# An episode of coastal advection fog over East Antarctica

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**An episode of fog during 8–9 January 1996 over the Schirmacher Oasis of East Antarctica was investigated. It revealed that the fog was formed due to advection of southeasterly winds by high moisture-containing northwesterly winds, blowing from the ocean over the cold ice shelf, which leads to the condensation of moisture, thereby forming fog for a duration of about 24 h. A monostatic acoustic sodar recorded the episode, which revealed the thickness of fog layer up to an altitude of about 300 to 400 m. Supplementary meteorological and radiosonde data were utilized to understand the mechanisms of the formation and dissipation of advection fog in this region. Supporting literature illustrates that this type of fog is an important source of water for photosynthesis, growth, reproduction and other metabolic activities of the poikilohydric microbiotic crust inhabiting the cold, arid and dry ecosystem of the coastal East Antarctic oases.**

**Keywords:** Acoustic sounder, meteorology, microbiotic crust, radiosonde, Schirmacher Oasis.

ANTARCTICA is the most remote, cold, windy and the highest continent in the world[1]. Here the average annual precipitation (expressed in terms of water) is between 50 and 150 mm, most of which falls as snow[2]. Data from 16 stations around the coast of East Antarctica show that the annual total column moisture (TCM) values were about 4 kg per sq. m, but this value is much smaller on the East Antarctic Plateau[3].

The coastal Antarctic planetary boundary layer (PBL hereafter) experiences varying external influences both from the interior of the continent and due to the moving depressions/cyclones along the coast[4]. Influence from the interior of the continent is dominated by katabatic flow of winds of varying intensities, often depositing snow/ice in the form of blowing snow, drift and blizzards[5,6]. However, cyclones push relatively warm and moist air towards the interior of the continent, leading to foggy weather conditions[7]. The acoustic sounder finds applications in the area of fog monitoring[8]. At the Indian Antarctic station, Maitri, a monostatic acoustic sounder was operated in 1996 to study PBL dynamics[9].

Stratiform clouds are common near the Antarctic coast[10]. Fog is essentially a dense cloud of water droplets, or cloud that is close to the ground[11]. Fog is also an important alternative source of moisture for plants. It has an appreciable effect on vegetation in certain climates. However, its importance in ecological studies has been difficult to estimate[12,13].

Virtually no higher plant life-form exists on the Antarctic continent. However, minute organisms survive in small pockets of ice-free areas[14–16]. Algae, lichens and mosses are the only poikilohydric microbiotic crusts inhabiting the continent[17–20]. In the driest and coldest habitats, especially where fog and dew are the major water sources, desiccation-tolerant algae or cyanobacteria, bryophytes and lichens may form the only vegetation[21].

Fog is the biggest forecast problem related to flights aborted due to bad weather and few studies have been undertaken on the Antarctic fog[22]. Fog and haze at Schirmacher Oasis (SO) have been rarely recorded. There have been no studies to quantify fog input to the water cycle in the SO[9]. In view of this, the present study was aimed to bridge the gap of the foggy boundary layer characteristics recorded by a sodar over the SO, and its role of providing moisture to the microbiotic crust and their survival in the pristine Antarctic continent.

## Materials and methods

### *Observational site*

The Indian Antarctic station, Maitri (70°45′S; 11°44′E) and Russian Antarctic station, Novolazarevskaya (70°46′S; 11°50′E) are in the SO of East Antarctica, which is one of the smallest (area ~ 35 sq. km) oases in Central Dronning Maud Land; it is about 70 km south of the Princess Astrid coast of East Antarctica (Figure 1). It is covered by snow/ice during the winter (June–August) and spring (September–November) seasons. In summer (November–February) season, the region becomes deglaciated, thereby exposing the rocky moraine surrounded by the polar ice cap and ice shelf[15]. It has a range of virtually barren and rocky low-lying hills, which provide a habitat only for the cold-hardy microbiota (algae, lichens, mosses, midges, mites and tardigrades) that thrive in harsh cold desert, dry permafrost polar region, generally known as 'oasis'[23–26] (Figure 1). About 30 freshwater lakes (large, small, shallow lakes) and many thaw streams exist during local summer season in

