Chapter 2: The Current State of Understanding of Sahel Climate

2.1. Introduction - different approaches

In his landmark review paper of 1989, Druyan provided five categories into which studies of West African rainfall could be divided (Druyan, 1989):

1. The search for interannual trends and periodicities in precipitation data, for example Kane and Trivedi (1986).

2. The analysis of spatial patterns of seasonal / annual precipitation, for example Nicholson and Palao (1993).

3. Analysis of synoptic observational data in case studies, for example Lamb (1978a).

4. Examination of teleconnections by calculation of correlations; for example Folland et al. (1986).

5. General Circulation Model (GCM) studies; for example Moron et al. (2003).

Whilst advances in statistical techniques and computing power have enabled more complex studies to be carried out, modified versions of Druyan's categories are still largely applicable. For example, category five should be expanded to include Regional Climate Models (RCM), and the second category should include analysis of daily precipitation. Moreover, since Druyan created his list, GCMs have been used to produce reanalysis data, such as the NCEP/NCAR Reanalysis (Kalnay et al., 1996). This has provided a wealth of extra data for researchers, particularly as physical measurements taken in the Sahel are usually too sparse for a thorough analysis. For example, see the attempt by Grist and Nicholson (2001) to use radiosonde and pibal data, compared to use of the NCEP reanalysis. Thus, Druyan's third category should be expanded to include reanalysis as well as observational data.

Druyan notes that each approach "can offer valuable information about one or more aspects of sub-Saharan rainfall". However, each approach also has a set of potential pitfalls that may trap the unwary researcher. They all involve the imposition of a model, be it a linear regression model or the set of equations, parameters and boundary values of a numerical climate model.

This chapter reviews the studies that have been carried out to date, and identifies the current state of knowledge about the causes of Sahelian drought. The initial focus is on the Sahel itself, the nature of rainfall variability and the main atmospheric processes active in the area. Next, other processes that have been suggested as factors in Sahel climate will be examined, whether external, such as sea surface temperatures, or internal, such as land albedo. Finally, the statistical methodology and theoretical basis of this thesis is reviewed, both in terms of a natural extension of this preceding research and as entirely new concepts made possible by the availability of improved data sources and recent additions to research techniques in climatology.

2.2. Elements of Sahel Rainfall Climatology

2.2.1. Monsoon Flow

This section reviews the physics of what might be described as “normal” Sahel climate, a regime where much human activity depends on regular highly seasonal rainfall. Subsequent sections address current understanding of deviations from this norm. That is, what does research tell us about the devastating droughts that have afflicted the region?

2.2.1.a. A simple monsoon model

The seasonal climate cycle in West Africa is dominated by the switch between the two climatic regimes driven by trade winds: the dry Harmattan northeasterly winds from the Sahara, and moist southwesterlies from the Gulf of Guinea. The boundary between these two regimes, the Intertropical Convergence Zone (ITCZ), marks the area of maximum rainfall. The classical view of the monsoon has been of the ITCZ migrating northwards with the sun as the year progresses, moving from 5°N in February to a most northerly position of 20°N in August, before retreating southward over the remainder of the year. When the ITCZ is south of the Sahel, the northeasterly Harmattan winds dominate, whereas when the ITCZ is north of the Sahel, the southwesterly monsoon winds dominate. This causes a single rainy season in the Sahel, lasting approximately from June to September, and two rainy seasons in the coastal regions of the Gulf of Guinea, the first as the ITCZ advances, the second as it retreats. This migration was considered to be a smooth transition, due to the lack of notable mountain ranges (Hastenrath, 1991). Figure 1.3 illustrates the mean passage of the wet season over the Sahel.

2.2.1.b. The monsoon "jump" model

Recent work, however, suggests that the onset of the monsoon is not as smooth as was previously thought. In a study of rainfall over the period 1971-1990, Le Barbe et al. (2002) noted that the start of the Sahelian rainfall season was 'not in continuity' with the onset of the first rainy season on the coast; the monsoon did not break smoothly across the whole of West Africa. Sultan and Janicot (2000) introduced the idea of an abrupt shift in the ITCZ, often referred to as a 'jump', from 5°N to 10°N at some point in late June. Their calculations suggested that, for the period 1968 – 1990, the mean date for this shift was the 24th June, and the standard deviation was 8.0 days. Research by Semazzi and Sun (1997) and Sultan and Janicot (2003) suggest that this jump may be due to interactions with the nearby Atlas-Ahaggar mountains, located in, and north of, the Sahara.

Lebel et al. (2003) suggest the shift in the ITCZ marks a break in a two-stage monsoon. They describe the first stage of the monsoon as the oceanic phase, which 'corresponds to a progressive onset of rain on the West African continent from the tropical Atlantic.' The jump in the ITCZ marks a shift to the second, continental phase, and a sudden rise in the mean daily rainfall and mean number of rain events across the whole Sahel, with this second phase accounting for 75-90% of total annual rainfall in the Sahel. The vast majority of rainfall occurring during this period is the result of large convective systems. The authors discovered that rainfall in the oceanic phase differs little between wet and dry years, as does the average rainfall of a convective event during the continental phase. Thus, they suggest the interannual variability of Sahelian rainfall is largely the result of the variability in the number of convective events occurring. Indeed, Grist et al. (2002) note that one or two very large disturbances can account for much of the difference between a wet and a dry summer.

2.2.1.c. Theoretical support for the "jump" model

The idea of a jump in monsoon flow is supported by a model proposed by Eltahir and Gong (1996). In this paper, the authors attempt to examine the theoretical framework behind the West African monsoon, by deriving a set of equations that explain the physics of a zonally symmetric circulation. They note that the West African monsoon seems much more sensitive to a number of factors than other areas where monsoon circulations dominate. The derived equations suggest that this is due to the proximity of the West African monsoon region to the equator, being situated at roughly 10°N, compared to 25°N for the Indian monsoon. Consequently, the Coriolis parameter, and hence planetary vorticity are considerably lower. Conversely, the rate of change of the Coriolis parameter with respect to latitude is much higher.

The derived equations describe the monsoon circulation as dominated by one of two regimes, either a radiative-convective equilibrium regime or an angular momentum conserving regime. Which regime dominates is largely controlled by the meridional gradient of boundary-layer entropy. Furthermore, the equations predict that a unit change in this gradient will have an affect fifteen times greater in West Africa than it would in India. Also, the zonal wind at upper levels is particularly sensitive to the gradient.

The strength of the boundary-layer entropy gradient also determines the strength of the monsoon circulation. Eltahir and Gong examine two years as a case study using the GFDL rawinsonde dataset (see Oort, 1983). Unfortunately, changes in reporting procedures result in a discontinuity in this dataset after 1968, so the study focuses on the comparatively wet year of 1958 and the comparatively dry year of 1960. The results confirm that in the drier year a flatter distribution of entropy existed, as predicted.

Le Barbe et al. (2002) suggest that Eltahir and Gong's theory fits into the idea of a two-stage monsoon. The jump between Lebel et al.'s (2003) oceanic and continental regimes occurs when the threshold level of the boundary-level entropy gradient is exceeded, the ITCZ jumps abruptly (Sultan and Janicot, 2003), and the circulation moves from the radiative-convective regime to the angular momentum conserving regime. Furthermore, Eltahir and Gong (1996) note that their theory fits in with the two main proposed drivers of change in West Africa; sea surface temperatures in the Atlantic Ocean, and surface conditions of the Sahel (see later section).

