# Namib Desert fog: can satellite imagery be used to monitor its distribution?

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## Introduction

Fog has long been recognised as an important aspect of the climate of the cool coastal deserts of the world (Meigs 1966). In the Namib Desert, fog has been studied as an important climatic factor particularly because of its effect on human activities (Met. Serv. 1944). In some deserts, fog has been proposed as a potential source of water (Gischler 1981) and Boss (1941, in Walter 1976) has collected amounts which indicate that it could be an effective water source in the Namib.

Early work on the climatic aspects of fog in the Namib Desert was carried out by Gulland (1907) who made a number of measurements in Swakopmund and the vicinity. Besler (1972), Logan (1960), Nagel (1962) and Niemann et al. (1978) have made further studies of fog from a climatological point of view. More recently, Lancaster et al. (1984) have published extensive data concerning fog-water precipitation and occurrence in the central Namib Desert. Estie (unpubl) studied the origins and climatic characteristics of advective and convective fog in the central Namib during one September.

Fog is extremely important as an ecological factor in the Namib. Direct uptake of fog-water has been demonstrated for several plants (Bornmann 1973, Louw and Seely 1980, Nott and Savage 1985, Seely et al. 1977). Precipitated fog-water, which collects on rock faces and is chanelled into the soil, contributes to the growth and germination of plants living in suitable localities (e.g. Giess 1962). The high humidity which accompanies fog reduces evaporative water loss in many higher plants (Walter 1976). In addition, the very rich lichen fields of the Namib coastal zone (Wessels and van Vuuren 1986) and the window algae (Vogel 1955) obtain their moisture requirements from the fog. A number of animals, invertebrates and vertebrates, also take up fog-water in a variety of ways (Hamilton and Seely 1976, Louw 1972, Robinson and Hughes 1978, Seely 1979, Seely and Hamilton 1976). As a geomorphological factor, fog influences weathering of rocks (Selby 1977) and affects soil composition (Martin 1950).

Despite the importance of fog in the Namib, most of the desert is not easily accessible by land transport and hence to direct measurement of fog. Previously most observations were made either on the coast or in the central Namib Desert, the two areas where land travel is feasible and there are population centres. For this reason, we sought alternate methods, of measuring the occurrence of fog, which would be applicable in remote areas. Remote sensing techniques provide one promising solution.

The purpose of this paper is to assess the feasibility of using satellite imagery to determine the occurrence of fog in remote areas of the Namib Desert. Our primary question was: could satellite imagery be used to monitor fog distribution on a routine basis using simple methodology? More specific questions with respect to the imagery available were: a) can fog be differentiated from other cloud types on visible and infrared photographic images? b) are there characteristic temperatures within a fog bank as measured on the ground? c) do these correspond to characteristic temperatures associated with the upper surface of a fog bank measurable by satellite? d) are temperatures of fog spatially uniform at ground level? e) are upper surface temperatures of fog spatially uniform?

## MATERIALS AND METHODS

Surface data for this analysis were obtained from autographic climatological stations located in the central Namib Desert. Five long term stations, and a sixth erected for this study, are situated on an east-west transect, at approximately 23°S, extending from 19 km to 117 km inland from the coast (Fig. 1). Data from a Weather Bureau First Order Weather Station located at Gobabeb, south of the main transect, were also considered.

At each of the six autographic stations fog-water precipitation data were collected by placing a cylindrical wire mesh screen (220 mm high by 100 mm diameter, mesh size 1.6 x 1.6 mm) (Fig. 2) over the funnel of an autographic Hellman-type rain gauge. Temperatures and humidities were recorded on a Lambrecht thermohygrograph and calibrated with maximum, minimum, wet bulb and dry bulb thermometers, all maintained in a standard Stevenson Screen. Corrected maximum and minimum humidity and temperature values were calculated for each day from the autographic charts. Autographic instrumentation is not completely reliable in harsh desert conditions (Lancaster et al. 1984). Therefore, we visited each of the climatological stations two to four times per month throughout our study period which extended from November 1985 until May 1986. Using this schedule, fog-water precipitation data was lost on only 3.6 % and humidity data on only 1.2 % of the 1731 instrument days of this study.

