SOME SPATIAL AND TEMPORAL ASPECTS OF FOG IN THE NAMIB

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ABSTRACT: Some spatial and temporal aspects of fog in the Namib. Fog is considered to be one of the most characteristic climatic features of the Namib desert. It provides a significant and reliable source of water to desert flora and fauna, may in future contribute towards the water supply of the inhabitants and constitutes a hazard to aviation and shipping. However, despite its importance, relatively little is known about its distribution, especially in the more remote parts of the southern and northern regions. This article describes aspects of both the spatial and the temporal characteristics of fog including annual, seasonal and diurnal fog occurrence patterns, as well as the commencement, cessation times and the intensity characteristics of fog episodes. An attempt is made to explain these characteristics in terms of local and synoptic scale controls. The role of the position and intensity of the South Atlantic Anticyclone and coastal lows are accentuated.

Key words: fog, Namib, spatial patterns, intensity, South Atlantic Anticyclone, coastal low

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 (Kamara 1989). 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. Studies have revealed that fog precipitation can be substantial, equalling or even exceeding the local rainfall (Nagel 1959). 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 these areas (SAWB 1986), yielding an amount of intercepted precipitation estimated to be equivalent to 130 mm of rainfall (Nagel 1962). (The normal annual fog precipitation yield is, however, between 34 and 45 mm (Eriksson 1958; Nieman *et al.* 1978).) Thus, except for the extreme aridity encountered in the Namib, fog can probably be considered as its most characteristic climatic feature (Lancaster, Lancaster & Seely 1984). The presence of fog not only moderates the temperature, but it also provides a significant and reliable source of moisture to the desert ecosystems (Goudie 1972; Seely 1987). It may also serve as a supplementary source of water to the human population in the Namib (Nagel 1959; Nieman *et al.* 1978). Furthermore, activities associated with the proposed offshore exploration of oil will almost certainly reveal fog to be a major hazard to shipping and aviation in the area.

In view of the undoubted importance of fog in the area, it is indeed surprising that few studies have dealt exclusively with the fog phenomenon. While most literature on the Namib, irrespective of the actual topic discussed, invariably makes some reference to the fog phenomenon, it is often given in the form of a subjective account of fog occurrence for a specific time and place. The

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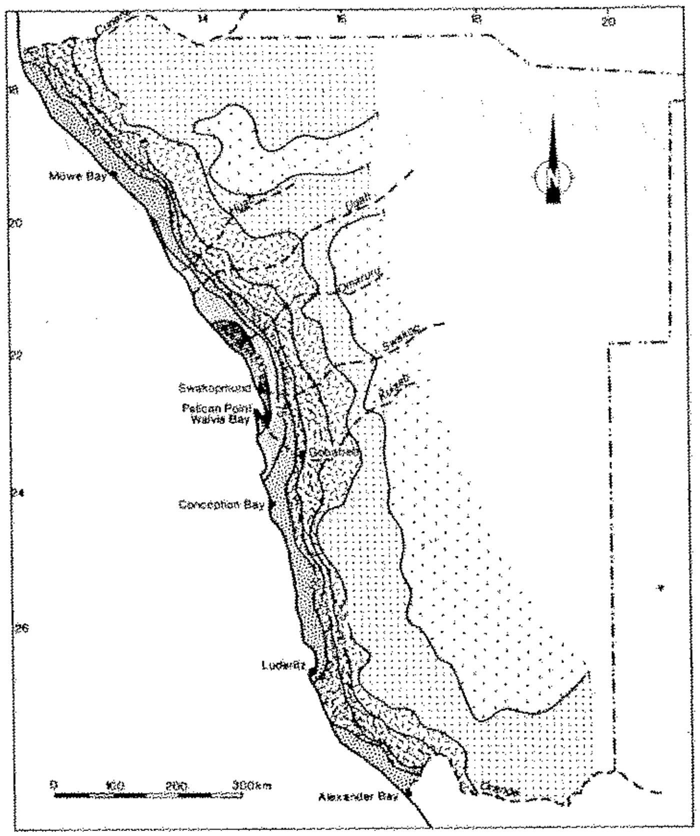

Figure 1: Fog/low cloud distribution during 1984.

available information is thus 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. Moreover, with the exception of the (unpublished) papers by Estie (1986) and Vendrig (1990), there has been little or no attempt to explain spatial and temporal variations in fog occurrence in terms of prevailing atmospheric conditions.

The aim of this article is two-fold. Firstly, it collates and summarizes the available information on the spatial and temporal (annual, seasonal and diurnal) characteristics of fog in the Namib, including the intensity, duration and mean commencement and cessation times of fog episodes. As such, the discussions integrate the results of research conducted by the author with information which has been obtained from a wide variety of previously published sources. Secondly, it attempts to explain fog occurrence patterns in terms of their meteorological and climatic controls.

All discussions pertain to the Namibian part of the Namib, i.e. to the area lying between the Cunene and Orange Rivers and bounded by the South Atlantic Ocean to the west and the western Escarpment to the east. The first part of the paper comprises a summary of the existing information on the spatial characteristics of fog occurrence in the Namib as well as of the various theories regarding the types of fog which occur in different regions. The second part, i.e. the discussion of the temporal characteristics of fog, draws more heavily on research results. Consequently, the description of the data and methods used in the analyses will be discussed in section 4.