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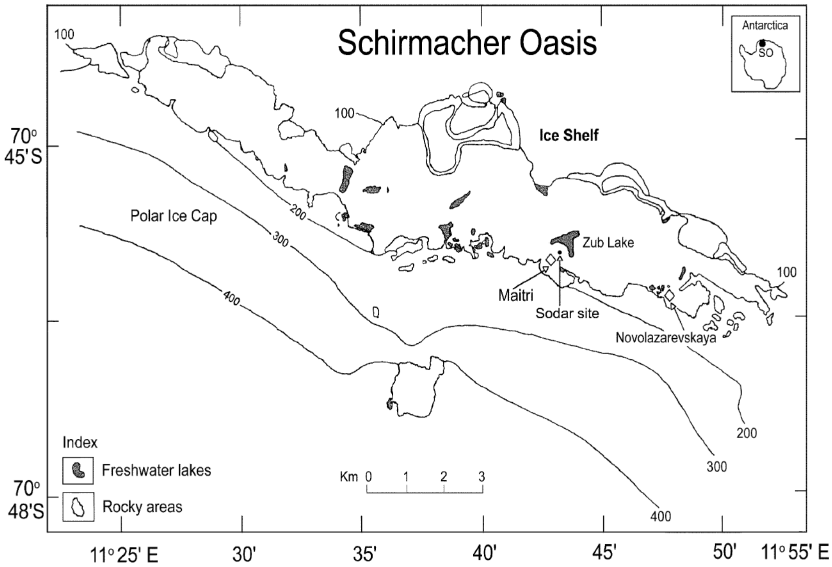


**Figure 1.** Map of Schirmacher region showing elevation, lakes, polar and shelf ice, sodar site, Indian Antarctic station, Maitri, and the Russian Antarctic station, Novolazarevskaya.

the oasis. Most of these lake banks are covered with thick, dark moss carpets. Lichens are observed mostly on the rocky surface, away from the lakes. The soils of this region have significant organic carbon, low humus content, low microbial activity and are common in Antarctica[17,27].

### *Sodar data*

A PC-based monostatic acoustic sounder was operated at Maitri station in 1996, near one of the biggest freshwater lakes known as the Zub Lake (area ~ 0.75 sq. km) of the region (Figure 1). It was operated at 2.0 kHz and had a probing range of 1.0 km. The acoustical transducer and the pre-amplifier assembly were heated to maintain the temperature at around –5°C, but the 6 ft parabolic fibreglass dish was not heated to maintain it snow/ice-free. Thus, it required manual maintenance/removal of accumulated snow/ice after every blizzard/snowfall event. The limitation of the system was basically due to noise caused by the high surface winds striking the metallic shield surrounding the fibreglass dish.

### *Surface meteorology*

The acoustic sounding data were supported by the 3 h surface meteorological observations taken at Maitri. In the SO, the synoptic conditions were influenced by a series of good and bad weather associated with cyclones/depressions along the coast. Severe katabatic winds from SSE and ESE directions associated with blowing snow/blizzards dominated the local weather[15].

The average air temperature recorded at Maitri in 1996 was –8.4°C and the minimum and maximum temperatures recorded were –30°C and 11.9°C on 12 May and 3 February 1996, respectively. In January 1996, the minimum and maximum temperatures recorded were –8.1°C and 7.5°C on 20 January and 1 January 1996 respectively. The average wind speed was 10.3 m $s^{-1}$ with a maximum recorded as 34.5 m $s^{-1}$ on 23 July 1996. Precipitation in the form of snow during the time of blizzards was high and the annual average was between 250 and 300 mm. The annual average relative humidity was about 52%. During austral summer, 24 h sunshine is observed for three months (November–January). During this season, the temperatures are high, wind speeds are low and the moisture is inducted towards the continent in the form of snow, fog, haze and at times by drizzle (light rain). The annual average total solar radiation input[9] over the oasis was of 93.8 kcal $cm^{-2}$.

### *Radiosonde data*

Interpretation of sodar echoes was facilitated by radiosonde data recorded at Novolazarevskaya during January 1996. The upper-air sounding was carried out once a day at 0 GMT at Novolazarevskaya. Powered by a water-activated battery, the instrument took measurements at approximately 1.3 s interval during ascent. Temperature, wind speed, wind direction and pressure were measured using three capacitive sensors. The standard resolution data files contained measurements taken at particular levels of the atmosphere. In this article, radiosonde data for 6, 9 and 10 January 1996 were utilized.

