplers used to monitor aerosol concentrations (PM_{2.5} to the left and PM₁₀ to the right) between 15 and 29 July 2019.

2.1.2 Dust Event Identification

There is no precise, agreed-upon method for defining dust events based on PM data (Wiggs et al., 2022). Therefore, in this study, we identified a dust event where the average hourly PM₁₀ measurements remained at or above 20 $\mu\text{g}/\text{m}^3$ for 80% of the day. This concentration represents a “severe dust storm” according to the classification by Leys et al. (2011) and is a very conservative identifier of a dust event. We chose this as the most appropriate classification for this study as the hourly PM₁₀ concentrations never reached the thresholds of the other classes. Days that met these criteria were classified as high aerosol episodes (HAEs), while days that did not were classified as low aerosol episodes (LAEs).

2.1.3 Meteorological Conditions

2.1.3.1 HYSPLIT Back Trajectory Analysis

The National Oceanic and Atmospheric Administration’s (NOAA) Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model was used to investigate the transport of air masses

to Henties Bay during the study period (Stein et al., 2015). 72-hour long back-trajectories were run for each day during the sampling period. This simulation started once every hour in the 24 hours each filter was sampled. The back-trajectories were started at 250 m above ground level to model the efficient transport of air masses into the marine boundary layer, which has a minimum height of about 500m over the Namibian region (Klopper et al., 2020). This height is also within the model's first and second vertical levels at 1000 hPa (~110 m amsl) and 975 hPa (~300 m amsl). The GDAS (Global Data Assimilation System) reanalysis dataset was used to model the trajectories. The resolution of this dataset is $1^\circ \times 1^\circ$ and is provided by the National Centre for Environmental Prediction (NCEP). Two open-source libraries, splitR version 0.4.0.9000 and Openair version 2.18-0, from the RStudio Windows interface, were used for the trajectory analysis (splitR available from <https://github.com/rich-iannone/SplitR>; Carslaw & Ropkins, 2017).

2.1.3.2 Synoptic meteorology

Four general circulation patterns impact the transport of air masses to the Namibian coast: continental highs, easterly waves, westerly waves and the South Atlantic high (Formenti et al., 2018). The influence of each pattern on circulation greatly depends on the season. The ERA5 reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach et al., 2020) was employed to study the effect of synoptic-scale circulation on the concentration measurements observed during the sampling period. This was done to associate the synoptic circulation with the air mass transport pathways identified in the HYSPLIT analysis. The hourly dataset (00:00-23:00 UTC) has a spatial resolution of $0.25^\circ \times 0.25^\circ$. It contains four variables: mean sea level pressure, geopotential height at 500 hPa, 10 m u-component of wind, and the 10 m v-component of wind. The u-component provides the east-west windspeed and movement, while the v-component provides the north-south windspeed and motion. The dataset was averaged daily with Climate Data Operators (CDO) (Schulzweida et al., 2022), and the mean sea level pressure and geopotential height were overlayed with MeteoInfo (Wang, 2014) while the wind components were analysed with Panoply (NASA, 2022).

2.2 Investigate southern African dust sources located in Angola

2.2.1 Dust Plume Identification

It has been established that mineral dust is the second leading source of aerosols over the coast at the HBAO, with a 14.7% contribution (Klopper et al., 2020), most likely from the surrounding riverbeds. These dust sources have been previously classified along the Namibian coast and interior (Eckardt & Kuring, 2005; Vickery & Eckardt, 2013; Vickery et al., 2013; von Holdt et al., 2017) (Figure 2-3). However, a very recent dust event revealed a gap in these classifications. During the analysis of the results from the previous objective, it was identified on satellite imagery that dust was emitted from sources located in the Angolan region. Figure 2-4 shows significant dust emissions from the southwest of this region (hereafter referred to as AS) to the Benguela current. Emissions from the AS have not yet been classified, prompting an update on understanding important southern African dust sources for the Benguela current.

When using remote sensing data for the detection of dust plumes or discrete dust emission events, there are certain aspects to note (Vickery et al., 2013):

1. **Detection Performance:** Different remote sensing algorithms exhibit varied dust detection capabilities.
2. **Satellite Overpass Timing:** Satellites have intervals between their overpasses, which might miss capturing a dust emission event.
3. **Cloud masks:** Clouds may interfere with dust plume detection.
4. **Subjectivity:** Identification of a dust event remains subjective (Baddock et al., 2009).

A multisensory methodology, similar to previous studies (Lee et al., 2009; Rivera Rivera et al., 2010; Vickery et al., 2013), was followed by combining MODIS visible composite Terra and Aqua datasets. Both datasets are based on the MODIS Corrected Reflectance algorithm, which uses MODIS Level 1B data at a nadir 0.25 km resolution (bands at 0.62 μm -0.67 μm and 0.841 μm -0.876 μm) (<https://worldview.earthdata.nasa.gov/>). The daily images were visually assessed to identify dust plumes between 1 January 2016 and 31 December 2017. These images were reviewed sequentially on the NASA EOSDIS website. The presence of visible plumes or hazes identified dust events. Differentiating brownish dust from white cloud masks was straightforward, as the dust

is contrasted against a dark oceanic backdrop. Mistaking dispersed haze for dust was minimised, as MODIS distinctly flags active fires (Vickery et al., 2013).

For some images, estimating the likely emission source was necessary, as not all identifiable plumes were attached to a continental source. The MODIS images were georeferenced and overlaid with a topographic map to determine the location of the emission sources. The length and frequency of the plumes were then determined with the ArcMap tool of ArcGIS. The identified source points reported for the study are potential and not definite, as the plumes may have originated from further on the interior. Establishing the exact source locations with the MODIS resolution is complex and requires further investigation.

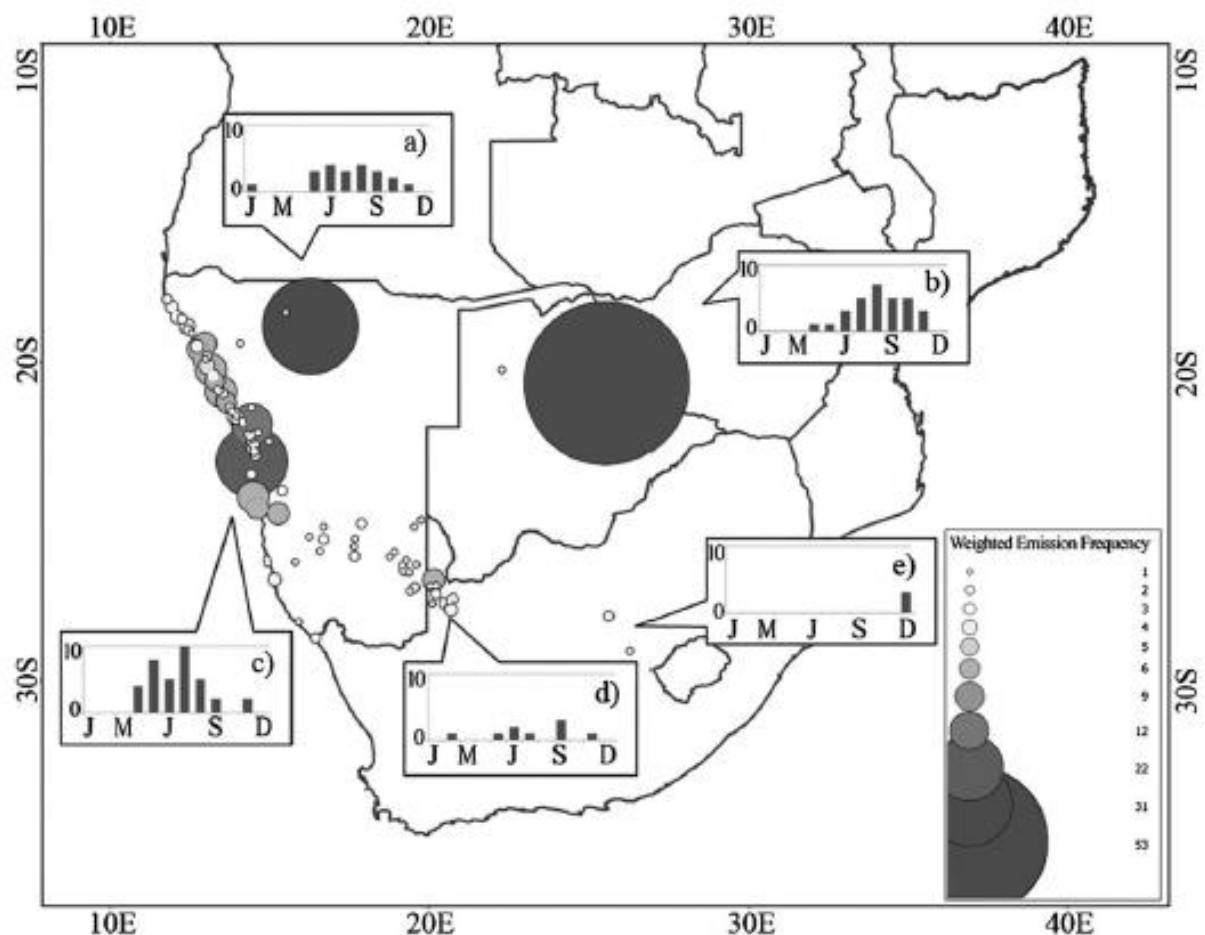


Figure 2-3: The existing southern African dust plume source inventory (Vickery et al., 2013).

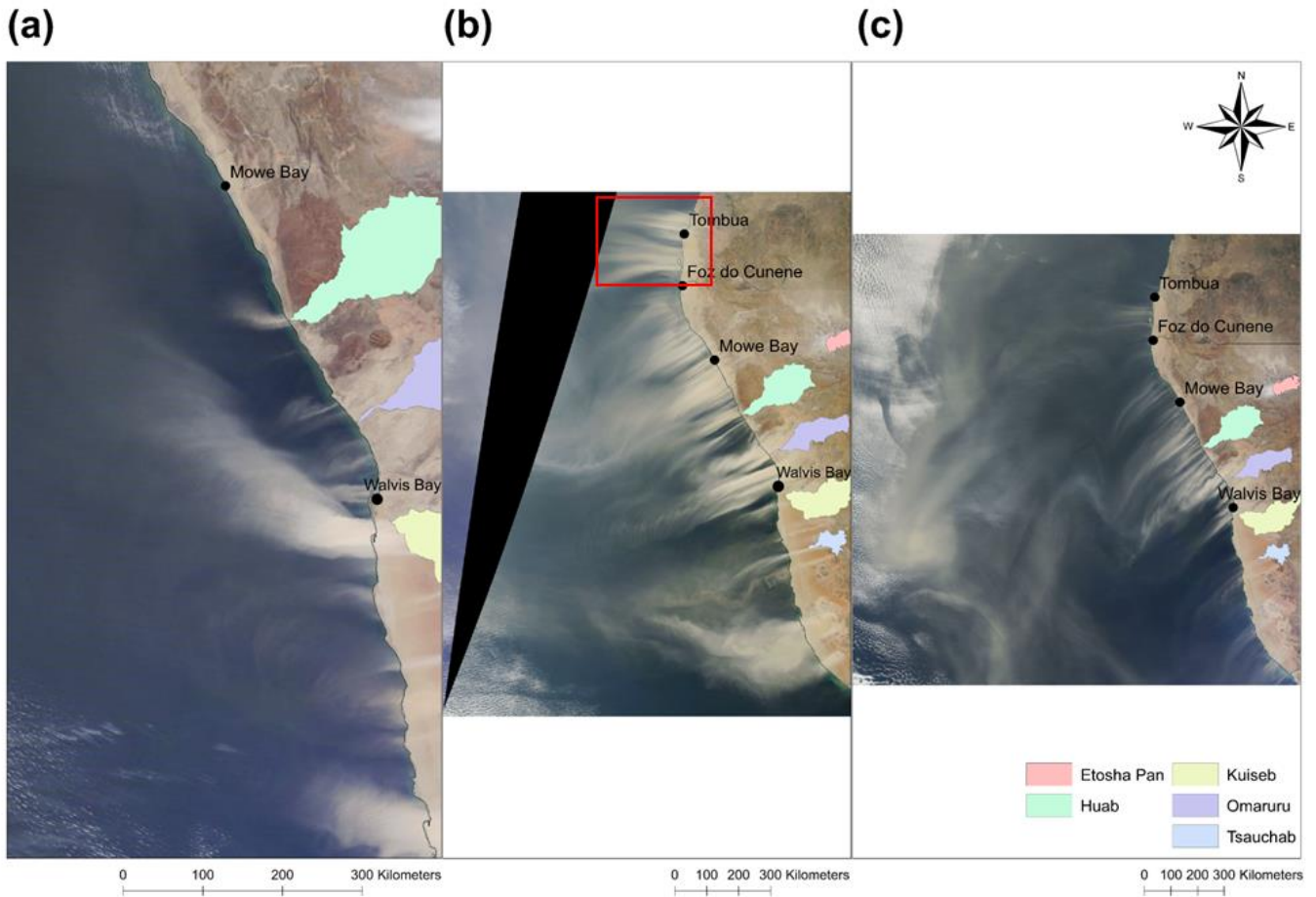


Figure 2-4: Dust emission event observed on a) 10 July 2023, b) 11 July 2023, and c) 12 July 2023 from Namibian and Angolan dust sources. The images were obtained from MODIS Terra Corrected Reflectance (True Colour) and accessed through the Earth Observing System Data and Information System (EOSDIS) (www.worldview.earthdata.nasa.gov). New potential sources are located in the red area of interest depicted in b).

2.2.2 Meteorological Conditions

Data from the ECMWF for the ERA5-Reanalysis dataset (Hersbach et al., 2023) was used to show the meteorological conditions from the day. The ERA5 dataset represents the latest generation gridded dataset, built on the assimilation of all available weather data since 1940 on a 25 km x 25 km resolution. Specifically, pressure level data was extracted, and for each case study day, we showed the lowest model U and V components (1000hPa) to represent surface winds.

2.3 Investigate the relationship between ambient Fe concentrations measured over the Namibian west coast and satellite Chl-a

2.3.1 Study Area

A previous study investigated the relationship between Namibian dust emission events and corresponding phytoplankton blooms in the Benguela current (Dansie et al., 2022). Through a visual assessment, they identified a boundary to which dust plumes may be transported from the continental shelf to the adjacent ocean (Figure 2-5). This identified boundary is indicated by the area of interest (AOI) in Figure 2-3, with an upper left corner at 18°S 5°E and a lower right corner at 26°S 15°E. Their study found a relationship between ephemeral riverbed dust emission and phytoplankton in the Benguela current at the daily scale.

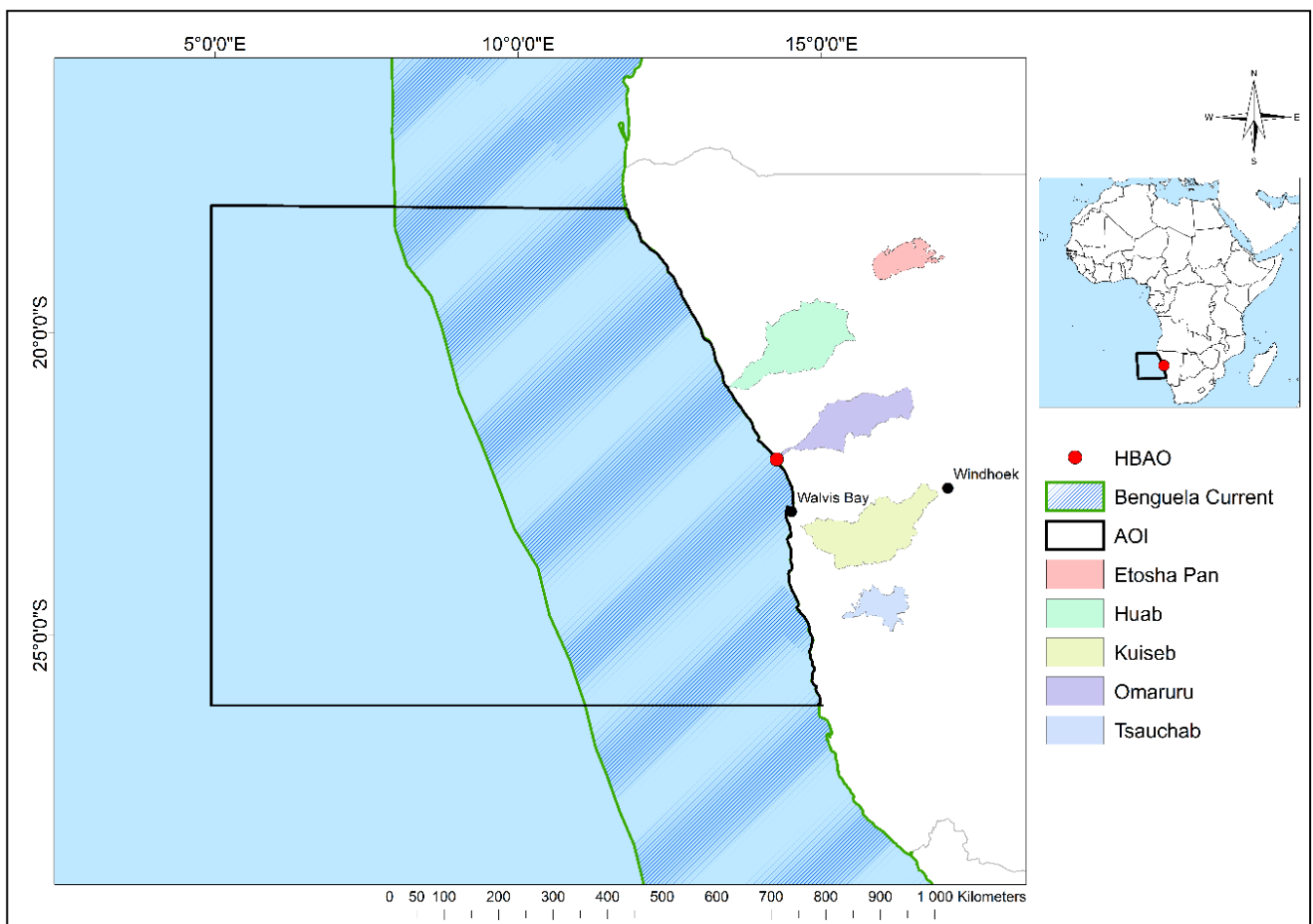


Figure 2-5: The Benguela current and location of 5 of 12 crucial Namibian coastal dust emitting sources. The black polygon shows the area of interest considered in this study.

In this study, we build upon previous research by investigating the hypothesis proposed by Dansie et al. (2022) that terrestrial dust deposition delivers sufficient iron (Fe) to create a Chl-a response in the Benguela current. An ambient Fe dataset collected during an intensive aerosol monitoring campaign at the Henties Bay Aerosol Observatory (HBAO) in Namibia was analysed between 25 February 2016 and 19 December 2017 (Figure 2-6). The aerosol sampling and elemental species analysis methods are described in detail by Klopper et al. (2020), who conducted a source apportionment of 24 elements, including the Fe data used in our study. Briefly, sampling was performed twice daily: 9 hours during the daytime and 9 hours at night. This was done on an alternating schedule of one week on and one week off. We examine the temporal variations of Fe concentrations at the site and explore their relationship with satellite-retrieved Chl-a data. A positive relationship between the measurements would not suggest a causal relationship, so one must account for other possible factors. Therefore, satellite aerosol optical depth (AOD) and sea surface temperature (SST) are also compared.

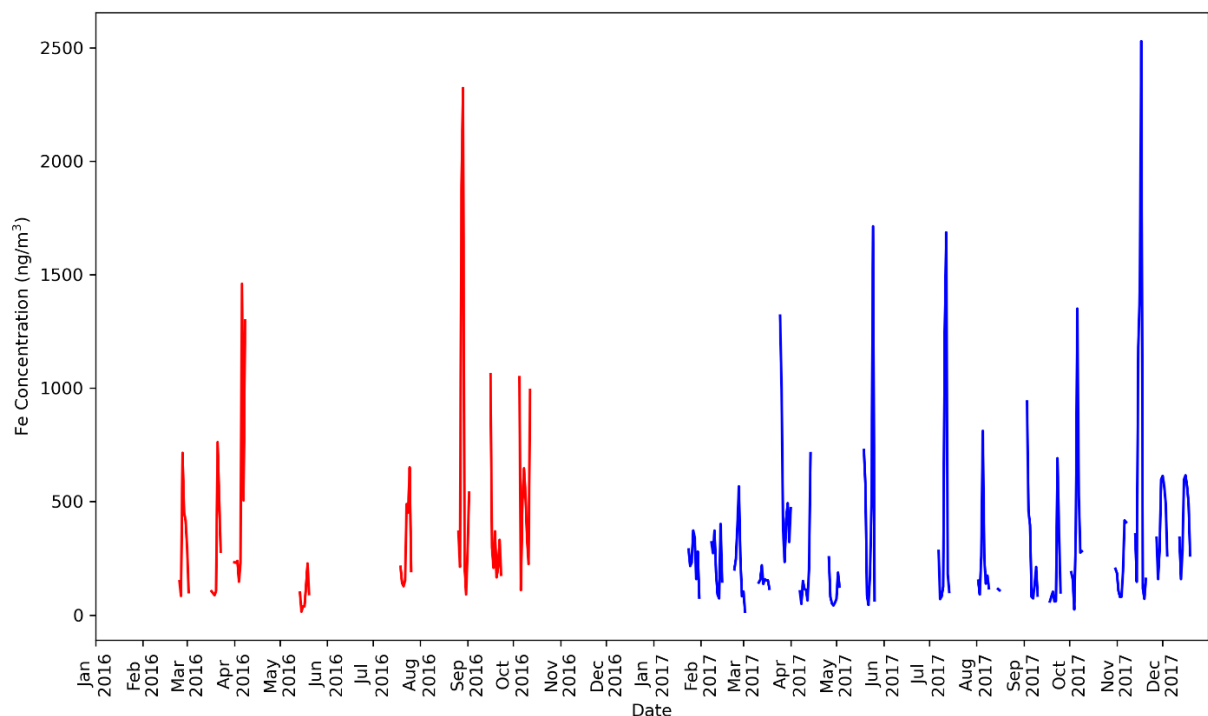


Figure 2-6: Time series of ambient Fe concentrations (ng/m³) at Henties Bay from February 2016 to December 2017. The red lines indicate 2016, and the blue lines indicate 2017 data.

Using the Fe data in this context, we hope to gain new insights into its behaviour and relationship with phytoplankton productivity in the Benguela current. In this study, the ambient Fe concentrations represent the frequent dust plumes emitted by the southern African dust sources.

2.3.2 Remote Sensing Data

The AOD is commonly used to indicate the optical properties of all aerosols in the atmospheric column (Remer, 2008; Zhang et al., 2010; Shen et al., 2020). The MODIS Dark Target Deep Blue AOD data for the 550nm band was used for this analysis. The band was extracted from a combination of the Terra (MOD04_3K) and Aqua (MYD04_3K) platforms (Levy et al., 2015). The two satellites synchronously orbit the sun, following a near-polar path at an altitude of 705 km. Terra crosses the equator daily at 10:30., while Aqua passes later at 13:30. These daily datasets belong to collection 061 and have a nadir resolution of 3 km x 3km. The 5-minute swath data contained several variables in a Hierarchical Data Format (HDF). The ‘Effective Optical Depth Average Ocean’ was extracted using OSGeo4W shell from QGIS. In addition, OSGeo4W was used to convert the extracted variable to GeoTiff format. The HDF datasets did not have a defined time dimension; hence, the dates were extracted from the filenames and assigned as a scan axis using Spyder. The GeoTiff files were clipped to the AOI and masked to show only data over the ocean. Lastly, the files were converted to netCDF format and merged along the newly assigned time dimension with NetCDF Operators (NCO) and CDO. A time series of the extracted AOD data is illustrated in Figure 2-7.

The SST dataset was obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) (Merchant et al., 2019). The daily level 4 dataset spans 1981-present at 5 km x 5 km spatial resolution from multiple satellites. A time series of the analysed SST is shown in Figure 2-8. A daily multi-sensor Chl-a dataset was obtained from the version 6 Ocean-Colour Climate Change Initiative (OC-CCI) (oceancolour.org/thredds/) (Sathyendranath et al., 2019). The dataset is a merged product of the OrbView-2, MODIS Aqua, Envisat, Suomi NPP, Sentinel-3a and Sentinel-3b satellites and has a resolution of 4 km x 4 km. Figure 2-9 illustrates the daily Chl-a concentrations. All subsequent analyses for these three datasets were performed for only the days on which Fe measurements were taken. Notably, a peak in Chl-a concentrations is observed to coincide with a peak in AOD between September and October 2017, during the lowest observed SST at the same time.

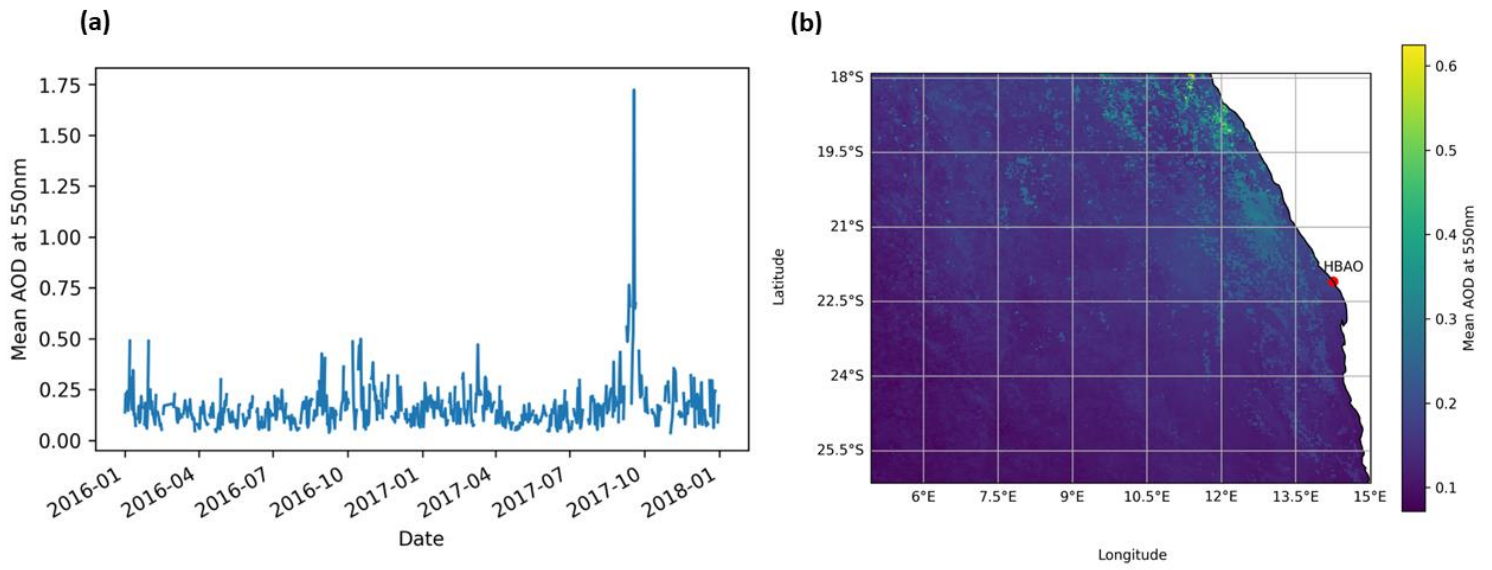


Figure 2-7: a) Time series of mean AOD at 550 nm in the AOI from January 2016 to December 2017 and b) its mean per pixel in the AOI.

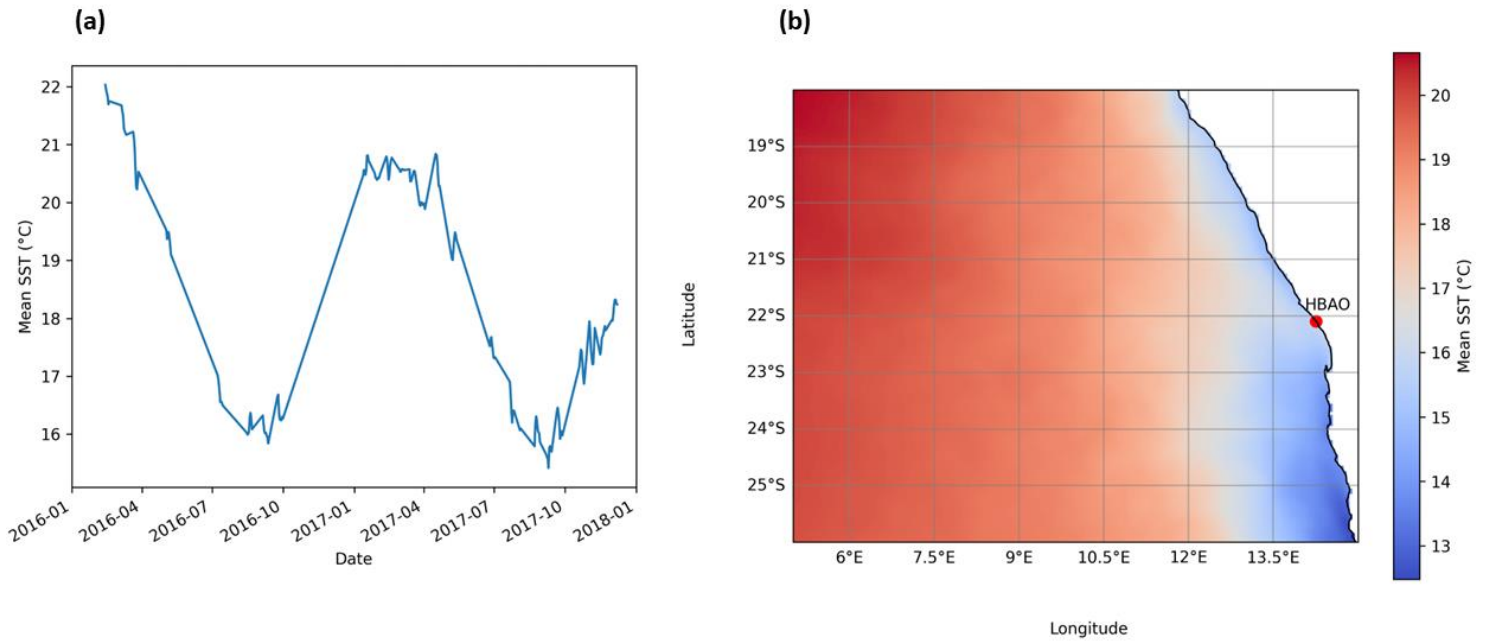


Figure 2-8: a) Time series of mean SST (°C) in the AOI from January 2016 to December 2017 and b) the mean temperature per pixel in the AOI.

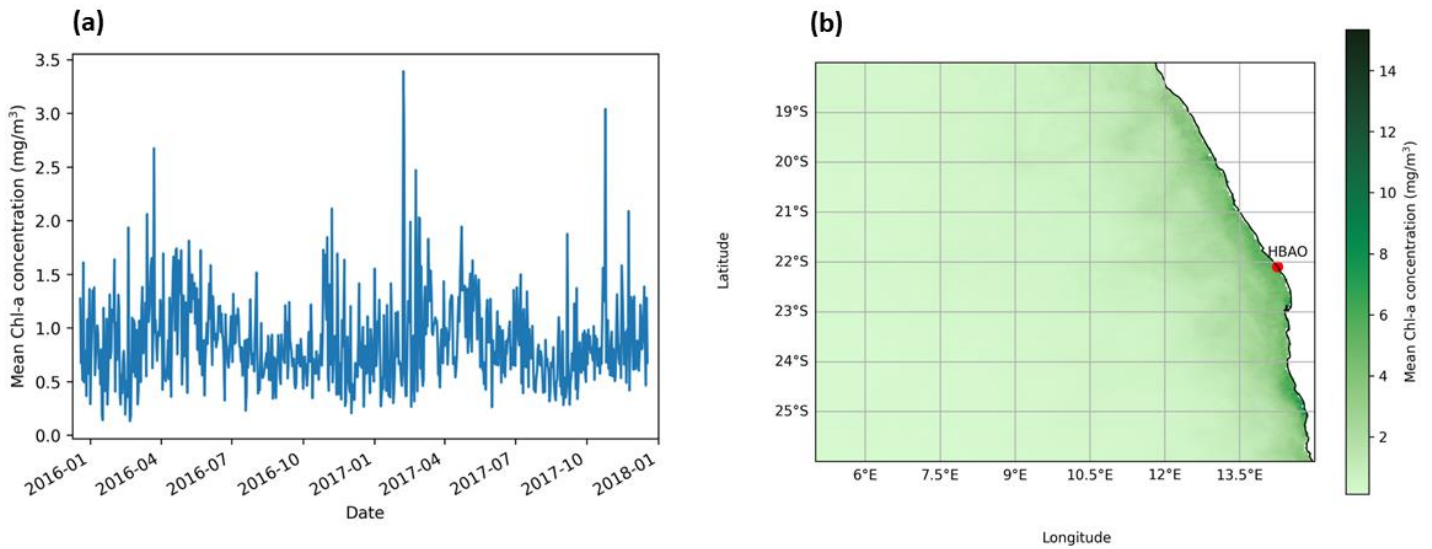


Figure 2-9: a) Time series of mean Chl-a concentration (mg/m^3) in the AOI from January 2016 to December 2017 and b) its mean concentrations per pixel in the AOI.

2.3.3 HYSPLIT Forward-trajectory Analysis

Extreme concentration episodes (ECEs) in the Fe dataset were first identified visually as outliers and then confirmed by extracting only the values within 1.5 the interquartile range of the 75th percentile. As mentioned, Dansie et al. (2022) found a relationship between dust emission and BUS Chl-a on a daily scale. Given that these sources emit nutrient-rich dust and presuming that the anomalous concentrations came from them, the HYSPLIT model was used to compute forward trajectories and determine where the Fe may have been deposited within the AOI. In total, 19 ECEs occurred during the day and 18 at night. Terra and Aqua observe AOD and Chl-a during the day and not at night, so only the daytime ECEs are considered in this analysis. Four ECEs were substantially more than the rest of the dataset, each exceeding 2500 ng/m^3 , and are the only events considered in this analysis.

The HYSPLIT forward trajectories were computed using the GDAS $0.5^\circ \times 0.5^\circ$ meteorology dataset (Figure 2-10). The trajectories were computed for 48 hours, with a new one starting every 8 hours at 100 m, 500 m, and 1500 m above ground level. The daytime Fe samples were measured between 07:00 and 19:00. Because land breezes are predominant at the site at night (Klopper et al., 2020), the trajectories were started at 19:00. The endpoints of the trajectories were used as locations where Fe, AOD, SST, and Chl-a measurements were compared—however, some

trajectory pathways ended outside the domain or over the interior. Where a pathway ended outside the AOI, the point just before it crossed was taken. If a trajectory ended over the interior but passed over the ocean at some time, one or more ocean points were taken and averaged if necessary. On days when trajectories did not pass over the ocean, data was extracted at a point right next to the HBAO. On some occasions, all three computed trajectories led to the ocean, and in these cases, the extracted data were averaged. To account for the identified daily relationship, the AOD, SST, and Chl-a data were extracted and compared one day after a Fe anomaly.

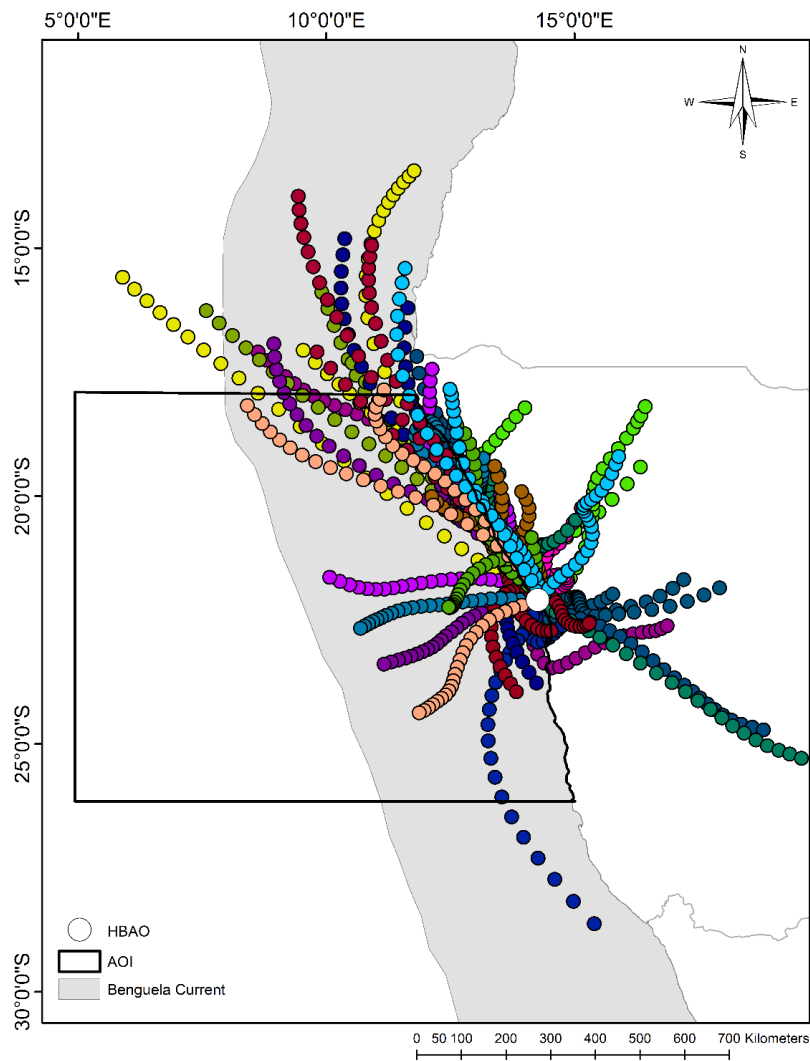


Figure 2-10: 24-hour forward trajectories from the HBAO at 100, 500, and 1500 m heights. The different colours indicate the trajectories for each anomalous day.

2.3.4 Meteorology on ECE Days

The meteorological conditions on the four considered anomalous days were investigated using data from the ECMWF for the ERA5-Reanalysis dataset (Hersbach et al., 2023). The dataset was used to make individual wind vector maps for each anomaly that exceeded 2500 ng/m^3 . The ERA5 dataset is the latest generation gridded dataset, assimilating all available weather data since 1940 on a $25 \text{ km} \times 25 \text{ km}$ resolution. Pressure level data was extracted, and for each case study day, the lowest model U and V components (1000hPa) were shown to represent surface winds. In addition, the ERA5 output maps are presented with the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) (©EUMETSAT, 2023) imagery and South African Weather Service (SAWS) synoptic maps as support. Similar to Section 2.1.1, wind roses were made for ECE days $> 2500 \text{ ng/m}^3$ using hourly wind speed and direction data from the SASSCAL data portal.

2.4 Evaluate a long-term CCAM simulation of dust deposition to the Benguela current

2.4.1 Simulated dust deposition

This study analysed simulated dust deposition to the Benguela current the CSIRO's (Commonwealth Scientific and Industrial Research Organisation) CCAM model (Conformal-Cubic Atmospheric model) (Mcgregor, 2005; Mcgregor & Dix, 2008). The resolution of the semi-implicit and semi-lagrangian CCAM model varies and may be applied in global (quasi-uniform resolution) or regional applications (stretched grid resolution). The model was run on an 8 km resolution domain centred over southern Africa (38S - 18S ; 15E - 35E), slowly decreasing to 50 km resolution outwards (stretched grid resolution) nudged within the ERA5 simulation. The CCAM run was simulated globally, and the changing resolution did not impact the results. The model output contained variables at 6-hour intervals in $\text{g/m}^2/\text{year}$ units. The CCAM model calculates dust deposition at 6-hour intervals. Each of these calculations represents the dust deposited during those 6 hours. These values are accumulated to represent the total dust deposition for a year to provide a comprehensive view of dust deposition over time. Therefore, even though the model operates at a 6-hourly interval, the output is presented in terms of $\text{g/m}^2/\text{year}$, providing an annual total of dust deposition. The variables included the common meteorology ones (temperature, precipitation, and wind speed and direction), aerosol optical depth (AOD), dimethyl sulphide (DMS) emissions (as a proxy for

phytoplankton activity), and dust variables (e.g., emissions, mixing ratios, AOD attributed to dust, wet deposition, and dry deposition).

As a first step towards understanding dust deposition in the region, this study aims to ascertain how much dust deposition CCAM simulates, where it simulates the deposition occurs, and what the seasonal cycle of the deposition is. The model simulated deposition between 1979 and 2013 in four size bins (0.1-1 μm , 1-2 μm , 2-3 μm , and 3-6 μm) for both dry and wet deposition processes. The results were analysed for total deposition, i.e., all size bins were combined individually for dry and wet deposition. The model predicts dust deposition through three methods: dry or wet deposition or gravitational settling, as Rotstayn et al. (2011) described. The approach to mineral dust emission is dependent on the wind speed and soil moisture, as outlined by Ginoux et al. (2004), and is grounded on satellite studies that pinpointed primary dust sources as topographical low points where a sufficiently thick layer of alluvium could gather (Prospero et al., 2002). The CCAM aerosol and dust deposition parameterisation has been described elsewhere (Rotstayn et al., 2011; Rotstayn et al., 2012).

2.4.2 Model output analysis

The daily average simulated deposition was analysed with CDO and RStudio to produce the domain's initial total deposition plot (Figure 2-11). However, this study is particularly interested in investigating the potential impact of dust deposition on productivity in the Benguela current. For this reason, the deposition was masked only to show deposition to the ocean. Following the initial analysis, two 'hotspots' of mean simulated dust deposition to the Benguela current could be identified through visual inspection: a region in the northern domain (hereafter Box N) and one in the south (hereafter Box S). The coordinates for the upper left and lower right corners of these domains are as follows: -16.4°S 11°E -18.5°S 12.2°E and -25°S 14.3°E -27.5°S 15.7°E, respectively. The bounding box for Box covers northern Namibia and southern Angola, while Box S is stated in a region surrounding Lüderitz in southern Namibia. The data in both regions were masked to show only values modelled to be deposited over the ocean – where a raster cell was considered if its centroid was over the ocean or on the land-ocean boundary. Dust may, on average, be transported from the Namibian interior to the adjacent ocean to distances of up to about 100 km (Piketh & Walton, 2004; Tlhalerwa & Piketh, 2005; Vickery et al., 2013). The optimal distance to analyse the modelled dust deposition was determined through buffers created from 5 to 100 km in 5 km increments (Figure 2-12).

