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FOG IN THE NAMIB : A SURVEY

CONTENTS

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1 INTRODUCTION

Fog is usually considered to be a meteorological hazard since it impairs visibility and combines with pollutants to form acid fog. These problems are especially acute in industrialized midlatitude countries where severe fog episodes frequently occur. However, the benefits of fog are often overlooked. The importance of fog as a source of water in certain locations has been recognised for a considerable time (Nagel, 1959). Studies have revealed that fog precipitation can be substantial, equalling or even exceeding the local rainfall. Recent estimates of the availability and cost of collecting water from high elevation fogs indicate that this may well be an important source of water for settlements in the dry coastal regions of Chile (Cereceda & Schemenauer, 1988; Fuenzalida, 1988; Schemenauer *et al.*, 1988). It is possible that other arid areas could also benefit from this 'neglected water resource'.

The Namib is one of the driest regions in the world with the central coastal strip receiving less than 20 mm rain per annum. By contrast, up to 200 fog days per year have been recorded in certain areas. Consequently, the Namib has been classified as a west coast fog desert (Lydolph, 1957). In fact, with the exception of the aridity, fog can be considered as its most characteristic climatic feature (Lancaster, Lancaster & Seely, 1984). It is therefore surprising that few studies have dealt exclusively with the fog phenomenon. While most papers, irrespective of the actual subject researched, invariably make some reference to it, this information is necessarily fragmented in nature and pertains mainly to places such as Swakopmund, Pelican Point, Diaz Point and Gobabeb where first or second order weather stations have been maintained. Little is therefore known about the occurrence of fog in the less accessible areas or where there is little to interest botanists or zoologists. In view of the importance of fog in the unique Namib ecosystem, it seems evident that there is a need for more detailed information of its spatial and temporal characteristics.

The advent of satellite imagery may offer a solution to the above problem. In this paper one such attempt is described in which a suite of 1984 Meteosat images was used to compile a fog distribution map of the Namib. These as well as other spatial characteristics of fog are discussed. A number of temporal fog characteristics are also examined, including annual, seasonal and diurnal patterns of fog occurrence, as well as the intensity, duration and mean commencement and cessation times of fog episodes.

The principal intent of this paper, however, is to provide an overview of fog distribution in the Namib. It follows that *the discussions are not based solely on the results of empirical research but attempt to integrate these with the considerable body of information which has been obtained from a wide variety of sources.*

2 THE NAMIB: SOME PHYSICAL AND CLIMATIC ASPECTS

The Namib stretches over 17 degrees of latitude from Mossamedes (Angola) in the north to the mouth of the Olifants River in the south, a total of about 2 000 km (Wellington, 1955; Logan, 1960). Longitudinally it is quite narrow (only 70 - 180 km) and is bounded by the Atlantic Ocean to the west and the Great Western Escarpment to the east (Logan, 1960; Meigs, 1966). The desert topography differs from other west coast deserts in that it is not flat but rises gradually from sea level to an altitude of 900 m - 1000 m at the foot of the Escarpment (Figure 1).

In the central parts, the coastal strip is characterised by extreme aridity. Swakopmund and Pelican Point have the lowest annual rainfall amounts (8 and 13 mm, respectively), followed by Lüderitz and Walvis Bay, each with 17 mm/yr (South African Weather Bureau (SAWB), 1986). The rainfall increases steadily towards the interior to reach about 60 mm at a distance of 100 km from the sea. It exhibits a distinct seasonal variation ranging from a late summer peak at Möwe Bay, Walvis Bay and Gobabeb in the north to a winter rainfall regime to the south. At Lüderitz, the little rain which does fall, is usually recorded between February and August, with most raindays occurring during May and June. At Alexander Bay in the south, the winter rainfall regime is clearly established.

The aridity of the Namib desert can be ascribed to, *inter alia*, its latitudinal position within the subtropical high pressure zone (together with the comcommitant subsidence and stability) and to the proximity to the low sea surface temperatures of the Benguela-upwelling system. It is these factors, amongst others, which are essential for the formation of coastal fog.

Fog occurs most frequently in the coastal regions. Nevertheless, its effects have been noted up to 100 km inland (Goudie, 1972; Lancaster, Lancaster & Seely, 1984). The modifying effect of the ocean is pronounced in the low-lying coastal plain which extends inland for a distance of 30 - 80 km. Here fog is a common occurrence with fog precipitation forming the principal moisture source. Further eastwards on the Namib Platform (lying between 70 and 900 m above MSL), fog occurrence is intermittent, the mornings being cool and foggy but hot dry conditions prevailing by noon. Consequently, this region experiences the most extreme climate in the Namib (Seely, 1987).

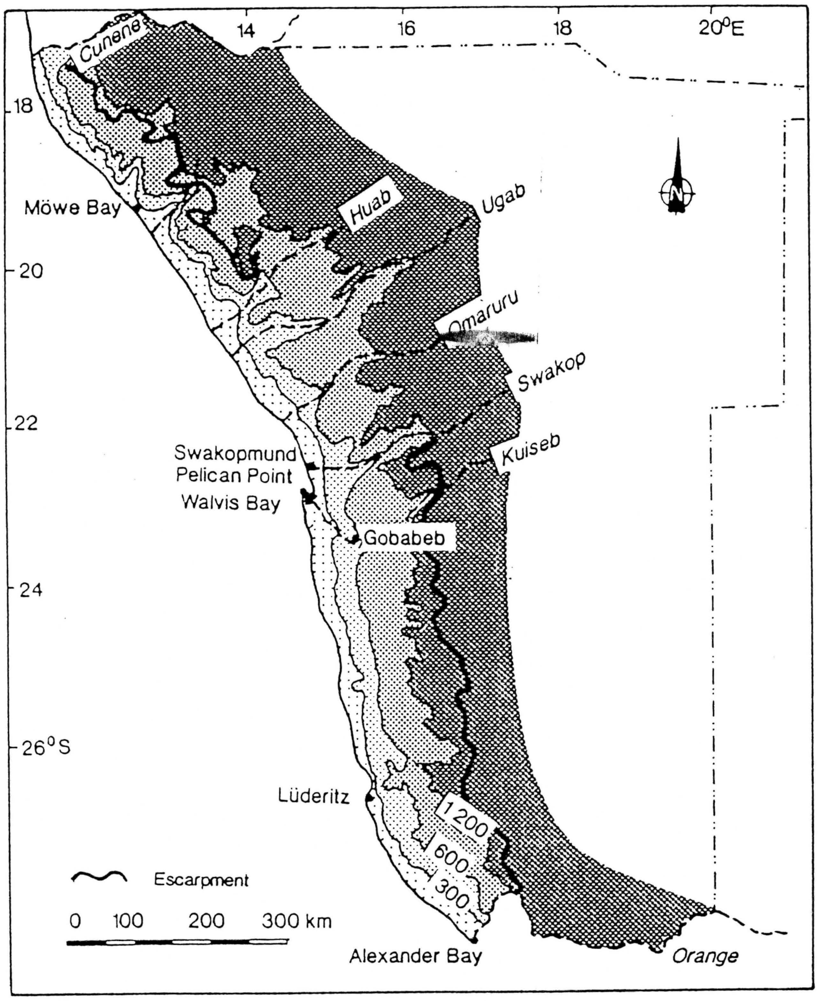

Figure 1 General topography of the Namib

3 MECHANISMS INVOLVED IN NAMIB FOG FORMATION

Although it is unlikely that all the Namib coastal fogs can be attributed to the same cause, there is consensus that the vast majority are of advective marine origin (Jackson, 1941; Bornman, Botha & Nash, 1973; Taljaard, 1979; Estie 1986; Heydorn & Tinley, 1980; Lancaster *et al.*, 1984, Hsu 1988). Sea fog may be formed when onshore breezes transport moist air over the cold upwelled water adjacent to the land. The warm moist air entrained off warmer offshore waters are subsequently cooled when flowing across progressively colder water until dew point is reached and fog or low stratus form (Heydorn & Tinley, 1980; Estie, 1986). Alternatively, sea fogs may form by nocturnal radiational cooling of the marine boundary layer. The loss of heat from the moist sub-inversion layer proceeds at a very high rate at night because the water particles radiate upwards through diathermanous dry air at rate approximating that of a black-body. Thus the moist surface layer cools rapidly and fog is easily formed (Taljaard, 1992 pers. comm.) Nevertheless, the occurrence of fog in the littoral zone is usually associated with southerly to south-westerly winds blowing around the eastern perimeter of the South Atlantic anticyclone or with the development and longshore movement of coastal lows after upwelling has occurred.

In addition to advection sea fogs, other fog types may also occur within the coastal zone. According to Jackson (1941), this is applies especially to the winter months when radiation fogs are likely.

The climatology of fog formation has not yet been fully investigated for the stations in the interior of the Namib. Nevertheless, it has been suggested that it is mainly sea fog which is advected inland (Bornman *et al.*, 1973; Lancaster *et al.*, 1984) with the distance of penetration being a function of the topography and the wind speed and direction at the coast and on the Plateau (Taljaard, 1979). The inland advection of fog has, in fact, been observed during light north westerlies. Estie (1986) and Vendrig (1990) maintain that this is necessarily a day-time phenomenon as nocturnal katabatic and land breezes would tend to oppose inland flows - particularly during winter. However, the disruption of local circulation patterns by synoptic systems such as the passage of a coastal low or a ridging anticyclone, may explain the occurrence of such fogs on winter nights.