2.2.2. Other moisture sources

It is important to stress that the southwesterly monsoon flow is not the only source of moisture in the Sahel. Indeed, a study from Fontaine et al. (2003) suggested that about 75% of moisture entering the West African monsoon region between 1000 and 300 hPa during July-September comes from the North and East. This suggests that the Mediterranean, East Africa and the Indian Ocean will play an important role in the strength of the monsoon. Similarly, Long et al. (2000) note that water vapour flux over West Africa is dominated by easterly flow. Furthermore, Gong and Eltahir (1996) note that evaporation from the land surface of West Africa contributes roughly 27% of moisture to rainfall over the region, suggesting that an accurate understanding of the region will need to consider feedbacks involving soil moisture and the biosphere.

2.2.3. Jet Streams

Advances in technology over the past few decades have enabled more detailed studies of the upper atmosphere to be conducted. The resulting discovery of jet streams has led to major advances in the understanding of atmospheric processes, as jet streams at various levels are essential mechanisms of energy and mass transfer within the general circulation of the atmosphere.

The African upper atmosphere in summer is heavily influenced by two easterly jets: the hemispheric Tropical Easterly Jet (TEJ) and the considerably weaker and more localised African Easterly Jet (AEJ), also known as the West African Mid-Tropospheric Jet. Although the AEJ is less important than the TEJ globally, it is arguably a more important influence on Sahel rainfall.

2.2.3.a. The Tropical Easterly Jet Stream (TEJ)

The Tropical Easterly Jet is a major factor in the global circulation. It is an upper-tropospheric phenomenon, centred at about 200 hPa. It forms in South Asia and plays a vital role in the Indian monsoon. It is limited to the summer circulation, appearing in late June and disappearing in early September. Winds speeds at the core are typically $40ms^{-1}$. The jet occurs at roughly 15 ºN, appearing off the east coast of China and passes through India and the Middle East, weakening over the Horn of Africa before appearing to dissipate over Sudan at roughly 20 ºE. In fact, this is a jet exit and entrance region for the TEJ, and a new TEJ appears at roughly 10ºN, continuing westwards to the West African coast before again appearing to dissipate over the eastern Atlantic (Koteswaram, 1958; Hastenrath, 1991, p129-131; Fontaine et al., 1995;).

As with most upper atmosphere processes, the TEJ is far from fully understood. However, it is believed to result from the meridional thermal gradient that forms in Asia and Africa due to the extreme summer heating of the subtropics compared to the equator. This gradient is exacerbated by the heating of the Himalayan plateau (Hastenrath, 1991; Fontaine et al., 1995).

2.2.3.b. The African Easterly Jet Stream (AEJ)

The African Easterly Jet occurs in the mid-troposphere, with a core at around 600 hPa, and typically reaches zonal speeds of about 12 ms^{-1}. Easterly flow at this level is present throughout the year, and from April to November in concentrated into the AEJ over western Africa (Burpee, 1972). Before 1968, the jet typically appeared at 13 °N, migrated northwards during the summer, reached its most northerly position at 17 °N in August, and then retreated southward. This progression changes considerably in drought years, when the AEJ migrates between 7 and 12 °N (Grist and Nicholson, 2001).

The African Easterly Jet also seems to be the result of a meridional temperature gradient. In this case, the gradient results from the contrast between the hot conditions over the Sahara (produced by extreme solar heating in the north), and the comparatively colder conditions in the south, (where less heating occurs and the maritime air from the Atlantic Ocean plays a cooling role).

Cook (1999) produced compelling evidence that the African Easterly Jet "owes its existence" to the negative meridional soil moisture gradient in West Africa. In the moist equatorial regions evaporation allows latent cooling to occur at the surface. The lack of water to evaporate in the dry Sahara means latent cooling cannot occur, and cooling can only occur through a sensible heat flux. This replacing of latent cooling by sensible cooling has two consequences, as noted by Cook:

> "First, the surface temperature is driven higher until cooling by the sensible and thermal radiation terms balance the solar heating… [Second], the heat flux from the surface is distributed in the lower troposphere by dry convection and diffusion, rather than being deposited in the middle and upper troposphere by condensational heating. A pronounced reversal of the meridional temperature gradient in the lower troposphere results, and the AEJ appears."

Cook demonstrated the importance of the soil moisture gradient by running a GCM, once with a realistic soil moisture gradient, and once with a constant level of soil moisture. The first run resulted in a somewhat weak and slightly lower level AEJ than that observed (attributed to weaknesses in the model) and the second did not produce a jet at all. Cook describes summer insolation and the moisture gradient as "necessary and sufficient conditions for the formation of the AEJ over West Africa in the model". Further experiments went on to suggest that sea surface temperatures and land surface roughness could influence the strength and position of the jet.

2.2.4. Mid-tropsopheric Instability: Easterly Waves and Squall Lines

The presence of easterly flow in the mid-troposphere, overlaying the low-level westerly monsoon flow, contributes to creating a region of instability from which African wave disturbances propagate. The exact nature and causes of this instability are uncertain, although it is generally thought that the waves are a result of the hydrodynamic instability of the AEJ and the presence of horizontal and vertical shear (Burpee, 1972; Hastenrath and Wolter, 1992). Embedded within these disturbances are squall lines, which are responsible for at least 70% of total Sahelian precipitation (Druyan, 1989) and are the seeds of tropical storms and hurricanes in the Atlantic (Thorncroft and Hodges, 2001; Landsea and Gray, 1992).

2.2.4.a. Easterly Waves

The wave elements of mid-tropospheric instability, normally referred to as African Easterly Waves (AEWs), typically originate west of 20 °E, with a period of 3-5 days, a wavelength of 2000-4000 km, westerly propagation speeds of 7-9 ms^{-1} and a mean latitude of 11-12 °N (Carlson, 1969; Burpee, 1972; Pytharoulis and Thorncroft, 1999). The waves normally appear along two tracks, located to the north and south of the AEJ, which converge into one track over the tropical Atlantic (Reed et al., 1988a; Reed et al., 1988b).

Diedhiou et al. (1999) described three possible patterns of activity over West Africa:

- activity to the north of the AEJ
- activity to the south of the AEJ

- activity both sides of the AEJ.

The authors discovered these three patterns occur with roughly equal frequency. Furthermore, they identified a second regime of easterly waves, with a periodicity of 6-9 days, which is more likely to be associated with a 'dipole' pattern between Sahel and Guinea Coast rainfall.

2.2.4.b. Squall Lines

Squall lines are often found embedded in the waves. Fink and Reiner (2003) provide a thorough description of squall lines, from which much of the following information is taken. They describe squall lines as "intense mesoscale convective systems" and separate them into two parts: the "convective region" and the trailing "anvil" or "stratiform region". The "convective region" is a convex line of convective cells typically a few hundred km long, and causes strong gusts followed by intense but short lived thunderstorms, with rain in excess of 30 mm per hour for about half an hour. These are followed by more durable but lighter rains in the "stratiform region", with rain rates falling to 4 mm per hour, but lasting for 2-3 hours (Chong et al., 1987; Roux, 1988; Fink and Reiner, 2003). The squall lines have a mean life of 10-13 hours and move at an average speed of 14-17 ms^{-1} (Aspliden et al., 1976; Payne and McGarry, 1977; Rowell and Milford, 1993).