2.4.3 MERRA-2 Reanalysis Data

The MERRA-2 reanalysis dataset (Gelaro et al., 2017) was used to evaluate the CCAM simulated dust deposition to the BUS. It is the latest atmospheric reanalysis dataset and is a product of a combination of the version 5 GEOS model (GEOS-5) and several observational datasets, which includes in-situ measurements (e.g., AERONET) and satellite observations from MODIS, MISR and AERONET. The monthly dataset, spanning January 1980 to December 2013, was accessed through the GIOVANNI database (<https://disc-beta.gsfc.nasa.gov/giovanni/>). MERRA-2 contains variable data, including AOD and mixing ratios. To evaluate CCAM, we downloaded MERRA-2 wet and dry deposition for four available size bins (0.1-1, 1-1.8, 1.8-3, and 3-6 μm) at a resolution of 0.5° by 0.625° . For this evaluation, the CCAM data in Box N and Box S was resampled with the nearest neighbour to match the coarser resolution of the MERRA-2 dataset. As for the CCAM deposition, the data in both regions was masked to show only deposition over the ocean for the MERRA-2 data. A t-test was used to assess whether the means between CCAM and MERRA-2 are significantly different. It is important to note that the MERRA-2 reanalysis deposition data should be considered ‘simulated’ as its output has not been validated due to few actual dust deposition measurements, and the satellite measurements do not measure dust deposition. The CCAM dust deposition results are compared to those of MERRA-2 to assess the consistency and reliability of the simulations. This comparative analysis aims to provide insights into the agreement or divergence between the two models, contributing to a comprehensive evaluation of the simulated deposition patterns in the BUS. It should be noted that the MERRA-2 dataset contains dust deposition data in $\text{kg}/\text{m}^2/\text{s}$. Given that the CCAM data is in $\text{g}/\text{m}^2/\text{year}$, the datasets were resampled to identical units before any comparisons.

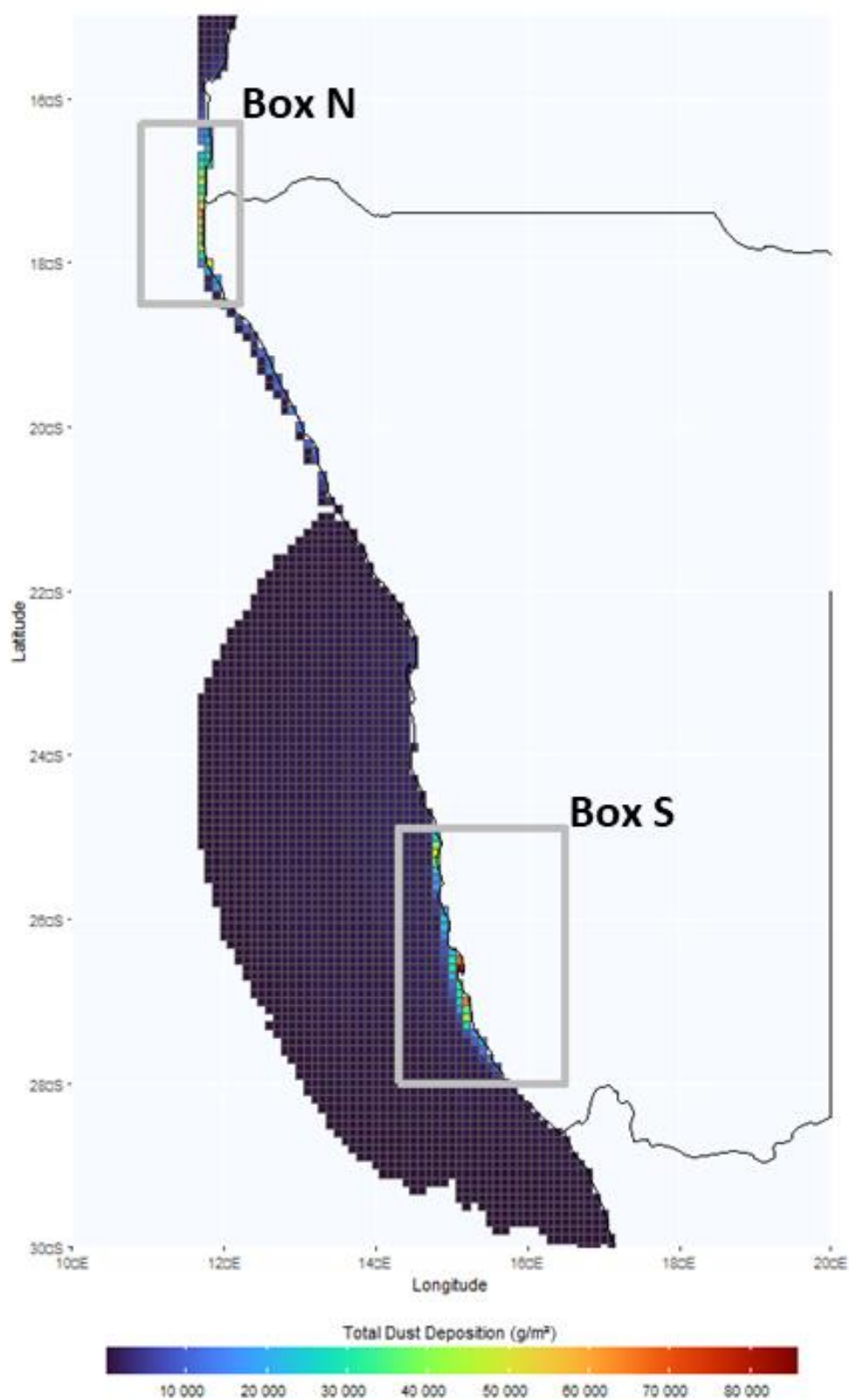


Figure 2-11: The mean CCAM dust deposition between 1979 and 2013 (g/m^2) and the identification of Box N to the north and Box S to the south of the domain.

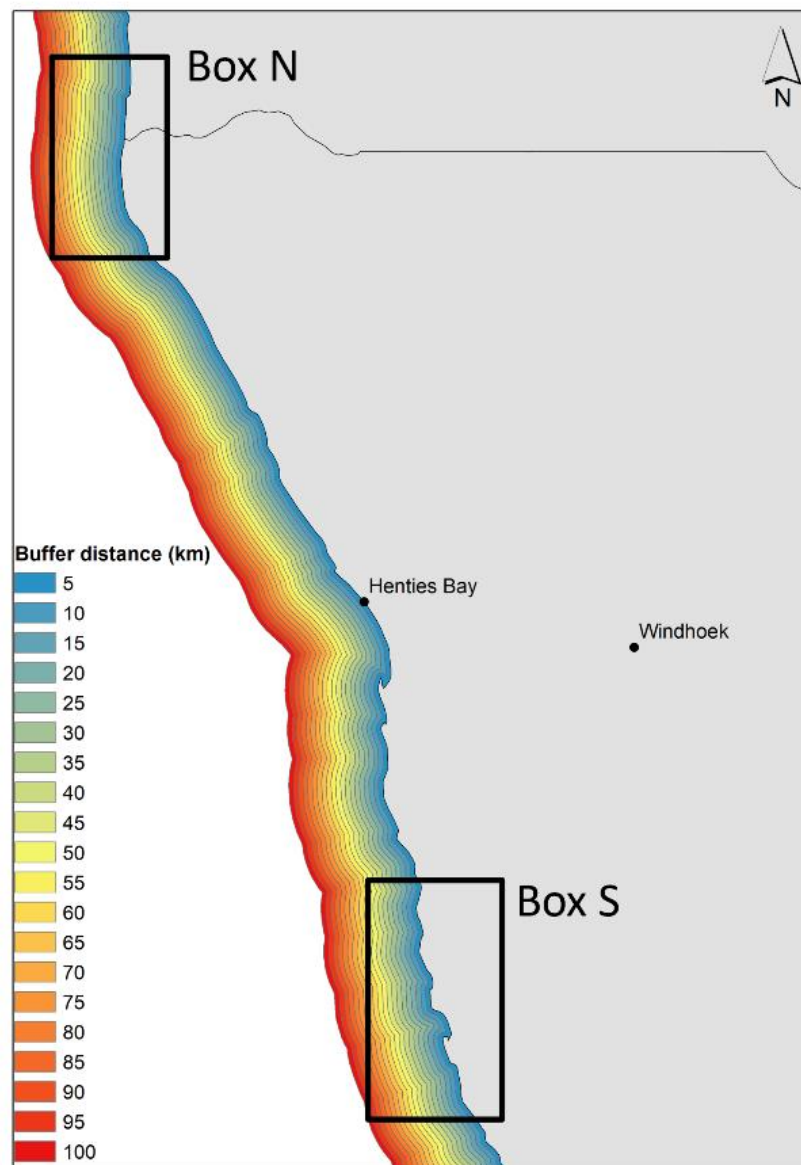


Figure 2-12: Map showing Boxes N and S to scale and the 5 km increment buffers.

2.4.4 Chlorophyll-a Data

A daily ESA OC-CCI version 6 dataset, available at oceancolour.org, was used to determine if the CCAM-modeled dust deposition aligns with the seasonal Chl-a cycle of the BUS. Unfortunately, this dataset does not span the entire CCAM modelling period. However, the dataset spans February 1997 to December 2013, which is more than appropriate to analyse the seasonal cycle of Chl-a in the Benguela current. The Chl-a dataset has a resolution of 4.6 km by 4.6 km and was only extracted for the identified hotspot regions. This dataset, too, was resampled with the nearest

neighbour to match the coarser resolution of the MERRA-2 dataset for comparison with it and CCAM's spatial distribution per pixel.

2.5 Investigate the response of phytoplankton to dust addition in a mesocosm experiment

2.5.1 Mesocosm Experiment: Phase 1 – Overview

The practicality of this approach was tested by conducting a baseline mesocosm study at the University of Namibia's Sam Nujoma campus between 15 and 29 July 2019. This initial experiment revealed areas for improvement for the second experiment, where an almost identical approach was followed. This section explains some of the methods that are not discussed in Section 2.3.2 but that were also followed. The results of this initial experiment are not reported. It was a new land-based mesocosm experimental setup and the first mesocosm experiment to investigate the response of BUS phytoplankton species to dust deposition from the Kuiseb riverbed. The campus is next to the Omaruru riverbed, southwest of the Etosha Pan and Huab riverbed and northwest of the Kuiseb and Tsauchab riverbeds.

In the first part of the experiment (15-21 July 2019), unfiltered seawater was pumped directly from the ocean into each of the five mesocosms. The second experiment (29 September to 12 October 2022) also involved filling the mesocosms with unfiltered seawater. Additionally, the water was spiked with phytoplankton species known to form blooms in the Benguela upwelling region. In this part of the experiment, a diatom (600 ml of *Chaetoceros*) and two dinoflagellates (150 ml of *Noctiluca* and 800 ml of *Scrippsiella*) were added to each mesocosm.

2.5.1.1 Production of dust amount to be added to each mesocosm

In this first phase, sediment collected from the Kuiseb ephemeral Namibia river was used (Figure 2-13). These soil sediment samples were obtained from 2 transects of an identical terrace and were, therefore, combined to make a composite sample to generate enough representative dust. The particle size distribution, mineralogy, chemical composition, and bioavailability of Fe of these sediment samples are available elsewhere (Kangueehi, 2017; von Holdt & Eckardt, 2018).

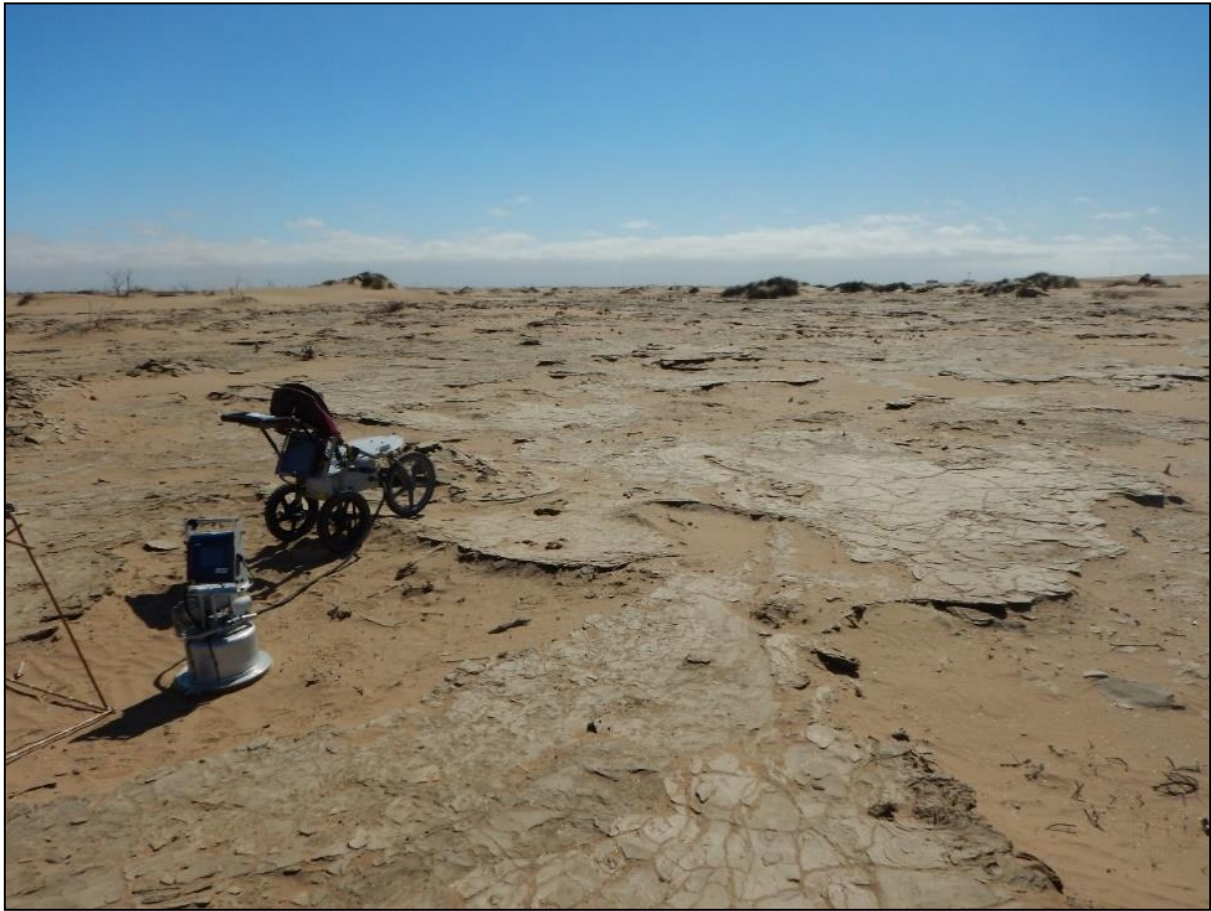


Figure 2-13: Soil sediment samples used during the first phase were collected from this ephemeral Kuiseb terrace (Photo courtesy of Johanna von Holdt).

Initially, it was thought that about 45g per mesocosm would be required per mesocosm (3x45g). However, closer to the commencement of the experiment, it was decided that 9g would be more appropriate for this study, given the depth and size of the mesocosms (Guieu, 2019). Only the $< 20 \mu\text{m}$ size fraction was considered in this mesocosm enriching experiment, as these particles tend to be transported over longer atmospheric distances. All materials used to handle the soil before the experiment were clean plastic or Nylon to avoid contamination, including Nylon mesh cloth used to sieve the soil to the appropriate size fraction. Additionally, these materials were cleaned with 10% HCl and rinsed thoroughly with deionized water. The $< 20 \mu\text{m}$ size fraction was produced following an intense dry-sieving process (about 18 hours on an electric shaker) using a $20 \mu\text{m}$ Nylon mesh cloth.

2.5.1.2 Experimental Setup

In this land-based mesocosm enriching experiment next to the Benguela upwelling region, the five selected mesocosms were made entirely of plastic. These comprised four 1000L mesocosms (238 cm in length, 122 cm in width, and 35 cm in height) and a larger one, about 5200L in volume (Figure 2-14). Three of the 1000 L mesocosms were used for experimental purposes, i.e., they were subject to dust addition; the other was used as a control. The larger mesocosm was left uncovered to investigate the effect of direct atmospheric input of aerosols.

Plastic pipes at the bottom of each mesocosm supplied a constant airflow that caused turbulence. This supply of air was essential to avoid stratification in the mesocosms. Continuous temperature measurements within the mesocosms were taken using three vacuum-sealed Thermochron temperature iButtons per mesocosm. Additionally, three temperature iButton sensors were installed outside. The sensors were programmed to measure temperature at 10-minute intervals. They were programmed in this way as they can only store 2048 temperature readings at 1–255-minute intervals – a 1-minute interval would provide readings for 1.4 days, while at a 255-minute interval, the user can retrieve a year's worth of readings. The sensor can measure temperature between -40°C and 85°C at a $\pm 0.5^{\circ}\text{C}$ resolution.



Figure 2-14: Experimental setup of mesocosms and aerosol samplers: To the far left at the back, the 5200L mesocosm. To the right is the control mesocosm, followed by the mesocosms subject to dust addition; in the front are the two E-samplers used to monitor aerosol concentrations during the experiments (Photo courtesy of Monray Belelie).

Hoods made of aluminium and covered with greenhouse plastic on the inside were fitted on the four smaller mesocosms (Figure 2-15) to avoid contamination from the outside of the system as much as possible, especially during an actual Namib desert dust event. Before the experiment, the hoods were cleaned with 10% hydrochloric (HCl) acid. The mesocosms were cleaned with HTH chlorine pool cleaning powder and rinsed with seawater. Each hood was fitted with an extraction fan at the back of the hood to suck air through the system to avoid a confinement effect within the system. At the front of each hood, a flow sensor was installed to measure the speed of air moving into the system along with polytetrafluoroethylene (PTFE) membrane filter cloth for filtration purposes (capable of retaining particles up to 2 μm). The hoods were also secured on the mesocosms using foam strips as best possible.

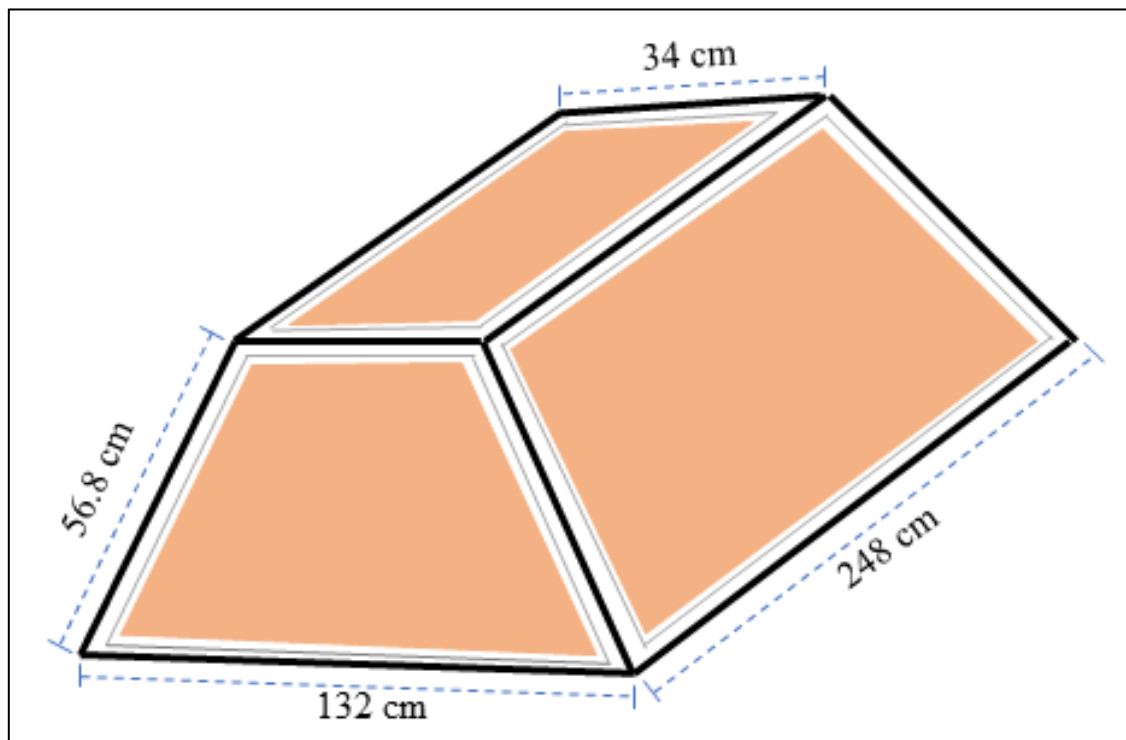


Figure 2-15: Aluminium (white) hood design covered with greenhouse plastic (orange).

2.5.1.3 Sampling Procedure

During this 1st phase, sampling was conducted with a peristaltic pump and Verderprene tubing at a depth of about 5 cm through a hole at the top of each mesocosm closed with duct tape between sampling sessions. Each mesocosm had its respective tube, and before each sampling session, the tubes were washed with 10% HCl and rinsed thoroughly with deionised water. The first sampling

session took place on 29 September at 09:20, and on 22 July at 19:00, the first sampling sessions took place for the respective experiments. This was done before dust addition to serve as initial conditions to be used as a reference. Following these initial sampling sessions, at about 16:45 and 20:00, dust was added to the three experimental mesocosms. Before each experiment, a mixture of 9g Kuiseb dust and 100 ml seawater was made. After that, sampling occurred daily at 08:00, 14:00, and 19:00. The parameters sampled were total iron (DFe) in 100 ml high-density polyethylene (HDPE) bottles, nutrients (PO_4^{3-} , total SiO_2 , NO_2^- , and NO_3^-) in 100 ml HDPE bottles, alkalinity in 250 ml glass bottles, salinity in 200 ml amber glass bottles, and 500 ml for Chl-a.

Samples for DFe were first filtered through a 0.45 μm syringe filter followed by immediate acidification with 200 μL of 65% HNO_3 (impurities: $\text{Cl} = 0.0001\%$; $\text{SO}_4 = 0.0002\%$; $\text{Fe} = 0.0002\%$; $\text{As} = 0.000004\%$; and $\text{Pb} = 0.000005\%$) under laminar flow and stored frozen until analysis. The nutrient samples were also filtered with a 0.45 μm syringe filter and immediately stored frozen. Samples for alkalinity were dispensed with 100 μL HgCl (10 mg/ℓ) and kept in the dark until analysis (Eco-Analytica). The caps of the salinity samples were adequately secured on their bottles with parafilm and stored in the dark until analysis (Eco-Analytica). About 300 ml of the Chl-a samples were filtered through 47 GF/F filters before being frozen in a freezer for the experiments. After that, the samples were stored frozen in liquid N until analysis. 100 ml of the remaining 200 ml Chl-a samples were stored in brown 100 ml HDPE bottles and preserved with Lugol's solution to count cells. Unfortunately, these cell counts could not be made in time.

2.5.2 Mesocosm Experiment: Phase 2 – Overview

A second mesocosm study was conducted at the Sam Nujoma campus between 29 September and 12 October 2022 to improve on the first phase experiment. The mesocosms were filled with seawater collected less than 2 m deep during high tide, 5-10 m away from the low water mark near the shore. The seawater was filtered using a system shown in Figure 2-16, which consisted of 4 inline filters ranging from a coarse 25 μm to a fine 1 μm filter. On September 27 at 14:00, the mesocosms were filled with filtered seawater mixed with granular pool chlorine and left until the following day at 09:00 to remove any residues from previous experiments. The mesocosms were then rinsed twice and cleaned with a pressure cleaner. Finally, each mesocosm was filled with filtered seawater and seeded with 2 L of *Chaetoceros*, 1 L of *Pavlova*, and 1 L of *Tetraselmis* (cell densities are reported in **Section 7.4**) at 16:30 on September 28, allowing the phytoplankton species to mix with the seawater. These reflect different species where *Chaetoceros* are diatoms,

Pavlova is haptophytes, and *Tetraselmis* are Chlorodendrales. Most of the procedure followed during this phase is identical to the first. Therefore, only deviations will be discussed in detail.



Figure 2-16: Filtration system through which seawater was filtered before being pumped into the mesocosms, from right to left: 25 μm , 10 μm , 5 μm and 1 μm (Photo courtesy of Monray Belelie).

2.5.2.1 Production of dust amount to be added to each mesocosm

This study supplied each mesocosm with 9 g of dust from the Kuseb ephemeral river delta, considering the mesocosms' depth and size (1000 L). The particle size distribution, mineralogy, chemical composition, and bioavailability of Fe in the dust samples are described elsewhere (von Holdt & Eckardt, 2018). To generate sufficient representative dust, soil sediment samples were collected from two transects of an identical terrace and combined to make a composite sample. These are the two sites in the northern arm's delta terraces, identified as one of the most active dust sources in the river and the Namib (von Holdt et al., 2017). However, the original composite sample did not yield enough of the $<20 \mu\text{m}$ size fraction. Therefore, the combined sample was crushed with a granite pestle and mortar, and the $<20 \mu\text{m}$ size fraction was produced by intense dry-sieving on a vibrating column using three Nylon mesh sheets (20, 40 and $100 \mu\text{m}$) for 12 to 36 hours. It has been suggested that this laboratory crushing and sieving of the soil mimics the effects of mechanical wind processes, such as saltation (Guieu et al., 2010). To avoid contamination, all materials used to handle the soil before the experiment were clean plastic or Nylon, cleaned with 10% HCl

and rinsed thoroughly with deionized water. The meshes were cleaned regularly with a brush to prevent clogging.

2.5.2.2 Experimental Setup

The experimental setup consisted of four mesocosms made entirely of plastic (Figure 2-17). One was used as a control mesocosm (referred to as CM), and the other three as the experimental group subject to dust seeding (referred to as DG (Dust Group): mesocosm experiment EX1, mesocosm experiment EX2, and mesocosm experiment EX3). Plastic pipes at the bottom of each mesocosm supplied a constant flow of air that caused turbulence. This supply of air was essential to avoid stratification in the mesocosms. Continuous temperature measurements were made within each mesocosm with three Thermochron temperature iButtons sensors, vacuum-sealed in plastic bags. One temperature iButton was also installed on the outside of each mesocosm. Like in the 1st phase, the sensors were programmed to measure temperature at 10-minute intervals to provide adequate data spanning the 14-day experiment timeframe. The hoods used to cover the mesocosms were cleaned with 10% HCl acid and rinsed with a pressure cleaner.



Figure 2-17: Experimental setup of mesocosms during the 2nd phase experiment. To the far left is the control mesocosm (CM). Right next to it are the three experimental mesocosms subject to dust addition (DG) (Photo courtesy of Monray Belelie).

2.5.2.3 Sampling Procedure

Sampling was conducted with a peristaltic pump and Verderprene tubing at a depth of about 5 cm through a hole at the top of each mesocosm. This time, the tubing was not removed between sampling sessions to avoid opening the mesocosms as much as possible. The sampling end of the tubing was covered with duct tape that was only removed before each sampling session. Each mesocosm had its tube, and before sampling commenced, the tubes were washed with 10% HCl and rinsed three times with deionized water.

After allowing the phytoplankton to mix with the seawater overnight, the initial conditions in the mesocosms were sampled the next day on 29 September at 09:20. Dust was added to the experimental mesocosms at about 11:00 on the same day. This mixture of 9g Kuiseb dust and 100 ml seawater was made before the experiment. After that, sampling occurred daily at 09:00. The parameters sampled were total iron (DFe) in 100 ml HDPE bottles, nutrients (PO_4^{3-} , total SiO_2 , NO_2^- , and NO_3^-) in 100 ml HDPE bottles and Chl-a in 500 ml glass bottles. This time, seawater was also sampled in a 250 ml glass bottle to measure pH, dissolved oxygen (DO), conductivity, salinity, and total dissolved solids (TDS) with a multimeter directly after sampling.

Samples for total Fe were filtered through a 0.22 μm Millex-GS sterile syringe filter followed by immediate acidification with 200 μL of 65% HNO_3 (impurities: Cl = 0.0001%; SO_4 = 0.0002%; Fe = 0.0002%; As = 0.000004%; and Pb = 0.000005%) under laminar flow and stored frozen until analysis (Figure 2-18). The nutrient samples were also filtered with a 0.22 μm syringe filter and immediately stored frozen. This is now the recommended syringe filter size, as the 0.45 μm filter does not remove all phytoplankton (Becker et al., 2020). The certificate of analysis of the nutrients is presented in **Appendix C**. Total Fe and total Si were analysed using an aliquot of a homogenised sample that was acid-digested before analysis using inductively coupled plasma optical emission spectroscopy (ICP-OES) (EPA, 1996). NO_2^- and PO_4^{3-} were analysed using a portion of a homogenised sample that was treated with specific reagents before a timed incubation and colour development in Gallery Plus Discrete Analyser (American Public Health Association, 1998). NO_3^- was determined by calculating the difference between combined nitrate/nitrite content and nitrite content.

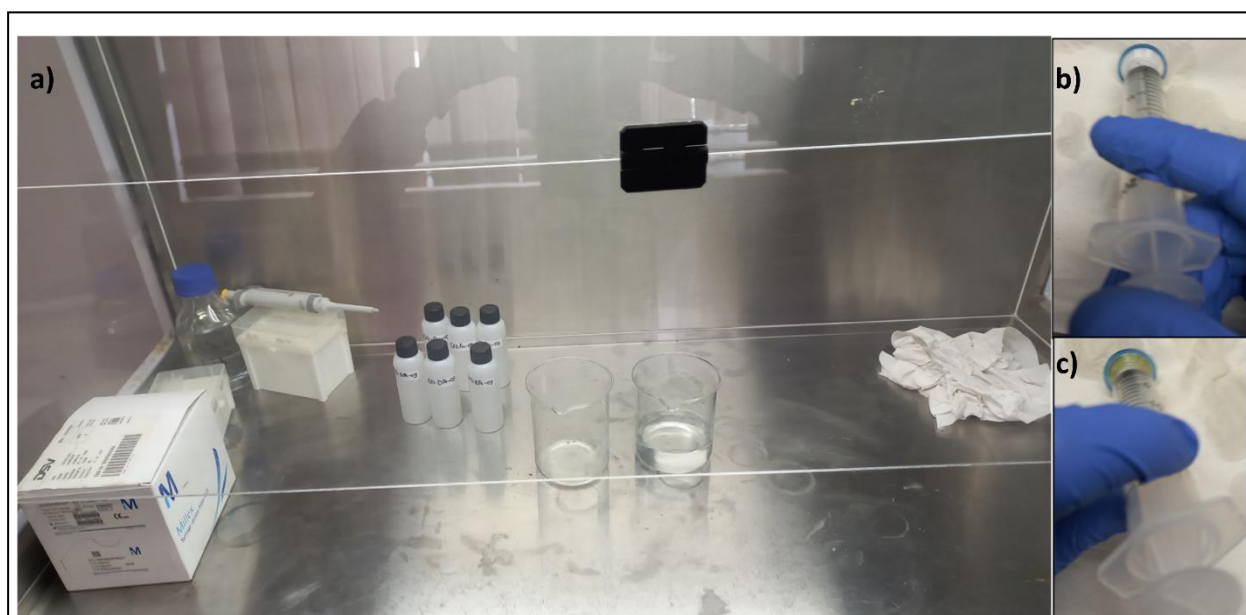


Figure 2-18: a) Equipment used for the filtration and acidification of DFe and nutrient samples after sampling; b) shows the syringe filter before filtration while c) shows the filter after.

150 ml of the 500 ml Chl-a samples were filtered through 47 mm Munktell MGC filters (nominal pore retention size of 1.2 μm) immediately after sampling. Next, the chlorophyll pigment was extracted from the filters in 90% acetone (10 ml) and stored in a freezer for between 12 and 24 hours. Finally, the chlorophyll raw fluorescence was measured with a Turner Trilogy fluorometer. On the final sampling day, additional samples were taken to test the homogeneity of the Chl-a in the mesocosms. These samples were taken at the front (sampling position used during both phases), middle and back of the mesocosms – for each of the three positions, samples were taken below the surface and at the bottom of each mesocosm. 100 ml of the remaining 350 ml Chl-a samples were stored in brown 100 ml HDPE bottles and preserved with Lugol's solution to count cells. After being kept in the dark for about a week, cells were counted under a microscope with a Neubauer haemocytometer (0.100 mm depth on a 0.0025 grid) by dispensing 1 ml of the sample.

As mentioned, the samples stored in the 250 ml glass bottles were analysed for pH, DO, conductivity, salinity, and TDS with a HACH HQ 40d multimeter. Three probes were used: a pH probe to measure pH, a DO probe to measure DO (mg/L), and a conductivity probe to measure conductivity ($\mu\text{S}/\text{cm}$), salinity (ppt), and TDS (mg/L). The pH probe was calibrated with pH4, pH7, and pH10 buffer solutions before each measurement session. The DO probe is calibrated annually at

the beginning of the year. The conductivity probe was calibrated before each measurement session with a NaCl standard solution (491 ± 2.5 mg/L; 1000 ± 10 μ S/cm).

Light intensity measurements within each mesocosm were taken daily at noon with a CRUMP Quantum/Radiometer/Photometer (Figure 2-19). For this purpose, the extraction fans at the front of the mesocosms (**Section 2.2.2**) were removed for about 1 minute at a time. The instrument sensor was fitted at the front of a 2 m long aluminium beam to measure the light intensity at the system's front, middle, and back. A Bosch level was also fitted at the back of the beam to ensure the sensor was level when taking measurements inside.

2.5.3 Statistical Analysis

The results' statistical significance was evaluated using a Levene test to check for equal variances between the CM and DG. A student's t-test was used for data of equal variance, and a Welch's t-test for data of unequal variances ($p < 0.05$). For some samples, the total Fe and PO_4^{3-} measurements were below the detection limits of 2.42 nM and 1.05 nM, respectively. In the CM, 11 out of 14 samples had total Fe below the detection limit, and one sample had PO_4^{3-} below the detection limit. In the case of DG, 13 samples had total Fe below the detection limit (EX1: $n = 2$; EX2: $n = 6$; and EX3: $n = 5$), and two samples had PO_4^{3-} below the detection limit (EX3 = 2). Twelve of the thirteen NO_3^- samples were below the detection limit of 4.03 nM. The fourteenth sample reached a concentration of 14.51 nM, most likely due to contamination. Regrettably, the NO_2^- concentrations were below the detection limit of 1.09 nM for all samples. Therefore, the NO_3^- and NO_2^- results were not used in subsequent statistical analyses. All statistical analyses were conducted using R for Windows and Python.



Figure 2-19: The aluminium structure that measured light intensity inside the mesocosms: a) Bosch level fitted at the back of the aluminium; b) CRUMP Quantum/Radiometer/Photometer. c) Light intensity sensor.

CHAPTER 3

The following chapter presents the results for Objective I: ‘*Analyse Particulate Matter Concentrations at Henties Bay*’. The Namibian coast has garnered global attention for aerosol research. The significance of this region to the worldwide radiation budget is attributed to the semi-permanent stratocumulus cloud along the coastline. The properties of aerosol particles, such as their ability to scatter or absorb radiation, can directly affect the lifespan of clouds by altering their characteristics. This chapter characterizes high and low-concentration aerosols and the meteorological conditions conducive to their occurrence. Also presented is a trajectory analysis to trace the transport of air masses during high and low episodes.

PARTICULATE MATTER EPISODES AT HENTIES BAY

3.1 Background

Ambient particulate matter (PM) is a crucial gauge for air quality, with implications for haze formation and climate change (Chen & Hoek, 2020; Liu et al., 2018). PM is commonly divided by size into PM_{2.5} (aerosols with an aerodynamic diameter of 2.5 µm or less) and PM₁₀ (aerosols with an aerodynamic diameter of 10 µm or less) (Kastury et al., 2017; Kastury et al., 2018). The horizontal and vertical distribution, as well as the physicochemical attributes of PM particles in the atmosphere, exhibit variability due to disparate source distribution and their brief lifespan, typically less than ten days for particles <1 µm and even shorter for particles >1 µm (Klopper et al., 2020).

PM emanates from many primary sources, encompassing both natural and anthropogenic origins. Additionally, secondary particle formation occurs through photochemical processes involving primary precursors (Dai et al., 2019; Zalakeviciute et al., 2020; Khan et al., 2021). Among other sources, biomass burning, road traffic, sea salt, and dust contribute to PM (Squizzato et al., 2017; Zalakeviciute et al., 2020; Psistaki et al., 2023). Consequently, PM concentration and composition at a specific location hinge on factors such as regional background and meteorological conditions (Yang et al., 2020; Zalakeviciute et al., 2020).

Of particular interest for PM studies and climate impact is the Namibian coast, where recent research indicates predominant PM inputs from sea salt (75%) and mineral dust (16%) (Klopper et al., 2020). Local wind stress significantly influences the production of primary marine aerosols, primarily consisting of pure sea salt, with marine particles ranging from < 20 µm in diameter and annual production estimates ranging from 2000 to 10000 T/yr (de Leeuw et al., 2011; Fuzzi et al., 2015). Ultra-fine marine particles (<1 µm) may undergo long-range atmospheric transport, while larger particles tend to deposit near their source regions. The adjacent cold BUS and a semi-permanent stratocumulus cloud layer shape the arid region's meteorology. The BUS is characterized by high marine biogenic productivity, emitting sulphur-containing compounds like dimethyl sulphide and hydrogen sulphide into the atmosphere (Klopper et al., 2020). These compounds may undergo oxidation in the atmosphere, leading to the formation of secondary particles that contribute to cloud droplet formation in the stratocumulus cloud (Andreae et al., 1995).

Dust, a prominent PM component, primarily originates from anthropogenically influenced land surfaces, desert regions, and global ephemeral dry lakes or riverbeds (Mahowald et al., 2009). Fluvial dust sources, especially dry ephemeral lakes such as Makgadikgadi and Etosha pans in Southern Africa, play a significant role in global aeolian dust transport to the ocean and have been proposed as substantial contributors to ocean fertilisation (Piketh et al., 2000; Prospero et al., 2002). Key Southern African dust sources, including the Kuiseb, Huab, Tsauchab, and Omaruru ephemeral riverbeds in Namibia, may also contribute substantially to phytoplankton fertilisation in the adjacent Benguela (Jacobson et al., 2000; Jacobson & Jacobson, 2013; Dansie et al., 2017). Remote sensing analyses have highlighted these riverbeds as notable sources of dust plumes transported to the southern Atlantic (Eckardt & Kuring, 2005; Vickery et al., 2013).

The Henties Bay Aerosol Observatory (HBAO) is instrumental in continually monitoring aerosol measurements, including chemical composition and concentrations (Klopper et al., 2020). This study builds upon previous HBAO research by identifying coastal episodes characterized by high and low PM concentrations and elucidating the weather conditions conducive to these episodes.

3.2 Daily PM Concentrations

Figure 3-1 shows a time series of the 15-minute $PM_{2.5}$ and PM_{10} concentrations between 15 and 29 July 2019. The figure also highlights days when HAEs were observed. During the sampling period, the $PM_{2.5}$ concentrations ranged from 1–105 $\mu g/m^3$ with a mean value of $17 \pm 14 \mu g/m^3$. On the other hand, PM_{10} concentrations ranged from 1–239 $\mu g/m^3$ with a mean value of $41 \pm 35 \mu g/m^3$. According to the ‘dust event’ criteria, 17, 18, 19, 20, 24, and 25 July were classified as HAEs and the rest as LAEs. During the HAEs, the mean $PM_{2.5}$ concentration was $24 \pm 18 \mu g/m^3$, and the mean PM_{10} concentration was $57 \pm 44 \mu g/m^3$. In contrast, during LAEs, the mean $PM_{2.5}$ and PM_{10} concentrations were $12 \pm 7 \mu g/m^3$ and $28 \pm 17 \mu g/m^3$, respectively. The daily windrose plots in Figure 3-2 provide additional insight into the meteorological factors that may have affected the observed differences in $PM_{2.5}$ and PM_{10} concentrations during HAEs and LAEs. On days with HAEs, the wind rose plots show predominant southerly and southwesterly winds at speeds exceeding, on most days, 6 m/s. These speeds were the highest during the sampling period, which agrees with Klopper et al. (2020). Given the location of the study site, of course, the dominant PM source located upwind in those directions is the adjacent ocean. On 20 and 25 July, however, winds exceeding 4 m/s from the north and northeast suggested a second potential emission source. This is expected as the study by Klopper et al. (2020) showed that aerosol concentrations at the site are

influenced mainly by sea salt (74.7%), followed by mineral dust (15.7%), ammonium (6.1%), fugitive dust sources (2.6%), and emissions from industry (0.9%). However, on 16 and 22 July, the predominant wind directions were also southwesterly and westerly during an LAE. This suggests other factors may have influenced the observed PM concentrations and subsequent HAEs and LAEs.

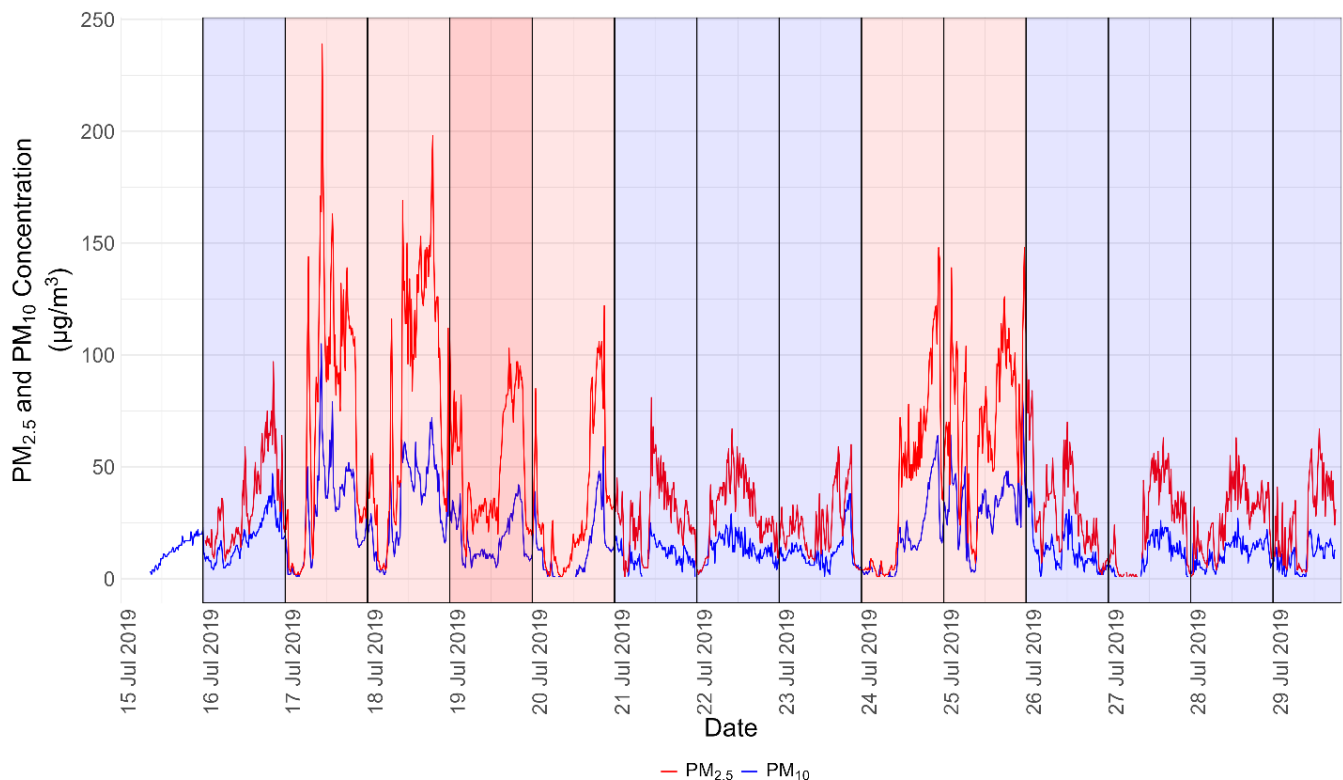


Figure 3-1: Time series showing the observed PM_{2.5} (blue) and PM₁₀ (red) concentrations (µg/m³) during the sampling period. The red boxes indicate the days HAEs were identified, while the blue boxes denote the LAEs.

