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A Review on Holocene Climate Changes in the Indian Subcontinent

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Abstract

Since the collision of Indian plate with Eurasia, the Indian subcontinent has experienced minor tectonic and major climatic changes. Summer monsoon plays an important role in the local and regional climate of Asia. General Circulation Model (GCM) experiments show that onset of monsoon is related to the Himalayan Mountain elevation. Near 8 Ma, the relative abundance of endemic upwelling species increases and is interpreted to reflect the intensification and onset of the strong modern monsoon circulation. Oxygen isotope data from the sediment cores of the Arabian Sea indicates that the onset of Holocene climate started around 13 ka in the Indian subcontinent. The summer monsoon intensification was initiated from 12 ka after a weak phase during the last glacial maximum. Higher lake levels and greater values of upwelling indices between 9 to 6 ka reflect the intense phase of monsoon rainfall. Pollen records from lake sediments in Rajasthan also reveal greater rainfall during 9 to 6 ka. Marine and terrestrial records document that the climate started shifting from humid to dry arid from 5 ka and reached an arid phase at 3.5 ka. In other tropics of the world also onset of arid climate was documented during the same period. The onset of arid climate at 3.5 ka in the Indian subcontinent might be responsible for weak summer monsoon rainfall. Drastic reduction in rainfall could have led to the collapse of Indus Valley Civilization and desiccation of River Sarasvati. Holocene Chronology with special reference to Indian subcontinent is proposed by synthesizing available marine, lacustrine, pollen and archeological records.

INTRODUCTION

Large climate changes on the earth during the last 18 ka have altered vegetation, ice volume, disappearance of desert lakes, extinction of many types of large mammals, and alteration in agriculture, which have changed the course of human history. The nature and timing of these changes have posed many puzzles to the scientific community. Why did monsoon vary in strength through Holocene? Does the rapid climatic shifts noticed in Asia traceable elsewhere in the tropics? What caused changes in vegetation during Holocene in the Indian subcontinent? Why were lakes desiccated during late Holocene? What kind of teleconnection exists between the high latitudes and Asian summer monsoon? To answer these questions one has to look for various sources of data such as marine, lacustrine and terrestrial and multi proxies to give meaningful interpretations. This communication is aimed at presenting

Holocene chronology and climatic changes in the Indian subcontinent based on marine, terrestrial and lacustrine records. Records of oxygen isotope, marine plankton, pollens and lake levels are chosen to arrive at quantitative or semiquantitative estimates of paleoclimate in the Indian subcontinent.

OXYGEN ISOTOPE RECORD

The pioneering study of Emiliani (1955) on oxygen isotopes suggest that $\delta^{18}\text{O}$ variations in the foraminifera reflects ambient water temperature. Subsequent researchers in this field were led to the conclusion that down core variations in $\delta^{18}\text{O}$ reflect changes in oceanic isotopic composition, and that these changes are caused primarily by waxing and waning of the great Pleistocene ice sheets (Olausson, 1965; Shackleton and Opdyke, 1973 and references therein). Oxygen isotope record therefore has become a primary tool for establishing stratigraphy of Pleistocene deep sea sediments in most of the ocean basins.

High-resolution marine $\delta^{18}\text{O}$ data from the Arabian Sea documents that the onset of Holocene climate took place around 13 ka (Sirocko et al. 1993) (Fig.1) and similarly another high-resolution $\delta^{18}\text{O}$ data from the Red Sea also

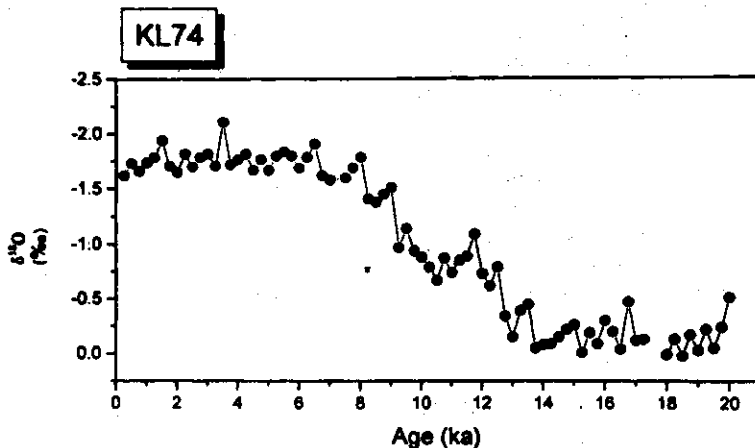


Fig.1. High-resolution oxygen isotope profile from the western Arabian Sea core KL74. Chronology is based on AMS ^{14}C dates (from Sirocko et al. 1993).