According to Taljaard (1979), the occurrence of radiation fog is also a possibility, especially during winter when low minimum temperatures are common. This is particularly likely to occur when a cloudless, near-calm night follows a period when moist air has been advected inland by south-westerly, westerly or north-westerly winds. While conceding that radiation fog may indeed occur at inland stations, Estie (1986) points out that, in general, the nocturnal dew point temperatures at Gobabeb are extremely low, indicating a dry katabatic flow which is not conducive to the formation of radiation fog.

There is mounting evidence to suggest that cloud interception is a major contributor of inland fog in the Namib (Estie, 1986; Vendrig, 1990; Lancaster *et al.*, 1984). Low stratus clouds are formed at a height of between 100 m and 600 m over the Atlantic Ocean and are usually topped by an inversion layer (Taljaard & Schumann, 1940; Jackson, 1941; Copenhagen, 1953; Taljaard, 1979). Westerly winds at cloud level would then transport the stratus deck inland where a decrease in air mass temperature could occur through turbulent overturning and radiation losses, resulting in a lowering of the cloud base (Estie, 1986). Alternatively 'inversion fog' may form under low clouds from which drizzle is falling into cooled air below (Jackson, 1941). The cloud interception theory of fog formation is given some support by two significant facts. Firstly, the heights of clouds correspond with the altitude of the area with maximum fog precipitation and secondly, the spring-summer cloudiness maximum at the coast coincides temporally with the peak fog day frequency (FDF) inland (Lancaster *et al.*, 1984).

4 SPATIAL DISTRIBUTION OF FOG IN THE NAMIB

4.1 Data and Method

The fog map (Figure 2) was compiled using Meteosat photos for 1984, kindly supplied by Mr I Hunter of the South African Weather Bureau weather office at DF Malan airport. These included both thermal infra-red and visual images, respectively, in the 5,7 - 7,1 and 10,5 µm as well as 12,5 and 0,4 - 1,1 µm wavelengths for various times of the day. Most use was made of the early morning Meteosat images, especially the 05:00, 06:00 and 08:30 ones since fog is known to occur most often during the cooler parts of the day. The 1984 fog occurrence map was compiled using the following procedure: A finely gridded (approximately 35 km x 35 km) overlay of the Namib (with the outline of southern Africa drawn in) was superimposed onto each image and each spatial unit evaluated with respect to the presence or absence of fog. The total number of fog occurrences were then determined for each grid square for each month. These were summed to obtain the fog day frequency (FDF) for the year. The resulting grid values were used to draw the isolines shown in Figure 2.

Extraction of data from this source is not a simple or straightforward operation and a number of problems were encountered in compiling the map. The most serious problem resulted from the difficulty in diffentiating between low stratus cloud and fog on satellite images. High clouds are relatively easily distinguishable by the brightness of the image, signifying very low temperatures, but there is little difference between the height and temperature of the top of a stratus deck and that of a fog layer. In fact, inland fog is often simply low stratus cloud which has been intercepted by a rising land surface. Although this problem could not be resolved satisfactorily, SAWB records showing the dates on which fog occurred at Pelican Point, Diaz Point and Gobabeb were used as a guide to distinguish between fog and clouds at these sites.

A second complication was that the data set was not quite complete. This was not too serious since one or more satellite photos were available for more than 90% of the days. However, some of the images were blurred, blotched, over- or underexposed and therefore could not be used. In addition, a number of photos showed only partial coverage of the area. This was mostly due to the camera angle (that part of the desert to the north of Möwe Bay was often not shown on the images) or to obstruction of the surface by middle or high level clouds. In such cases it was assumed that fog was absent. This probably resulted in an under-count of fog days in the vicinity of the Cunene during the summer rainy season. It seems clear, therefore, that inaccuracies on the map are more likely to occur towards the northern boundary of the study area. Unfortunately the absence of meteorological recording stations this area precludes verification of the FDF in this region.

A third and final problem arose from the fact that the Meteosat satellite is in geostationary orbit 36 000 km above the point of intersection of the equator and the Greenwich meridian. Since the panoramic distortion becomes greater with distance from the nadir (Mather, 1987), the study area is slightly distorted in both the north - south and the east - west directions. Fortunately the position of the Orange, Kuiseb and Ugab river valleys were distinguishable on the images and could be used to determine the approximate location of towns, recording stations and major physical features. The distortion did create numerous difficulties, however, especially in the determination of scale and compass directions. Moreover, it hampered easy identification of possible associations between physical features such as topography and vegetation and the spatial occurrence of fog.

4.2 Results and Discussion

The fog distribution map reveals a number of notable features of the general distribution patterns of fog in the Namib. Firstly, the well-known trend of decreasing fog occurrence with distance from the sea is clearly illustrated by the parallel-running north-south isolines on Figure 2.

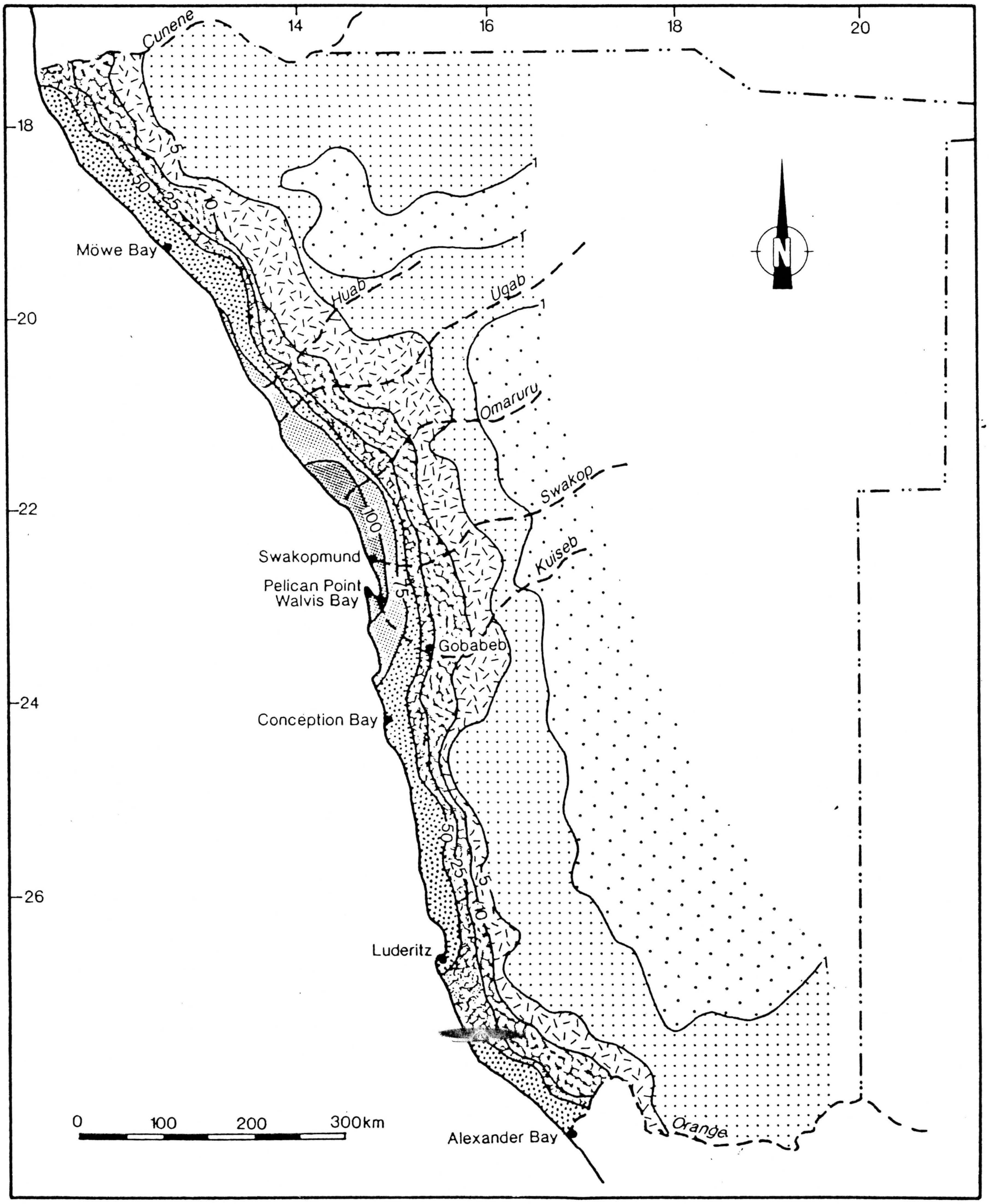

Figure 2 Fog/low cloud distribution during 1984 Fog days / yr.

