While WETE allows climate projections with fewer uncertainties than those in forecasts from numerical climate models, the latter are necessary to examine and assess the impact of processes like doubling of CO_2. A component of impact assessment can be introduced in WETE by considering a certain degree of change in the future epochal change, but it may be difficult to quantitatively relate such a change in the trend to processes like the doubling of CO_2. However, trend analyses have their inherent limitations and it is necessary to involve dynamical considerations for their improved reliability.

1. Trenberth, K. E., Fasullo, J. and Smith, L., Trends and variability in column-integrated water vapour. *Climate Dyn.*, 2005, **24**, 741.
2. Houghton, I. T. *et al.* (eds), In *Climate Change 2001: The Scientific Basis*, Cambridge University Press, Cambridge, 2001.
3. Palmer, T. N., Predicting uncertainty in forecasts of weather and climate. *Rep. Prog. Phys.*, 2000, **63**, 71–116.
4. Claussen, M., Variability of global biome patterns as a function of initial and boundary conditions in a climate model. *Climate Dyn.*, 1996, **12**, 371–376.
5. Storch, H. V., Zorita, E. and Culbasch, U., Downscaling of climate change estimates to regional scales: An application to Iberian rainfall in winter time. *J. Climate*, 1993, **6**, 1161–1171.
6. Storch, H. V., Inconsistencies at the interface of climate impact studies and global climate research. *Meteor. Z.*, 1995, **4**, 72–80.
7. Chowdhury, A. and Abhayankar, V. P., Does precipitation pattern foretell Gujarat climate becoming arid? *Mausam*, 1979, **30**, 85–90.
8. Srivatsava, H. N., Dewan, B. N., Dikshit, S. K., Prakasa Rao, G. S., Singh, S. S. and Rao, K. R., Decadal trends in climate over India. *Mausam*, 1992, **43**, 7–20.
9. Palmer, T. N. and Raisanen, J., Quantify the risk of extreme seasonal precipitation events in a changing climate. *Nature*, 2002, **415**, 512–514.
10. Toth, Z. and Kalnay, E., Ensemble forecasting at NCEP and the breeding method. *Mon. Weather Rev.*, 1997, **125**, 3297–3319.
11. Peterson, A. T. *et al.*, Future projections for Mexican faunas under global climate change scenarios. *Nature*, 2002, **416**, 626–629.
12. Rajeevan, M., Bhate, J., Kale, J. D. and Lal, B., Development of high resolution daily gridded rainfall data for the Indian region. India Meteorological Department, Met. Monograph Climatology, 2005, 22/2005, pp. 1–26.
13. Rao, K. N. and Jagannathan, P., Climatic changes in India. In Proceedings of Symposium on Changes in Climate, Rome, UNESCO and WHO, 1963, pp. 49–66.
14. Kucharski, F., Molteni, F. and Yoo, J. N., SST forcing of decadal Indian monsoon rainfall variability. *Geophys. Res. Lett.*, 2006, **33**, L03709.

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Ventilation of northwestern Arabian Sea Oxygen Minimum Zone during last 175 kyrs: A pteropod record at ODP Site 728A

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Pteropod assemblages were studied at ODP Site 728A near the Oman margin (northwestern Arabian Sea) lying at a water depth of 1428 m, just below the present-day Oxygen Minimum Zone (OMZ) and aragonite compensation depth (ACD). Variations in the strength of OMZ over the past 175 kyrs in the northwestern Arabian Sea were reconstructed on the basis of changing abundances of pteropod at this site. The down-core abundance reveals pteropod spikes at the transitions of isotope stage MIS 6/5, MIS 2/1 and during glacial stages MIS 6 and MIS 2, reflecting deepening of ACD and relatively less intense OMZ in this region, possibly due to deep-sea mixing and thermocline ventilation, and the relative decline in surface productivity during winter monsoon. In general, the interglacial periods are largely devoid of, or marked with low pteropod abundances, indicating dissolution of aragonite due to increased intensity of OMZ in the northwestern Arabian Sea. The distinct peak of abundance of *Limacina inflata* and mesopelagic forms during transition of MIS 6/5 reflects relatively lower surface productivity compared to MIS 2/1 transition. However, both these transitions are marked with intense deep-sea ventilation. This explains that the pteropod preservation is mainly influenced by the fluctuations in the OMZ due to deep-sea ventilation and remains largely independent of variations in the surface productivity. Thus, the dissolution and not the lack of supply is mainly responsible for the low abundances of pteropod shells in the deep-sea sediments of the high-productivity regions like the Oman margin.