For example, PM₁₀ mainly comprises particles directly emitted into the atmosphere (Wong et al., 2022). However, some of its constituents may also form through secondary processes like nitric acid, produced by the oxidation of nitrogen oxides and reacts with pre-existing alkaline aerosols like sea salt and dust particles (Bian et al., 2014). Another factor might be present at the synoptic scale, where synoptic meteorology has been shown to influence the land and sea breezes at the site (Klopper et al., 2020). Polar plots were created to examine and display the potential sources of

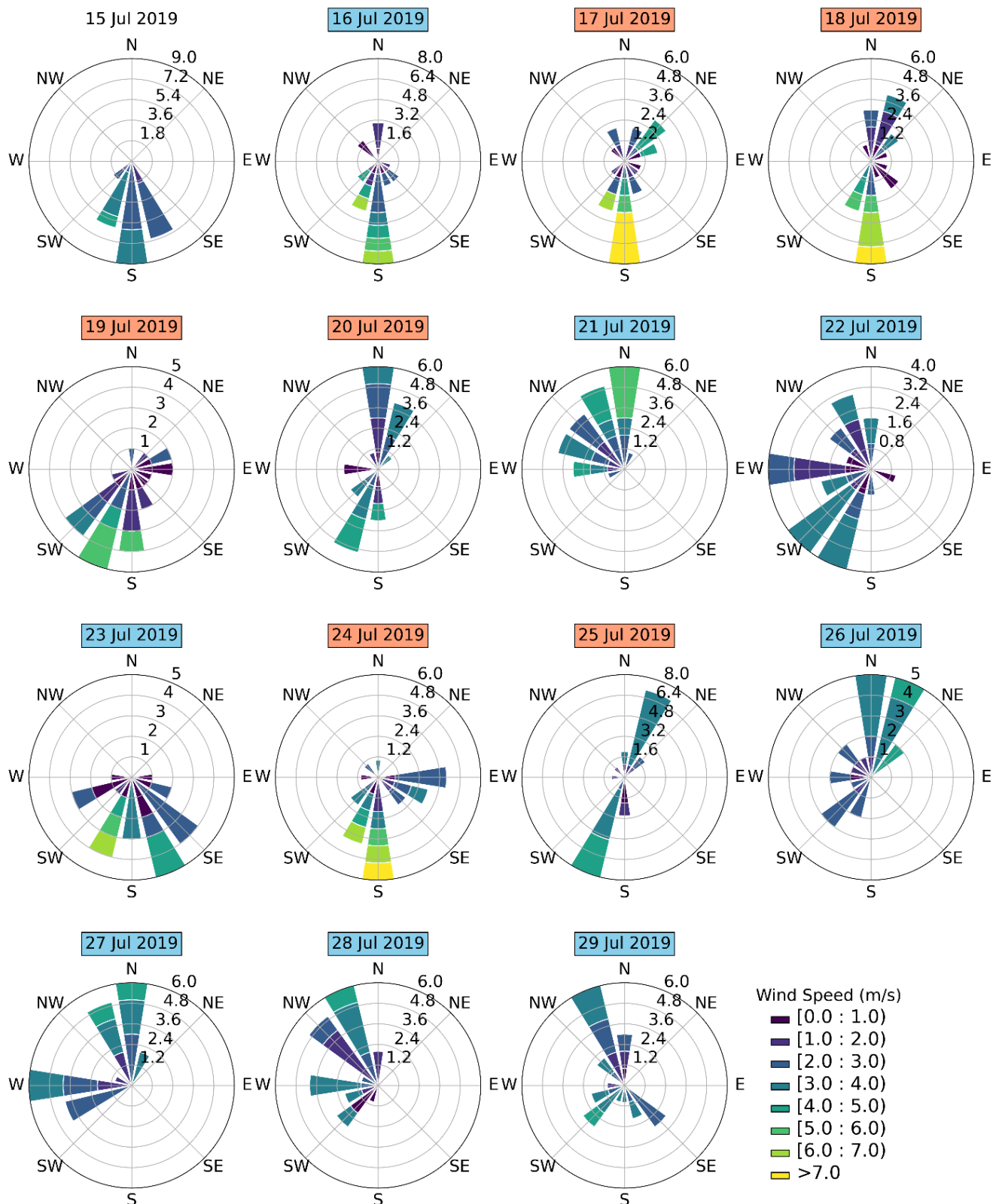


Figure 3-2: The prevailing daily wind speed and direction at the Sam Nujoma campus during the sampling period. The dates highlighted in red represent the days of HAE events, while LAEs are highlighted in blue.

PM_{2.5} and PM₁₀ emissions during HAEs and LAEs (Figure 3-3). These plots illustrate the variations in PM concentrations based on the wind speeds and directions using polar coordinates, indicating emissions that may affect the receptor site. In addition to the expected dominant contribution of marine sources during HAEs, there appear to be potential continental sources located to the north-northwest and north-northeast of the site. **Section 2.1.1** Figure 2-1 shows that the Huab riverbed is a likely primary source in that direction.

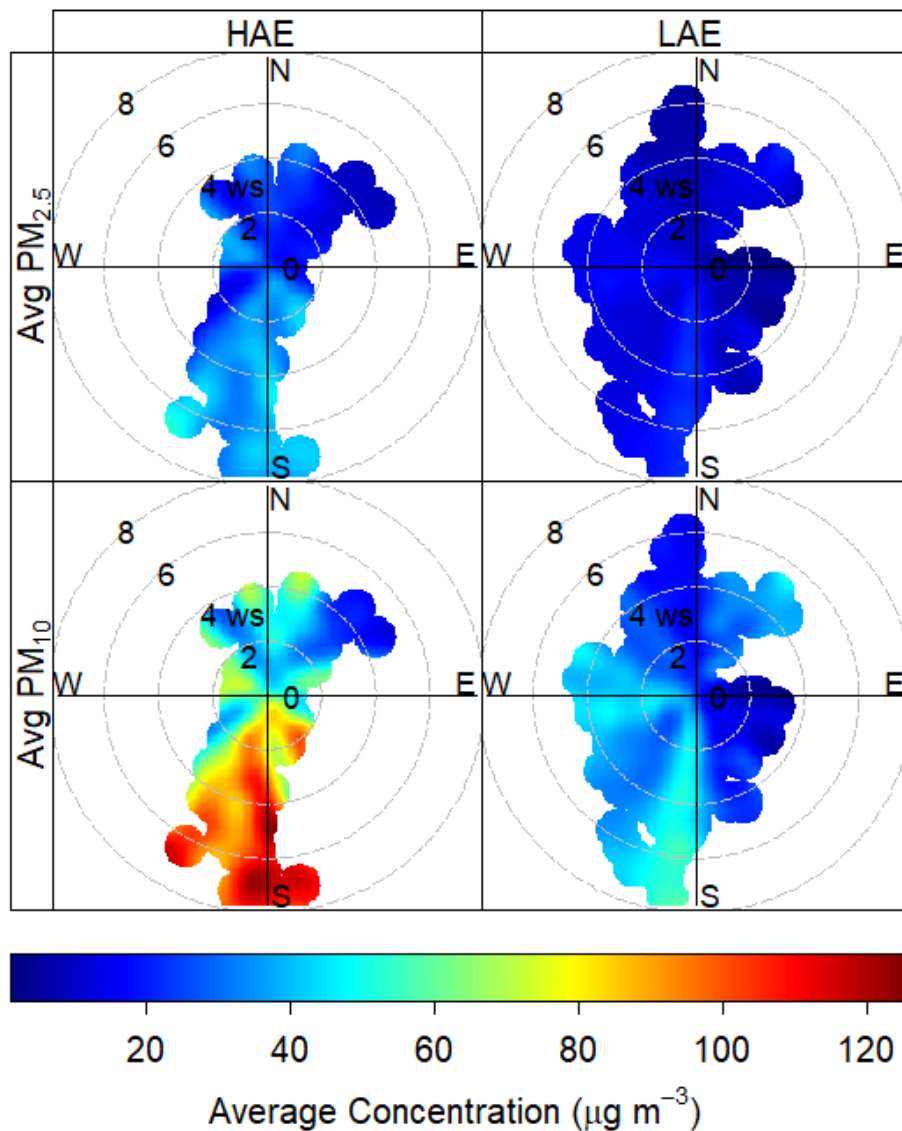


Figure 3-3: Polar plots illustrating potential PM_{2.5} and PM₁₀ emission sources affecting observed concentrations at Henties Bay.

There is also a possible source to the south-southeast and southeast of the site, which may be contributions from the Kuiseb riverbed. There is also a contribution around and to the east of the site, which is most likely the adjacent Omaruru riverbed. Perhaps worth noting is that a recent study at a Greek coastal site found Fe concentrations to be much higher in PM₁₀ than in PM_{2.5}, but only if the source is natural (Chatoutsidou & Lazaridis, 2022). As Klopper et al. (2020) show, the leading sources at the HBAO are almost entirely natural and unaffected by industrial contributions. Considering the proximity of the HBAO to several dust sources surrounding it, it's reasonable to assume that the concentration of iron Fe in PM₁₀ particles at HBAO is significantly higher.

In contrast, the Greek site is primarily affected by dust from the Saharan desert but is much further away. PM₁₀ particles, being larger, tend to settle out of the atmosphere near their source. Therefore, it's likely that a substantial amount of PM₁₀ remains in the atmosphere at HBAO, while a more significant portion may be removed from the atmosphere before reaching the more distant Greek site. However, linking these results to Fe in this context is complex, given the factors that may play a role, such as source proximity and mineralogy.

3.3 Hourly PM Concentrations

The boxplots in Figure 3-4 show the hourly variation in PM_{2.5} and PM₁₀ concentrations over the 2-week sampling period. The plots for both fractions show two clear periods in the daily concentrations. This indicates that the peaks observed in the morning and the beginning of the evening between the two studies are from different sources. The mean PM concentrations were generally lower during the early morning hours (01:00–09:00) and then increased throughout the day, reaching their highest values during the late afternoon and evening hours (16:00–21:00). The maxima and minima also show an extensive range which indicates that there is much variability in the data. Figure 3-5 shows the predominant hourly wind directions with a clearly defined and strong day-night signal. There is a distinct break in the wind direction at around 10:00 and 23:00. From 01:00 to 10:00, the wind direction varied between West-Northwest (WNW) and East (E). Later, from 13:00 to 23:00, it shifted and blew from West-Southwest (WSW) to East-Southeast (ESE). This agrees with the observation by Klopper et al. (2020) at the site in July 2016. They found that these day and night wind patterns are associated with sea and land breezes. Therefore, the high PM concentration from 09:00 to 21:00 may be explained by the dominant sea breezes from the south and southwest during this time. This, in other words, signifies the importance of marine sources to HAE in the region.

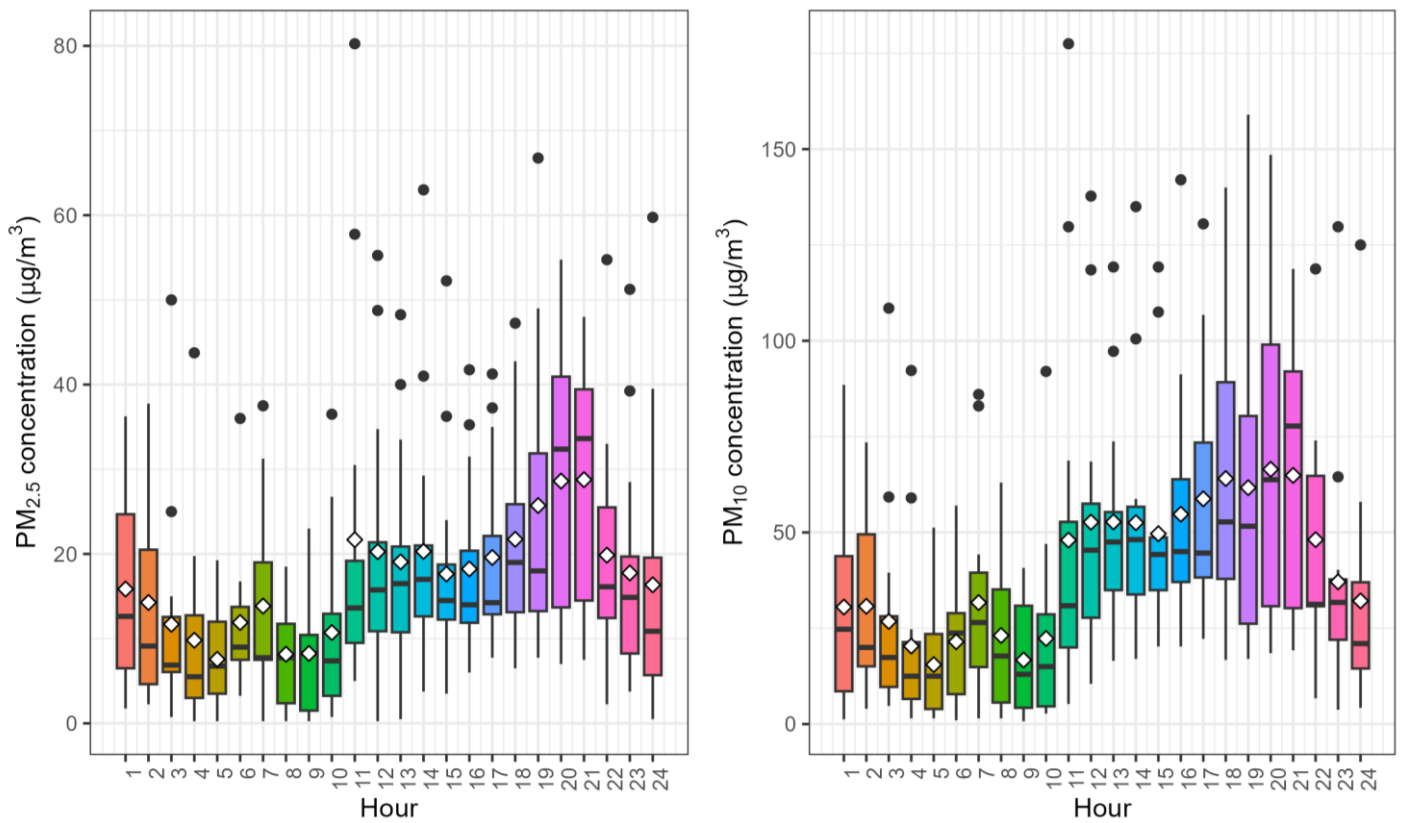


Figure 3-4: Diurnal variation in PM_{2.5} (left) and PM₁₀ (right) concentration (µg/m³) observed during the sampling period. The white dots indicate the mean, while the black dots indicate outliers. Please note that the graphs are on different y-axis scales.

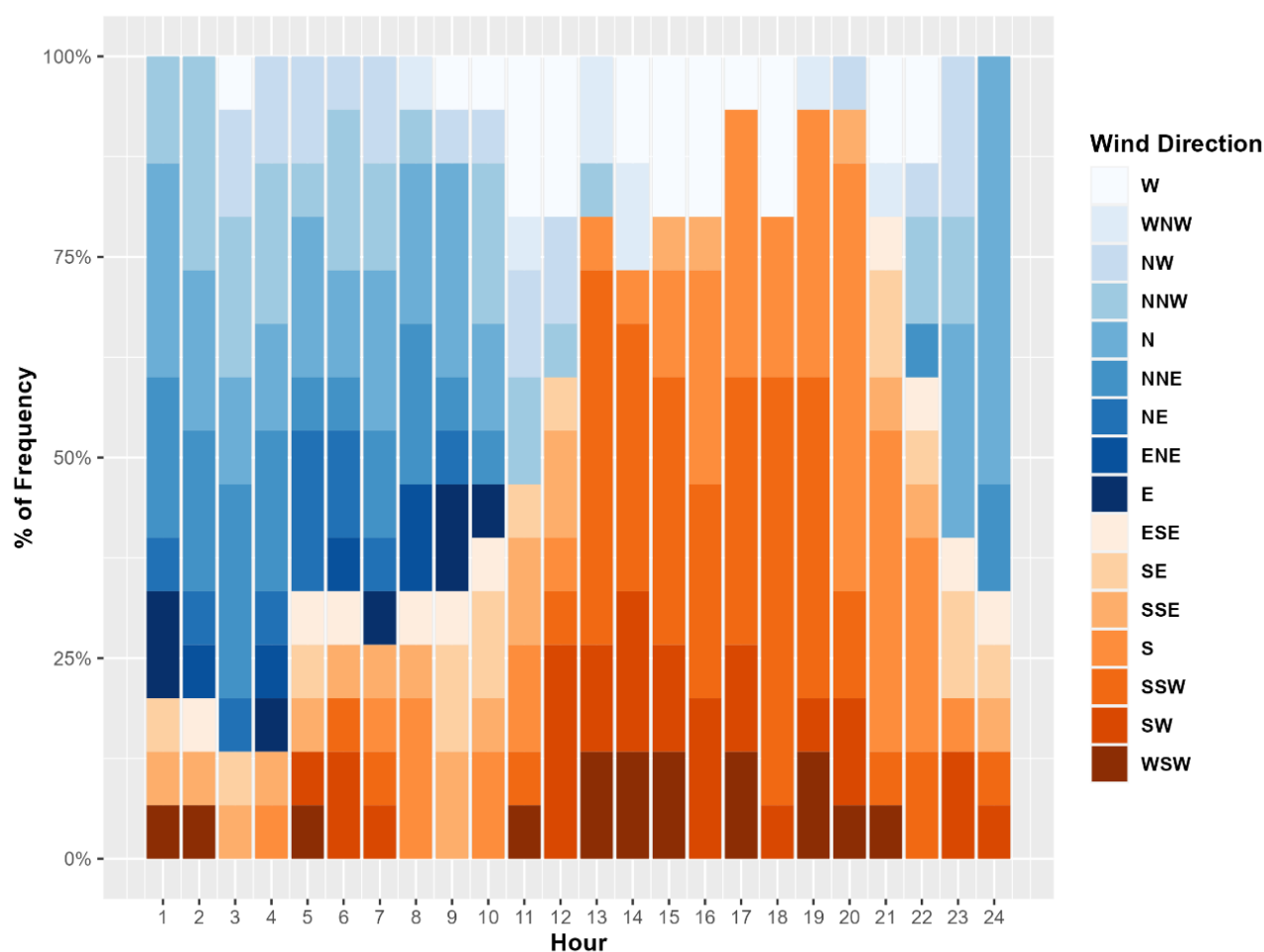


Figure 3-5: Stacked bar graph illustrating the predominant wind directions per hour.

3.4 Back-trajectories and Synoptic Meteorology

Figure 3-6 illustrates the 72-hour back-trajectories computed for the sampling period from 15 to 29 July. During most of the study period, air masses were predominantly transported from the interior. During HAEs, air masses originated from the northeastern interior, with some from the adjacent ocean. During LAEs, the transport was more varied – on some days, air masses were transported from the sea and others from the continent. The lowest PM concentrations were observed between 23-24 July (LAE); during these days, the dominant transport pathway was from the adjacent ocean. The synoptic conditions during the sampling period are summarised in Table 3-1. Generally, HAEs occurred under west coast trough conditions, requiring a strong pressure gradient and enhanced easterly winds from the central regions. The sources of the aerosols might be as far as southern Zambia, the Caprivi, and dry western Namibian regions, as indicated by the

back trajectory. These conditions were also present on 25 and 26 July, with transport from as far as central Zimbabwe. Transport during July may coincide with large veld fires over the region, which can explain why circulation with an inland origin is associated with high aerosol concentrations.

Table 3-1: Summary of the synoptic meteorology during the study period. The days on which there were HAEs are highlighted in yellow.

Date	Episode	Synoptic Condition	Transport Origin
15-16 July	LAE	West coast trough, easterly transport	No long-range transport from further east
17-19 July	HAE	West coast trough, strong pressure gradient	Transport of air from central South Africa, Zimbabwe, Zambia
20-21 July	LAE	West coast trough, strong pressure gradient	Transport of air from central South Africa, Zimbabwe, Zambia
22 July	LAE	High pressure directly over the study site	Very little air transport from the subcontinent
23 July	LAE	Onshore flow along South-Atlantic High	Dominant circulation is driven onshore
24-25 July	HAE	West coast trough, strong pressure gradient	Transport of air from central South Africa, Zimbabwe, Zambia
26 July	LAE	West coast trough, strong pressure gradient	Transport of air from central South Africa, Zimbabwe, Zambia
27-28 July	LAE	Stable weather, no pressure gradient	No pressure gradient near Henties Bay, stable weather

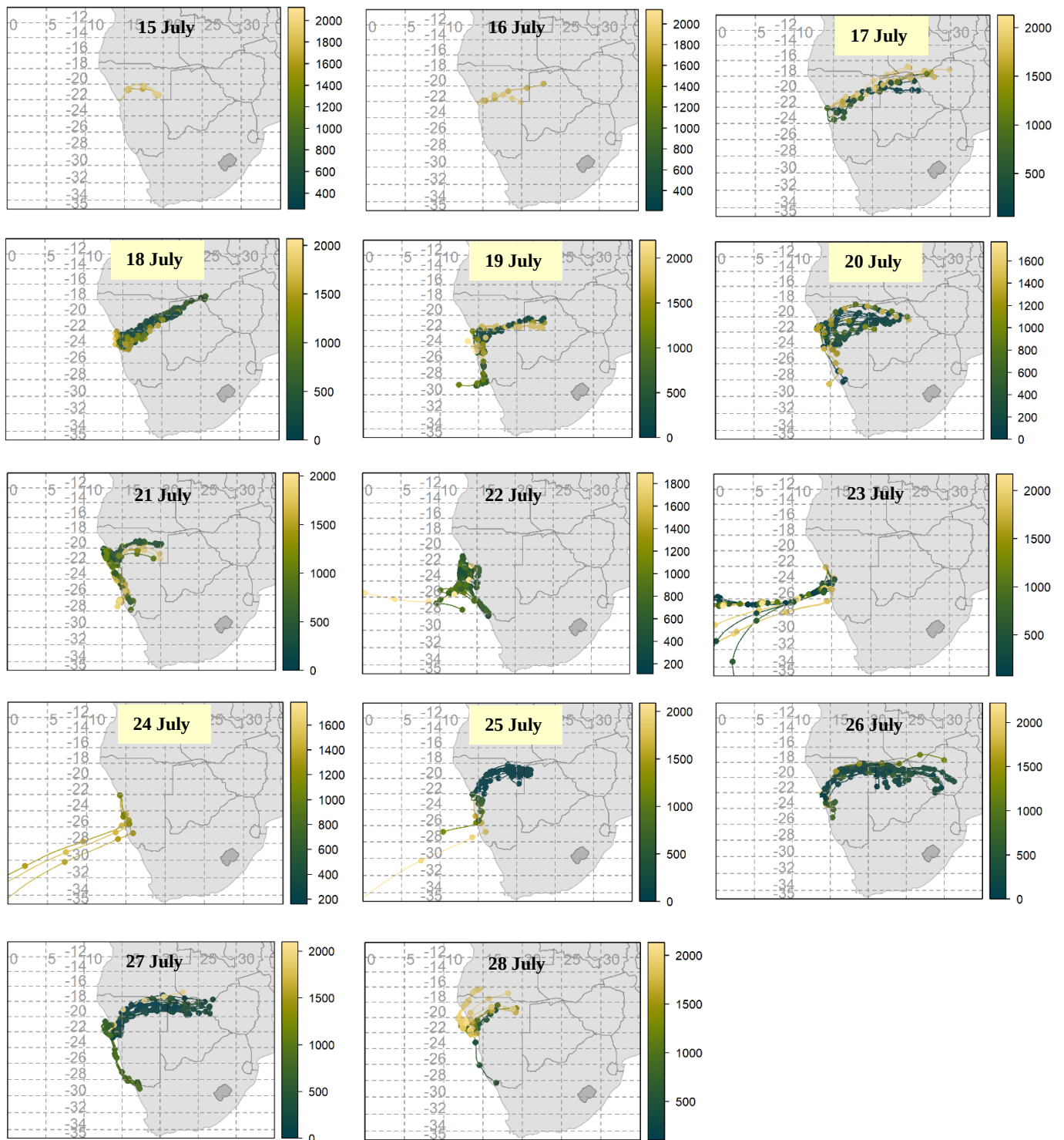


Figure 3-6: Back-trajectories of 72-hours during 15-28 July 2019 (the different colours indicate the different computed trajectories). The scale to the right indicates the height above ground level (m). The dates on which there were HAEs are highlighted in yellow.

3.5 Chapter Conclusions

The objective of the results portrayed and discussed in this chapter was to analyse PM concentrations at Henties Bay by:

- Identifying episodes of high and low particulate matter concentrations;
 - Identifying the dominant transport patterns of particulate matter and coupling their contributions with air mass back-trajectories; and
 - Identifying the atmospheric conditions conducive to high and low particulate matter episodes.
-

The following inferences can be made:

This study presents a detailed analysis of daily $\text{PM}_{2.5}$ and PM_{10} concentrations between 15 and 29 July 2019 at Henties Bay, Namibia. The results show that during HAEs, the mean $\text{PM}_{2.5}$ concentration was $28 \pm 18 \mu\text{g}/\text{m}^3$, and the mean PM_{10} concentration was $68 \pm 44 \mu\text{g}/\text{m}^3$. During LAEs, the mean $\text{PM}_{2.5}$ and PM_{10} concentrations were $13 \pm 9 \mu\text{g}/\text{m}^3$ and $30 \pm 23 \mu\text{g}/\text{m}^3$, respectively. During HAEs, the predominant southerly and southwesterly winds are from the adjacent ocean. The results also show three other sources of PM emissions to the north and southeast of the site, most likely the Namibian ephemeral river valleys. Hourly, the highest PM concentrations were observed during the late afternoon and evening hours (16:00–21:00). The dominant sea breezes from the south and southwest may explain these concentrations.

During most of the study period, air masses originated from the interior. During high aerosol episodes (HAEs), air masses were predominantly transported from the northeastern interior, with some from the adjacent ocean. In contrast, during low aerosol episodes (LAEs), the transport was more varied, with air masses transported from the ocean and the continent. HAEs generally occurred under west coast trough conditions, requiring a strong pressure gradient and enhanced easterly winds from the central regions. The sources of aerosols might be as far as southern Zambia, the Caprivi, and dry western Namibian regions, as indicated by the back-trajectories. The occurrence of winter veld fires may explain why circulation with an inland origin is associated with HAEs.

CHAPTER 4

The following chapter presents the results for Objective II: *‘Identify preliminarily new southern African dust sources’*. As discussed, dust transport is the primary pathway of essential nutrients to the ocean. Following a dust emission event in July 2023 that was visible on NASA satellite images, a region in Angola was identified to have emitted dust like the extensively classified Namibian emission sources. This chapter presents the locations of these new potential southern African dust sources. The meteorological conditions that were present during the emission are also shown.

ANGOLAN DUST SOURCES

4.1 Background

Four primary sources of dust emissions exist in southern Africa. Prior investigations have recognized Etosha Pan in Namibia and the Makgadikgadi Depression in Botswana as the principal contributors to dust in the region (Bryant, 2003; Washington et al., 2003; Prospero et al., 2002; Li et al., 2008; Bhattachan & D’Odorico, 2014). The emphasis on these sources in earlier research may be attributed to using coarser resolution Total Ozone Mapping Spectrometer (TOMS) data, which initially garnered attention for their regional dust emissions (Prospero et al., 2002). Subsequent studies confirmed them as leading sources of emission, with evidence suggesting widespread deposition of dust from these sources throughout southern Africa (Vickery et al., 2013; Haywood et al., 2003; Resane et al., 2004; Dansie et al., 2017).

Past studies have explored the potential of the southern Kalahari Desert as a third significant dust source in the southern hemisphere (Bhattachan et al., 2012; Bhattachan et al., 2013). Although infrequent, this source emits dust during the dry winter (Vickery et al., 2013). Subsequent research revealed enrichment in N, P, and Fe in this source, with evidence of dust deposition reaching the Benguela and Southern Ocean (Bhattachan et al., 2015; Tesfaye et al., 2015; Tatlhego et al., 2020).

The fourth crucial dust-emitting source is the Namibian ephemeral riverbeds, identified and classified by Eckardt and Kuring (2005) between 1998 and 2001. Due to resolution limitations, global dust models and satellite surveys often overlook smaller dust-emitting sources (Vickery & Eckardt, 2013). The TOMS studies, characterized by coarse resolution, failed to detect these sources (Dansie, 2017). Despite the potential for small-scale sources to contribute significantly to global and regional dust emissions, there was a lack of information on them (Ginoux et al., 2012). Later remote sensing studies employing Moderate Resolution Imaging Spectroradiometer (MODIS) between 2005-2008 (Vickery et al., 2013) and Landsat imagery between 1989-2016 (von Holdt et al., 2017) identified high-resolution dust events from Namibian ephemeral riverbeds and the Namib gravel plain. Notably, these studies indicated that the Namibian coastline, including riverbeds, pans, and wetlands, exhibited a higher emission frequency (34%) than both Makgadikgadi (16%) and Etosha (11%).

However, a recent dust event between 10 and 13 July 2023 prompted a re-evaluation of the existing inventory. In addition to substantial emissions from recognized Namibian sources, contributions were noted from previously unclassified sources southwest of Angola, referred to as AS. The finding is not that novel, as it is known that the dust extends to the region (Engelbrecht & Derbyshire, 2010; Chappell et al., 2023). However, the surface characteristics of the area have not been looked at in much detail. The frequency and times of emission from the AS has also not been classified. Here, the frequency is classified during a short period between January 2016 and December 2017, but a dataset between 2005 and 2015 is available and will be analysed at a later stage. Notably, the study period identifies similar but new emission source locations compared to the 2005-2015 dataset. The period between 2016 and 2017 is regarded as appropriate for an initial classification of the emission frequency. In addition, to provide insights into the emission from the AS, the atmospheric conditions conducive to dust emission from the source are investigated. The investigation of this source motivates a deeper understanding of the evolving desert landscape under future climate change conditions, as new dust sources may emerge with potential regional desertification. This source potentially also impacts Henties Bay episodes, as discussed in the previous chapter.

4.2 Source location identification

As anticipated, the dust emission from the unclassified AS was not found to be as frequent (3 days) as those from the Namibian ephemeral riverbeds (34 days), which aligns with previous research (Vickery & Eckardt, 2013; von Holdt et al., 2017). The three identified emission days were 24 June 2016, 25 June 2016, and 16 November 2017. These emissions were traced back to 47 unique source locations (Figure 4-1), as Figure 4-2 depicts. Please note that although the point locations to the south appear over the ocean, they are over land on the satellite images, as shown later. The locations of these sources are presented in **Appendix B**. Detailed observations for the mentioned days are as follows:

- **24 June 2016:** Dust emissions predominantly originated from the northern Namibian riverbeds and the AS. Visibility constraints arose due to cloud cover masking southern Namibia.
- **25 June 2016:** No discernible dust emissions from the southern Namibian sources were recorded due to the presence of a cloud mask.
- **16 November 2017:** Determining the specific source of the haze recorded on this day was challenging. It was posited that the dust could have been emitted either from the northern

Namibian ephemeral riverbeds or the AS. A similar ambiguity was noted for a dust plume on 07 June 2017, potentially originating from either the small sandy Angolan island of Baia dos Tigres or the Angolan coast. On this occasion, the haze stretched approximately 49 km from the Angolan coast.

The 24 and 25 June 2016 images show dust emissions observed by MODIS Terra. MODIS Aqua passes the region later than Terra, so its images showed already dissipated plume locations. Therefore, Terra was used for plume origin identification. The Aqua images were used for the plume length identification as they were visually farther from the coast. The AS was most active during the winter months, consistent with the seasonal movement of the Benguela Low-Level Jet (BLLJ) (Lima et al., 2018). Seasonal trends in dust emissions have consistently been observed in various parts of the world. These patterns are particularly prominent in southern Africa, with dust activity directly correlating with specific seasonal changes. In our study, these seasonal trends align with the established literature (Eckardt & Kuring, 2005; Vickery et al., 2013). A closer look at the AS's dust emission patterns reveals similarities with those from the Namibian sources. Specifically, the AS displayed its highest dust-emitting activity during winter when two of the three observed dust events occurred. The present study suspects that the landform types are similar to the Namibian sources to the south (von Holdt et al., 2019).

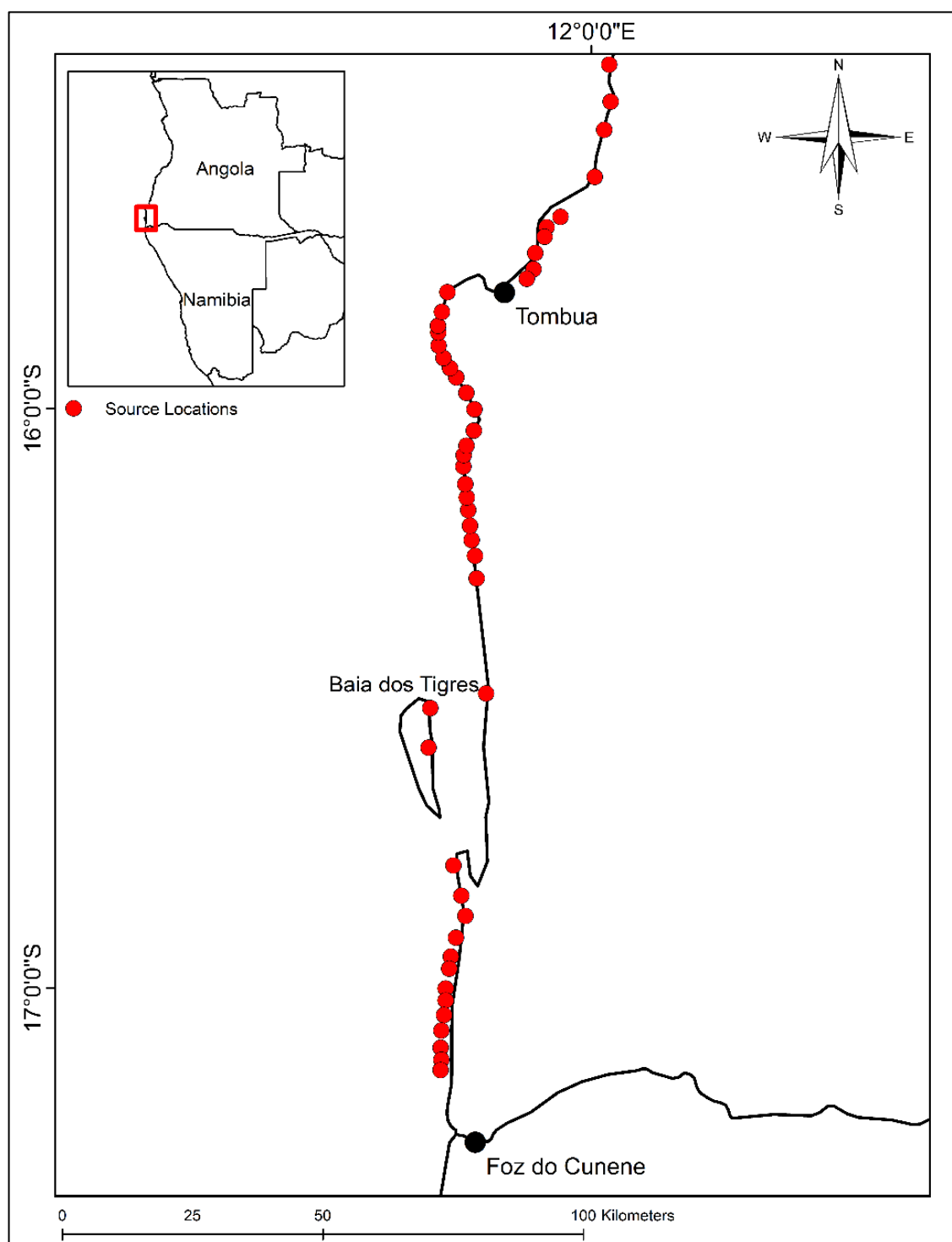


Figure 4-1: The identified new southern African dust source locations. Each source location is indicated as a red point.

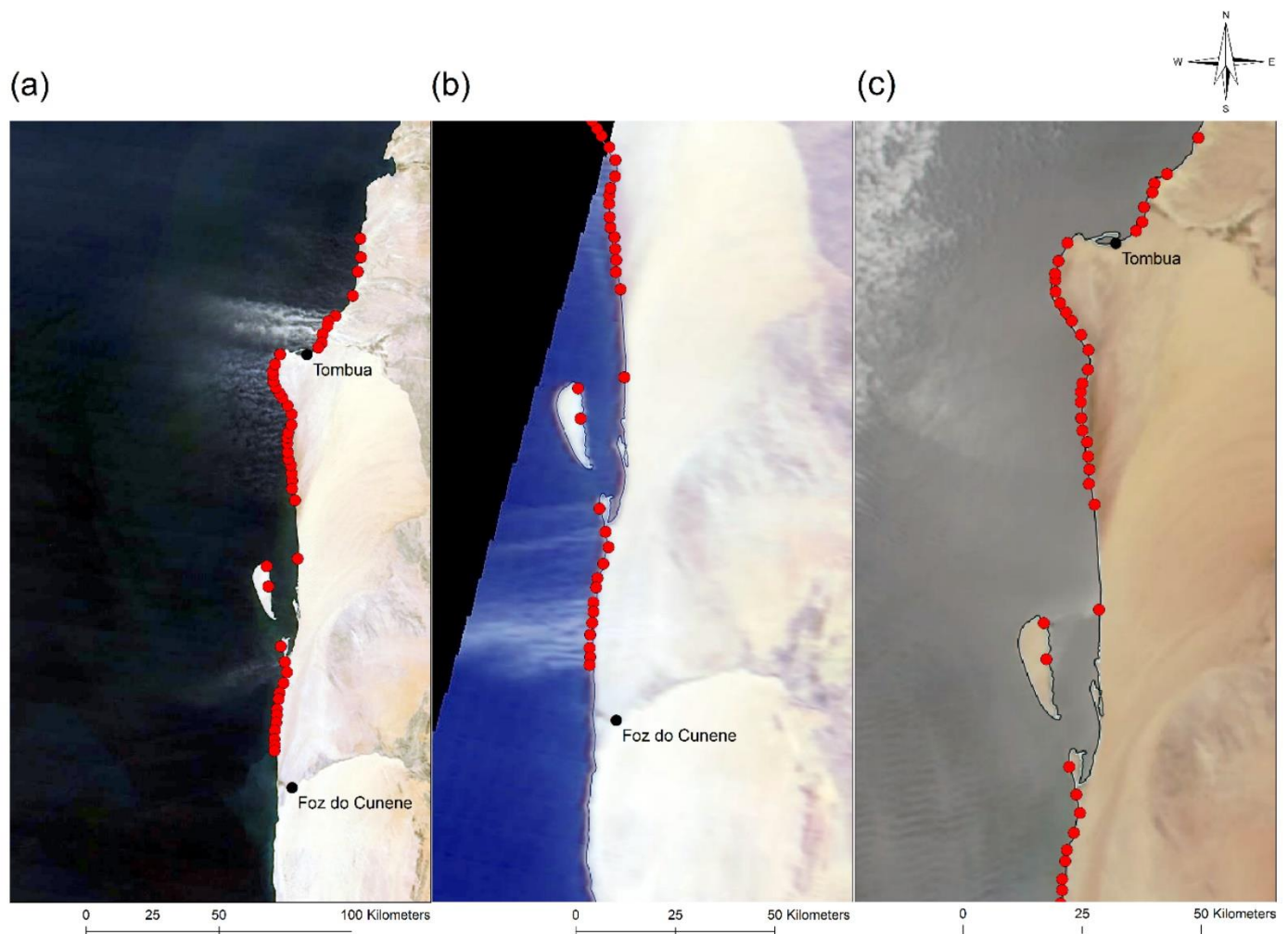


Figure 4-2: The observed dust plumes from MODIS Terra on a) 24 June 2016, b) 25 June 2016, and from Aqua on c) 16 November 2017.

4.3 Meteorological conditions on emission days of source locations

As discussed in the previous section, the AS was most active during the winter months, consistent with the seasonal movement of the Benguela Low-Level Jet (BLLJ). The BLLJ migrates northward to about 17.5° S during the peak winter months (Lima et al. 2018). This movement potentially influences dust emission dynamics, as the jet's presence might induce conditions favourable for the observed dust events at different latitudes during dry winter months. All detected plumes by Aqua stretched beyond a 100 km threshold, with their lengths ranging between 118 km and 300 km. This finding suggests the emission events' intensity and the transported dust's potential regional impacts.

A meteorological analysis of 24 and 25 June 2016 offers further insights. The ERA5 data shows an offshore (easterly) flow along the AS during these days (Figure 4-3). This flow might have been influenced by the presence of the Angolan Low (Howard & Richardson, 2019). With its easterly surface wind patterns, the Angolan Low might play a role in dust emissions, especially in arid areas during austral winter.

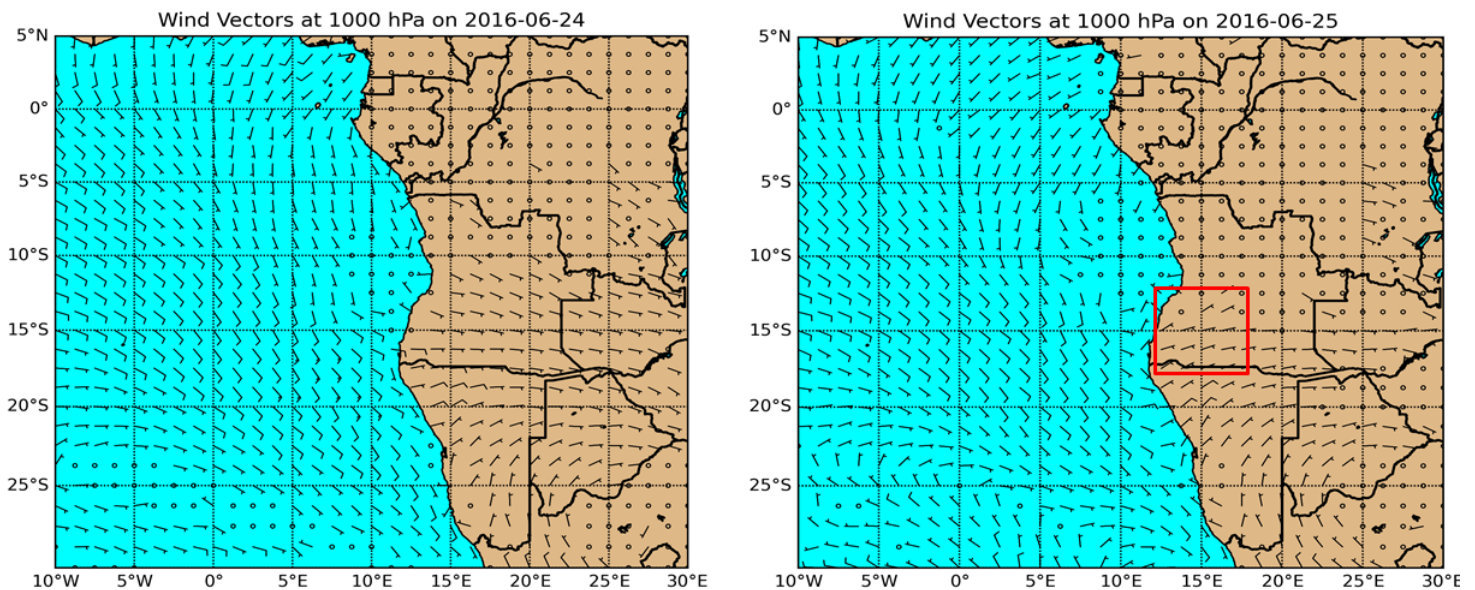


Figure 4-3: The observed wind vectors at 1000 hPa during the 24 and 25 June 2016 dust events.