A zone of high fog frequency (> 50 fog days/annum) hugs the coast over almost the entire length of the Namibian Namib. The zone with highest FDF (>100 FD/yr) is confined to a narrow coastal strip stretching from about 21,5^{o}S to 23,5^{o}S. This zone includes the weather stations at Swakopmund and Pelican Point with means of 113 and 139 FD/yr, respectively (SAWB, 1986). Examination of the weather records, however, reveals that the latter station recorded only 110 fog days in 1984. North and south of this core area, the FDF at the coast drops slightly but still exceeds 50. Lüderitz, which falls within this zone, reported 98 fog days in 1984. (The under-count of FDs here may be due to The intermittent nature of fog occurrence vs the fixed times of satellite photos, high cloud obscuring the desert surface or the incompleteness of the satellite data set.) Although the FDF decreases southwards, a pocket of higher fog incidence is found in the vicinity of the Orange River mouth. According to Figure 2, Alexander Bay fell within the 50 to 75 fog days zone in 1984. The recorded value was, in fact, 59.

Closer inspection of Figure 2 indicates that between Lüderitz and Conception Bay- and, to a lesser extent, northwards from Möwe Bay (± 18.5^{o}S) - the 50 and 5 FD isolines are more closely spaced than elsewhere, signifying a more abrupt decrease in fog occurrence with distance from the sea. The fact that the coastal plain also narrows in these regions seems to suggest that there is a link between topography and fog incidence. (At St Francis Bay, high dunes actually front on the beach.) Comparison of Figures 1 and 2 reveals that there is some degree of spatial correspondence between the seaward edge of the Escarpment and the 5 FD isoline over large parts of the study area. This is especially applicable to the area to the north of Conception Bay. To the south, however, the fog frequency at the edge of the escarpment is less than 5 days per annum. It is also apparent that the high fog zone (> 100 FD/annum) is largely confined to the coastal plain which lies below 200 m above MSL. Furthermore, the 50 and 25 FD isolines follow the 300 and 600 m contours, respectively, except in the region between the Kuiseb and Huab rivers where fog penetrates further inland.

The width of the fog belt (based on the 5 FD isoline) clearly increases in the area between Conception Bay and the Ugab river. According to Figure 2, some places located 40 km from the sea could have experienced as much as 75 fog days during 1984. It is interesting to note that the Welwitschia Flats as well as some lichen fields (vegetation types known to be largely dependent upon fog precipitation for their water requirements (Airy Shaw, 1947; Bornman *et al.*, 1973), occur within this area (Seely, 1987).

Another prominent feature which can be distinguished on the map is that fog penetrates further inland in that region in which a distinct Escarpment is lacking as well as along the valleys and canyons of the larger rivers. The latter is illustrated by the eastward bulging of some of the isolines along the courses of, for example, the Swakop-, Omaruru- and Ugab rivers. It seems probable that a combination of factors could be responsible for this phenomenon. On the one hand, the inland advection of sea fog may be facilitated by the channelling of onshore breezes up the river valleys and/or the reinforcement of sea breezes by valley-mountain (anabatic) winds. On the other hand, the likelihood of katabatic fog formation is enhanced by nocturnal downslope airflow, especially in the river valleys where the air is likely to have a higher moisture content.

Measurements on the ground may (to some degree) be used as a check on the fog distribution pattern depicted on Figure 2. Thus Besler (1972) indicates that, in the Central Namib, the mean annual FDF generally decreases from about 120 days at the coast to around 40 days at a distance of 40 km inland, to 5 days at 100 km from the sea (Barnard, 1988, pers. comm.). This is precisely the situation illustrated on Figure 2 for the region to the east of Conception Bay. It also applies (in part) to the area between Walvis Bay and Swakopmund. Here the fog frequency did indeed decrease from over 100 days to 40 within the first 40 km, but thereafter the decline was slower so that > 5 fog days were recorded at a distance of 100 km inland. Notwithstanding these discrepancies, there is some degree of similarity between measurements on the ground and the fog distribution patterns shown on the map. This is most gratifying, since it implies that the technique used - despite its limitations and the degree of generalisation which was applied in the compilation of the map - has successfully differentiated between fog and low stratus cloud and thus Figure 2 does indeed represent the 1984 *fog* distribution map.

There are, however, a number of important fog characteristics in the Namib which cannot be gleaned from Figure 2. During analysis of the Meteosat images it was noticed that a layer of fog at times enveloped a part of the desert along its entire longitudinal extent. This is quite an infrequent event since it usually appeared as a dense bank confined to the coastal zone or as thinner patches over part of the interior or as a relatively dense plume protruding inland. Nevertheless, it confirms earlier statements that the effects of fog have been noticed up to distances exceeding 100 km from the sea (Goudie, 1972; Lancaster *et al.*, 1984).

Secondly, the prevalence of thick fog banks lying just offshore as observed on many satellite images is not be shown on Figure 2. Whether these banks actually reached the land or whether they withdrew and dissipated out to sea could not be ascertained since the images merely portrayed conditions occurring at a particular instant in time. (The interval between successive photos was usually 1 to 1,5 hours.) However, the fact that Pelican Point has a higher annual FDF than Walvis Bay (eg. 151 days at Pelican Point in 1976 as opposed to 83 at Walvis Bay (SAWB, 1981)), seems to suggest that many of these fog banks do not make a complete landfall, reaching only as far as the most westerly projections of the coastline.

A third feature not depicted concerns fog precipitation. Some researchers have found that the amount *increases* from the coast inland to a distance of about 35 to 60 km in the central Namib, after which it decreases further eastwards (Lancaster *et al.*, 1984). Besler (1972) measured 38 mm at a distance of 2 km from the coast; 67 mm at 22 km; 61 mm at 33 km and only 29 mm at a distance of 56 km inland. The initial increase is apparently related to altitude, with most precipitation occurring at a height of 300 to 600 m above MSL (Seely, 1987). This has been ascribed to the interception of low stratus clouds by the land surface (Lancaster *et al.*, 1984). The location of fog precipitation gauges may also affect this pattern since fog precipitation is considerably higher on the seaward side of obstructions. This is apparent even on the micro-scale, where succulents and other desert adapted vegetation coat the seaward side of dunes, small mounds and rocks, while the leeward side is almost devoid of growth (Seely, 1987).

In contrast to the above findings, Meigs (1966) found that fog precipitation *decreased* from 1,4 - 1,6 inches (35 - 41 mm) at the coast but 0,8 - 1,2 inches (20 - 30 mm) 25 miles (40 km) inland. The apparent discrepancy between these findings and those discussed earlier may be ascribed to the fact that Meigs' measurements were taken in the vicinity of Lüderitz where no coastal plain exists. Therefore the initial increase in fog precipitation - if it does indeed occur - would be expected to occur over a much shorter distance so that stations located too far inland would in fact 'miss' this increase. It is of course also possible that the relative importance of cloud interception in comparison to advection sea fog may be considerably less at Lüderitz than in the Central Namib.

5 TEMPORAL FOG PATTERNS

Fog day frequency (FDF) does not only differ markedly from one part of the Namib to another, but it is also extremely variable over time. This variability is evident in the annual, seasonal and diurnal fog incidence patterns, as well as in the duration, commencement and cessation of fog episodes, and in the fog intensity patterns of three fog recording stations, namely, Pelican Point (Walvis Bay), Diaz Point (Lüderitz) and Gobabeb.

5.1 Data and method

South African Weather Bureau printouts or publications (SAWB 1954, 1981, 1982, 1986) were used as primary data sources for the analyses. The printouts comprised daily fog occurrence records for the 1960 - 1978 period and past weather records for the post-1978 period. The former indicated fog intensity by means of the codes 0, 1 and 2, indicating light, moderate and heavy fog, respectively. These codes were based on horizontal visibilities ranging from 600 - 1000 m for light fogs; 300 - 600 m for moderate fogs; and less than 300 m for dense fogs (Bothma, 1992, pers. comm.). After 1978, the intensity codes were replaced by data giving the time period during which fog was recorded at a specific site. The discussion of fog intensity in the Namib is thus based on 1970 - 1978 data only whereas all analyses relating to diurnal patterns (including commencement and cessation times) used data for the 1979 - 1986 period.

Daily fog occurrence data for the 1960 - 1986 period were analysed and monthly and annual FDFs computed. Fog intensity characteristics and the time of fog formation and cessation were also extracted from the relevant daily printouts for the two coastal stations, Pelican Point (Walvis Bay) and Diaz Point (Lüderitz) and the inland station Gobabeb. Information on other climatic parameters were obtained from the Weather Bureau publication, WB 40, (1986) which gives mean monthly and annual rainfall, temperature and cloud cover statistics for, *inter alia*, Pelican Point, Walvis Bay, Gobabeb, Diaz Point, Lüderitz and Alexander Bay. Although data for Pelican Point and Diaz Point were used in the analyses, it is assumed that the temporal characteristics prevailing at these stations would apply equally to Walvis Bay and Lüderitz, respectively.

