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Spatial distribution of fog in the Namib

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Fog is considered to be one of the most characteristic climatic features of the Namib desert. Despite its importance to desert flora and fauna, relatively little is known about its distribution, especially in the more remote parts of the region. This research note describes the use of Meteosat images for the compilation of annual and seasonal fog distribution maps of the entire Namib. The technique used, as well as the general spatial characteristics of fog as inferred from the maps, are discussed. Comparison between the Meteosat derived annual fog day frequency (FDF) patterns and ground measurements reveals a high level of correspondence.

Keywords: Namib; Meteosat; fog distribution; fog day frequency patterns

Introduction

Two features epitomize the climate of the Namib, namely, extreme aridity on the one hand and an abundance of fog on the other. While the causes of both phenomena are reasonably well understood and atlas maps give some indication of rainfall patterns in the area, relatively little is known regarding the spatial distribution of fog. This is surprising in view of its importance in the desert ecosystem. Fog not only moderates the temperature in the coastal regions, but it also provides a significant and reliable source of moisture to the desert fauna and flora (Goudie, 1972; Seely, 1987). Furthermore, in view of the rapid depletion of underground water reserves in the vicinity of Walvis Bay, it seems likely that fog precipitation could, in the near future, also serve as a supplementary water source for the human population in the area (Nagel, 1959; Nieman *et al.*, 1978). Recent events regarding the granting of concessions for the exploration of oil off the northern Namibian coast further underscores the growing importance of reliable information on fog distribution in the area. The exploration process will necessarily also entail the transport of people, provisions and equipment to and fro between the land and the oil rig. Since fog impairs visibility, it could constitute a major hazard to the associated shipping and aviation. It seems evident, therefore, that reliable information on fog distribution patterns could contribute substantially towards minimizing the resultant risk.

The present paucity of detailed information regarding fog occurrence can probably be ascribed to a lack of adequate data sets. Records of acceptable length and quality are only available for a limited number of coastal locations such as Swakopmund, Pelican Point, Diaz Point and Möwe Bay, where first and second order weather stations are maintained. Hence the greater part of the region is virtually *terra incognita* as regards reliable information on fog distribution at ground level.

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The use of satellite imagery appears to offer an obvious solution to the above problem. However, the cost of obtaining digital images on a daily basis for a lengthly period of time is prohibitive. There is also the problem of distinguishing between cloud cover and fog on such images. Nevertheless, in the belief that neither of these problems are insoluble, an exploratory study using a restricted range of images and aimed at establishing a reliable fog distribution map of the Namib, was recently undertaken. The images used were a suite of daily Meteosat photos for one full calendar year (1984) and covering the entire Namib, i.e. the area extending from the Orange River in the south to the Cunene in the north, and ranging longitudinally from the Atlantic coast in the east to the Great Escarpment in the west.

This paper describes the method used and the resulting annual and seasonal spatial fog patterns which emerged. These patterns were compared with available ground observations in order to obtain at least some check on the accuracy of the maps.

Data and method

The Meteosat images used in the study were kindly supplied by I. Hunter of the South African Weather Bureau weather office at DF Malan airport. They 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 0500 h, 0600 h and 0830 h ones, since fog is known to occur most often during the cooler parts of the day. Figures 1 and 3 show the resultant annual and seasonal fog distribution maps for the study area in 1984. The annual fog occurrence map (Fig. 1) was compiled using the following procedure: a finely gridded (approximately 35 km × 35 km) overlay of the Namib (with the outline of southern Africa drawn in) was superimposed onto each image and each spatial unit visually 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 Fig. 1. In addition, successive months with similar spatial fog patterns were combined to give the seasonal FDF maps (Figs 3(a–d)). All values shown on these figures were adjusted to give fog frequencies for a 31-day month.

Extraction of data from satellite photos is not a simple or straightforward operation and a number of problems were encountered in compiling the maps. The most serious problem concerned the difficulty in differentiating between low stratus cloud and fog on the 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, the dates on which fog occurred at Pelican Point were used as a guide to distinguish between fog and cloud at this site. These dates were obtained from South African Weather Bureau (SAWB) records and printouts.

