Stable isotopic signatures in precipitation of 2006 southwest monsoon of Tamil Nadu

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Southwest monsoon (SWM) controls the majority of the agricultural activities in Tamil Nadu (TN), though the amount of rainfall received due to this is relatively less. The nature and behaviour of water vapour over TN reveal the other dynamic processes that are in operation during this period of the year. Hence, the stable isotope signatures of $\delta^{18}O$ and δD obtained here were used to derive the first local meteoric water line for the State with SWM precipitation. The d-excess parameter was also used in conjunction and it was found that three dominant processes were in operation during this period: (i) vapours from southeast Arabian Sea, (ii) local evaporating vapours from inland tanks and (iii) vapours from the Indian Ocean.

Keywords: d-excess, precipitation, southwest monsoon, stable isotopes.

PRECIPITATION forms the key component of the hydrological cycle. There are different types of precipitation, of which monsoonal rains are the most prominent. Hence understanding the formation of the monsoon and its variation is important. The summer or the southwest monsoon (SWM) comes from the southwestern part of India and brings heavy rains to the west coast and large areas of southern India between June and August. The winter or northeast monsoon (NEM) sweeps down from the plateau of Asia and the Himalayas, and brings rain and cool weather to southeast India between October and December. In the Indian context, the Arabian Sea (AS) and the Bay of Bengal (BOB) are the two oceanic moisture sources that primarily feed the rainfall during the two monsoons[1,2]. Pearce and Mohanty[3] suggested that the Indian summer rain originates mainly in the southern Indian Ocean (IO), based on vapour flux studies in the troposphere. Studies on stable isotope signatures of the south Indian peninsula were carried out by Gupta and Deshpande *et al.*[4,5]. They had observed that there was no direct precipitation isotope data available from any station along the east coast of India and the isotopic signatures of the precipitation on this coast had been interpreted from the neighbouring stations of Hyderabad and Shillong in India and few stations in Sri Lanka, Myanmar and Thailand, and that too with data based on only a few years[5]. Hence, this is probably the first preliminary work on measured isotope data to be reported from the collected precipitation samples in different locations of Tamil Nadu (TN) during the SWM, to understand the behaviour of the stable isotopes, and their spatial variation, and thus form the baseline data for any future study to understand the precipitation behaviour in TN. It will also help us understand the source of the vapour, interaction behaviour of different components in the hydrosphere, lithosphere and biosphere, and the control of geography precipitation. The SWM is a large complex climatic system which, during monsoonal seasons, behaves in different ways in different years, with active and more passive phases[6].

TN is the southern-most state falling in the east coast of India, situated between 8°5′–13°35′N lat. and 76°15′–80°20′E long. (Figure 1). The State receives rainfall during both SWM and NEM, but NEM is more prominent. The SWM shows an impact on the agricultural activity of the State. Agroclimatic studies carried out by the Tamil Nadu Agricultural University (TNAU), Coimbatore showed the importance of the SWM in the agricultural context[7]. Hence the present study aims to find the behaviour of the SWM by isotopic composition from the precipitation samples. Samples were collected from 37 different loca-

Figure 1. Sample location map of the study area.

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tions in TN (Figure 1) during July and August 2006 and sent to Centre for Water Resources Development and Management (CWRDM), Kozhikode for analysis of oxygen (δ^{18}O) and deuterium (δD) isotopes. δ^{18}O and δD present in the samples were analysed using isotopic ratio mass spectrophotometer (Finnigan Delta^{plus} Xp, Thermo Electron Corporation, Bermen, Germany; the standard deviation of our measurements was ± 1.72‰ for oxygen and ± 0.8‰ for hydrogen). All the measurements were carried out against laboratory sub-standards that were periodically calibrated against the international isotope water standards recommended by the IAEA (Vienna Standard Mean Ocean Water (V-SMOW)).