5.2 Results and Discussion:

5.2.1 *Inter-annual fog frequency:*

Table 1 gives some indication of the year-to-year variability of fog occurrence at the selected stations. These statistics were calculated from daily fog records for the period indicated. It is, therefore, not surprising that the values for mean annual FDF shown on Table 1 differ from those of WB 40 (South African Weather Bureau, 1986). 1960 - 1986

Table 1 Some annual fog day frequency distribution characteristics for selected Namib stations

	ALEXANDER BAY	DIAZ POINT	PELICAN POINT	GOBABEB
Record length (yrs)	32 (1954 - 1985)	32 (1954 - 1985)	27 (1958 - 1985)	16 (1970 - 1985)
Mean annual FDF	81,3	126,7	146,5	94,1
Standard deviation	21,5	19,4	26,8	16,6
Highest Max FDF (year)	144 (1979)	159 (1967)	200 (1971)	117 (1975)
Lowest Min (year)	50 (1966)	98 (1984)	105 (1959, 74)	70 (1970)
Range	94	61	95	47
Coeff of Variation (%)	26,4	15,3	18,3	17,6

In the coastal region, the observed number of fog days ranges from a minimum of 50 at Alexander Bay to a maximum of 200 at Pelican Point. Diaz Point has the lowest inter-annual variability - as indicated by both the standard deviation and the coefficient of variation. This can probably be ascribed to the nature of the upwelling cell centered off Lüderitz, since it is a well-known fact that this cell occurs more often, is larger and the water is colder that anywhere else along the West Coast (Shannon, 1985). Generally, however, conditions at the coast - particularly at Pelican Point and Alexander Bay - appear to be more variable than at the inland station. (This is in direct contrast to observations in Sierra Leone where the variation is higher at inland stations (Kamara, 1989).) The explanation for this unexpected finding may be sought, *inter alia*, in the variability in the speed of onshore winds. Coastal fog will only form when onshore breezes are light. When the wind speed is high (> 10 m/s over land and about 15 m/s over the sea), turbulence may cause a relatively deep mixed layer to form. This will inhibit the formation of coastal fog in favour of low stratus or stratocumulus clouds (Oke, 1978; Estie, 1986; Hsu, 1988). Conversely, it is specifically the stronger winds blowing at cloud level at the coast which promote the inland transport of low stratus decks, thereby increasing the probability of cloud interception.

Since coastal stations experience higher wind speeds than inland ones, wind speed, and hence fog occurrence, is more variable there. In addition, the surface wind characteristics are subject to a greater amount of fluctuation that those at higher levels (which affect inland fog occurrence) and even the slightest changes in synoptic conditions will not only influence wind speed and direction, but could bring about changes in other factors, such as the extent of the upwelling cells or the stability of the atmosphere. This could affect fog formation in the coastal zone but not necessarily further inland.

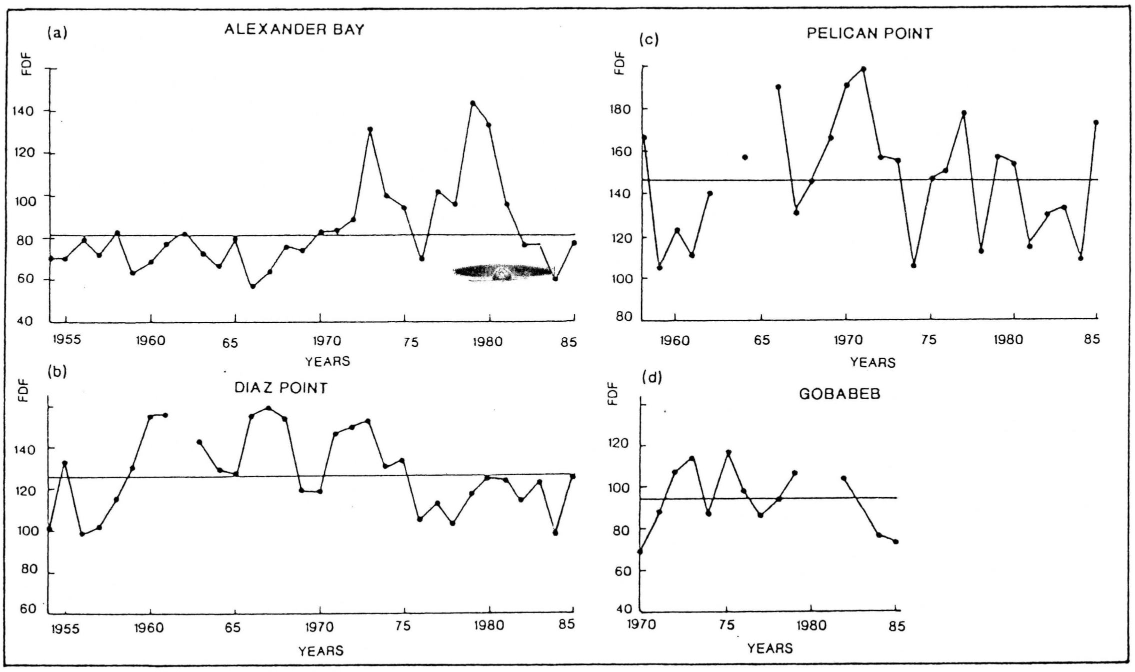

Figure 3 **Annual fog day frequency for (a) Alexander Bay (1954 - 1985) (b) Diaz Point (1954 - 1985) (c) Pelican Point (1958 - 1985) and (d) Gobabeb (1970 - 1985)**

Perusal of Table 1 also reveals that there is no temporal coincidence between the years of highest (or lowest) fog day frequency at the four stations. This is confirmed by a comparison of their annual time series (Figure 3). The coastal stations each experienced an extended period with above average and one with below average FDF. At Alexander Bay, annual fog frequency was low between 1954 and 1970, while the following 14 years showed a higher incidence. Paradoxically, both Lüderitz and Walvis Bay were characterised by above average fog occurrence during the early part of the record (1959 to 1975 at Lüderitz, and 1963 to 1973 at Walvis Bay) followed by a spell of below average FDF. This lack of synchronization of foggy and less foggy periods at different stations seems to indicate that the mechanisms involved in coastal fog formation differ from one part of the Namib to another and may not be as straightforward as was previously supposed.

5.2.2 *Seasonality:*

Not only does Figure 4 illustrate the high degree of reliability of fog incidence throughout the year in the Namib, but the high FDF at the coastal stations and at Rooibank and Swartbank during most months lends some support to the spatial distribution pattern shown in Figure 2. High and low fog seasons are nevertheless distinguishable at most sites, except perhaps at Pelican Point and Diaz Point where fog is frequent throughout the year and where it would be more correct to distinguish between a foggy and a less foggy season. In general, the distribution of fog days is more-or-less normal around the month with peak FDF.

Contrary to earlier findings (Schulze & McGee, 1978), the fog and rainfall seasons do not coincide and fog occurrence does not display the clear north - south trend in seasonality that is discernable in the occurrence of rainfall (Lancaster *et al.*, 1984). Instead, a transition from an autumn/winter fog regime along the coast to a spring/summer peak further inland seems to apply. This appears to be confirmed by the situation at Rooibank located about 20 km from the coast, and to a lesser extent at Swartbank, where there are signs of an autumn - spring bimodality. This probably reflects the combined influence of maritime and continental controls.

The winter fog maximum along the coast reflects the frequent occurrence of conditions which are ideal for fog formation. Winter winds are light, the subsidence inversion is strong with the base relatively close to the ground (Nieman *et al.*, 1978; Taljaard, 1979) and the sea surface temperature is low due to the presence of upwelling. The effect of the weaker surface and elevated onshore winds is to limit the distance which fog and low clouds are advected inland. This is reinforced by stronger downslope winds and land breezes which occur during the night (Heydorn & Tinley, 1980), culminating in a lower FDF at Gobabeb.