2.2.4.c. Interactions between Squall Lines and Easterly Waves

The role of African Easterly Waves in squall line generation is still not well understood, as reviewed in Fink and Reiner (2003). For example, Reed et al. (1977) examined eight AEWs, and observed that the greatest ascent, cloud cover and rainfall was to be found just to the west of the trough, possibly suggesting the presence of squall lines. Conversely, the study of Rowell and Milford (1993) examined 186 squall lines, and found no significant relationship between generation and decay of the squall lines and AEWs, but speculated that AEWs influence squall lines west of their study region (9-12°N, 2.5°W-14°E). Furthermore, Bolton (1984) found no correlation between AEWs and squall line passage at Minna in Nigeria (9° 37' N, 6° 32' E), and Druyan et al. (1996) found 30% of AEWs passing Niamey, Niger, in 1987-1988 did not produce 'appreciable precipitation'. Taleb and Druyan (2003) conclude that seasonal statistics of AEWs at a station give 'no unambiguous indication about the season precipitation'.

In their own study, Fink and Reiner (2003) study the relationship using 81 AEWs and 344 squall lines that occurred in 1998 and 1999. The study attempts to separate squall lines into those that were 'AEW-forced' and those that were not. They recorded that the AEW-forced squall lines did not exhibit any different characteristics from unforced squall lines, suggesting the 'impact of AEWs is largely restricted to the squall lines initiation and growth process.' Furthermore, the influence of AEWs upon squall lines increases substantially to the west of the Greenwich Meridian, and peaks near the coast. This supports the theory of Rowell and Milford (1993) mentioned above, and is in keeping with the experiments at Minna and Niamey. The diurnal solar heating cycle is critical in the creation of squall lines, with 55% originating between 12-18 UTC (Aspliden et al., 1976), and the few squall lines that originate at night are mostly AEW forced. AEWs prove most important in August and September, at the height of the rainy season. Fink and Reiner conclude by suggesting AEWs do not directly trigger squall lines, but that the "weak synoptic ascent … might be sufficient to organize isolated convective cells that were, for example, triggered by the daytime heating into squall lines."

Clearly, the study of the interaction between the mid-atmospheric elements of Sahel climate is extremely difficult, with no firm consensus arising from the research. This is partly because of the complex nature of the three-dimensional physics involved, but also because of the paucity of reliable upper air and surface data over the region. This thesis addresses both these issues.

2.3. Changes in Sahel Climate

The devastating impact of drought in the Sahel has created newspaper headlines throughout the western world for decades. This section reviews the science behind current thinking on the causes of the droughts.

As mentioned in Chapter 1, the rainfall in West Africa is characterised by a high level of variability over a wide range of temporal and spatial scales. The next two sub-sections will examine changes in the year-to-year variability of Sahel rainfall and the broader West African climate. The first sub-section will consider changes in the mean state, the second changes in the annual cycle.

2.3.1. Seasonal Variability – Changes in the mean state

2.3.1.a. Interannual trends and periodicity in Sahel rainfall

Droughts have occurred in the Sahel in the 1910s, 1940s and 1970s, leading some to hypothesise that the droughts are a part of a long-term climatic cycle. Previous studies, categorised under Druyan's research classification one, have searched for interannual trends and periodicities in precipitation data, but have not proved particularly successful.

Amongst the most cited examples are the studies by Faure and Gac (1981) and Kane and Trivedi (1986). Both focus on the time series of total annual rainfall averaged across the Sahel by using an index similar to that displayed in Figure 1.4. Faure & Gac examined the time series for periodicites, and by fitting a series of cycles to the data predicted that "the present drought should end in 1985 with full wet conditions being re-established in about 1992". In fact, 1983-1985 were the driest consecutive years of the century, and the wet conditions have not returned since (Hulme, 2001). Kane and Trivedi (1986) employed a similar philosophy, and fitted long-term periodicities to a Sahel index stretching back to 1900. They fitted a model based on the years 1900-1969 that successfully captured the drought in the 1970s, but they were unable to model the severe droughts of the 1980s. Thus, the recent droughts cannot simply be understood as a mix of a trend and cycles in rainfall.

Nevertheless, techniques such as spectral analysis can reveal important insights into the temporal nature of rainfall. For example, Rowell et al. (1995) examine the spectrum of the yearly July – September rainfall series of three indices representing the Sahel (here defined as the region 12.5 – 17.5 °N), the Soudan (the area to the south of the Sahel, at about 10 ºN) and the Guinea Coast for 1906-92. The Sahel and Soudan spectra are similar, both being dominated by long term variability, with frequencies greater than ten years accounting for about 50% of total variance. The Soudan series also shows a peak at 3 to 8 years, which the authors highlight even though it fails to achieve significance at a 5% level, as it suggests ENSO time-scale variability might be more important in the Soudan (see Section 2.4 for further discussion). The Guinea Coast region has a very different spectrum, with low frequencies far less important, only accounting for about 10% of total variance. Most variance occurs at shorter time-scales, with the peak occurring at 2-3 years. However, the authors note this only applies to the northern hemisphere summer, and the low frequency variability is far higher in other seasons. Furthermore, the July-September period does not coincide with the peak period of rainfall along the Guinea Coast.

2.3.1.b. Spatial patterns in seasonal and annual Sahel rainfall

Principal component analysis (PCA)

Druyan's second category, the analysis of spatial patterns of seasonal and annual precipitation, has proved much more fruitful. A typical method has been to carry out a principal component analysis (PCA – see Chapter 4 for further details) on seasonal rainfall totals for a set of locations. This illustrates the principal modes of variability of the region considered. By this method, Nicholson (1986) splits spatial variability into six 'configurations' that show a high level of spatial coherence. This suggests that large-scale anomalies determine the nature of African rainfall in any given year (Druyan, 1989).

Principal component analyses carried out on seasonal data in the West Africa (such as Nicholson, 1980; Nicholson, 1981; Nicholson and Palao, 1993 and Janicot, 1992a) tend to define two main modes of rainfall variability (Nicholson and Grist, 2001). The most common is rainfall anomalies of opposite sign in the Sahel and along the Guinea Coast, with the divide between the two regions at 10 ºN. So wet conditions in the Sahel are opposed by dry conditions on the Guinea Coast, and vice versa. This mode is often referred to as a 'dipole'. The second mode has anomalies of the same sign over the whole region. Nicholson and Grist (2001) describe these two modes as 'so fundamental that they are evident on interannual and interdecadal time scales and in the historical record of past centuries (Nicholson, 1994; Nicholson, 1995).'

One of the most comprehensive of such studies was carried out by Nicholson and Palao (1993), who examined the rainfall series of 19 regions of West Africa (as defined in Nicholson, 1986 and Nicholson, 1988) covering the area 0-22 °N, 20 °W - 30 °E over the period 1901-1985. They examine the time series of annual rainfall, June/July rainfall and August/September rainfall for each region.

The results of these analyses suggest there are important differences in the variability in June/July and August/September in the Sahel. August/September rainfall is more highly correlated with annual rainfall than June/July is. Unsurprisingly August/September rainfall has a negative trend twice as strong as that in June/July, which is in agreement with the findings of Farmer and Wigley (1985). Furthermore, the spectra of the rainfall series demonstrate that low-frequency components of variability are more important in August/September than in June/July. High-frequency components dominate along the Guinea Coast.

The authors split the area into three 'homogeneous sectors', a Guinea Coast region, a West Coast region centred on Senegal, and a continental Sahel zone, on the basis of the results of a PCA carried out on the 19 regions. The first principal component (PC) is the common anomaly of the whole region, the second the Sahel vs. Guinea Coast dipole, and the third a coastal vs. inland pattern, with Guinea and West Coast anomalies opposite to those in the continental Sahel. Analysis of the PC time series suggests PC1 is most closely associated with low frequency rainfall variability, PC3 with high frequency and June/July rainfall, and PC2 with all frequencies of variability and August/September rainfall. These results suggest the early and late parts of the rainy season could be controlled by different mechanisms, supporting Lebel et al.'s (2003) two-stage monsoon theory outlined in Section 2.2.1.b.