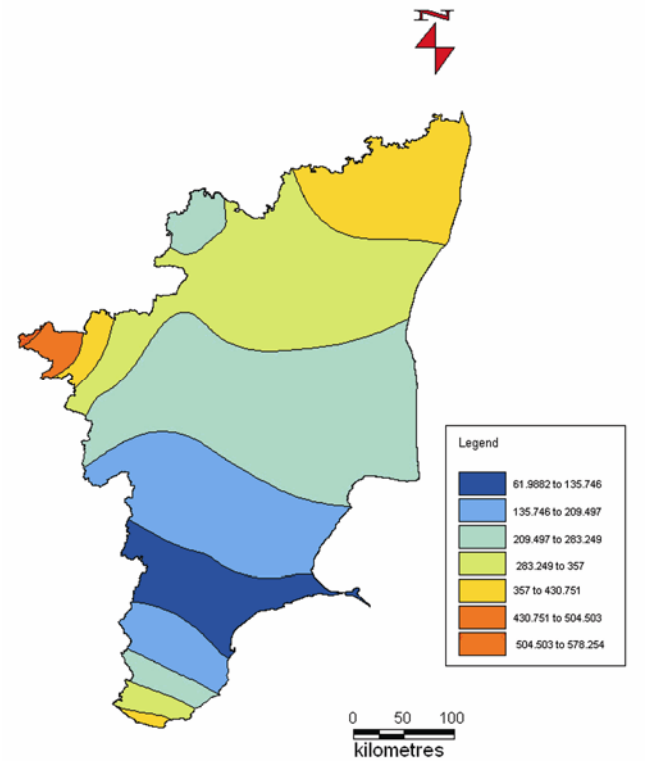

Figure 2. Rainfall distribution pattern in southwest monsoon 2006 (in mm).

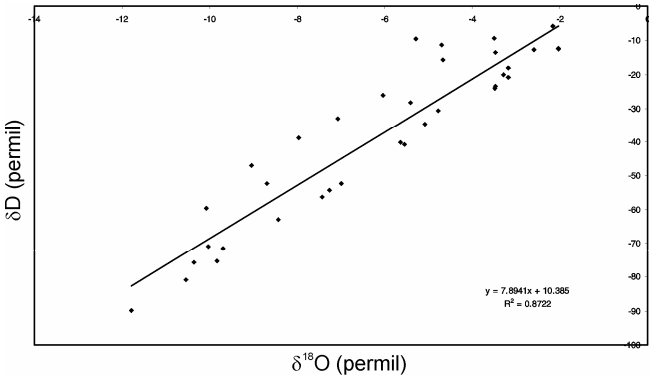

Figure 3. Local meteoric water line derived from the stable isotope composition in precipitation of 2006 SWM.

The monsoon rainfall performance was 13% below normal till the third week of July 2006. However, it started to revive by the third week of July and good rainfall activity extended till September. The enhanced rainfall during the second half of the monsoon season could be attributed to the enhanced convection from the IO to the northwest coast of India and joining the northeast AS[8]. The precipitation ranged from 62 to 628 mm. Rao *et al.*[9] suggested that nearly 40% of the AS evaporation is precipitated locally and the rest is transported to the Indian subcontinent. It has been also witnessed that most of the rainfall is concentrated along the western coast. The spatial distribution of the SWM (Figure 2) shows higher amount of precipitation in the Nilgiris and Nagerkoil (>518 mm) regions. The region with lower rainfall is approximately along the EW across the Madurai–Ramnad region.

The isotope results obtained were given in terms of δ units (permil deviation of the isotope ratio from the international standard V-SMOW), δ being defined by

$$\delta = (R_{sample} - R_{SMOW}/R_{SMOW}),$$

where R = D/H or ^{18}O/^{16}O.

The plot of δ^{18}O and δD (Figure 3) was drawn to derive the local meteoric water line (LMWL). A regression of 0.8722 was noted for various samples collected. The LMWL[10] showed an equation of δD = 7.8941 δ^{18}O + 10.385, against the global meteoric water line (GMWL) δD = 8δ^{18}O + 10 of Criag[11]. This equation was substantially confirmed by Yurtserver and Gat[12] and more recently by Rozanski *et al.*[13], who obtained the following equation considering the results obtained by IAEA, Vienna,

$$\delta D = (8.20 \pm 0.07)\delta^{18}O + (11.27 \pm 0.65).$$

Similarly, the LMWL for Italy[14] showed δD = 7.61 δ^{18}O + 9.21.

Table 1. Elevation of the rainfall stations

Location	Elevation (m amsl)	Location	Elevation (m amsl)
Chennai	6	Thiruvarur	13
Kovai	408	Villupuram	44
Cuddalore	8	Portnova	3
Dharmapuri	486	Annamalai Nagar	5
Dindugal	300	Kovilpatti	100
Kanyakumari	4	Ariyalur	68
Karur	137	Devakottai	50
Krishnagiri	682	Sirkazhi	7
Madurai	135	Pinnathur	4
Nammakal	190	Palayar	2.5
Ooty	2262	Pumpuhar	2
Puthukottai	93	Puthuthurai	4
Ramnad	6	Kancheepuram	64
Salem	250	Tiruvannamalai	258
Thanjavur	60	Thuthukudi	4
Trichy	81	Aathur	240
Tirunelveli	31	Erode	175
Theni	310	–	–

The present LMWL derived for the State is near the GMWL derived by Rozanski *et al.*[14].