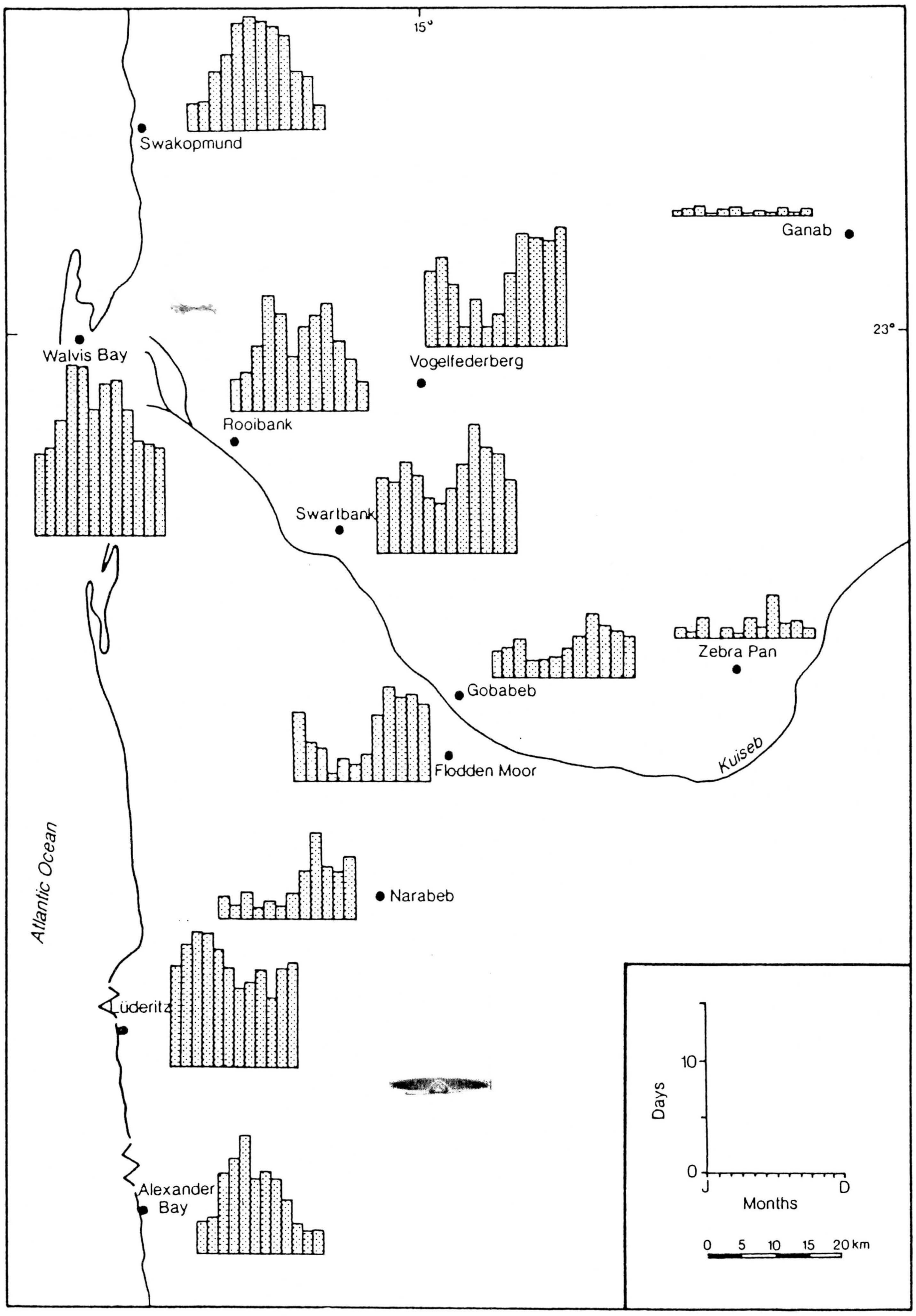

Figure 4 **Mean monthly FDF for coastal and inland stations** (after Lancaster, Lancaster and Seely, 1984)

During summer, onshore winds are considerably stronger, favouring the formation of stratus cloud rather than fog at the coast. Conversely, these conditions promote inland advection of low clouds. Analysis of wind speeds at Pelican Point during and immediately prior to a fog episode at Gobabeb indicated that they are consistently higher than normal. The importance of cloud interception fog is further emphasized by the fact that, during 1983, fog at Gobabeb was preceded by fog at Pelican Point on only nine out of 72 fog events, fog episodes occur simultaneously at the two stations on 17% of occasions whereas low level stratus cloud at Pelican Point accompanies (or precedes) fog at Gobabeb 80% (65%) of the time.

Although the mean annual FDF at Walvis Bay exceeds that of Lüderitz, fog occurs more frequently at Lüderitz during each of the summer months (November - March). This southward shift in the summer incidence of fog mimics the seasonal migration of the South Atlantic Anticyclone. The poleward position of the high pressure cell and its proximity to land would probably result in the base of the subsidence inversion being lower in the vicinity of Lüderitz than at Walvis Bay. Moreover, it would in all likelihood generate winds with greater onshore and longshore components at Lüderitz in comparison to Walvis Bay. It is therefore not surprising that the upwelling core exhibits a north - south shift from winter to summer (Shannon, 1985; Lutjeharms and Meeuwis, 1987). An additional factor contributing to the discrepancy in intra-annual fog occurrence along the coast, is the enlargement of the upwelling cell off Lüderitz during autumn and winter (Shannon, 1985). An extensive upwelling region has been shown to suppress fog formation behind coastal lows (Olivier & Stockton, 1989). The fact that the highest wind speeds are recorded at Lüderitz during summer (Jackson, 1954) would ostensibly contradict the high FDF there. However, it should be kept in mind that such winds are produced when the circulation around the South Atlantic Anticyclone reinforces sea breezes (Schulze, 1972; Tyson & Seely, 1980), and are thus mostly confined to the day time. By contrast, all the conditions conducive to fog formation are present at Pelican Point (Walvis Bay) at night.

5.2.3 *Diurnal fog incidence*

The severity of fog as an environmental hazard depends to a large extent on the time of the day when it occurs. Fogs which occur when human activities are most intense pose more serious problems than those which occur at a time of minimal activity (Kamara, 1989).

Figure 5 shows the probability of fog occurrence at Lüderitz, Walvis Bay and Gobabeb during different times of the day. As expected, it follows an inverse diurnal thermal rhythm with maximum fog frequencies occurring during the cool nocturnal period (00:00 - 08:00), decreasing with increasing temperature and turbulence towards a noon-to-16:00 minimum. The probability of fog during the 00:00 to 08:00 period was found to be 0,20; 0,29 and 0,57 for Lüderitz, Walvis Bay and Gobabeb, respectively whereas the equivalent values for the 12:00 to 14:00 time slot was 0,13; 0,09 and 0. The earlier period is characterised by high humidity, low temperatures and minimal turbulence - conditions conducive to the formation of fog - whereas hotter, drier and more unstable conditions usually prevail by noon.

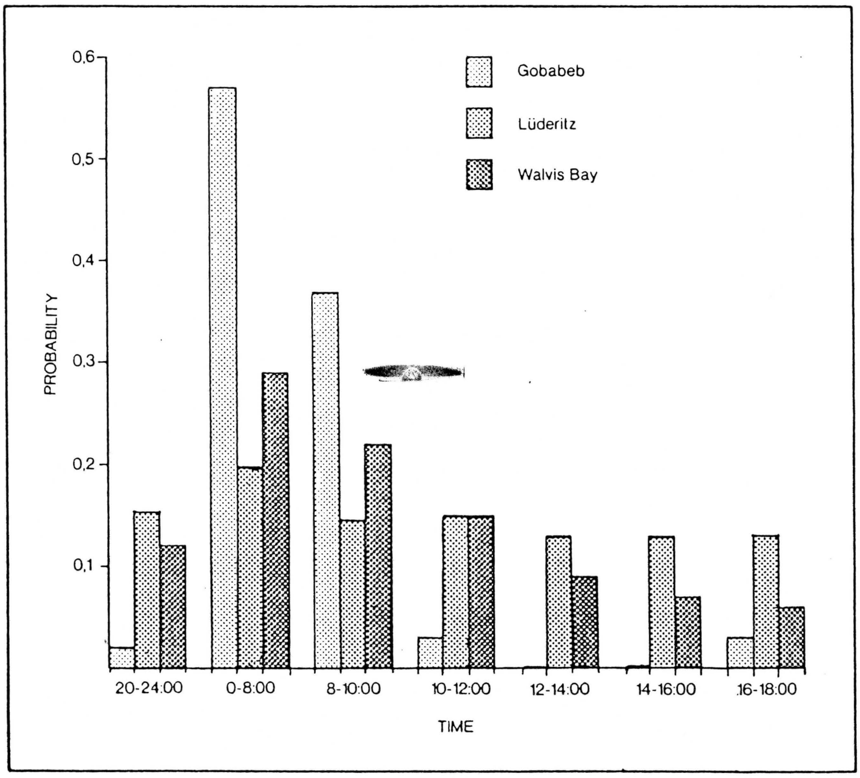

Figure 5 **Diurnal fog occurrence patterns for Gobabeb, Diaz Point (Lüderitz) and Pelican Point (Walvis Bay)**

It is also evident (Fig. 5) that the variation in the diurnal fog incidence is more accentuated in the interior than along the coast, where the midnight to noon contrast decreases southwards from Walvis Bay to Lüderitz. This probably reflects the modifying influence of the ocean and the low sea surface temperatures at the coastal sites. Further inland, the diurnal heating cycle is the main control. Consequently, there is a total absence of fog during the hottest period, i.e. between 12:00 and 16:00, while late morning fogs (10:00 - 12:00) are almost exclusively winter phenomena at Gobabeb.

An unexpected feature revealed by Figure 5 is the low incidence of fog during the 20:00 to 24:00 time slot. With the exception of Lüderitz, fog occurs more frequently shortly after sunrise than it does during the four hours preceding midnight. At Gobabeb, 40% of all fog episodes persist until after 08:00, as opposed to only 2% which are recorded between 20:00 and midnight whereas at Walvis Bay, both the early and mid-mornings have a greater chance of being foggy than the pre-midnight period. The persistence of fog throughout the morning period may, in part, be ascribed to the influence of the fog cover itself on ambient conditions. The relatively high albedo of the fog top, coupled with absorption within the fog layer would significantly deplete the amount of radiation reaching the ground. Hence the high humidities and low temperatures prevailing around dawn, would tend to be maintained for some time.