2. SPATIAL DISTRIBUTION OF FOG

2.1 Fog occurrence patterns

The general remoteness of the region and the paucity of weather stations have imposed severe restrictions on the amount and quality of information regarding the spatial aspects of fog distribution. It is therefore not surprising that, until recently, no attempt had been made to compile a fog distribution map of the Namib. However, the advent of satellite imagery may offer a solution to the problem. Accordingly, Olivier (1993) visually analysed a set of 1984 Meteosat photos to produce the 'fog' map shown in Figure 1. In view of the quality of the data set used and the difficulty in distinguishing between fog and low cloud on satellite photos, it is likely that this figure is not very accurate - especially in the northern parts of the region where cloud cover often obscures the surface. It should also be kept in mind that Figure 1 reflects only the 1984 fog/low cloud incidence patterns. Notwithstanding these limitations, it was found that there was some agreement between the patterns depicted on the map and fog incidence recorded at a number of weather stations in the Namib. Thus, assuming some degree of accuracy, the following general fog distribution patterns can be discerned from the map:

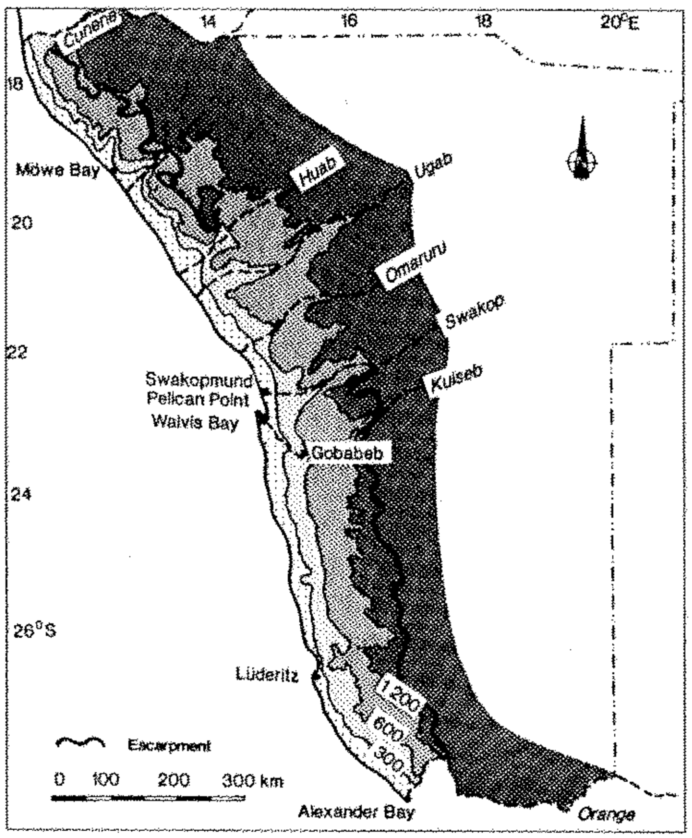

Figure 2: General topography of the Namib.

(1) Fog occurrence in the Namib decreases with distance from the sea. This accords with previous observations and is characteristic of west coast deserts (Meigs 1966; Copenhagen 1953). Fog statistics of weather stations in the central Namib indicate that, in general, the mean annual FDF decreases from about 120 days at the coast, where the modifying effect of the ocean is most pronounced, to around 40 days at a distance of 40 km inland, to 5 days at 100 km from the sea (Barnard 1988, personal communication).

(2) The annual fog incidence exhibits considerable latitudinal variation within the coastal fog belt. Although the entire coastal strip of the Namib receives fog on at least 50 occasions every year, the area extending from about 21,5°S to 23,5°S is particularly foggy, with Swakopmund and Pelican Point recording an annual average of 113 and 139 fog days, respectively (SAWB 1986). The FDF decreases progressively north and southwards of this centrally situated foggy zone - as shown by the FDFs for Möwe Bay (79), Diaz Point (117) and Alexander Bay (67).

(3) There is some degree of spatial coincidence between topography and FDF over the entire Namib (compare Figures 1 and 2). For instance, the 5 FD isoline corresponds (approximately) with the seaward edge of the Escarpment over large parts of the Namib - especially in the area to the north of Conception Bay. It is also apparent that the high fog zone (>100 FD/annum) is largely confined to the coastal strip which lies below 200 m above MSL. Furthermore, the 50 and 25 FD isolines follow the 300 and 600 m contours, respectively, except in parts of the central Namib where fog penetrates further inland. The interior edge of the coastal plain is characterised by a rapid decrease in FDF with fog occurring relatively infrequently on the Namib Platform (lying between 70 and 900 m above MSL). Nevertheless, its effects have been noted up to 100 km inland (Goudie 1972; Lancaster *et al.* 1984).

(4) The coastal fog belt is rather narrow (±30 km) but widens considerably in the area between Conception Bay and the Ugab river as well as just to the south of Möwe Bay. It also extends further inland along the courses of some of the larger river valleys, such as the Swakop-, Omaruru- and Ugab rivers. A number of factors may account for this feature. 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.