The 16 November 2017 event coincided with a strong BLLJ (Figure 4-4) (Lima et al., 2019). Embedded within this strong southerly flow, we identified a dust event originating between the Baia dos Tigres off the AS coast. The ERA5 data shows that at the specified region, there is marked vorticity with winds shifting from South to Westerly winds at the surface along the coast, at the position of the potentially identified dust plume. There is some uncertainty regarding this event as satellite images reveal low-level clouds, possibly fog, in the area, which masks the clear identification of the plume. The strong meridional flow also indicates dust transport from regions further down the coast—the role of Baia dos Tigres as a potential dust source warrants further examination. The southerly plumes are much more difficult to spot on True Colour images than the easterly plumes. It highlights the importance of the BLLJ in identifying these plumes or any system that produces dust associated with southerly winds (Corbett, 2018; Clements & Washington, 2023). Notably, a trajectory analysis of the region has shown that air masses are occasionally transported from the AS between 15° and 22°S to the HBAO (Klopper et al., 2020). Albeit a single day, this

potential is also illustrated by the trajectories for 28 July in **Chapter 3**. This observation is also described by Formenti et al. (2018), who note that a low-pressure system was responsible for pulling air masses from the coastal regions of northern Namibia and Angola to the site. The AS may thus also contribute to aerosol episodes observed at the HBAO.

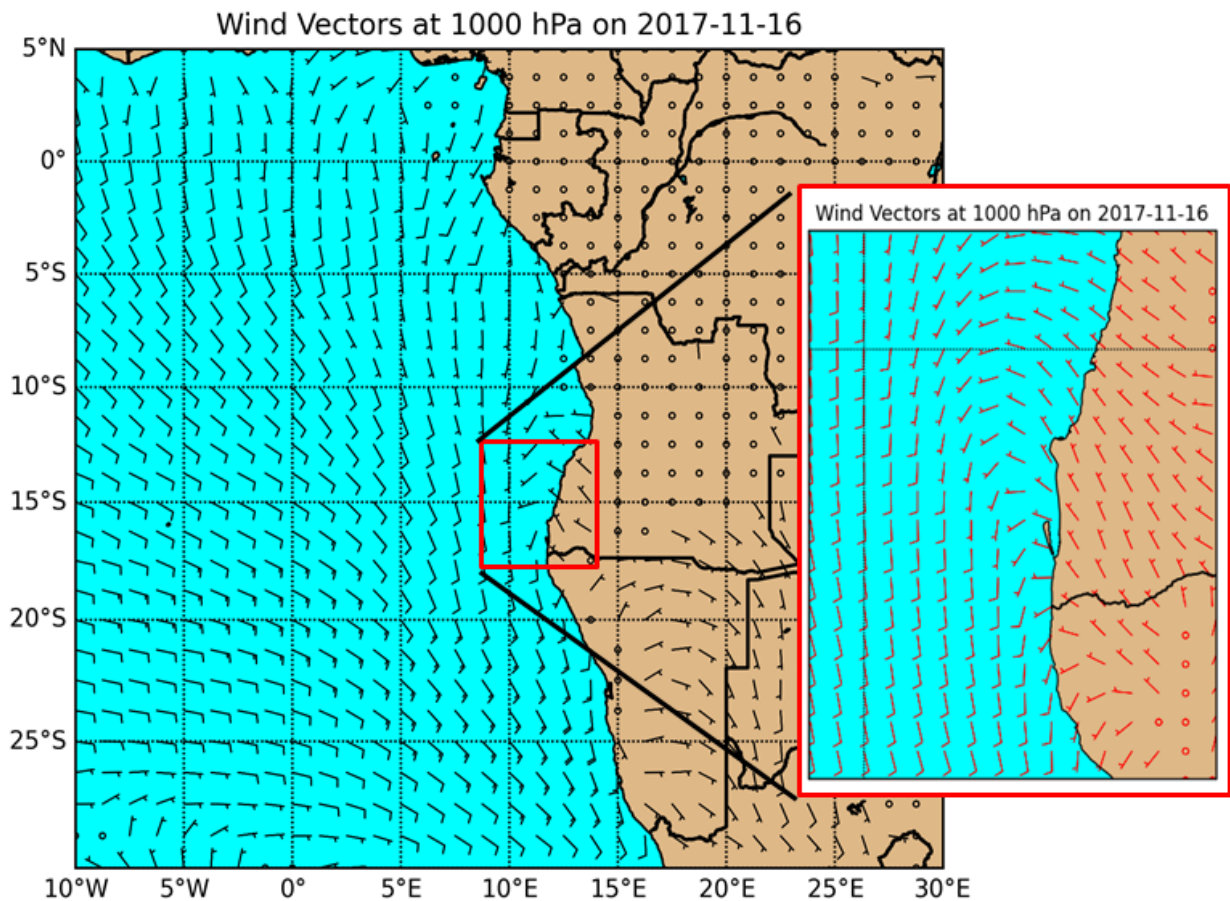


Figure 4-4: The observed wind vectors at 1000 hPa during the dust event on 16 November 2017.

4.4 Chapter Conclusions

The objective of the results portrayed and discussed in this chapter was to update the current dust source inventory for southern Africa by:

- Identifying potential new dust source locations for the region;
 - Identifying the dominant transport patterns of particulate matter and coupling their contributions with air mass back-trajectories; and
 - Identifying the atmospheric conditions conducive to high and low particulate matter episodes.
-

The following inferences can be made:

This research has pinpointed 47 potential dust emission sources in southern Africa. The AS is most active during the winter, coinciding with the seasonal shift of the BLLJ. All detected plumes from the AS stretched over 100 km, suggesting a substantial potential for emission and deposition. In winter 2016, plumes were seen with an easterly offshore flow, potentially connected to the Angolan Low. A dust event linked to the BLLJ was observed on November 16, 2017. The source may have originated from the island of Baia dos Tigres, warranting further investigation. This study underscores the importance of the BLLJ for sources located in the AS region, possibly extending to northern Namibia. The easterly dust plumes are easily discernible on True Color satellite imagery, but the southerly plumes are more complex and uncertain. The significance of the BLLJ in identifying these southerly plumes on True Colour imagery is demonstrated. This study is the first to categorize the frequency of events in the AS, although the analyzed record from 2016 to 2017 is relatively brief. For these reasons, further investigation is needed. The AS is unique due to its location and shape relative to the BLLJ and possibly other southerly systems. It may, therefore, be subject to increased dust emission from the southerly winds, such as from the BLLJ. It may be a potentially worthwhile question to explore in prospective studies. The southern African dust sources shouldn't be considered 'fixed in time and space'. Instead, identifying the AS should highlight that you might find new source locations every time you assess satellite imagery. In other words, these are not necessarily 'new' sources but more an indication of the dynamic nature of the source regions.

CHAPTER 5

The following chapter presents the results for Objective III: ‘*Investigate the relationship between ambient Fe concentrations measured over the Namibian west coast and satellite Chl-a*’. As discussed in *Section 1*, Fe is a crucial nutrient for oceanic productivity. This chapter presents a characterisation of ambient Fe concentrations over the Namibian coast. Following this characterisation, anomalies were identified in the dataset. Then, the transport of air masses on certain anomaly days is investigated with forward trajectories to determine the fate of Fe. Finally, the meteorology during the anomalies is investigated by analysing the meteorology during their occurrence.

COASTAL AMBIENT FE AND BENGUELA CHLOROPHYLL-A

5.1 Background

It is widely acknowledged that atmospheric deposition plays a crucial role in the biogeochemical processes of remote ocean regions, supplying essential bioavailable nutrients to oceanic biota (Fung et al., 2000; Jickells et al., 2005; Jickells et al., 2016; Heimbürger et al., 2013). Numerous studies have underscored the significance of atmospheric deposition in providing trace elements for oceanic productivity (Jickells et al., 2016). Despite decades of research, the deposition of trace elements into the ocean remains a complex and poorly understood interplay of conditions (Shi et al., 2010; Chance et al., 2015). It is commonly assumed that dissolved trace elements are directly bioavailable to phytoplankton, but quantifying this process proves intricate (Shi et al., 2012). The bioavailability of these elements hinges on various factors, including physicochemical speciation and the soluble fraction thereof (Boyd et al., 2010).

A recent study revealed the concentration of bioavailable Fe from the Huab and Tsauchab ephemeral river valleys to be 5.1 ppm in deflated dust and 7.1-7.5 ppm in surface sediments (Dansie et al., 2017b). The study suggested that other Namibian ephemeral river valleys might exhibit similar bioavailable Fe. However, understanding Fe's bioavailability post-deposition remains limited (Mahowald et al., 2009). The commonly considered bioavailable fraction is Fe^{2+} (labile Fe fraction) (Mahowald et al., 2005), although Fe^{3+} may also be bioavailable (Barbeau et al., 2001; Barbeau, 2006), as Fe^{2+} may not always be accessible to biota (Visser et al., 2003). Fe undergoes conversion from primary Fe^{3+} to Fe^{2+} during atmospheric and oceanic transport. Due to the challenge of quantifying the bioavailable fraction, 'soluble Fe' is often used as a proxy for bioavailable Fe (Kangueehi, 2017). Recent modelling research suggests that Fe species become increasingly bioavailable through their interaction with acids emitted from anthropogenic sources, with pollutants like SO_2 dissolving Fe species in aerosols (Baker & Croot, 2010; Li et al., 2017). The solubility of the element is also size-dependent, as larger particles are removed during atmospheric transport through gravitational settling (Baker & Jickells, 2006).

In a recent study employing remote sensing techniques (Dansie et al., 2022), the investigation into the fertilizing potential of iron (Fe) for Benguela Upwelling System (BUS) phytoplankton involved assessing dust emissions from the iron-rich Namibian river valleys. This assessment was correlated with satellite-derived parameters such as aerosol optical depth (AOD), chlorophyll-a

(Chl-a), and sea surface temperature (SST). AOD was utilized to indicate potentially Fe-rich mineral aerosols, while Chl-a and SST were used to evaluate phytoplankton growth and nutrient-rich water upwelling. By monitoring changes in these variables, this approach offers valuable insights into the intricate dynamics and interactions between Fe-rich dust transport and the BUS marine ecosystem. The study revealed a robust and immediate positive correlation between Fe-rich dust emission, AOD, and daily BUS Chl-a levels. At the same time, no such association was observed on the monthly scale. In simpler terms, increases in AOD corresponded to increases in Chl-a.

Additionally, the study found no correlation between SST and Chl-a. This study expands on their research by measuring ambient Fe concentrations at Henties Bay, identifying extreme Fe concentration events, and tracking the forward movement of these events using HYSPLIT trajectories. Through this refined approach, we aim to observe changes in BUS Chl-a levels.

5.2 Characterisation of ambient Fe concentrations at Henties Bay

The variation in ambient Fe concentrations (ng/m^3) during daytime and night-time on measured days between February 2016 and December 2017 are depicted in Figure 5-1. The daytime concentrations ranged from 3.00-3687.00 ng/m^3 with a mean of $351.67 \pm 496.58 \text{ ng/m}^3$. At night, concentrations ranged from 3.00-2400.00 ng/m^3 with a mean of $362.06 \pm 410.95 \text{ ng/m}^3$. Extreme concentration episodes (ECEs) are observed for both times, with 19 for the day and 18 for the night (Figure 5-2). In this study, ECEs were defined as unusually high (above 1.5 times the interquartile range) or low values (below 1.5 times the interquartile range) compared to the rest of the data. Notably, two ECEs were observed from 28-29 August 2016 and 11-12 July 2016, and three from 15 to 17 November 2017. The ECEs that exceeded 2500 ng/m^3 occurred on

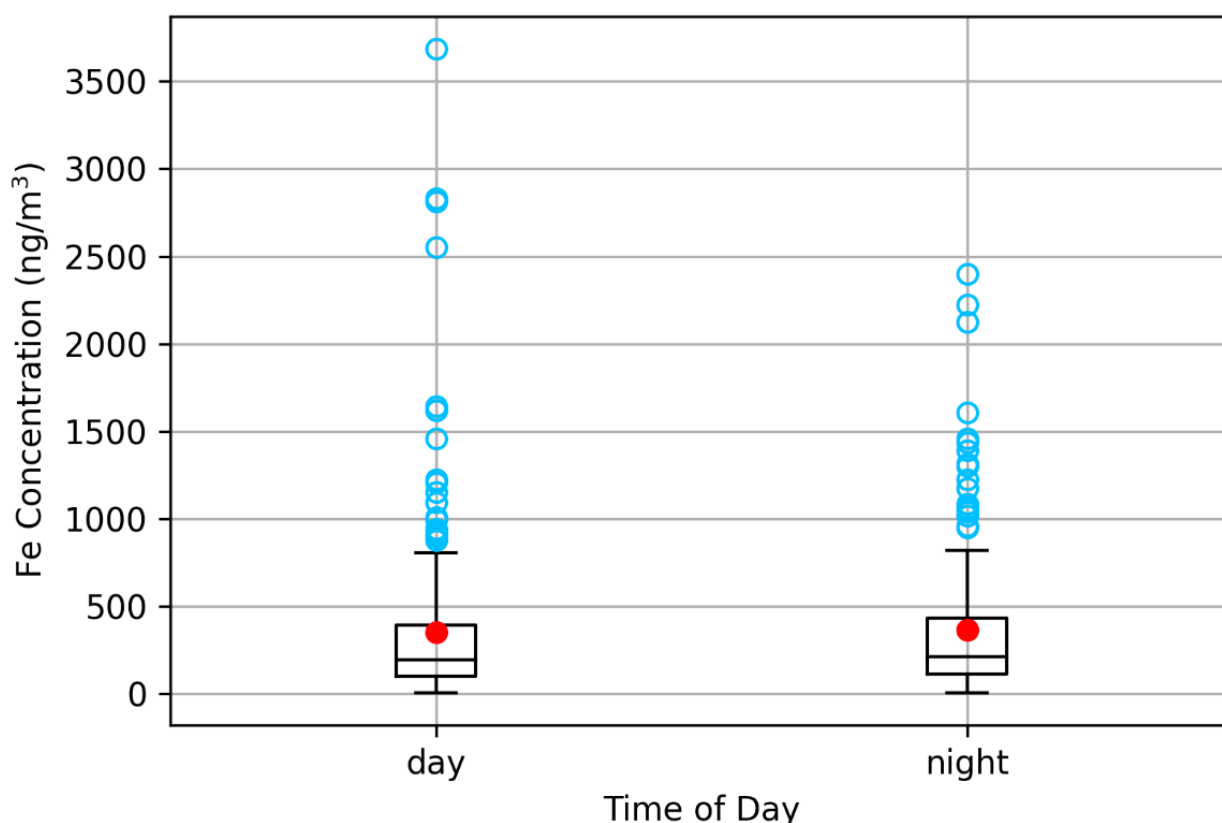


Figure 5-1: Variation in ambient Fe concentrations (ng/m³) by the time of day. The red dot indicates the mean concentration, while the blue dots represent outliers.

29 August 2016 (3687.00 ng/m³), 25 May 2017 (2814.00 ng/m³), 12 July 2017 (2553.00 ng/m³), and 17 November 2017 (2832 ng/m³) (hereafter EP1, EP2, EP3, and EP4, respectively). Interestingly, three of these ECEs occurred during consecutive ECE events. The prevailing winds during the ECEs varied from southwest, south, and southeast during EP1, southwest and south during EP2, south and northwest during EP3, and southwest and northeast during EP4 (Figure 5-3). As shown in **Chapter 3**, the surface winds might not be as important for Fe concentrations measured at the site if transported over long ranges. However, according to Vickery and Eckardt (2013), dust emission events from the Namibian riverbeds are associated with wind speeds exceeding 10 m/s, often with berg winds. Given the location of the HBAO relative to some of the major riverbeds (**Section 2.1.1** in **Chapter 2**) and the results from **Chapter 3**, the sources in the vicinity contribute to aerosol episodes at the site. Therefore, the possibility that these sources contributed to the observed ECEs is likely high. The closest Fe sources to the HBAO are located right next to it (Omaruru), to the southeast (Kuseb and Tsauchab), north (Huab) and northeast (Etosha Pan). At a wind speed of 3.9 m/s, the most likely source during EP1 was the Kuseb and Omaruru. The sources

were likely the same, with no prevailing wind from the source directions during EP2 at a similar wind speed from the direction of the Kuiseb. Wind speeds exceeding 6 m/s were prevalent during EP3 but were from the south, and with low wind speeds from the northern region, the likely source was the Omaruru. During EP3, the prevailing wind suggests the source may have been the Huab or Etosha Pan at wind speeds ≤ 5.4 m/s. However, as shown in **Chapter 3**, the surface winds may not be important for dust transport to the coast. Transporting air masses at a higher atmospheric pressure may be more important.

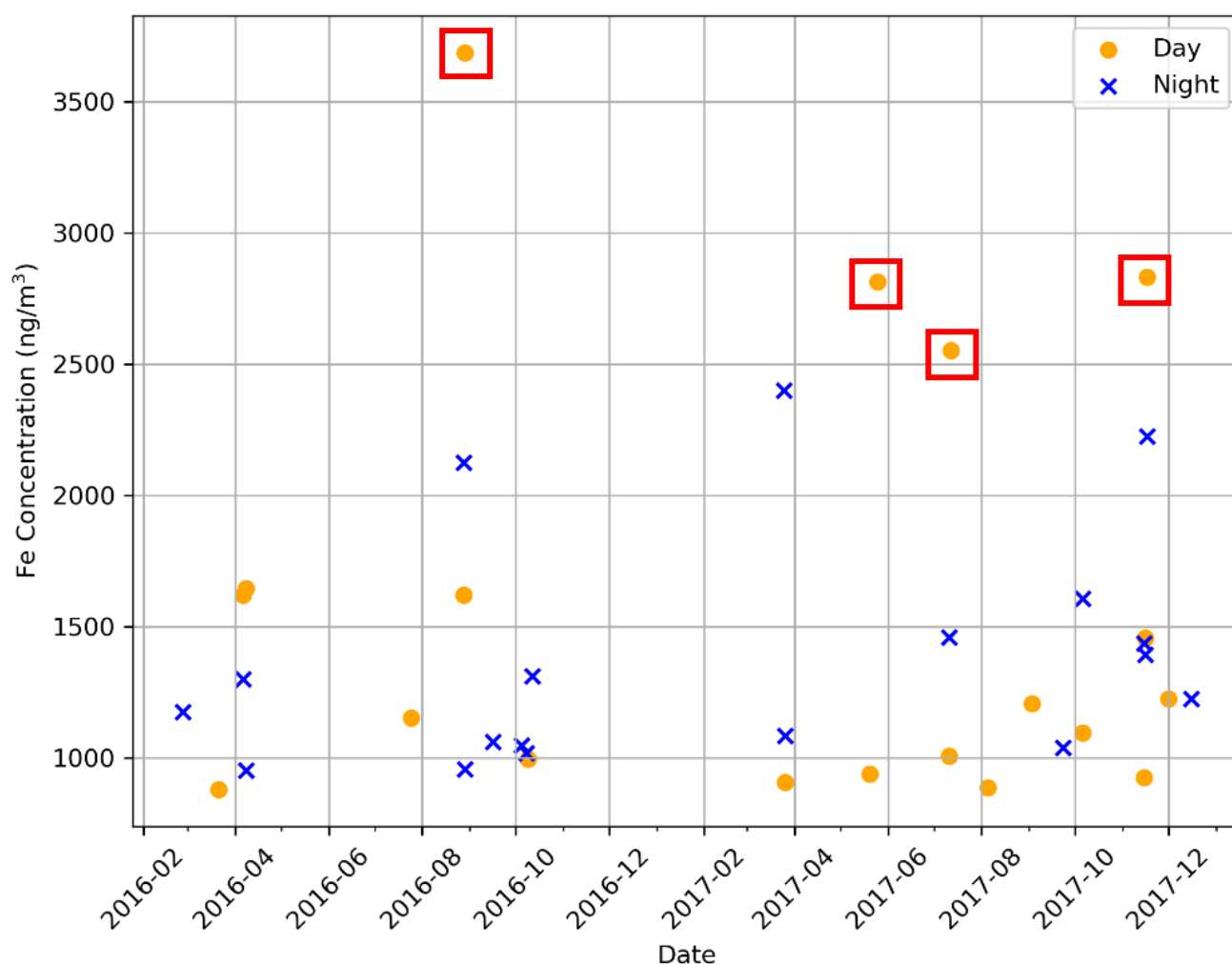


Figure 5-2: The observed day and nighttime ECEs (ng/m^3) at Henties Bay during the monitoring period between 2016 and 2017. The ECEs are indicated with a red square.

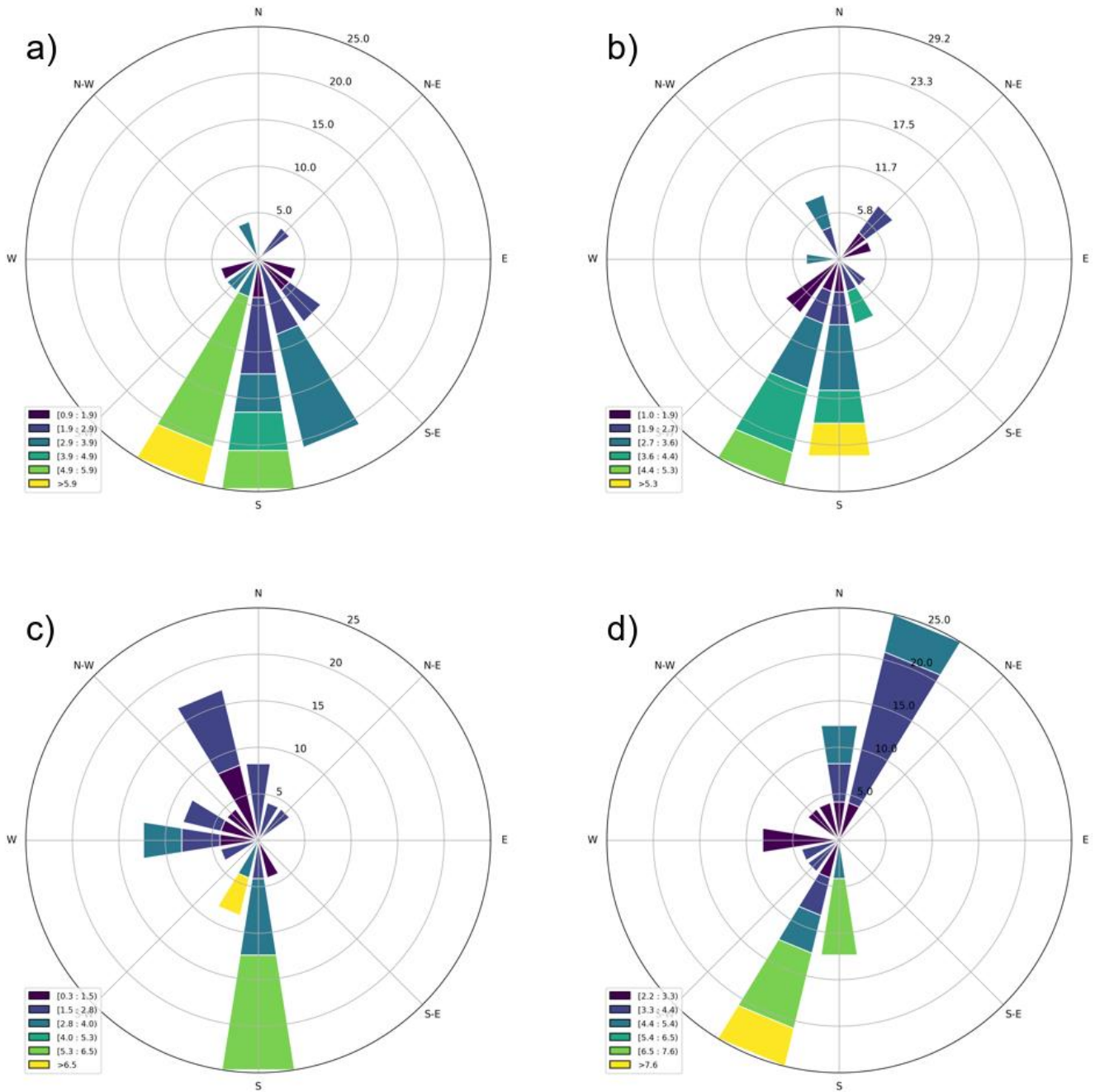


Figure 5-3: The prevailing hourly wind speed and direction at the HBAO during a) EP1, b) EP2, c) EP3, and d) EP4.

The monthly variation in the Fe concentrations is illustrated in Figure 5-4. The overall monthly mean concentrations in decreasing order were 492.34 ng/m³ (August), 475.14 ng/m³ (November), 454.23 ng/m³ (December), 443.81 ng/m³ (October), 402.17 ng/m³ (July), 312.02 ng/m³ (March),

298.93 ng/m³ (April), 287.97 ng/m³ (February), 287.70 (May), 277.23 ng/m³ (September), and 254 ng/m³ (January) – no measurements were taken during June of any year. In decreasing order, the most ECEs were observed in March (7), May and November (6), July and August (5), April (4), September (3), October and December (2), and February (1).

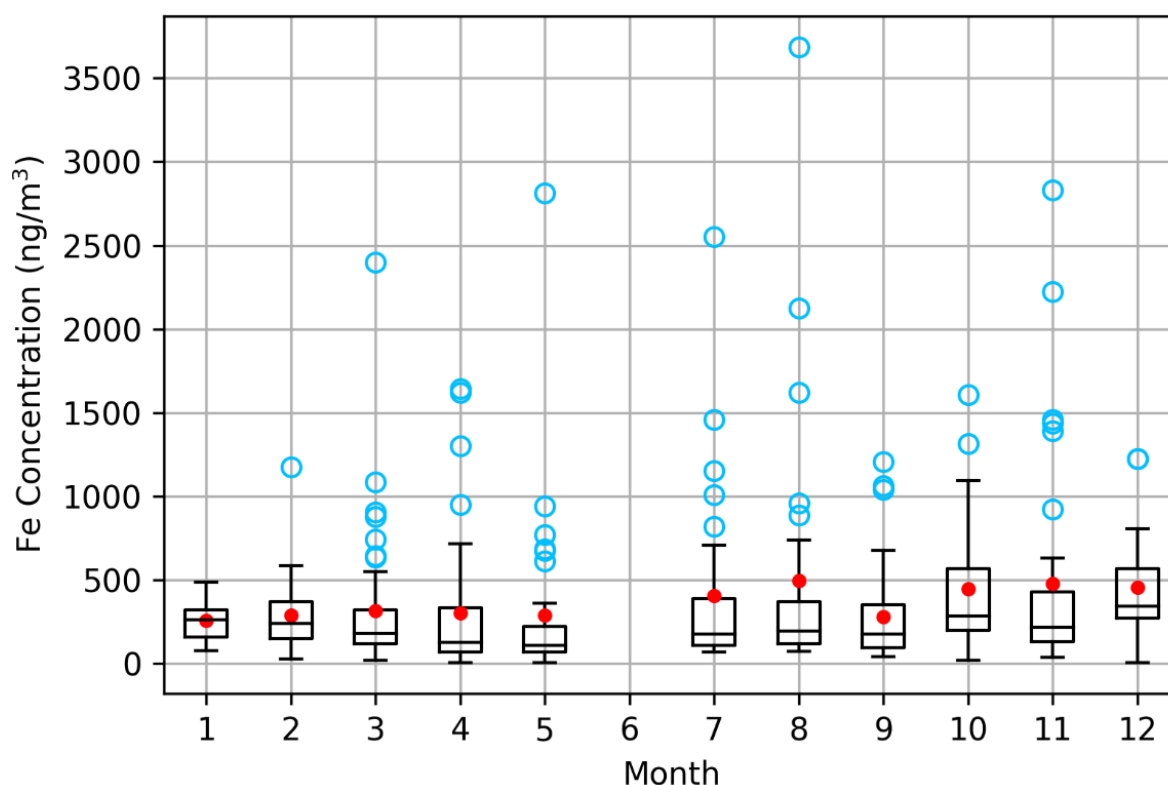


Figure 5-4: Monthly variation in ambient Fe concentrations (ng/m³) between 2016 and 2017.

Whether Fe impacts marine productivity significantly depends on the total Fe in PM and its solubility (Zhu et al., 2020), with the solubility between sources ranging greatly (Mahowald et al., 2005). As a previous study has shown, the two main mechanisms affecting Fe solubility are how much soluble Fe is present in its sources and the ability of soluble Fe to be produced through chemical transformations (Myriokefalitakis et al., 2015). A recent study at a coastal Chinese site made an interesting observation about the solubility of Fe in total suspended particles (Shi et al., 2020). The study found that the solubility was notably higher under fog conditions in winter and spring. The previous was particularly true when wind speeds were ≤ 4 m/s. They noted that the solubility was lower under haze, dust, and clear conditions. For example, even though the Fe concentration under dust conditions was substantially higher at 15000 ng/m³, it had a solubility of 0.1%. In contrast, under fog conditions, the Fe concentration was 2720 ng/m³ but with a solubility

of 5.8%. Fog has water droplets that acidify aerosols to convert insoluble Fe to its soluble form (Shi et al., 2015).

Given its location along the BUS, fog events on the Namibian coast occur frequently (Weston et al., 2022), thus possibly significantly impacting the solubility of the Fe in the region. Dansie et al. (2017a) previously suggested that the Namibian ephemeral riverbeds, as discussed earlier, are a significant source of nutrients to the BUS. The riverbeds are rich in N and P, especially bioavailable Fe (Dansie et al., 2017b). The solubility is the ratio of the soluble portion to the total nutrient. It is worth noting that solubility is used as a proxy for bioavailability since it remains unknown which factors control bioavailability (Schulz et al., 2012). However, although the site here is also located on the coast, the bioavailability depends on several factors. As discussed in detail by Schulz et al. (2012), these factors include the composition of the dust source, the chemical changes the dust undergoes while being transported, the mechanism through which the dust is transported, and the composition of the seawater it's transported to. This study assumes that the BUS seawater is Fe-deficient (Capone & Hutchins, 2013) and investigates the hypothesis by Dansie et al. (2022) that Fe emission from the Namibian riverbeds affects marine productivity in the adjacent BUS daily. Therefore, the identified ECE days exceeding 2500 ng/m³ are used to investigate the impact of high Fe concentrations on the BUS. As shown by Liu et al. (2021), a higher Fe concentration does not necessarily mean a higher Fe solubility; this study assumes the 'worst case' where the concentrations were at their maxima. In other words, the analysis assumes that higher Fe concentrations mean higher Fe solubility.

5.3 HYSPLIT Trajectory Analysis

As discussed in **Sections 2.2.3** and **2.2.4**, ECEs in the Fe dataset were first identified visually as outliers and then confirmed by extracting only the values within 1.5 the interquartile range of the 75th percentile. In total, 19 ECEs occurred during the day and 18 at night. Given that the Terra and Aqua satellites observe AOD and Chl-a during the day and not night, only the daytime ECEs are considered in this analysis. Furthermore, four ECEs were substantially more than the rest of the dataset (EP1, EP2, EP3, and EP4), each exceeding 2500 ng/m³, and are the only events considered in this analysis. HYSPLIT forward trajectories were computed for 48 hours, with a new one starting every 8 hours at 100 m, 500 m, and 1500 m above ground level at 19:00. The endpoints of the trajectories were used as locations where Fe, AOD, SST, and Chl-a measurements were compared.

One of the assumptions this analysis makes is that the Fe ECE only occurred over the Henties Bay coast, which is plausible given the site's proximity to several dust sources. However, offshore flow from north and south of the site might have also contributed to Chl-a responses in the adjacent BUS. Similar or higher unmonitored ECEs may also have been present north and south of the HBAO, which may better explain the observed Chl-a variations.

The HYSPLIT trajectory analysis results for the four ECEs are illustrated in Figures 5-5, 5-6, 5-7, and 5-8, respectively. The figures also show the corresponding Chl-a, AOD, and SST. As illustrated, the computed 48-hour trajectories for EP1 and EP4 never crossed the path of satellite Chl-a and are, therefore, not considered in this section's discussion. For EP1, three trajectories were simulated over the ocean, but unfortunately, they did not reach the observed Chl-a concentrations. For EP4, none of the computed trajectories were simulated to be transported to the sea. This analysis did not consider these anomaly days because changes were measured at each trajectory point that passed over the observed Chl-a.

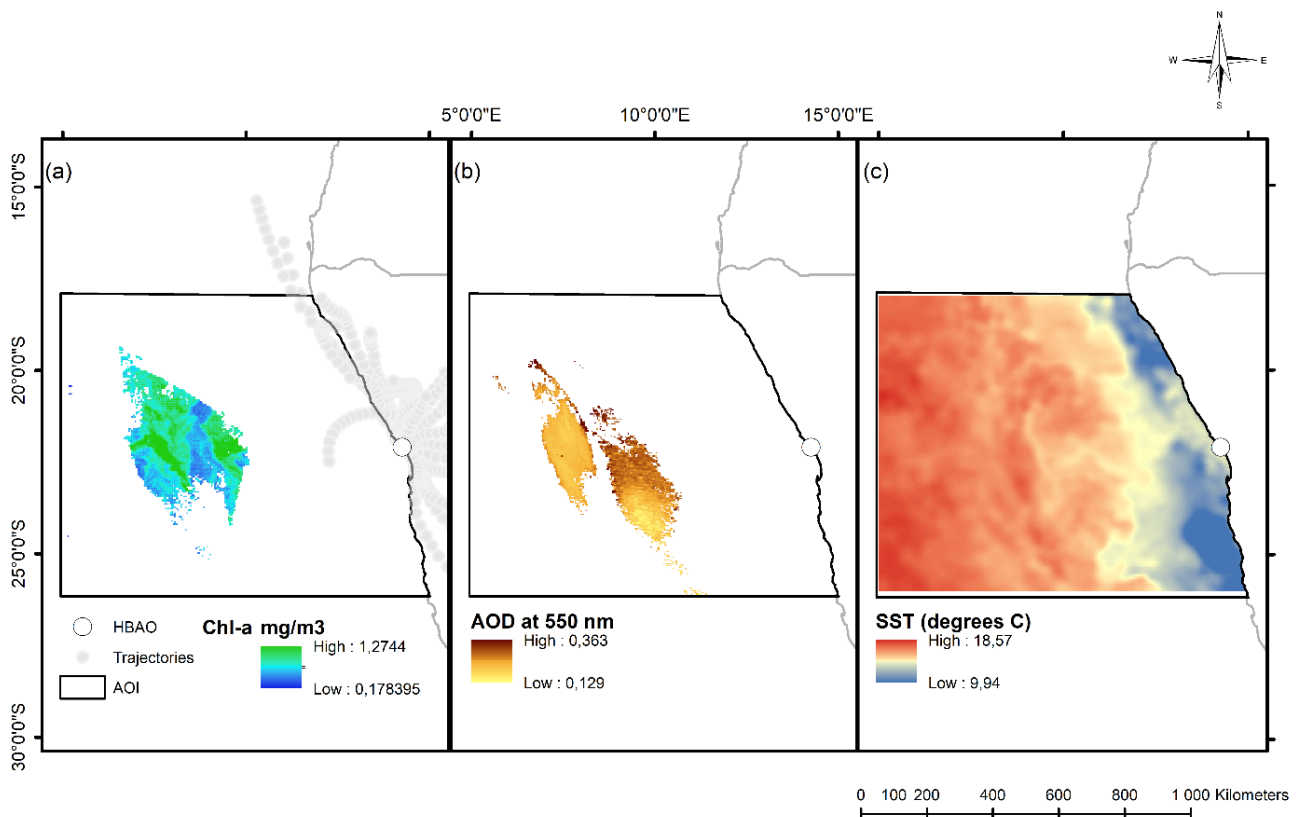


Figure 5-5: The observed a) Chl-a concentrations (mg/m^3), b) AOD at 550 nm, and c) SST ($^{\circ}\text{C}$) on 29 August 2016. The grey dots represent the computed 48-hour forward HYSPLIT trajectories at 100m, 500m, and 1500m.

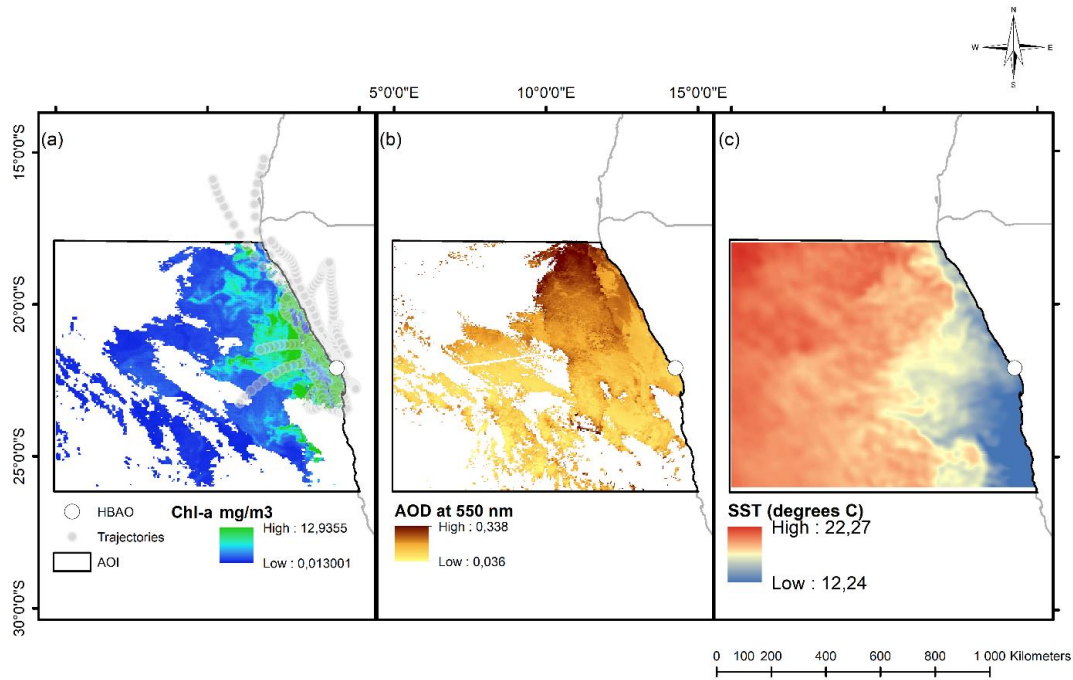


Figure 5-6: The observed a) Chl-a concentrations (mg/m^3), b) AOD at 550 nm, and c) SST ($^{\circ}\text{C}$) on 25 May 2017. The grey dots represent the computed 48-hour forward HYSPLIT trajectories at 100m, 500m, and 1500m.

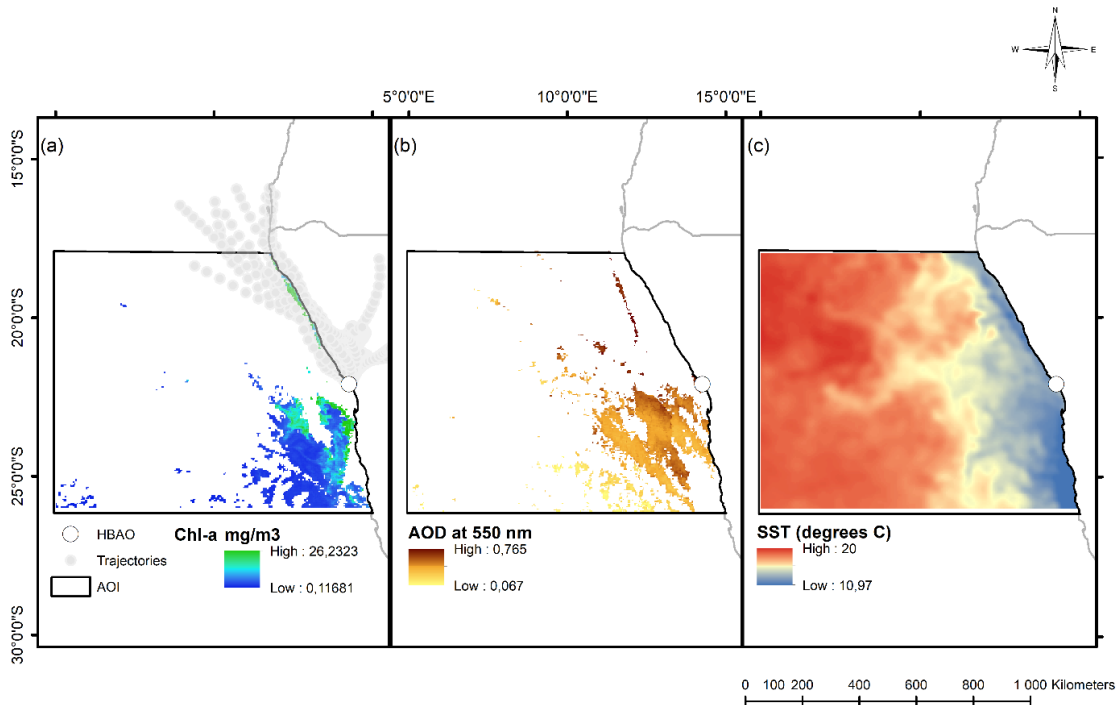


Figure 5-7: The observed a) Chl-a concentrations (mg/m^3), b) AOD at 550 nm, and c) SST ($^{\circ}\text{C}$) on 12 July 2017. The grey dots represent the computed 48-hour forward HYSPLIT trajectories at 100m, 500m, and 1500m.