The second source of difficulty concerned the quality of the data set. The fact that the set was not quite complete did not pose a particularly serious problem since one or more satellite photos were available for 90% of the days. (Only January and February had significant gaps in the data set). However, some of the images were over- or underexposed, blurred or blotched and could therefore 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 Namib to the north of Möwe Bay was often absent from the image) 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.

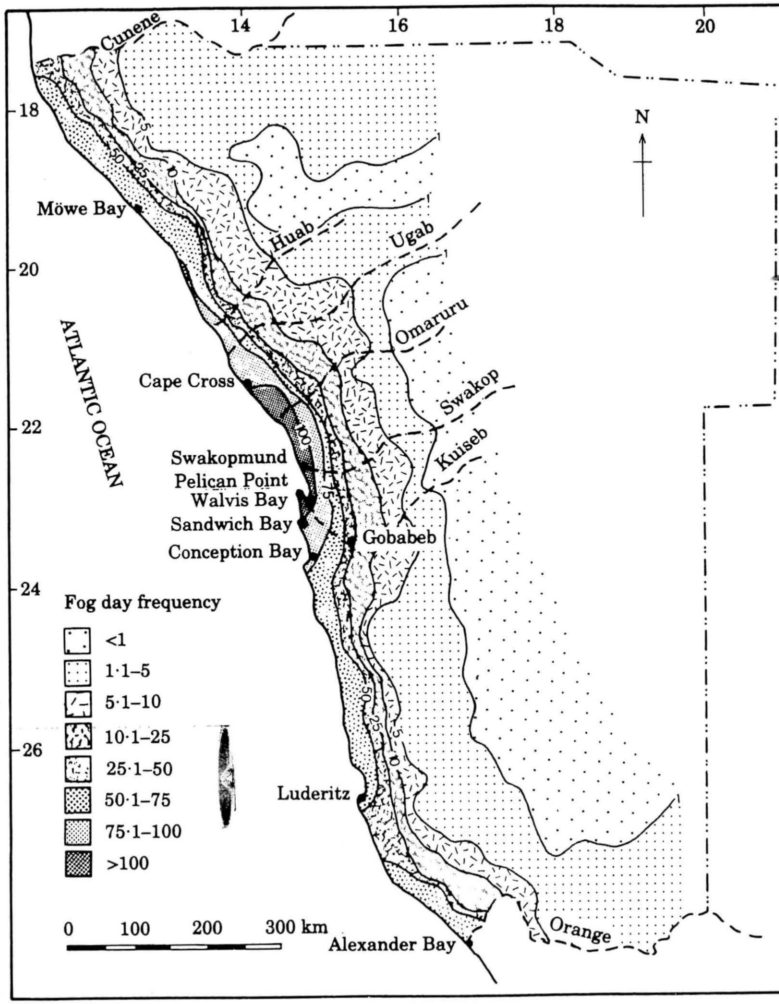

Figure 1. Fog/low cloud distribution in the Namib during 1984.

Unfortunately, the absence of meteorological recording stations in these areas 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 zones and the spatial occurrence of fog.

Results and discussion

Annual (1984) FDF patterns

Figure 1 reveals a number of notable features concerning the general distribution pattern of fog in the Namib. Firstly, the well-known trend of decreasing fog occurrence with distance from the sea (Lydolph, 1957; Logan, 1960; Meigs, 1966; Besler, 1972; Seely, 1972, 1987; Lancaster *et al.*, 1984) is clearly illustrated by the parallel north–south isolines on the map. A zone of high fog frequency (>50 fog days $annum^{-1}$) hugs the coast over almost the entire length of the Namib. The zone with highest FDF (>100 FD $year^{-1}$) is confined to a narrow coastal strip stretching from about 21·5°S to 23·5°S. North and south of this core area, the annual FDF at the coast drops slightly but still exceeds 50 days. The general southward decrease in FDF is terminated by a resurgence of higher fog incidence in the vicinity of the Orange River mouth.