documents the onset of Holocene climate around 13 ka (Naqvi and Fairbanks, 1996). Although the onset of Holocene climate started at 13 ka, the summer monsoon intensified from 12 ka onwards as evidenced from upwelling indices data in the Arabian Sea (Divakar Naidu and Malmgren, 1996).

VARIABILITY OF MONSOON RAINFALL

Marine plankton responds to physical and chemical variations in the

surface waters of the world oceans. During summer SW monsoon winds drive intense upwelling off Oman and Somalia and sporadic upwelling along the west coast of India (Wyrki, 1973). Distinct planktonic fauna and flora thrive in upwelling waters and eventually settle in sediments. The Arabian Sea sediments therefore consist of distinct fauna that are endemic to areas of upwelling. The strength of the SW monsoon winds, upwelling and precipitation are all related. Thus, Arabian Sea sediments provide a record of past monsoon variability covering time span of few million years. Analyses of upwelling indices such as total planktonic foraminifera and *Globigerina bulloides* flux from ODP Site 723A from the western Arabian Sea give firsthand information on the high resolution variability of SW monsoon in the Indian subcontinent (Divakar Naidu, 1995).

Increase in upwelling indices at 12 ka indicate initiation of SW monsoon winds (Fig. 2). This increase in upwelling coincides with the maximum rate of glacial melt-water discharge in the northern hemisphere (Fairbanks, 1989) and increase in summer insolation (Berger, 1978). Maximum values of the upwelling indices from 10 to 5 ka reflect most intense upwelling and strongest SW

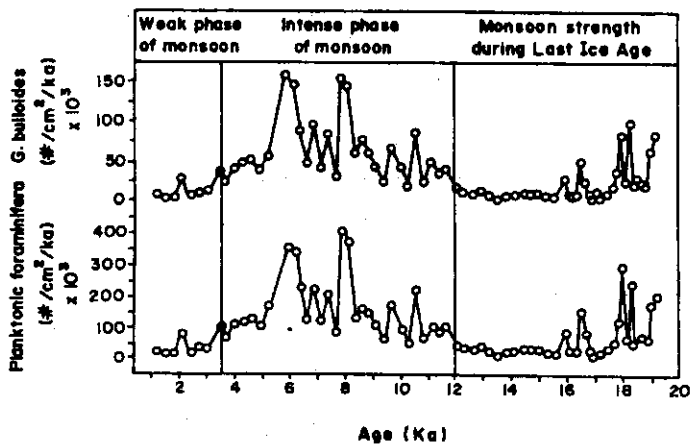


Fig.2. Variations in mass accumulation rates of planktonic foraminifera and *G. bulloides* through the last 19,000 years BP in Ocean Drilling Program Site 723A from the western Arabian Sea. These microfossil indices are sensitive to upwelling intensity and may, therefore, be employed to monitor the history of the SW monsoon climate in the Arabian Sea and rainfall in Southeast Asia (from Divakar Naidu, 1995).

monsoon in the western Arabian Sea during the time interval covered by Divakar Naidu (1995). This period coincides with higher water level in lakes from Africa, Arabia, and India (Street and Grove, 1979). Although the present record demonstrates that the SW monsoon strength was greatest during 10 to 5 ka, a few intervals during this period are marked by low values of upwelling indices, reflecting brief periods of weaker SW monsoon. On the other hand, even these values are higher than the minimum values noticed in the interval

<15 to 12 ka and after 5 ka, which suggests that the SW monsoon was generally stronger during 10 - 5 ka period.

Values of upwelling indices started to decrease at 5 ka, indicating weakening of the SW monsoon. The lowest upwelling indices in the Holocene are recorded between 3.5 and 1 ka. At 3.5 ka upwelling indices exhibit the same values as those at 12 ka, when the monsoon started to intensify after the last glacial period (Fig. 2). The onset of an arid climate at 3.5 ka in the Indian subcontinent has two implications in the present context: i) climate impact on Indus Valley Civilization and ii) poor rainfall influence on desiccation of River Sarasvati.