2.2 Fog precipitation patterns

In contrast to the fog occurrence patterns described above, fog precipitation in the central Namib has been found to *increase* from the coast to a distance of about 35 to 60 km inland. Thereafter it decreases further eastwards (Lancaster *et al.* 1984). Fog precipitation measurements by Besler (1972) were found to vary from 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 occuring at a height of 300 to 600 m above MSL (Lancaster *et al.* 1984; 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 even smooth rocks, while the leeward side is almost devoid of growth (Seely 1987).

In direct 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 the coastal plain is absent. Therefore the initial increase in fog precipitation - if it does indeed occur - would be expected to occur over a much shorter distance so that measurements from stations located some distance inland would not reflect 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. According to Nagel (1962), radiation fog is the principal source of fog precipitation at coastal sites.

3. NAMIB FOG: COASTAL AND INLAND TYPES

Although it is unlikely that all 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; Heydorn & Tinley 1980; Lancaster *et al.* 1984; Estie 1986; 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 moving 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 a rate approximating that of a black-body. Thus the moist surface layer cools rapidly and fog is easily formed (Taljaard 1992, personal communication). Nevertheless, the occurrence of fog in the littoral zone is usually associated with either southerly to south-westerly winds blowing around the eastern perimeter of the South Atlantic Anticyclone or with westerlies and north-westerlies associated with the development and longshore movement of coastal lows over upwelled water (Logan 1960; Estie 1984, 1986; Lancaster *et al.* 1984).

In addition to advection sea fogs, other fog types may also occur within the coastal zone. According to Jackson (1941), this 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 and a number of possible explanations have been proposed. One such suggestion is that inland fog is mainly sea fog which has been 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, often been observed during light north-westerlies (Estie 1986). Estie (1986) and Vendrig (1990) argue that this would necessarily be a day-time phenomenon as nocturnal

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katabatic and land breezes would tend to oppose inland flows - particularly during winter (Tyson & Seely 1980; Lindesay & Tyson 1990). 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 in the interior. 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.

Thirdly, there is mounting evidence to suggest that cloud interception is a major contributor of inland fog (Lancaster *et al.* 1984; Estie 1986; Vendrig 1990). 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 when drizzle falls into cooled air below (Jackson 1941). The cloud interception theory of fog formation is given some support by three significant findings. Firstly, the average heights of clouds correspond with the altitude of the area with maximum fog precipitation. Secondly, the spring-summer cloudiness maximum at the coast coincides temporally with the peak fog occurrence frequency inland (Lancaster *et al.* 1984). Finally, it was found that, during 1983, fog at Pelican Point preceded fog at Gobabeb on only nine out of 72 fog events, fog episodes occurred simultaneously at the two stations on 17% of occasions whereas low level stratus cloud at Pelican Point accompanied (or preceded) fog at Gobabeb 80% (65%) of the time.

4. TEMPORAL FOG PATTERNS

Fog day frequency 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; in the duration, commencement and cessation times of fog episodes; and in the fog intensity patterns at three fog recording stations, namely, Pelican Point (Walvis Bay), Diaz Point (Lüderitz) and Gobabeb. These temporal fog characteristics are discussed in the following section. In addition, possible explanations for the observed patterns are proposed.

4.1 Data and method

South African Weather Bureau printouts or publications 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, personal communication). After 1978, the intensity codes were replaced by

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 (1959,1974)	70 (1970)
Range	94	61	95	47
Coeff of Variation (%)	26,4	15,3	18,3	17,6

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.

The available daily fog occurrence data for Alexander Bay, Diaz Point, Pelican Point, Gobabeb and Möwe Bay 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. (It is assumed that the temporal characteristics prevailing at Pelican and Diaz Points apply equally to Walvis Bay and Lüderitz, respectively.)

Information on other climatic parameters were obtained from Weather Bureau publications of 1954, 1981, 1982 and 1986. The latter, WB 40 (1986), 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.

4.2 Results and discussion

4.2.1 *Inter-annual fog frequency*

Table 1 gives some indication of the year-to-year variability of fog occurrence at the selected stations. It should be kept in mind that these values were derived from analyses of daily weather records as supplied by the Weather Bureau and hence apply only to the periods indicated. (This explains the discrepancy between the mean annual FDF values shown in Table 1 and those given in WB40 (SAWB 1986).)

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

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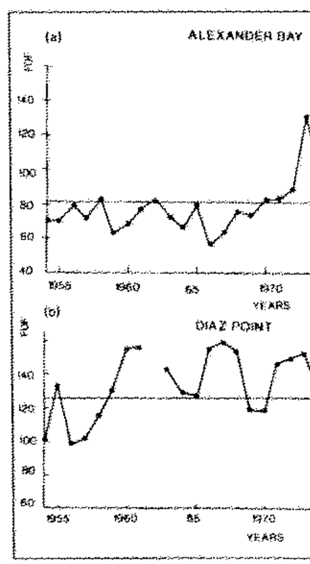

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ascribed to the nature of the upwelling cell centered off Lüderitz, since it is a well-known fact that this cell occurs more often, is larger and colder than anywhere else along the West Coast (Shannon 1985). In general, however, conditions at the coast - particularly at Pelican Point and Alexander Bay - appear to be more variable than at the inland station. 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 (Estie 1986). 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 there. Since coastal stations experience higher wind speeds than those located inland, wind speed, and hence fog occurrence, is more variable there. In addition, the surface wind characteristics are subject to a greater amount of fluctuation than 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.