## Results

### *Definition of fog and its characteristics on sodar echogram*

Fog is defined as a cloud that touches the ground and reduces the visibility to 1 km or less. There is no physical difference between a fog and a stratus cloud, other than altitude[11]. Unlike thick, rain-producing clouds which are characteristically formed by the expansion and cooling of rising air, the cooling of humid surface air below its dew point temperature usually causes fog. This cooling can result from radiational processes, from the mixing of warm and cool air masses, or from warm moist air moving over a cooler surface[28]. The induction of warm, marine oceanic air to the interior causes low-level cloud over the SO[7].

Between 8 and 9 January 1996, the PBL dynamics revealed unique sodar facsimile features (Figure 2). During this period, the Schirmacher region was under the influence of thick fog. The facsimile data revealed that the formation of fog started at about 2115 h on 8 January in the form of a light, elevated layer at an altitude of about 300–400 m. Later, the elevated layer became more intense and persisted at a stretch for more than 24 h, ending around 2200 h on 9 January 1996. The fog layer persisted in spite of formation of thermal plumes created by solar heating of the ground between 0500 and 0930 h, and later on from 1420 to 2000 h on 9 January 1996. The fog layer ultimately diminished, as the flow of northerly air weakened and was taken over by the gravity-driven flow (katabatic wind) around 2200 h on 9 January.

During foggy days the sodar echogram showed a continuous echo layer at varying heights and the height corresponded to that of low-level clouds[7]. The elevated layer was also seen capping the thermal plumes formed during free convection (well-mixed atmospheric boundary layer) due to solar heating of the ground.

### *Surface meteorological condition*

Figure 3 *a–d* shows the 3-h surface meteorological data plotted between 1 and 15 January 1996. It depicts variation of mean sea level pressure (MSLP), temperature, wind speed and direction. On 8 January 1996, the mean sea level was high at around 1000 mb and on 9 January, it decreased slightly to 997 mb. Maximum MSLP was recorded on 10 January 1996, a value of around 1001 mb. From 10 January onwards the pressure gradually decreased indicating normal weather conditions.

The surface air temperature showed diurnal variation, which is influenced or altered by various short and long-term meteorological conditions. In the afternoon of 8 January 1996 the temperature climbed up to about 2°C and gradually fell till the morning of 9 January 1996. On 9 January morning, the surface air temperature dipped down to –3.7°C and as the day advanced it went up to around –0.5°C and remained almost constant till the morning of 10 January 1996. Then in the afternoon of 10 January 1996, the temperature suddenly increased and the katabatic wind started at >7 $ms^{-1}$. The daily averaged wind speed for January 1996 showed that 9 January was the lowest at a value of 1.4 $ms^{-1}$.

The three surface meteorological parameters, viz. pressure, temperature and wind speed, which were low compared to the days before and after the fog episode, provide contrasting observations for the formation of fog. However, further investigation on the wind direction gives us an idea of how the fog was formed. In Figure 3 *d*, wind direction shows that the winds are coming mostly from the northern quadrant on 8 January 1996. Similarly, the direction of the surface wind on 9 January remained basically from the NE sectors for most of the time during the foggy period (Figure 3 *d*). It is pertinent to mention here that the wind directions over Maitri are dominated by the ESE direction; these are mostly katabatic winds flowing from the interior of the continent[7,9,15]. Thus, the present case of winds from the northern quadrants is clearly oceanic