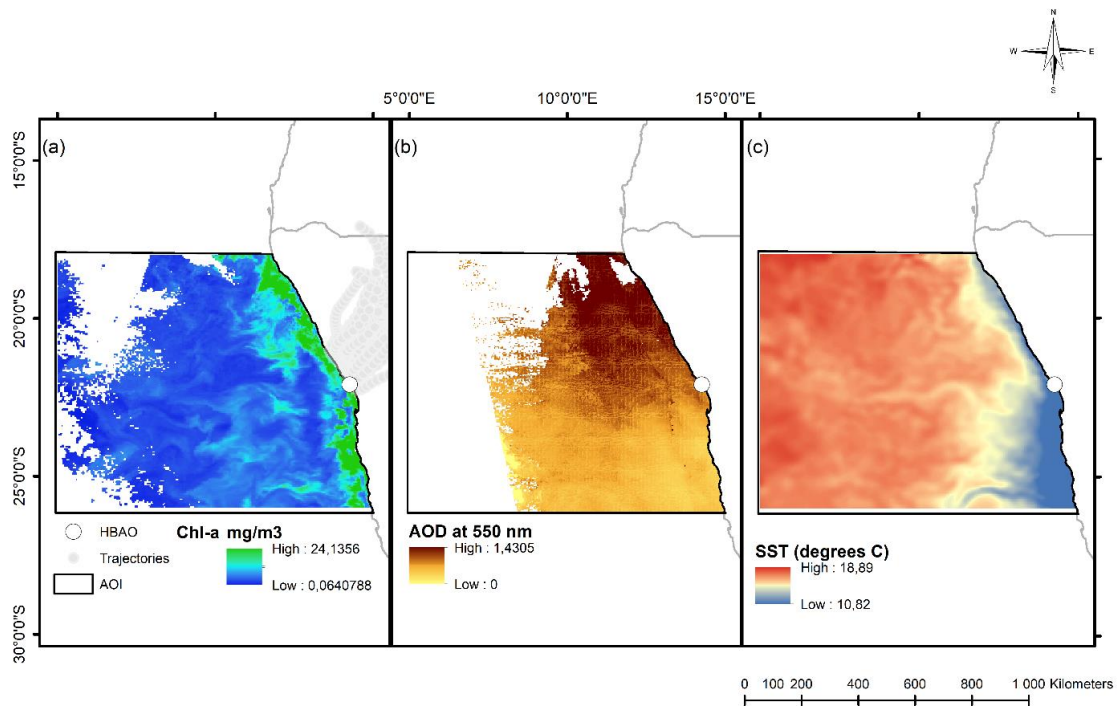


Figure 5-8: The observed a) Chl-a concentrations (mg/m^3), b) AOD at 550 nm, and c) SST ($^{\circ}\text{C}$) on 17 November 2017. The grey dots represent the computed 48-hour forward HYSPLIT trajectories at 100m, 500m, and 1500m.

The EP2 trajectory analysis results are shown in Figure 5-9. There is no apparent pattern in the Chl-a concentrations and no relationship between them and the Fe concentrations one day prior. Except for the 23 and 24 May outliers, the Chl-a concentrations remained relatively unchanged. These Chl-a concentrations were unaffected by the increase in Fe concentrations between 23 and 26 May and the decrease on 27 May 2017. In addition, while there is a slight decrease in the Chl-a concentrations, this does not match the fluctuation in the AOD. Except for outliers, the AOD stayed relatively constant between 23 May and 2 May 2017, which somewhat agrees with the observed pattern of Chl-a. However, a significant increase in AOD was observed on 26 and 27 May 2017, while the Chl-a kept steady. These results do not agree with previous findings where rapid growth in Chl-a was observed in response to AOD increases in EBUS (Carr and Kearns, 2003) and specifically the BUS (Dansie et al., 2022). The previous suggests that the BUS surface waters were not limited in essential growth-enhancing nutrients or were already abundantly present. It is unsurprising given the frequent dust emission from nearby high Fe-containing sources and deposition to the BUS (e.g. Vickery & Eckardt, 2013). It may also suggest that there was already sufficient Fe in the BUS water or that the Fe was not bioavailable or immediately scavenged by the phytoplankton. The observed Fe may also have settled out at the monitoring site and not transported along the pathway.

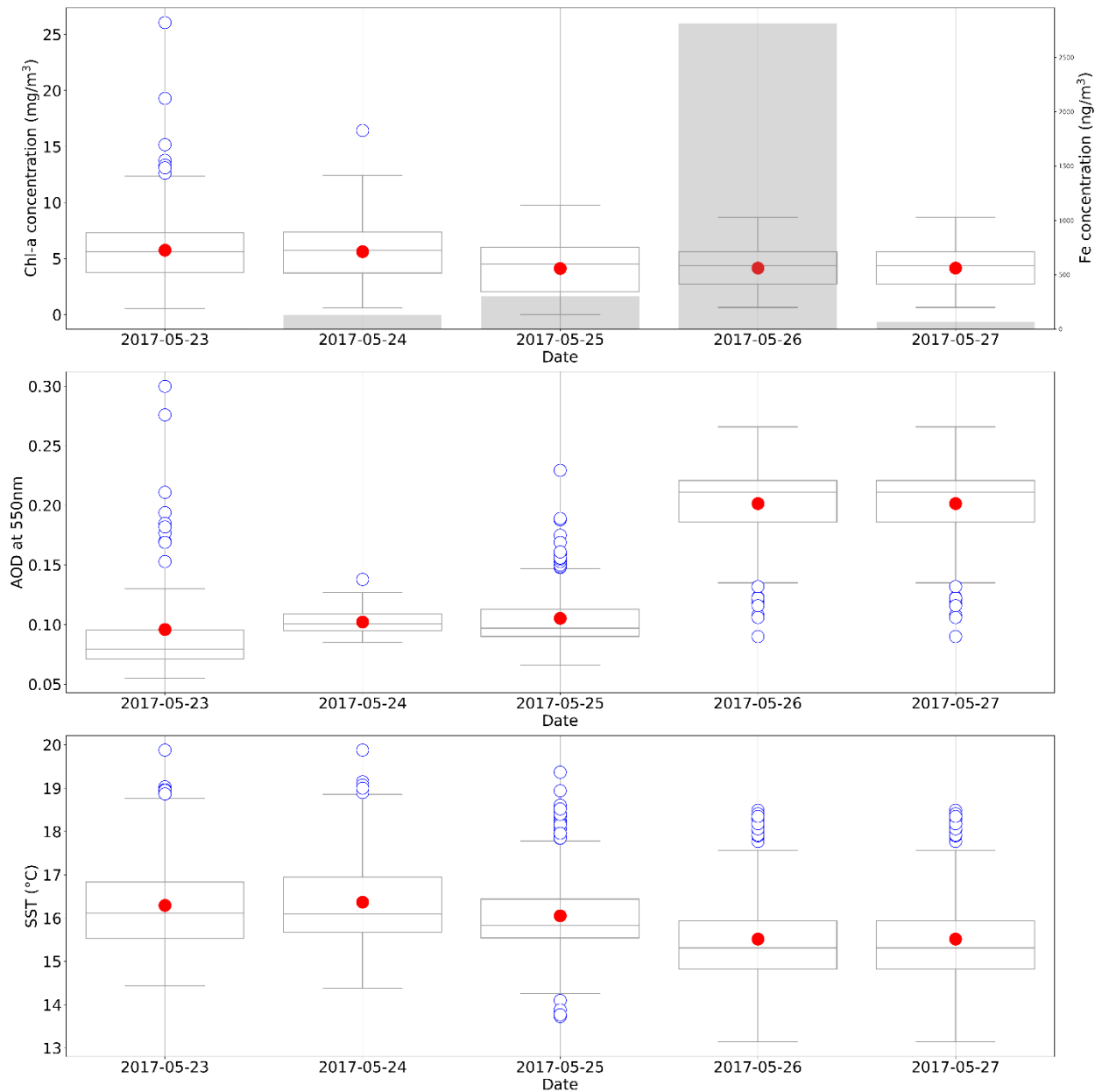


Figure 5-9: Boxplots showing the Chl-a concentration (mg/m³), AOD at 550nm, SST (°C) during EP2. The grey bars indicate the Fe concentration (ng/m³) one day before the observations.

A recent remote sensing study showed that SST, or BUS upwelling, is not an essential driver of productivity at the daily scale in the BUS (Dansie et al., 2022). To a certain extent, the results of this study suggest otherwise - the decrease in the Chl-a concentrations does appear to have coincided with an overall decrease in the SST. However, the results remain primarily inconclusive based on the study period.

The EP3 trajectory analysis results are portrayed in Figure 5-10. In this case, the results are inconclusive, given the absence of data for 10 July, 11 July, and 13 July 2017. It is shown, however, that the mean Chl-a concentrations were higher on 12 July than on 14 July. The Fe concentration was also higher on 11 July than on 14 July 2017, the day before the observed concentrations.

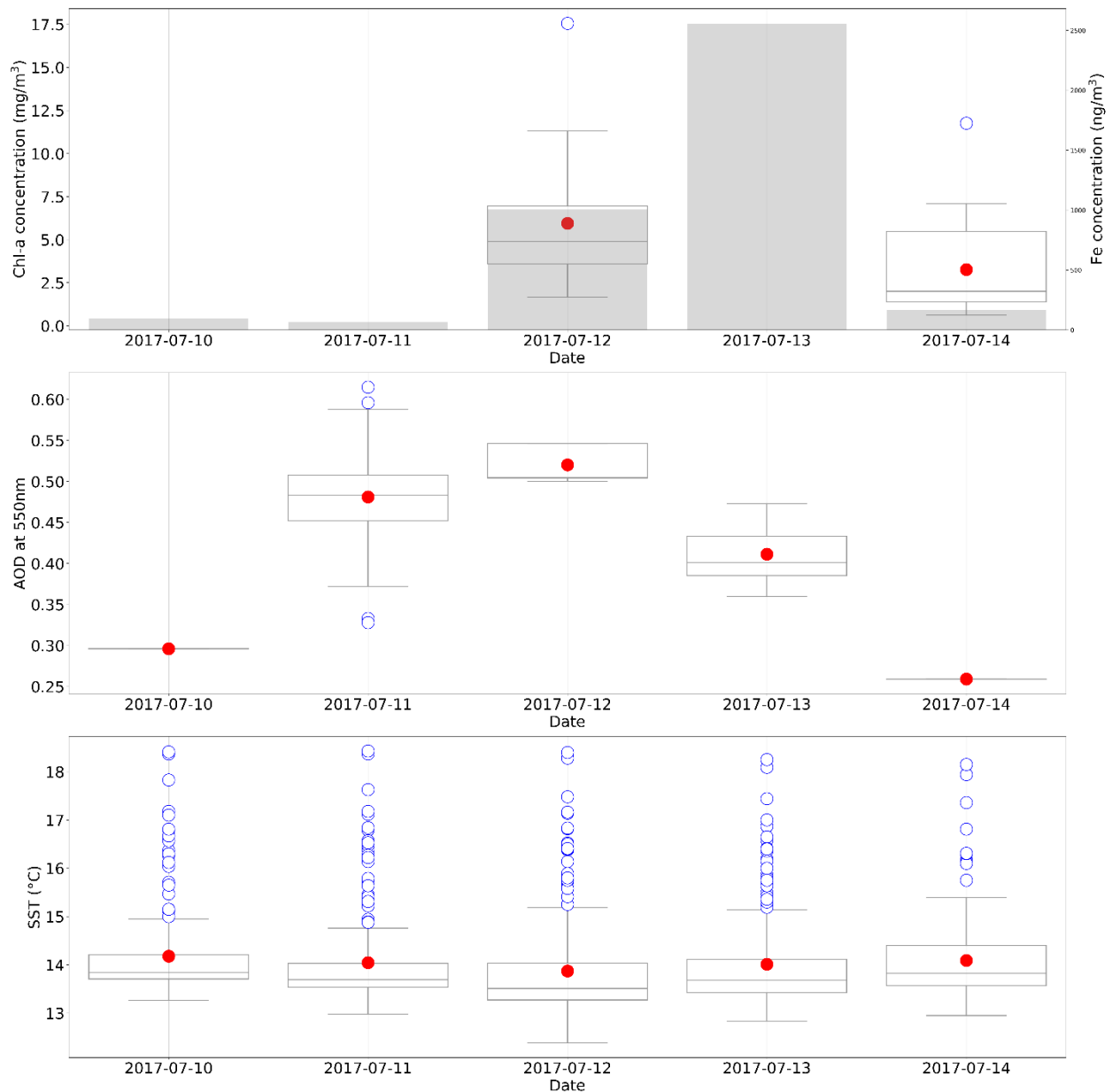


Figure 5-10: Boxplots showing the Chl-a concentration (mg/m³), AOD at 550nm, SST (°C) during EP3. The grey bars indicate Fe concentration (ng/m³) one day before the observation.

5.4 Meteorological Conditions

The meteorological conditions of the four ECEs are illustrated in Figure 5-11. From top to bottom, EP1, EP2, EP3, and EP4. From left to right are each anomaly's ERA-5, SAWS, and EUMETSAT images. On 29 August 2016, during EP1, it was interesting because there was warm air along the boundary of the west coast trough over Namibia extending to Angola in the north and to the BUS. This air advects to the western coast, where once it comes in contact with the cold BUS, cooling down rapidly to form a cloud layer, as seen in the satellite image (Figure 5-11, EP1). The wind blows almost entirely offshore from the northeast of the interior. Classic bergwind conditions were observed on 25 May 2017 during EP2 (Figure 5-11, EP2) and 17 November 2017 during EP4 (Figure 5-11, EP4). These days, a high-pressure system over the interior caused strong easterly flow towards a low-pressure system at the coast. However, although the 12 July 2017 meteorology resembles Berg wind conditions, it is not classic, even though a meso-low can be observed from the low-level winds (Figure 5-11, EP3). Berg winds are most frequent during winter, occur between May and September and transport plumes to about 100 km offshore (Tlhalerwa et al., 2005; Vickery et al., 2013).

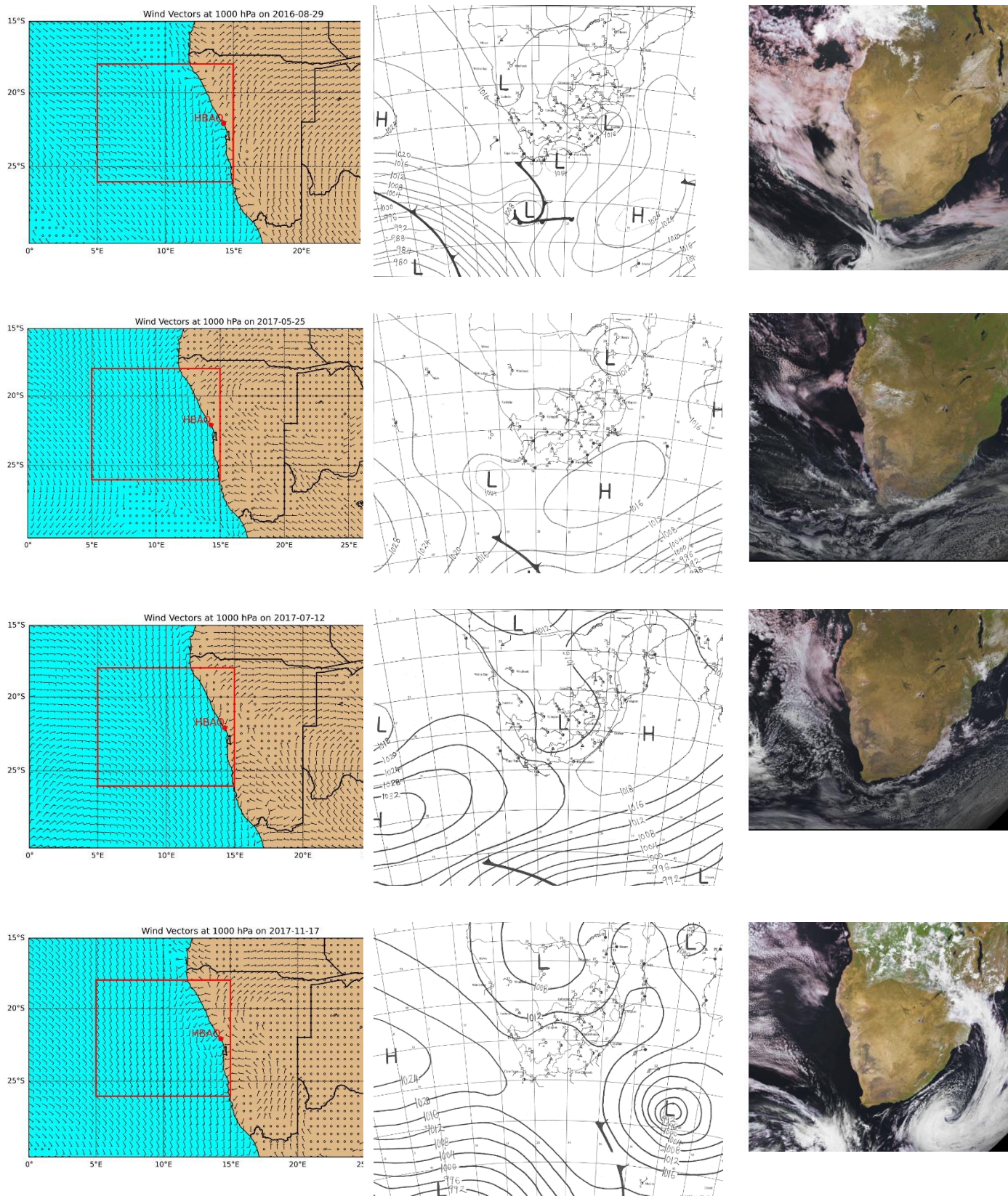


Figure 5-11: Observed meteorological conditions during the four anomalies, from top to bottom EP1-EP4.

5.5 Chapter Conclusions

The objective of the results portrayed and discussed in this chapter was to investigate the relationship between ambient Fe concentrations measured over the Namibian west coast and satellite Chl-a by:

- Correlating measured Fe with satellite-retrieved Chl-a, AOD, and SST;
 - Identifying the fate of Fe concentrations; and
 - Identifying the synoptic circulation favouring anomaly occurrence.
-

The following inferences can be made:

During the day, the Fe concentrations varied between 3.00 and 3687.00 ng/m³, averaging 351.67±496.58 ng/m³. These concentrations were generally lower at night, ranging from 3.00 to 2400.00 ng/m³ and averaging 362.06±410.95 ng/m³. There were three anomalies exceeding 2500 ng/m³ during consecutive anomaly events. The monthly mean concentrations, in descending order, were as follows: August (492.34 ng/m³), November (475.14 ng/m³), December (454.23 ng/m³), October (443.81 ng/m³), July (402.17 ng/m³), March (312.02 ng/m³), April (298.93 ng/m³), February (287.97 ng/m³), May (287.70 ng/m³), September (277.23 ng/m³), and January (254 ng/m³). No measurements were recorded in June of any year. Regarding the frequency of anomalies, the most were observed in March (7), followed by May and November (6 each), July and August (5 each), April (4), September (3), October and December (2 each), and finally February (1).

The results of the trajectory analysis are inconclusive. There does not seem to be a discernible pattern in the concentrations of Chl-a, and they do not appear to show a clear relationship with the Fe concentrations from the previous day for EP2. The results for EP3 are also inconclusive, where the Chl-a concentrations did not follow a specific pattern and did not seem to be related to the Fe concentrations observed a day earlier. Interestingly, the Fe concentration was higher on 11 July than on 14 July 2017, the day before the concentrations were measured.

Two exceptional instances where the readings exceeded 2500 ng/m³ were observed during the typical bergwind conditions - one in autumn (EP2) and the other in spring (EP4). During EP3, the weather conditions were similar to those of a Berg wind, but they were not typical. A meso-low was noticeable in the low-level winds of that day.

CHAPTER 6

The following chapter presents the results for Objective IV: ‘*Evaluate a long-term simulation of dust deposition to the Benguela current*’. The chapter reports the first long-term simulation of dust deposition to the BUS and compares it to dust from the MERRA-2 reanalysis dataset. The objective also investigates whether the CCAM simulated dust deposition seasonal cycle aligns with the seasonal cycle of Chl-a.

A LONG-TERM DUST DEPOSITION SIMULATION TO THE BENGUELA CURRENT

6.1 Background

The Benguela upwelling system (BUS), situated along the southwestern coast of Africa (19-34°S) (Hutchings et al., 2009; McKay et al., 2016), is a region of significant ecological and climatic importance. It is extensively studied concerning its ecology, primary production and trophic levels (Ware, 1992; Zonneveld et al., 2001; McKay et al., 2016). Characterised by its strong upwelling system (Shannon, 1985), the Benguela Current plays a crucial role in shaping the marine ecosystem and influencing regional climate patterns. One key factor that can impact the marine and atmospheric dynamics in this region is the presence of airborne dust particles. For instance, Messie & Chavez (2015) have shown that the primary production in eastern upwelling systems like the BUS varies with season, space, and from each other. The supply of macronutrients is the main regulating factor.

Atmospheric dust, comprising mineral aerosols lifted from arid and semi-arid regions, can be transported over long distances, influencing local weather patterns and marine biogeochemistry through nutrient delivery (Prospero et al., 2002; Engelstaedter et al., 2006). The intricate interplay between dust aerosols and the BUS affects climate studies, ecosystem health, and human well-being in the surrounding regions. This intricacy is commonly investigated through the use of atmospheric models.

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) Conformal Cubic Atmospheric Model (CCAM) is one such model that has been employed in diverse climatic studies. It has been widely used in simulations of regional severe precipitation weather (e.g., Bopape et al., 2022), large-scale synoptic circulation (e.g., Gibson et al., 2023), and climate projections like heatwaves (e.g., Mbokodo et al., 2020) and drought potential (e.g., Nurlatifah et al., 2019), and the loading of aerosol optical depth (AOD) (e.g., Horowitz et al., 2017). CCAM also simulates dust emission, transport, and deposition, a facet yet to be thoroughly examined.

Unexplored aspects include the quantity of dust the model simulates in the BUS and the specific locations of simulated deposition. The conditions governing dust emission in the model (e.g., wind speed) are already known as they are coded into the model's equations. Thus, the primary objective

of this study is to characterize the simulated deposition in space and time. This understanding of the accuracy of dust simulations in the BUS is crucial for several reasons. Firstly, it contributes to a broader comprehension of atmospheric processes in this ecologically sensitive region. Secondly, it aids in refining climate models, ensuring their effectiveness in capturing regional nuances. Finally, it provides valuable insights into potential impacts on air quality, marine ecosystems, and human health in the coastal areas influenced by the Benguela Current. Consequently, CCAM's deposition is compared to that of MERRA-2, and its seasonal cycle is assessed for alignment with the remotely sensed seasonal cycle of Chl-a in the BUS.

6.2 CCAM Modelled Total Dust Deposition to Box N and Box S During 1979-2013

6.2.1 Zonal Breakdown of Box N and Box S

As explained in **Section 2.4.1**, two regions were visually identified to have had the highest simulated deposition (Figure 6-1) (Box N to the north and Box S to the south of the domain). Outside these domains, the simulated deposition was predominantly non-existent or near zero. Please note that Figure 6-1 shows the dust deposition in g/m^2 since it shows the average per pixel over the complete study period (1979 to 2013).

Figure 6-2 shows the daily summed (the deposition in all pixels over the domain) time series of total dust deposition in Box N and Box S, where clear seasonal cycles are observed for both graphs. The plots show that CCAM simulated a higher deposition in Box S than Box N, ranging from 0.00-98.83 $\text{g/m}^2/\text{day}$ with a mean of 6.95 ± 8.77 (mean $\pm$ standard deviation) $\text{g/m}^2/\text{day}$ for the domain. The daily total dust deposition to Box N ranged from 0.08-45.87 $\text{g/m}^2/\text{day}$ with a mean of 3.86 ± 3.85 $\text{g/m}^2/\text{day}$ for the domain. This difference in deposition may be explained by the difference in potential source regions in that northern Namibia is mostly gravel plain, and the south mostly consists of dunes. Figures 6-3 and 6-4 illustrate the mean of these concentrations per pixel over the domain of each hotspot between 1979 and 2013. Please note that there's no time in the unit for these maps as they show the mean per pixel throughout the modelling period. The model simulated most of the deposition along the coast in both Box N and Box S. In Box N, most of this deposition was simulated between 16.8°S and 17.7°S, while in Box S, most deposition was modelled to occur between 26.5°S and 27.1°S. Notably, the simulated CCAM deposition to Box N agrees with the findings reported in **Chapter 4**. As shown and discussed, the identified and

previously unclassified Angolan sources emit and deposit dust to the adjacent BUS during the winter months – in the same region as Box N. While CCAM functions as a model, it cannot identify new source regions. It only simulates dust emissions from regions explicitly designated as sources. Although the results convey deposition and not emission, it's still fascinating that the model simulates high deposition in Box N. From the simulation, three locations in Box N experienced the highest depositions, exceeding 40 g/m^2 between 1979 and 2013. These locations are $17^\circ\text{S } 11.7^\circ\text{E}$, $17.4^\circ\text{S } 11.7^\circ\text{E}$, and $17.6^\circ\text{S } 11.7^\circ\text{E}$. In Box S, however, CCAM simulated the bulk of the domain deposition at $26.6^\circ\text{S } 15.1^\circ\text{E}$, with slightly less deposition occurring at $27^\circ\text{S } 15.2^\circ\text{E}$.

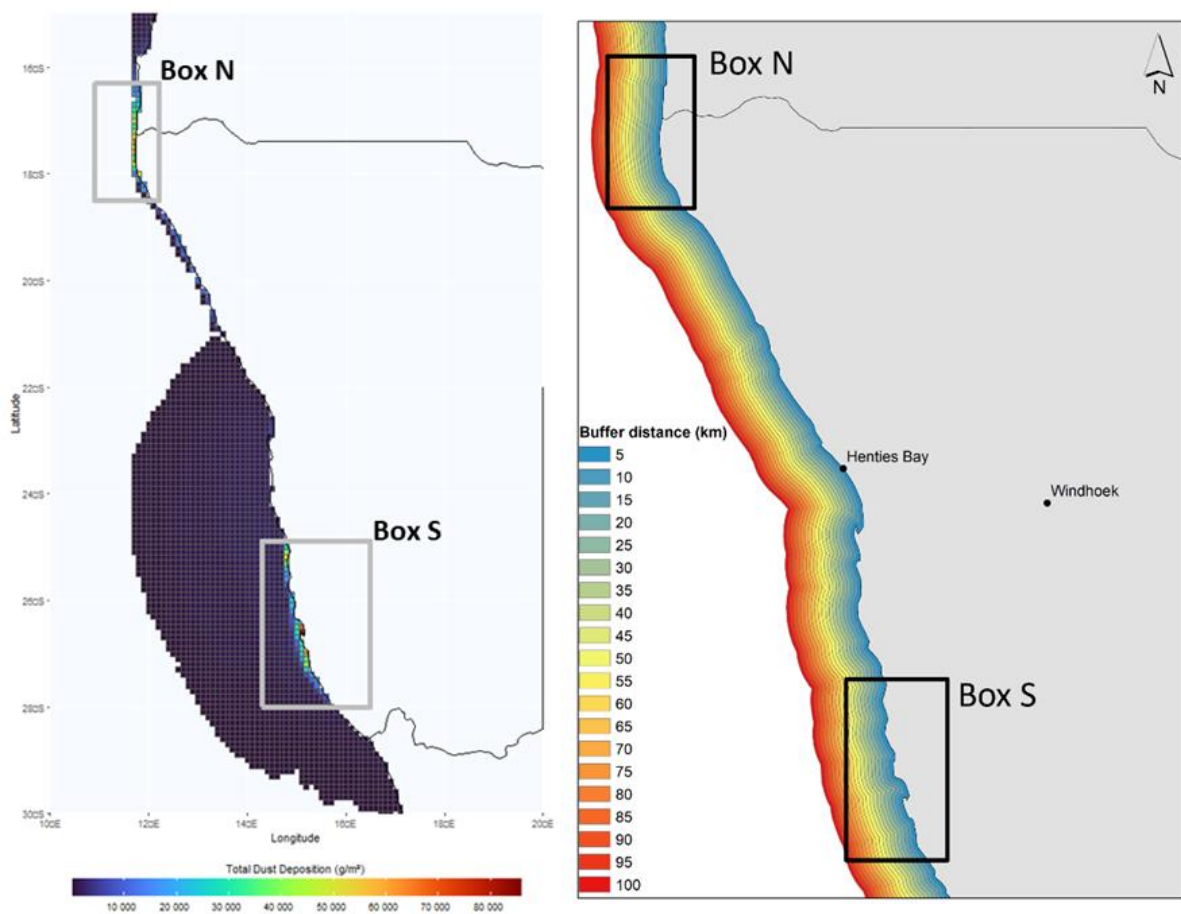


Figure 6-1: The identification of Box N to the north and Box S to the south of the domain and 5 km increment buffers.

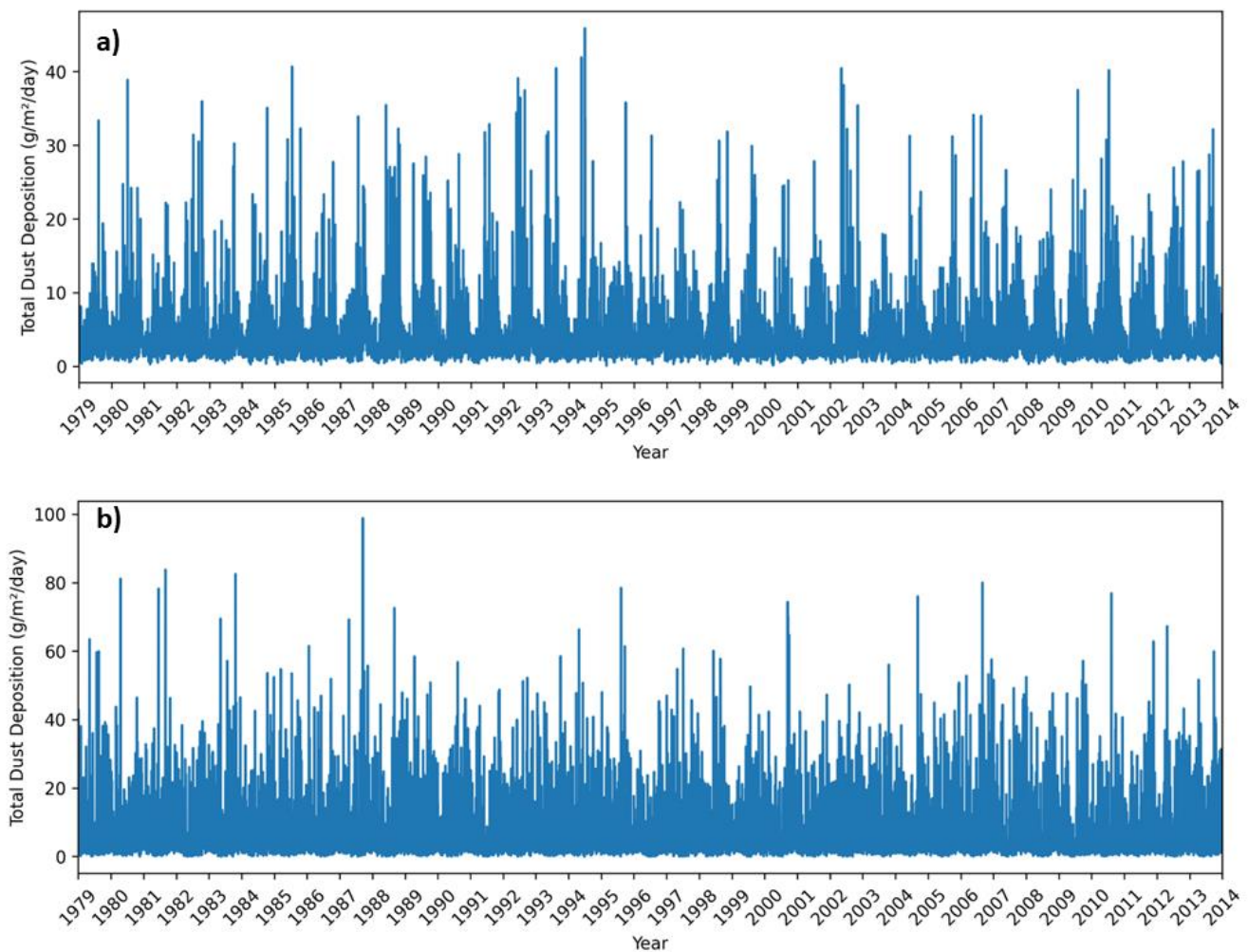


Figure 6-2: Time series of daily summed CCAM daily dust deposition (g/m²/day) between 1979 and 2013 in a) Box N and b) Box S. Please note that the y-axis scales are different.

Most of this deposition was simulated to occur within 20 km of both coastlines (Table 6-1 and Table 6-2), with the highest deposits occurring within 5 km of both Box N (sum of 11.50 g/m²/year and mean of 0.88 g/m²/year) and Box S (sum of 13.12 g/m²/year and mean of 1.09 g/m²/year). Note the unit as the analysis ensued for annual statistics and not daily. This observation is most likely due to the gravitation as although CCAM simulates dust being removed through wet and dry deposition processes, it also simulates dust being removed through gravitational settling of the coarser particles (Lohmann et al., 1999; Ginoux et al., 2001; Rotstayn & Lohmann, 2002; Horowitz et al., Horowitz et al., 2017). The model simulation also agrees with an earlier proposal that the southern African dust sources have a more substantial local than global impact, given the size of the sources and generally weaker winds (Li et al., 2008). In Box N, no dust deposition was modelled between 70 km and 100 km offshore. In Box S, however, deposition was simulated up

to 100 km from the coast, although very low between 95 km and 100 km. Interestingly, the CCAM total dust deposition was highest closest to the coast, decreasing with distance from the land. This spatial pattern is also observed in Box S.

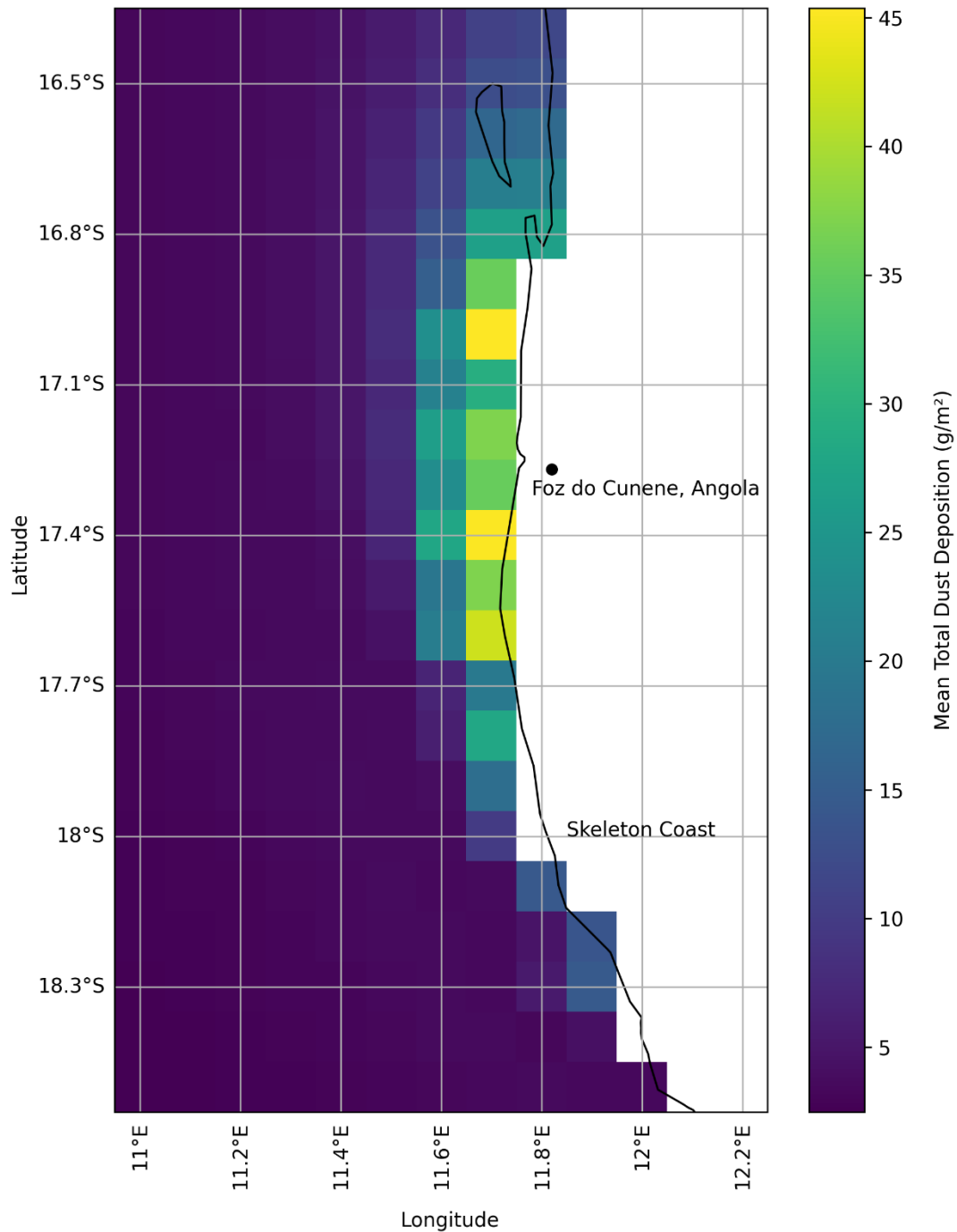


Figure 6-3: Mean CCAM modelled dust deposition (g/m²) to each pixel over the modelled period (1979-2013) of Box N.

Table 6-1: Zonal statistics of simulated yearly dust deposition (g/m²/year) to the ocean in Box N during 1979-2013.

Distance (km)	Min	Max	Mean	Stdev	Sum of all years
5	0.02	1.76	0.88	0.50	11.50
10	0.07	1.62	0.88	0.44	8.81
15	0.00	1.19	0.50	0.37	5.97
20	0.00	1.06	0.50	0.42	4.99
25	0.00	0.39	0.15	0.14	1.92
30	0.00	0.41	0.24	0.18	2.17
35	0.00	0.22	0.06	0.08	0.78
40	0.00	0.16	0.08	0.07	0.84
45	0.00	0.11	0.03	0.04	0.33
50	0.00	0.05	0.01	0.02	0.11
55	0.00	0.05	0.02	0.02	0.17
60	0.00	0.04	0.01	0.01	0.07
65	0.00	0.01	0.00	0.00	0.01
70	0.00	0.00	0.00	0.00	0.00
75	0.00	0.00	0.00	0.00	0.00
80	0.00	0.00	0.00	0.00	0.00
85	0.00	0.00	0.00	0.00	0.00
90	0.00	0.00	0.00	0.00	0.00
95	0.00	0.00	0.00	0.00	0.00
100	0.00	0.00	0.00	0.00	0.00

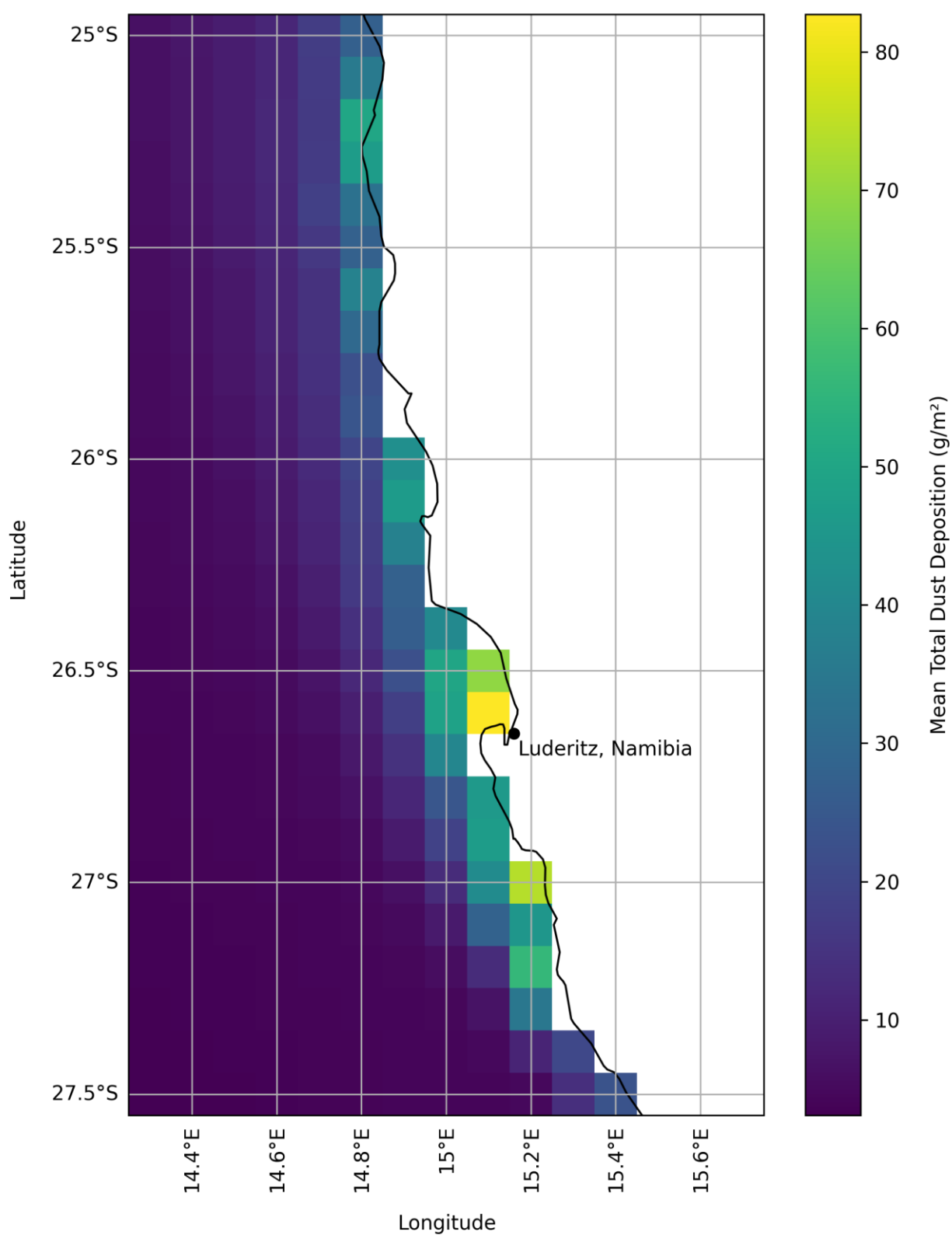


Figure 6-4: Mean CCAM modelled dust deposition (g/m^2) to each pixel over Box S's modelled period (1979-2013).

Table 6-2: Zonal statistics of simulated yearly dust deposition (g/m²/year) to the ocean in Box S from 1979-2013.

Distance (km)	Min	Max	Mean	Stdev	Sum of all years
5	0.25	2.52	1.09	0.68	13.12
10	0.11	1.19	0.61	0.34	9.79
15	0.05	0.90	0.24	0.27	3.14
20	0.05	0.48	0.12	0.11	1.86
25	0.05	0.08	0.06	0.01	0.60
30	0.04	0.10	0.05	0.01	0.78
35	0.04	0.05	0.05	0.00	0.75
40	0.04	0.05	0.05	0.00	0.61
45	0.04	0.06	0.05	0.01	0.75
50	0.04	0.06	0.05	0.01	0.57
55	0.04	0.06	0.05	0.00	0.73
60	0.04	0.05	0.05	0.00	0.69
65	0.03	0.05	0.04	0.01	0.20
70	0.03	0.05	0.04	0.01	0.42
75	0.03	0.05	0.03	0.01	0.17
80	0.02	0.04	0.03	0.01	0.16
85	0.02	0.03	0.03	0.00	0.11
90	0.02	0.02	0.02	0.00	0.07
95	0.02	0.02	0.02	0.00	0.04
100	0.02	0.02	0.02	0.00	0.04

6.2.2 Annual Variation in CCAM Total Dust Deposition

The CCAM-modelled annual total dust deposition varied considerably between years, as shown in Figure 6-5. The annual results for both domains are within the mean dust deposition average for the Namibian/Angolan region of 2-20 g/m²/year modelled in previous studies (Luo et al., 2003; Ginoux et al., 2004; Tegen et al., 2004; Textor et al., 2006; Schulz et al., 2012). In Box N, after reaching one of the lowest modelled concentrations in 1991, there was a substantial increase to reach its peak (8.20 g/m²/year) in 1993. The lowest modelled deposition was reached in 2001 (6.60 g/m²/year) and 2004 (6.50 g/m²/year). Box S has an almost identical inter-annual variation, with one notable exception: between 1979 and 1986, the pattern appears to be the reverse of what is seen in Box N. The maximum was reached in 1988 (14.40 g/m²/year). From 1992, however, the

pattern in Box is strikingly similar to that of Box N except for reaching its minimum (10.20 g/m²/year) in 2002 rather than 2004.

