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ORIGINAL PAPER

Changes in atmospheric water content associated with an unusual high snowfall during June 2004 at Maitri station (Schirmacher Oasis, East Antarctica) and the role of South West Indian ridge geodynamics

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Abstract We study changes in the atmospheric water vapour associated with the unusual snowfall during June 2004 polar night at the Indian Antarctica station Maitri (MAIT), located ~70 km inland of the East Antarctic north coast. The GPS-derived Zenith Total Delay data for the 2004 polar night are used to evaluate the atmospheric water content at four GPS locations along the northern margin of East Antarctica. Stations Maitri and Syowa (SYOG) showed significant increase in atmospheric water vapour from GPS day 162 (10 June 2004) to 176 (24 June 2004) and correlate well with the duration of heavy snowfall at MAIT. The precipitable water vapour values computed for IGS station SYOG confirm high water vapour during this high snowfall period. Such an anomalous water vapour over East Antarctica in this peak winter time, characterized by the complete absence of solar radiations, suggests a link between this phenomenon and the high evaporation rate over South West Indian Ridge triggered by the geothermal heat radiated to the sea bottom through active magma spreading.

Keywords Antarctica · Snowfall · GPS ZTD · Seismic swarm · SWIR

1 Introduction

Antarctica, the most exciting continent of modern times, is known for hostile living conditions due to the prevailing extreme cold and dry climate over this icy continent. The severe weather conditions in the Antarctic coast include frequent heavy wind gusts (strong winds), blizzards, and occasional intense snow falls (Weyant 1966; Parish 1982; Deshpande and Tripathy 2010). The interior of Antarctica records an average temperature of

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−70 and −35 °C during winter and summer, respectively; however, the coastal zones have warm temperature conditions in the range of −15 to −32 °C in winter and −5 to +5 °C in summer. Thus, the region is characterized by little (or no) precipitation (Bromwich 1990; Turner et al. 1997; Cullather et al. 1997). The annual snow fall in Antarctica is about 50 mm of rain equivalent, but the estimate ranges between 119 and 197 mm year^{-1} at the coastal regions (Monaghan et al. 2006).

The Indian Antarctic base station Maitri is located in the Schirmacher Oasis at the northern margin of East Antarctica, about ~80 km inside of the Prince Astrid's coast. In the year 2004, the annual snow fall recorded at Maitri was 81.5 mm (Deshpande and Tripathy 2010). During June 2004, which falls in the polar night period observed at Maitri from 20 May 2004–22 July 2004, unusual heavy snow fall of 45 mm occurred as compared to the normal snow fall around the year (Deshpande and Tripathy 2010). The large quantity of snow fall requires significantly high amount of water content in the troposphere, which is interesting since the region generally has low level of precipitation.

The variations in water vapour content of the troposphere can be studied qualitatively and quantitatively from the delay experienced by GPS signals during their passage through the atmosphere (Saastamoinen 1970; Nilsson and Elgered 2008; Bevis et al. 1992). The delay caused by the troposphere component of the atmosphere, which is known as the Zenith Total Delay (ZTD), consists of Zenith Wet Delay (ZWD) and Zenith Hydrostatic Delay (ZHD), which are due to the wet water vapour and dry gaseous components in the troposphere, respectively (Nilsson and Elgered 2008). The ZHD component is related to the atmospheric pressure at the surface with a slow and negligible temporal variation. The wet component ZWD is controlled by the water vapour in the atmosphere with significant variations in space and time. Thus, observed changes in ZTD are commonly attributed to water content variation in the troposphere. This parameter is used to study changes in the water vapour content due to various meteorological events and applications such as in numerical weather prediction (Bocolari et al. 2002; Seco et al. 2009; Jin et al. 2007; Akilan et al. 2015a). In this paper, we study the perturbations in the tropospheric water content in terms of ZTD changes, over the northern margin of East Antarctica during the period of intense snow fall event in June 2004. Since the high snowfall events occurred during the polar nights with a complete absence of sun in the area, it can be argued that the atmospheric changes (climate/weather) are not influenced by solar activity or radiations, but must have a different cause. Hence, we investigate the probable reasons for the presence of high precipitation (water content) in an, otherwise, dry atmosphere over the region.