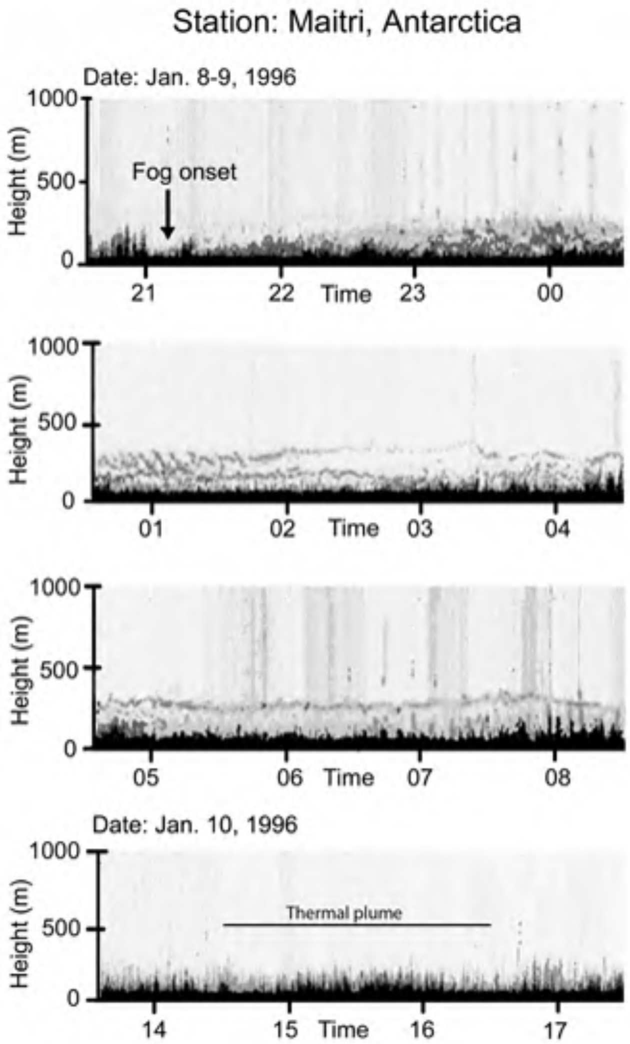


**Figure 2.** Facsimile pictures of foggy and non-foggy days during 8–10 January 1996 at Maitri. Formation of fog started at around 21 : 15 h (UTC).

in nature. It has also been observed that in the evening and afternoon of 8 and 9 January 1996, the surface wind directions briefly altered. This must have influenced the diurnal pattern of the surface air temperature (Figure 3 *b*).

The above results therefore suggest that the slow wind from the NE quadrant brought moisture-containing air masses from the ocean, which is about 70 km from the oasis. As the temperature in the evening of 8 January was below 0°C, condensation of moisture had taken place from the night of 8 January. Visual observations also suggested that the condensation of fog was considerable and the ground was wet during this episode. The fog started precisely at 2115 hours on 8 January 1996 on the sodar echogram (Figure 2).

## *Radiosonde interpretation*

The surface-based data were also supported by radiosonde-derived measurements of temperature, wind speed, relative humidity (RH) and wind direction at various altitudes (Figure 4 *a* and *b*). On 9 January 1996 there was the appearance of a near surface-based temperature inversion between 0.6 and 1.2 km altitude, as depicted by radiosonde temperature profiles in Figure 4 *a*. Below 0.6 km altitude, temperature was lower (–6.9°C) than the other days and at 1.2 km the temperature remained same at –8.1°C, indicating an inversion layer capping the warmer surface. Figure 4 *a* also showed an increasing wind speed (10 m $s^{-1}$) just above the surface (about 0.6 km). The wind speed then steadily decreased as the altitude increased up to 1.2 km on 9 January 1996.

Figure 4 *b* shows that RH was highest on 9 January 1996. RH at the surface was about 55%, and at 0.6 km altitude, it was 73.4%. Normally at Antarctica the surface-level RH is low due to low temperatures and high winds as seen from the values on other days. Wind direction also changed from ESE near the surface to NW at 0.6 km altitude (Figure 4 *b*). This indicates a weak front from the