Relevant data recorded at the First Order Weather Station at Gobabeb included: air temperature and humidity from wet and dry bulb thermometers, minimum and maximum temperatures, fog as assessed by horizontal visibility, and cloud type and per cent cover.

Previous observations had indicated that fog, as determined visually according to Weather Bureau Manual (1982), may not produce fog-water precipitation (Seely et al. 1983). To use the autographic data, we needed to ascertain the presence of fog at the autographic stations when no fog-water precipitation was recorded. From the daily synoptic observations at Gobabeb, it had been noted that 'high fog' occurred at relative humidities of 80% - 95%. Fog determined visually was usually associated with relative humidities of > 95%. We therefore used three categories of relative humidity, < 80%, 80% - 95%, >95%, to determine conditions of no fog, high fog or ground fog, in conjunction with the record of fog-water precipitation.

We used imagery from the Meteosat weather satellite. Meteosat is part of an international system of five geostationary meteorological satellites positioned 35 800 km above the equator (ESA 1981). The area for qualitative use of its images extends from 60° S to 60° N (Fig. 3). Meteosat measures electromagnetic radiation in three spectral bands: visible (0.4 - 1.1 um), water vapour (5.7 - 7.1 um) and thermal infrared (10.5 - 12.5 um).1

The Meteosat imagery readily available to us came from two sources. The Satellite Remote Sensing Center, Hartbeeshoek, provided enlarged black and white imagery from the visible and the infrared spectral bands on which the coastline had been superimposed (Fig. 4). The Climatology Section of the Weather Bureau, Pretoria, provided a matrix of temperature values from the thermal infrared channel of Meteosat (Fig. 5). We converted Greenwich Mean Time to South African Standard Time in all instances (SAST = GMT + 2 hours).

On visible images, the grey shades depend on the reflectivity of the radiating surface which, in turn, depend on many factors such as electrical properties, surface properties, vegetation, etc. In general, clouds appear white and space is seen as black; the thicker the cloud, the whiter it appears. Although the thermal infrared images are superficially similar to those from the visible channel, in the thermal infrared, grey shades represent varying temperatures; pure black, at one extreme, indicates very high temperatures and white, at the other extreme, very low temperatures. Ground resolution of the visible imagery was 5 by 2.5 km. Images covered the entire Namib. We attempted to interprete this imagery by eye.

Thermal infrared data for one date and time consisted of temperatures (°C) of the first encountered surface. Ground resolution of these data was 5 by 5 km. The area covered was 480 km wide and 600 km; it extended from the Huab River in the north, Ichaboe Island in the south, the Atlantic Ocean in the west to approximately 30 km east of Windhoek. We analyzed this imagery manually.

The orientation of a geostationary satellite such as Meteosat is not constant, thus the location of the data points on an image is not fixed with respect to earth coordinates. To locate our climate stations on the thermal infrared data matrix, we used the coastline which showed up as a distinct thermal discontinuity, on some images, as the land warmed up during the day. On one set of values (identified as R 104090) the coastline showed up clearly and features from the 1:1 000 000 map (1979) of SWA/Namibia could be superimposed. Using this source we created an overlay sheet in the scale of the computer data set. Further calculations to locate our control climatological stations were extrapolated from a point at Walvis Bay which could be identified on the map (22° 57′ S, 24° 24′ E).

To establish the repeatability of locating ground stations with thermal infrared values, we used data from 11h00 for 12 different days. For each day, we located the coastline and then superimposed the overlay sheet. At each climatological station we marked the relevant pixel and then used a pixel coordinate system (the top left-hand corner of the print-out was designated 0/0) to determine the pixel coordinates of each station. From these data, we then calculated for each station the mean pixel coordinates and their standard deviations (Table 1).

To examine the problem further, we used data from the three days on which we were able to locate the coastline at two different times. We determined the pixel coordinates for each data set separately and then calculated the standard deviation for each climatological station per day. The smaller standard deviations (Table 2), particularly in an east - west direction, meant that we could individually locate all but the two western-most climatological stations. The procedure we thus adapted was to first locate the coastline on the 11h00 output, fit the overlay onto it, determine the pixel coordinates, and then transfer these coordinates to print-outs from earlier in the day at which time fog occurred and therefore no indication of the coastline was apparent.