2 ZTD estimation from GPS data

The meteorological application of GPS data makes use of the tropospheric delay of the GPS signal reaching the receiver (Davis et al. 1985). As already mentioned, the total delay imparted by the troposphere (ZTD) consists of two components, namely ZWD due to the wet water vapour and ZHD caused by the dry gaseous constituents (nitrogen—78 %, oxygen—20 %, and other gases—1 %) in the troposphere (Nilsson and Elgered 2008). The ZWD is the minor component (~10 %) of the ZTD, and it is proportional to the tropospheric integrated water vapour (IWV) content, where $IWV = \int_0^\infty \rho_w \mathrm{d}Z$; ρ_w—density of water vapour, dZ—vertical coordinate. The distribution of air gases within the troposphere is essentially uniform, whereas the water vapour shows high temporal and spatial variability. Therefore, though the ZHD is the major part of ZTD, the variations in ZTD mostly represent variations in ZWD and hence changes in water vapour content. Since ZHD is proportional to the surface pressure, it may also contribute to the ZTD variation at conditions where sudden changes of the surface total pressure occur. The water vapour content, defined as the height of an equivalent liquid water column of the atmosphere in zenith direction, refers to the precipitable water (P_w), which can be estimated from ZWD as (Nilsson et al. 2013):

$$P_w = k\Delta L_w^z \tag{1}$$

where ΔL_w^z is the ZWD and $= \frac{10^6 M_w}{\left[k'_2 + \frac{k_3}{T_m}\right] R \rho_{wl}}$, where $k'_2 = 16.52$ K/mbar and $k_3 = 3776 \pm 0.004 \times 10^5$ K^2/mbar are the constants (Askine and Nordius 1987), M_w is the molar mass of water (18.0152 g/mol), T_m is the mean temperature $\approx 70.2 + 0.72$ T_0, T_0 is the Earth surface temperature, R is the universal gas constant, $R = 8.314$ J/mol, and ρ_{wl} is the density of liquid water in kg/m^3.

In this study, data from four GPS stations located at different places along the northern margin of East Antarctica are used. The four stations include the GPS station at Maitri (MAIT) operated by CSIR-National Geophysical Research Institute (CSIR-NGRI), India, and three IGS stations, namely Syowa (SYOG), Davis (DAV1), and Palmer (PALM) (Fig. 1). CSIR-NGRI maintains the MAIT station equipped with Trimble 9 channel dual frequency GPS receiver. The GPS signals were recorded with a uniform sampling rate of 15 s. The tracking of satellites at too low elevation was avoided by keeping the elevation cut-off angle of the GPS antenna to 5°. Choke ring antenna was used to eliminate the multipath signals. The recorded data in binary format were converted to Receiver Independent Exchange (RINEX) format (Galas and Kohler 2001) for further processing and analysis (Table 1; Akilan et al. 2013).

The raw GPS data from 20 May 2004 (GPS day 141) to 22 July 2004 (GPS day 204), coincident with the high snow fall occurrence during June 2004 at Maitri, were processed using the Bernese 5.0 software (Dach et al. 2007). The Bernese software assumes an