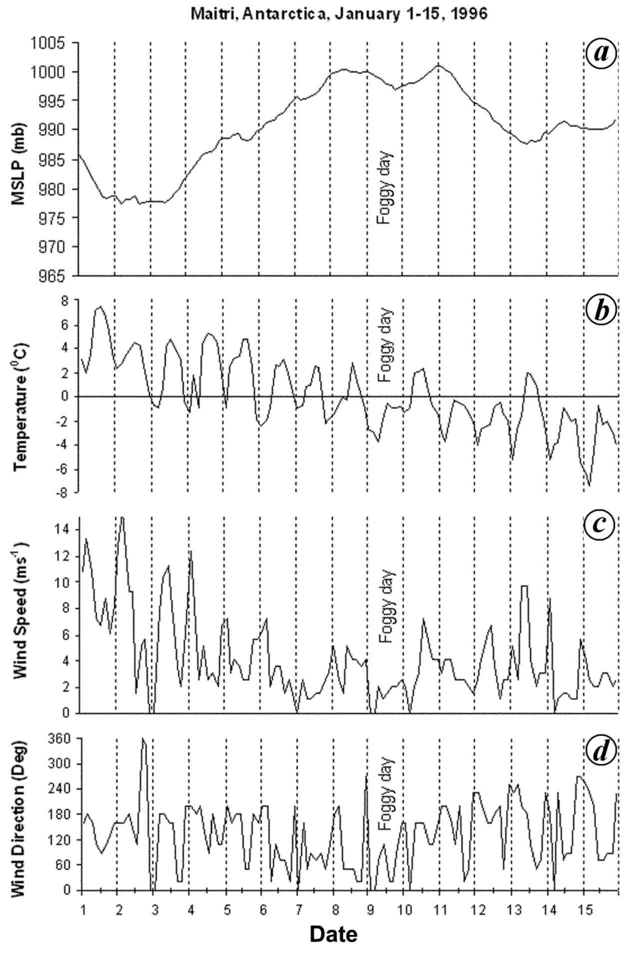


**Figure 3.** Three-hourly meteorological data recorded at the Maitri station during 1–15 January 1996. Fog occurred on 8 and 9 January 1996.

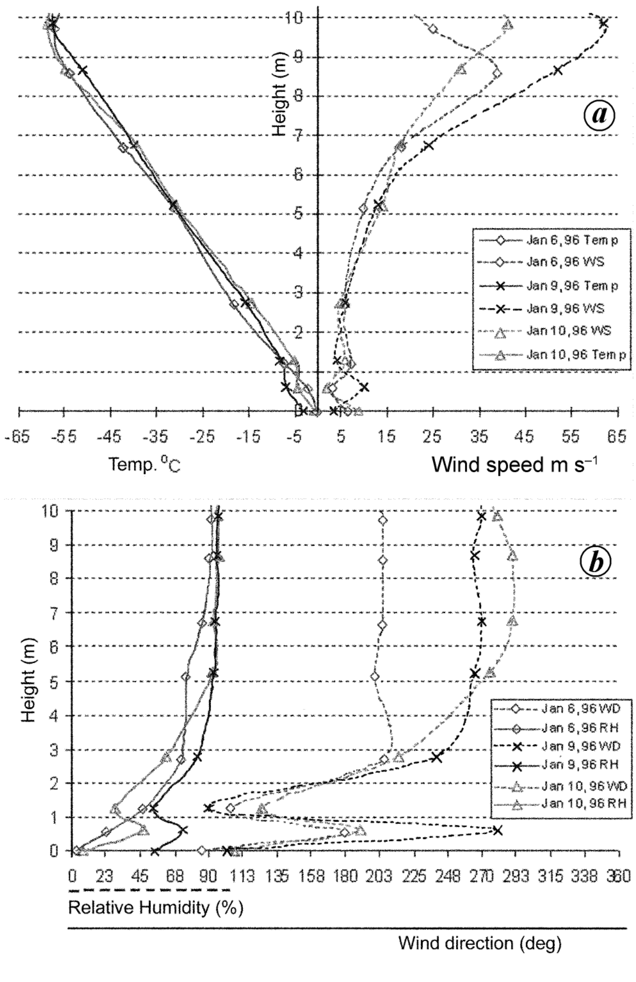


**Figure 4.** ***a***, Radiosonde-derived temperature and wind speed at different altitudes recorded on 6, 9 and 10 January 1996. Intrusion of high moisture containing air mass is seen to be maximum at around 0.6 km altitude on 9 January 1996. ***b***, Radiosonde-derived relative humidity and wind direction at different altitudes on 6, 9 and 10 January 1996. The direction of the wind shows intrusion of northerly air at 0.6 km over the Schirmacher region on 9 January 1996.

ocean side. Thus, the strong oceanic wind gust caused a surface-level pressure of 997 mb on this day (Figure 3 *a*). At higher altitudes, the direction of wind again changed from NW to NE direction at an altitude of 1.2 km. The wind shear at 0.6 km altitude is the reason for the elevated layer seen from the sodar echogram during these foggy days (Figure 2). Wind directions for other days remained in the ESE direction.