Keywords: Arabian Sea, monsoon, pteropod, surface productivity, ventilation.

ARAGONITE, a metastable polymorph of $CaCO_3$, is relatively more soluble than calcite in sea water[1,2]. Hence, the aragonite lysocline and aragonite compensation depth (ACD) are located at much shallower depths than calcite compensation depth (CCD). Pteropods, important aragonite producers in the sea, are used to reconstruct the fluctuations in the aragonite lysocline and ACD, which are the depths at which pteropod shells are strongly affected by dissolution or disappear in the sea-floor sediments respectively[3].

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High surface-water productivity combined with moderate rate of thermocline ventilation[4] results in the intense Oxygen Minimum Zone (OMZ) between 250 and 1200 m (off Oman, down to 1500 m) water depth[5,6]. Higher input and decay of organic matter within the OMZ raise the dissolved inorganic carbon (DIC) concentrations in the subsurface waters and lower the pH, resulting in a shallow aragonite saturation depth of 600–800 m in the Arabian Sea[7]. Below this depth bottom waters are under-saturated with respect to aragonite, and aragonite sediments begin to dissolve. Decomposition of organic matter within the sediments releases metabolic CO_2 to the pore water and lowers the pore-water pH, leading to a further increase in dissolution[7]. In addition, the OMZ is strengthened by the contribution of low oxygenated and highly saline Red Sea Outflow Water and Persian Gulf Outflow Water that are centred around 800 m water depth. Beneath the OMZ, the Arabian Sea is bathed by the more saline and oxygenated North Indian Deep Water extending between approximately 1200 and 3800 m water depth[8]. Fluctuations in the intensity and thickness of the OMZ also control the depth of the ACD in the Arabian Sea. Lying just below the OMZ, ODP site 728A is suitable to reconstruct the variability in the OMZ of northwestern Arabian Sea in response to the climatic variations.

The ODP site 728A is located in the northwestern Arabian Sea on the continental margin off Oman (lat. 17°40.49′N; long. 57°49.55′E) at a water depth of 1428 m (Figure 1)[9]. Thirty-six core samples of about 9.0 m thick section were selected for pteropod study. These samples are 10 cubic cm plugs of sediment commonly taken at 25 cm intervals. Each core sample was treated with 10% calgon solution for at least 20 h, wet-sieved using Tyler sieves (125 μm) and oven-dried at 50°C. After drying, samples of >125 μm fraction were weighed and examined under streozoom microscope to pick the pteropod shells. All the pteropod specimens were identified and counted. The total number of pteropod shells per gram sediment was calculated. The relative abundance (%) and number of shells per gram dry sediment of four most dominant pteropod species were calculated. The ratios of total pteropod shells with the total planktic foraminifera (%*Pt*/*Pf* + *Pt*) in each sample along with the relative abundances of two significant planktic foraminiferal species, i.e. *Globigerina bulloides* (high surface-productivity indicator) and *Neogloboquadrina pachyderma* (a well-known temperate species) were also measured. Relative abundances of the mesopelagic and epipelagic pteropods were also plotted on the basis of pteropod ecology described by Almogi-Labin *et al.*[10] and Singh *et al.*[11]. Age of each sample was calculated (in ka), following the time–depth relationship at this site provided by Steens *et al.*[12].