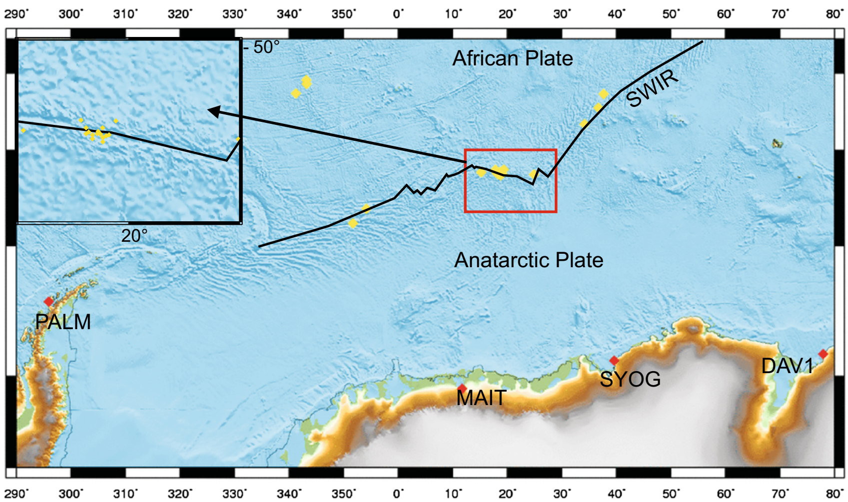

Fig. 1 Seismic events recorded during the 2004 polar winter are shown over the bathymetry of the region. The GPS stations are marked by *red symbols*. The *red rectangular block* shows the area noted with earthquake swarms. The *inset* shows a closer look of the earthquake swarms. *SWIR* South West Indian Ridge

Table 1 Location details of the GPS stations used in this study

Station ID	Location	Latitude (°)	Longitude (°)	Remarks
MAIT	Schirmacher Oasis, Antarctica	−70. 77	11.73	NGRI permanent station
SYOG	East Ongle Island, Antarctica	−69.01	39.58	IGS station
PALM	Palmer station, Antarctica	−64.78	−64.05	IGS station
DAV1	Davis, Antarctica	−68.58	77.97	IGS station

azimuthally homogeneous atmosphere. Terrestrial reference frame coordinates of the station MAIT were fixed using ITRF-97 for data processing. The ambiguities in the carrier phase were corrected by eliminating the receiver clock error, satellite clock error, and cycle slip. The double-differenced network solution was used for carrier phase correction. The mapping function of Niell (1996) included in the Bernese processing software was used to compute the hourly ZTD values over the four GPS stations. The correction models used are: IERS2003 for solid tide correction, GOT00.2 for ocean tide model, FES99 for long-period ocean tide, and L3 frequency to overcome the errors due to the ionosphere. The ZTD time series for all the four stations are shown in Fig. 2. The root mean square error of the ZTD estimation for the stations DAV1, MAIT, SYOG, and PALM is 3.57, 3.22, 4.81, and 3.48 mm, respectively.

3 Results

The ZTD data recorded by the four sites located on the northern coast of East Antarctica broadly range from 2050 to 2450 mm during the polar night period in June 2004. Temporal changes in ZTD are seen on daily basis at every station. Relatively higher and persistent ZTD values are observed at MAIT and SYOG stations between the GPS days 162 (10 June 2004) and 176 (24 June 2004) that overlap with the time period of high snow fall at Maitri. During the same month of June 2004, high snow fall events took place at MAIT and recorded 45 mm of snowfall in an 11-day period, which is very much higher than the values reported for other months of the same year (Deshpande and Tripathy 2010). Thus, the elevated ZTD values induce the anomalously high snowfall events occurred at MAIT. Similarly, the higher ZTD values observed at SYOG during the same period also represent a similar snowfall event. However, no such changes in ZTD during the period of such high snowfall events are visible from sites PALM and DAV1.

To verify the reliability of our ZTD estimates, we compared the results with those derived from numerical weather models (NWM) (Boehm et al. 2006; Bock et al. 2014) published by the European Centre for Medium Weather Forecasting (ECMWF) [http://www.ecmwf.int/]. For this purpose, we used the ZHD and ZWD values produced by the ECMWF numeric weather models and the sum of the above two gave the numerical ZTD value. The comparison was carried out for the IGS stations SYOG and DAV1 using the data retrieved from the URL http://ggosatm.hg.tuwien.ac.at/. The comparison shows reasonable agreement between the ZTD values of the two different computations (Fig. 3). The good consensus between the two different ZTD estimates can also be confirmed from the statistically significant *t* test value that showed more than 95 % confidence level. We could not perform this comparison for MAIT as this is not an IGS station, for which NWM data are not available.