From the data it is clear that on 9 January 1996, an inversion layer caused by the cooling and turbulent mixing of air between the surface and 1 km altitude existed. In such a situation, a layer of stratus cloud is seen frequently below the base of the inversion. Thus, the high moisture-containing air stream advected from the ocean towards the interior of the continent might have surrendered heat to the underlying cold, icy Antarctic continent surface and an advection fog developed over this region.

## Discussion and conclusion

Cyclones are persistent around the Antarctic circumpolar trough. These cyclones push relatively warmer, moisture-containing air masses towards the continent, which resulted in the formation of fog, cloud, haze and precipitation over the continent periphery[9]. Weather plays a vital role in the development and survival of the few cold-hardy microbiota in this continent[16].

The sodar echogram revealed that an elevated layer capped the thermal plumes during foggy conditions, while on normal days the echogram showed spiked features (Figure 2). On non-foggy days[29], the inversion layers were mostly found to decay between 1000 and 1130 h. However, in the present study the inversion layers dissipated after 1200 h. The weather also showed higher humidity with constant temperature, having low wind velocity. Knowing the characteristics of the vertical profile helps to better parameterize height-varying processes, e.g. fog deposition and eddy diffusion[30]. Gera *et al.*[29] estimated vertical movement of the surface-based inversion from the acoustic sounder echograms during non-foggy days, and the magnitude was observed to be between 35 and 60 m $h^{-1}$, while on foggy days, the magnitude decreased to 23–35 m $h^{-1}$. Thus, in the present study, the solar heating of the ground and formation of thermal plumes had less effect on the formation and dissipation of the fog episode. The dissipation of fog was only after the katabatic wind started flowing from the interior of the continent. Therefore, this type of fog can be regarded as advection fog[11].

Again, our observation of fog layer within 300–400 m continuously for about 24 h due to the influence of oceanic air is an important feature for the microbiota of this cold and dry region. Stoutjesdijk and Barkman[31] mentioned that for many organisms which cannot take up water from the soil, the presence of liquid water in the air is important, from dew or from precipitation. In the case of dense fog, with visibility less than 100 ft, there may be as much as 3 g $m^{-3}$ of liquid water in the air[11]. Lichens and mosses can absorb water up to saturation from a dry starting point and retain this water. Certain desert plants possess the power of absorbing moisture from fog through their leaves[12]. For example, lichens in the desert, which were initially inactivated following the preceding dry day, but after a slight fog, their quantum yield increased, indicating activation of photosynthetic capacity due to thallus hydration[32]. Hydration of lichen thallus through fog and high air humidity proved to be the most important parameter that controlled the pattern of metabolic activity and defined the response types[32]. Fog extended the time period of photosynthetic activity before the lichens again became desiccated. During dry periods of the year, daily $CO_2$ exchange of Antarctic lichen *L. muralis* resembled the activity patterns of desert lichens for which dew is the main source of water[33,34]. Dawson[35] has clearly documented the importance of fog drip for soil moisture and root uptake. In the Arctic, foggy weather cut down the photosynthetic rates, but the net amount of carbon fixed by the end of the growing season was high, at about 174 gC per sq. m per season[36].

Thus fog is a significant source of water because it provides the much-needed moisture to the microbiotic crusts in cold and arid regions. Desmet and Cowling[13] mentioned that fog is a potentially significant source of water in the desert, and is a far more predictable source of moisture than rainfall. Nevertheless, fog is an important source of water for the epiphytic lichens on rocks, which cannot take up water from the substrates for continuous photosynthesis. To carry out photosynthesis efficiently, lichens require sufficient light and moist (but not wet) conditions during daytime. In the austral summer over the SO, there is 24 h sunshine and no rainfall except during rare occasions[9,15]. Thus, fog here will be more favourable to the lichens than rain, i.e. especially fog during austral summer. However, in the SO, the number of days with fog is generally low throughout the year. Correspondingly, the epiphytic lichen floras are also considerably impoverished.

