Chapter 1: Introduction

1.1. Background

One of the most striking changes in the Earth's climate system in the latter half of the twentieth century was the change in rainfall over areas of West Africa. The semi-arid region to the south of the Sahara Desert, known as the Sahel, saw a series of droughts from 1968 onward, which placed great stress upon the local population and the predominantly pastoral and agricultural economies of the region. It has been estimated that rainfall since 1968 has been 20-40% lower than in the period 1931-1960 (Nicholson et al., 2000). Shukla (1995) notes that in the past 100 years 'there is no other region on the globe of this size for which spatially and seasonally averaged climatic anomalies have shown such persistence.'

The scientific community has focused a considerable amount of attention on the causes of the Sahelian drought, but the complexities of weather and climate in the region mean no simple explanation for this change has been found. However, several atmospheric, oceanic and biospheric factors have been linked to the precipitation changes. This thesis investigates some of those links by the creation of an empirical model on a daily time scale.

1.2. Where is the Sahel and what is its climate?

The term 'Sahel' has come to refer to the semi-arid area of Africa to the south of the Sahara Desert and north of the verdant coastline of the Gulf of Guinea (see Figure 1.1), between 10 and 20 °N. The marked contrast between the arid interior and the humid conditions nearer the coast, combined with the lack of major orographic features, result in a strong meridional rainfall gradient, and a strong zonal symmetry (Shukla, 1995), as represented in Figure 1.2.

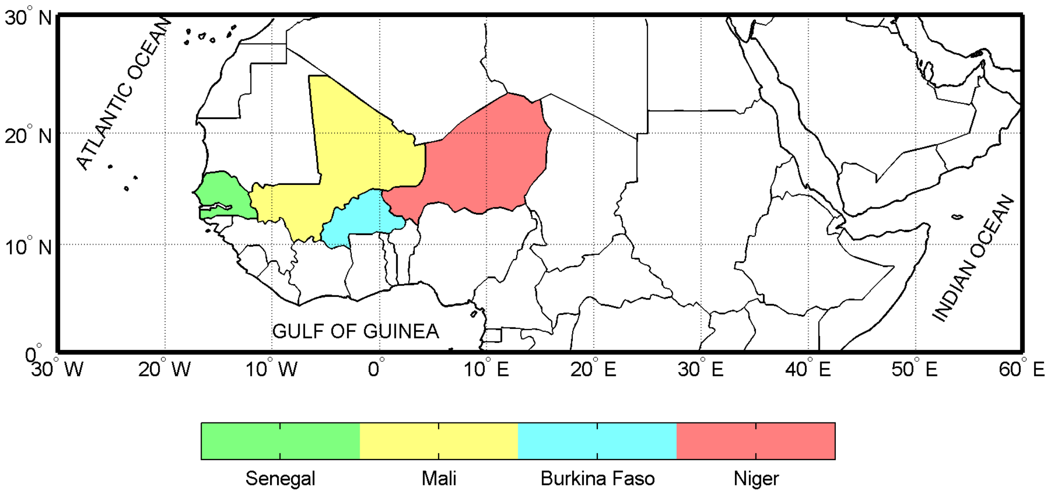

Figure 1.1. Map of the Sahel. For the purposes of this study, 'The Sahel' refers to the four countries shown in colour.

The exact boundaries of the Sahel are nebulous, due to the high levels of rainfall variability. Average rainfall (as shown in Figure 1.2) and vegetation cover increase as one travels south. Different authors have used different definitions of the Sahel (Nicholson and Palao, 1993). In common with many authors, the definition of the Sahel used in this thesis will depend on available data, covering Senegal, southern Mali, Burkina Faso and western Niger.