Closer inspection of the fog map indicates that between Lüderitz and Conception Bay—and, to a lesser extent, northwards from Möwe Bay (+18·5°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 (Fig. 2) seems to suggest that there is a link between topography and fog incidence. This appears to be confirmed by the fact that there is some degree of spatial correspondence between the seaward edge of the Escarpment (Fig. 2) and the 5 FD isoline (Fig. 1) over large parts of the study area, especially in 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 $annum^{-1}$. It is also apparent that the high fog zone (>100 FD $annum^{-1}$) 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 Huab river. According to Fig. 1, 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 feature which is evident from the map is that fog penetrates further inland along the valleys and canyons of the larger rivers. This is illustrated by the eastward bulging of some of the isolines in that region where a distinct Escarpment is absent as well as along the courses of 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 into river valleys where the air is likely to have a higher moisture content.

Records of actual fog occurrence at weather stations together with general information concerning fog distribution patterns in certain areas may (to some degree) be used as a check on the fog distribution pattern depicted in Fig. 1. Thus the high fog zone (>100 FD $annum^{-1}$) in the central coastal region includes both Swakopmund and Pelican Point with mean recorded annual fog day frequencies of 113 and 139, respectively (South African Weather Bureau, 1986). Examination of the 1984 weather records reveals that the latter station recorded only 110 fog days in that year. Furthermore, according to Fig. 1,

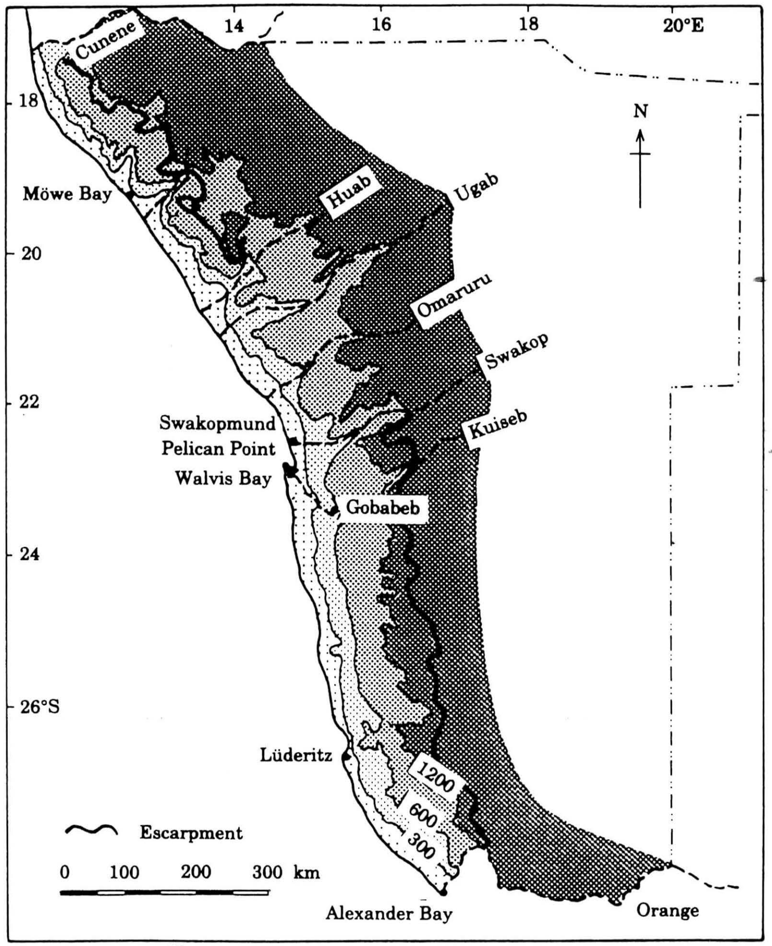

Figure 2. General topography of the Namib.