"Wet" and "Dry" composites

Another major approach has been to consider how atmospheric variables have varied from year-to-year, and whether these changes can be related to wet / dry years. Often, these are performed by comparing the mean atmospheric state in two 'composites', one from a wet period, and one from a dry period. Many of the theories on the nature of Sahel rainfall variability owe their existence to application of this methodology.

"Drift" of the ITCZ

A typical example of this, and one of the most contested, is the hypothesised link between rainfall in the Sahel and the most northerly extent reached by the ITCZ. Many early papers (e.g. Winstanley, 1973; Kraus, 1977a; Kraus, 1977b; Lamb, 1978a; Lamb, 1978b) and some more recent (e.g. Fontaine and Janicot, 1992; Janicot, 1992a; Janicot, 1992b; Lamb and Peppler, 1992) suggest during the drought years, the ITCZ did not penetrate as far north over West Africa. Consequently, less monsoon moisture is available over the Sahel, and rainfall in diminished. However, the theory has some major flaws. For example, it would suggest that the monsoon season would be shorter in dry years, which is not the case (Nicholson, 1981; Le Barbe and Lebel, 1997).

Furthermore, a southward shift in the ITCZ would suggest less rain in the Sahel would be accompanied by more rain on the coastal regions. This theory could explain the Sahel vs. Guinea dipole pattern. However, the dipole was investigated in Janicot et al. (2001), by examining the changing correlation between Sahelian and Guinea rainfall when calculated over 20-year running windows from 1945-1964 to 1974-1993. The dipole, indicated by a negative correlation, was only significant for the start of the period, before the major drought began. This suggests that whilst the position of the ITCZ could explain occurrences of Sahel drought before 1970, it cannot in the latter period.

Nevertheless, the ITCZ still seems an important factor in determining rainfall. Nicholson (1981) and Grist and Nicholson (2001) suggest that the ITCZ is intensified in wet years, as demonstrated by stronger meridional winds. This is supported by Newell and Kidson's (1984) finding that lower tropospheric southwesterlies are shallow and weaker in dry years, but penetrate almost as far north as in wet years (Folland et al., 1986).

Similar controversy has surrounded the role of moisture advection in the monsoon flow, as reviewed in Grist and Nicholson (2001). Lamb's (1983) comparison of moisture advection in wet and dry years suggests that drought is not associated with the "northward supply of unusually dry surface air to West Africa from the tropical Atlantic." However, recent work suggests that a significant change is taking place in the nature of the low-level monsoon flow. Analyses of the NCEP dataset suggests that whilst in the past the westerly flow during the monsoon season typically extended up to 400 hPa, recent decades have seen it restricted to 700-800 hPa. Furthermore, throughout the year the core speeds of the flow have fallen, from a mean of roughly 12 ms^{-1} at the start of the 1960s to about 4 ms^{-1} by the end of the decade (Nicholson and Grist, 2001). These reduced speeds could inhibit the transfer of moisture to the Sahel region.

The influence of the Tropical Easterly Jet

There seems to be a clear change in the strength of the TEJ in dry years (Kidson, 1977). The composite analysis of Grist and Nicholson (2001) indicates that jet core speeds throughout the wet season fall from 20 ms^{-1} in wet years to 8-16 ms^{-1} in dry years. It is hypothesised that the increased jet speed would increase the shear and upper level divergence necessary to produce the wave disturbances that produce most Sahelian rainfall (Druyan, 1989; Grist and Nicholson, 2001).

Curiously, another analysis has suggested that an increase of speeds in the Asian branch of the TEJ between India and Lake Chad is often associated with reduced rainfall in the Sahel (Camberlin et al., 2001). However, the authors note that a stronger high-level easterly jet east of the Sahel implies a sharp decrease in 200 hPa zonal velocity over the Sahel, and hence convergence that could 'hinder deep convection over the area'.

The influence of the African Easterly Jet

Whilst the role and changing nature of the TEJ in forcing West African rainfall has remained something of a mystery, there have been advances in the understanding of the role of the AEJ. Newell and Kidson (1984) reported that Sahelian droughts coincided with a strengthening of the AEJ at 700mb in August. Such a discovery caused a problem. Would not a stronger mid-tropospheric jet increase wind shear leading to greater instability and more wave activity, which is associated with Sahelian rainfall (Druyan, 1989)? Druyan suspected the presence of a negative feedback process, and also noted that ‘even when the dynamics favour a high frequency of African wave disturbances, deficiencies in the moisture supply will limit seasonal rainfall totals.’

Another problem in understanding the relationship between AEJ and rainfall is the inability to separate cause from effect. Newell and Kidson (1984) suggested that the strengthening of the AEJ could be the result of reduced rainfall. They state that 'decreased rainfall would lead to decreased evapotranspiration, greater surface energy loss by sensible heat, warmer surface and boundary layer air and an increased thermal wind and zonal wind shear.'

Again, understanding of the role of the AEJ was enhanced by studies of the NCAR-NCEP reanalysis dataset. The increased amount of data available allowed not only a study of the strength of the jet, but also the position of the jet. Wet years average an AEJ core of 10 ms $^{-1}$ located at 15 ºN in August. Dry years average a core of 12 ms^{-1} at 12 ºN (Grist and Nicholson, 2001; Camberlin et al., 2001).

Thus, in the dry years the AEJ tends to be directly above the low-level monsoon flow. In the wet years, the AEJ tends to be further north, and the monsoon flow extends upwards to the mid-troposphere. As the ITCZ tends to be more intense in wet years, and hence the low level westerlies are stronger, wind shear is enhanced, and hence wave activity is greater (Grist and Nicholson, 2001).

This theory was tested by Grist (2002). The author confirms that in the NCEP reanalysis, the season when waves are active is 30-50 days longer in wet years than in dry years. Furthermore, stronger waves are present in the wetter years. This view is supported by a modelling study in the companion paper by Grist et al. (2002). However, the authors admit the link is still unclear, because the link between AEWs and rainfall is not fully understood. However, the increase in the strength of wave activity seems consistent with an increase in the intensity of rainfall events.

A note of caution

Of course, the above studies all have made assumptions which need to be considered whilst interpreting them. For example, the studies of Grist and Nicholson (2001), Grist (2002) and Grist et al. (2002) are based on differences in the NCEP reanalysis between the four wet years of 1958-1961, and four dry years of 1982-1985. To draw conclusions from these results assumes that these eight years represent the variability in all years, in particular omitting what happens in 'average' years. Furthermore, any flaws in the NCEP reanalysis will affect the results; and Janicot et al. (2001) and Camberlin and Diop (2003) document some serious concerns over NCEP prior to 1968 (see Section 4.1 for further details). Therefore, in isolation, the results of these papers should be treated with caution.

2.3.2. Seasonal Variability – Changes in the annual cycle

Another aspect of rainfall variability, examined in a series of studies including Le Barbe and Lebel (1997) and Le Barbe et al. (2002), is the analysis of the development of the yearly monsoon cycle. For example, the Le Barbe and Lebel (1997) study decomposes rainfall series across Niger into two daily series for each rainfall station; the number of rainfall events per day, and the average rainfall per event. They conclude that the decrease in rainfall in drought years is closely associated with a decrease in the number of rainfall events, particularly in the core rainy season months of July and August, whilst the amount of rain per event changes little. However, they also note that the drought is not caused by a shorter rainfall season either.