LMWL plots are close to the GMWL line, but with slight deviation. Such deviation results from differences in climatic factors such as air temperature, secondary evaporation, seasonality of precipitation and moisture source[15], that occur in precipitations globally[15–17].

The δD value ranged from –80.94‰ in the Nilgiris to –5.85‰ near the coast (Figure 4). Spatial variation of δD showed that the region with < –57‰ diagonally crosses the northwestern part of TN. The eastern part of the TN coast showed lesser values, > –34‰. As the monsoon originates beyond the western coast of Kerala, the first precipitation along the Kerala coast should have been enriched with heavier isotopes and the vapour would travel inward diagonally into TN and show comparatively lesser values of δD in the Western Ghats of Nilgiris[10]. Moreover, the altitude of the Nilgiri is nearly 2300 m amsl (Table 1). Hence a lowest value of –81‰ was noted here. A higher value was noted near the coast around Nagapattinam and Chennai. The altitude effect is temperature-related because condensation is caused by temperature drop due to increasing altitude. The observed δ^{18}O effect gradually varied between –0.15 and –0.5‰/100 m of altitude, often decreasing with increasing altitude[18–20], with a corresponding decrease of –1 to –4‰ for δD. The progressive rainout process based on the Rayleigh fractionation/condensation model showed that the relation between the observed annually averaged δD and δ^{18}O values in precipitation and the mean are in reasonable agreement with the observed values from the worldwide GNIP data network. The latitude effect was about δ^{18}O = –0.6‰/° lat. There was a large variation in altitude than in latitude of the state.

Similarly the dominant part of the study area was covered by δ^{18}O values (Figure 5) ranging from –8 to –5‰ covering diagonally the central part of TN[10]. The southern and NE parts showed δ^{18}O values > –5‰. The surface water of the BOB is lighter in δ^{18}O due to the large influx of surface run-off from the surrounding continental area[22–23]. This influx of freshwater into the BOB reduces the salinity and enriches the lighter isotope concentration. One of the possible mechanisms to account for the higher δ^{18}O offset between the BOB and the east coast, includes contribution from the AS vapour depleted due to rainout over the land area and low δ^{18}O of the surface water of the BOB during the SWM[5]. Another possible reason for this in the southern part may be due to the proximity of the vapour source to the IO, and that in the NE due to mainly evaporated vapour from the local reservoirs. These two regions are separated by a region with lower value ranging from –8 to –5‰.

The source of water vapour for precipitation is supplied through evaporation of sea water and also inland water and its isotopic ratios are controlled by isotopic fractionation and mixing rate of two kinds of vapour from oceans and inland. The isotope fractionation mainly produced in equilibrium isotopic exchange reaction involves redistribution of isotope between the product and the

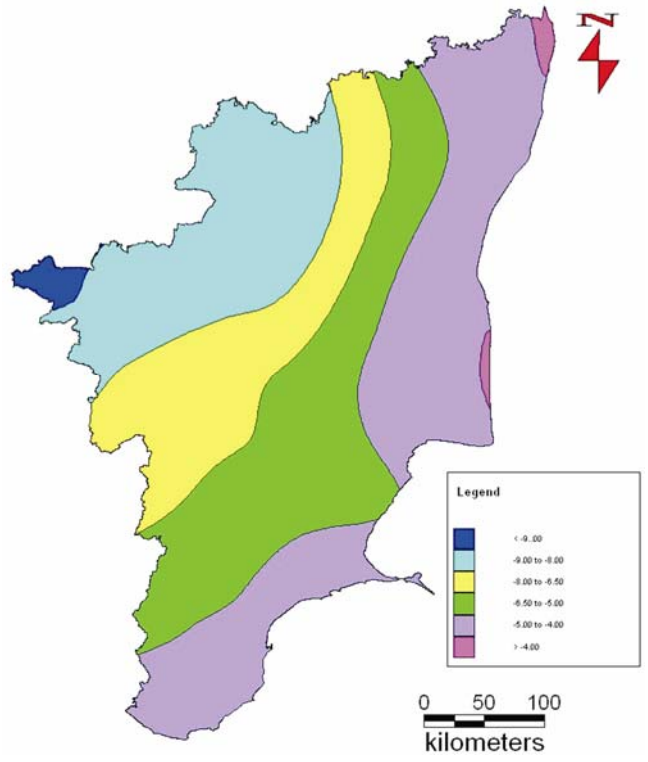

Figure 4. Spatial distribution of δ^{18}O (per mil) in SWM of 2006.