We also estimated the quantity of precipitable water in the atmosphere (P_w) using Eq. (1). The ZWD values (ΔL_w^z) in Eq. (1) were obtained by subtracting the NWM-derived

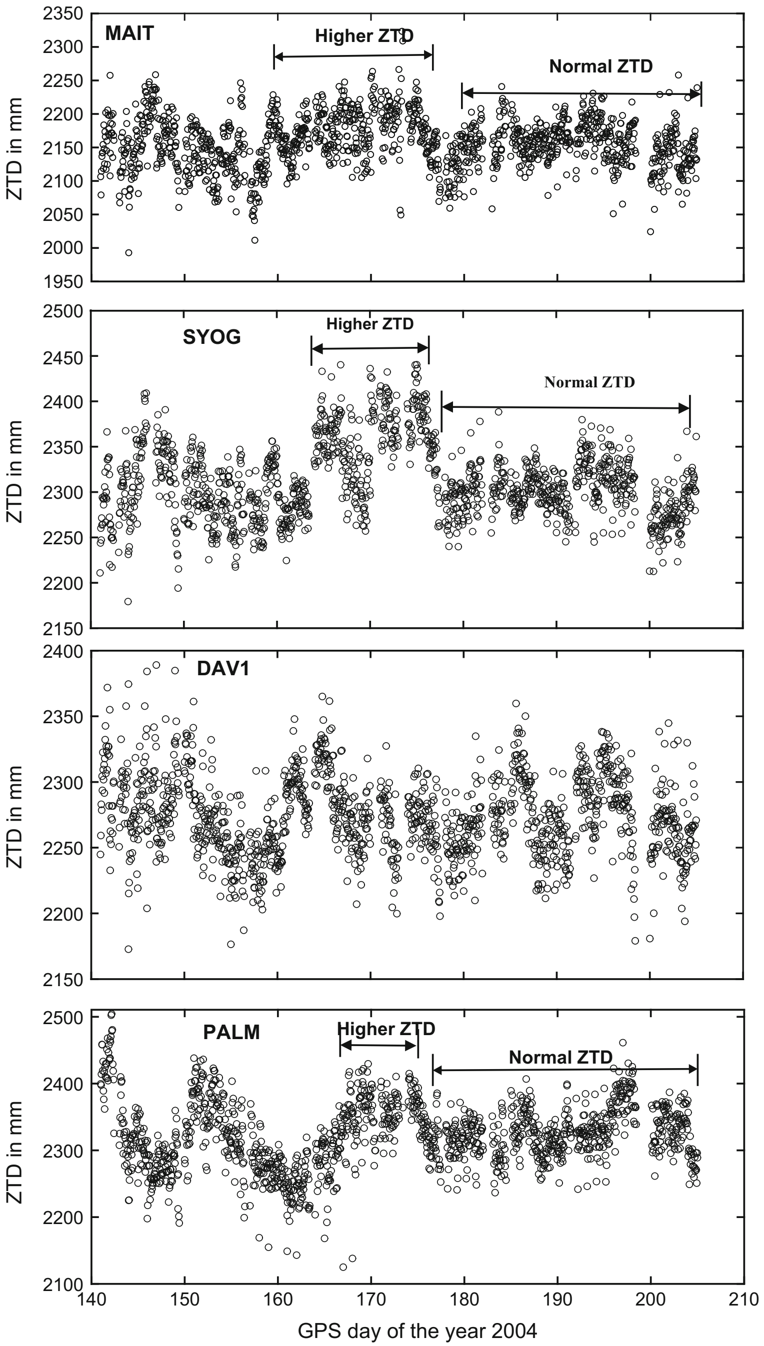

Fig. 2 ZTD time series computed for the four different GPS stations in Antarctica