The dearth of pre-midnight fog, on the other hand, is probably due to the fact that nocturnal cooling has not yet lowered temperatures sufficiently for fog to form. Diurnal temperature cycles are known to display considerable lags in desert areas. Perusal of hourly temperature and humidity data (SAWB, 1954) reveals that the air is considerably drier and warmer at 20:00 than it is at 08:00. Even at midnight, temperatures exceed those recorded at 08:00.

5.2.4 *Duration, commencement and cessation of fog episodes*

Figure 6 gives some indication of the duration of fog episodes at the three sites and should be used in conjunction with Table 2, which shows the periods during which a fog event commenced and ceased. It should be kept in mind that it is not possible to determine exact times of commencement and cessation from the Weather Bureau data. Consequently it was assumed that fog which was recorded during any particular period, for instance the 0:00 - 8:00 period, started at midnight and lasted until 08:00. Hence, while no deductions can be made concerning the exact duration of a fog episode or about the precise commencement and cessation times, the above-mentioned information may be used for comparison between the recording stations.

The information shown on Table 2 is consistent with the findings discussed

Table 2 **Time of commencement and cessation of fog events (mean no. days/annum) at Diaz Point (Lüderitz), Pelican Point (Walvis Bay) and Gobabeb.**

	Same day							Next day							
Start / End	0 - 8:00	8 - 10:00	10 - 12:00	12 - 14:00	14 - 16:00	16 - 18:00	18 - 24:00	0 - 8:00	8 - 10:00	10 - 12:00	12 - 14:00	14 - 16:00	16 - 18:00	18 - 24:00	longer
DIAZ POINT (LüDERITZ)															
0 - 8:00	16,3	7,7	3,0	2,0	3,3	3,0	0,7	0,7	-	0,3	-	-	-	-	-
8 - 10.00		3,0	2,7	0,7	-	1,0	0,3	-	-	-	-				
10 - 12:00			4,7	2,3	1,0	2,3	1,0	1,0		0,7				0,3	
12 - 14:00				3,0	1,0	4,3	1,0	1,0		0,3			0,3	0,1	
14 - 16:00					1,0	2,7	1,0	1,3							
16 - 18:00						5,0	2,7	1,0	0,7		0,3	0,7	0,3		0,7
18 - 24:00							8,7	5,0	2,7	0,7	0,3	1,3	0,7	1,0	1,0
PELICAN POINT (WALVIS BAY)															
0 - 8:00	54,0	17,3	14,3	4,0	1,7	0,7				0,3				0,3	
8 - 10:00		20,3	7,3	2,0	0,3	1,0	0,7								
10 - 12:00			11,0	2,0	1,7	1,0	0,3								
12 - 14:00				9,0	4,7	2,3	0,3			0,7					
14 - 16:00					6,0	1,3		0,3	0,3						
16 - 18:00						9,0	1,7	0,3	0,3	0,3					
18 - 24:00							27,2	3,0	1,3	2,7	0,3	0,3		0,3	
GOBABEB															
0 - 8:00	24,3	34,7	2,7												
8 - 10:00		7,7				0,3									
18 - 24:00							0,7	1,0	0,7	0,3					

above. It shows that at Walvis Bay and at Lüderitz, fog usually forms and dissipates during the same time interval - most often during the 00:00 to 08:00 period - and therefore eight hour episodes are most common. At Gobabeb they are more likely to persist until 10:00. In view of the modifying effect of the

Benguela-upwelling system on temperatures, it is not surprising that the duration of fog episodes (recorded during the 1983 to 1985 period) were greater at the two coastal sites. The longest fog episode lasted for 58 hours and occurred at Lüderitz during November, 1984. By contrast, the duration of fog events at Gobabeb never exceeded 18 hours during the study period. As expected, nocturnal fogs usually persist for a longer period than those forming after 08:00. While this certainly applies to Gobabeb and Walvis Bay, at Lüderitz, protracted fog episodes (>24 hours) are equally likely to start during any of the times intervals.

As previously stated, fog events last longest during the winter months (July and August) at Gobabeb. This is also the case at Walvis Bay where April, May and June fogs are most persistent. The latter can probably be ascribed to the general decrease in wind speed and frequency at the coast during this season. Paradoxically, the longest fog episode at Lüderitz was recorded during November. Evening fog (20:00 - 0:00) is especially prevalent during July, September and October at Lüderitz where it invariably persists throughout the night until approximately 08:00, whereas at Walvis Bay it occurs most often from April to July, rarely lasting beyond midnight.

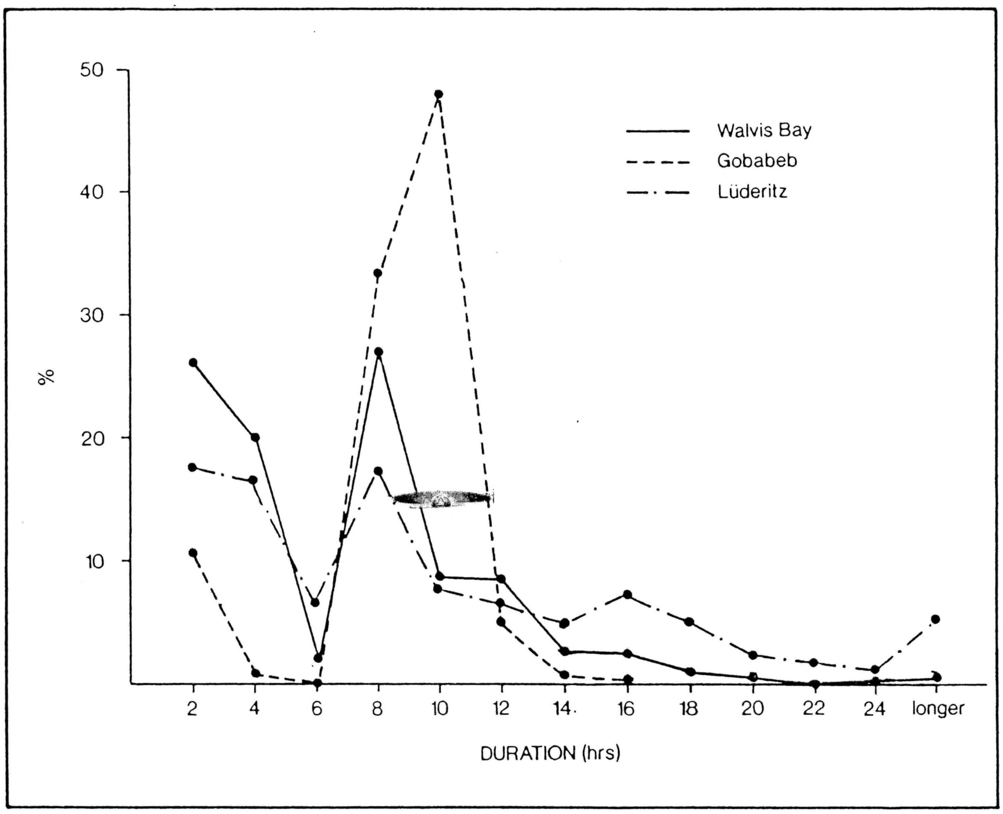

Figure 6 **Duration of fog episodes at Pelican Point (Walvis Bay), Gobabeb and Diaz Point (Lüderitz)**

5.2.5 *Fog intensity*

The intensity of fog is probably its most important characteristic since it determines the visibility and hence the severity of the hazard. Figure 7 illustrates the relative proportion of light, moderate and heavy fogs at Gobabeb, Walvis Bay and Lüderitz, respectively. The fog intensity characteristics of the coastal stations differ markedly from those of Gobabeb. While all three fog types have approximately the same probability of occurrence at Gobabeb, the frequency of heavy fogs far exceeds that of the lighter fogs at both Lüderitz and Walvis Bay.

