

Correlative evidences of monsoon variability, vegetation change and human inhabitation in Sanai lake deposit: Ganga Plain, India

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Lake-fill deposits spanning the last 15,000 years provide the first dated record of changes in vegetation, human inhabitation and monsoon variability during the latest Pleistocene–Holocene in the Ganga Plain. The lake vegetation, pollen of plants cultured by man, carbon isotopes and lithology exhibit marked changes with changing monsoon rainfall. A relatively dry spell for 15,000–13,000 ¹⁴C yrs BP humid conditions from 13,000 to 5800 ¹⁴C yrs BP and again dry conditions from 5000 to 2000 ¹⁴C yrs BP are identified. From ~1700 ¹⁴C yr BP, there is evidence of climatic amelioration. A prominent dry spell corresponding to the Younger Dryas event is identified around an estimated age of 11,500–10,500 ¹⁴C yrs BP and is accompanied by evidences of decreased human activity during this phase.

Keywords: Ganga Plain, human inhabitation, monsoon variability, Sanai lake, vegetation change.

THE objective of this study is to provide palaeoclimatic information from the heart of the Indian subcontinent, one of the poorly understood areas of the tropics, where rainfall is essentially controlled by the monsoon variability. Most climatic reconstructions so far are based on deep-sea or ice-core records, which allow only indirect inferences on environmental changes on the continents. Reconstruction of monsoon and inferences on climate change in India are based on deep-sea cores from the Arabian Sea and the Bay of Bengal^{1–13}. Some palaeoclimatic reconstructions are also available from Rajasthan^{14–18}, Himalaya^{19–24}, Ganga Plain^{25,26} and the Nilgiris²⁷. However, reconstructions on refined scale are useful considering large spectral variability of monsoon rainfall²⁸. No well-dated, comprehensive records on palaeoclimatic variations are available from the Indo-Gangetic Plains. In this study, we provide a palaeoclimate reconstruction in the Ganga Plain for the last 15,000 years and have also made an attempt to relate these palaeoclimatic variations to changes in human inhabitation.

The Ganga Plain is one of the largest alluvial plains of the world. Quaternary deposits are exposed in various cliff sections, and attempt has been made to date these sections by luminescence methods²⁹. These sediments are highly oxidized, and only mineralogical and geochemical studies can be carried out to infer the palaeoclimate. However, upland interfluvial areas (T₂ surface) in the central Ganga Plain show the presence of a number of small and large shallow water bodies referred to as ponds or lakes, which are part of abandoned channel belts, meander cut-offs and disrupted drainage systems^{30,31}. Here, we present detailed studies of 15,000 year long chronology from deposits of Sanai Lake (Figure 1), a meander cut-off related to an abandoned channel belt. At present, except during monsoon months it is dry most of the year. A trench was dug into the lake bed down to a channel sand layer at a depth of 2.10 m. Detailed lithology of the profile is shown in Figure 1. The samples were analysed for pollen abundances, carbon isotopes of organic matter and sediment geochemistry. Radiocarbon dates were determined on total organic carbon from seven sediment samples using the AMS facility at the Physics Department, University of Erlangen, Germany. All ages reported are uncalibrated conventional radiocarbon dates given in years before present. For carbon isotope analysis of total organic carbon, sediment samples were treated with 1 N HCl in order to dissolve any carbonate. When visible reaction ceased, the residues were washed several times with distilled water. The residues were dried at 50°C and homogenized. The carbon isotopic composition was measured by combusting the samples in a Carlo–Erba element analyzer connected to a Thermo Finnigan Delta plus mass spectrometer. Precision for $\delta^{13}\text{C}_{\text{org}}$ analyses based on duplicate analyses is better than $\pm 0.1\text{‰}$ (1 S.D.). All isotopic values are reported in the standard δ -notation in permil relative to V-PDB. For major and trace element analysis, 1 g of sediment was weighed in a porcelain crucible. To avoid any contamination, all porcelain crucibles were cleaned with concentrated HCl and dried at 120°C. About 4.830 mg lithium tetraborate and 1–2 mg di-iodine pentaoxide were added to the sediment samples. After homogenization, the samples were heated in platinum containers and pellets were prepared. Major (SiO₂, TiO₂, Al₂O₃, Fe₂O₃, MnO, MgO, CaO, Na₂O, K₂O and P₂O₅) and trace element contents (V, Cr, CO, Ni, Cu, Zn, Y, Zr, Nb, Rb, Sr and Ba) were investigated using a Philips PW 2400 X-ray spectrometer. Precision and accuracy of the data were checked using international reference samples (JSd-1, JSd-2, JLk-1, SARM-46, SARM-52, JB-2, JGb-2 and IAEA-SL-1), which were measured as ‘unknowns’ with samples and sample duplicates.

