



FOG WATER CHEMISTRY IN THE NAMIB DESERT, NAMIBIA

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Abstract—This study documents the ion concentrations and ion enrichment relative to sea water, in Namib Desert fog water, with the purpose of establishing its suitability for future fogwater collection schemes, while also examining claims that Namib Desert fog water carries exceptionally high concentrations of sulphate, which may be responsible for the formation of gypsum deposits in the desert. The work suggests that Namibian fog water is at least as clean as has been reported from other coastal deserts in South America and Arabia, and provides a source of very clean water for the coastal desert region of south-western Africa. It does not appear that fog is an efficient sulphur source for the formation of the gypsum deposits, unless rare events with high concentrations of marine sulphur compounds occur. © 1998 Elsevier Science Ltd. All rights reserved

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1. INTRODUCTION

Fog water chemistry in coastal deserts has been given increasing attention lately, particularly since fog is being used as a water resource serving domestic and agricultural users in Chile (Schemenauer and Cereceda, 1992a), Peru and Ecuador (Schemenauer and Cereceda, 1994). Similar utilisation is currently being evaluated in the Namib Desert where small Topnaar settlements along the lower course of the Kuiseb River seek an alternative water source. Low stratus clouds are very common along the coastline of the Namib Desert (Olivier, 1995). As a result of nocturnal advection they may produce frequent fog events and significant fog deposition (Lancaster *et al.*, 1984), which has been considered a vital source of water for the endemic flora and fauna of the Namib Desert (Seely, 1979, 1981).

The chemical composition of Namib Desert fog water is potentially also of geological relevance as it has long been considered to be a significant pathway of decomposition marine biogenic sulphur (H_2S) from off-shore sediment gas eruptions into the Namib Desert (Martin, 1963). Sulphur tends to be the limiting element in the formation of gypsum ($CaSO_4 \cdot 2H_2O$) a common desert evaporite. Due to the absence of significant sulphate sources within the underlying regional geology, fog deposition has been considered to

promote the formation of Southern Africa's most extensive accumulation of superficial, pedogenic gypsum minerals, on the desert gravel plain between the Ugab and Kuiseb Rivers. This process is as yet unproven and potentially unique. While the presence of shallow H_2S saturated marine sediments in the Benguela shelf has been established (Rogers and Bremner, 1991), the exact nature of marine sulphur contributions to the atmosphere have to date not been studied and are outside the scope of this work.

Despite existing fog water data that are contradictory and sampling devices that were inappropriate, the general literature favours fog water to be a major vector of marine sulphur into the Namib Desert (Watson, 1985; Wilkinson, 1992). Previous fog water chemistry results for the Namib Desert were obtained by collecting water from roof tops (Boss, 1941; 44 samples in $NaCl\ g\ L^{-1}$) and from raingauges (Besler, 1972; Goudie, 1972, 4 samples), which suggest that fog carries exceptionally high ionic loads (795–9860 total ionic concentration in ppm). The collection of fog water on sterilised metal plates on the other hand (Louw, 1972) suggests it to be very clean (unspecified number of samples in $m\text{-osmol}\ L^{-1}$), though a detailed account of the ion chemistry was not provided.

This study determines the ion concentrations in Namib Desert fog water and examines the origin of the ions. By implementing the same sampling and analysis procedure as has been used in Chile (Schemenauer and Cereceda, 1992a) and Oman (Schemenauer and Cereceda, 1992b), the results in this study will be directly comparable with the chemistry of coastal desert fog elsewhere. In every fog collection

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project undertaken to date in a developing country, the sample numbers are small, leading to a question of representativeness. This is a result of limited resources and the temporal and spatial variability of major fog events. The samples obtained in this study will be typical for the region but will not necessarily represent the full range of possible ionic concentrations for Namib Desert fog. The results should establish the usefulness of fog water for human consumption as well as determine its significance as a pathway of marine biogenic sulphur in the formation of pedogenic desert sulphate minerals. The sampling and analytical procedures are also identical to those of a major high elevation fog study in eastern Canada (Schemenauer *et al.*, 1995).

The main fog sampling site in this study was at the Desert Ecological Research Unit at Gobabeb (15° 53' 10" E, 22° 44' 19" S) on the banks of the Kuiseb River, 420 m above sea level and 55 km from the South Atlantic Ocean. The overall terrain of the Central Namib Desert rises gently from the shore and consists of an extensive gypsiferous, gravel plain pavement to the north of the Kuiseb River, with dunes of the Namib Sand Sea to its south. In addition, single fog samples have been obtained from within the Namib Sand Sea south of Gobabeb and on the gravel plain near the coastal town of Swakopmund.