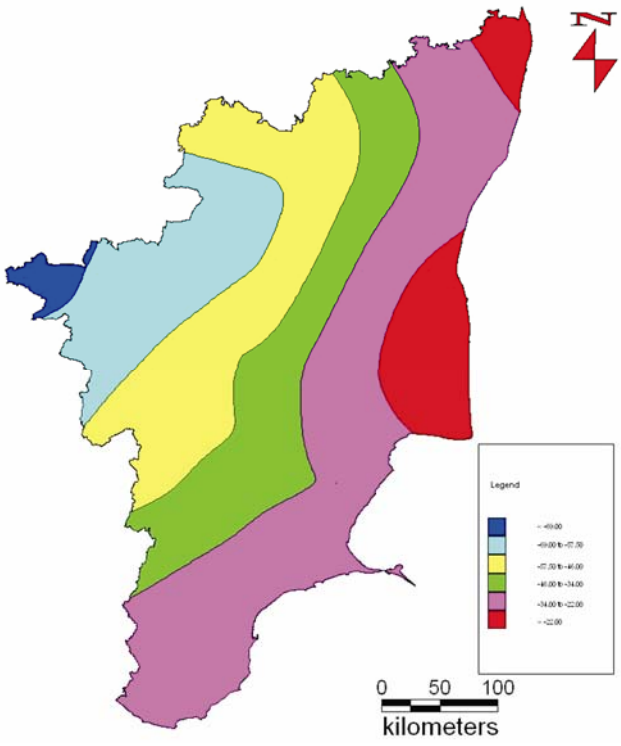

Figure 5. Spatial distribution of δD (per mil) in SWM of 2006.

reactants in contact with each other. It is understood that the heavier isotopes are more enriched in the denser material. If the reaction is unidirectional and the reaction products are physically isolated from the reactants, it is called kinetic fractionation. Another mechanism of fractionation of the isotope is the diffusion of atoms or molecules across the concentration.

In the evaporation process from the oceans and inland, if the vapour is isotopically in equilibrium with water, the Craig constant (+10) on the GMWL ($\delta D = 8\delta^{18}O + 10$) should be zero. Therefore, this constant term must be due to certain non-equilibrium effects or kinetic effects on the isotopic fractionation in evaporation. The isotopic fractionation, including such kinetic effects is expressed as follows:

$$\alpha_n = \alpha_e \times \alpha_k,$$

where suffixes n, e and k stand for net, equilibrium and kinetic respectively. If the kinetic effect is caused by differences is diffusivity in air among the three isotopomers of water ($^1H_2{}^{16}O$, $^1H^2H^{16}O$ and $^1H_2{}^{18}O$), the kinetic effect is expressed as[23]:

$$\alpha_k = (m^1/m)^{n/2},$$

where m^1 is the molecular weight of the heavier isotopomer (19 or 20) and m that of lighter (18), and n is a constant between 0 and 1 depending on the contribution degree of the kinetic effect. Then the relationship of the vapour source with kinetic effect is expressed as:

$$\delta D = 8\delta^{18}O + d,$$

$$d = \delta D - 8\delta^{18}O.$$

The value (deuterium excess d-excess) is useful to distinguish the vapour sources. The correlation factor between $8\delta^{18}O$ and δD is variable and shifts little from 8, in actual precipitation the d-value must change[24] depending on difference between the actual factor and 8.

The d-excess of the evaporating water body will progressively decrease and that of the resulting vapour will progressively increase[25]. Hence this process helps in understanding the undergoing kinetic evaporation under humidity <100%. It is also evident from the study of Gupta and Deshpande *et al.*[4] that the rainout process will not affect the d-excess of the precipitating vapour.