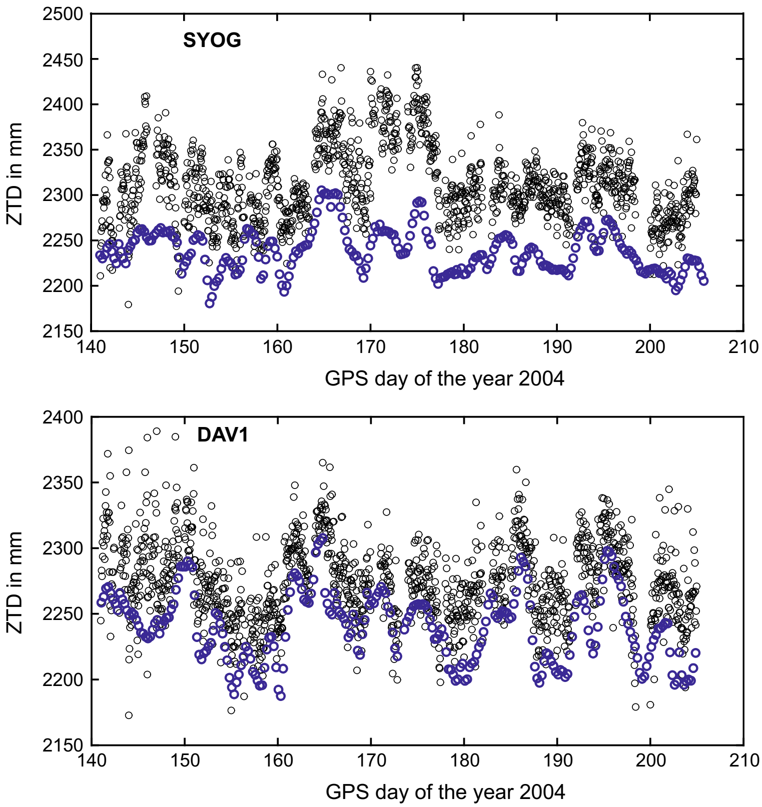

Fig. 3 Comparison of ZTD estimates made using GPS data (*open black circles*) and NMW (*open blue circles*) for SYOG (*top*) and DAV1 (*bottom*)

ZHD estimates from the GPS-estimated ZTD values. We estimated the precipitable water at SYOG and DAV1 (Fig. 4), assuming the values of M_w (0.0180152 kg/mol) and Md (0.028964 kg/mol). The mean temperature (T_m) value used in the P_w computations was obtained from the Vienna University of Technology Database (http://ggosatm.hg.tuwien.ac.at/DELAY/ETC/TMEAN/). For both SYOG and DAV1, the ZTD and P_w time series shows similar pattern of change in the time series (Figs. 3, 4), which suggests that the increase in ZTD is purely due to an increase in water vapour content. The atmosphere over SYOG shows high water content during the occurrence time of the unusual snowfall (Fig. 4). The P_w data for site DAV1 do not show any change in these values corresponding to the changes seen at SYOG and MAIT.

4 Discussion

The atmosphere over Antarctica is generally dry, although slight moisture is common in the coastal zones (e.g. Thomas et al. 2011). Hence, extremely low atmospheric water discharges, such as snow and/or rainfall, occur over Antarctica. In general, the atmosphere over Maitri is extremely dry, mostly without any water content during the winter

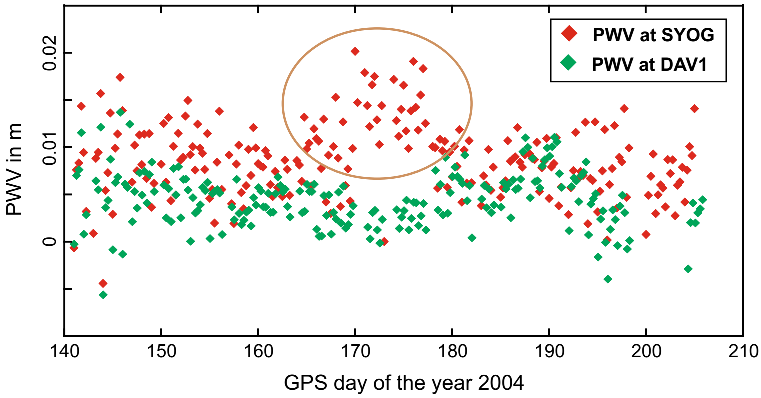

Fig. 4 PWV variation observed at the GPS locations SYOG and DAV1. The higher PWV values observed over SYOG are highlighted