The basal part of the lake fill in zone II (just above the channel sand layer of zone I) gives an age of $14,833 \pm 147$ ¹⁴C yrs BP, and we assume that the change from fluvial deposition to lake deposition took place 15,000 years ago. The lower part of the lake fill deposits, i.e. zone II

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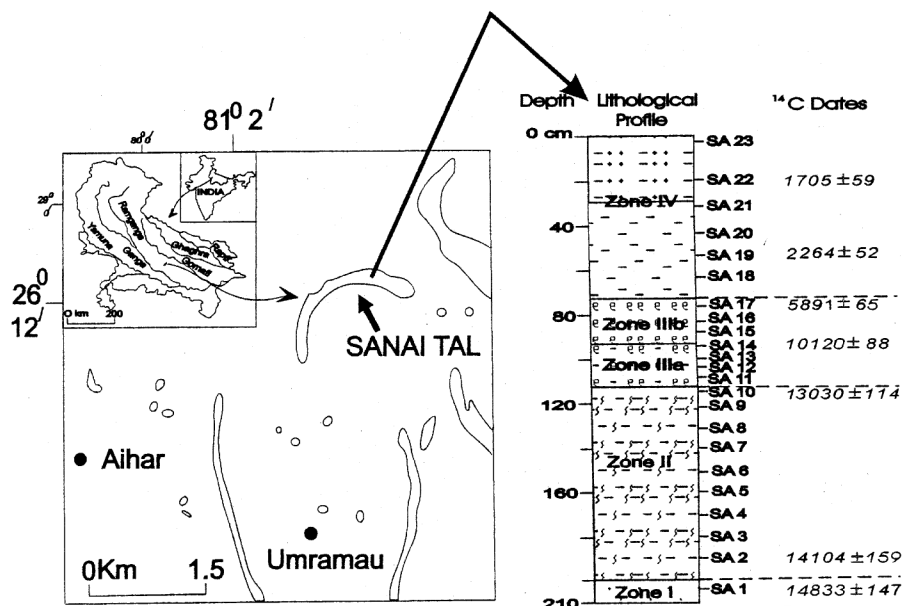


Figure 1. Location map of Sanai lake. The lithology consist of a fine sand layer overlain by a sandy clayey silt lithology followed by a black clayey silt layer and Marl zone. Top part of the profile is composed of a black clayey silt layer capped by the sub-soil. Sampling interval is ~10 cm in terrigenous clastic sediments and ~5 cm in the shell zone. Exact position of samples is marked in the litholog along with the respective uncalibrated ^{14}C AMS dates.