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.

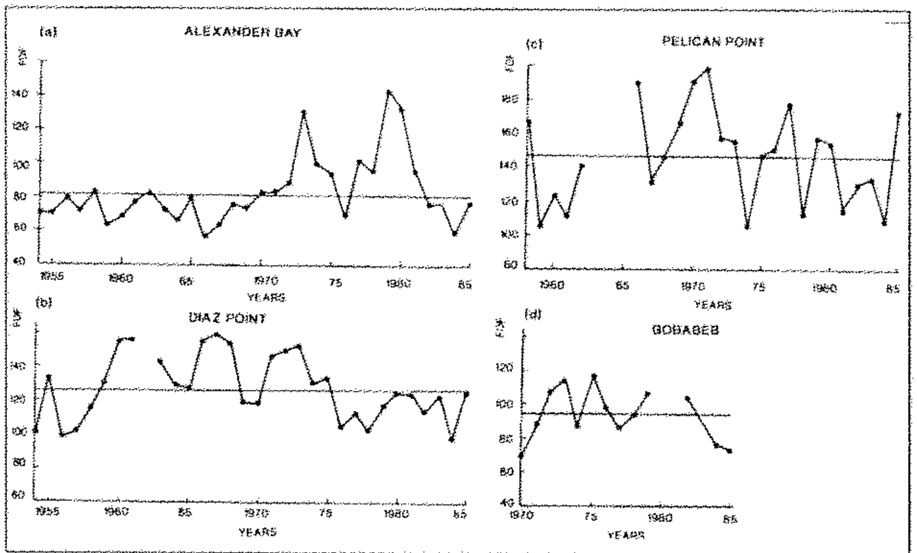

Figure 3: Annual fog day frequency for (a) Alexander Bay (1954 - 1985) (b) Diaz Point (1954 - 1985) (c) Pelican Point (1958 - 1985) and (d) Gobabeb (1970 - 1985).

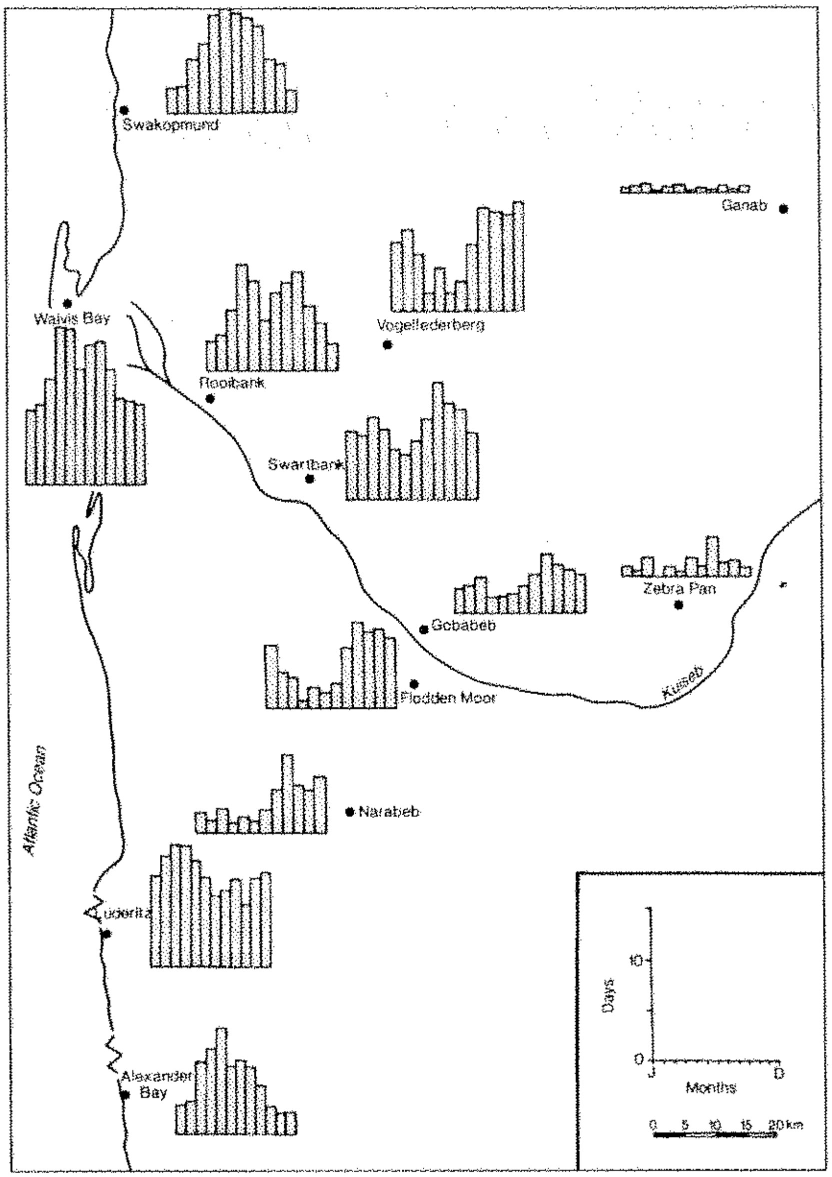

Figure 4: Mean monthly FDF for coastal and inland stations (after Lancaster, Lancaster and Seely, 1984).