(Venkateswarulu and Singh 2000; Jain et al. 2008b); hence, the heavy snowfall reported at Maitri station in the peak winter time of June 2004 is quite unusual and represents a very rare event. However, some occasional heavy snowfall was reported, which indicate a high precipitation level in the atmosphere over the area. However, such high precipitation is least possible under the prevailing weather conditions, absence of sunny weather during the winter period time in Maitri and surroundings. Hence, it is reasonable to argue that the precipitation and associated evaporation processes might have occurred at farther locations and migrated to the atmosphere over Maitri and its surroundings. Since the high snowfall events discussed in this study occurred during the polar nights with a complete absence of sun rays in the area, it can be argued that the atmospheric changes (climate/weather) are not influenced by solar activity or radiations, but must be attributed to a different cause.

The South West Indian Ridge (SWIR) is a major active tectonic feature in the Southern Ocean that is located ~1500 km north of MAIT and SYOG stations in the northern coast of East Antarctica (Fig. 1). This slow spreading ridge (spreading rate between 13 and 18 mm/year) (e.g. DeMets et al. 2010; Akilan et al. 2015b) is characterized by significant upper crustal seismicity (Negishi et al. 1998; Premkishore et al. 2006; Rao et al. 2007; Srinivas et al. 2008; Akilan et al. 2010; Rao et al. 2012). Table 2 lists the earthquakes occurred in the SWIR segment between the Bovet hot spot (54°24′S, 3°24′E) and Marion (46°54′S, 37°36′E) during the complete polar night period. Table 2 shows that a seismic swarm has occurred between 26 and 31 day of May, 2004. The earthquake swarm activity in this magma spreading segment, which is under the influence of the Bouvet and Marion hot spots (e.g. Georgen et al. 2001), could be of volcano-tectonic origin.

In the polar winter period, several earthquake events (swarm) originated at different segments of the SWIR arm between 10°W and 40°E longitudes (Fig. 1). The volcano-tectonic seismic events associated with the magma injections at the upper crustal depths and/or eruptions onto the ocean surface indirectly indicate the release of heat energy to the ocean bottom and overlying water column. Moreover, thermal energy is also supposed to be radiated from the earthquake source, whose effect is felt near the epicentre zones (Pulinets et al. 2003; Ouzounov and Freund 2004; Pulinets et al. 2006; Saraf and Choudhury 2005; Yuan-Sheng et al. 2011). Thus, an elevated temperature at the sea bottom associated with the volcano-tectonic events is capable of increasing the temperature of the

Table 2 Earthquake events occured in the southern ocean during 2004 Antarctica polar night

Date	Date	Time	Latitude	Longitude	Depth	Mag (mb)
146	2004-05-26	10:33:55.66	−52.6593	18.7227	10.0	4.2
146	2004-05-26	11:20:58.28	−52.6249	18.6201	10.0	4.8
146	2004-05-26	11:27:23.47	−52.7723	18.8633	10.0	3.9
146	2004-05-26	19:52:36.39	−52.6465	18.6243	10.0	4.7
147	2004-05-27	09:02:06.36	−52.8706	18.8295	10.0	4.0
147	2004-05-27	13:10:16.04	−52.6516	18.0764	0.0	4.0
147	2004-05-27	13:33:59.77	−52.7685	18.3921	10.0	4.5
147	2004-05-27	15:30:56.01	−52.7232	19.0095	10.0	4.0
147	2004-05-27	20:49:26.50	−52.6839	18.3663	10.0	5.0
148	2004-05-28	06:16:45.66	−52.2840	19.4020	10.0	4.2
149	2004-05-28	21:42:50.36	−46.8414	34.2569	0.0	3.8
150	2004-05-29	09:18:15.92	−52.4861	18.8210	10.0	4.0
150	2004-05-29	09:39:02.29	−52.6971	19.0809	10.0	4.0
151	2004-05-30	00:26:31.39	−52.6011	18.1935	10.0	4.6
151	2004-05-30	00:34:59.13	−52.2758	17.8409	10.0	3.6
151	2004-05-30	00:39:09.02	−52.4843	18.0738	10.0	4.4
152	2004-05-31	18:29:56.41	−56.4162	−5.7953	10.0	4.3
153	2004-06-01	01:52:54.77	−52.5553	15.2432	0.0	3.9
157	2004-06-05	22:02:16.86	−44.7321	36.7479	10.0	4.2
163	2004-06-11	08:09:19.21	−41.5443	−16.7179	10.0	4.1
164	2004-06-12	12:41:47.37	−57.8852	−8.2504	10.0	4.7
169	2004-06-17	02:00:52.43	−52.7990	24.9626	10.0	4.1
169	2004-06-17	22:04:07.31	−40.9719	−16.7834	10.0	5.2
171	2004-06-19	09:53:21.99	−42.9156	37.7002	0.0	3.5
187	2004-07-05	06:41:38.62	−42.8374	−18.6859	10.0	4.1