Facsimile pictures of the monostatic acoustic sodar show clearly the formation and dissipation, height and timing of fog incidence. In the SO, there is little or no rainfall, and thus the localized fogs contributed atmospheric moisture to the few poikilohydric microbiotic crusts as their sole water source. It is also likely that due to changing climate over Antarctica, frequent fog may occur in the near future. The monostatic acoustic sounding data in association with the study of microbiotic crusts retention of atmospheric moisture especially during foggy period will help in understanding the complex physiological and metabolic characters of the various microbiota of Antarctica. The cytological mechanisms of the microbiotic communities of SO, which used fog moisture are unclear. Therefore, research on this aspect will be fruitful.


1. Drewry, D. J., Laws, R. M. and Pyle, J. A. (eds). In *Antarctica and Environmental Change*, Royal Society, Clarendon Press, Oxford, 1993, pp. 1–135.
2. Schwerdtfeger, P., Review on icebergs and their uses. *Cold Regions Sci. Technol.*, 1979, **1**, 59–79.
3. Connolley, W. M. and King, J. C., Atmospheric water–vapor transport to Antarctica inferred from radiosonde data. *Q. J. R. Meteorol. Soc.*, 1993, **510**, 325–342.
4. Wendler, G. and Kodama, Y., The kernlose winter in Adélie Land. Special AGU publication of the Antarctic Research Series, *Antarctic Meteorology and Climatology*, 1994, vol. 61, pp. 130–147.
5. Argentini, S., Mastrantonio, G., Viola, A., Pettre, P. and Dargaud, G., Sodar performances and preliminary results after one year measurements at Adelie coast, East Antarctica. *Boundary-Layer Meteorol.*, 1996, **81**, 75–103.
6. Du, Y. and Bromwich, D. H., Katabatic airflows over Siple Coast, Antarctica. *Antarct. J. U.S.*, 1992, **7**, 291–293.
7. Naithani, J. and Dutta, H. N., Acoustic sounder measurements of the planetary boundary layer at Maitri, Antarctica. *Boundary-Layer Meteorol.*, 1995, **76**, 199–207.
8. Beran, D. W. and Hall, F. F., Remote sensing for air pollution meteorology. *Bull. Am. Meteorol. Soc.*, 1974, **55**, 1097–1105.
9. Gajananda, Kh, Study of atmospheric parameters in relation to Antarctic ecosystem over the Schirmacher region of East Antarctica. Ph D thesis, Department of Environmental Science and Engineering, Guru Jambheshwar University, Hisar, 2003.
10. Bromwich, D. H. and Stearns, C. R. (eds). In *Antarctic Meteorology and Climatology: Studies Based on Automatic Weather Stations*, AGU, 1993, pp. 1–207.
11. Petterssen, S., *Introduction to Meteorology*, McGraw-Hill and Kogakusha Co Ltd, Tokyo, 1958, pp 1–313.
12. Miller, A. A., *Climatology*, Methuen & Co Ltd, London, 1965, pp. 1–307.
13. Desmet, P. G. and Cowling, R. M., Biodiversity, habitat and range-size aspects of a flora from a winter-rainfall desert in north–western Namaqualand, South Africa. *Plant Ecol.*, 1999, **142**, 23–33.
14. Moorhead, Daryl, L. and John, C. P., The McMurdo dry valley ecosystem: Organization, controls, and linkages. In *Ecosystem Processes in a Polar Desert: The McMurdo Dry Valleys, Antarctica*, Antarctic Research Series, 1998, vol. 72, pp. 351–363.
15. Gajananda, Kh, Kaushik A. and Dutta, H. N., Thermal convection over East Antarctica: Potential microorganism dispersal. *Aerobiologia*, 2004, **20**, 21–34.
16. Gajananda, Kh and Dutta, H. N., Terrestrial vegetation community structure and biomass of the Schirmacher Oasis ecosystem, East Antarctica. *Int. J. Ecol. Dev.*, 2005, **3**, 39–64.
17. Gajananda, Kh., Soil organic carbon and microbial activity: East Antarctica. *Eur. J. Soil Sci.*, 2007, **58**, 704–713.