The procedure applied assumed no major distortion inland from the coast. To check this assumption, we attempted to locate the Great Western Escarpment and the expected heat-island of Windhoek (Oke 1978, p 254 - 260). However, neither feature produced a marked effect on the isotherms, thus neither the existence nor magnitude of possible distortion could be assessed.

Computer print-outs of thermal infrared data were available for 113 of our 181 day study period (Table 3 and 4); we were able to locate our ground stations on 54 of these days by the above techniques. Satellite data were available for 35 days of our study period which experienced no fog or cloud at Gobabeb. At Gobabeb fog occurred on

18 days at 08h00; of these days, satellite data was available for 15 days of which data from 7 days could be used.

## Results

Fog data from our ground stations (Figs 6,7 and Tables 5) agreed with previous measurements of number of fog days and amount of fog-water precipitation in the central Namib (Lancaster et al. 1984). These values vary across the desert, with maxima occurring at elevations between about 300 and 600 m. Precipitating fog occurred on 82 days during our study period providing adequate control for evaluation of the satellite data.

After evaluating the visible and thermal infrared enlargements we found that the resolution was not sufficient for us to locate our ground control climatological stations. The line superimposed to indicate the coast was itself seven kilometers wide. A second problem was that of distinguishing the various types of cloud from the single type, stratocumulus, which produces fog. We could not distinguish the grey shades, by eye, in a reproducable manner.

Analysis of the thermal infrared temperature values indicated the impossibility of attributing a fixed location (with reference to the top left-hand corner of the print-out) to the climatological stations (Table 3). Considering the distances between our climatological stations, standard deviations of three pixels (15km) in either direction would preclude locating the individual stations. We were thus unable to use our overlay sheet in a general fashion. When orientation of the data matrix was dependent on two data sets from the same day, however, the ground stations could be more precisely located (Table 4).

Our preliminary results indicated that the satellite temperatures were usually somewhat higher (3.12 $\pm$ 3.83 °C) than those recorded in the Stevenson Screen at Gobabeb at 08h00 (Fig. 8). When all the data were compared, the differences were found to be significantly different (two-sample t-test, Sokal and Rohlf 1981, $t = 3.51$, $P<0.05$). Closer inspection of the data from November, the month with the greatest recorded deviations, indicated that the differences were not only noticeable at 08h00 but also later in the day. At 11h00 the radiometer recorded temperatures for four days which were a mean of 10°C higher than the maximum ground temperature for that day (which occured between 14h00 and 15h00). We therefore disregarded the data for November and assume that variations in data are a regular feature of the satellite data set.

After discarding the November data sets, we re-analysed the differences between ground and satellite-derived temperatures at 08h00 and found that they did not differ significantly (two sample t-test, $t = 1.74$, $P>0.05$). We have thus concluded that on many, but not all, clear days atmospheric interactions are too small to cause significant differences between temperatures measured by satellite radiometer and dry bulb thermometers in a Stevenson Screen (Fig. 8).

Temperatures measured on foggy days by thermohygrograph at Gobabeb and by Meteosat (Fig. 9) were not found to be significantly different (two sample t-test, $t = 0.184$, $P>0.05$). The standard deviation for the satellite temperatures was, however, far greater than that for the thermohygrograph values.

To determine if there is a specific temperature for fog, we used three relative humidity categories and examined the relationship between relative humidity and temperature. We used relative humidity data from our ground stations and temperature data from the ground stations and from Meteosat (Fig. 10). In neither case was there a temperature range which was specific to the relative humidity ranges associated with fog. We then examined the temperatures associated with single precipitating fogs at the six autographic stations. The results from both ground and satellite derived temperatures (Fig. 11) indicated that for a single fog, temperatures were not uniform but varied spatially, usually increasing with distance inland from the coast.