sea water column and consequently could accelerate the evaporation process. Such accelerated evaporation would bring larger volume of hot air (hence high pressure) to the atmosphere over the SWIR. This hot air with more water vapour content will move towards the colder atmospheric zones over the southern latitudes and hence may reach to the regions over Antarctic continent. Due to the significant difference in atmospheric temperature between the warm oceanic and frozen Antarctica continental regions, the warm water vapour entering the coastal zones of Antarctica could produce low-pressure conditions over the atmosphere, which eventually leads to the condensation of water vapour and discharge through heavy snow falls/blizzards.

We infer that the elevated water content inferred from the increase in tropospheric parameters (ZTD and PWV) over the MAIT and SYOG stations could be the reflection of the additional water vapour generated over the SWIR during the swarm period, which due to additional subsurface heat generation associated with the seismic events, further moved to the south and reached the Antarctica coast. The mechanism for the rare high snowfall during the peak winter in Antarctica can thus be related to the magma movement in the SWIR spreading zone. Several studies observed the presence of gaseous and other components of volcanic origin in the atmosphere over Maitri. For example, high variability of carbon monoxide (42.77–73.25 ppb) (Kulkarni et al. 2010), and varying levels of CH_4 and CO_2 (Jain et al. 2008a), along with sulphate or droplets of Sulphuric acid (Pant et al. 2012), SO_2 and NO_2 (Kulandaivelu and Rao 2005) in the troposphere around the Maitri station can be related to volcanic eruptions (Boichu et al. 2011) and may have transported to the area by the wind. The increasing concentration of aerosols beyond 40°S (Deshpande and Kamra 2000), and its very high concentration around 50°S latitude (Gupta and Qasim 1983), which decrease gradually towards the East Antarctica coast, suggests that the source of volcanic activity is near around mid-fifty southern latitudes and the aerosols get consumed in various atmospheric processes, such as precipitation towards Antarctica in the southern direction. Shallow ice cores from the area (69°S, 11°E) have shown spherules of volcanic origin (Vohra 1983). Since there is no evidence of volcanic activity near Maitri station, the source of volcanic materials is somewhere else. The nearest intense volcanic activity is the mid-oceanic ridge system to the north of East Antarctica, particularly the SWIR surrounded by the Bouvet and Marion hot spots (Georgen et al. 2003; Burnard et al. 2014; Cartigny et al. 2001).