Alexander Bay fell within the 50 to 75 fog days zone in 1984. The recorded value was, in fact, 59. Diaz Point, which falls within the 50 to 75 fog day zone, reported 98 fog days in 1984. The undercount of fog days here may be due to either the intermittent nature of fog occurrence or to high clouds obscuring the earth's surface or to the incompleteness of the data set. Despite the anomalies, however, there would appear to be broad agreement between weather station data for the coastal stations in 1984 and the fog occurrence patterns derived from the Meteosat images.

Information regarding inland fog patterns is even less abundant than for the coastal zone and, where available, usually pertains to the Central Namib. An example of this is Besler's (1972) comprehensive study of the Namib, in which she found that 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 in Fig. 1 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 10 fog days were recorded at a distance of 100 km inland. Notwithstanding these discrepancies, it is again clear that there is also some degree of similarity between measurements on the ground and the inland fog distribution patterns shown on the map. This is most gratifying, considering the limitations of the technique employed and the degree of generalization which was applied in the compilation of the map.

Seasonal patterns

It is generally accepted that all inferences drawn from statistical analyses are contingent upon the size and the representativeness of the sample used. Since Fig. 3(a–d) were compiled from relatively small sets of Meteosat photos, they should not be regarded as giving an accurate indication of the frequency of fog occurrence during the relevant periods. The isolines should rather be considered as demarcating zones with relatively higher and lower fog incidence. As such they may be expected to give some indication of intra-annual changes in fog occurrence in the Namib.

Comparison of the four maps (Fig. 3(a–d)) reveals seasonal variations in the frequency of fog occurrence as well as its longitudinal and latitudinal extent. An unexpected feature shown on Fig. 3 is the presence of two centres or 'cores' with very high fog incidence throughout the study period. The more southerly of the two was semi-stationary, being located in the area between Cape Cross and Sandwich Bay. By contrast, the position of the northern core fluctuated considerably from one season to the next between the Ugab mouth and north of Möwe Bay. This probably explains why it could not be discerned on the annual fog map (Fig. 1).

The FDF also exhibited considerable seasonal variation. Figure 3(d), depicting the 1984 summer situation exhibited the highest monthly values (>15 days month^{-1}) in the southern core area. The next highest monthly fog incidence (10–15 FDs) occurred during winter (Fig. 3(b)), followed by the autumn and spring months.

Figures 3(a, b and c) show remarkably similar patterns regarding the longitudinal extent of fog occurrence in the Namib. During the entire period March to October 1984, fog was confined to a relatively narrow belt within the coastal zone. In the southern half of the Namib it was restricted to the region lying below 600 m, whereas it extended somewhat further into the interior north of the Kuiseb river. In contrast to the above, the width of the entire fog zone underwent a marked eastward expansion during November and December 1984 (Fig. 3(d)), with fog occasionally extending up to and even beyond the Escarpment in the southern and central regions. There is some uncertainty regarding the inland boundary of the fog zone in the far northern part of the Namib, however, since it is possible that some warm clouds associated with the Inter-Tropical Convergence Zone may have been misclassified as fog.

The expansion of the fog zone during summer signifies a more frequent incursion of the phenomenon into the interior of the desert and explains the summer maximum which is recorded at the majority of inland weather stations. This is clearly illustrated by the situation at Gobabeb, where the progressive eastward migration of the 2·5, 5 and 10 FD isolines on Fig. 3 coincides with the March–December increase in actual FDF recorded there during 1984.

In contrast to the longitudinal extent of fog occurrence in 1984, seasonal variations in its latitudinal pattern were less well defined. Nevertheless, two trends could be discerned. Firstly, there was a distinct north–south migration of the northern fog core from winter to summer. During autumn it was located between the Huab and Ugab rivers, in winter and spring it shifted northwards to the vicinity of Möwe Bay, while in summer it again retreated southwards towards the Huab River. The 'bulge' in the 0·5 FD isoline (indicating the widest part of the fog zone) displayed a similar N–S migration. Comparison