## Discussion

The occurrence and distribution of fog varies throughout the Namib Desert. On the coast, the duration of fog appears to be greatest at Port Nolloth, decreasing northward and southward toward the extremities of the desert (Met. Serv. 1944). In the central Namib Desert, the number of fog days decreases from the coast inland. This contrasts with the pattern of fog-water precipitation which reaches a maximum, not on the coast, but approximately 30 - 60 kms from the coast at an elevation of between 300 and 600 metres above sea level (Lancaster et al. 1984). These observations of the pattern of fog-water precipitation correspond with the frequent occurrence of a stratus cloud layer at about the same elevation during the morning hours (Taljaard and Schumann 1940). The seasonal pattern of the fog occurrence also varies from north to south and from the coast inland (Met. Serv. 1944, Lancaster et al. 1984). The time at which fog occurs also varies; fog may occur from early evening to late morning on the coast. Further inland the duration of the fog is shorter, and centered around the early morning hours near sunrise (Seely et al. 1983). Perusal of a few odd examples of satellite imagery also indicated variable occurrence of fog at different positions along the coast. Thus, all of the sources of which we are aware indicate great temporal and spatial variability of fog in the Namib Desert.

Using enlarged black and white imagery and thermal infrared values from Meteosat and the methods available to us, we were unable to conclusively ascertain the presence and distribution of fog in the Namib Desert or to characterise fog as it appears in the satellite imagery. Because of the importance of fog to the Namib Desert environment, however, further pursuit of this question is considered worthwhile and some alternative approaches are suggested.

To analyse the black and white imagery more easily, enlargements of specific areas may prove useful. These would not allow for evaluation of the occurrence and distribution of fog in the Namib Desert, but may help to develop techniques which would allow fog to be satisfactorily distinguished on the imagery. Technically, the use of a densitometer to distinguish shades of grey may also improve detection of fog on the imagery (Gurka 1975).

Analysis of the thermal infrared values would be facilitated if the coast could be identified, perhaps using a computer programme which works with the temperature discontinuity characteristic for the coast line. The time of day that the fog occurs, and the presence of the fog itself, mitigates against this solution, however. More extensive comparison of data sets from two times of day, and comparison of these data sets by computer, may contribute to solving the problems of orientation. Data measured by other satellites, e.g. NOAA with its better resolution, may also prove to be more suitable with further analysis.

Earlier studies using thermal infrared have shown that it is not only temperatures which influence the infrared emissivity, but also relative humidity, barometric pressure, wind speed and wind direction, sun angle and radiation history (Itten 1973). In particular, water vapour absorption (Kern 1963) might influence the assessment of the surface temperature from the respective measured radiation temperature (Otterman and Tucker 1985). Factors such as these may be influencing some of the temperature values which we found to be so different from those measured on the ground.

Fog has previously been found to be accompanied by temperatures which may range from near 0 to above 20°C (Seely et al. 1983). Thus the finding that Meteosat temperatures of the upper surface of the fog bank were not uniform was not entirely surprising. We expected the temperatures of the fog surface to be above zero, values which we predicted would contrast with the expected below zero temperatures of the upper surfaces of higher cloud. The thermal infrared matrix indicated no temperatures below zero, however, further contributing to the difficulty of distinguishing fog from higher cloud.

Because the temperatures of fogs themselves were neither characteristic nor uniform, we have concluded that use of thermal infrared data obtained from Meteosat are by themselves not sufficient to determine the presence of fog in the Namib. A workable solution might be found, however, if photographic enlargements of visible and infrared images were used in conjunction with thermal infrared data from the same area. If a small enough area were used a technique could be derived from comparison of the two types of data, however, large scale imagery would again be required to examine fog conditions over the entire Namib at the one time.

Although the application of satellite imagery to the question of the occurrence and distribution of fog in the Namib is probably the best way to answer the questions posed, alternative data sources and/or more sophisticated analytical procedures may have to be applied. We must conclude that the use of Meteosat imagery to monitor fog in the Namib on a routine basis does not appear to be feasible at the present time.

## ACKNOWLEDGEMENTS

We thank the Foundation for Research Development and the National Programme for Weather, Climate and Atmosphere Research of the CSIR for financial support, and the Department of Agriculture and Nature Conservation for facilities and permission to work in the Namib-Naukluft Park. D C Boyer, J R Henschel, F S Malan and R D Pietruszka kindly commented on a draft of the manuscript.