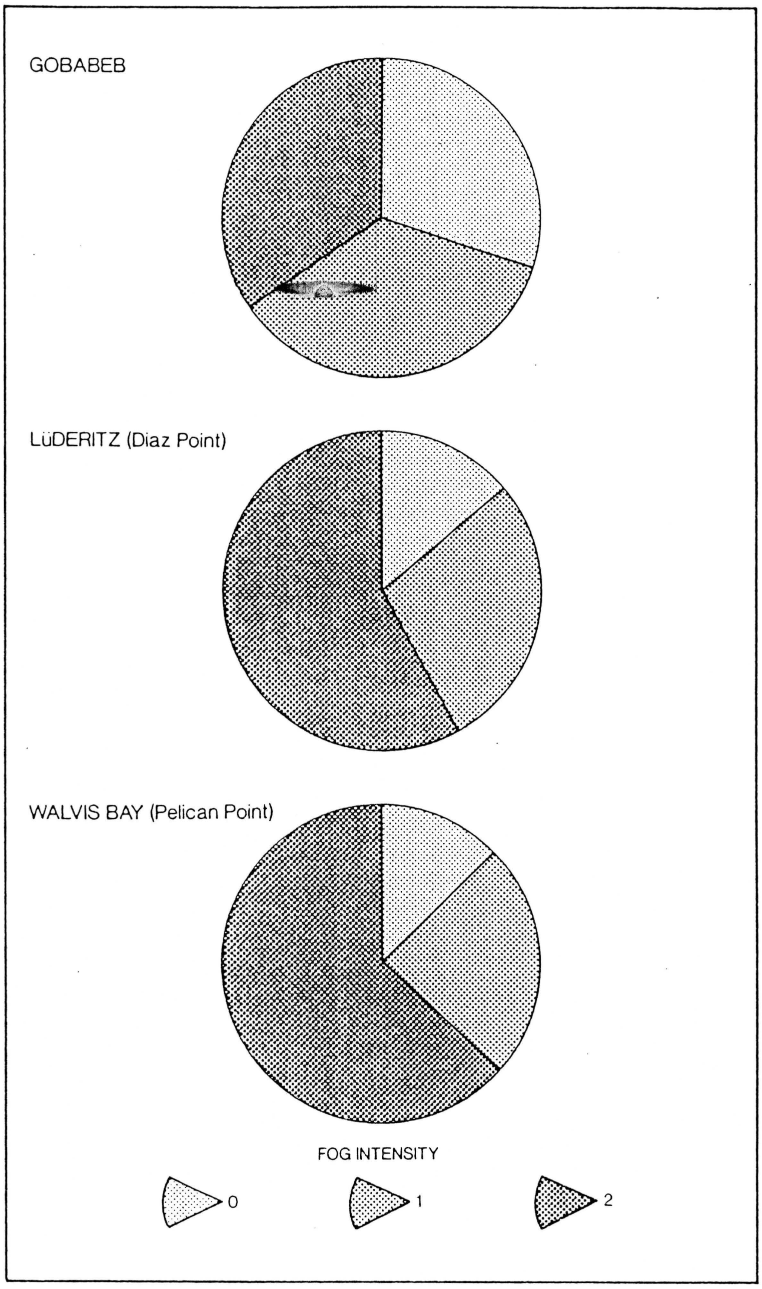

Figure 7 **Relative proportion of light, moderate and heavy fog episodes at Gobabeb, Diaz Point and Pelican Point**

The seasonal incidence of light, moderate and heavy fogs also exhibit interesting and diverse patterns at the three stations under investigation (Fig. 8). At Gobabeb, light fog prevails during the summer (November, December and January) but in winter (May - August), the situation is reversed with heavy fogs predominating. The lowest relative incidence (13,3%) of heavy fog occurs during November, but from then onwards its occurrence increases progressively until a peak is reached during August when over 57% of the fog episodes are classified as being 'heavy'. During September and October the relative contribution of heavy fog diminishes with a corresponding increase in moderately intense fogs. With the exception of February, when light, moderate and heavy fogs have approximately the same likelihood of occurrence, a clear progression from light fogs during summer, moderate fogs during autumn (April) and spring (September & October) and heavy fogs during winter is evident.

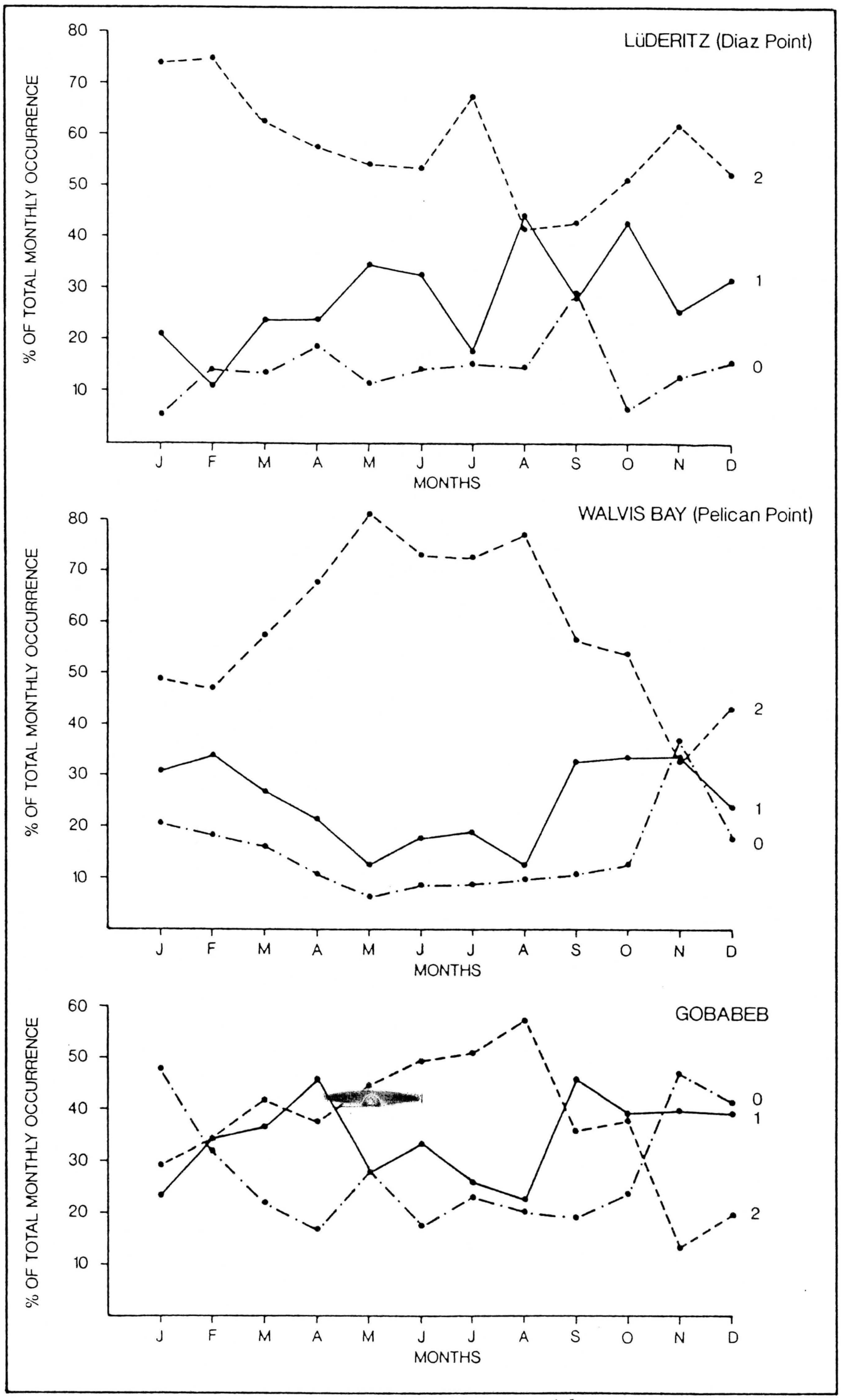

Figure 8 Monthly distribution of light, moderate and heavy fog incidence at Diaz Point, Pelican Point and Gobabeb

At Lüderitz, by contrast, heavy fog is more likely to be experienced during any month except August. The seasonal pattern of heavy fog occurrence at Lüderitz is almost a mirror image of that found at Gobabeb, in that the relative proportion of these fogs decreases systematically from a high in February to reach a minimum during August, after which it slowly increases again. Only the anomalously high value during July breaks the almost perfect annual cycle. Light fogs are rare in all months, but especially in January and October when the relative occurrence frequency values drop to 5,3% and 6,4%, respectively.

The seasonal fog intensity characteristics at Walvis Bay resemble those of Gobabeb in some respects, while in others they are similar to those of Lüderitz. In general, heavy fogs predominate for most of the year, as they do at Lüderitz, but peak occurrence is reached during winter with the minimum in November - a situation reminiscent of Gobabeb. Whereas the latter station has a spring peak, at Walvis Bay the highest frequency of heavy fogs occurs in early winter i.e. May, with over 80% of fog occurrences having a visibility of less than 300 m. Light fogs are very rare, except during November, when 37% of occurrences are classified as light, 32,2% as moderate and 33,3% as heavy.

The occurrence of heavy fogs at the coast throughout the year is probably linked to the high relative humidity of the air, the availability of large amounts of hygroscopic condensation nuclei, relatively low air temperatures, the presence of a subsidence inversion and generally windy conditions. The preponderance of heavy fogs during winter are probably due to, *inter alia*, lower surface temperatures and a decrease in inversion base height, especially at Walvis Bay and Gobabeb (Taljaard, 1979). In addition, dust-laden Berg winds are more common on winter (Jackson, 1954) thereby contributing to the concentration of aerosols present in the air. Moreover, since the size of the condensation nucleus influences the size of the fog droplet (Woodcock, 1978), those formed on dust particles would be considerably smaller than those condensed on particles of marine origin.

The greater proportion of heavy fogs at Lüderitz in summer may, in part, be ascribed to the seasonal migration and fluctuation in size of the upwelling cell. Apparently upwelling is more prevalent in this area during summer but the extent of the cell peaks during winter (Shannon, 1985; Lutjeharms & Meeuwis, 1987). Therefore, moist air moving from warmer oceanic regions would cool rapidly when passing over the cold upwelling to produce heavy summer fogs.

During winter, however, the increase in size of the cell would ensure that the onshore breeze is colder and the air, drier. Consequently, those fogs which do form would probably tend to be less dense.