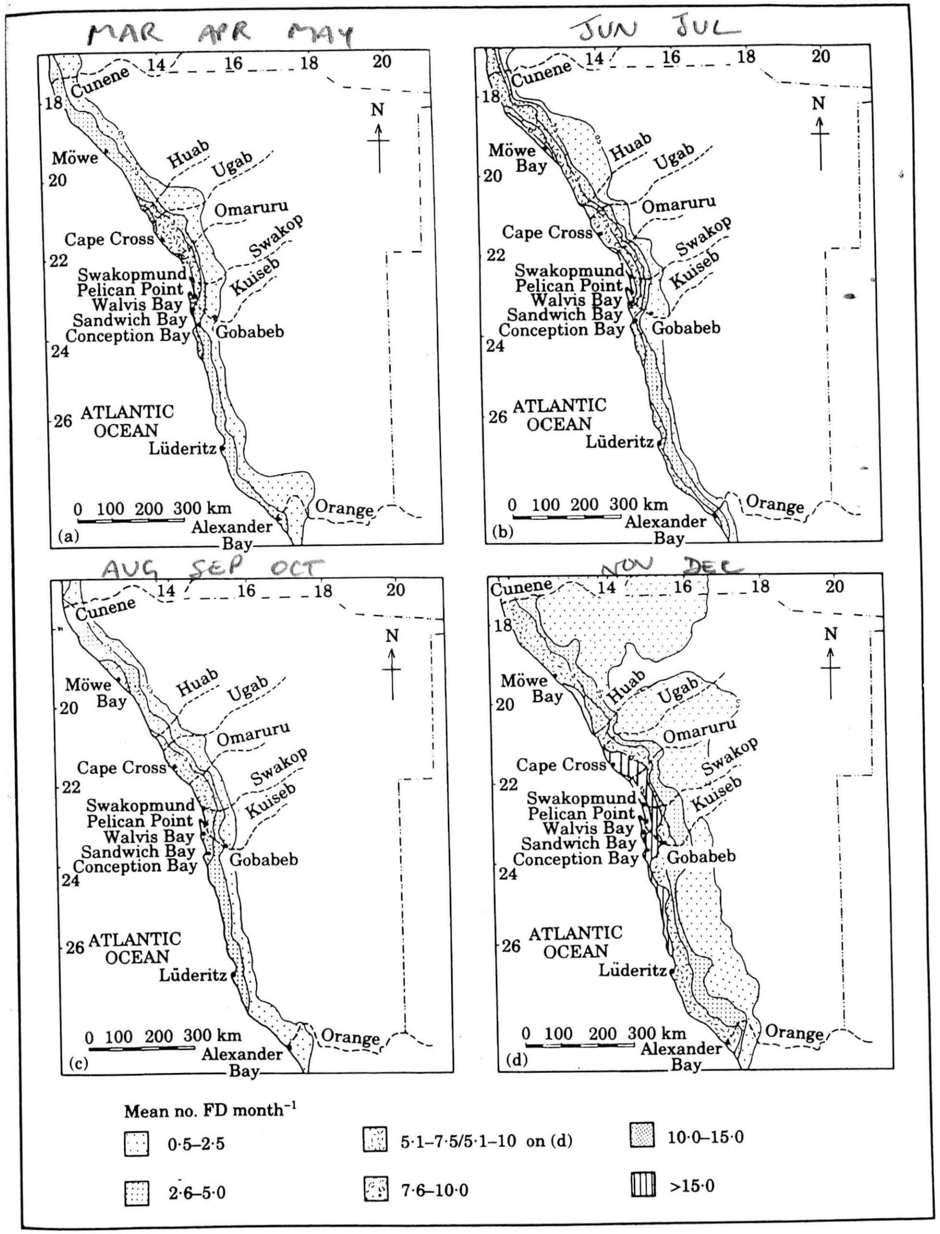

Figure 3. Fog/low cloud patterns during (a) autumn (March–May), (b) winter (June, July), (c) spring (August–October), (d) summer (November, December).

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of Fig. 3(a–d) shows that it shifted from the vicinity of the Ugab River during autumn to about 19·5°S in winter, and back to the Ugab in spring and summer. These N–S movements coincide with the seasonal migration of global pressure systems, thereby emphasizing the importance of the South Atlantic Anticyclone in the formation of West Coast fog (Olivier, 1991/92).