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Table 1

Standard deviations (in pixels) of the pixel coordinates for the six autographic climatological stations in the central Namib. These values were obtained by applying a map overlay to the 11h00 SAST thermal infrared computer print-outs from twelve days.

| Distance (km) | North - South | East - West from coast |
|---|---|---|
| 19 | 3.2 | 3.2 |
| 31 | 3.3 | 3.1 |
| 46 | 3.3 | 3.3 |
| 61 | 3.3 | 3.2 |
| 87 | 3.3 | 3.3 |
| 117 | 3.2 | 3.3 |

Table 2

Standard deviations (in pixels) from two different scans on a single day for the six autographic climatological stations in the central Namib Desert. On those three days, the coastline could be clearly distinguished on the thermal infrared temperature print-outs.

| Distance (km) from coast | Day 338 08h00 & 12h00 | | Day 339 04h00 & 08h00 | | Day 341 08h00 & 12h00 | |
|---|---|---|---|---|---|---|
| | N-S | E-W | N-S | E-W | N-S | E-W |
| 19 | 1.4 | 0 | 0.7 | 2.8 | 2.1 | 2.1 |
| 31 | 2.1 | 0 | 0.7 | 3.5 | 2.1 | 0.7 |
| 46 | 2.1 | 0 | 0 | 2.8 | 2.8 | 1.4 |
| 61 | 2.1 | 0.7 | 0 | 2.1 | 2.8 | 1.4 |
| 87 | 2.8 | 0.7 | 0.7 | 0 | 2.8 | 0.7 |
| 117 | 2.8 | 0.7 | 0.7 | 3.5 | 2.8 | 1.4 |
| mean | 2.2 | 0.4 | 0.5 | 2.5 | 2.6 | 1.3 |

Table 3

Number of days when no fog was recorded at Gobabeb at 08h00 SAST for which adequate thermal infrared temperature values were also available.

| Month | Number of days with no fog | infrared data | high cloud | Number of images with recognizable coastline and no cloud |
|---|---|---|---|---|
| Nov 85 | 22 | 9 | 1 | 8 |
| Dec 85 | 21 | 7 | 0 | 7 |
| Jan 86 | 28 | 8 | 5 | 3 |
| Feb 86 | 21 | 3 | 0 | 3 |
| Mar 86 | 28 | 0 | - | - |
| Apr 86 | 29 | 14 | 0 | 14 |

Table 4

Number of days when fog was recorded at one or more of our ground stations in the central Namib Desert, and number of fog days for which thermal infrared data, with and without a recognizable coastline, were also available.

| Month | Number of days with precipitating fog | Number of days with infrared data | Number of images with recognizable coastline |
|---|---|---|---|
| Nov 85 | 18 | 11 | 6 |
| Dec 85 | 19 | 16 | 6 |
| Jan 86 | 10 | 7 | 1 |
| Feb 86 | 12 | 6 | 2 |
| Mar 86 | 13 | 0 | - |
| Apr 86 | 10 | 10 | 5 |

Table 5

Average number of days with precipitated fog-water recorded by a Hellman type rain-gauge fitted with a wire mesh screen at seven autographic climatological stations in the central Namib Desert.