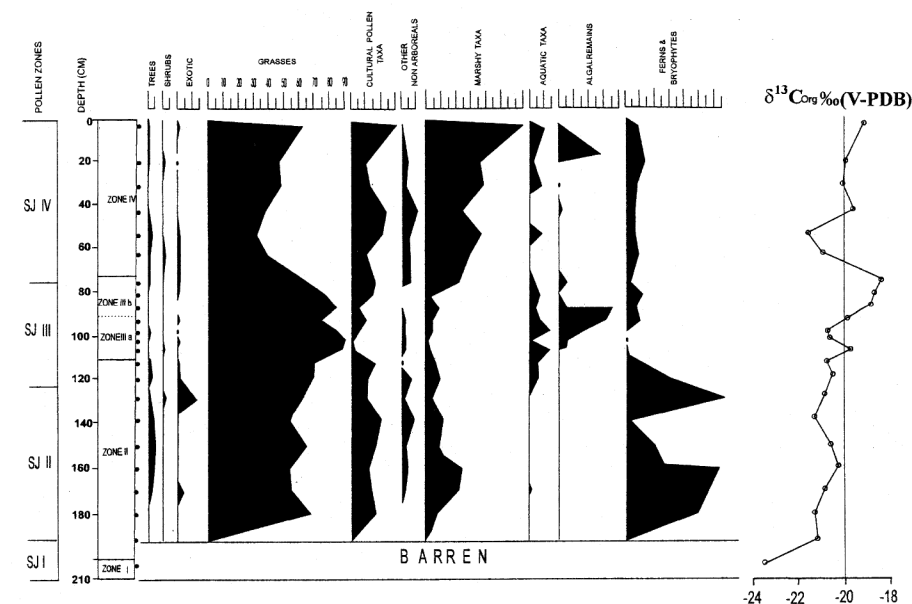
(~15,000–13,000 ^{14}C yrs BP) indicates fast sedimentation rate of ~41 cm/1000 yr followed by slow rate of depositions of ~7.7 cm/1000 yr (13,000–10,000 ^{14}C yrs BP) in zone IIIa and 4 cm/1000 yr (10,000–5800 ^{14}C yrs BP) in zone IIIb. The upper part of the profile (2000–1000 ^{14}C yr BP) shows a fast sedimentation of ~57 cm/1000 yr.

A summary of the pollen diagram for this sequence shows four pollen zones (Figure 2). Cultural pollens (Cerealia associated with Chenopodiaceae/Amranthaceae, Caryophyllaceae, Utricaceae, etc.) are present throughout the succession, indicating human activity in the region throughout the lake history. The pollen data reveal that the area of the Sanai lake was dominated by grasses throughout the recorded depositional history (Figure 2). Measured $\delta^{13}\text{C}_{\text{org}}$ values of sedimentary organic carbon of the samples from the lake profile range from –18 to –24‰. To understand the $\delta^{13}\text{C}_{\text{org}}$ variations, some measurements were done on modern vegetation. Isotopic analysis of the perennial grass *Dicanthium annulatum*, which today is common in the Ganga Plain, gave a $\delta^{13}\text{C}$ value of –12.2‰. In contrast, average $\delta^{13}\text{C}$ values of modern algae, aquatic plants, ferns and marshy taxa from Sanai lake area are in the range –20 to –29‰ (see Table in Figure 2). This suggests that there was significant contribution from algae, lacustrine plants, ferns and marshy taxa to the total organic carbon of the lake sediments, besides grasses. Variation in $\delta^{13}\text{C}_{\text{org}}$ in the lake profile is correlated with changes in relative representation of the different types of vegetation throughout the lake history.

Pattern of pollen distribution, $\delta^{13}\text{C}_{\text{org}}$ and sediment lithology show significant variations in the profile. The palaeoclimatic information obtained from this multiproxy data can be related to changes in SW monsoon intensity during the last 15,000 years as the SW Indian Ocean monsoon system had a major impact on climatic changes in Asian and African regions, probably during the entire Quaternary.

Formation of the Sanai lake took place around 15,000 ^{14}C yrs BP in the form of a meander cut-off of the abandoned channel belt of the region. The sandy deposit before 15,000 ^{14}C yrs BP (zone I) represents an active channel deposition during LGM. This phase is characterized by stray occurrence of grass pollen; hence no definite inferences can be drawn regarding the palaeovegetation scenario. The mottled sandy silty clays of zone II indicate that the channel was abandoned and got converted into a lake. Lack of aquatic pollen and abundance of pollen from sedges and ferns (Figure 2), suggest that rainfall was not enough to support a large water body; so the lake was shallow with prominent marshes. The lighter $\delta^{13}\text{C}_{\text{org}}$ values could be related to higher contribution from isotopically light ferns. The climate was probably relatively less humid. The low vegetation cover would have resulted in high rate of erosion and subsequently high rate of sedimentation (~41 cm/1000 yr). Some palaeoenvironmental interpretations from the Arabian Sea region also report^{5,6} a drop in SW monsoon intensity at about 14,400 ^{14}C yrs BP.