The study of Le Barbe et al. (2002) uses a similar approach on a larger region, extending southward to the coast, and focuses more on the intensity of the rainfall events. Again, they note a close link between number of rainfall events and total seasonal rainfall, and little connection with event rainfall. In addition, the authors compare the mean conditions of a 'wet period' of 1951-1970 and a 'dry period' of 1971-1990. They conclude that in the Sahel, the core of the rainy season occurs between 10-20 days earlier in the dry period, but that the overall length of the rainy season was again largely unaffected.

A recent paper by Camberlin and Diop (2003) used the novel approach of considering the cumulative score of the leading principal component of square-rooted daily rainfall over Senegal to study the 'shape' of the rainy season in any given year. The plot of the cumulative score resembles a distorted inverted sine wave, and the authors found the turning points of the curve provided a good definition of the start and end of the rainy season. The yearly time series of these start and end dates show a clear trend towards an earlier cessation of the monsoon (at a 1% level of significance), and a weaker trend (with 10% significance) toward a later start. The authors discovered little correlation between seasonal rainfall and cessation date (0.17), but a strong negative correlation (-0.51, significant at a 5% level) between seasonal rainfall and onset date.

The authors suggest that the years 1988 and 1989 illustrate these results well. Both years saw a similar amount of seasonal rainfall. However, in 1988 the season started about 1.5 months later, and intense rain late in the wet season made up for the early deficit. These years also stress the importance of the timing of the rain for local farmers. Millet yields were 521 kg ha^{-1} is 1988, compared to 664 kg ha^{-1} in 1989, and groundnut yields were 794 kg ha^{-1} compared to 1072 kg ha^{-1}. The results of the lack of early rains did not affect total seasonal rainfall, but did produce low yields for the most important food and cash crops (Camberlin and Diop, 2003).

2.3.3. Intraseasonal Variability

Variations in Sahel rainfall within a season are obviously also important, particularly if linked to quasi-periodic factors. Because of the lack of suitable data, this type of study has only recently become practicable. The few studies that have been carried out have revealed some of the driving forces are similar to those behind interannual variability.

2.2.3.a. Daily Variability

Perhaps the most extensive intraseasonal study to date is by Sultan et al. (2003), which investigated intraseasonal variations in convection between 1968 and 1990. The study notes that there are quasi-periodic fluctuations in rainfall of more than 30% over the seasonal cycle. These fluctuations are made of wet and dry sequences lasting about 9 days, resulting in a cycle lasting on average 15 days. A second, weaker signal also exists over a period averaging 38 days.

Sultan et al then form composites of wind and vertical velocity for 'wet' and 'dry' periods; the same approach as used by Grist and Nicholson (2001), but forming composites on a daily rather than yearly basis.

The results indicate that a wet period is characterised by enhanced convection in the ITCZ, the northern boundary of which is located further north. Monsoon flow is stronger, as is the speed of the TEJ, whereas the AEJ is weaker. Conditions for the dry period are the opposite, so for example, the AEJ is stronger.

It is apparent that these characteristics are the same of those found by Grist and Nicholson (2001) when examining interannual variability. Hence, the authors argue there are similar connections between convection and atmospheric circulation at both timescales.

Sultan et al. continue by analysing the mean wind and convection fields over a larger scale for the seven days either side of a rainfall minima, thus covering the course of the proposed fifteen day cycle. The results demonstrate that anomalies in convection propagate westward from East Africa, crossing the Sahel and continuing as far as the western tropical Atlantic. Furthermore, five days before a rainfall maximum over the Sahel, cyclonic circulation is stronger at 20 ºE. This induces an increase in southerly winds along 25 ºE, where convection is enhanced. This connection again stresses the importance of events to the east of the Sahel.

A recent study by Mounier and Janicot (2004) suggests that intraseasonal fluctuations in convection over West Africa can be separated into two independent modes, both with cycles lasting, on average, fifteen days. The first displays a Sahel vs. Guinea dipole pattern across West Africa, associated with a westward propagating signal of convection, and linked to changes in the location of the ITCZ. The second, representing changes the strength of the ITCZ, and is linked to the strength of zonal flow over the Atlantic. Again, these results are reminiscent of those found in interannual studies (e.g. Nicholson and Palao, 1993).

2.3.3.b. Madden-Julian Oscillation

Phenomena such as westward propagations cannot be identified by interannual studies, as averaging over the course of a season cancels out the extremes of intraseasonal variability. Thus, other forces influencing Sahel rainfall can be identified by examining events over the shorter time scale. For example, the study by Matthews (2004) suggests a link between Sahelian rainfall and the Madden-Julian oscillation.

The Madden-Julian oscillation (MJO, see Madden and Julian, 1994) is a large-scale pseudo-periodic fluctuation in convection, and hence rainfall, in equatorial regions, displaying a cyclical patterns typically lasting between 30 and 60 days. Patterns of anomalous deep convection propagate eastward from the equatorial Indian Ocean to the West Pacific.

Matthews (2004) links fluctuations in the MJO with African rainfall via Kelvin and Rossby waves. During the phase of the MJO cycle when convection is reduced over the West Pacific, a westerly equatorial Kelvin wave and two easterly off-equatorial Rossby waves are triggered. These waves propagate in their opposite directions, reuniting twenty days later, when the Kelvin wave reaches the coast of West Africa, and the Rossby waves reach the east coast of Africa either side of the equator (at approximately 10 °N and 10 °S). Upon reaching their respective coastlines, the three waves cause an increase in convection. Furthermore, the arrival of the Kelvin wave in West Africa increases the cyclonic shear near the AEJ, increasing barotropic instability, and hence easterly wave production, further increasing convection.

These intraseasonal variations are a valuable area of future research. Better understanding of the links between Sahelian rainfall and quasi-periodic oscillations such as the MJO could lead to better mid-range forecasts.

2.4. Sea Surface Temperatures

As with the physics of Sahel rainfall, this section is divided into a review outlining the "normal" relationship between sea surface temperature and Sahel rainfall, and a summary of how the relationship is thought to vary over time.

2.4.1. Linking Global Sea Surface Temperatures to Sahel Rainfall

The previous sections have examined the internal variability of Sahelian rainfall on a range of scales, and considered how changes in atmospheric dynamics affect the monsoon season. But what factors drive these changes? Many mechanisms have been proposed, and the following sections examine some of the most prominent.

The link between West African rainfall and sea surface temperature (SST) has been studied in detail. Lamb was the first to notice a link between rainfall over the Sahel and SST variability in the local tropical Atlantic Ocean (Lamb, 1978a; Lamb, 1978b). This and further studies (such as Hastenrath, 1984; Lough, 1986 and Servain, 1991) suggest the West African rainfall dipole, characterised by an anomalously dry Sahel and wet Guinean Coast associated with an Atlantic SST dipole, is linked with anomalously warm temperatures in the tropical south Atlantic, and anomalously cool temperatures in the north Atlantic.

Global Teleconnections

The link between West African rainfall and SSTs was extended to a global scale in two complementary papers from the Hadley Centre (Folland et al., 1986; Palmer, 1986). These papers used composite analysis techniques similar to those described earlier in the discussion of Grist and Nicholson (2001), but focusing on SSTs instead of wind. They calculated the worldwide SST difference between composites made of the five driest and wettest years in the Sahel over 1901-1985. The resulting pattern showed that changes in the Sahel rainfall are associated with changes in the interhemispheric SST difference. Dry conditions in the Sahel tend to be related to cold SSTs in the northern hemisphere, and warm SSTs in the southern hemisphere (provided the 'southern hemisphere' is taken to include the northern Indian Ocean). As noted by Nicholson (1995), this interhemispheric contrast increased in the Sahelian wet period of the mid 20th century and decreased sharply during the droughts of the 70s and 80s. Most results of the Hadley Centre studies were not statistically significant, but were supported by a GCM experiment. A GCM forced by the SST difference pattern showed 30% less Sahel rainfall than the comparable control run.