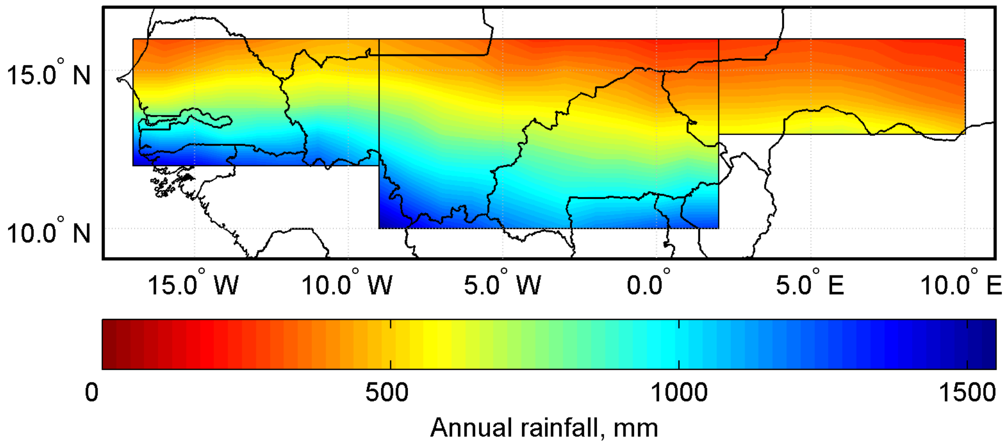

Figure 1.2. Average annual rainfall across the Sahel, 1958-1997. Data for this figure is interpolated from the gridded data set created in Chapter 3.

Rainfall in the Sahel is characterised by a single monsoon-type season centred on the Northern Hemisphere summer, and exhibits high spatial and temporal variability.

The typical seasonal evolution of the monsoon is illustrated by Figure 1.3. The high level of interannual and interdecadal variability makes the notion of a single figure representing 'average' rainfall for the Sahel unhelpful (Hulme, 2001). Therefore the long-term climatological means represented in Figures 1.2 and 1.3 should not be considered a typical state of Sahel climate. They are only included for illustrative purposes. The tendency of Sahelian rainfall to be either 'wet' or 'dry', illustrated in Figure 1.4, means this mean state is rarely achieved.

Figure 1.4, an index measuring rainfall in western Mali, 1958-1997, illustrates the extent of the interannual variability over the Sahel. Unfortunately, such an index gives no indication of the high degree of spatial variability. For example, Le Barbe et al. (2002) report a case from the EPSAT study from 1998, when two stations located only 80 km apart recorded seasonal totals of 450 and 1050 mm. Furthermore, simple indices only indicates one type of temporal variability. Tarhule and Lamb (2003) note that the high level of variability extends to all major rainfall indicators, including monsoon onset and retreat dates, and length of dry spells.

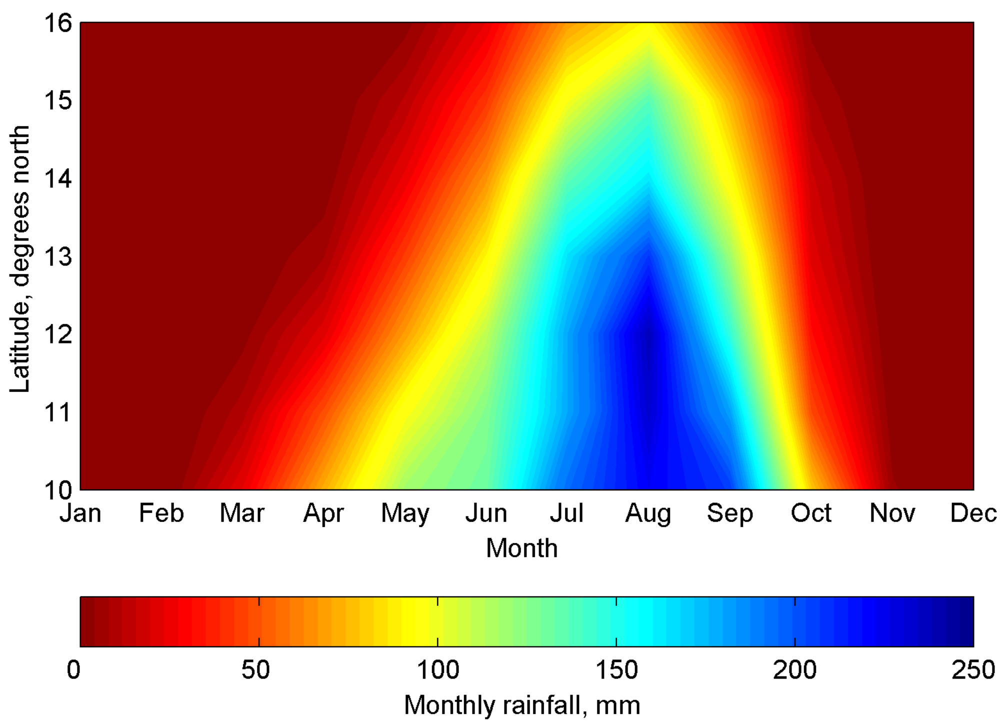

Figure 1.3. Average seasonal evolution of the West African monsoon at 3°W. The data displayed represents the average value for 1958-1997 in the gridded data set created in Chapter 3.