The d-excess in precipitation is determined by the air/sea interaction process over the ocean surface, as determined by several workers[24,26,27]. The process fixes the d-excess value, which remains unchanged as the air moves across the continents and loses moisture by rainout. However, the air masses are impacted by secondary process, which return moisture to the air, such as evaporation from an open surface water body (i.e. recycling of water)[28,29]. The inherited d-excess value can be altered as the air mass moves inland. It has been shown that for a reasonable range of temperatures and relative humidity over the ocean, the initial d-excess value of the transported moisture should be between 3 and 5 per mil. A d-excess value less than 3 per mil should be used with caution to determine the source of evaporative enrichment with certainty, as it may have been impacted by evaporation from the collector[30].

The d-excess values ranged from 3.17 to 24.87‰ (Figure 6). The extremely low values of d-excess are indicative of evaporation from the raindrops during occasional rains. According to measurements during the International Indian Ocean Expedition (IIOE)[3], evaporation from the AS is the major contributor to the Indian summer monsoon. d-excess values <6.5‰ were noted along the higher altitudes of the Western Ghats. d-excess values of 6–10‰ covered the northwestern part of TN, and divided two regions had higher d-excess values (>10‰). One region is located in the southern part of TN and the other in the northeastern part. Higher values of d-excess (14–17‰) were noted in the central part of the State and in the centre of the east coast near the Cauvery delta region (Tanjore, Thiruvarur, Cuddalore Pumpuhar, Nagapattinam). Still higher values (>17.5‰) were noted in the northern part of the State near Krishnagiri and Dharmapuri. Gupta and Deshpande *et al.*[4] found that the region of <8‰ d-excess overlay the rainshadow region of the Western Ghats. It was also stated that in the Western Ghats, $\delta^{18}O$ in precipitation decreased due to various reasons and the d-excess value of the west coast in SWM ranged between 8 and 12‰.

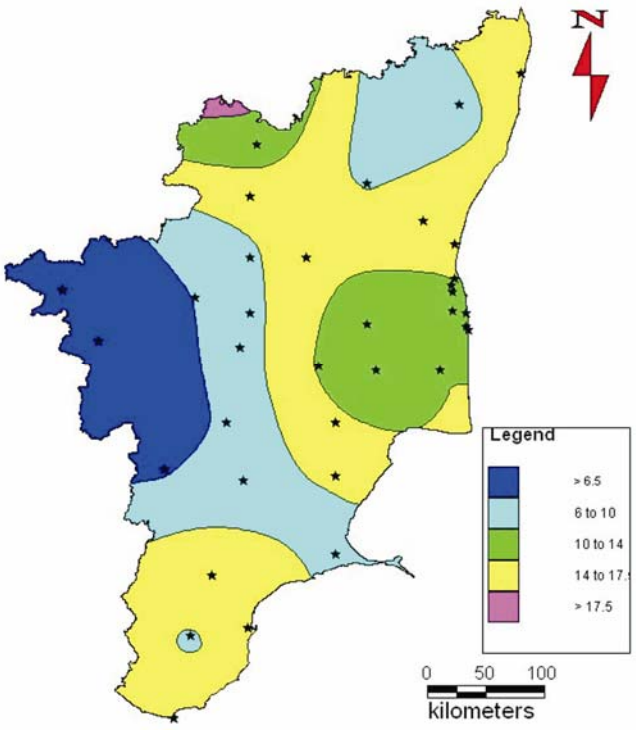

Figure 6. Spatial distribution of d-excess (per mil) in SWM of 2006.

Values with d-excess >10% are likely to arise by the cycling of precipitated water by evaporation from the large area of reservoirs like Veeranam, Perumal Eri and other minor tanks. Evaporation from wetlands near the coast like Pichavaram and Muthupet and agricultural fields around the Tanjore delta region, might have also enhanced the d-excess values. This vapour disperses in all directions, with more ease towards the northwestern part. The overall irrigation data for TN indicate that there is 9% increase in total net area irrigated[7]. Near Dharmapuri and Krishnagiri the $\delta^{18}O$ values ranged from –8 to –6.5‰, with higher d-excess values (>17‰), indicating influx of vapour progressively increasing westward due to local recycling. Alternatively, this could indicate evaporation from the tanks under low humidity, <85%. This vapour extends up to the boundary of the SWM precipitation. Dominance of the SWM was noted only in the northwestern part of the state.