The Importance of Individual Ocean Basins

The approaches used by Folland et al. (1986) and Palmer (1986) have been refined in order to investigate the influence of individual ocean basins in a number of studies. This section will focus on the results of three key studies:

- Rowell et al. (1995). This is another Hadley Centre study, using a similar approach to Folland et al. (1986) and Palmer (1986). The study correlates three rainfall series (representing the Sahel, the Guinea Coast, and the region between them, referred to as the Soudan), with global SSTs. The use of filters allows high and low frequency variability to be considered separately. Low frequency results for the Sahel are very similar to the earlier studies, suggesting long-term trends in rainfall are related to interhemispheric SST difference. The high frequency results show important differences between the role of each basin, as described below.

- Ward (1998). Ward uses the same approach and data as Rowell et al. (1995), but splits high frequency analysis into years which exhibit the dipole pattern between Sahelian and Guinean rainfall and years which do not.

- Camberlin et al. (2001). This study uses a similar, but inverted, approach to Rowell and Folland (1995), correlating SST indices to a gridded rainfall data set. The rainfall data set covers most of sub-Saharan Africa at a 3.75 ° × 3.75 ° resolution. The authors compute the correlation between a given SST index and every rainfall grid point for each month of the year. The results are then subjected to a Hierarchical Cluster Analysis, to split the rainfall grid points into a small number of groups. This results in a map that splits African rainfall into several regions that respond in a similar way to variation in the SST index, although the nature of this response may change throughout the year. The results from two indices are examined in detail: one representing the equatorial South Atlantic (0-20 °S, 30 °W - 10 °E, referred to as SATL), and the NIÑO3 Pacific Index (5°N - 5°S, 150-90 °W), chosen to represent ENSO events.

  Camberlin et al. conclude their study by investigating the changes in atmospheric dynamics associated with SST anomalies. They achieve this by forming composites of the wind field across Africa in the NCEP reanalysis at 200, 700 and 1000 hPa, the approach used in Grist & Nicholson (2001). Three different composites are created: 'Sahel dry years' minus 'Sahel wet years' (i.e. the average pattern of years with a low Sahel rainfall index minus the patterns for years with a high index), 'warm minus cold' for the NIÑO3 index (the pattern for warm East Pacific years minus the pattern for cold East Pacific years), and 'warm minus cold' for the SATL index.

The results of these studies are presented by ocean basin in turn:

The Atlantic Ocean

As, mentioned above, early studies of the Atlantic noted that the West African rainfall dipole mode was often associated with an Atlantic SST dipole. By splitting variability into low and high frequencies, Rowell et al. (1995) refined this view.

Rowell et al.'s analysis of low frequency data suggests that the Atlantic dipole is a major influence on Sahel and Soudan rainfall, as part of the wider interhemispheric SST difference. Conversely, no long-term relationship between Guinea Coast rainfall and the Atlantic (or any other ocean) is identified.

The analysis of high frequency data suggests that short-term variability in the equatorial and eastern South Atlantic is a major factor in the Sahel – Guinea Coast rainfall dipole. These two indices show very similar correlation patterns in those sections of the Atlantic, but have opposite signs. Hence, warm waters in the equatorial and eastern South Atlantic tend to be associated with a dry Sahel and a wet Guinea Coast. The Soudan shows a similar pattern to the Sahel, but with weaker correlations. Ward (1998) confirms the Atlantic SST dipole is dominant in years exhibiting the rainfall dipole, but other basins are dominant in non-rainfall dipole years (see the Pacific / ENSO section).

Camberlin et al. are able to reproduce the rainfall dipole using only the SATL index, suggesting the role of the North Atlantic is less important. They suggest that a large-scale warm SST anomaly in the South Atlantic reduces the temperature gradient toward the African continent. As a result, the ITCZ is prevented from moving as far north, causing greater rainfall along the Guinea coast, and less rainfall in the Sahel.

Camberlin et al.'s composite analyses create some surprising results. If drought in the Sahel is linked with South Atlantic SST anomalies, then one would expect to see similar maps for the 'Sahel dry minus wet' and 'SATL warm minus cold' composites. However, they have few features in common. The rainfall composite has the usual features mentioned in section 3.2.1 (a weaker TEJ, stronger and southward-shifted AEJ, enhanced convergence in the ITCZ), but shows surprisingly little change in the southwesterly monsoon flow at the surface. The main feature in the SST composite is a reduction of this monsoon flow. The authors suggest that this increase flow may be cancelled out in the rainfall composite by the enhanced ITCZ convergence that appears in the NIÑO3 composite (see the Pacific / ENSO section).

The Pacific Ocean / ENSO

Rowell et al.'s (1995) analysis of correlations between the Pacific basin and the high frequency Sahel and Soudan series suggest a link between Sahel rainfall and ENSO events. Rainfall tends to be lower when there is a warming in the central and eastern tropical Pacific and a cooling in the west tropical Pacific. The relationship is slightly stronger for the Soudan index, and in both cases much stronger than that for the raw (unfiltered) data.

Ward's analysis (1998) notes that in non-rainfall dipole years, the correlations between Sahel rainfall and the Pacific exhibit a typical ENSO signal: drought over the Sahel is associated with a warmer east Pacific, and a cooler west Pacific. However, Ward also notes that the tendency for Sahel drought during El Niño events is focused on the July-September period, whereas June and October have tended to be wetter.

Camberlin et al's (2001) correlation analysis suggests the link is not so clear. Much of the Sahel shows no significant correlation with the NIÑO3 index, except for the Sahel-Soudan border grid points (here defined at about 12.5 °N). However, the 'warm minus cold' composite for the NIÑO3 index shows a very similar pattern to the Sahel rainfall composite, suggesting "a direct control of ENSO on Sahel rainfall". This control is probably via the North Atlantic and Americas, as the Indian Ocean anomalies in the NIÑO3 composite do not appear in the rainfall composite.

These mixed results are indicative of the ongoing debate into the influence of ENSO events on West African rainfall. More attention is given to this subject in section 2.4.2.

The Indian Ocean

The role of the Indian Ocean has been subjected to less scrutiny than the other main basins. The early Hadley Centre studies (Folland et al., 1986; Palmer 1986) suggested Sahel drought is associated with a warm Indian Ocean. Rowell et al.'s

(1995) study suggested that, for high-frequency variability, this pattern is strongest in the areas close to the eastern coast of north and equatorial Africa.

A recent study by Giannini et al. (2003) suggests the role of the Indian Ocean may have been underestimated. This paper uses a GCM to suggest that a warming trend in the Indian Ocean may have played a vital role in the Sahel droughts of the late 1960s to the 1980s. The warming of the Indian Ocean, combined with a warm Atlantic, form a "ring of warm SSTs around Africa", weakening the land-ocean temperature contrast necessary for the monsoon.

The Mediterranean Sea

Other recent studies have stressed the importance of the Mediterranean to Sahel climate. Raicich et al. (2003) suggest Sahelian rainfall is negatively correlated to both sea levels and surface pressure in the Mediterranean. Rowell (2003) studies the impact of Mediterranean SSTs on the Sahel. The paper follows a similar approach to other Hadley Centre studies (such as Folland et al., 1986 and Rowell et al., 1995), firstly examining empirical evidence for teleconnections, then investigating proposed teleconnections with a numerical model. A July to September Mediterranean SST index showed a similar pattern to Sahel rainfall since 1950, being warm in the 50s and 60s, cooler in the 70s and 80s, and recovering in the 90s. Rowell concludes that the observational evidence suggests the impact of the Mediterranean on the Sahel is as great as that of ENSO, and a little less than the tropical Atlantic.