In spite of these drawbacks, a simple index such as that illustrated by Figure 1.4 can depict some of the broader trends exhibited over a large area. The high interannual variability of Sahel rainfall is evident, as are the recent changes to the level of interdecadal variability, illustrated by the marked difference in the index before and after 1968. Conditions since 1968 have been anomalously dry, and while periods of droughts are not unprecedented (for example, droughts occurred in the early 1910s), the persistent drought during recent decades has no parallel over the instrumental period. Analyses of longer indices note that the persistently wet conditions in the 1950s are equally curious (Hulme, 2001).

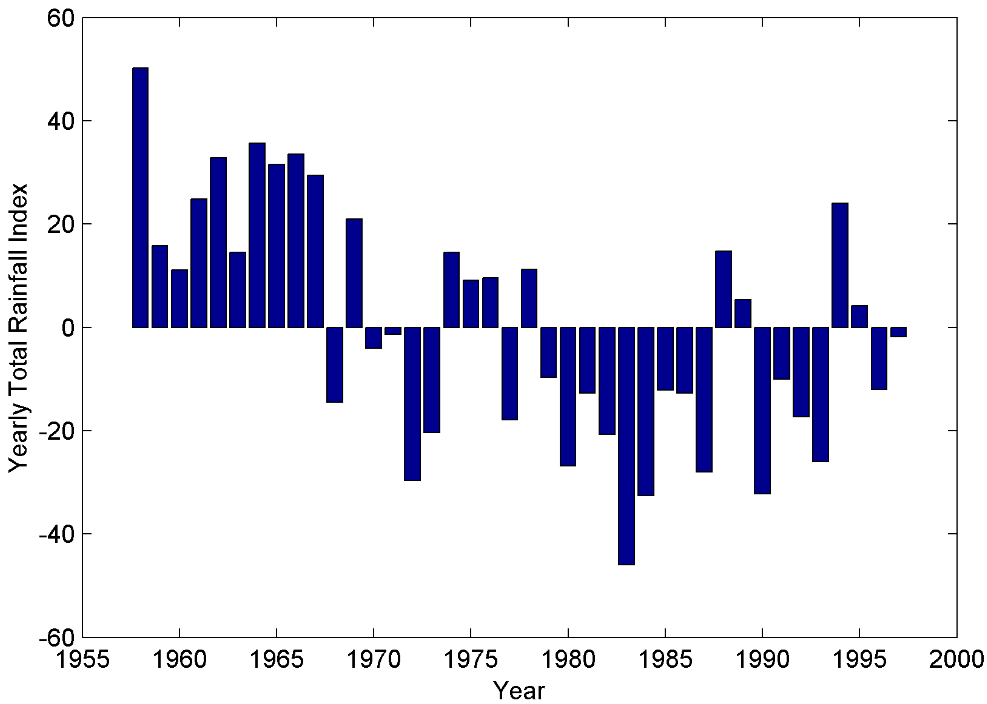

Figure 1.4. A Sahel rainfall index, 1958-1997. The index displayed is the annual time series of the gridded data set for the 'Central West' region displayed in Figure 5.1, and represents rainfall in western Mali. See section 4.2.3 for details of the creation of this time series.

1.3. Historical Sahelian Climate

There is little direct evidence of the nature of Sahelian climate prior to the twentieth century, due to the lack of meteorological observations. However, as Sahel rainfall exhibits a high variability on all time scales from days to decades, it seems reasonable to assume the Sahel may also exhibit high intercentennial variability. This claim seems to be supported by what little proxy evidence exists.

Nicholson (2001) suggests that the Sahelian climate has varied considerably over the past few millennia. 18 000 years ago, toward the end of the last Ice Age, most of the African continent was covered by desert. As the ice age retreated, the continent became much more humid, and by 5000 years ago, the Western Sahara was marshland and Lake Chad was ten times its present size.

Nicholson notes that although past studies indicate semi-arid conditions have been prevalent in the Sahel since about 2000 years ago (Lézine, 1989), humidity has continued to vary. For example, the period from the 9^{th} to the 14^{th} centuries was particularly humid; the Mali civilisation flourished and elephants and giraffes were found in what is now desert. Conversely, the 1820s and 30s were exceptionally dry; Lake Chad dried up entirely. Such variations have continued to date, with the end of the 19^{th} century humid enough to grow wheat near Tombouctou, and the 1910s dry enough to prompt talk of the 'desiccation of Africa'.