The deposit of 13,000–5800 ^{14}C yrs BP interval (zone III) is predominantly made up of shell-rich sediments



Plant material	$\delta^{13}\text{C}_{\text{org}} \text{‰ (V-PDB)}$	Plant material	$\delta^{13}\text{C}_{\text{org}} \text{‰ (V-PDB)}$
Perennial grass (<i>Dicanthium</i> sp.)	-12.18	Marshy plant (<i>Polygonum</i> sp.)	-28.7
Aquatic grass	-12.78	Aquatic plant (<i>Iopomea</i> sp.)	-28.29
Fern (<i>Pteris</i> sp.)	-27.75	Aquatic plant (<i>Potamogeton</i> sp.)	-23.43
Algae	-19.78	Aquatic plant (<i>Typha</i> sp.)	-29.65

Figure 2. Summary pollen diagram of the sequence. Basal zone (zone SJ-I) is palynologically barren. Zone SJ-II has predominantly grasses (Poaceae), marshy taxa like sedges (Cyperaceae), ferns (monoletes and triletes) and bryophytes. Aquatic pollens are absent. Zone SJ-III is characterized by an increase in grasses, aquatic plants (*Typha* sp., *Potamogeton* sp.) and algal remains (*Botryococcus* sp.). At the same time, there is a decrease in ferns, bryophytes and marshy plants. This zone corresponds to a phase of maximum lake expansion. It also shows a prominent positive shift in $\delta^{13}\text{C}_{\text{org}}$ except two samples SA12 and 13 in zone IIIa. Zone SJ-IV shows an increase in pollen of marshy taxa (*Polygonum* sp.) and a decline in grasses, aquatic plants and algal remains. However, towards the top the representation of grasses, algae and aquatic taxa (*Lemna* sp., *Nymphoides* sp., *Potamogeton* sp.) increases and $\delta^{13}\text{C}_{\text{org}}$ values become heavier. The table below gives $\delta^{13}\text{C}$ values of modern vegetation from Sanai lake area.

with an extremely slow rate of sedimentation (~ 7.7 cm/1000 yr in the lower part and 4 cm/1000 yr in the upper part). It indicates an expansion of the lake which is also supported by prominent contribution of aquatic plants and contemporary decline in the marshy taxa sedges. It can be inferred that around 13,000 ^{14}C yrs BP, rainfall increased and led to submergence of marshy and adjoining areas, converting them into a lake (Figure 3). The positive shift in $\delta^{13}\text{C}_{\text{org}}$ can be attributed to the increase in contribution from isotopically heavy grasses and algae to the lake sediments. Supply of terrigenous clastic was reduced due to enlargement of the lake and humid climate. The sediments were quickly eroded and deposited because of a shift from a swamp to a lake environment, and hence low chemical index of alteration (CIA plot, Figure 3). Formation of the lake could correspond to an abrupt transition towards stronger SW monsoon at about 12,500 ^{14}C yrs BP, as a result of combination of variations in atmospheric circulation and disappearance of snow/ice cover in Central Asia and Tibet⁶. Around 11,500–10,500 ^{14}C yrs BP, there

is a short-lived event of distinct decline in all plant taxa; trees, shrubs, aquatic taxa, herbs and ferns, except grasses and *Botryococcus*, which exhibit increasing trend. The cultural pollen taxa also show a poor representation and CIA values also decrease further (Figure 3) in this period, indicating a dry spell with low plant growth causing a high rate of erosion in the catchment of the lake. This short phase represents deterioration of climate. The short arid phase identified around 11,500–10,500 ^{14}C yrs BP coincides chronologically with the Younger Dryas event witnessed globally. This supports the view that cooler Northern Hemisphere climate weakens the southwest monsoon³². In the upper part of this zone, 10,000–5800 ^{14}C yrs BP (zone IIIb), a large lake was established and only little sediment with intense weathering was brought into the lake, as indicated by slow sedimentation rate and sharp rise in CIA values (Figure 3). This phase is characterized by the maximum development of vegetation cover, as evidenced by the better representation of most of the taxa (Figure 2). The high prevalence of aquatic elements such