Paradoxically, both Pelican Point and Diaz Point were characterised by above average fog occurrence during the early part of the record (1959 to 1975 at Diaz Point, and 1963 to 1973 at Pelican Point) 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.

4.2.2. *Seasonality:*

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4.2.3 *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 Diaz Point, Pelican Point 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

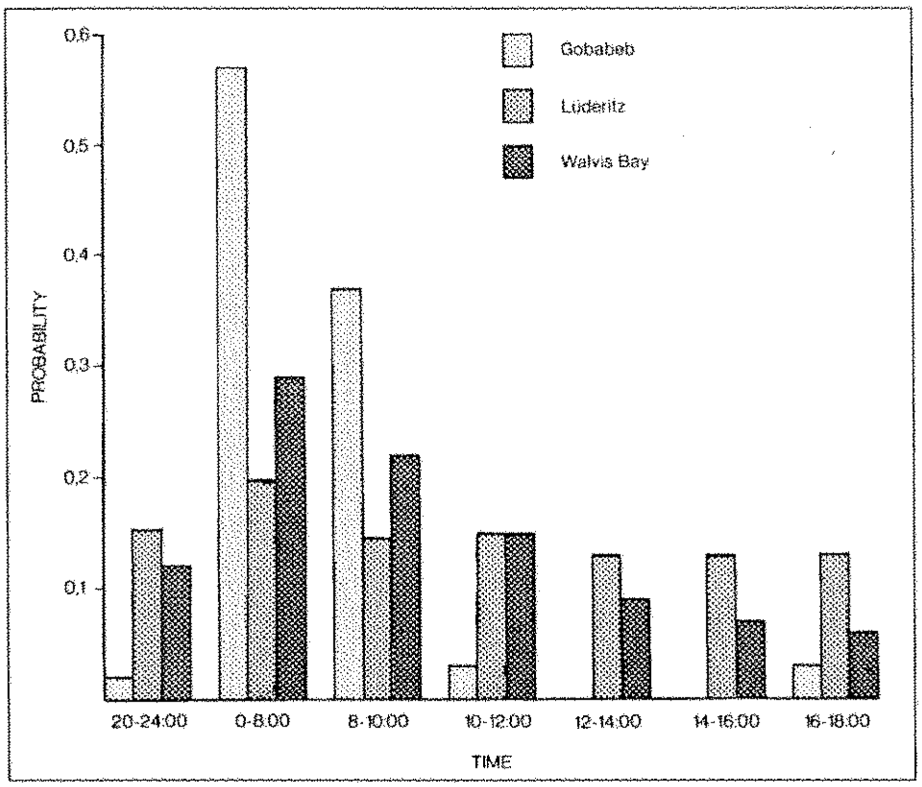

Figure 5: Diurnal fog occurrence patterns for Gobabeb, Diaz Point (Lüderitz) and Pelican Point (Walvis Bay).

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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 Diaz Point, Pelican Point and Gobabeb, respectively, whereas the equivalent values for the 12:00 to 14:00 time slot were 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.

It is also evident (Figure 5) that there is greater variation in the diurnal fog incidence in the interior than along the coast. The latter probably reflects the modifying influence of the ocean and the low sea surface temperatures. Further inland at Gobabeb, 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, with late morning fog (10:00 - 12:00) being an almost exclusive winter phenomenon. The smaller amount of diurnal variability at Diaz Point is most likely associated with the windy conditions which tend to persist throughout the day.

An unexpected feature revealed by Figure 5 is the low incidence of fog during the 20:00 to 24:00 time-slot. At Pelican Point and Gobabeb, fog occurs more frequently shortly after sunrise than it does during the four hours preceding midnight. At Gogabeb, 40% of all fog episodes persist until after 08:00, as opposed to only 2% which are recorded between 20:00 and midnight. At Pelican Point, 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 persist 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. (Desert areas are known to have quite long lags in their daily temperature cycles). Perusal of hourly temperature and humidity data (SAWB 1954) reveals that the air is considerably drier and warmer at 20:00 than at 08:00. Even midnight temperatures exceed those recorded at 08:00.