The modelling part of the study allows the investigation of the atmospheric changes related to the lack of rainfall. In the GCM used, anomalous SSTs in the Mediterranean provoked a 'strong and significant response' in wet season rainfall in the Sahel. In years when Mediterranean SSTs were warmer than usual, enhanced evaporation leads to greater moisture content at the bottom of the atmosphere. This moisture is carried southward over the Sahara by the prevailing wind, which increases moisture convection, and therefore rainfall, over the Sahel. Rowell also notes several feedback mechanisms which enhance rainfall further.

Validation by GCMs

Many GCM studies into the link between Sahel rainfall and SSTs have been carried out. These back up the theory that the Atlantic and the Pacific have a major influence on Sahel rainfall (for example, Semazzi et al., 1988; Folland et al., 1991; Palmer et al., 1992 and Semazzi et al., 1996). However, GCMs forced by SST temperatures alone tend to reproduce the low frequency variability well, but the high frequency variability poorly, as demonstrated by Moron et al. (2003). This suggests that whilst SSTs may be a major factor in causing a drought, other processes control whether a drought occurs or not. Indeed, it might be hypothesised that SST anomalies are a necessary condition for a drought, but not sufficient. This idea will be developed further in section 2.5.

2.4.2. Changes in the links between SSTs and West African rainfall.

Most of the empirical studies detailed in the previous section examined the correlation between rainfall and sea surface temperatures over a given period. However, drawing conclusions from the results assumes that the nature of this correlation does not change over time. This section will examine studies that demonstrate this assumption is not true, and explain what this means for our understanding of Sahel climate.

The Atlantic Ocean

Janicot et al. (2001) demonstrate the changing nature of correlations between July-September Sahelian rainfall and global SSTs by calculating the correlations over two period, 1954-1973 and 1970-1989. The results show that in the first period, Sahelian rainfall is most closely linked with the South Atlantic and Indian basins, whereas in the second period the Pacific dominates. The authors then use 20-year running windows between 1945-1964 and 1974-1993 and calculate the correlation between July – September Sahel rainfall and four SST indices. The four SST indices used are those defined by Fontaine et al. (1998), based on the four leading modes of a rotated principal component analysis. The first of these (referred to as RPC1) broadly represents a typical ENSO event, whilst the second (RPC2) and third (RPC3) represent the variability in the north and south Atlantic respectively.

As noted in section 2.3.1, Janicot et al. noted the tendency for a 'dipole' between Sahel and Guinea rainfall has disappeared in the recent Sahelian dry period. When this dipole exists, the link between Sahelian rainfall and the Atlantic SST dipole is strong. Furthermore, when the correlation between the Sahel vs. Guinea dipole is recalculated, removing the effect of the Atlantic SST dipole, the significant correlations in the earlier part of the analysis disappear.

Janicot et al. represent the Atlantic SST dipole by the difference between two indices, RPC3 representing the equatorial southern Atlantic minus RPC2 representing the north Atlantic. The correlation between these indices, representing the SST dipole, also disappears in the early 1970s, becoming a weak positive correlation. Hence, Janicot et al's study suggests both dipoles may have broken down in the dry period. However, the authors note that the details of the selected indices are vital to the analysis. Whilst their link between Atlantic SSTs and Sahelian rainfall breaks down in the Sahelian dry period, the link in Rowell (2001) does not, as it emphasises SSTs in the area between 15 and 25 °S.

The Pacific Ocean / ENSO

The previous section includes studies which suggest a link between ENSO and Sahelian rainfall. However, there have been some papers that have been unable to establish a link (such as Ropelewski and Halpert, 1987 and Goddard et al., 2001). Druyan's (1989) review notes that whilst the link often holds, during some El Niño years rainfall is only marginally lower than usual. Some years, such as 1984, have seen droughts without an El Niño, whereas the El Niño years of 1952, 1954 and 1958 were all wet. This debate led to investigation into whether these relationships have evolved over time.

Studies by Moron (1994) and Janicot et al. (1996) investigated the nature of this evolution by calculating the correlation between Sahelian rainfall and a measure of ENSO over different time scales. Moron (1994) calculated the correlation coefficient between a Sahel rainfall index and the Southern Oscillation Index (SOI) over twenty year running windows between 1945-1964 and 1974-1993. Under these conditions, the correlation coefficient varies between about 0.1 and 0.5, and statistical analysis suggested the correlation has been significant since 1968. Janicot et al. (1996) computed correlations between two West African rainfall indices and five SST indices (covering the three major oceans) over two time periods, 1945-1969 and 1970-1993. The results indicate marked changes between the two periods, for example the link between Sahel rainfall and equatorial South Atlantic SSTs weakened dramatically in the second period.

Rowell (2001) examined the stationarity of the Pacific – Sahel link by evaluating running correlations from 30-year windows over the period 1900-1929 to 1967-1996. He found a strong correlation existed in the early decades of the twentieth century, decaying to a weak, perhaps non-existent link mid century, and strengthening from the 1970s onward. The later results mirrored the findings of Janicot et al. (1996). However, a Monte Carlo test could not reject the possibility that the decadal variations in the link were simply the result of sampling error.

The correlations between Janicot et al's (2001) RPC1, which represents ENSO, and Sahel rainfall concur with the earlier results; correlations are always negative, but only significant outside of the period 1955-1974 to 1962-1981. They develop a test that indicates whether 'the signal of ENSOs impact on the Sahel is not significant' on a particular 20-year window. This test can be rejected for all windows except those that begin before 1963. Hence, whilst Rowell's (2001) result suggests we cannot demonstrate that decadal variations in the ENSO vs. Sahel link exist, Janicot et al.'s results suggest this link has been statistically significant since the 1970s. However, later in the paper, the authors discover that if the effect of the other SST indices is removed, the ENSO vs. Sahel link remains strong in the wetter period. This may suggest that at that time ENSO's influence was masked by other factors.

The analyses above suggest ENSO is related to Sahelian rainfall. However, whilst a statistical link may exist, it says nothing about the causality of the two processes. Statistics alone cannot tell if ENSO has a direct impact on Sahel rainfall, if they both fluctuate in common with some global factor or, most unlikely of all, if Sahel rainfall drives ENSO. If a cause-effect relationship is to be established, then a physical mechanism for the relationship must be proposed.

Such a mechanism is yet to be discovered for the ENSO-Sahel link, although possible processes have been suggested. Rowell (2001) suggests an El Niño events result in the propagation of Kelvin and Rossby waves. The Kelvin waves travel eastward over the Atlantic Ocean, and the Rossby waves travel westward over the Indian Ocean. Upon reaching the Sahel, these waves force large-scale subsidence, and therefore reduce rainfall. Janicot et al. (2001) notes that an El Niño event results in an eastward mean sea level pressure gradient between the eastern tropical Pacific and West Africa. This leads to enhanced trade winds over the tropical Atlantic, and weaker moisture advection, and hence rainfall, over West Africa.

Janicot et al.'s results suggest that the influence of each oceanic basin on Sahelian rainfall has changed over the decades. In the Sahel wet period of the 1950s and early 1960s, Sahel rainfall was linked to the Atlantic SST dipole. Contrarily, in the following dry period, the relationship with Pacific SSTs in the form El Niño seems dominant. This view is supported by the discovery that the ENSO vs. Sahel rainfall link remains significant over the whole study period if the influence of the other three SST indices on Sahel rainfall is removed.