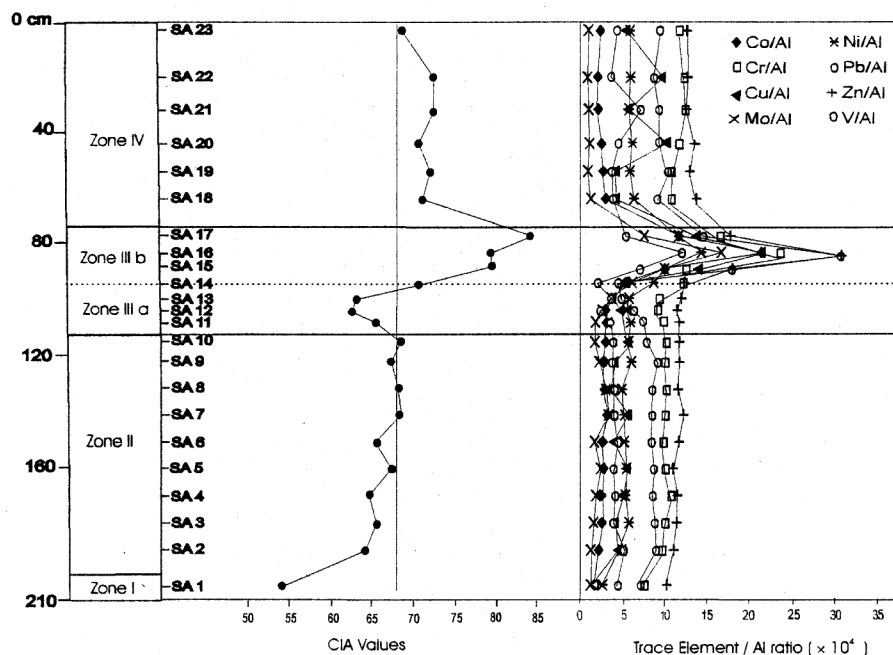


Figure 3. Depth variation of various trace elements bound to organic matter (V, Mo, Ni, Co, Cr, Cu, Pb and Zn) and chemical index of alteration (CIA) ($\text{Al}_2\text{O}_3/(\text{Al}_2\text{O}_3 + \text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO}) \times 100$). Trace element concentrations were divided by the Al contents to exclude a dilution effect by varying carbonate contents in the profile. Trace elements show homogenous concentrations, except in zone IIIb, where they are exceptionally concentrated. CIA is used as a parameter for the extent of chemical weathering. Calculated CIA values in this profile show moderate values in zones I and II. In the lower part of zone III (zone IIIa) CIA values show a prominent decrease, while in the upper part of zone III (zone IIIb), the values are extremely high.

as *Potamogeton* sp. and *Typha* sp. and decline in sedges and ferns further suggest that the lake expanded considerably. High organic productivity would have resulted in higher organic matter production, which in turn functioned as a substrate for absorbing trace elements which are known to be bound to organics (Figure 3). This scenario of lake expansion implies that the region experienced a humid climate during this period on account of the prevalence of active SW monsoon. The period of 10,000–5800 ^{14}C yrs BP denotes the time of maximum lake expansion. Increased monsoon activity in SE Asia with a peak around 6 ka is also reported from other parts of the continent^{13,15,16}.

In zone IV, the time-span of 5000–2000 ^{14}C yrs BP shows considerable reduction in aquatic elements and a simultaneous increasing trend of marshy plants such as sedges (Figure 2), suggests an increase of swamps along the lake margins. A negative shift in $\delta^{13}\text{C}_{\text{org}}$ can be related to the increased representation of isotopically light marshy taxa and decline in isotopically heavy grasses. This reduction in lake area could be due to the onset of a relatively dry spell and reduced monsoon activity. The CIA value of the sediment also decreases (Figure 3), indicating comparatively faster erosion in the catchment area. In the Central Ganga Plain, evidence of aridity at 5000 BP is also recorded in the form of disruption of fluvial chan-

nels and deposition of aeolian sand²⁹. The evidence of aridity around 5000–3000 ^{14}C yrs BP coincides well with the reduced SW monsoon activity in SE Asia reported from other areas^{4,5,17}.

In the last 2000 years (upper part of zone IV), there is an increased rate of sedimentation in Sanai tal (~57 cm/1000 yr), accompanied by evidences of climatic amelioration, i.e. increased representation of grasses, aquatic plants, algae and marshy taxa (Figure 2). This trend towards higher humidity at ~1500 ^{14}C yrs BP is also inferred from pollen data of Dunde ice-cap, Tibet³³ and speleothem evidence from Pokhara Valley, Nepal³⁴.