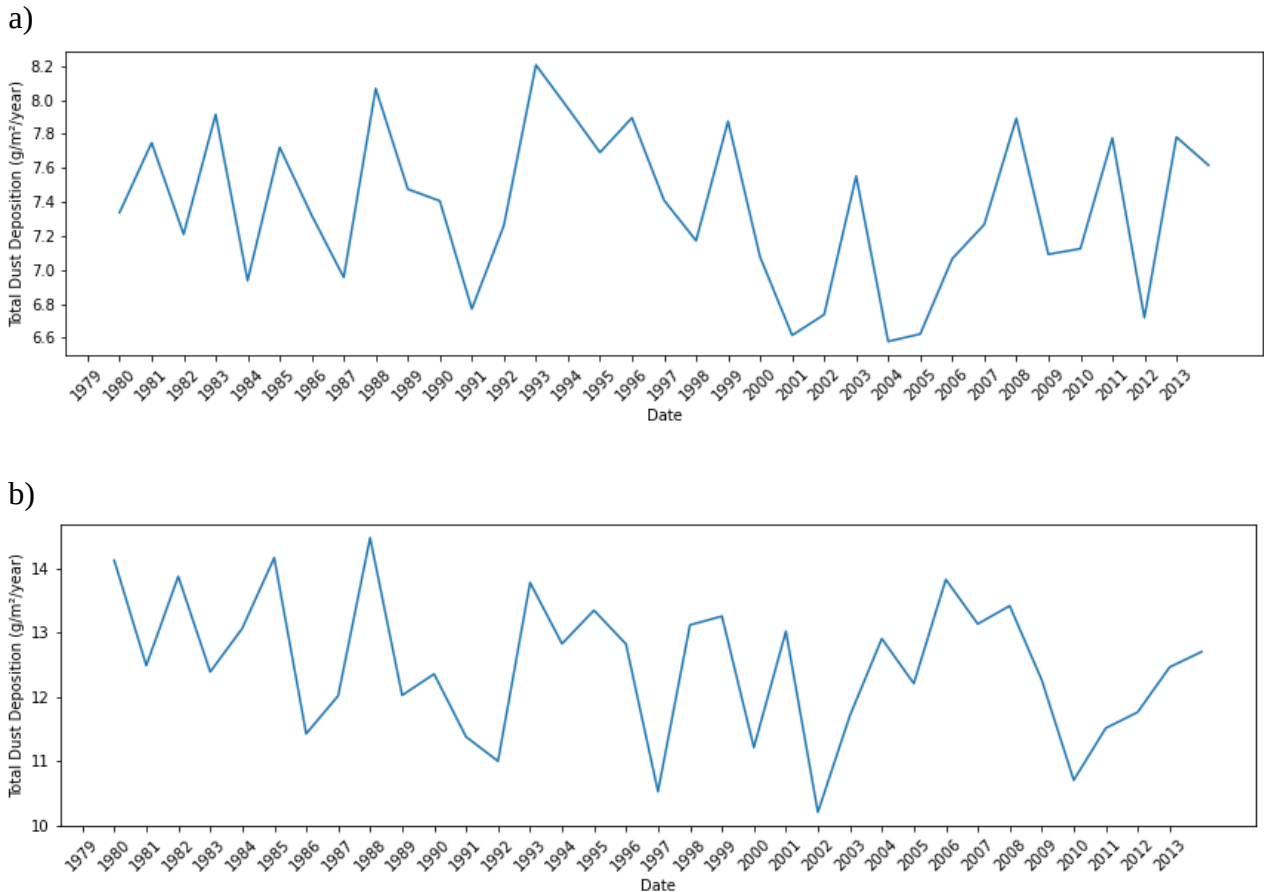


Figure 6-5: Annual variation in the mean modelled CCAM dust deposition (g/m²/year) to a) Box N and b) Box S between 1979 and 2013. Note that the scales on the y-axis are different.

6.2.3 Monthly Variation in CCAM Total Dust Deposition

Most southern African dust sources are active during the dry austral winter, peaking in August/September (Vickery et al., 2013). Figure 6-6 presents the CCAM-modelled seasonal variation in the dust deposition as monthly boxplots. There was a significant difference in modelled deposition between seasons in Box N, where it followed a clear seasonal pattern. The deposition was modelled to increase in summer (December to February), reaching their lowest overall concentrations during the Autumn months (March, April and May). Then, the concentrations increased significantly in July, followed by a decline from thereon to the August concentrations. After that, the

deposition steadily increased from September to November, reaching its maximum in October. The seasonal pattern in Box S appears to be similar but with notable exceptions.

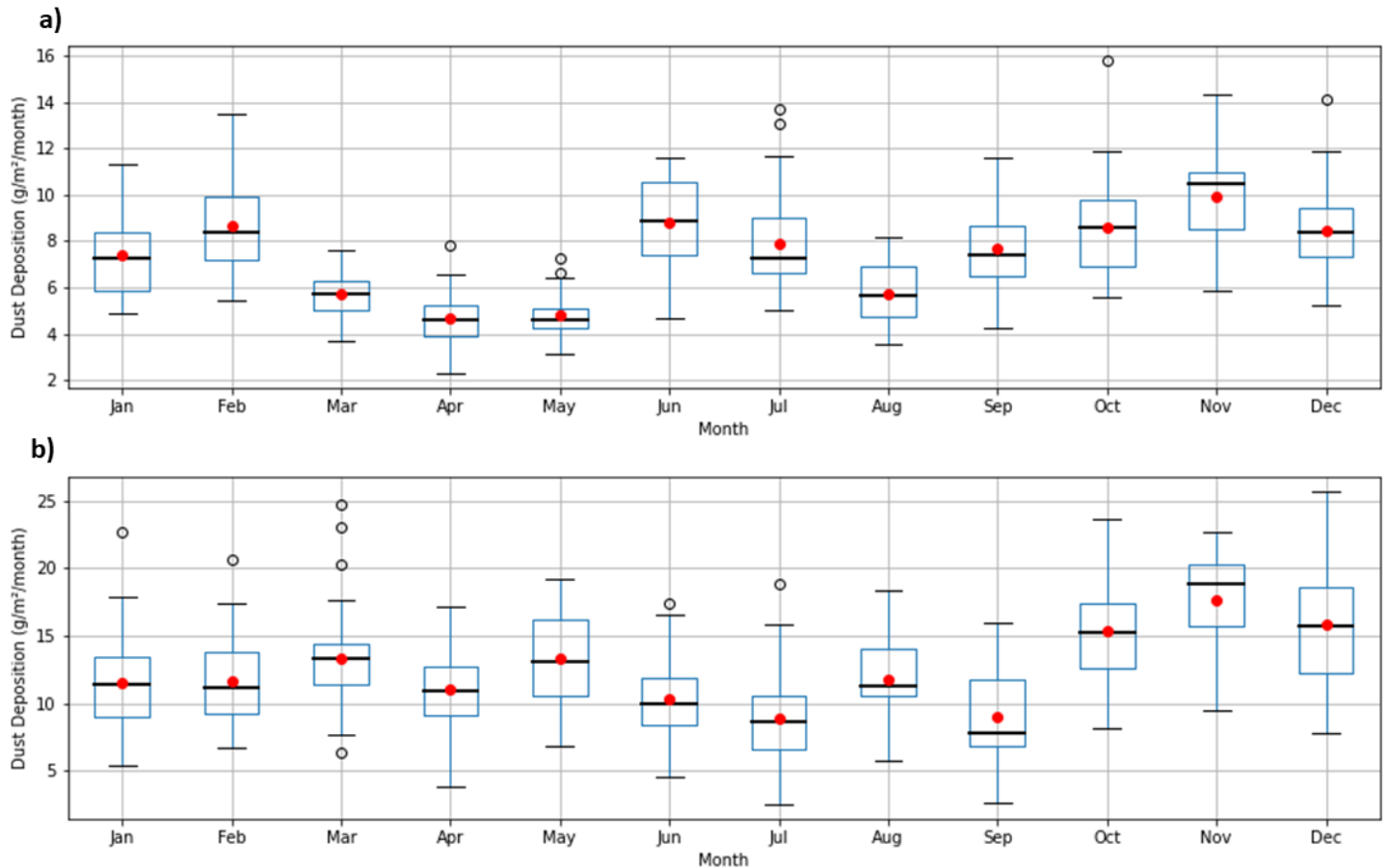


Figure 6-6: Monthly boxplots showing the seasonal variation in CCAM-modelled dust deposition ($\text{g/m}^2/\text{year}$) to a) Box N and b) Box S. The red dot represents the mean dust deposition per month over all years. The black horizontal line in the middle represents the median, while the blue horizontal lines represent the 25th and 75th percentiles. The top and bottom whiskers (black horizontal lines) extend to the maximum and minimum data values. The black circles signify the modelled outliers. Note that the scales on the y-axis are different.

In Box S, to some extent, the deposition appears to decline from its maximum deposition during the summer (December), with no significant transition to the autumn season until a visible increase during May. A decrease follows this in reaching the minimum deposition during July. After that, the deposition increased in August and decreased again during September. Notably, the deposition periods between the regions were modelled to be opposite between February and September.

CCAM, of course, has inherent uncertainties and does not perfectly represent the complex processes which occur in the real world. The differences in the simulated dust deposition to Box N

and Box S may be due to several factors. First, the dust source and soil properties are critical factors impacting simulated dust in the model (Textor et al., 2006). The dust source fluxes are very sensitive to the wind speed distribution over a domain (Timmreck & Schulz, 2004). The particle size may be the second reason for the difference (Textor et al., 2006), as larger particles are removed the closer they are to their emission source, affecting their dispersivity. The previous question may be worthwhile as the model outputs deposition in four particle-size bins, but it was not an objective of the present study.

6.3 MERRA-2 Total Dust Deposition to Box N and Box S During 1980-2013

Figure 6-7 shows the MERRA-2 dust deposition evaluation. Please note that the plots show the mean dust deposition per pixel between 1979 and 2013 (g/m^2) and not the sum. It revealed similarities with the CCAM-modelled dust deposition in both domains. When considering the total dust deposition areas in Box N, CCAM and MERRA-2 exhibit similar patterns. However, it's noteworthy that the dust deposition from CCAM is nearly twice as much as that from MERRA-2. The CCAM dust deposition mean ranged from 2.68 to 3.60 g/m^2 , while the MERRA-2 dust deposition ranged from 0.20 to 1.50 g/m^2 . While CCAM simulated the highest deposition between 16.5°S 11°E and 17.5°S 11°E (exceeding 3.5 g/m^2 at three locations), the MERRA-2 dust deposition was highest at 18.5°S 11.9°E. Interestingly, both datasets had the lowest dust deposition in the southeastern portion of the domain at 18.5°S 11.25°E. Although the mean dust deposition and the spatial variation between CCAM and MERRA-2 in Box N were similar, their monthly values were positively correlated but weak ($r^2=0.12$; $p<0.05$), as shown in Figure 6-8. It should be noted that the MERRA-2 dataset contains dust deposition data in $\text{kg/m}^2/\text{s}$. Given that the CCAM data is in $\text{g/m}^2/\text{year}$, the datasets were resampled to identical units before any comparisons. Figure 6-8 shows the mean variation over time of the $\text{g/m}^2/\text{month}$.

At first glance, the spatial distribution of the CCAM and MERRA-2 dust deposition to Box S appear to be similar, with the lowest deposits occurring along the western edge of the domain.

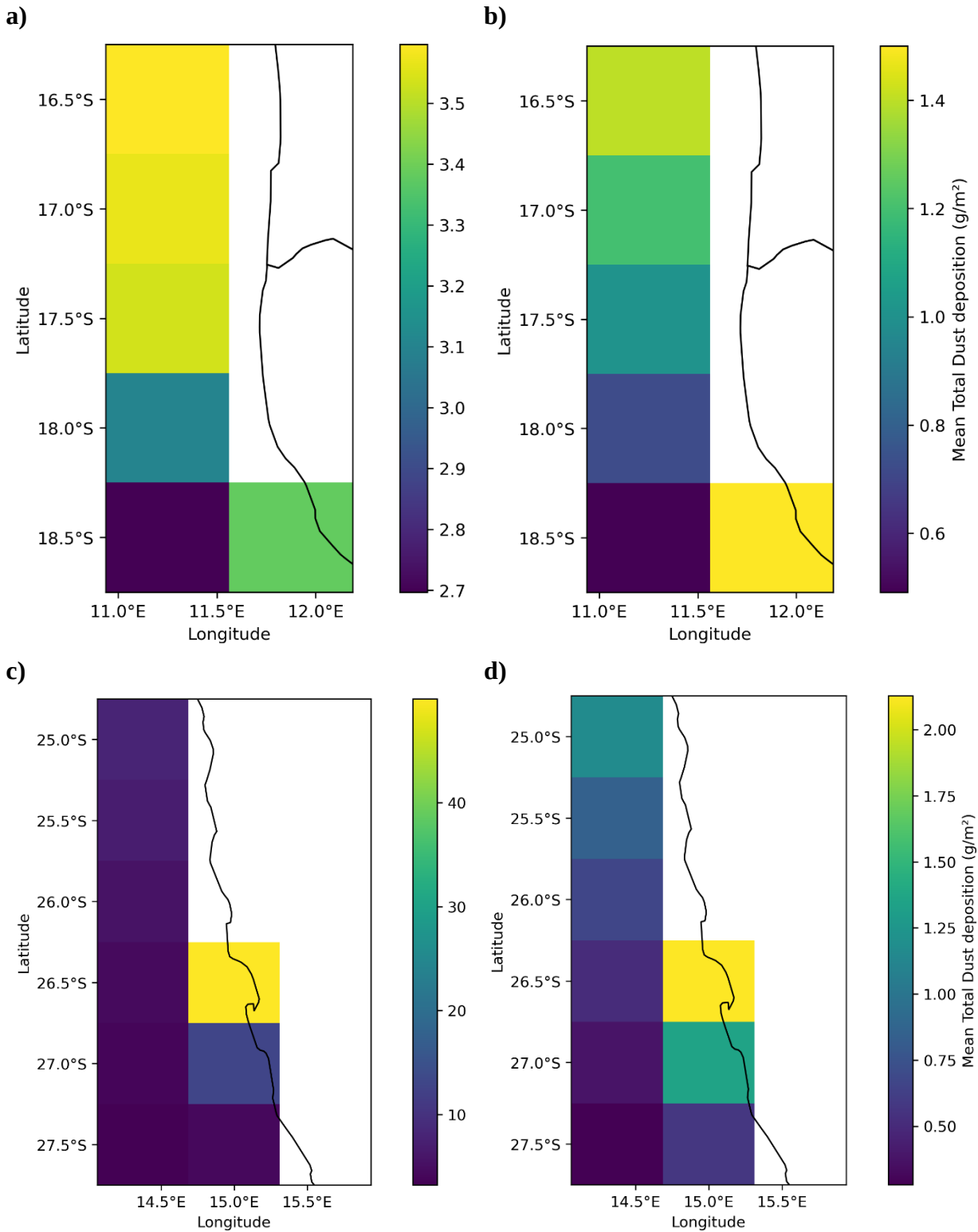


Figure 6-7: Mean dust deposition (g/m²) per pixel in a) the CCAM Box N domain, b) the MERRA-2 Box N domain, c) the CCAM Box S domain and d) the MERRA-2 Box S domain (1980-2013).

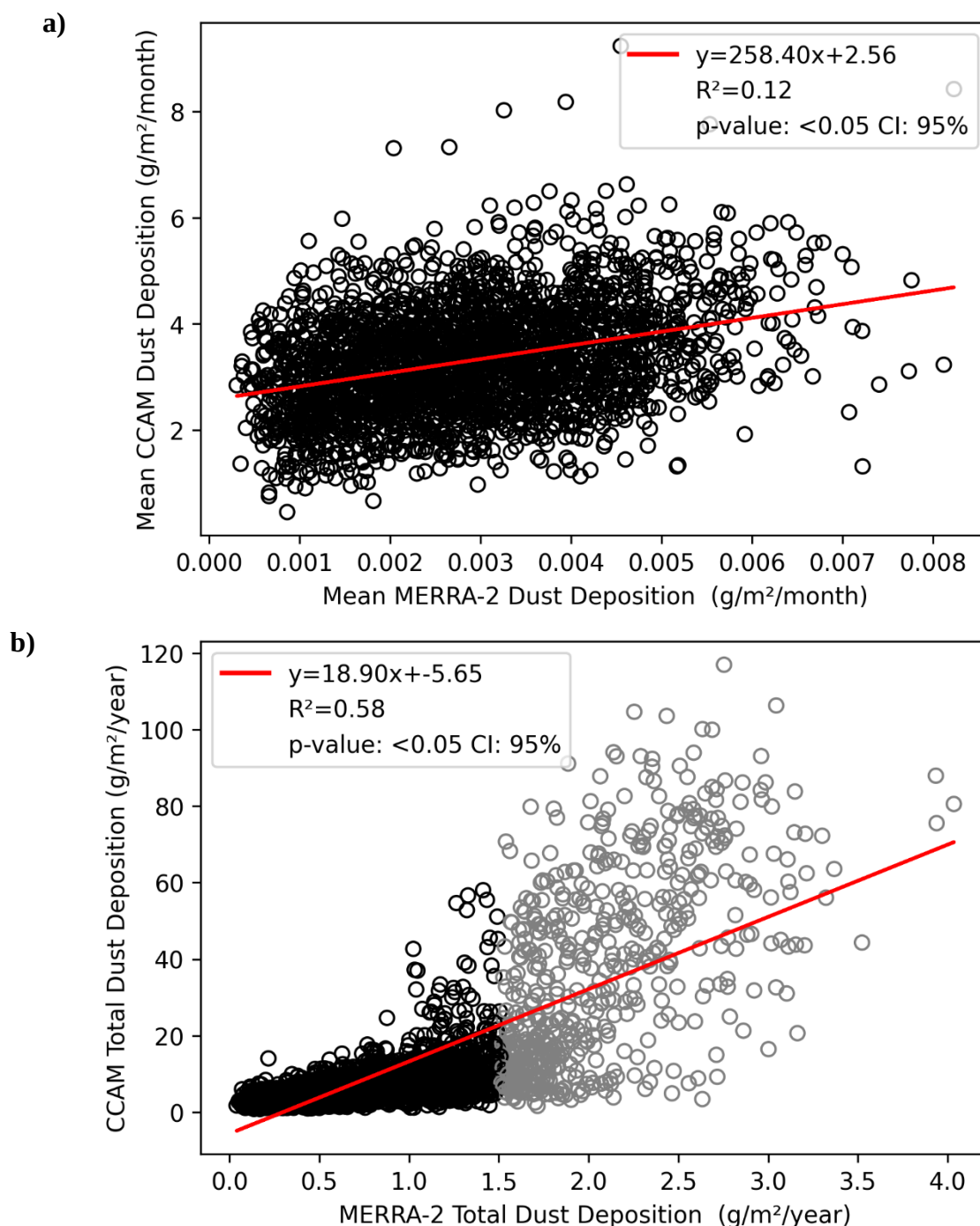


Figure 6-8: This figure illustrates the correlation between the monthly mean dust deposition values of CCAM and MERRA-2 in a) Box N and b) Box S. The black and grey dots represent two distinct patterns of correlation that were observed in the data.

However, the mean dust deposition modelled by CCAM is significantly higher (0.04-50.00 g/m²) than that in the MERRA-2 data (0.00-2.25 g/m²) by a factor of about 25. Both datasets had the highest dust deposition at 26.5°S 15°E, and like in Box N, their lowest deposition was in the southwestern corner of the domain. The spatial variation between the datasets was similar, although the CCAM-simulated deposition was significantly higher. Despite this difference, the monthly values between the datasets were significantly positively correlated ($r^2=0.58$; $p<0.05$) (Figure 6-8), where two regimes can be identified at about $\leq 1.7.1$ on the x and ≤ 20 on the y-axis. The previous result means that in Box S, some results are closely aligned while others are sparser. However, while the last statement holds spatially, it does not apply quantitatively, as the dust deposition from CCAM is significantly higher.

6.4 Chlorophyll-a Concentrations in Box N and Box S During 1997-2013

This section uses a satellite Chl-a dataset to investigate whether the seasonal cycle in the BUS aligns with CCAM-modelled dust deposition. The spatial distribution of the Chl-a concentration (mg/m³) for Box N and Box S from February 1997 to December 2013 is shown in Figure 6-9. The plots indicate that although the Chl-a concentrations between Box N and Box S are very similar, ranging from 0-2.81 mg/m³, the concentrations vary spatially. Mirroring the patterns observed in the simulated dust deposition in Box N for MERRA-2, the Chl-a concentration exhibited its peak mean concentration in the southeastern raster cell of the domain. Until this point, the Chl-a concentration was at its lowest in the northern part of the domain, gradually increasing as it moved southward.

Interestingly, the MERRA-2 dust deposition displayed an inverse pattern, decreasing deposition levels from north to south. An almost identical spatial distribution to MERRA-2 was observed for the CCAM deposition, except that the highest deposition was not simulated in the southeastern part of the domain. The Chl-a spatial distribution in Box S is much more similar to the deposition observed for CCAM and MERRA-2, with the highest concentration over the centre of the domain. In an evaluation of the MERRA-2 dust deposition performance over Patagonia, a previous study found that its performance varies from little discrepancy to underestimations as large as 21-fold depending on where over the domain (Cosentino et al., 2021). The study ascribed the underestimation to the exclusion of local dust-emitting sources. As MERRA-2 attributes sources at a scale of 1° by 1° (Ginoux et al., 2001), smaller-scale sources like deflated pans and ephemeral riverbeds might have been excluded. Bullard et al. (2006) argue that this underestimation may be improved

by correctly representing sources at a smaller scale. That said, this doesn't necessarily mean that the MERRA-2 deposition is over- or underestimated; instead, it serves as a potential explanation for the significant difference in deposition in the Box S domain. Perhaps the previously identified small-scale sources (Eckardt & Kuring, 2005; Vickery & Eckardt, 2013; von Holdt et al., 2017) are not well represented in the MERRA-2 dataset, and perhaps this information is well or better constrained within CCAM.

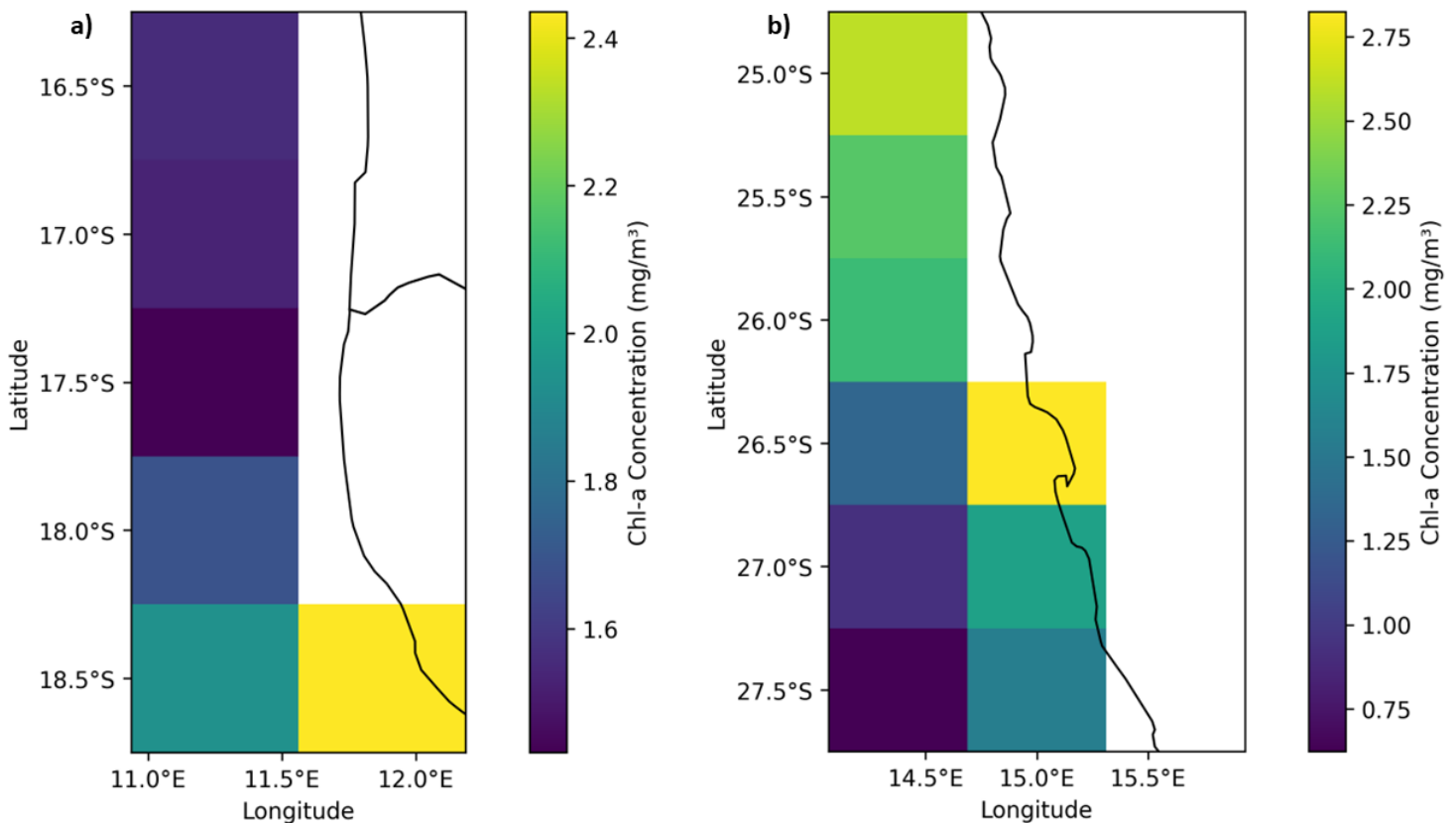


Figure 6-9: Mean Chl-a concentration (mg/m³) per pixel in a) Box N and b) Box S between February 1997 and December 2013.

The mean monthly variation in Chl-a concentrations is illustrated in Figure 6-10. As shown, the Chl-a concentrations in Box N and S followed an apparent and similar seasonal pattern. In Box N, the Chl-a concentrations increased from December to January and decreased to February when the minima were reached. Then, the highest overall concentrations were reached in autumn, with the maxima observed during May. These concentrations were significantly higher compared to the other months. The transition to the winter months started with a significant decrease in

concentrations during June and a moderate increase towards August. From thereon, no significant variation was observed towards November except for outliers.

The seasonal pattern observed in Box S followed a similar trend to that observed in Box N, with some exceptions. For example, the maxima and significantly higher concentrations were also observed during autumn, but this time, in April. The concentrations during the middle summer (February) and early to mid-winter (June and July) were significantly lower than in other months. Another exception is observed where the concentration variations in August are very similar to those during Autumn. The concentrations then decreased to September, followed by an increase towards October and November. These results somewhat agree with an earlier observation that inshore Chl-a in the Benguela typically peaks during August, December and late Autumn (April) (Louw et al., 2016).

The Chl-a seasonal cycle is not in line with the CCAM-modelled total dust deposition seasonal cycle in both domains. Box N's overall lowest dust deposition was modelled during autumn, while the highest Chl-a concentrations were observed during this time. CCAM also modelled some of the highest deposition during June and July, while the Chl-a concentrations were some of the lowest during these months. There are, however, some similarities between the seasonal cycles of CCAM-modelled dust deposition in Chl-a concentrations in Box S. For instance, some of the highest dust deposition was modelled during autumn and is in line with the overall highest Chl-a concentrations during the same season. Also, CCAM modelled some of the lowest deposition during June and July, which agrees with the lowest observed Chl-a concentrations.

Moreover, the increase in CCAM deposition towards August and a decrease in September also align with the observed Chl-a variation during the same period. The relationship between dust deposition and Chl-a in the Benguela has previously been shown to have a strong and positive linear association (Dansie et al., 2022). In the present study, correlation analysis revealed that the Chl-a monthly means between the domains are well correlated ($r^2=0.60$) but that the CCAM-modelled dust deposition is not correlated ($r^2=0.08$). The analysis also revealed that CCAM dust deposition negatively correlates with Chl-a in Box N ($r^2=0.58$) and not with Chl-a in Box S ($r^2=0.08$). Therefore, the results reveal that the dust deposition and Chl-a in Box N and Box S are somewhat aligned in space but not in time.

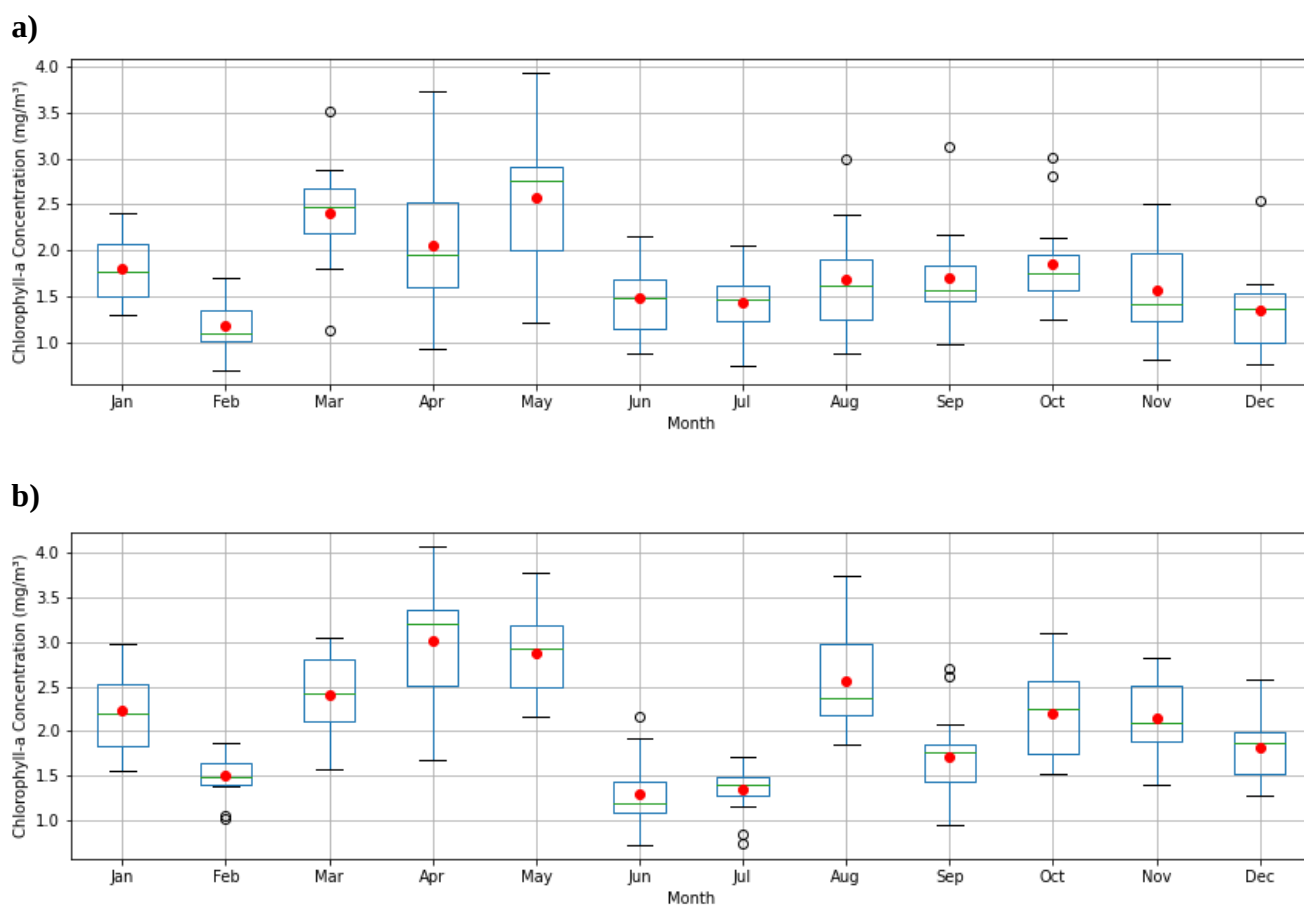


Figure 6-10: Monthly boxplot of chlorophyll-a concentrations (mg/m³) in a) Box N and b) Box S during 1997-2013. The red dot represents the mean Chl-a concentration per month over all years. The green horizontal line represents the median, while the blue horizontal lines represent the 25th and 75th percentiles. The top and bottom whiskers (black horizontal lines) extend to the most extreme data value within 1.5 times the interquartile range, and the black circles signify the outliers.

6.5 Chapter Conclusions

The objectives of the results portrayed and discussed in this chapter were to evaluate a long-term CCAM dust deposition simulation to the Benguela current by:

- Analysing the CCAM-modelled total dust deposition to the Benguela current
 - Evaluating the model performance relative to the MERRA-2 dust deposition
 - Investigating whether the seasonal cycle of CCAM dust deposition is similar to the seasonal cycle of Chl-a in the Benguela current
-

The following inferences can be made:

Overall, CCAM simulated a higher dust deposition to Box S than Box N during 1979-2013. This may be because Box N is within the gravel region of northern Namibia and southern Angola, and Box S is in the southern Namibian dune region. Most dust deposition occurred within 20 km of the coast in both domains. This can be explained by the dominance of dry deposition processes or the gravitational settling of coarser particles, which would cause particles to fall out over land or closer to the shore. There are well-defined locations where CCAM simulated the highest depositions in both domains. In Box N, there were multiple locations at 17°S 11.7°E, 17.4°S 11.7°E, and 17.6°S 11.7°E. In Box S, however, CCAM simulated the vast majority of the domain deposition at 26.6°S 15.1°E, with somewhat less deposition modelled at 27°S 15.2°E. These findings agree with an earlier suggestion that the southern African dust sources have a predominantly localized influence. Annually, the modelled deposition reached its lowest levels in Box N (6.5 g/m²/year) in 2004 and in Box S (10.2 g/m²/year) in 2002, and its highest levels in Box N (8.2 g/m²/year) in 1993 and Box S (14.4 g/m²/year) in 1988. The findings are within the mean annual dust deposition simulated range by global models (2-20 g/m²/year), ranging from 6.5-8.2 g/m²/year in Box N and 10.2-14.4 g/m²/year in Box S.

The evaluation between CCAM and MERRA-2 reanalysis total dust deposition revealed comparable mean values, especially in Box N. In Box S, however, the mean dust deposition modelled by CCAM is notably higher (0.04-50.00 g/m²) than that in the MERRA-2 data (0.00-2.25 g/m²). For both datasets, the spatial variation in deposition in both domains is very similar at distinct locations. However, despite the similarities in the mean values in Box N, a weak positive correlation between the monthly values was observed ($r=0.35$; $p<0.05$). Although there was a significant

difference in the mean monthly deposition in Box S, the datasets were significantly positively correlated. The deposition between CCAM and MERRA-2 is similar spatially but not quantitatively, given the substantially higher deposition in CCAM.

The results reveal that the dust deposition and Chl-a in Box N and Box S are somewhat aligned in space but not in time. The comparison between the domains showed that the Chl-a data is correlated but that CCAM simulated distinctly different dust deposition between them. The model simulation is not aligned with the seasonal Chl-a cycle. No seasonal correlation and agreement were found in comparing the CCAM dust deposition with the observed Chl-a concentrations separately for Box N and S. In Box N, there appears to be a completely random response, while in Box S, a negative correlation was observed. There seems to be no direct link between the modelled dust deposition and Chl-a because CCAM is a model and Chl-a reality, with MERRA-2 being closer to reality although not sufficiently verified. The finding that dust deposition in the model doesn't impact reality is correct and makes sense. In other words, the CCAM results do not directly influence real-world phenomena like phytoplankton abundance or Chl-a. The CCAM model predicts dust deposition, which can influence Chl-a concentrations. However, the model's predictions are not always perfectly accurate, and thus, the modelled dust deposition may not perfectly align with the actual dust deposition observed in reality. This is as far as the objectives of this study go, but some gaps have been identified for prospective studies. The CCAM dust deposition might agree with the seasonal Chl-a cycle for a single dust-size bin or all the size bins in either wet or dry deposition.

CHAPTER 7

The following chapter presents the results for Objective V: ‘*Investigate the response of phytoplankton to dust addition in a mesocosm experiment*’. The results presented are significant and novel in that the direct relationship between Namib desert dust and BUS phytoplankton has not yet been investigated in a mesocosm study. The nutrient and Chl-a variations over a two-week experiment and the correlation between Chl-a changes and that of the nutrients and light intensity are presented.

THE RESPONSE OF BENGUELA CURRENT PHYTOPLANKTON TO NAMIB DESERT DUST ADDITION

7.1 Background

Eastern Boundary Upwelling Systems (EBUS), despite covering only 1% of the Earth's ocean surface, stand out as globally significant and highly productive regions (Pauly & Christensen, 1995; Carr, 2001; Dansie et al., 2022). The Benguela Upwelling System (BUS), situated along the west coast of South Africa, Namibia, and Angola within the 19-34°S range, is a notable EBUS (Hutchings et al., 2009). Nestled in the South Atlantic tropical gyre, the BUS is renowned for its robust production of diatoms, dinoflagellates, and small flagellates, supporting a thriving fishing industry (Louw et al., 2016). Distinguishing itself from other EBUS, the BUS is bordered by warmer waters on its northern and southern perimeters, with a significant upwelling cell marked off the Lüderitz coast at 26°S (Duncombe Rae, 2005; Hutchings et al., 2009; Flohr et al., 2013). The subsystems within the BUS exhibit variability, influenced by different mechanisms (Hutchings et al., 2009; Verheye et al., 2016). The northern BUS experiences constant upwelling, while the southern BUS encounters seasonal upwelling, peaking during spring and summer due to prevailing south-east trade winds and associated Ekman spiral offshore (Shannon and Nelson, 1996; Romero et al., 2003; Hutchings et al., 2009). This seasonal upwelling triggers the influx of nutrient-rich waters, fuelling phytoplankton productivity (Shannon, 1985; Lutjeharms & Meeuwis, 1987; Louw et al., 2016), with the northern BUS exhibiting approximately an order of magnitude higher upwelling intensity (Rixen et al., 2021).

While nutrient-rich waters drive productivity in eastern boundary upwelling systems, differences in chlorophyll (Chl-a) productivity exist among them (Carr & Kearns, 2003). This discrepancy suggests that factors such as phytoplankton fertilisation from dust may be crucial in explaining productivity variations (Dansie et al., 2022). These systems are recognized for displaying characteristics of high nutrient low chlorophyll (HNLC) ocean regions (Capone & Hutchins, 2013). Iron (Fe) is identified as a limiting factor for primary production in these regions (Mahowald et al., 2005), mirroring its role in the eastern boundary upwelling systems' productivity limitation (Messié & Chavez, 2015). Dust plays a vital role in transporting macronutrients like nitrogen (N) and phosphorus (P), as well as biologically essential Fe, to oceanic phytoplanktonic communities

(Okin et al., 2011). Although the precise biogeochemical role of N, P, and Fe in various marine environments remains uncertain (Achterberg, 2014), the overall contribution of dust to nutrient loading is deemed crucial for primary productivity in aquatic systems (Mahowald et al., 2008; Zehr & Kudela, 2011; Bouwman et al., 2013)

An estimated 477 Tg of dust is annually emitted from continental sources, with the South Atlantic receiving the sixth-highest amount at 17 Tg yr⁻¹, including approximately 0.11–0.32 Tg of soluble Fe (Jickells et al., 2005). Anthropogenically induced land surfaces, desert regions, and ephemeral dry lakes or riverbeds are primary sources of these dust supplies (Mahowald et al., 2003). Some research suggests that the primary input pathway for Fe is from continental shelves and ocean plateaus through lateral advection and upwelling of sediments (Meskhidze et al., 2007; Chever et al., 2010). The BUS, situated adjacent to such sources, experiences periodic dust inputs from nearby upwind desert regions (Eckardt and Kuring, 2005; Vickery and Eckardt, 2013).

Incubation studies have demonstrated positive growth responses to dust addition in various regions, including the Yellow Sea, the eastern and northwestern Mediterranean, the subtropical gyre, the northwest Pacific, and the western Tropical Atlantic Ocean. However, some studies indicate negative relationships between dust addition and phytoplankton, attributed to aerosol toxicity and specific metals, mainly observed for *Prochlorococcus* in marine regions. The primary dust emitters for the BUS are Makgadikgadi and Etosha pans, as well as Kuiseb, Huab, Tsauchab, and Omaruru ephemeral riverbeds, rich in Fe, N, and P (Dansie et al., 2017b). Despite the potential importance of dust inputs from these sources to the BUS, the effects of this dust on phytoplankton biomass have been relatively understudied until recently. A dust monitoring and Chl-a remote sensing study observed enhanced Chl-a concentrations daily. While some studies have investigated the response of phytoplankton to single nutrient treatments in the northern BUS, the response of BUS phytoplankton to a composite sample of Namib dust addition has not been explored. To address this gap, we conducted the first mesocosm study to investigate the impacts of Kuiseb riverbed dust on phytoplankton biomass in the BUS.

7.2 Initial Conditions

Before the addition of dust, at timestep 0, two samples were taken to measure the initial conditions in each mesocosm: one for total Fe and one for total Si, NO₃⁻, NO₂⁻, and PO₄³⁻. The CM had an

initial total Fe concentration of 3.87 nM. In comparison, the DG had a slightly higher total Fe concentration of 4.3 ± 0.95 nM. The initial total Si concentration was 65.16 nM for the CM and higher at 86.17 ± 5.33 nM for the DG. The initial NO_3^- concentration for both the CM and DG were below the detection limit of 4.03 nM. These concentrations remained below the detection limit for most of the experiment, except for at timestep 3, where the concentration in the CM reached 14.53 nM, possibly due to contamination.

Similarly, the NO_2^- concentrations remained below the detection limit of 1.09 nM for the duration of the experiment. For PO_4^{3-} , the initial concentration was 3.79 nM for the CM and 2.60 ± 0.99 nM for the DG. Chl-a concentrations were high for both groups, with the Control mesocosm having a concentration of 3.84 mg m^{-3} and the Dust mesocosm having a concentration of 4.94 mg m^{-3} . This experiment was conducted during the dry winter when most southern African dust sources are active (Vickery et al., 2013). This is important because the experiment was conducted near the Omaruru riverbed. Typically, Chl-a concentrations in the Benguela peak during August, December, and late Autumn (April) (Louw et al., 2016). This means the experiment was conducted weeks before potential phytoplankton blooms. In other words, the experiment was conducted during one of the year periods when there was a likely response from Benguela's current phytoplankton to southern African dust source deposition. However, there were no observable dust events during the experiment.