Whilst proxy data illustrates the variability in climate, it is "neither widespread enough nor sufficiently quantitative to resolve and date Sahel droughts over recent millennia" (Hulme, 2001). Hulme imagines what challenges researchers of the year 2500 would face in trying to reconstruct climate of this era, and suggest that the Blue Nile flood of 1988 would leave a greater hydrological mark than a sequence of dry years. Hence, an imprudent researcher might mark the late twentieth century as wet.

Nevertheless, all the evidence suggests that the climate of the Sahel has varied greatly in the past. Such variability suggests that the Sahel is highly sensitive to changes in forcing mechanisms. This will be explored in more detail in the next chapter.

1.4. A social perspective

The lack of rainfall in the Sahel has had severe impacts on the local populations and economies, and in particular on the food and water supplies. The dominance of rainfed agriculture renders the people of the Sahel particularly vulnerable to famine following a drought. A recent study rated 3.8 million inhabitants of the Sahel as "moderately food insecure" in a high-rainfall year (USAID, 2000). Natural forces can easily exacerbate a drought: for example the combination of low rainfall and locust infestations of 2004 resulted in the widely reported famine of the following year. Furthermore, the effects of low rainfall on water availability and crops are not straightforward. Lebel et al. (2003) note that the relative river discharge deficit in dry periods is twice the relative rainfall deficit, further reducing the water available for irrigation.

The unprecedented nature of the recent Sahel dry period has rendered many of the coping strategies employed by the local populations untenable (Tarhule and Lamb, 2003). For example, Wickens (1997) notes that the lack of rainfall lowers the water table, which may prevent the cultivation of previously common crops in some areas. Rapid population growth and urbanisation has added to the problem: recently the population of the Sahel has been doubling every 20 years (Zeng, 2003). Stress on natural resources increases with each year. Furthermore, this growth has also blocked the traditional migration routes of nomadic herdsmen (Tarhule and Lamb, 2003), forcing them to spend longer in the drier Sahel regions, putting their livestock at great risk.

The countries of the Sahel are some of the poorest in the world. The four countries examined in this thesis (Burkina Faso, Mali, Niger and Senegal) are all recognised as "Least-Developed Countries" by the UN (UNCTAD 2004, p xiv). Increased external debt and declining trade balances have reduced the ability of local governments to avoid or mitigate the effects of such a long period of low rainfall (Tarhule and Lamb, 2003). Therefore, the effects have been severe. The Sahelian droughts of 1968 to 1973 are believed to have claimed as many as 250,000 lives (UNCOD, 1977).

The extreme change in the nature of Sahelian rainfall after 1968, and its tragic consequences, has attracted the attention of scientists from a wide variety of disciplines. The causes of this change, reviewed in Chapter 2, are still unclear, but some important factors have been identified.

1.5. Aims and Organisation of the Thesis

This thesis aims to increase the understanding of the causes of Sahelian rainfall by investigating the link between daily rainfall and atmospheric variability using an empirical model. It begins with a review of the past studies of Sahel climate in Chapter 2, documenting the current state of understanding and providing a justification for the approaches taken later. The review starts with a description of Sahel climate, then investigates the main factors influencing it. First, atmospheric components are considered, then the role of the oceans, and finally the effect of land surface conditions in the Sahel and surrounding areas.

The study itself is described in Chapters 3 to 5. Chapter 3 focuses on the creation of a response variable for the empirical model. It describes the acquisition of daily rainfall data for 523 stations across the Sahel, and the amalgamation of these data into a new gridded daily rainfall data set. The technique used to perform the gridding is described, justified, applied and verified therein.

In Chapter 4, attention is turned to the other side of the statistical model: the predictor variables. This chapter describes the dimension-reduction technique of Principal Component Analysis (PCA). This technique is applied to the NCEP reanalysis data set to create 37 predictor variables that represent atmospheric variability in three-dimensions. PCA is also used to reduce the gridded rainfall data set into six response variables.

A suitable method to link the response and predictor variables is identified in Chapter 5: Generalised Linear Models (GLM). Again, the chapter follows the pattern of describing the technique used, explaining how it was implemented and ensuring the method is suitable. Finally, the output is interpreted, and the implications for understanding of Sahel climate are considered.

The thesis ends with Chapter 6, a brief summary of the thesis. The main findings are collated and expounded, and possible avenues for future research are explored.