4.2.4 *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 fog events 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 - 08:00 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 in Table 2 is consistent with the findings discussed previously. It shows that at both Pelican and Diaz Point, 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

TABLE 2

Time of commencement and cessation of fog events (mean no. days/annum)
(means calculated for 1983-1985 data)

DIAZ POINT (LÜDERITZ)

	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
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)

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
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

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
0–8:00	24,3	34,7	2,7												
8–10:00		7,7				0,3									
118–24:00							0,7	1,0	0,7	0,3					

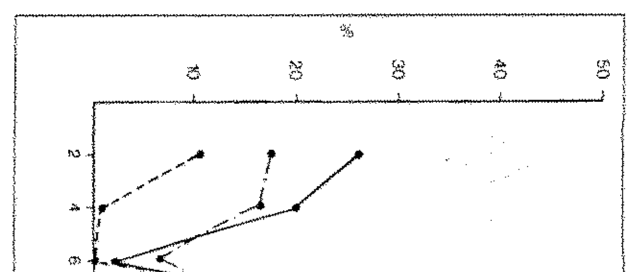

Figure 6: Duration of
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4.2.5 *Fog intensity*

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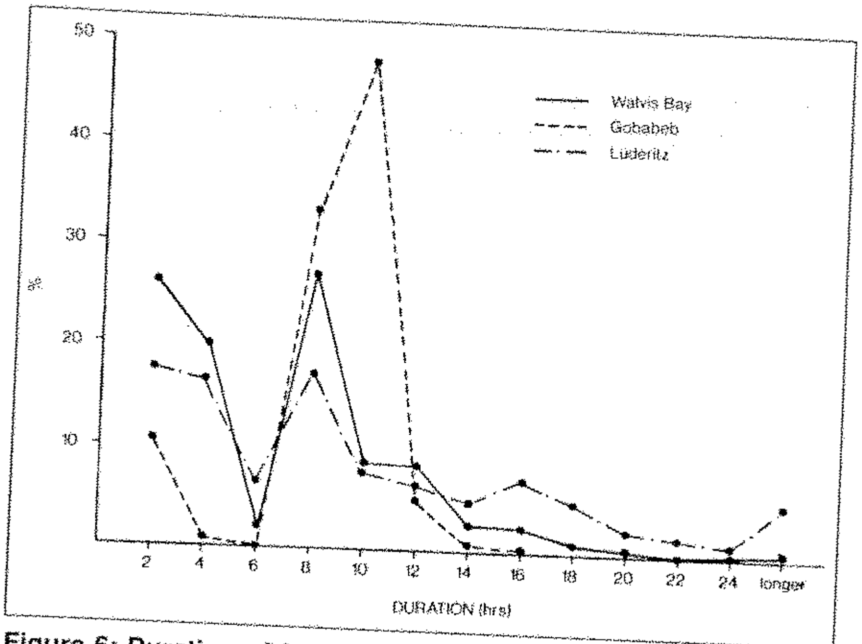

Figure 6: Duration of fog episodes at Pelican Point (Walvis Bay), Gobabeb and Diaz Point (Lüderitz).

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 were greater at the two coastal sites. The longest fog episode (during the 1983 to 1985 period) lasted for 58 hours and occurred at Diaz Point during November 1984. By contrast, the duration of fog events at Gobabeb never exceeded 18 hours during this three year period. As expected, nocturnal fogs usually persist for a longer period than those forming after 08:00. While this certainly applies to Gobabeb and Pelican Point, at Diaz Point protracted fog episodes (>24 hours) are equally likely to start during any of the time intervals.

As previously stated, fog events last longest during the winter months (July and August) at Gobabeb. This is also the case at Pelican Point 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 winter. Paradoxically, the longest fog episode at Diaz Point was recorded during November. Evening fog (20:00-0:00) is especially prevalent during July, September and October at Diaz Point where it invariably persists throughout the night until approximately 08:00. At Pelican Point it occurs most often from April to July, rarely lasting beyond midnight.

4.2.5 *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, Pelican Point and Diaz Point, 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 Diaz and Pelican Points.

The seasonal incidence of light, moderate and heavy fogs also exhibit interesting and diverse patterns at the three stations under investigation (Figure 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.

At Lüderitz (Diaz Point), by contrast, heavy fog is more likely to be experienced during any month except August. The seasonal pattern of heavy fog occurrence there is almost a mirror image of that found and 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.