2. METHODS

Fog water was sampled using two identical, Canadian built (Atmospheric Environment Service, AES), passive samplers similar to the collector used by Mohnen and Kadlec (1989), which in turn was a modified version of that of Falconer and Falconer (1980) (Atmospheric Sciences Research Center, ASRC). The collectors (AES/ASRC) have two polypropylene plates 48.5 cm apart separated by three Teflon-coated stainless-steel rods. A continuous length Dupont Teflon Fluorocarbon Monofilament #ME19835A, caliber 0.020", is wound onto the collector to make 370 collection filaments each 48.5 cm long and 0.5 mm in diameter. The fog droplets collected on the filaments drain into a polyethylene funnel and empty into a polyethylene collection bottle. As in Chile (Schemenauer and Cereceda, 1992a) dry deposition samples were obtained by exposing the collector surfaces for 24 fog-free hours to the passive deposition of dry aerosols. A rinse with 300 ml of deionised water was made available for analyses. The volume of water is similar to what would be collected during a 24 h fog event in Namibia. The dry deposition samples enable one to examine the water-soluble

component of the aerosols, to determine if the major ions are present in the same proportions as in the fog water. The small influence of dry deposition on the fog samples collected by one AES/ASRC collector has been discussed in (Schemenauer *et al.*, 1995).

The AES/ASRC collectors were cleaned between events by copious rinsing of all surfaces with up to 5 l of deionized water (conductivity of $< 1 \mu\text{S cm}^{-1}$) sprayed from a polyethylene reservoir. The conductivity of the rinse was measured until it reached $< 2 \mu\text{S cm}^{-1}$ (Yellow Springs Instrument Co. Inc conductivity meter). At this point the AES/ASRC collector was considered clean and covered with a polyethylene bag until it was exposed during a fog event. The bag was of a quality used for network precipitation chemistry sampling. The final rinse was stored in a polyethylene collection bottle, was refrigerated, and was subsequently analysed in conjunction with the fog water and dry deposition samples.

Samples were collected following detailed procedures given in the Operator's Manual for the Chemistry of High Elevation Fog (CHEF, 1987) Program of Canada and shipped in insulated boxes within days, to Les Laboratoires Savoie-Dufresne Inc. in Montreal, Canada. Shipment was by parcel courier service. Laboratory analyses were performed according to procedures given in the Laboratory Manual for the CHEF program. Analyses for Na, K, NH_4 , Cl, NO_3 , Ca, Mg and SO_4 were performed with a Waters Ion Chromatograph. Analytical protocols are reviewed in Schemenauer *et al.* (1995). Enrichment factors relative to Cl were calculated, using the method outlined in Schemenauer and Cereceda (1992a) based on elemental sea water ratios by (Kennish, 1989).

3. RESULTS AND DISCUSSION

Between April 1994 and October 1995, seven samples from six distinct fog events were obtained from a variety of locations within the Central Namib Desert (Tables 1 and 2) producing comparable sample sizes to other studies on desert fog (Schemenauer and Cereceda, 1992a, b). Sampling was not carried out continuously during this period and not all fog events in the vicinity of the Gobabeb research station were sampled. Exposure times for the fog collector were from two to eight and a half hours. The period covered by the sample collection was considered dry by the local people and precipitation was less than normal. The events from which the samples were obtained were considered typical inland fog events in the Namib Desert by staff of the Desert Ecological Research Unit at Gobabeb.

Table 1. Concentration of major ions (ppm) in fogwater samples obtained with the AES/ASRC fog collector in the Central Namib Desert, Namibia in 1994 and 1995. TIC is the total ion concentration