A second feature was that the fog zone (as defined by the 5 FD isoline) appeared to undergo a semi-annual 'cycle' of latitudinal expansion and contraction. The autumn and spring maps (Fig. 3(a and c)) both show the fog belt as stretching from the vicinity of Conception Bay in the south to (approximately) the Huab River in the north; in spring an isolated pocket also appeared at Möwe Bay to the north. During winter and summer, by contrast, the northern boundary of the fog zone was displaced northwards into Angola (Fig. 3(b and d)). Its southern extremity (apart from an interruption in the area between 25°S and 26°S during winter) was located just south of the Orange River. Overall, summer is clearly the season of highest fog prevalence, with the fog belt extending along the entire length of the desert coast to well beyond the Orange and Cunene rivers and further inland than during the other seasons.

The patterns described above, i.e. the spatial and temporal fluctuations in FDF, the distance of inland fog penetration, the position of the fog cores and the latitudinal extent of the fog zone, are in line with the seasonal differences in fog maxima as recorded for various weather stations in the Namib. During 1984, Möwe Bay and Alexander Bay experienced peak FDFs during winter, Gobabeb and Diaz Point recorded summer maxima and Pelican Point had above average fog incidence during both winter and summer. The fog incidence patterns shown on Fig. 3 are consistent with these, except in the case of Alexander Bay, where the anomalously high summer FDF value (Fig. 3(d)) probably reflects some misclassification of clouds as fog.

While there appears to be some degree of similarity between the seasonal patterns observed on the maps and those measured on the ground, it should be kept in mind that the monthly FDFs recorded at weather stations during 1984 differed significantly from the long-term means. It seems unlikely, therefore, that the patterns depicted on Fig. 3(a–d) are representative of the situation which would normally be expected to occur in the Namib.

Other fog features

There are a number of important fog characteristics in the Namib which cannot be gleaned from the fog maps but which were observed during analysis. For instance, fog usually occurred as either a dense bank confined to the immediate vicinity of the coastline, as thinner patches covering parts of the interior, or as a relatively dense plume protruding inland. On a few occasions, however, it was observed as a relatively dense layer enveloping part of the desert from the coast up to the Escarpment. This appears to corroborate claims of fog effects being noticed up to distances exceeding 100 km from the sea (Goudie, 1972; Lancaster *et al.*, 1984).

The high incidence of thick fog banks lying just offshore is also not indicated on the maps. 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 one to 1·5 h.) However, the fact that Pelican Point has a higher annual FDF than Walvis Bay (151 days as opposed to 83 in 1976 (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.

Synthesis

This paper describes the annual and seasonal distribution of Namib fog as mapped with the aid of Meteosat images for 1984. The main problem encountered using this compilation technique was the difficulty in differentiating between fog and low cloud.

Nevertheless, it was found that there was considerable correspondence between the annual fog pattern depicted on Fig. 1 and recorded ground observations for the same period. This implies that the method used was reasonably successful in identifying fog on the satellite images. It is therefore assumed that the maps do, in fact, reflect the spatial distribution of fog in the Namib during 1984.

Figure 1 reveals a number of features with regard to the annual spatial distribution of fog. First, fog day frequency decreases from the coast towards the interior. The highest frequency occurs on the coastal plain where it usually exceeds 50 days annum^{-1}. The decrease in FDF towards the interior shows a marked degree of spatial coincidence with rising topography.

Secondly, the frequency of fog occurrence varies latitudinally within the coastal zone. The highest FDF occurs in the vicinity of Pelican Point (with a recorded long-term mean of 139·3 fog days year^{-1} (SAWB, 1986)). From this area, FDF decreases both to the north (Möwe Bay = 79 FD year^{-1}) and to the south (Alexander Bay = 67·1 FD year^{-1} (SAWB, 1986)). It seems likely that this pattern may be associated with inter- and intra-annual spatial variations in the occurrence of optimal fog forming conditions (e.g. light onshore breezes, sea surface temperatures which approximate the dew point and stable atmospheric conditions (Tremant, 1989)).