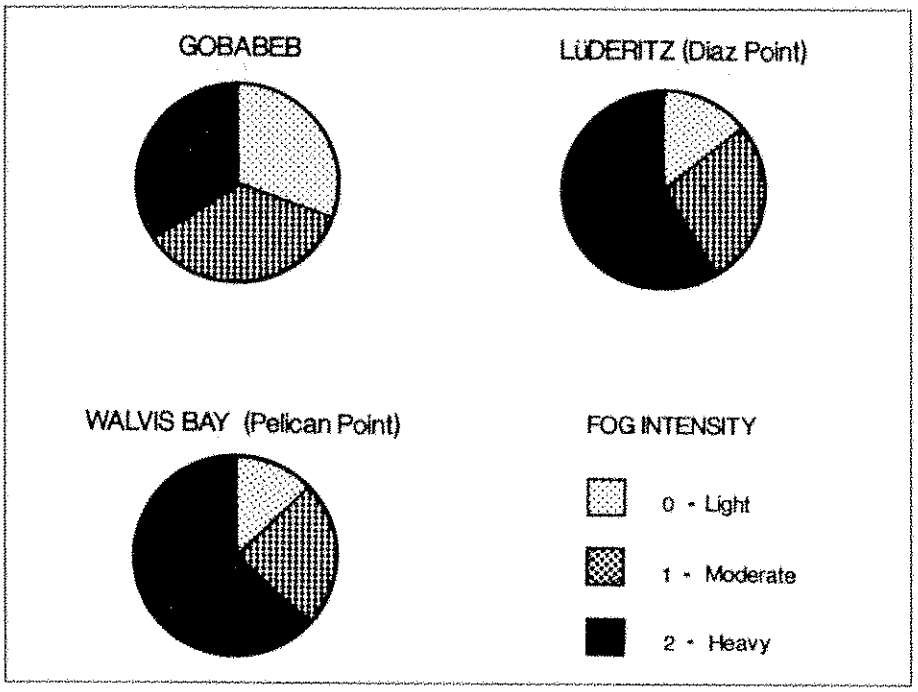

Figure 7: Relative proportion of light, moderate and heavy fog episodes at Gobabeb, Diaz Point and Pelican Point.

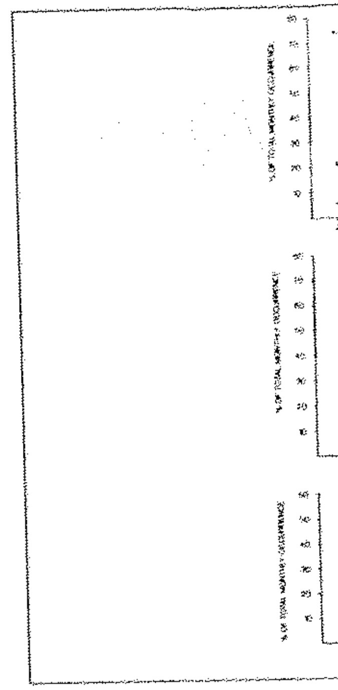

Figure 8: Monthly dist incidence at Di

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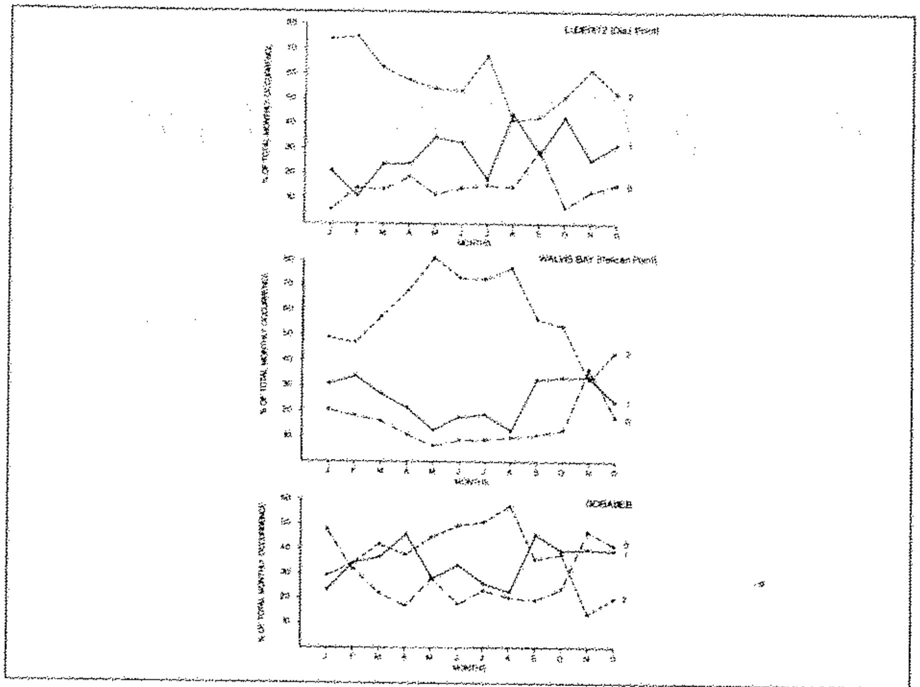

Figure 8: Monthly distribution of light, moderate and heavy fog incidence at Diaz Point, Pelican Point and Gobabeb.

The seasonal fog intensity characteristics at Pelican Point resemble those of Gobabeb in some respects, while in others they are similar to those of Diaz Point. In general, heavy fogs predominate for most of the year, as they do at Diaz Point, but peak occurrence is reached during winter with the minimum in November - a situation comparable to that at Gobabeb. Whereas the latter station has a spring peak, at Pelican Point 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 36,0% of occurrences are classified as light, 32,3% as moderate and 31,7% 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 sufficient air motion to ensure mixing. The preponderance of heavy winter fogs are probably due to, *inter alia,* lower surface temperatures and a decrease in inversion base height, especially at Pelican Point and Gobabeb (Taljaard 1979). In addition, dust-laden Berg winds are more common in winter (Jackson 1954) thereby contributing to the concentration of aerosols present in the air.

The relatively high incidence of heavy summer fog at Diaz Point may, in part, be ascribed to the seasonal migration and fluctuation in size of the upwelling cell. According to Shannon (1985) and Lutjeharms & Meeuwis (1987), upwelling is more prevalent off Lüderitz during summer whereas the extent of the cell peaks during winter. 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), moist maritime air would be advected far enough into the interior of the desert to reach Gobabeb and beyond, raising 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). Comparison of monthly fog precipitation values (Lancaster *et al.* 1984) with FDF reveals that, despite the fact that the total amount of fog precipitation is greatest during spring at the inland stations, the intensity of fog 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 ($r = -0{,}78$, $\propto = 0{,}02$). The wetness of fog is thus probably dependent 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.