Independent evidences such as benthic foraminifera and pollen studies from the eastern Arabian Sea (Nigam and Khare, 1992; Nigam, 1993; Caratini et al. 1994) and down core variations of calcium carbonate in the western Arabian Sea and $\delta^{18}\text{O}$ data from Tibet lakes also document arid climate around 3.5 ka (Gasse and Van Campo, 1994). This observation is further corroborated by an abrupt change in solar radiation, precipitation, temperature and southwesterly winds at about 3.5 ka in the Arabian Sea (Zahn, 1994). The declining strength of the SW monsoon since 3.5 ka can therefore be interpreted as the result of arid climate onset in the Asian tropics. The onset of arid climate and decline of the SW monsoon at 3.5 ka resulted in a change in vegetation along the Western Ghats (Caratini et al. 1994).

Onset of an arid climate and its possible effect on the Indus Valley Civilization

Indus Valley Civilization was at its height of glory during the period when Egyptian, Babylonian and Mesopotamian civilization were flourishing in the Middle East. Archeologists believe that the Indus Valley Civilization belonged to the period between 3500 BC (5.5 ka) and 2800 BC (4.8 ka). Agriculture was the main occupation of the Indus Valley people; crops such as wheat, barley, peas and bananas were grown. It is well established that the downfall of Chalcolithic Culture (about one million BC) is ascribed to severe droughts in western and central India. Similarly the decline of the Indus Valley Civilization around 2000 BC (4 ka) approximately corresponds with the onset of arid climate and low rainfall. Rapid salinisation of lakes followed remobilization of dune fields coinciding with the disappearance of Indus Culture. These evidences suggest that the collapse of Indus Culture was linked to the collapse of their agriculture base as a consequence of aridity.

Maya Civilization developed around 3 ka in Mesoamerika, and after flourishing during so-called Classic Period, collapsed around 750-900 AD. The onset of driest climate between 800 and 1000 AD was reported in Central America based on variation of $\delta^{18}\text{O}$ and gypsum/calcite ratio in a sediment core from Lake Chichancanab (Hodell et al. 1995). The timing of this climate change coincides with the collapse of the Classic Maya Civilization between 750 and 900 AD. Although it is difficult to decipher the cause-and-effect

Table 1. Important events during the Holocene in the Indian subcontinent

1200 years B.P. to present day	Present day conditions of vegetation and climate began at 1200 years BP. Sea level was 2 m lower than the present level.
3500 to 1200 years B.P.	No pollens were preserved, in Indian lakes dried up in an oscillatory fashion. Climatic conditions were drier. Less rainfall. Decline of Indus Valley Civilization and desiccation of River Saraswati.
5000 to 3500 years B.P.	Moist conditions with good rainfall characterized by high values of sedges, trees, and shrubs. Sea level was 6 m lower than the present day.
9000 to 5000 year B.P.	Relatively high rainfall as indicated by the presence of <i>Typha</i> , <i>Artemisia</i> in lake sediments of Rajasthan and also greater values of upwelling indices in the Arabian Sea sediments. Sea level was 40 m lower than the present day.
10000 to 9500 years B.P.	Rainfall belts shifted west ward and precipitation was about 250 mm/yr greater than the present, lake levels rose dramatically.
12000 to 10000 years B.P.	Major deglacial event, intensification of the southwest monsoon. Younger Dryas Event. Sea level was 90 m lower than the present day.

relationship, the observed association between the drier climate at 3.5 ka and between 800 and 1000 AD and their coincidence with the collapse of Indus Valley Civilization and Maya Civilization respectively, makes a point that climate has played a role on the collapse of ancient civilizations.

Influence of rainfall on desiccation of the River Sarasvati

The area lying between the rivers Indus and Ganga was the cradle of Aryan civilization. The availability or lack of water in the rivers flowing in the region determined the growth and decay of these civilizations. The River Sarasvati is said to have been a mightier river than even the Indus in the Vedic or pre-Vedic times (Radhakrishna, 1998a and b). LANDSAT imagery has been used for delineating the palaeochannels of the Sutlej, the Yamuna and Sarasvati to unravel the mystery of the 'lost' Sarasvati (Yash Pal et al. 1980). They find that LANDSAT imagery with its synoptic views provide clear evidence for the delineation of palaeochannels and hence the course of the Sarasvati.