Sample no.	pH	TIC	SO_4	NO_3	Cl	Na (ppm)	K	Ca	Mg	HCO_3	NH_4	Date/Time
1003	6.5	3.3	0.58	0.22	0.38	0.36	0	0.3	0.03	0.63	0.81	19 April 1994/ 03 30-0900
1005	6.4	9.7	2.23	0.27	2.79	1.59	0.2	1.08	0.18	0.49	0.92	23-24 July 1994/ 2200-0630
1007	6.6	9.4	1.86	0.32	2.55	1.41	0.18	1.27	0.17	0.75	0.93	23-24 July 1994/ 2200-0630
1009	6.2	16.4	4.99	0.72	4.4	2.57	0.33	1.76	0.31	0.31	1.05	18 October 1994/ 0600-0930
1012	5.9	27.9	6.71	0.44	10.0	6.11	0.5	2.48	0.65	1.86	0.84	12 Sept. 1995/ 0340-0540
1023	5.6	20.4	3.77	0.58	8.33	4.98	0.12	0.69	0.98	0.07	0.85	11 October 1995/ 0340-0710
1025	6.4	13.7	2.21	0.28	5.31	3.1	0.28	0.72	0.38	0.44	0.98	16 October 1995/ 0245-0805

Table 2. Sample location, wind direction and surface conditions associated with individual fog samples from the Central Namib Desert, Namibia

Sample no.	Location	Wind direction	Surface composition
1003	Gobabeb	NW-NE	Sand, Rock, Gravel
1005	Gobabeb	NW-NE	Sand, Rock, Gravel
1007	Gobabeb	NW-NE	Sand, Rock, Gravel
1009	Sand Sea	NW	Mainly Sand
1012	Gobabeb	N	Sand, Rock, Gravel
1023	Gravel Plain	SW	Sand, Rock, Gravel
1025	Gobabeb	NW-N	Sand, Rock, Gravel

Table 3. A comparison of major ions (ppm) in fogwater samples from the coastal deserts of Chile, Oman and Namibia. The maximum allowable World Health Organisation (WHO) drinking water concentrations are also shown

Location	Type	n	pH	TIC	SO ₄	NO ₃	Cl	Na (ppm)	K	Ca	Mg	HCO ₃	NH ₄
Chile ^a	Fog	7	4.7	31.5	12.3	1.6	8.7	5.4	0.5	1.0	0.7	0.00	1.4
Chile ^a	Dry	1	5.0	102.4	17.5	5.9	42.9	27.4	1.3	2.8	2.8	—	1.7
Oman ^b	Fog	7	7.4	103.8	3.4	4.7	44.1	24.1	1.1	15.1	2.9	10.7	0.2
Namibia	Fog	7	6.2	14.5	3.2	3.4	4.8	2.9	0.2	1.2	0.4	0.7	0.9
Namibia	Dry	3	6.3	151.3	18.7	3.01	67.3	41.3	1.8	12.9	4.9	2.1	0.3
WHO			6-8.5		250	45	250			200	125		

^aSchemenauer and Cereceda (1992a).^bSchemenauer Cereceda (1992b).

The total ion concentrations (mean 14.5 ppm) as well as SO₄ levels measured (mean 3.2 ppm) for Namib fogwater samples are considerably lower than indicated by the data of Boss (1941), Besler (1972) and Goudie (1972) (SO₄ range from 88 to 1158 ppm). Samples also had lower concentrations than AES samples obtained from Chile and Oman (Schemenauer and Cereceda, 1992a, b) and are amongst the cleanest samples ever collected with the AES/ASRC collector (Table 3). The comparable mean SO₄ value for 599 fog sample pairs in southern Quebec, Canada was 13.4 ppm (Schemenauer *et al.*, 1995). Table 3 suggests that Namib fog is potable and has been overestimated in its role as a sulphur vector into the Namib Desert.

As in Chile, the three dry deposition samples, collected by rinsing the fog collectors at Gobabeb, produced much higher total ion concentrations (Table 3) (mean 151.3 ppm) than were present in the fog samples, suggesting that this may be a more effective mode of sulphur aerosol delivery into the coastal desert (mean 18.7 ppm SO₄ in the dry deposition samples). However, the concentrations depend directly on the amount of the rinse water used. The dry accumulation on the AES/ASRC collector also effectively demonstrates the level of contamination to which previous fog collection devices must have been exposed (Boss, 1941; Besler, 1972; Goudie, 1972). While one cannot deduce deposition rates on the desert surface, the data indicate the potential significance of dry atmospheric contributions to the gypsum

accumulations and encourages further work on this subject. The long-range transport of marine aerosols has already been demonstrated to be significant in the formation of gypsum accumulations in continental salt pans of southern Africa (Reimer, 1986) and Australia (Chivas *et al.*, 1991) and it is likely, therefore, that the Namibian coastal accumulations also do not require the assistance of fog in their formation. However, the fog may play a role in the washing of dry deposited sulphur off vertical surfaces (trees, shrubs, rocks) as will, of course, the occasional rains that occur.