18. Upreti, D. K. and Pant, G., Lichen flora in and around Maitri region, Schirmacher Oasis, East Antarctica. In *The 11th Indian Expedition to Antarctica*, Technical Publication No. 9, Department of Ocean Development, India, 1995, pp. 229–241.
19. Fogg, G. E., *The Biology of Polar Habitats*, Oxford University Press, New York, 1998.
20. Antarctica – Great stories from the frozen continent. *Reader's Digest*, New York, 1985.
21. Alpert, P. and Oliver, M. J., Drying without dying. In *Desiccation and Survival in Plants* (eds Black, M. and Pritchard, H. W.), CAB International, 2002, pp. 4–31.
22. Lazzara, M. A., Wang, P. K. and Stearns, C. R., Observations of Antarctic fog particles. In 7th Conference on Polar Meteorology and Oceanography and Joint Symposium on High-Latitude Climate Variations, Hyannis MA, 12–16 May 2003; http://ams.confex.com/ams/pdfpapers/60786.pdf
23. Stephenson, A., The southern journey. In *Southern Lights: The Official Account of the British Graham Land Expedition* (ed. Rymill, J.), Chatto and Windus, London, 1938, pp. 193–437.
24. Richter, W., Haendel, D. and Junghane, P., The animals of the Schirmacher Oasis (East Antarctica). *Geodatische Geophys. Veroeff., Reihe 1, Berlin*, 1990, **16**, 495–503.
25. Shivaji, S., Rao, N. A., Saisree, L., Shethi, V., Reddy, G. S. N. and Bhargava, P. M., Isolation and identification of *Pseudomonas* sp. from Schirmacher Oasis, Antarctica. *Appl. Environ. Microbiol.*, 1989, **54**, 1066–1067.
26. Vincent, W. F., *Microbial Ecosystem of Antarctica*, Cambridge University Press, Cambridge, 1988, pp. 1–304.
27. Cameron, R. E., Antarctic soil microbial and ecological investigations. In *Research in the Antarctic*, American Association for the Advancement of Science (ed. Quam, L. O.), Washington DC, USA, 1971, vol. 93, pp. 137–189.
28. Ingraham, N. L. and Matthews, R. A., The importance of fog drip water to vegetation: Point Reyes Peninsula, California. *J. Hydrol.*, 1995, **164**, 269–285.
29. Gera, B. S., Gurbir, S., Ojha, V. K., Pasricha, P. K., Gajananda, Kh and Dutta, H. N., Sodar studies of foggy boundary layer characteristics. In Proceedings of the 11th International Symposium on Acoustic Remote Sensing (ISARS) and Associated Techniques of the Atmosphere and Oceans, Rome, Italy, 24–28 June 2002, pp. 263–266.
30. Davidson, C. I., Bergin, M. H. and Kuhn, H. D., The deposition of particles and gases to ice sheets. In *Chemical Exchange Between the Atmosphere and Polar Snow* (eds Wolff, E. W. and Bales, R. C.), Springer–Verlag, New York, 1996, pp. 275–306.
31. Stoutjesdijk, Ph and Barkman, J. J., *Microclimate Vegetation and Fauna*, Opulus Press, AB, 1991.
32. Lange, O. L., Photosynthetic productivity of the epilithic lichen *Lecanora muralis*: Long-term field monitoring of $CO_2$ exchange and its physiological interpretation II. Diel and seasonal patterns of net photosynthesis and respiration. *Flora*, 2003, **198**, 55–70.
33. Kappen, L., Ecophysiological relationships in different climatic regions. In *Handbook of Lichenology* (ed. Galun, M.), CRC Press, Boca Raton, 1988, vol. 2, pp. 37–100.
34. Veste, M., Littmann, T., Friedrich, H. and Breckle, S. W., Microclimatic boundary conditions for activity of soil lichen crusts in sand dunes of the north–western Negev desert, Israel. *Flora*, 2001, **196**, 465–474.
35. Dawson, T. E., Fog in the redwood forest: Ecosystem inputs and use by plants. *Oecologia*, 1998, **117**, 476–485.
36. Billings, W. D. and Peterson, K. M., Some possible effects of climatic warming on Artic tundra ecosystems of the Alaskan North Slope. In *Global Warming and Biological Diversity* (eds Robert, P. L. and Thomas, L. E.), Yale University Press, New Haven, 1992, pp. 233–243.


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