Regions with $\delta^{18}O$ values > –5‰ are noted in the southern part of the State around Kanyakumari and Tuticorin may be due to the vapour source from the IO. This region also had higher d-excess value of 14–17‰. This may be due to the lesser humidity observed in this region[31] (65–70%). It was also noted that d-excess is a function of humidity, during kinetic evaporation from the ocean surface[26]. Lesser amount of rainfall (<60 mm) was noted in the Madurai–Ramnad region. This might be because they fall in the rainshadow region during this monsoon. But this region serves as the upper limit of the precipitation from vapours of the IO and the lower limit for evaporating vapours from the local sources in northeastern TN.

The movement of the SWM across the State is clearly witnessed along the western and northwestern part of TN. Certain regions in the southern tip also receive rainfall during the monsoon. This may be due to the vapour source from the IO below. During the months preceding the summer monsoon, the sea surface temperature (SST) with this warm pool generally exceeds 29°C. In the IO, the warmest SST is found in three preferred locations: (a) the western equatorial IO, (b) southeastern AS (SEAS); (c) eastern BOB. The onset vortex for the SWM forms around 10°N in the SEAS and moves northward; the monsoon advances along the Indian west coast during the SWM[32].

The southern tip with higher rainfall is below 10°N. The open-ocean monsoon current, the winter monsoon current and the coastal current and the East Indian coastal current (EICC) enable the transport of low-salinity water from the BOB into the SEAS from November to February. All available observations of salinity and current suggest that the source region of the low-salinity water in the SEAS is the BOB. The low-salinity water is carried towards the equator along the IO by the EICC[14,19,33]. This shows that there is variation in salinity in the IO and SEAS. The salinity of water in this region is altered by the inflow of freshwater into the oceans. This freshwater flowing into the oceans generally has lesser concentration of heavier isotopes. As a result, it alters the isotopic composition of the evaporated vapour. Thus these salinity variations may also contribute to isotope fractionations. Hence the southern tip which is close to the source of vapour has a $\delta^{18}O$ value >5 per mil.

The local meteoritic water line developed almost matches with the global line. Higher values of d-excess and $\delta^{18}O$ were noted along the NE and the southern parts of TN coast. Higher d-excess values in the NE region of TN are probably due to the water vapour evaporation from the surface tanks during the previous summer and in the southern part, higher values are due to the influence of the adjacent of the Arabian Sea/Indian Ocean. In the NE part of TN, the SWM monsoon receives rainfall due to recycling of the local evaporating vapour. Evaporation is prominent along the eastern margin of the TN coast, as several tanks and lands with paddy cultivation are dominant. Hence, it is evident that there are three major sources of vapour in operation during the SWM in TN, namely AS, IO and that from the local reservoirs. This first preliminary work based on the field and laboratory data of the region, fills up the exiting lacunae in developing a local meteoritic water line for the state, the isotope studies to determine the sources and movement of water vapour responsible for SWM rainfall in TN.

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ACKNOWLEDGEMENTS. We thank Dr James, CWRDM for help in the analysis of the samples. We also thank DST, New Delhi for financial assistance under IRHPA facility at Kozhikode and Dr S. M. Rao, BARC, Mumbai, for guidance and support. We are grateful to the reviewers for useful suggestions.

Received 2 August 2007; revised accepted 9 March 2009

Principal component and spectral analyses of palaeo-climate time series

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Mathematical modelling and time series analysis techniques are important tools for extracting information from complex geotime series. These techniques also facilitate a fair degree of prediction, which is one of the prime goals of science. The data analysis strategy for such a purpose mainly involves spectral analysis and pattern classification. The aim of pattern classification and frequency analysis is to assign observations or patterns into semantic categories. Traditional statistical methods generally applied during the past years fail to recognize patterns from high dimensional geo-records. Principal component analysis (PCA) is a powerful tool in identifying patterns in such records and provides useful means for reducing the number of dimensions without loss of much information. Here we have carried out spectral analysis and PCA of a climate record for approximately 28,000 yrs spanning from 1.15 to 29.78 kyr, off central Japan in the northwest Pacific. Our analysis reveals a dominant oscillation corresponding to the well known 'Heinrich Cycle'. The physical significance of the results has been discussed and the observed cyclic pattern corresponding to the global 'Heinrich Cycle' originating from the North Atlantic and Greenland ice rafting fluctuations has been linked to the Pacific phenomenon and Asian monsoon system.

Keywords: Heinrich Cycle, Last Glacial Maximum, palaeoclimate, principal component analysis, spectral analysis, time series.

THE climate system dynamics is a complex and coupled phenomenon because it is the result of interactions of various components of the land–ocean–atmosphere and cryosphere. Extracting physical information and making

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