The swarm may occur during subsurface magma movements and volcanic eruptions. The magmatic over-pressure is more than the sea water pressure in the mid-oceanic ridges at the time of volcanic eruptions (Colin et al. 2013). Therefore, the fine volcanic elements along with various gaseous elements could reach above the sea level and subsequently into the atmosphere. The atmospheric water vapour produced over the area above SWIR, due to excess evaporation induced by the subsurface heat transferred to ocean bottom through magmatic activity, will travel to different locations in the atmosphere depending on the wind pattern and directions and hence having moved towards the northern coast of Antarctica. This would explain the elevated ZTD and PWV values observed over the stations MAIT and SYOG a week after the swarm activity. The delay between the swarm occurrence at mid-oceanic ridge and the onset of higher ZTD over MAIT and SYOG could represent the transportation time of the water vapour over the swarm location to the coastal areas of East Antarctica. No GPS data are available from locations near to the area of swarm activity; hence, the ZTD and water vapour content changes in its immediate vicinity cannot be studied. Our GPS-derived ZTD data show that this transfer of water from distant oceanic areas is visible at MAIT and SYOG, which are located down south of SWIR. Similar ZTD anomalies are not seen at DAV1 and PALM stations, suggesting that wind pattern was such that most of the transportation may be confined to regions around the stations MAIT and SYOG. A probable explanation for the absence of notable ZTD changes (due to change in atmospheric water vapour content) at DAV1 and PALM as compared to MAIT and SYOG is that the water vapour associated with the swarm activity might have moved directly southward, which most likely might have been controlled by wind direction, and affected the nearest coastal locations. Thus, the water vapour produced by the swarm activity may not have reached the stations DAV1 and PALM, which are not lying directly south of the swarm area and located much away from the swarm location. The ZTD increase is more pronounced for SYOG than MAIT, which might be due to the spatial location of these sites. SYOG is nearer to the coast than MAIT, which is $\sim$100 km inside the continental shelf.

Heavy snowfalls and rains were observed following the occurrence of large earthquakes (Yuan-Sheng et al. 2011). Anomalously high near-ground air temperature during polar night period in comparison with those of other periods was observed during persistent seismic activities (Pulinets et al. 2006), and the observed thermal anomalies were related to occurrence of larger earthquakes (Prakash and Srivastava 2015). Variability in the thermal structure of ocean waters due to strong seismic activity was also reported (Levin et al. 2006).

5 Summary and conclusion

An unusual high snowfall was recorded at the Indian Antarctic station Maitri during the polar night period of June 2004 in East Antarctica (Deshpande and Tripathy 2010). We studied the perturbations in atmospheric water vapour observed during the 2004 polar night in terms of ZTD and PWV values estimated from GPS signals recorded at Maitri station (MAIT) and IGS GPS sites located along the northern margin of East Antarctica, i.e. SYOG, DAV1, and PALM. The GPS data from the four sites show significantly high ZTD values at MAIT and SYOG from the GPS day 162 (10 June 2004) to 176 (24 June 2004), during which heavy snowfall was reported from MAIT. As the change in ZTD reflects a change in water content of the atmosphere, the correspondence between the snowfall events and presence of elevated ZTD values over the area can be linked to represent high concentration of water vapour. This correspondence becomes clearer from the PWV estimates derived using the ZTD estimates and other parameters retrieved from a numerical weather model. However, we do not see such changes in atmospheric water content at PALM and DAV1 stations.

The odd occurrence of heavy snowfall during the peak cold weather conditions suggests that the precipitation required for heavy snowfall might have happened at far distant locations, where suitable conditions were available for precipitation, and moved to the East Antarctica coast zones by suitable atmospheric wind directions. As the wind moves from hotter region to colder region in the atmosphere and the low latitude regions in the southern hemisphere have colder atmospheric conditions during the polar winter periods as compared to the higher latitude regions, the origin of water-rich air must have travelled from north of East Antarctica coast into the Antarctic continent. When the hot air containing water molecules from the north interacts with the cold atmospheric temperature conditions over the Antarctica margin, the water particles get discharged immediately in the form of snowfall. The SWIR located about 1500 km north of Antarctica coast has shown significant swarm activity, which was observed a week prior to the high snowfall events at East Antarctica coast locations. From the circumstantial evidences, we infer that the increased evaporation and hence increased water vapour induced into the atmosphere over the SWIR region are due to the thermal energy radiated to the ocean bottom at this active spreading zone, where the seismic events are generally associated with subsurface magma movement and ejections on to sea floor. We conclude that the increased water vapour at MAIT and SYOG could be due to the atmospheric water moved from the SWIR region to the south, where it met the cold front at East Antarctic coast yielding snowfall.

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