Enrichment factors for Namibian fogwater SO₄ (Table 4) show appreciable levels of enrichment (mean value 5.8) relative to sea water, and are higher than those for dry aerosols in the Namib Desert (mean value 2.0), which are considered to represent various marine compounds and remobilised terrestrial gypsum (Annegarn *et al.*, 1983; Eltayeb *et al.*, 1993). High enrichment factors are associated with Ca (mean value 17.3), suggesting considerable terrestrial aerosol contributions from extensive Precambrian and Tertiary calcareous exposures in the area. These exposures could also account for the slightly enriched presence of K (mean value 2.3) in the fog samples, though the values are so near to those for seawater that the contribution may not be great. Enrichment factors for Na (mean value 1.2) and Mg (mean value 1.1) are even more conservative and remarkably consistent for all Namib AES/ASRC samples, suggesting that these ions are predominantly of seawater origin. Overall,

Table 4. Enrichment factors relative to chlorine in fogwater samples from this study, plus the mean values from the coastal deserts of Chile, Oman and Namibia

Location		EFCa	EFSO ₄	EFK	EFMg	EFNa
1003		38.0	10.9	0.0	1.2	1.7
1005		18.4	5.7	3.4	1.0	1.0
1007		23.7	5.2	3.3	1.0	1.0
1009		19.0	8.1	4.0	1.0	1.0
1012		11.8	4.8	2.4	1.0	1.1
1023		3.9	3.2	0.7	1.8	1.0
1025		6.5	3.0	2.5	1.1	1.0
Chile ^a	Fog	5.3	10.1	2.6	1.3	1.1
Chile ^a	Dry	3.1	2.9	1.5	1.0	1.2
Oman ^b	Fog	16.3	0.5	1.2	1.0	1.0
Namibia	Fog	17.3	5.8	2.3	1.1	1.2
Namibia	Dry	9.1	2.0	1.2	0.9	1.1

^aSchemenauer and Cereceda (1992a).^bSchemenauer Cereceda (1992b).

enrichment factors for fog and dry collections do not differ greatly in the Namib Desert.

Namibian samples are similar to fogwater samples from the coastal deserts of Oman and Chile, with the conservative nature of Na and Mg also being evident in samples from these countries. Enrichment levels for K in the other deserts are also moderate, while the general presence of Ca-rich terrestrial nuclei is evident in all samples. Enrichment of SO₄ is most noticeable in Chile (mean 10.1), which is thought to be caused by marine biogenic DMS production associated with the cold Humboldt current (Schemenauer and Cereceda, 1992a). Analogue oceanic conditions generated by the Benguela current produce similar levels of SO₄ enrichment in Namibia (mean 5.8). There is no comparable cold current along the coast of Oman, though there may be some cool upwellings, and the SO₄ enrichment factor is considerably lower (0.5). It is not possible to determine the relative contributions of marine biogenic H₂S, primary DMS production, sea spray, and remobilised terrestrial gypsum to the chemical composition of the AES/ASRC samples. In light of the overall chemistry of the Namibian samples it seems, however, unlikely that the sulphur flux in the Namib Desert is dominated by H₂S eruptions. The sulphur deposited to the surface of the Namib Desert will have a number of sources, whose relative contributions at a given time are determined by the changes in atmospheric and oceanographic conditions.

4. CONCLUSION

It is apparent that Namib Desert fog is extremely clean, with levels of enrichment and ion concentrations comparable to those measured in the coastal deserts of Oman and Chile. Given these data, Namibian fog is unlikely to be a major vector of marine biogenic sulphur compounds and unlikely to contribute directly to gypsum accumulation. The

small dry deposition data set suggests that the deposition of background aerosols is probably a more effective sulphur flux into the desert environment. These results do not however preclude the occurrence of much higher atmospheric sulphur loads in conjunction with sporadic and major biogenic H₂S emissions from the Benguela sediments. That such events do occur is supported by anecdotal evidence from the people living along the coast of Namibia. Definitive answers can only come from long-term monitoring of gas, particulate and fog chemistry, coupled with measurements and models of the relevant deposition processes.