| Station | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Double Three | | | | | | | | | | | | |
| Days:Mean | 2.0 | 1.0 | 4.0 | 5.0 | 4.5 | 2.0 | 8.0 | 5.5 | 8.0 | 1.0 | 2.0 | 3.5 |
| Range | | | | | | | | | | | | |
| Pptn:Mean | 1.8 | 0.4 | 2.5 | 4.9 | 8.0 | 6.0 | 11.9 | 6.8 | 8.2 | 0.6 | 1.3 | 1.7 |
| Range | | | | | | | | | | | | |
| Kleinberg | | | | | | | | | | | | |
| Days:Mean | 5.0 | 4.0 | 8.3 | 10.3 | 9.7 | 0.5 | 5.3 | 10.0 | 11.2 | 8.0 | 6.8 | 8.3 |
| Range | | | | | | | | | | | | |
| Pptn:Mean | 3.9 | 4.5 | 13.6 | 20.2 | 17.7 | 14.7 | 15.6 | 24.9 | 21.8 | 10.0 | 10.6 | 10.6 |
| Range | | | | | | | | | | | | |
| Hamiltonberg | | | | | | | | | | | | |
| Days:Mean | 5.8 | 3.3 | 6.8 | 7.7 | 5.8 | 5.8 | 4.0 | 10.8 | 13.7 | 8.7 | 9.8 | 9.5 |
| Range | | | | | | | | | | | | |
| Pptn:Mean | 11.4 | 5.1 | 13.8 | 16.3 | 12.6 | 10.3 | 9.3 | 2.7 | 26.5 | 12.8 | 16.6 | 15.0 |
| Range | | | | | | | | | | | | |
| Vogelfederberg | | | | | | | | | | | | |
| Days:Mean | 6.3 | 8.4 | 5.9 | 2.5 | 3.4 | 4.3 | 3.9 | 5.8 | 8.1, | 8.6 | 10.7 | 10.5 |
| Range | | | | | | | | | | | | |
| Pptn:Mean | 11.9 | 11.8 | 13.2 | 4.1 | 8.0 | 5.3 | 7.4 | 15.5 | 20.1 | 15.4 | 18.6 | 24.8 |
| Range | | | | | | | | | | | | |
| Gobabeb | | | | | | | | | | | | |
| Days:Mean | 2.1 | 2.7 | 3.5 | 1.4 | 1.5 | 1.7 | 2.6 | 3.7 | 5.6 | 4.5 | 4.2 | 3.6 |
| Range | | | | | | | | | | | | |
| Pptn:Mean | 1.4 | 2.0 | 2.6 | 1.7 | 1.2 | 2.1 | 2.3 | 3.9 | 5.0 | 3.6 | 2.4 | 2.5 |
| Range | | | | | | | | | | | | |
| Garnet Hill | | | | | | | | | | | | |
| Days:Mean | - | - | 0 | 0 | 0 | 0 | 3.0 | 0 | 3.0 | 2.0 | - | - |
| Range | | | | | | | | | | | | |
| Pptn:Mean | - | - | 0 | 0 | 0 | 0 | 4.2 | 0 | 0.6 | 1.1 | - | - |
| Range | | | | | | | | | | | | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ganab | | | | | | | | | | | | |
| Days:Mean | 0.3 | 0.3 | 0.5 | 0.2 | 0.4 | 0.4 | 0.3 | 0.5 | 0.4 | 0.4 | 0.2 | 0.4 |
| Range | | | | | | | | | | | | |
| Pptn:Mean | 0.2 | 1.1 | 0.7 | 0.4 | 0.4 | 0.6 | 0.5 | 0.4 | 0.4 | 0.3 | 0.4 | 0.2 |
| Range | | | | | | | | | | | | |

Figure captions

Figure 1 Location of meteorological stations used in this study.

Figure 2 Diagramme of the fog-water precipitation screen which is used in conjunction with a Hellman type autographic rain gauge (from Lancaster et al. 1984).

Figure 3 Areas covered by the five geostationary meteorological satellites currently in use.

Figure 4 Examples of photographic imagery available from the visible (left) and infrared (right) channels of Meteosat.

Figure 5 One page of thermal infrared data with overlay depicting location of the coastline, the location of three central Namib Desert localities (S = Swakopmund; W = Walvis Bay; SH = Sandwich Harbour), the autographic climatological stations and the First Order Weather Station at Gobabeb.

Figure 6 Mean annual number of days with precipitated fog-water plotted against distance of climatological station from the coast.

Figure 7 Mean annual fog-water precipitation (mm), plotted against distance of climatological station from the coast.

Figure 8 Histogram of differences between Meteosat data and air temperatures measured in the Stevenson Screen at Gobabeb, on non-foggy days, during the five month study period.

Figure 9 Histogram of differences between Meteosat data and air temperatures measured at Gobabeb in the Stevenson Screen, on foggy days, during the five month study period.

Figure 10 Histograms of the temperatures recorded by Meteosat (    ) and in the Stevenson Screens (    ) of six autographic stations at 05h00 in the central Namib Desert, associated with three ranges of relative humidities.

Figure 11 Temperatures recorded by Meteosat for six autographic stations in the central Namib Desert on days when fog was recorded by at least three of the stations.