With regard to intra-annual (seasonal) fog patterns, the following came to light: (1) Fog day frequency within the coastal zone is higher during winter and summer than during autumn and spring.

(2) Two zones with high fog frequency were distinguished. The more southerly core is a stationary phenomenon located between Cape Cross and Sandwich Bay, whereas the northern core migrates southwards during summer and northwards during winter.

(3) The fog zone (as defined by the 5 FD month^{-1} isoline) expands latitudinally during winter and summer and contracts during the equinoxial seasons.

(4) The width of the fog zone increases in summer, thereby signifying higher fog incidence at inland stations during the warmer months.

In conclusion a word of caution is called for. Although the maps shown give some indication of the spatial incidence of fog in the Namib, a number of constraints cast some doubt on their accuracy and hence their usefulness. These include the fact that the maps are based on the analysis of only 1 year's satellite photos; that it is difficult to differentiate between fog and low cloud on these images; that the quality of the images used was particularly poor in the northern parts of the area; that light fogs such as radiation fog could not be identified on the images; and that the method used was rudimentary and relied heavily on subjective decisions. Nevertheless, it does represent a first attempt at constructing a fog map for the entire Namib.

Additional analyses (and hence more data) are now needed to verify these findings and to determine how fog patterns differ from one year to the next. This would require the establishment of more weather stations with fog recording equipment in various parts of the desert. Furthermore, since the technique used in this study is extremely time consuming, some other method — preferably using a GIS — will have to be devised if this line of research is to be continued. It is hoped that this will indeed be the case since the socio-economic, ecological and other scientific benefits which may be derived from an understanding of fog incidence in the region cannot be ignored.

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Stomatal responsiveness to changing light intensity increases rain-use efficiency of below-crown vegetation in tropical savannas

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To test the effects of shade on understorey herbaceous productivity in tropical savannas, water relations of important grass species that either grow primarily under tree crowns or in open grasslands were studied in Tsavo National Park, Kenya. The relationship of stomatal conductance to light intensity was investigated under well-watered conditions; and the relationship of stomatal conductance to light intensity, vapor pressure deficit, and leaf water potential was studied during a period of decreasing soil moisture. Below-crown species were more responsive to reductions in light intensity than open-grassland species, with stomatal conductance of below-crown species declining linearly with reductions in light intensity. Conductance of open-grassland species was relatively unchanged at all except the lowest light levels. Below-crown species therefore reduced their water loss when shaded, conserving soil water for later growth. Open-grassland species appeared to be more efficient than below-crown species at extracting water from dry soils under full-sun conditions.

Keywords: *Cynodon nlemfuensis*; *Digitaria macroblephara*; *Eustachys paspaloides*; irradiance; *Panicum maximum*; rainfall-use efficiency; stomatal conductance; tropical grasses; water potential

Introduction

Annual herbaceous productivity in arid and semi-arid grasslands and savannas is directly related to annual rainfall (Laurenroth, 1979; Van Wijngaarden, 1985; Robertson, 1988; Scholes, 1990), with productivity increasing both along geographic gradients of increasing rainfall, and also in years of higher rainfall. Herbaceous productivity in one important savanna microhabitat, however, is often higher in areas of lower, rather than higher, rainfall. This habitat is the area directly below the crowns (canopies) of widely distributed trees. In spite of overhead tree crowns that intercept and reduce the amount of rain reaching the ground, and in spite of possible competition for this water by the tree, herbaceous productivity is often higher under tree crowns than in surrounding grasslands. This higher productivity has been documented in tropical and subtropical grasslands and savannas in Africa (Charreau & Vidal, 1966; Radwanski & Wickens, 1967; Sandford *et al.*, 1982; Stuart-Hill *et al.*, 1987; Belsky *et al.*, 1989, 1993*a*, *b*), Asia (Singh & Lal, 1969),

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