A number of possible explanations could account for the frequent occurrence of light fogs recorded at Gobabeb during summer. It is likely that at least some of these fogs result from nocturnal radiation. Since onshore breezes are stronger during the summer months (Schulze, 1972; Tyson & Seely, 1980), it is likely that moist air is advected far enough into the interior of the desert to reach Gobabeb and beyond. This would raise the dew point there. Subsequent nocturnal cooling under cloudless skies would lower the temperature sufficiently to initiate condensation.

Intuitively, some relationship between the intensity of fog and the amount of fog precipitation is expected. However, this is not necessarily the case. Heavy fogs may sometimes yield little or no precipitation while on other occasions enough fog water is produced to thoroughly wet surfaces and collect in pools on the ground (Logan, 1960). Surprisingly, comparison between monthly fog precipitation values (Lancaster *et al.*, 1984) and FDF reveals that, despite the fact that fog precipitation peaks during spring at the inland stations, the intensity of precipitation i.e. the amount of (fog) precipitation per (fog) day is consistently higher during winter - the season with the highest incidence of *heavy* fogs. On closer scrutiny, however, it appears that the incidence of *light* fog is the more important (albeit negative) determinant of fog precipitation (r = -0,78). The wetness of fog is thus dependant on both the size (and hence the type) of the condensation nucleus around which the fog droplet forms as well as the density of the nuclei. Therefore, it seems evident that the amount of fog water precipitated is largely determined by the origin of the fog.

According to the information available concerning the frequency, density (intensity), and amount of fog precipitation recorded at Gobabeb, together with the well-known fact that sea fogs are usually quite dense and radiation fogs relatively light, it seems apparent that many winter fogs at Gobabeb are katabatic or advection sea fogs while summer fogs most likely arise through radiational processes or cloud interception. This does not, of course, totally preclude the occurrence of other types of fogs at different times of the year.

6 SYNTHESIS

The aim of this article was to provide a general overview of the spatial and temporal characteristics of fog in the Namib and to propose possible explanations for these. To this end a suite of 1984 Meteosat images was used to compile a fog distribution map of the area while South African Weather Bureau data were used to analyse the temporal aspects. The latter comprised annual, monthly and diurnal fog occurrence patterns - including commencement and cessation times - and fog intensity characteristics. In addition to presenting the results of empirical research, the discussions relied heavily on established fog trends as described by other researchers in the region.

The results reported above revealed a number of distinctive spatial and temporal patterns associated with fog occurrence in the Namib. In addition to verifying and quantifying well-known fog distribution patterns, the research also indicated some salient facts not previously documented.

With regard to the spatial patterns, it was found that fog distribution as shown on the map accorded well with observations on the ground. The spatial coincidence between topography and FDF is marked and highlights the general decrease in FDF towards the interior - a feature characteristic of all west coast deserts. This was ascribed to the simultaneous occurrence of one suite of factors promoting fog formation at the coast and another, inhibiting its formation in the interior.

Fog incidence also varies latitudinally within the coastal zone. The highest FDF occurs at Pelican Point with an average of 139,3 fog days per year (SAWB, 1986). From there, it decreases to the north (Möwe Bay = 79 FD/yr and Alexander Bay = 67,1 FD/yr (SAWB, 1986)). It seems likely that this may be associated with the spatial variation in the occurrence of optimal fog forming conditions including light onshore breezes, sea surface temperatures which approximate the dew point and stable atmospheric conditions (Tremant, 1989) - at different times of the year. The position of the South Atlantic Anticyclone, the point of origin and subsequent movement of coastal lows and the presence of cold water upwelling are thus of crucial importance.

Whereas there is consensus that coastal fog is mainly advection sea fog (with a possibility of some radiation fog occurring), far less progress has been made in elucidating the processes involved in fog formation in the interior of the Namib.

However, the high moisture content and intensity of winter fogs at Gobabeb seem to indicate that these are probably advection sea fogs and cloud interception fog (with some dry katabatic fogs also occurring). The lighter, and in some cases drier, summer fogs may result from cloud interception and radiative cooling. Cloud interception thus appears to be a major contributor to fog incidence in the interior of the desert.

Analysis of the temporal characteristics of Namib fogs indicated that:

- Extended periods of above and below normal FDF are discernable in the time series of the coastal stations - but their temporal incidence differed from one station to the next
- Inter-annual fog occurrence is often less reliable at the coast
- On a seasonal basis, the highest frequency of fog days occurs during winter at the coast and during spring at the inland stations. Slight north-south differences can also be discerned within the coastal zone. Thus, despite the fact that Pelican Point has the highest mean annual FDF in the Namib, Diaz Point is foggier during summer
- Most fogs form and dissipate between midnight and 08:00 and hence they generally last for about 8 hours. Episodes lasting for more than 10 hours usually start before 08:00 at Gobabeb whereas those at the coast may commence at any time
- Heavy fogs predominate throughout the year at the coast with a higher proportion occurring during winter at Walvis Bay and during summer at Lüderitz. At Gobabeb, however, light fogs are more common during summer

Explanations for the above are largely speculative. Nevertheless, it is certain that most phenomena can be explained in terms of a combination of local and synoptic conditions.

Local factors such as diurnal temperature and stability regimes as well as thermo-topographically induced circulations are especially important in the interior where they may, in part, account for the diurnal fog occurrence patterns, including their commencement and cessation times (and hence their duration) as well as the type of fog formed.

However, the major factor controlling fog distribution patterns in the Namib is the position and intensity of the subtropical high pressure cells - in particular the South Atlantic Anticyclone. Its seasonal shift towards the north-west in winter and the south-east in summer influences the speed of onshore winds (at the surface and at cloud level), the inversion characteristics of the boundary layer, the position and extent of the upwelling cells as well as the formation and subsequent behaviour of coastal lows.

Coastal lows are also of major importance for the formation of advection sea fog since they, too, affect wind speed and direction and the height of the inversion base. The approach of a coastal low is heralded by a drop in pressure and inversion height whereas its passing is accompanied by a wind shift from offshore easterlies to onshore north-westerlies. Whether these onshore breezes will produce fog is, in turn, dependent on the sea surface temperature and the extent of the upwelling.

The presence of onshore winds are vital for the landwards advection of sea fogs. The speed of the onshore wind influences the relative proportion of coastal fog vs. low-level cloud and controls the distance of their inland penetration. The presence of a subsidence inversion affects the stability characteristics of the atmosphere in the coastal regions and the height of fog and cloud layers. This again, may influence spatial fog distribution patterns in the interior as well as inter-seasonal fluctuations in FDF and fog precipitation. Moreover, it is possible that it also affects fog density.

As previously shown, the presence of cold water upwelling adjacent to the coast is another factor which is essential for the formation of the majority of coastal fogs. The characteristics of the upwelling cells at various locations, their north-to-south shift in summer and the seasonal variations in their spatial extent probably account for the differences in fog characteristics at Walvis Bay and Lüderitz, including the annual and monthly fog occurrence frequency and variations in the precipitable water content and density of fog. Upwelling also modifies the local climate, thereby influencing the duration of fog episodes.

Since there is some interaction between the South Atlantic Anticyclone and the coastal low, it is possible that the latitudinal migration of the South Atlantic high pressure cell influences the source location of coastal lows and their subsequent movement. There is some evidence which suggests that when the Anticyclone ridges in to the south of the sub-continent, the coastal low moves southwards along the west coast and may even round the Peninsula. However, when the Anticyclone ridges in over the land the coastal low may in fact move northwards beyond Walvis Bay (Estie, 1986). It is postulated that during summer, when the South Atlantic Anticyclone reaches its southernmost position, coastal lows would be formed further to the south - probably between Walvis Bay and Lüderitz. In winter, they would be spawned to the north of Walvis Bay. If this is indeed the case, it would explain many aspects of the annual and monthly fog incidence patterns in the Namib and their variation over time and space.

The above hypothesis would also give some indication of the relative importance of the South Atlantic Anticyclone versus coastal lows in fog occurrence in the coastal zone. It implies that the contribution of coastal low generated fogs is greater in the southern than in the northern region. This seems to be borne out by the findings (albeit preliminary) by Olivier *et al.* (1989) and Vendrig (1990). According to these authors, coastal lows were associated with 76% of fog days at Lüderitz whereas they accounted for only 63% of fog events at Gobabeb. The relative contribution of these two systems has not yet been determined for Walvis Bay, nor has it been ascertained whether there is any difference in the mechanisms involved in fog formation during periods of high and low fog occurrence.

From the foregoing it is clear that the processes involved in the formation of fog in the Namib littoral are complex and that an understanding of their interplay is important. The prediction of both long and short-term fog occurrence is relevant and could aid in decision-making processes relating to a multitude of social, economic and ecological issues. In addition, since fog forms relatively quickly and easily along the West Coast, its presence could be used as an indicator of atmospheric conditions prevailing at the surface and at higher levels, at both meso- and macro-scales. It is not inconceivable that such knowledge could be fruitfully employed in predicting the occurrence of other weather phenomena at places far removed from the Namib. But it is essential that more weather stations be opened, especially in the far northern and southern parts of the desert, at the coast as well as further inland. Until this has been done, and upper air and longer runs of data are available, and until the vertical structure of the local wind regimes have been investigated, the results presented here can only be accepted as preliminary. Clearly much remains to be researched.

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