7.3 Temporal Dynamics in the Dissolved Nutrients

The seawater temperature during the experiment ranged from 13.5–24.5 °C (Figure 7-1), with a significant increase observed from 06 October until the end of the experiment. Provided that no other factors impose phytoplankton growth limitations, a temperature increase from 18 to 21.5 °C could potentially lead to an approximate 25% enhancement in growth (Finkel et al., 2010) but is species-specific (Zinser et al., 2007). Figure 7-2 shows the changes in the total Fe concentration in the CM and DG throughout the experiment. The total Fe concentration in the CM typically remained below the detection limit of 2.42 nM throughout the experiment, with slight elevations evident on days 8 and 10, where they reached maxima of 2.9 and 2.74 nM. In the DG, the mean total Fe concentrations (3.84 ± 2.01 nM) were typically higher (57.14%) than in the CM. Most days, the standard deviations were relatively small, indicating a good agreement between the DG. However, the deviation was exceptionally high at timestep 9. One of the total Fe concentrations at this

timestep was considered an outlier (32.57 nM measured in EX3) and almost certainly reflects contamination during sampling/storage. As such, this value was discarded from further analysis.

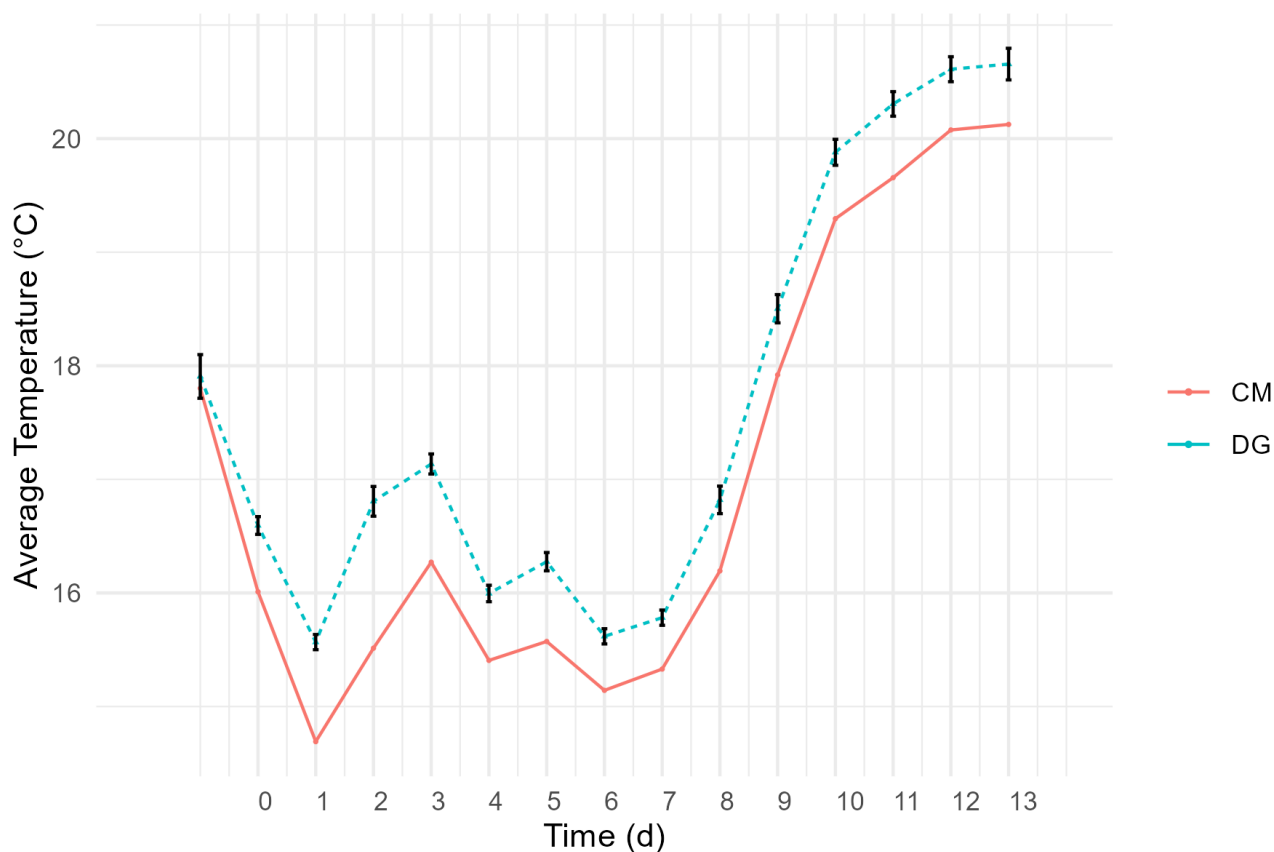


Figure 7-1: Temperature evolution in the mesocosms during the experiment. The error bars indicate the standard deviation in the DG group temperatures.

Notably, the concentrations were highest at the beginning of the time series for the two days following dust addition (5.21 ± 3.31 nM and 5.21 ± 2.78 nM). The concentrations subsequently decreased on day three and remained similarly low for the rest of the incubation period (2.53 ± 0.19 nM to 4.46 ± 2.51 nM). The observed changes in the total Fe concentration may have been due to several aspects of its chemistry, like its solubility, complexation, and the ligand exchange of the nutrient (Öztürk et al., 2003).

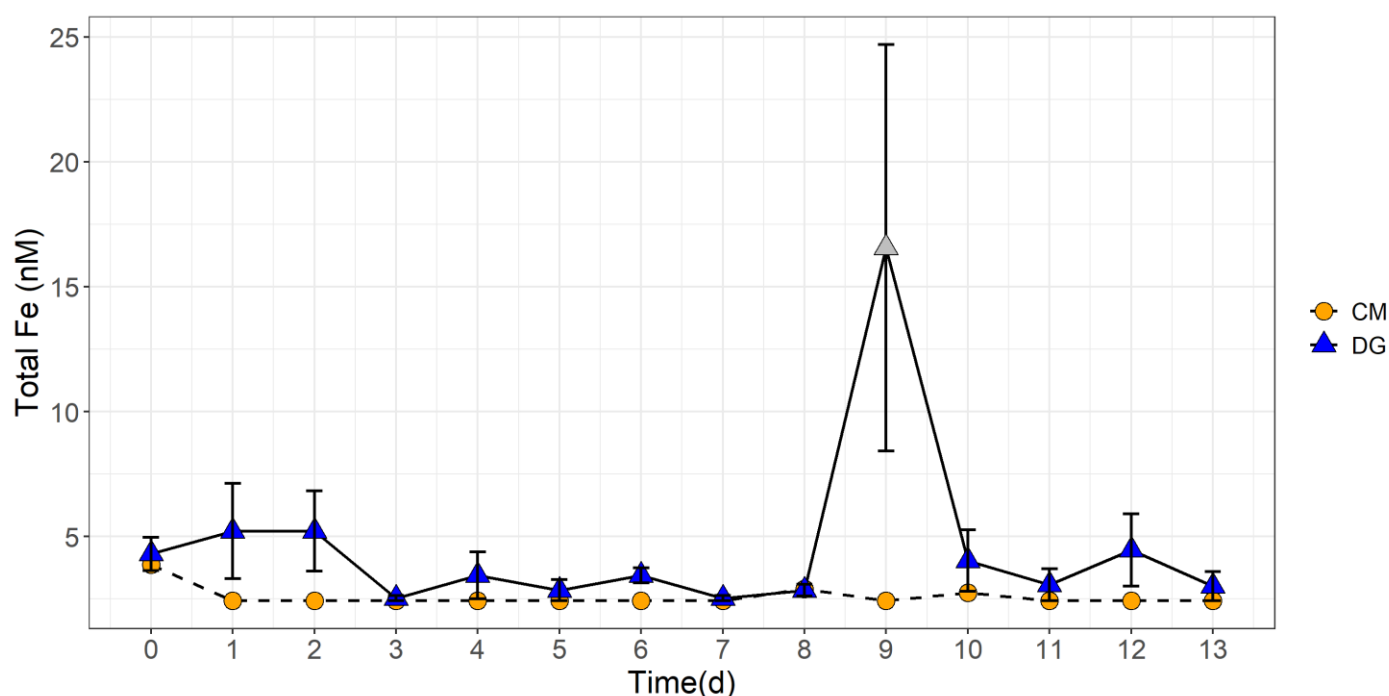


Figure 7-2: Concentration of total Fe in each group for the duration of the experiment. Time = 0 indicates the initial conditions, while Time = 1 represents the first measurement taken after dust addition to the DG. The error bars in the graph represent the standard deviation from the mean concentration. The grey triangle indicates a contaminated sample.

Dissolved Si in the BUS is typically highest during summer (5870 nM) and lowest during the winter (70 nM) (Wasmund et al., 2016). Figure 7-3 shows the total Si concentration in the present study's CM and DG, indicating strong variation between days. In the CM, the initial total Si concentration slightly increased to 81.54 nM on day 1 and then decreased to 45.22 nM on day 4. The concentration sharply increased to 95.78 nM on day 5, followed by a decline to 58.39 nM on day 6. On day 7, the highest concentration of 124.98 nM was reached, followed by a significant decrease to its minimum on day 9 of 37.74 nM. A second peak was reached on day 10 of 110.38 nM, followed by a decline to 43.08 on day 11 and a steady increase to 69.07 nM on the final day. Like the CM, the total Si concentration in the DG was never exhausted but showed a more pronounced general decline over time with some fluctuations. The concentrations remained generally stable over the first three days after dust addition from 74.18 ± 5.50 nM to 78.69 ± 11.04 nM. The mean concentration then slightly increased to its maximum on day 6 of 97.79 ± 7.87 nM.

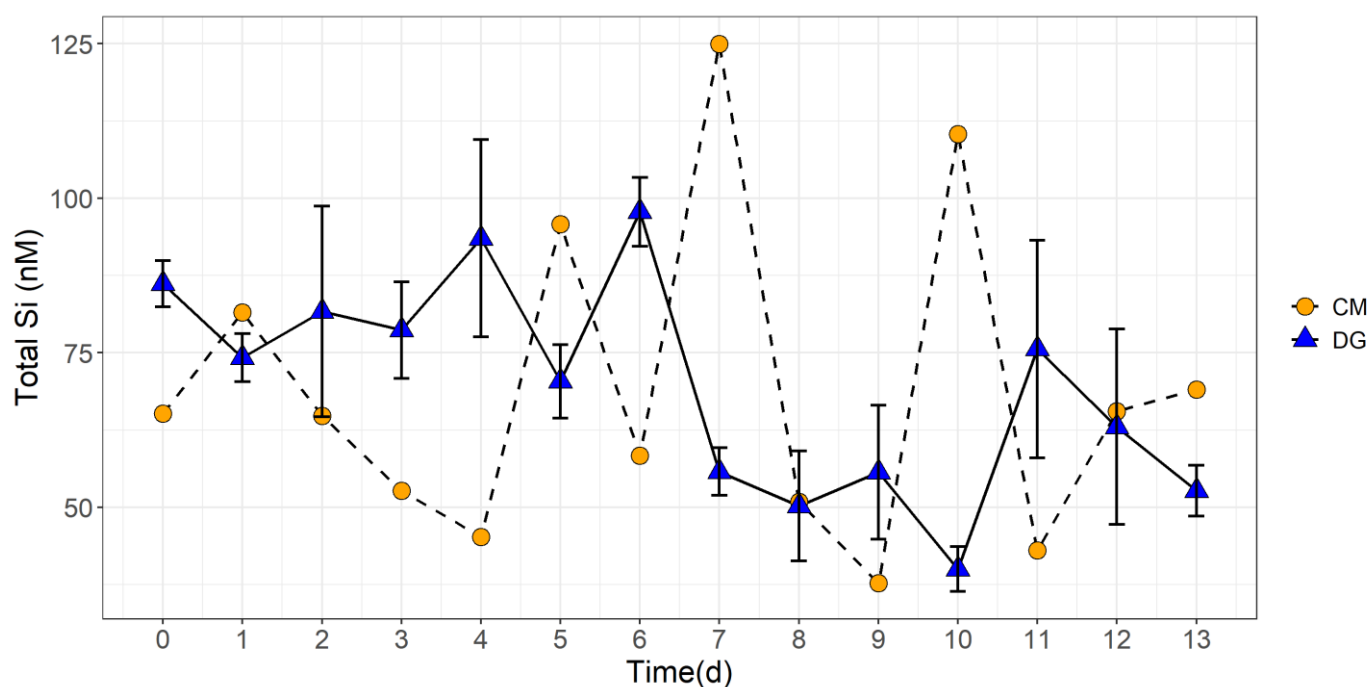


Figure 7-3: Concentration of total Si in each group for the duration of the experiment. Time = 0 indicates the initial conditions, while Time = 1 represents the first measurement taken after dust addition to the DG. The error bars in the graph represent the standard deviation from the mean concentration.

A decline in concentrations towards day 10 followed, reaching its minima of 40.00 ± 5.14 nM, an increase to day 11 of 75.60 ± 24.87 nM and a decrease to 52.70 ± 5.80 nM on the final day. Wasmund et al. (2016) also observed this fluctuation in their shipboard BUS mesocosm study, and the pattern was primarily similar in their winter experiment. In their summer experiment, however, they observed an initial decline in the Si concentration over the first four days, which then increased to the experiment's conclusion on day 18.

Dissolved PO_4^{3-} in the BUS typically ranges from 560 nM in the summer to 1280 nM in the winter (Wasmund et al., 2016). Figure 7-4 shows the changes in the PO_4^{3-} concentration in the CM and DG throughout the current study. In general, the concentration in the CM following the first four days after dust addition remained below 6 nM. The concentration steadily increased to 11.16 on day 7, followed by a sharp increase to its maximum concentration of 26.53 nM on day 8. The concentration then sharply decreased to its minimum concentration of 1.05 nM on day 9 and remained below 6 nM for the duration of the experiment. There is no apparent pattern in the DG concentrations except for some fluctuations. The most notable is the increase from the initial

concentration to 12.78 ± 1.01 nM on day 1. After that, the concentrations remained generally stable below 12 nM. A similar pattern has been observed for adding Saharan dust to oligotrophic waters (Pitta et al., 2017). However, a previous mesocosm study for the BUS observed different patterns. In the summer, the dissolved PO_4^{3-} decreased from their initial concentration until around day 4, remained relatively stable until day 8, and finally steadily and slightly increased. In the winter, the concentration also decreased from the initial concentration but showed little to no change for the duration (Wasmund et al., 2016).

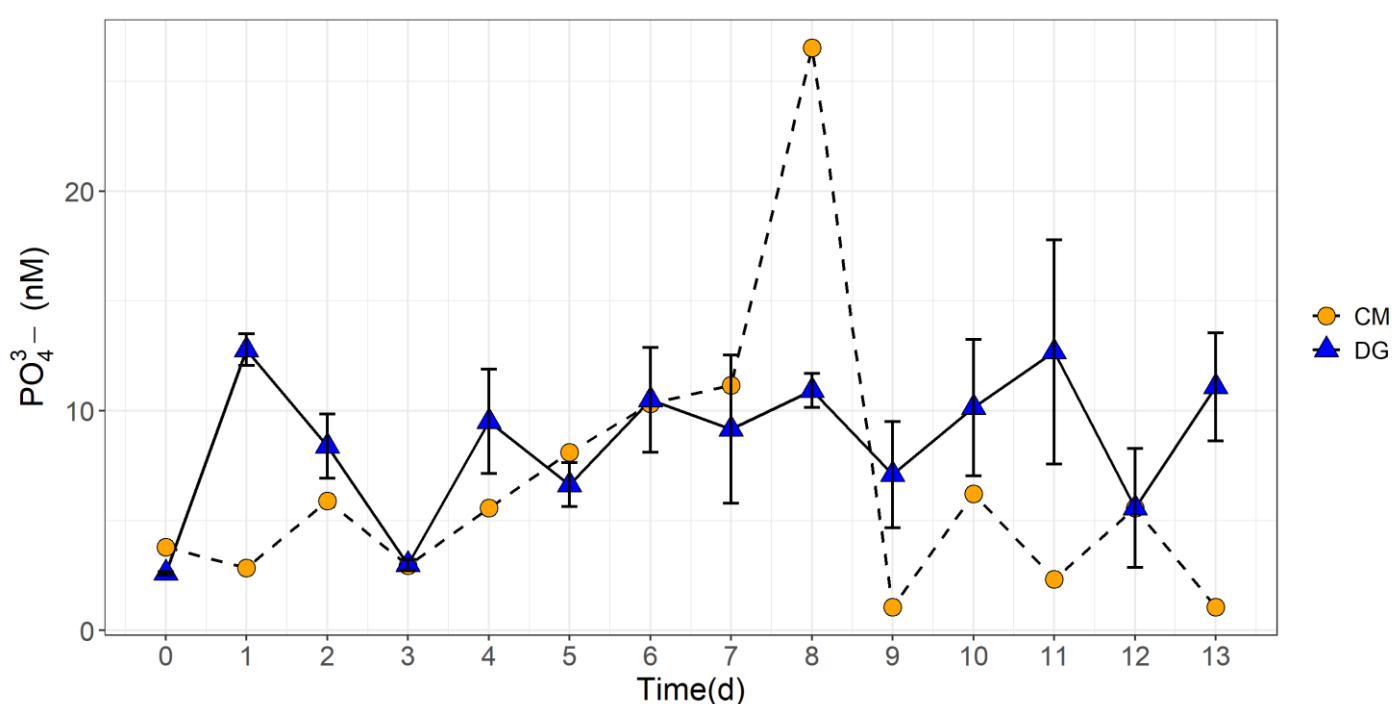


Figure 7-4: PO_4^{3-} concentrations in each group for the duration of the experiment. Time = 0 indicates the initial conditions, while Time = 1 represents the first measurement taken after dust addition to the DG. The error bars in the graph represent the standard deviation from the mean concentration.

7.4 Temporal Dynamics in Chl-a and cell densities

The observed Chl-a concentrations are illustrated in Figure 7-5. Both the CM and the DG had relatively low Chl-a concentrations at the beginning of the experiment, with values of 0.26 mg/m^3 and 0.23 mg/m^3 and cell densities of 2.05×10^5 cells/ml and 1.61×10^5 cells/ml (Table 7-1), respectively. However, over the first few days, the Chl-a concentrations increased until both groups reached peak concentration at step 6 (26.55 mg/m^3 and $39.95 \pm 0.64 \text{ mg/m}^3$). The

concentration in the CM then gradually decreased to time step 13 to reach a final concentration of 14.15 mg/m^3 and cell density of $1.35 \times 10^6 \text{ cells/ml}$. The second elevation in concentrations for the DG at timestep 8 is not considered a second peak but rather a prolonged duration of the peak observed at timestep 6.

Table 7-1: Measured cell counts (cells/ml) at different timesteps during the experiment.

Mesocsm ID	Timestep	Cell Count (cells/ml)
C-01	0	2,05E+05
EX1-01	0	1,58E+05
EX2-01	0	2,10E+05
EX3-01	0	1,15E+05
C-02	1	1,83E+05
EX1-02	1	1,95E+05
EX2-02	1	4,55E+05
EX3-02	1	3,85E+05
C-07	6	5,20E+05
EX1-07	6	7,38E+05
EX2-07	6	1,23E+06
EX3-07	6	1,34E+06
C-12	11	1,08E+06
EX1-12	11	1,03E+06
EX2-12	11	1,14E+06
EX3-12	11	1,18E+06
C-14	13	1,35E+06
EX1-14	13	1,53E+06
EX2-14	13	1,50E+06
EX3-14	13	1,74E+06

In other words, the peak in the DG is higher and longer relative to the amplitude and duration of the peak in the CM. In the DG, however, a second peak in concentration was reached at timestep 8 with a slightly higher concentration of $40.04 \pm 5.86 \text{ mg/m}^3$. After that, the Chl-a concentrations in the DG followed a very similar decline in concentrations to time step 13, like the CM, to reach a final concentration of $18.79 \pm 1.41 \text{ mg/m}^3$ and cell density of $1.59 \times 10^6 \pm 1.07 \times 10^5 \text{ cells/ml}$. The Chl-a concentrations were similar at the onset of the experiment and reached a maximum

difference of $13.40 \pm 0.79 \text{ mg/m}^3$ during the peak at timestep 6. At timestep 13, on the final day of the experiment, their concentrations converged somewhat, but the DG remained higher by $3.6 \pm 1.73 \text{ mg/m}^3$.

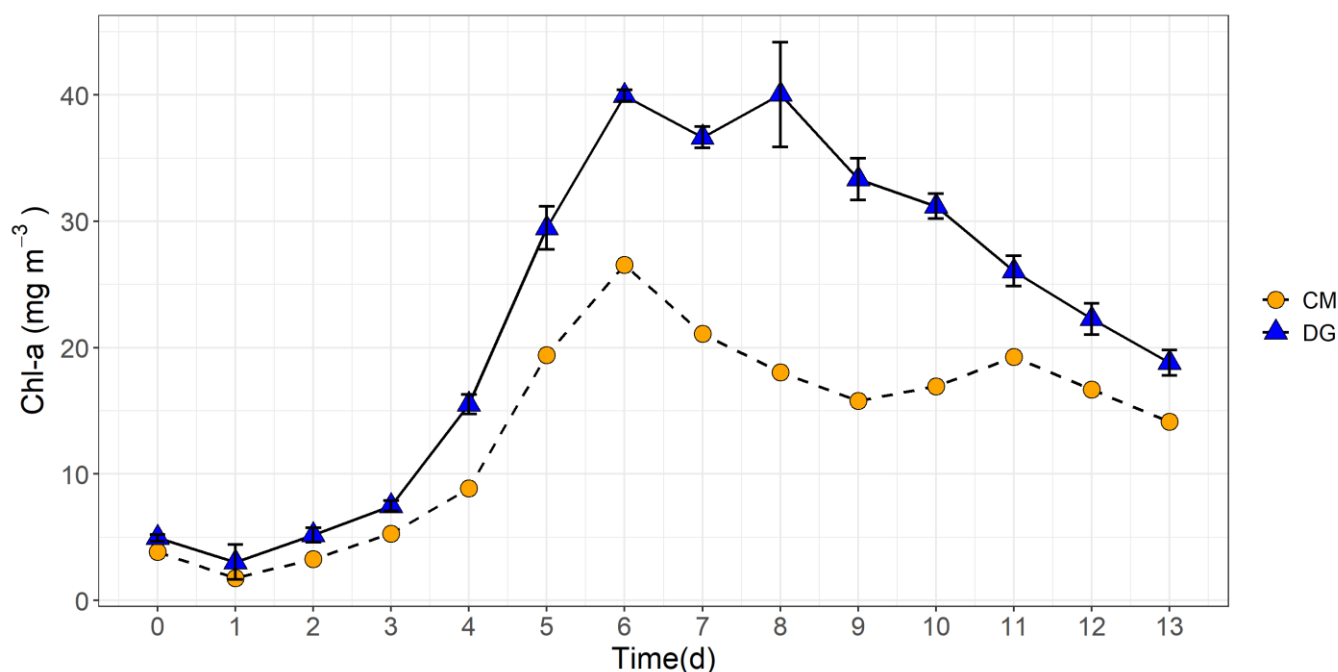


Figure 7-5 Concentration of Chl-a in each group for the duration of the experiment. Time = 0 indicates the initial conditions, while Time = 1 represents the first measurement taken after dust addition to the DG. The error bars in the graph represent the standard deviation from the mean concentration.

The addition of dust resulted in much higher Chl-a concentrations observed in the DG than those observed in the CM. The Benguela current is close to a continental shelf and in a region with substantial aeolian dust supply. Coupled with the nutrient upwelling phenomenon within the system, one expects that the phytoplankton in the Benguela already enjoys sufficient nutrient availability. Consequently, adding nutrients may not significantly affect their growth, as they already thrive in a nutrient-abundant environment. The finding that adding Kuiseb riverbed dust stimulated the DG is significant and unexpected. The response in the DG was consistent in that each DG mesocosm had significantly higher mean Chl-a concentrations than the CM. The positive reaction of phytoplankton biomass to dust addition varied temporally following the peak concentrations; the concentrations declined but remained higher than the CM. As previously explained, the decline following the peak may have been influenced by several factors. The specific concentration at

which a nutrient becomes limiting can vary depending on several factors, including the type of phytoplankton, the availability of other nutrients, and environmental conditions (Dzialowski et al., 2005; Ramos et al., 2017).

It is commonly assumed that dissolved trace elements such as Fe are directly bioavailable to phytoplankton, as quantifying this process is complex (Shi et al., 2012). The bioavailability of this element depends on several factors, such as its physiochemical speciation and the soluble fraction thereof (Boyd et al., 2010). It has been established that the Namibian ephemeral river valleys contain approximately 43 times more bioavailable Fe, N, and P than Etosha and Makgadikgadi pans (Dansie et al., 2017a). Contrastingly, a second study found the opposite, arguing that bioavailability is primarily affected by mineralogy, not particle size (Kangueehi, 2017). The study above conducted this bioavailability assessment on the same samples used in this experiment and found that the Kuiseb dust sample had the lowest overall solubility (0.002%) compared to a sample collected from Etosha pan (25.8%). It is worth noting that the studies by Dansie et al. (2017a) and Kangueehi (2017) used different methods in their bioavailability assessments. Prospective studies on the dust fertilisation potential might consider investigating titanium (TiO_2) as an additional measure, as it has been shown to significantly increase the dissolution and bioavailability of Fe(II) in the dark (Hettiarachchi et al., 2019).

Dissolved Si is essential for oceanic diatoms like *Chaetoceros* (Capelacci et al., 2013; Hawkings et al., 2016) and often limits their growth (Finkel et al., 2010). Phytoplankton can store nutrients when they are abundant (Salmaso & Tolotti, 2021), allowing them to sustain high growth rates even during subsequent periods when these concentrations decline (Reynolds, 2006). In the present study, there was no apparent drawdown of the total Si by the *Chaetoceros*, as the species was incubated with sodium metasilicate, which should have already supplied the nutrient abundantly. In other words, the total Si was not limited at the start of the experiment because the *Chaetoceros* might have had enough Si to support their growth without significantly depleting the Si in the water. The fluctuations in the total Si and PO_4^{3-} may have resulted from some cells increasing while others died, decomposed and released the nutrients back into the system (Manzoni et al., 2010; Hattich et al., 2022).

7.5 Correlation of Chl-a with total Fe, total Si, PO_4^{3-} and light intensity

The Levene's test was conducted to check the equality of variances in Chl-a between the CM and DG. The test statistic was approximately 7.12, and the p-value was 0.01. This result means that the variances between the two groups are unequal. For Welch's t-test, which assumes unequal variances, the t-test statistic was approximately -3.03, and the p-value was 0.004. The previous suggests a statistically significant difference between the means of CM and DG.

7.6 Chapter Conclusions

The objective of the results portrayed and discussed in this chapter was an investigation of the Chl-a response to the addition of dust to seawater seeded with phytoplankton species by:

- Measuring and analysing the nutrient conditions conducive to Chl-a concentration fluctuations.
-

The following inferences can be made:

This study provides important baseline data for future mesocosm studies conducted in the Benguela region, which can be used to investigate further the effects of various environmental factors on phytoplankton growth and nutrient dynamics in this important marine ecosystem. The data indicates that Namib desert dust addition resulted in a positive response from the Benguela current phytoplankton, given the higher Chl-a concentrations in the DG compared to the CM. The Benguela current, near a continental shelf and in an area with a substantial supply of aeolian dust, is expected to provide ample nutrients for the phytoplankton due to the nutrient upwelling phenomenon within the system. As such, supplementing nutrients might not significantly impact their growth since they are already in a nutrient-rich environment. The observation that adding dust from the Kuiseb riverbed stimulated the DG is both significant and surprising. Given that this experiment was conducted in an upwelling system near the continental shelf and within a region frequently exposed to substantial aeolian dust supply, it is plausible to expect that phytoplankton in the Benguela would be nutrient-replete. While a distinct response from the phytoplankton in the DG was noted, it was not consistent, indicating that other factors might have constrained productivity.

Throughout the experiment, the total Fe concentration in the CM usually stayed under the detection threshold of 2.42 nM, with minor increases observed on the 8th and 10th days, reaching peaks of 2.9 and 2.74 nM, respectively. On the other hand, the average total Fe concentrations in the DG (3.84 ± 2.01 nM) were typically 57.14% higher than those in the CM. The correlation between Fe and Chl-a was weak and insignificant in both mesocosms.

Chapters 1, 5, 6, and the current chapter explored the impact of dust on marine productivity, particularly Chl-a levels in the BUS. While **Chapter 1** and the results from the current chapter note

the importance of dust in enhancing marine productivity, **Chapters 5** and **6** found no clear link or consistent correlation between dust deposition and Chl-a levels. As discussed, the analysis in **Chapter 5** was limited in that the assumption was made that Fe ECEs only occurred over the Henties Bay coast. However, the flow from the north and south of the location that moves offshore might have also influenced the Chl-a reactions in the nearby BUS. It is possible that unmonitored ECEs of similar or greater intensity were present to the north and south of the HBAO, which could provide a more accurate explanation for the observed variations in Chl-a. The finding from **Chapter 6** makes sense given that a modelled seasonal dust deposition cycle was compared to the BUS Chl-a cycle in reality.

CHAPTER 8

This study investigated the relationship between dust deposition and seawater fertilisation in the Benguela current with various methods and datasets. This study yielded several significant but also inconclusive results. These results, which are related to each research objective outlined in *Chapter 1, Section 1.4*, are summarised in this chapter.

SUMMARY AND CONCLUSIONS

The complexity of environmental systems, particularly in marine ecosystems, is evident in the varied findings and conclusions across the chapters, demonstrating the challenges in establishing transparent causal relationships between atmospheric phenomena and marine biological responses.

8.1 Analyse Particulate Matter Concentrations at Henties Bay

This analysis classified high and low aerosol concentration episodes at Henties Bay, Namibia. The objective also characterized the meteorological conditions conducive to aerosol episode occurrence and conducted a trajectory analysis to trace the transport of air masses during high and low episodes. The study observed significant variability in particulate matter concentrations at Henties Bay. It identified high and low concentrations episodes and linked them to specific atmospheric conditions. The data indicate that particulate matter concentrations and their impact on the marine environment are subject to temporal and spatial variability.

The main findings, per sub-objective, are as follows:

8.1.1 Episodes of high and low PM concentrations

- 1) During HAEs, the mean $PM_{2.5}$ concentration was $28 \pm 18 \mu g/m^3$, and the mean PM_{10} concentration was $68 \pm 44 \mu g/m^3$. During LAEs, the mean $PM_{2.5}$ and PM_{10} concentrations were $13 \pm 9 \mu g/m^3$ and $30 \pm 23 \mu g/m^3$, respectively.
- 2) The prevailing winds during HAEs were southerly and southwesterly, originating from the adjacent BUS.
- 3) There are three additional sources of PM emissions to the north and southeast of the site, most likely the Namibian ephemeral river valleys.

8.1.2 The atmospheric conditions conducive to high and low PM episodes

- 4) The highest hourly PM concentrations were observed during the late afternoon and evening (16:00–21:00). These concentrations may be attributed to the dominant sea breezes from the south and southwest.
- 5) HAEs typically occurred under west coast trough conditions, requiring a strong pressure gradient and enhanced easterly winds from the central regions.

- 6) The occurrence of winter veld fires may explain why circulation with an inland origin is associated with HAEs.

8.1.3 *The dominant transport patterns of PM*

- 7) Most of the air masses during the study period originated from the interior.
- 8) During HAEs, air masses were primarily transported from the northeastern interior, with some from the adjacent ocean. Conversely, during LAEs, the transport was more varied, with contributions from the ocean and the continent.
- 9) Even though the origin of the air masses is in the northeast, they do not reach the surface from that direction.
- 10) Only sometimes is linking source areas based on surface winds a good idea.
- 11) As suggested by the back-trajectories, the aerosol sources could be as distant as southern Zambia, the Caprivi, and dry western Namibian regions.

8.2 Investigate southern African dust sources located in Angola

This objective was addressed by using MODIS Terra and Aqua daily images to identify the source locations of preliminarily new southern African dust sources. It is known that these sources exist in the Angolan region, but their locations and emission frequency have not yet been classified. The study successfully identified significant dust sources in southern Africa, particularly in the Angolan region (AS). Although infrequently emitted, these sources may be crucial dust contributors to the BUS region. Identifying and investigating these sources and their emission patterns enhances the understanding of dust dynamics in this region.

The main findings, per sub-objective, are as follows:

8.2.1 *Potential new dust-emitting sources for the AS region*

- 12) The locations of 47 potential southern African dust sources were identified. However, these source regions are dynamic, and these locations are likely more of an indication that they change from event to event.
- 13) The landform types are suspected to be similar to the Namibian sources to the south.
- 14) The AS is most active during the winter, coinciding with the seasonal shift of the BLLJ.

- 15) All detected plumes from the AS stretched over 100 km, suggesting a substantial potential for emission and deposition.

8.2.2 *The atmospheric conditions that are conducive to dust emission in the AS.*

- 16) In winter 2016, plumes were detected with an easterly offshore flow, potentially connected to the Angolan Low.
- 17) A dust event linked to the BLLJ was observed on November 16, 2017. The source may have originated from the island of Baia dos Tigres, warranting further investigation.
- 18) This study underscores the importance of the BLLJ for sources located in the AS region, possibly extending to northern Namibia.
- 19) The easterly dust plumes are easily discernible on True Color satellite imagery, but the southerly plumes are more complex and uncertain. The significance of the BLLJ in identifying these southerly plumes on True Colour imagery is demonstrated.
- 20) This study is the first to categorize the frequency of events in the AS, although the analysed record from 2016 to 2017 is relatively brief. For these reasons, further investigation is needed.
- 21) The AS is unique due to its location and shape relative to the BLLJ and possibly other southerly systems. It may, therefore, be subject to increased dust emission from the southerly winds, such as from the BLLJ. It may be a potentially worthwhile question to explore in prospective studies.

8.3 Investigate the relationship between ambient Fe concentrations measured over the Namibian west coast and satellite-retrieved datasets

For this objective, the relationship between ambient Fe observed over the west coast of Namibia and BUS Chl-a data retrieved from the NASA MODIS satellite was examined. Firstly, the objective characterised daily and monthly Fe concentrations and identified anomalies exceeding a 2500 ng/m³ threshold. Then, the transport of air masses on the anomaly days was investigated with HYSPLIT forward trajectories to determine the fate of Fe. Finally, the analysis identified the meteorology that occurred during the anomalies. The main findings, per sub-objective, are as follows:

8.3.1 *Characteristics of ambient Fe concentrations*

- 22) Daytime Fe concentrations varied between 3.00 and 3687.00 ng/m³, averaging 351.67±496.58 ng/m³.
- 23) Nighttime concentrations were typically lower, ranging from 3.00 to 2400.00 ng/m³ and averaging 362.06±410.95 ng/m³.
- 24) There were three anomalies exceeding 2500 ng/m³ during consecutive anomaly events.
- 25) The monthly mean concentrations, in descending order, were as follows: August (492.34 ng/m³), November (475.14 ng/m³), December (454.23 ng/m³), October (443.81 ng/m³), July (402.17 ng/m³), March (312.02 ng/m³), April (298.93 ng/m³), February (287.97 ng/m³), May (287.70 ng/m³), September (277.23 ng/m³), and January (254 ng/m³).
- 26) Regarding the frequency of anomalies, the most were observed in March (7), followed by May and November (6 each), July and August (5 each), April (4), September (3), October and December (2 each), and finally February (1).

8.3.2 *Relationship between measured Fe and satellite-retrieved Chl-a, AOD, and SST*

- 27) The overall results of the trajectory analysis are inconclusive.
- 28) There does not seem to be a discernible pattern in the concentrations of Chl-a, and they do not appear to correlate with the Fe concentrations from the previous day for EP2.
- 29) For EP3, the Chl-a concentrations did not follow a specific pattern and did not seem related to the Fe concentrations observed a day earlier. Interestingly, however, the Fe concentration was higher on 11 July than on 14 July 2017, the day before the concentrations were measured.

8.3.3 *The synoptic circulation favouring anomaly occurrence*

- 30) During EP1, the wind blew almost entirely offshore from the northeast of the interior.
- 31) Two instances where the Fe concentration exceeded 2500 ng/m³ were observed during the typical bergwind conditions: autumn (EP2) and spring (EP4).
- 32) During EP3, the weather conditions were similar to those of a Berg wind, but they were not typical. A meso-low was noticeable in the low-level winds of that day.

8.4 Evaluate a long-term CCAM dust deposition simulation to the BUS

For the first time, this objective evaluated a long-term CCAM dust deposition simulation to the BUS and compared the results to the MERRA-2 reanalysis dust deposition. The objective also investigated whether the seasonal cycle of CCAM dust deposition aligns with the seasonal cycle of Chl-a in the BUS. Using models like CCAM and remote sensing data provides valuable insights into dust deposition patterns and their potential impact on the Benguela Current. However, these tools also have inherent limitations and uncertainties. The study underscores the need to interpret model simulations and satellite data carefully.

The main findings, per sub-objective, are as follows:

8.4.1 *Characteristics of CCAM-modelled total dust deposition to the Benguela current*

- 33) CCAM simulated a higher dust deposition to Box S than Box N from 1979-2013. This may be because Box N is within the gravel region of northern Namibia and southern Angola, and Box S is in the southern Namibian dune region.
- 34) Most dust deposition occurred within 20 km of the coast in both domains. This can be explained by the dominance of dry deposition processes or the gravitational settling of coarser particles.
- 35) There are well-defined locations where CCAM simulated the highest depositions in both domains. In Box N, there were multiple locations at 17°S 11.7°E, 17.4°S 11.7°E, and 17.6°S 11.7°E. In Box S, however, CCAM simulated the vast majority of the domain deposition at 26.6°S 15.1°E, with somewhat less deposition modelled at 27°S 15.2°E.
- 36) These findings agree with an earlier suggestion that the southern African dust sources have a predominantly localized influence.
- 37) There was a significant difference in modelled concentrations between seasons in Box N, where concentrations followed a clear seasonal pattern. The seasonal fluctuation in Box S appears to be similar but with notable exceptions. For instance, the deposition periods between the regions were modelled to be opposite between February and September.
- 38) Annually, the modelled deposition reached its lowest levels in Box N (6.5 g/m²/year) in 2004 and in Box S (10.2 g/m²/year) in 2002, and its highest levels in Box N (8.2 g/m²/year) in 1993 and Box S (14.4 g/m²/year) in 1988.

- 39) The findings are within the global models' mean annual dust deposition simulated range of 2-20 g/m²/year.

8.4.2 CCAM vs MERRA-2 modelled dust deposition

- 40) The modelled dust deposition between the datasets has comparable mean values, especially in Box N.
- 41) In Box S, however, the mean dust deposition modelled by CCAM is notably higher (0.04-50.00 g/m²) than that in the MERRA-2 data (0.00-2.25 g/m²).
- 42) For both datasets, the spatial variation in the deposition for both domains is very similar at distinct locations. However, despite the similarities in the mean values in Box N, a weak positive correlation between the monthly values was observed ($r=0.35$; $p<0.05$).
- 43) Although there was a significant difference in the mean monthly deposition in Box S, the datasets were significantly positively correlated.
- 44) While the spatial deposition between CCAM and MERRA-2 shows similarities, they differ quantitatively due to the significantly greater deposition observed in CCAM.

8.4.3 CCAM and BUS Chl-a seasonal cycles

- 45) The modelled dust deposition and Chl-a in Box N and S are somewhat aligned in space but not in time.
- 46) The seasonal CCAM dust deposition simulation is not coupled with the seasonal Chl-a cycle. No seasonal correlation and agreement were found in comparing the CCAM dust deposition with the observed Chl-a concentrations separately for Box N and S. In Box N, there appears to be a completely random response, while in Box S, a negative correlation was observed.
- 47) There appears to be no direct link between the modelled dust deposition and the Chl-a.
- 48) This is as far as the objectives of this study go, but some gaps were identified for investigation by prospective studies.
- 49) The CCAM dust deposition might agree with the seasonal Chl-a cycle for a single dust-size bin or all-size bins in either wet or dry deposition.
- 50) The model does not seem suited for this study, so either the model parameterization needs some modifications, or there is no correlation.

8.5 Investigate the response of phytoplankton to dust addition in a mesocosm experiment

This objective was addressed through a mesocosm experiment to investigate the response of BUS phytoplankton to Namib desert dust addition. The study highlights the intricate relationship between atmospheric dust deposition and the marine ecosystems in the Benguela Current. Dust transport, primarily composed of macronutrients like nitrogen, phosphorus, and iron, is vital in influencing marine biogeochemistry. However, the exact impact of these nutrients on marine productivity, especially phytoplankton growth, is complex and affected by various environmental factors. The relationship between Fe concentration and phytoplankton response, particularly Chl-a levels, is not straightforward. The study indicates a potential positive impact of Fe-rich dust on Chl-a concentrations but also acknowledges the complexity of this relationship.

The objective had a single sub-objective, and the main findings are as follows:

- 51) Namib desert dust addition resulted in a positive response from the Benguela current phytoplankton, given the higher Chl-a concentrations in the DG compared to the CM.
- 52) The observation that adding dust from the Kuiseb riverbed stimulated the DG is both significant and surprising.
- 53) A distinct response from the phytoplankton in the DG was noted, but it was not consistent, indicating that other factors might have constrained productivity.
- 54) The total Fe concentration in the CM usually stayed under the detection threshold of 2.42 nM, with minor increases observed on some days.
- 55) The mean total Fe concentrations in the DG (3.84 ± 2.01 nM) were typically 57.14% higher than those in the CM.
- 56) The correlation between Fe and Chl-a was weak and insignificant in both mesocosms. The total Fe might have been soluble but not bioavailable to the phytoplankton.
- 57) Future research on the potential of dust fertilisation could include TiO_2 as an extra parameter. It has been demonstrated to considerably enhance the dissolution and bioavailability of Fe(II) in dark conditions.
- 58) There was no noticeable decrease in the total Si caused by the *Chaetoceros*, a species with an affinity for the nutrient. The previous may be ascribed to the incubation of the species with sodium metasilicate, which should have provided an ample supply of this nutrient. In essence, the total Si was not scarce at the beginning of the experiment, as the *Chaetoceros*

likely had sufficient Si to facilitate their growth without drastically reducing the Si in the water.

- 59) The variations in the total Si and PO_4^{3-} could have been due to an increase in some cells while others perished, decomposed, and reintroduced the nutrients into the system.

8.6 Study Limitations and Assumptions

The objectives assume a degree of predictability in environmental responses to dust deposition. However, natural systems are inherently variable, and numerous factors, such as water temperature, current patterns, and biological factors within the marine ecosystem, can influence responses. This variability can make it challenging to attribute changes in Chl-a concentrations or phytoplankton biomass directly to dust inputs.

The following are the study's limitations and assumptions:

Objective I: A dust event was classified where the average hourly PM_{10} measurements remained at or above $20 \mu\text{g}/\text{m}^3$ for 80% of the day. According to a previous classification, this concentration represents a “severe dust storm” and is a very conservative identifier of a dust event in the present study.

Objective II: Identifying a dust plume using remote sensing is subjective and an inherent limitation of the study. Likely, the locations aren't precise, given the coarse resolution of the imagery used. Different remote sensing algorithms exhibit varied dust detection capabilities. Satellites have intervals between their overpasses, which means that MODIS Terra and Aqua might have missed capturing a dust emission event. The cloud masks on the images may also have interfered with detecting a dust plume.