The monsoons became weak during the 3.5 ka because of the onset of arid climate in the tropics (Divakar Naidu, 1996). Therefore, desiccation of River Sarasvati could be partly attributed to drastic climatic changes at 3.5 ka and reduction in monsoon rainfall.

Lake level changes

Under certain conditions, lakes act as natural rain gauges. Closed-basin lakes are sensitive to the balance between precipitation and evaporation, which is directly linked to atmospheric circulation. Majority of lake levels in western India are directly related to monsoon rainfall, hence lake level records of the past provide valuable information about monsoon rainfall in the subcontinent.

Salt water lakes in western Rajasthan and a fresh water lake in the Aravalli Range indicate that the early Holocene was arid prior to about 10 ka (Swain et al. 1982). Since that time the region has passed through a humid phase. The rise in lake levels since 10 ka is a clear indication of an increase in monsoon rainfall. More intense phase of the monsoon is documented between 9 to 5 ka marked by lake level rise. From 4.5 ka a strong drying trend began in the lake levels of Rajasthan (Fig. 3). A similar trend was noticed in lake levels of tropical Africa, the Middle East, India, and Australia (Street and Grove, 1979). The present millennium appears to be one of the most arid in the late Quaternary.

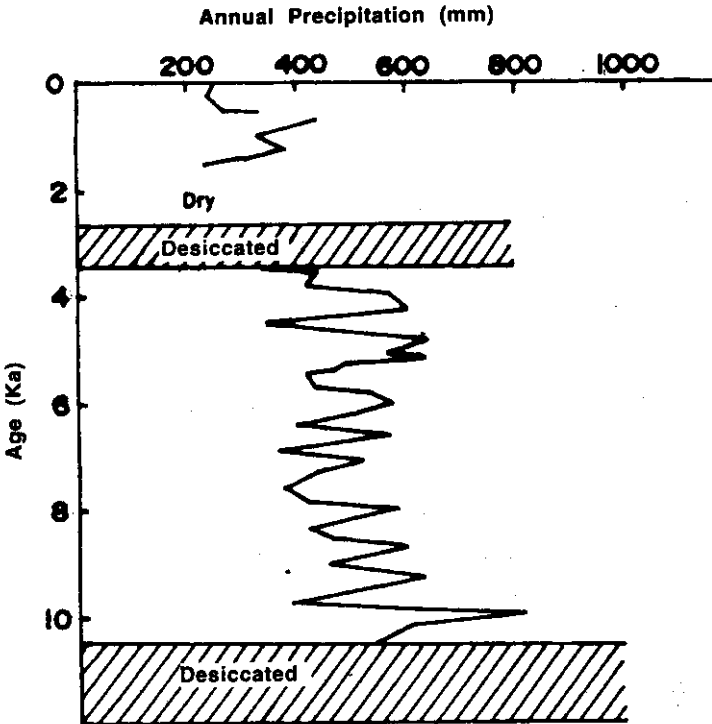


Fig.3. Reconstructed summer monsoon rainfall based on pollen data at Didwana Lake, Rajasthan (from Bryson and Swain, 1981).

Singh et al. (1974) reported an overall increase in precipitation (250 mm/yr) during the period of 10.5 to 5.5 ka and even greater increases between 5.5 to 3.5 ka. Singh et al. (1974) estimates of precipitation based on pollens was questioned by Vishnu-Mittre (1974) saying that Singh (1971) incorrectly assessed the botanical remains and concluded that the climate of northwest India had not changed over the past 5 ka. In contrast, oxygen isotope records (Sirocko et al. 1993), upwelling indices (Divakar Naidu, 1995) and pollen data (Gasse and Van Campo, 1994) clearly show that climate did change during the last 5 ka in the Indian subcontinent.

Pollen Record

Lake and marine sediments contain pollen that represent the local and regional vegetation. Over a broad region, the relative abundance of each pollen type reflects the distribution of its source taxon. Through time, variations in pollen abundance reflects variation in such climate variables as summer and winter temperature and annual moisture.