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REFERENCES

- Annegarn, H. J., Van Grieken, R. E., Bibby, D. M. and Blotnitz, F. V. (1983) Background aerosol composition in the Namib Desert, S.W.A. (Namibia). *Atmospheric Environment* 17 (10), 2045–2053.
- Besler, H. (1972) Klimaverhältnisse und Klimageomorphologische Zonierung der Zentralen Namib (Südwestafrika). *Stuttg. Geogr. Stud.* 83.
- Boss, G. (1941) Niederschlagsmenge und Salzgehalt des Nebelwassers an der Küste Deutsch-Südwestafrikas. *Bioklim. Beibl.* 8 (1), 1–14.
- CHEF (1987) *Operator's Manual for the Chemistry of High Elevation Fog (CHEF) Program*, #87-1, 15 April, pp. 135. Prepared for the Atmospheric Environment Service of Environment Canada by the Environmental Applications Group Ltd., Willowdale, Ontario, Canada.
- Chivas, A. R., Andrew, A. S., Lyons, W. B., Bird, M. I. and Donnelly, T. H. (1991) Isotopic constraints on the origin of salts in Australian playas. 1. Sulphur. *Palaeo, Palaeo, Palaeo* 84, 309–332.

- Eltayeb, M. A. H., Van-Grieken, R. E., Maenhaut, W. and Annegarn, H. J. (1993) Aerosol-soil fractionation for Namib Desert samples. *Atmospheric Environment* **27A** (5), 669–678.
- Falconer, R. E. and Falconer, P. D. (1980) Determination of cloud water acidity at a mountain observatory in the Adirondack Mountains of New York State. *Journal of geophysical Research* **85** (12), 7465–7470.
- Goudie, A. S. (1972) The chemistry of world calcrete deposits. *Journal of Geology* **80** (4), 449–463.
- Kennish, M. J. (1989) Section 2: chemical oceanography. *Practical Handbook for Marine Science*, pp 55–62. CRC Press, Boca Raton, FL.
- Lancaster, J., Lancaster, N. and Seely, M. K. (1984) Climate of the Central Namib Desert. *Madoqua* **14** (1), 5–61.
- Louw, G. N. (1972) The role of advective fog in the water economy of certain Namib Desert animals. In *Comparative Physiology of Desert Animals*, ed. G. M. O. Maloiy. Zoological Society of London Symposium, London vol. 31, pp. 297–314.
- Martin, H. (1963) A suggested theory for the origin and a brief description of some gypsum deposits of South West Africa. *Transaction of the geological Society South Africa* **66**, 345–350.
- Mohnen, V. A. and Kadlecsek, J. A. (1989) Cloud chemistry research at Whiteface Mountain. *Tellus* **41B**, 79–91.
- Olivier, J. (1995) Spatial distribution of fog in the Namib. *J. Arid Env.* **29**, 127–138.
- Reimer, T. O. (1986) Isotopic constraints on the derivation of sulphate in gypsum in inland salt pans of southern Africa. *Abstracts Geocongress '86 Geological Society South Africa* 1049–1052.
- Rogers, J. and Bremner, J. M. (1991) The Benguela ecosystem; Part VII, Marine-geological aspects. *Oceanography Marine Biology, Annual Review* **29**, 1–85.
- Schemenauer, R. S. and Cereceda, P. (1992a) The quality of fog water collected for domestic and agricultural use in Chile. *Journal of Applied Meteorology* **31**(3), 275–290.
- Schemenauer, R. S. and Cereceda, P. (1992b) Monsoon cloudwater chemistry on the Arabian peninsula. *Atmospheric Environment* **26A** (9), 1583–1587.
- Schemenauer, R. S. and Cereceda, P. (1994) Fog collection's role in water planning for developing countries. *Natural Resources Forum*, vol. 18. United Nations, New York, pp. 91–100.
- Schemenauer, R. S., Banic, C. M. and Urquiza, N. (1995) High elevation fog and precipitation chemistry in southern Quebec, Canada. *Atmospheric Environment* **29**(17), 2235–2252.
- Seely, M. K. (1979) Irregular fog as a water source for desert dune beetles. *Oecologia (Berlin)* **42**, 213–227.
- Seely, M. K. (1981) Desert plants use fog water. *Scientific Programme* **14** (2), 4.
- Watson, A. (1985) Structure, chemistry and origins of gypsum crusts in southern Tunisia and the central Namib Desert. *Sedimentology* **32**, 855–875.
- Wilkinson, M. J., Helms, D. R. and Whitehead, V. S. (1992) Albedo patterns and gypsum generation in the Central Namib Desert: Land, Sea, Air Interactions on an Arid West Coast. *Proceedings of International Geoscience and Remote Sensing Symposium* 26–29 May (IGARSS '92), Houston, Texas.