Objective III: The assumption was made that the Fe ECEs were only active along the Henties Bay coast, which is reasonable considering the nearby dust sources. However, other factors may have influenced the Chl-a levels in the BUS, such as winds from north and south of the site. There may have also been similar or stronger ECEs that were not detected north and south of the HBAO, which could account for the Chl-a variations. Other Fe-enriched dust events may have impacted the locations of the trajectory points before the HBAO trajectory passed or the Chl-a at the points simultaneously. This study's last important assumption was that the phytoplankton was already Fe-limited at the locations at the trajectory points over the BUS. Given the frequent dust emission

from the adjacent continental sources, however, the phytoplankton might have already had sufficient amounts of the nutrient.

Objective IV: Tools like the CCAM model have inherent limitations and uncertainties. For example, the parameterisation of dry and wet deposition and gravitational settling may not capture the complex nature and variability of the ‘actual’ atmosphere. Models like CCAM have been shown to favour dry deposition and gravitational settling, meaning that the bulk of dust may be modelled to occur over land or close to their emission source. The model relies on user input with associated errors and uncertainties like the poor spatial capture of soil moisture or the failure to update a model’s source data. Depending on the finest scale a model can operate at, whatever happens at a finer scale than that may not be resolved. These are just examples of some uncertainties associated with models like CCAM.

Objective V: Mesocosms are excellent and widely used tools to investigate the natural environment under controlled conditions. The interaction of Fe with the marine environment is quite complex as its dissolution, and consequently, bioavailability to phytoplankton depends on several factors. This study used a composite soil sample from the ‘dustiest riverbed in Namibia’, proven to have high concentrations of nutrients such as Fe, N, and P, and assumed that the Fe would be bioavailable to the phytoplankton species used. The mesocosm experiment, however, had very different physical, chemical and biological conditions than the actual ones in the BUS. The measurement techniques and instruments have errors and biases, causing uncertainties due to the calibration of instruments, how the experiment was designed, or the analytical procedures used. Likely, the temperature of the mesocosm is not at all representative of the ocean water, given the absorptive material the water is contained in.

8.7 Contribution to the current body of knowledge

This research is the first to characterise high and low aerosol episodes over the coast of Namibia at Henties Bay. The study identified and classified forty-seven dust source locations in the Angolan region of southern Africa and recorded their emission frequency, albeit briefly, from 2016 to 2017. Their identification and emission patterns enhance the understanding of dust dynamics in this region. The research also provides the first characterisation of ambient Fe concentrations over the Namibian coast, including identifying extreme concentration events. This research is novel in demonstrating the significance of the BLLJ for dust emission from the Angolan region. For the

first time, a land-based mesocosm experiment was conducted to investigate the response of BUS phytoplankton to the addition of dust from the Kuiseb riverbed. The research found that dust from the Namib desert stimulated growth in BUS phytoplankton. Finally, the study includes the first long-term assessment of dust deposition modelling to the BUS using CCAM.

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APPENDICES

The appendices are supplementary materials and referenced in the text where applicable.

APPENDIX A. PARTICULATE MATTER EPISODES AT HENTIES BAY

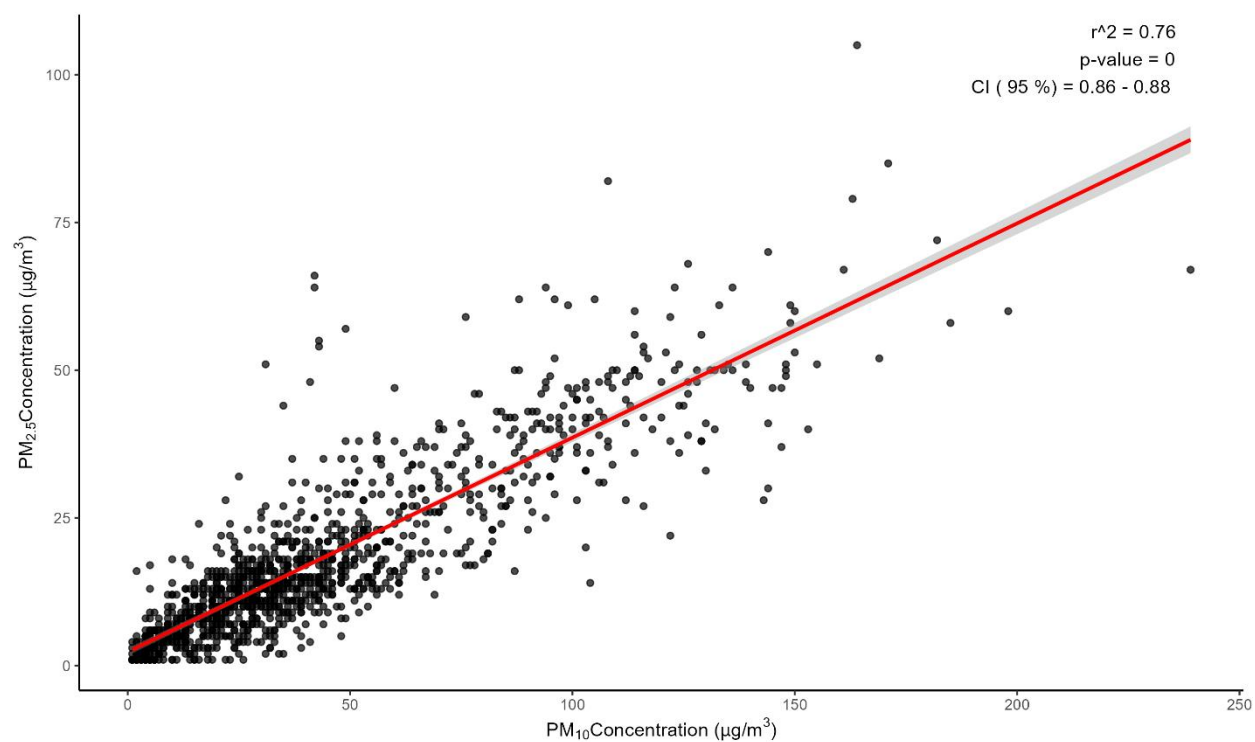


Figure A. 1: Correlation plot between PM_{2.5} and PM₁₀ during 15-29 July 2019 at Sam Nujoma campus, Henties Bay.

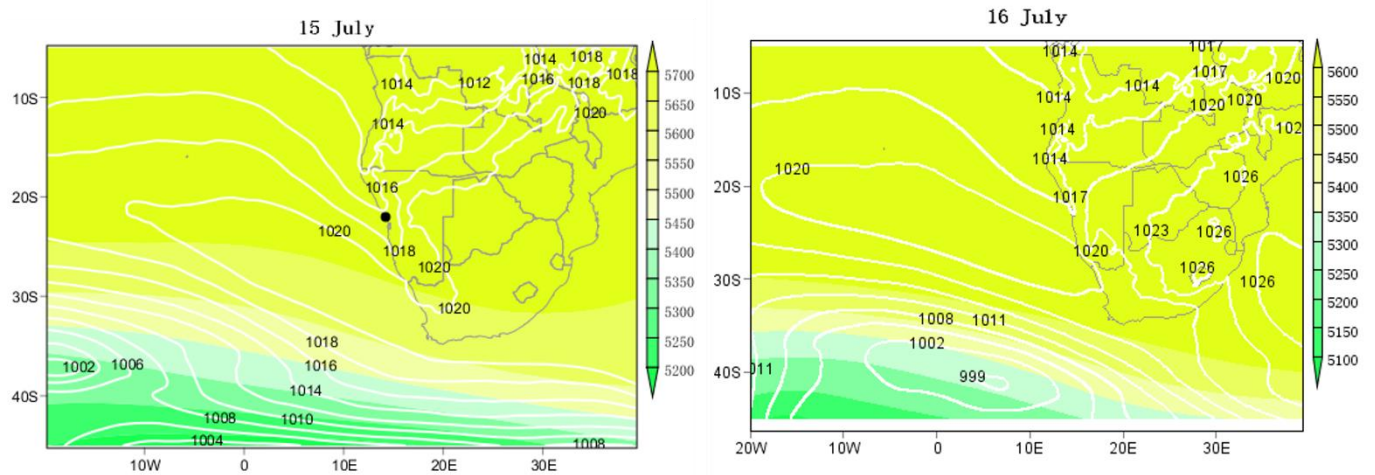


Figure A. 2: The synoptic circulation during the first LAE between 15 and 16 July 2019. The scale to the right represents the geopotential height in geopotential meters, indicated as shaded colours. The isobars indicate the mean sea level pressure in hPa.

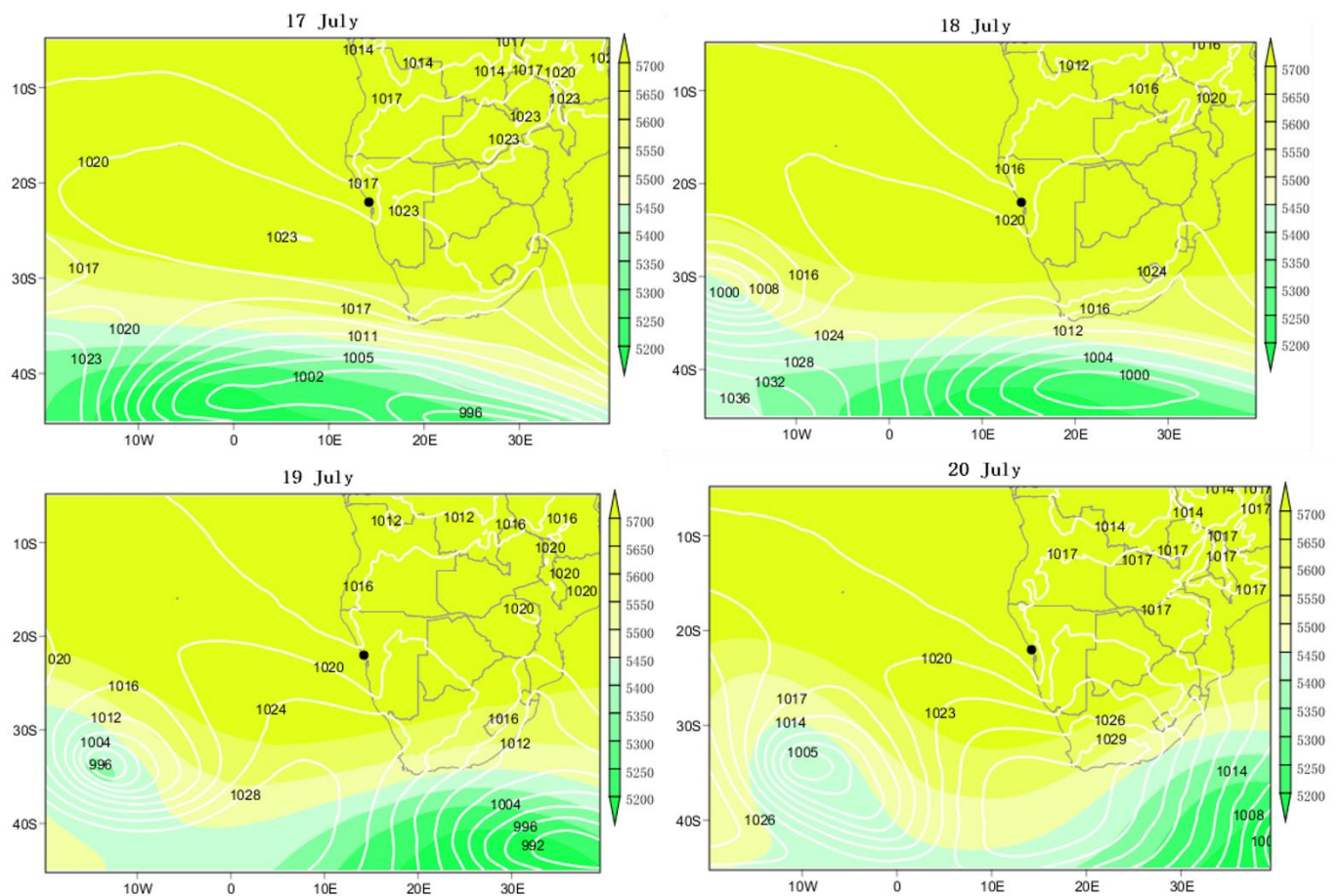


Figure A. 3: The synoptic circulation during the second HAE between 17 and 20 July 2019.

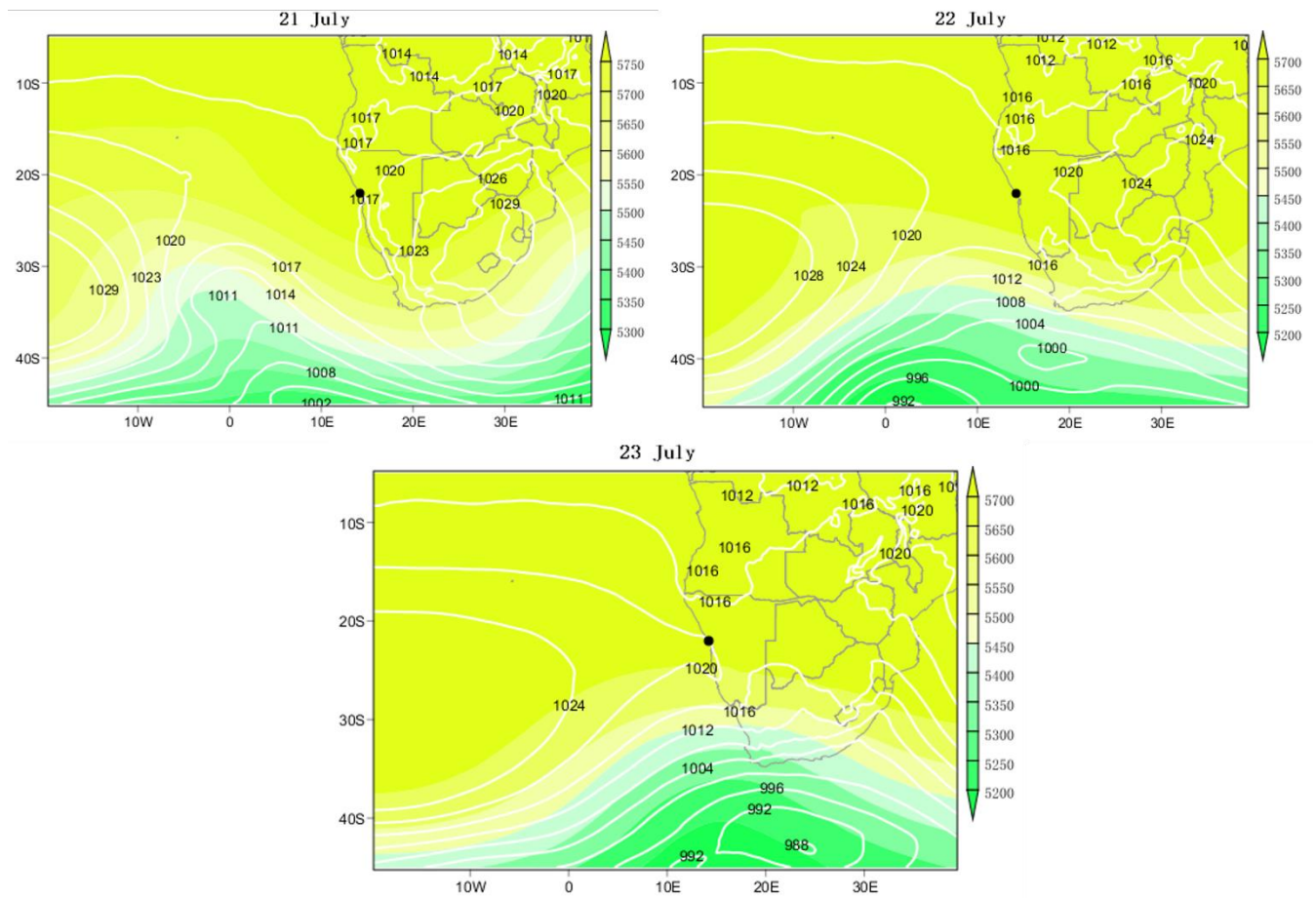


Figure A. 4: The synoptic circulation during the second LAE between 21 and 23 July 2019.

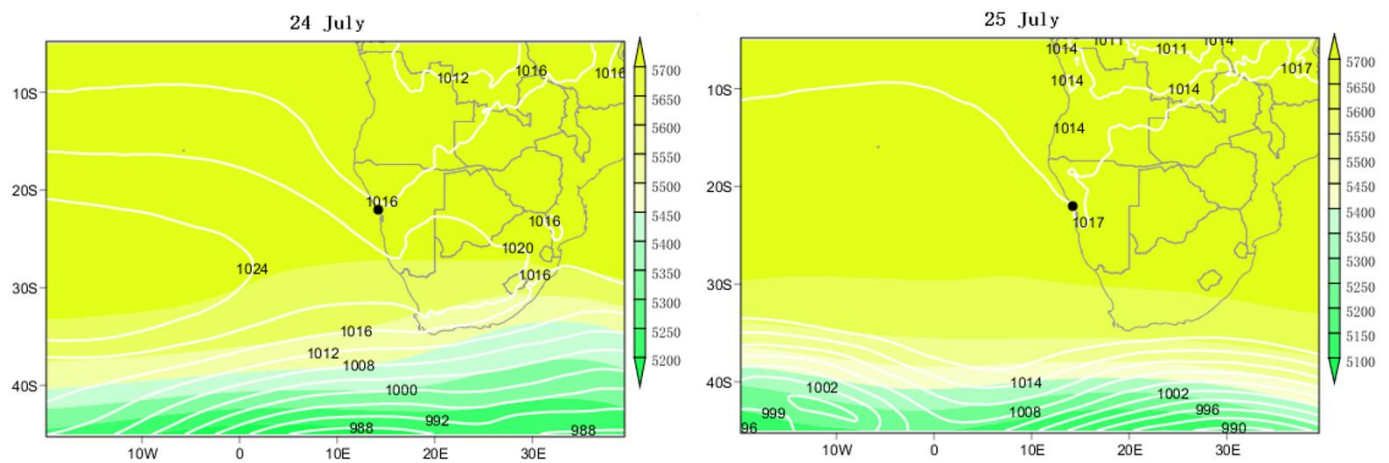


Figure A. 5: The synoptic circulation during the second HAE between 24 and 25 July 2019.

APPENDIX B. INVESTIGATE SOUTHERN AFRICAN DUST SOURCES LOCATED IN ANGOLA

Table B. 1: Locations of new potential southern African dust sources.

Source Location ID	Latitude	Longitude
46	11.714	-16.5168
47	11.71911	-16.585
17	11.73552	-15.8571
16	11.73582	-15.8686
15	11.73639	-15.8912
40	11.73988	-17.1028
42	11.73988	-17.1414
39	11.74136	-17.0731
41	11.74136	-17.1236
18	11.74224	-15.8332
14	11.74483	-15.9127
38	11.74581	-17.0464
36	11.74878	-17.0004
37	11.74878	-17.0212
35	11.75471	-16.9663
13	11.75633	-15.9301
34	11.75768	-16.9455
19	11.759	-15.7991
32	11.76213	-16.7883
12	11.76695	-15.9462
33	11.771	-16.9129
26	11.77579	-16.8406
27	11.78275	-16.8754
6	11.784	-16.0999
7	11.784	-16.0803
11	11.78436	-15.9726
5	11.785	-16.1301
4	11.787	-16.1534
8	11.787	-16.0641
3	11.796	-16.1751
9	11.79741	-16.0381

2	11.798	-16.2022
10	11.79842	-16.0013
43	11.79945	-16.2541
1	11.8	-16.2266
44	11.81	-16.2931
45	11.81851	-16.4916
25	11.88846	-15.776
24	11.90036	-15.7594
23	11.90333	-15.7314
22	11.9194	-15.7035
21	11.92297	-15.6868
20	11.94676	-15.669
28	12.00603	-15.6003
29	12.02229	-15.5191
31	12.03104	-15.4065
30	12.03354	-15.4703

Appendix C. INVESTIGATE THE RESPONSE OF PHYTOPLANKTON TO DUST ADDITION IN A MESOCOSM EXPERIMENT



[010194/22], [2023/02/14]

Certificate of Analysis

Project details

Customer Details

Quotation number:	Q2210-078_A
Company name:	NORTH WEST UNIVERSITY
Contact address:	PRIVATE BAG X1290, POTCHEFSTROOM, 2520
Contact person:	MONRAY BELELIE

Sampling Details

Sampled by:	CUSTOMER
Sampled date:	2022/09/29

Sample Details

Sample type(s):	SEAWATER SAMPLES
Date received:	2022/11/25
Delivered by:	COURIER SERVICE
Temperature at sample receipt (°C):	22.3

Report Details

Testing commenced:	2022/11/25
Testing completed:	2023/02/10
Report date:	2023/02/14
Our reference:	010194/22



Analytical Results

Methods	Determinands	Units	030909/22	030910/22
			NUTRIENT SAMPLES: SAMPLE 1, EX1-NU-01 29.09.2022	NUTRIENT SAMPLES: SAMPLE 1, EX2-NU-01 29.09.2022
Chemical				
87	Total Iron	mg Fe/l	0.66	0.17
128	Total Silicon*	mg Si/l	2.26	2.62
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.26	0.24
Methods	Determinands	Units	030911/22	030912/22
			NUTRIENT SAMPLES: SAMPLE 1, EX3-NU-01 29.09.2022	NUTRIENT SAMPLES: SAMPLE 1, C-NU-01 29.09.2022
Chemical				
87	Total Iron	mg Fe/l	0.28	<0.15
128	Total Silicon*	mg Si/l	2.38	1.83
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.24	0.36
Methods	Determinands	Units	030913/22	030914/22
			NUTRIENT SAMPLES: SAMPLE 2, EX1-NU-02 30.09.2022	NUTRIENT SAMPLES: SAMPLE 2, EX2-NU-02 30.09.2022
Chemical				
87	Total Iron	mg Fe/l	0.28	<0.15
128	Total Silicon*	mg Si/l	2.23	1.87
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	1.30	1.26
Methods	Determinands	Units	030915/22	030916/22
			NUTRIENT SAMPLES: SAMPLE 2, EX3-NU-02 30.09.2022	NUTRIENT SAMPLES: SAMPLE 2, C-NU-02 30.09.2022
Chemical				
87	Total Iron	mg Fe/l	0.15	<0.15
128	Total Silicon*	mg Si/l	2.15	2.29
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	1.08	0.27

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Methods	Determinands	Units	030917/22	030918/22
			NUTRIENT SAMPLES: SAMPLE 3, EX1-NU-03 01.10.2022	NUTRIENT SAMPLES: SAMPLE 3, EX2-NU-03 01.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.17	<0.15
128	Total Silicon*	mg Si/l	1.84	3.25
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.52	0.93
Methods	Determinands	Units	030919/22	030920/22
			NUTRIENT SAMPLES: SAMPLE 3, EX3-NU-03 01.10.2022	NUTRIENT SAMPLES: SAMPLE 3, C-NU-03 01.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.33	<0.15
128	Total Silicon*	mg Si/l	1.79	1.82
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.94	0.56
Methods	Determinands	Units	030921/22	030922/22
			NUTRIENT SAMPLES: SAMPLE 4, EX1-NU-04 02.10.2022	NUTRIENT SAMPLES: SAMPLE 4, EX2-NU-04 02.10.2022
Chemical				
87	Total Iron	mg Fe/l	<0.15	<0.15
128	Total Silicon*	mg Si/l	2.28	1.80
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.27	0.33
Methods	Determinands	Units	030923/22	030924/22
			NUTRIENT SAMPLES: SAMPLE 4, EX3-NU-04 02.10.2022	NUTRIENT SAMPLES: SAMPLE 4, C-NU-04 02.10.2022
Chemical				
87	Total Iron	mg Fe/l	<0.15	<0.15
128	Total Silicon*	mg Si/l	2.55	1.48
65Gc	Nitrate	mg N/l	<0.25	0.9
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.26	0.28

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Methods	Determinands	Units	030925/22	030926/22
			NUTRIENT SAMPLES: SAMPLE 5, EX1-NU-05 03.10.2022	NUTRIENT SAMPLES: SAMPLE 5, EX2-NU-05 03.10.2022
Chemical				
87	Total Iron	mg Fe/l	2.15	<0.15
128	Total Silicon*	mg Si/l	3.50	2.36
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.62	0.74
Methods	Determinands	Units	030927/22	030928/22
			NUTRIENT SAMPLES: SAMPLE 5, EX3-NU-05 03.10.2022	NUTRIENT SAMPLES: SAMPLE 5, C-NU-05 03.10.2022
Chemical				
87	Total Iron	mg Fe/l	<0.15	<0.15
128	Total Silicon*	mg Si/l	2.02	1.27
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	1.35	0.53
Methods	Determinands	Units	030929/22	030930/22
			NUTRIENT SAMPLES: SAMPLE 6, EX1-NU-06 04.10.2022	NUTRIENT SAMPLES: SAMPLE 6, EX2-NU-06 04.10.2022
Chemical				
87	Total Iron	mg Fe/l	<0.15	<0.15
128	Total Silicon*	mg Si/l	1.89	2.30
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.47	0.80
Methods	Determinands	Units	030931/22	030932/22
			NUTRIENT SAMPLES: SAMPLE 6, EX3-NU-06 04.10.2022	NUTRIENT SAMPLES: SAMPLE 6, C-NU-06 04.10.2022
Chemical				
87	Total Iron	mg Fe/l	<0.15	0.57
128	Total Silicon*	mg Si/l	1.74	2.69
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.62	0.77

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Methods	Determinands	Units	030933/22	030934/22
			NUTRIENT SAMPLES: SAMPLE 7, EX1-NU-07 05.10.2022	NUTRIENT SAMPLES: SAMPLE 7, EX2-NU-07 05.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.19	<0.15
128	Total Silicon*	mg Si/l	2.45	2.81
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	1.08	1.34
Methods	Determinands	Units	030935/22	030936/22
			NUTRIENT SAMPLES: SAMPLE 7, EX3-NU-07 05.10.2022	NUTRIENT SAMPLES: SAMPLE 7, C-NU-07 05.10.2022
Chemical				
87	Total Iron	mg Fe/l	<0.15	0.22
128	Total Silicon*	mg Si/l	2.98	1.64
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.57	0.98
Methods	Determinands	Units	030937/22	030938/22
			NUTRIENT SAMPLES: SAMPLE 8, EX1-NU-08 06.10.2022	NUTRIENT SAMPLES: SAMPLE 8, EX2-NU-08 06.10.2022
Chemical				
87	Total Iron	mg Fe/l	<0.15	0.21
128	Total Silicon*	mg Si/l	1.62	1.36
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.85	1.51
Methods	Determinands	Units	030939/22	030940/22
			NUTRIENT SAMPLES: SAMPLE 8, EX3-NU-08 06.10.2022	NUTRIENT SAMPLES: SAMPLE 8, C-NU-08 06.10.2022
Chemical				
87	Total Iron	mg Fe/l	<0.15	0.31
128	Total Silicon*	mg Si/l	1.72	3.51
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.55	1.06

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Methods	Determinands	Units	030941/22	030942/22
			NUTRIENT SAMPLES: SAMPLE 9, EX1-NU-09 07.10.2022	NUTRIENT SAMPLES: SAMPLE 9, EX2-NU-09 07.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.17	<0.15
128	Total Silicon*	mg Si/l	1.47	0.95
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.90	1.06
Methods	Determinands	Units	030943/22	030944/22
			NUTRIENT SAMPLES: SAMPLE 9, EX3-NU-09 07.10.2022	NUTRIENT SAMPLES: SAMPLE 9, C-NU-09 07.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.35	<0.15
128	Total Silicon*	mg Si/l	1.81	1.43
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	1.15	2.52
Methods	Determinands	Units	030945/22	030946/22
			NUTRIENT SAMPLES: SAMPLE 10, EX1-NU-10 08.10.2022	NUTRIENT SAMPLES: SAMPLE 10, EX2-NU-10 08.10.2022
Chemical				
87	Total Iron	mg Fe/l	<0.15	<0.15
128	Total Silicon*	mg Si/l	1.21	1.31
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.97	0.83
Methods	Determinands	Units	030947/22	030948/22
			NUTRIENT SAMPLES: SAMPLE 10, EX3-NU-10 08.10.2022	NUTRIENT SAMPLES: SAMPLE 10, C-NU-10 08.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.18	<0.15
128	Total Silicon*	mg Si/l	2.17	1.06
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.22	<0.1

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Methods	Determinands	Units	030949/22	030950/22
			NUTRIENT SAMPLES: SAMPLE 11, EX1-NU- 11 09.10.2022	NUTRIENT SAMPLES: SAMPLE 11, EX2-NU- 11 09.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.89	0.22
128	Total Silicon*	mg Si/l	1.24	0.92
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.88	1.51
Methods	Determinands	Units	030951/22	030952/22
			NUTRIENT SAMPLES: SAMPLE 11, EX3-NU- 11 09.10.2022	NUTRIENT SAMPLES: SAMPLE 11, C-NU-11 09.10.2022
Chemical				
87	Total Iron	mg Fe/l	<0.15	<0.15
128	Total Silicon*	mg Si/l	1.21	3.10
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.50	0.59
Methods	Determinands	Units	030953/22	030954/22
			NUTRIENT SAMPLES: SAMPLE 12, EX1-NU- 12 10.10.2022	NUTRIENT SAMPLES: SAMPLE 12, EX2-NU- 12 10.10.2022
Chemical				
87	Total Iron	mg Fe/l	<0.15	<0.15
128	Total Silicon*	mg Si/l	2.31	1.19
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	1.79	1.58
Methods	Determinands	Units	030955/22	030956/22
			NUTRIENT SAMPLES: SAMPLE 12, EX3-NU- 12 10.10.2022	NUTRIENT SAMPLES: SAMPLE 12, C-NU-12 10.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.29	0.22
128	Total Silicon*	mg Si/l	2.87	1.21
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.24	0.22

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Methods	Determinands	Units	030957/22	030958/22
			NUTRIENT SAMPLES: SAMPLE 13, EX1-NU-13 11.10.2022	NUTRIENT SAMPLES: SAMPLE 13, EX2-NU-13 11.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.26	0.29
128	Total Silicon*	mg Si/l	2.64	1.18
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.50	0.99
Methods	Determinands	Units	030959/22	030960/22
			NUTRIENT SAMPLES: SAMPLE 13, EX3-NU-13 11.10.2022	NUTRIENT SAMPLES: SAMPLE 13, C-NU-13 11.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.28	<0.15
128	Total Silicon*	mg Si/l	1.49	1.84
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	<0.1	0.53
Methods	Determinands	Units	030961/22	030962/22
			NUTRIENT SAMPLES: SAMPLE 14, EX1-NU-14 12.10.2022	NUTRIENT SAMPLES: SAMPLE 14, EX2-NU-14 12.10.2022
Chemical				
87	Total Iron	mg Fe/l	<0.15	0.16
128	Total Silicon*	mg Si/l	1.71	1.37
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.60	1.18
Methods	Determinands	Units	030963/22	030964/22
			NUTRIENT SAMPLES: SAMPLE 14, EX3-NU-14 12.10.2022	NUTRIENT SAMPLES: SAMPLE 14, C-NU-14 12.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.16	0.20
128	Total Silicon*	mg Si/l	1.36	1.94
65Gc	Nitrate	mg N/l	<0.25	<0.25
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	1.38	<0.1

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Methods	Determinands	Units	030965/22	030966/22
			DFE SAMPLES: SAMPLE 1, EX1-DFE- 01 29.09.2022	DFE SAMPLES: SAMPLE 1, EX2-DFE- 01 29.09.2022
Chemical				
87	Total Iron	mg Fe/l	0.22	0.35
128	Total Silicon*	mg Si/l	2.20	1.80
65Gc	Nitrate	mg N/l	302	432
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.85	0.81
Methods	Determinands	Units	030967/22	030968/22
			DFE SAMPLES: SAMPLE 1, EX3-DFE- 01 29.09.2022	DFE SAMPLES: SAMPLE 1, C-DFE-01 29.09.2022
Chemical				
87	Total Iron	mg Fe/l	0.23	0.24
128	Total Silicon*	mg Si/l	3.65	1.61
65Gc	Nitrate	mg N/l	310	152
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.81	1.35
Methods	Determinands	Units	030969/22	030970/22
			DFE SAMPLES: SAMPLE 2, EX1-DFE- 002 30.09.2022	DFE SAMPLES: SAMPLE 2, EX2-DFE- 002 30.09.2022
Chemical				
87	Total Iron	mg Fe/l	0.55	<0.15
128	Total Silicon*	mg Si/l	1.05	0.86
65Gc	Nitrate	mg N/l	413	203
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	1.62	0.65
Methods	Determinands	Units	030971/22	030972/22
			DFE SAMPLES: SAMPLE 2, EX3-DFE- 002 30.09.2022	DFE SAMPLES: SAMPLE 2, C-DFE- 002 30.09.2022
Chemical				
87	Total Iron	mg Fe/l	0.27	<0.15
128	Total Silicon*	mg Si/l	1.16	1.31
65Gc	Nitrate	mg N/l	366	311
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.93	0.66

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Methods	Determinands	Units	030973/22	030974/22
			DFE SAMPLES: SAMPLE 3, EX1-DFE- 03 01.10.2022	DFE SAMPLES: SAMPLE 3, EX2-DFE- 03 01.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.51	0.29
128	Total Silicon*	mg Si/l	2.34	1.66
65Gc	Nitrate	mg N/l	367	218
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.56	0.55
Methods	Determinands	Units	030975/22	030976/22
			DFE SAMPLES: SAMPLE 3, EX3-DFE- 03 01.10.2022	DFE SAMPLES: SAMPLE 3, C-DFE-03 01.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.17	<0.15
128	Total Silicon*	mg Si/l	1.07	1.21
65Gc	Nitrate	mg N/l	291	279
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	1.15	0.57
Methods	Determinands	Units	030977/22	030978/22
			DFE SAMPLES: SAMPLE 4, EX1-DFE- 04 02.10.2022	DFE SAMPLES: SAMPLE 4, EX2-DFE- 04 02.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.15	<0.15
128	Total Silicon*	mg Si/l	1.08	1.37
65Gc	Nitrate	mg N/l	239	309
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	9.26	1.89
Methods	Determinands	Units	030979/22	030980/22
			DFE SAMPLES: SAMPLE 4, EX3-DFE- 04 02.10.2022	DFE SAMPLES: SAMPLE 4, C-DFE-04 02.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.17	<0.15
128	Total Silicon*	mg Si/l	1.15	1.02
65Gc	Nitrate	mg N/l	324	151
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	1.00	1.41

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Methods	Determinands	Units	030981/22	030982/22
			DFE SAMPLES: SAMPLE 5, EX1-DFE-05 03.10.2022	DFE SAMPLES: SAMPLE 5, EX2-DFE-05 03.10.2022
Chemical				
87	Total Iron	mg Fe/l	<0.15	0.16
128	Total Silicon*	mg Si/l	1.94	1.32
65Gc	Nitrate	mg N/l	357	268
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	2.23	2.04
Methods	Determinands	Units	030983/22	030984/22
			DFE SAMPLES: SAMPLE 5, EX3-DFE-05 03.10.2022	DFE SAMPLES: SAMPLE 5, C-DFE-05 03.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.33	<0.15
128	Total Silicon*	mg Si/l	2.47	1.65
65Gc	Nitrate	mg N/l	215	226
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.25	0.30
Methods	Determinands	Units	030985/22	030986/22
			DFE SAMPLES: SAMPLE 6, EX1-DFE-06 04.10.2022	DFE SAMPLES: SAMPLE 6, EX2-DFE-06 04.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.23	<0.15
128	Total Silicon*	mg Si/l	1.38	1.28
65Gc	Nitrate	mg N/l	221	124
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.35	0.26
Methods	Determinands	Units	030987/22	030988/22
			DFE SAMPLES: SAMPLE 6, EX3-DFE-06 04.10.2022	DFE SAMPLES: SAMPLE 6, C-DFE-06 04.10.2022
Chemical				
87	Total Iron	mg Fe/l	<0.15	<0.15
128	Total Silicon*	mg Si/l	2.85	1.46
65Gc	Nitrate	mg N/l	157	185
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.11	0.44

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Methods	Determinands	Units	030989/22	030990/22
			DFE SAMPLES: SAMPLE 7, EX1-DFE- 07 05.10.2022	DFE SAMPLES: SAMPLE 7, EX2-DFE- 07 05.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.20	0.19
128	Total Silicon*	mg Si/l	1.04	1.79
65Gc	Nitrate	mg N/l	214	271
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.62	0.61
Methods	Determinands	Units	030991/22	030992/22
			DFE SAMPLES: SAMPLE 7, EX3-DFE- 07 05.10.2022	DFE SAMPLES: SAMPLE 7, C-DFE-07 05.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.25	<0.15
128	Total Silicon*	mg Si/l	1.23	1.00
65Gc	Nitrate	mg N/l	167	296
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.60	0.35
Methods	Determinands	Units	030993/22	030994/22
			DFE SAMPLES: SAMPLE 8, EX1-DFE- 08 06.10.2022	DFE SAMPLES: SAMPLE 8, EX2-DFE- 08 06.10.2022
Chemical				
87	Total Iron	mg Fe/l	<0.15	0.17
128	Total Silicon*	mg Si/l	1.28	1.58
65Gc	Nitrate	mg N/l	265	289
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.18	0.65
Methods	Determinands	Units	030995/22	030996/22
			DFE SAMPLES: SAMPLE 8, EX3-DFE- 08 06.10.2022	DFE SAMPLES: SAMPLE 8, C-DFE-08 06.10.2022
Chemical				
87	Total Iron	mg Fe/l	<0.15	<0.15
128	Total Silicon*	mg Si/l	0.96	1.17
65Gc	Nitrate	mg N/l	273	396
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.55	0.12

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Methods	Determinands	Units	030997/22	030998/22
			DFE SAMPLES: SAMPLE 9, EX1-DFE- 09 07.10.2022	DFE SAMPLES: SAMPLE 9, EX2-DFE- 09 07.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.18	<0.15
128	Total Silicon*	mg Si/l	1.08	1.40
65Gc	Nitrate	mg N/l	310	255
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.35	0.14
Methods	Determinands	Units	030999/22	031000/22
			DFE SAMPLES: SAMPLE 9, EX3-DFE- 09 07.10.2022	DFE SAMPLES: SAMPLE 9, C-DFE-09 07.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.20	0.18
128	Total Silicon*	mg Si/l	2.22	0.68
65Gc	Nitrate	mg N/l	318	317
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	1.76	1.32
Methods	Determinands	Units	031001/22	031002/22
			DFE SAMPLES: SAMPLE 10, EX1- DFE-10 08.10.2022	DFE SAMPLES: SAMPLE 10, EX2- DFE-10 08.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.69	2.02
128	Total Silicon*	mg Si/l	1.34	0.93
65Gc	Nitrate	mg N/l	321	253
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.22	0.58
Methods	Determinands	Units	031003/22	031004/22
			DFE SAMPLES: SAMPLE 10, EX3- DFE-10 08.10.2022	DFE SAMPLES: SAMPLE 10, C-DFE- 10 08.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.37	<0.15
128	Total Silicon*	mg Si/l	1.07	1.02
65Gc	Nitrate	mg N/l	320	292
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.99	1.15

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Methods	Determinands	Units	031005/22	031006/22
			DFE SAMPLES: SAMPLE 11, EX1- DFE-11 09.10.2022	DFE SAMPLES: SAMPLE 11, EX2- DFE-11 09.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.40	<0.15
128	Total Silicon*	mg Si/l	0.36	0.86
65Gc	Nitrate	mg N/l	320	304
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.11	0.81
Methods	Determinands	Units	031007/22	031008/22
			DFE SAMPLES: SAMPLE 11, EX3- DFE-11 09.10.2022	DFE SAMPLES: SAMPLE 11, C-DFE-11 09.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.20	0.17
128	Total Silicon*	mg Si/l	0.92	1.05
65Gc	Nitrate	mg N/l	203	17.4
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.12	0.16
Methods	Determinands	Units	031009/22	031010/22
			DFE SAMPLES: SAMPLE 12, EX1- DFE-12 10.10.2022	DFE SAMPLES: SAMPLE 12, EX2- DFE-12 10.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.15	0.27
128	Total Silicon*	mg Si/l	0.39	0.52
65Gc	Nitrate	mg N/l	17.1	159
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.11	0.11
Methods	Determinands	Units	031011/22	031012/22
			DFE SAMPLES: SAMPLE 12, EX3- DFE-12 10.10.2022	DFE SAMPLES: SAMPLE 12, C-DFE- 12 10.10.2022
Chemical				
87	Total Iron	mg Fe/l	<0.15	<0.15
128	Total Silicon*	mg Si/l	0.31	0.37
65Gc	Nitrate	mg N/l	171	134
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	<0.1	0.16

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Methods	Determinands	Units	031013/22	031014/22
			DFE SAMPLES: SAMPLE 13, EX1- DFE-13 11.10.2022	DFE SAMPLES: SAMPLE 13, EX2- DFE-13 11.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.45	0.23
128	Total Silicon*	mg Si/l	0.31	0.27
65Gc	Nitrate	mg N/l	204	239
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.11	0.13
Methods	Determinands	Units	031015/22	031016/22
			DFE SAMPLES: SAMPLE 13, EX3- DFE-13 11.10.2022	DFE SAMPLES: SAMPLE 13, C-DFE- 13 11.10.2022
Chemical				
87	Total Iron	mg Fe/l	<0.15	<0.15
128	Total Silicon*	mg Si/l	0.26	0.44
65Gc	Nitrate	mg N/l	173	192
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.16	0.22
Methods	Determinands	Units	031017/22	031018/22
			DFE SAMPLES: SAMPLE 14, EX1- DFE-14 12.10.2022	DFE SAMPLES: SAMPLE 14, EX2- DFE-14 12.10.2022
Chemical				
87	Total Iron	mg Fe/l	0.26	<0.15
128	Total Silicon*	mg Si/l	0.69	0.44
65Gc	Nitrate	mg N/l	209	261
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	0.15	0.12
Methods	Determinands	Units	031019/22	031020/22
			DFE SAMPLES: SAMPLE 14, EX3- DFE-14 12.10.2022	DFE SAMPLES: SAMPLE 14, C-DFE- 14 12.10.2022
Chemical				
87	Total Iron	mg Fe/l	<0.15	<0.15
128	Total Silicon*	mg Si/l	0.37	0.37
65Gc	Nitrate	mg N/l	132	168
65Gb	Nitrite	mg N/l	<0.05	<0.05
66G	Orthophosphate	mg P/l	<0.1	<0.1

Refer to the "Notes" section at the end of this report for further explanations.

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Specific Observations

None

Quality Assurance

Technical signatories



Inorganic Chemistry, Sipho Ngobho

Notes to this report

Limitations

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Uncertainty of measurement

Talbot Laboratories' Uncertainty of Measurement (UoM) values are:

- Identified for relevant tests.
- Calculated as a percentage of the respective results.
- Applicable to total, dissolved and acid soluble metals for ICP element analyses.
- Available upon request.

Analysis explanatory notes

Tests may be marked as follows:

^	Tests conducted at our Port Elizabeth satellite laboratory.
*	Tests not included in our Schedule of Accreditation and therefore that are not SANAS accredited.
#	Tests that have been sub-contracted to a peer laboratory.
NR	Not required -shown, for example, where the schedule of analysis varied between samples.
σ	Field sampling point on-site results.
a	Testing has deviated from Method.

*****End of Report*****