The two independent palaeoecological records derived from pollen and diatom analyses in the Sumxi-Longmu Co Basin show consistent trends in the past changes of the regional vegetation and hydrology in western Tibet. The Sumxi-Longmu Co Basin lake records document that the region was arid from 14 ka to at least 12.5 ka and then experienced a permanent strengthening of the Indian Monsoon until the middle Holocene (Van Campo and Gasse, 1993). The major climatic features documented in Sumxi-Longmu Co Basin also agree with those of Lunkaransar, Didwana, and Sambhar in the Thar Desert (Singh et al. 1974; Swain et al. 1983).

Recent studies in the Dunde Ice Cap, Qinghai-Tibetan Plateau based on total pollen concentrations reveal that in the late Holocene humid periods occurred at 2700-2000, 1500-800 and 600-80 yr B.P. (Liu et al. 1998). The documented changes in pollen concentration are probably the result of neoglacial cooling. The same record also documents drastic pollen grain changes corresponding to Medieval Warm Period (790-620 yr B.P.) and the Little Ice Age (330-80 yr B.P.).

Ice core records from Qinghai-Tibetan Plateau

Ice core record from the Dunde Ice Cap on the north-central Qinghai-Tibetan Plateau provide a detailed record of Holocene and late glacial stage climatic changes in the subtropics. The records reveal that the last glacial stage conditions were apparently colder, wetter, and dustier than Holocene conditions (Thomson et al. 1989). The last glacial part of the core is characterized by more negative $\delta^{18}\text{O}$ ratios, increased dust content and decreased soluble aerosol concentrations. In addition, $\delta^{18}\text{O}$ data of the low latitude ice cores reveal that the last 60 years were one of the warmest period equalling levels of the Holocene maximum between 6 and 8 ka ago.

SEA LEVEL CHANGES

Sea level for the Indian coasts are not well constrained yet. Though a few records are available from the western margin of India (Kale and Rajaguru, 1985; Hashimi et al. 1995 and Rao et al. 1996), they are inconclusive because of poor chronology. The only sea level curve widely accepted by the scientific community is that of Barbodas and hence referred to here.

During the last glacial maximum sea level was at 120 m below the present

level. Sea level started rising from 18 ka and by 12 ka the sea level had risen by about 30 m. A steep rise of sea level took place between 12 and 9 ka, within 3 ka a 50 m rise was documented in the Barbodas coral record (Fairbanks, 1989). Such a steep rise must be due to higher melting of northern and southern hemisphere ice sheets during this period. From 9 to 6 ka, sea level rose about 32 m. Minor sea level rise was documented from 5 ka to the present day of the order of 6 m.

Relationship to global climate change during Holocene

Summer monsoon influences climate on a seasonal basis in the Indian subcontinent. Comparison of marine records from high and low latitudes and terrestrial records from Africa, Australia, Europe and Americas suggest that common factors have controlled major changes in the ocean and atmosphere both in low and high latitudes during the last deglaciation. The principal steps of the arid-humid transition, seem to have occurred about the same time as two intervals of rapid sea level rise deduced from coral-reef drilling and described as melt-water pulses at 12 ka and 9.5 ka (Fairbanks, 1989).

Mineralogic and geochemical data from Sumxi-Longmu Co Basin suggest an increasing moisture and temperature after 12.5 ka, with a maximum at 11.5 - 11 ka. Despite higher summer solar insolation values, a reversal event towards dry, cold conditions is centered around 10.5 ka and ends at 9.9 ka. This short event appears to match with European Younger Dryas event, which is widely traced in several North Atlantic Sediment cores. However, it is not known yet whether the Younger Dryas event is a Global Event or not.

Milankovitch (1930) proposed that the glacial and interglacial cycles during the Quaternary are driven by the orbital variations of earth and associated solar insolation changes. The long-term climatic variations documented in a wide range of palaeoceanographic records show periodicities at 100 ka, 41 ka and 23 ka corresponding to the Earth's orbital changes in eccentricity, obliquity and precession, respectively. This leads one to conclude that orbital changes of the earth has a strong bearing on climate change (Imbrie and Imbrie, 1980). A comparison of climate changes during the Holocene (Figs.1-3) and solar insolation data for 30°N and 30°S (Fig.4) reveals that the solar insolation changes can account for the general pattern of climate change during Holocene. However, solar insolation changes may not account many climatic events such as high frequency fluctuations in the upwelling indices, onset of arid climate at 3.5 ka, humid period occurrence at 2700-2000, 1500-800 years and Medieval warm period, documented in the marine, terrestrial and lacustrine records (Figs.1-3). Therefore, Milankovitch theory will not hold good in explaining ultra past climate changes in the Holocene.