Janicot et al.'s paper presents a picture of two periods, with very different influences dominating in each. In the Sahelian wet period of the 1950s and 60s, conditions are dominated by a Sahel vs. Guinea rainfall dipole associated with an Atlantic SST dipole and the northernmost extent of the ITCZ's migration. In the later dry period, the Sahel vs. Guinea dipole has broken down, and ENSO dominates. They suggest ENSO's influence was masked in the wet period by the effect of other SSTs.

2.5. The Influence of Land Surface Processes on Sahel Rainfall

The study of the links between West African rainfall and sea surface temperatures indicates that a large-scale evolution of global SSTs may have been partly responsible for the recent dry period of Sahel rainfall. However, the role of land surface changes on Sahelian rainfall has also been a major area of investigation.

In 1975, Charney proposed a possible cause of the Sahel drought. Charney proposed that human activities, such as overgrazing and deforestation, had led to increased exposure of the soil across the West Africa. As bare soil is more reflective than cropland or forest, the albedo of the area was increased. Because of this desertification, radiative losses are increased. As a result, the land cools, and in the atmospheric column above, either convection is reduced or subsidence is enhanced. This results in reduced rainfall. Furthermore, reduced rainfall will reduce the growth of plant matter, and increase desertification, and hence the albedo. This results in a positive feedback; raised albedo inhibits rainfall and reduced rainfall increases albedo.

This theory was supported by a number of GCM experiments, for example Charney et al. (1975) and Charney et al. (1977). Similarly, Xue and Shukla (1993) ran an idealised study whereby a GCM was run twice with differing vegetation across the Sahel, and all other conditions equal. The first run, referred to as the 'desertification experiment', set the whole of the Sahel as covered by shrubs above bare soil. The second run, the 'reforestation experiment', considered a Sahel covered by broadleaf trees above ground cover. The difference in rainfall patterns between the two runs was broadly similar to that a 'dry years minus wet years' composite pattern. Both patterns showed reduced rainfall in the Sahel, and enhanced rainfall on the Guinean Coast, suggesting a southward shift of the ITCZ. The desertification run also saw a weakening of the TEJ and a strengthening of the AEJ, reducing the intensity of easterly waves. This theory was also supported by Claussen (1997), in which a simulated western Sahara covered by savannah had a major impact on the monsoon circulation.

Whilst these studies managed to show a reduction in precipitation, they depended on extreme changes in conditions. For example, the studies by Charney et al. (1975) and Charney et al. (1977) rely on an albedo change from 0.14 to 0.35. As noted by Druyan (1989), these changes far exceed values obtained from observational studies. Nicholson (2001) reports that the observations of Norton et al. (1979) and Courel et al. (1984) suggest that whilst albedo in the southern Sahel increased from 0.29 to

0.34 between 1967 and 1973, it decreased in the following wetter period of 1973 to 1979. Hence, the extent of deforestation does not seem widespread enough to have caused the drought. Furthermore, rather than changes in albedo forcing a change in rainfall, albedo tended to shadow the changes in rainfall. A later study by Nicholson et al. (1998) supported this view by associating yearly variability of vegetation cover with annual rainfall, and only recording albedo changes of 0.02-0.03 over the period 1980-1995.

These results suggest that a large-scale change in albedo has not occurred, and hence Charney's hypothesis fails. However, many studies suggest land-surface changes have the capacity to influence Sahelian rainfall, as reviewed in Nicholson (1988). Changes in albedo will also be accompanied by changes in the production of atmospheric dust, and changes in the biosphere will affect evapotranspiration, all of which could have an influence on rainfall. In particular the impact of Saharan dust is not well understood (Nicholson, 2001), but a series of studies have suggested it can have a significant impact on synoptic conditions, and can alter the thermal structure of the atmosphere by scattering and absorbing radiation (Karayampudi and Carlson, 1988; Tegen and Fung, 1994; Tegen and Fung, 1995; Tegen et al., 1996).

Areas outside of the Sahel may also play a critical role. The studies of Zheng and Eltahir (1998) and Zheng et al. (1999) suggested the changes on the Sahel / Sahara border typical of desertification only have a small effect on the monsoon. However, simulated deforestation in the Guinea Coast region had a considerable effect on the boundary-layer entropy gradient that Eltahir and Gong (1996) note is central to the monsoon circulation, causing it to collapse.

Recent improvements in computing power have allowed for the creation of regional climate models of greater complexity. This has permitted a greater study of possible feedbacks mechanisms. As noted in section 2.2.2, Cook (1999) used a model to demonstrate the importance of a meridional soil moisture gradient to the creation of the AEJ. In another example, Taylor et al. (2002) examined the effect of land use change on the Sahel rainfall based on conditions in 1961, 1996, and estimated land use in 2015. They modelled a decrease in rainfall of 4.6% between 1961 and 1996, and a decrease of 8.7% by 2015. The decreases are largely a result of a later onset of the core wet season during July, similar results to those found in the empirical studies of Le Barbe and Lebel (1997) and Le Barbe et al. (2002). Once the monsoon is established, it appears to be relatively insensitive to the land surface conditions.

Furthermore, the role of biological feedbacks must be considered. A study by Wang et al. (2004) using a climate model with a dynamic vegetation feedback has suggested that SST forcing alone would lead only to a slight drought. When their model incorporated the vegetation feedback, that slight drought was enhanced. They state that whilst "SST forcing may have acted as a trigger of the drought, SST is clearly not the full story". Moreover, their model does not consider anthropogenic influence on vegetation; human activities could potentially strengthen this feedback.

2.6. Summary and Conclusions

The review carried out in this chapter has identified the principal factors involved in driving Sahelian rainfall. In particular, several components of atmospheric variability have a major influence, namely the ITCZ, the monsoon flow, the mid-level African Easterly Jet, the upper-level Tropical Easterly Jet, and the squall lines embedded within easterly waves. Links between these components and rainfall that exist on an interannual scale are also present on an intraseasonal basis. However, the interannual scale cannot pick up higher frequency influences (such as the Madden-Julian oscillation). Therefore, this thesis will attempt to examine variability on a daily basis.

The factors behind the atmospheric circulation are still not well understood, although the most important seem to be sea surface temperatures and land surface conditions. Prior to 1968, high rainfall in the Sahel was most strongly associated with a warm north Atlantic and a cool south Atlantic. However, a change in the relative influence of the oceans seems to have occurred in the late 1960s, and since then, ENSO has been the most important factor.

The highly influential theory of Charney (1975), that a feedback loop between drought and albedo caused the Sahelian drought, seems to have been proved insufficient by observational evidence. However, the land surface affects rainfall through a combination of changes in many factors, including albedo, soil moisture, evapotranspiration and atmospheric dust.

Sea surface temperatures and land surface measures usually vary over a longer period than the circulation. Therefore, it is difficult to incorporate them into intraseasonal studies. Furthermore, changes in any of these factors can only affect rainfall via the atmosphere. For this reason, this study will focus solely on atmospheric variability.

Finally, the high spatial variability of Sahel rainfall needs to be considered. By focusing on the daily scale, this study demands a higher spatial resolution too. Therefore, it will be necessary to consider several sub-regions of the Sahel.

So the aim of this thesis is to consider the relationship between atmospheric variability and rainfall across the Sahel at a daily time scale. Several steps are necessary to accomplish this. First, a suitable daily rainfall data set spanning as much of the Sahel as possible will be created, a process described in Chapter 3. In Chapter 4, the selection of a set of atmospheric predictors will be reported. Finally, these two data sets will be linked together in a daily statistical model in Chapter 5.