5. SYNTHESIS

The results reported above revealed a number of distinctive spatial and temporal patterns associated with fog occurrence in the Namib. The following spatial patterns were discerned:

(1) Fog day frequency decreases from the coast 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.

(2) There appears to be some spatial coincidence between topography and FDF.

(3) 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). It seems likely that this may be associated with the spatial variation in the occurrence of optimal fog forming

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conditions - such as 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 also 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. A limited amount of dry katabatic fogs are also formed. The lighter, and in some cases drier, summer fogs may result from cloud interception and radiative cooling. Cloud interception thus seems to be a major contributor to fog incidence in the interior of the desert.

Analysis of the temporal characteristics of Namib fogs indicated that:

(1) Extended periods of above and below normal FDF are discernable in the time series of the coastal stations - but their temporal incidence differ from one station to the next.

(2) Inter-annual fog occurrence is often less reliable at the coast.

(3) 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 distinguished 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.

(4) 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.

(5) Heavy fogs predominate throughout the year at the coast with a higher proportion occurring during winter at Pelican Point (Walvis Bay) and during summer at Diaz Point (Lüderitz). At Gobabeb, however, light fogs are more common during summer.

Explanations for the above are largely speculative. Nevertheless, it is certain that most fog occurrence characteristics 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. The presence of coastal fogs are governed by, *inter alia*, the speed of onshore breezes, the stability characteristics of the atmosphere and the position and size of the upwelling cells.

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 versus 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. 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 southward migration in summer and the seasonal variations in their spatial extent probably account for the differences in fog characteristics at Pelican Point and Diaz Point, including the annual and monthly fog occurrence frequency and variations in their precipitable water content and density. Upwelling also modifies the local climate, thereby influencing the duration of fog episodes.

The synoptic requirements for coastal fog formation are clearly satisfied in the form of coastal lows and a ridging South Atlantic Anticyclone (Brundrit *et al.* 1984; Estie 1984, 1986; Lancaster *et al.* 1984; Jury *et al.* 1986). Coastal lows are of major importance for the formation of advection sea fog since they 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.

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.

It is also possible that the latitudinal migration of the South Atlantic Anticyclone controls 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 1984). 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 Diaz Point 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

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fog in the Namib littoral are complex and an understanding of their interplay is important. In view of its potential as a water resource and its impact on aviation and shipping, the prediction of fog occurrence (including long-term trends) 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 vital that more weather stations be opened in especially the far northern and southern parts of the desert - at the coast as well as further inland. Until this has been implemented and more surface and upper air data from existing weather stations 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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THE COAST

ABSTRACT: The coastal Nam
low habitat diversity, low prima
consumers (Herbivores). These
array of carnivores subsist to a v

Key words: Namib Desert coast

1. INTRODUCTION

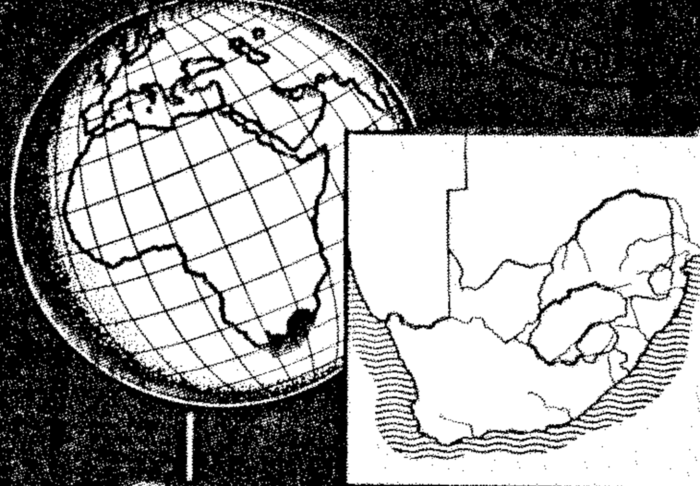
The Namib Desert e
Southern Africa from th
to the Olifants River in
Lancaster 1983). We
Escarpment, the narro
a climate moderated
north-flowing Benguel
part of the year, and a
climatic gradient preva
interior (Lancaster, Lar
in altitude (ca 1000 m
diversity. The Namib is
and in its mosaic of h
evolved (Seely & Griffi

The coastal strip - san
bleak, often windswe
action and resultant sa
precipitation (<20 mm
against dense, high pe
river mouths; permane
the vegetation on the
probably extremely low
1976) and lack of orga
primary production and
the greater part of the
should be expected. Th
along most of the Na
occurrence of kelp bec
produces an energy i
along the drift line. A
provide a food base
offshore marine life; th
carnivores.

In addition, in places
rivers. Some, e.g. the
every year; others are
mouths ephemeral we

* Professor of Zoology, Univers

Die Suid-Afrikaanse Geograaf



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