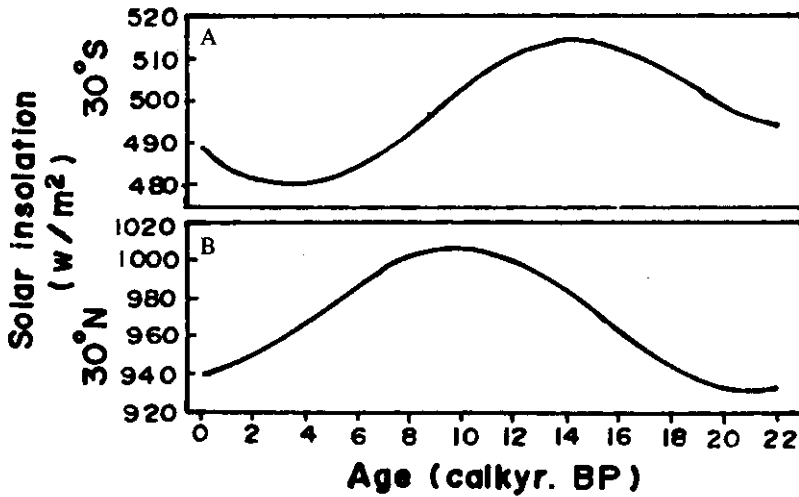


Fig.4. Solar insolation changes for last 20 ka (A) insolation at 30°S during May, (B) summer insolation (June, July, August) at 30°N. (from Berger, 1978).

An array of researchers believe that north Atlantic Ocean is holding the key in driving the glacial and interglacial changes and rapid and abrupt climate changes at least in high latitudes through conveyor belt mechanism (Broecker et al. 1985; Broecker and Denton, 1989 and references therein). More recent studies from the Indian Ocean show that sea surface temperature changes in the northern hemisphere lags Antarctic warming by several millennia (Bard et al. 1997). This supports the idea that changes in the ocean's global thermohaline circulation were not the only cause of interhemispheric climate teleconnections during the last deglaciation. Therefore, the scientific community is yet to identify the forcing mechanisms that drive ultrapast climate changes in both high and low latitudes.

Sirocko et al. (1996) documented that the major deglacial intensification of the southwest monsoon occurred at 11.4 ka (calendar year), which coincides with the major climate transition as recorded in Greenland ice. Therefore, they proposed that there was a teleconnection between subtropical monsoon and high latitude climates during the last deglaciation. However, Sirocko et al. (1996) did not explain the underlying physical cause-effect relation between the teleconnection of high and low latitudes. A much more intriguing question is how the deep water formation changes in the north Atlantic affected climate in the low latitudes of Indo-Pacific Ocean? There is a real need to generate new data from low latitudes of Indo-Pacific oceans to answer all these questions.

SUMMARY

Climate has influenced human activities in one way or the other. Great

cultural developments emerged at the time of major environmental change during the transition of climate from glacial to Holocene (about 12 to 13 ka) such as, earliest appearance of agriculture and extinction of Pleistocene megafauna. Major climatic events noticed in the Indian subcontinent during Holocene are summarized here.

Both marine and terrestrial oxygen isotope records show that the major deglaciation transition event occurred between 12 to 13 ka. Marine upwelling indices and oxygen isotope data from the tropical ice core records also corroborate this event.

Data on marine upwelling indices, lake levels and pollen during the Holocene reveal that deglacial intensification of the SW monsoon occurred at 12 ka. The SW monsoon was at its peak between 9 and 6 ka, monsoon started weakening from 5 ka and reached the glacial strength at 3.5 ka.

Onset of arid climate at 3.5 ka coincides with the decline of Indus Valley Civilization emphasizing that climate had a bearing on the waxing and waning of ancient civilizations. Onset of arid climate at 3.5 ka and the associated weak monsoon rainfall might have caused the desiccation of River Sarasvati.

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