The pollen diagram shows dominance of grasses throughout the lake's depositional history. Contributions of trees and shrubs is low, suggesting that throughout the last 15,000 years of the lake, the Ganga Plain was essentially a Savannah landscape with some forest thickets. This contradicts the existing conjectures that until late Holocene, the Ganga Plain was covered by dense forest inhibiting humans to settle in this region. An important aspect of pollen study is the presence of cultural pollens throughout the 15,000 years of the depositional history of the lake. Agricultural activity can be well correlated to changes in pollen and climate during the lake's depositional history. During the time interval (estimated to be around ~11,500–10,500 ^{14}C yrs BP) interpreted to corre-

spond to cold and dry Younger Dryas event, the cultural pollen taxa show a prominent low and concurrently percentage representation of grasses increases. This suggests that there was reduction in agriculture activity due to arid conditions. Similarly, in zone IV (5000 ^{14}C yrs BP-present), enhancement of anthropogenic activity is evidenced by more frequent occurrence of culture pollen taxa. In this region of the Ganga Plain, there are also archaeological evidences of large-scale occupation of abandoned levees close to lakes by humans around 3500–2500 yrs BP, who predominantly practised agriculture. The clearance of land on large scale might have been carried out for expansion of agriculture land, which is supported by decline in representation of grasses. The practice of agriculture must have increased soil erosion, causing quick siltation of lakes in the upper part of zone IV. Some mesolithic sites (~9000 yrs BP) are present 100–200 km east of the study area, in the Pratapgarh district within the Ganga Plain which show evidence of agricultural practices^{35,36}. Moreover, there are numerous sites of epipalaeolithic tools in the same region, which on the basis of tool typology are considered around 18,000 yrs BP³⁵. The data further supports evidence of human occupation in Sanai lake since 15,000 yr BP.

Studies carried out so far on the lake deposits from Sanai tal^{25,37}, Basha jheel²⁶ and Lahuradewa lake³⁸ have brought out significant inferences on palaeoclimatic oscillations and commencement of agricultural practice in the Ganga Plain, based mainly on pollen and other allied disciplines. Further investigations of other potential lakes from this region using multidisciplinary approach are expected to generate more data, which could be employed to develop the precise palaeomonsoon trend for the Indian subcontinent during late Quaternary period, as well as to understand the major effect of global climatic event in this region.

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Challenges in Southern Ocean oceanographic research: Indian efforts and preliminary results

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The Indian pilot expedition to Southern Ocean was launched by the National Centre for Antarctic and Ocean Research, Goa in January 2004. During this expedition a number of studies/experiments such as atmospheric observations, physical oceanographic observations, biological studies and chemical oceanographic observations were undertaken. In addition, to understand and reconstruct palaeoclimatic conditions in this part of the world, a number of surface and sub-surface sediment samples were collected along a north-south transect from 9.69°N to 55.01°S between 80 and 40°E long. The preliminary results of these studies in varied fields are presented here. These efforts of Indian scientists on Southern Ocean oceanography have yielded valuable data. The encouraging results have their bearing on the understanding and reconstruction of the glacial hydrography, sea ice extent and changes (if any) in the position of the palaeo front during the Holocene and the LGM over this sector of the Southern Ocean.

Keywords: Antarctic continent, Indian pilot expedition, Southern Ocean.

THE Antarctic continent with its surrounding Southern Ocean represents one of the major climate engines of the earth¹. Due to their dynamic nature, the Southern Ocean processes have played a key role in the long-term global palaeo-environmental evolution². Nevertheless, the Southern Ocean has received even less attention than the high northern latitude and the oceanic records are few and sparse³. This situation is true in the Indian context as well. Oceanographic research in India has been in existence for more than four decades. However, most of the studies were concentrated on the Arabian Sea, Bay of Bengal or Indian Ocean basin and meagre attention was paid to the southern hemisphere.

The importance of the Southern Ocean for Indian marine geosciences was realized quite late and highlighted in detail by Rajan and Khare^{4,5}. It was pointed out that India must be in the Southern Ocean mainly because of palaeoclimatic studies and that a bihemispheric approach needs to be adopted. The millennial-scale climate changes seem to originate in the southern hemisphere⁵ and the Southern Ocean governs the global climate system. While the mil-

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