A total of eleven species of pteropod were recorded in the present work and some important taxa are illustrated using scanning electron micrographs (Figure 2). Pteropods show significant fluctuations in the total abundance (number of pteropods per gram) and in simple diversity (number of pteropod species) during the last ~175 kyrs (Figures 3 and 4). Several intervals in the examined section do not contain any pteropod shell representing periods of intense aragonite dissolution. The encountered pteropod species belong ecologically either to the epipelagic or

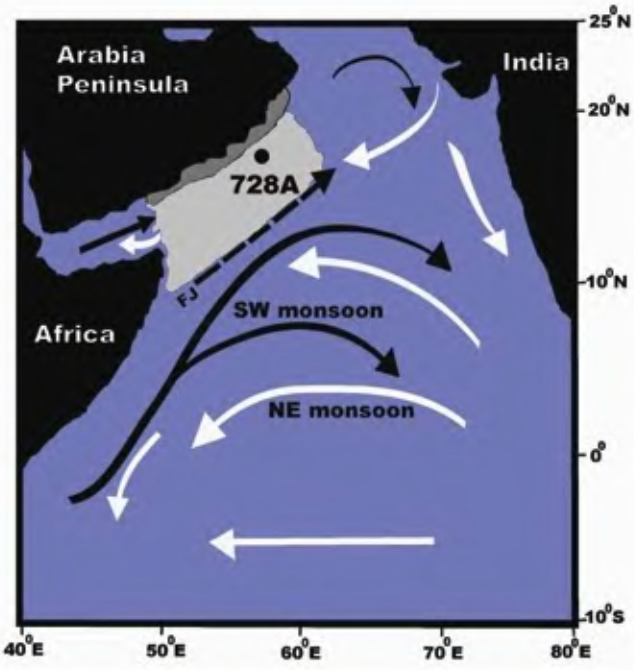

Figure 1. Surface hydrography in the Arabian Sea and location of ODP Site 728A (solid circle; modified from Ishikawa and Oda[9]). A strong clockwise surface ocean circulation (black arrows) develops during the SW monsoon, which follows the direction of the Findlater Jet (FJ, arrows with broken line). Coastal upwelling area is indicated by dark grey; and the open ocean upwelling area by light grey. Anticlockwise NE monsoonal circulation is indicated by white arrows.

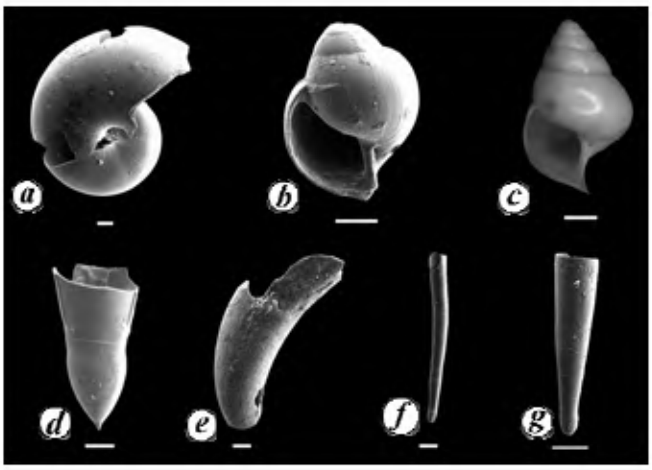

Figure 2. Photomicrographs of dominant pteropod species recorded at ODP site 728A. (Scale bar = 100 μm). ***a***, *Limacina inflata* (d'Orbigny); ***b***, *Limacina trochiformis* (d'Orbigny); ***c***, *Limacina bulimoides* (d'Orbigny); ***d***, *Clio convexa* (Boas); ***e***, *Cavolinia gibbosa* (d'Orbigny); ***f***, *Creseis acicula* (Rang) and ***g***, *Creseis virgula* (Rang).

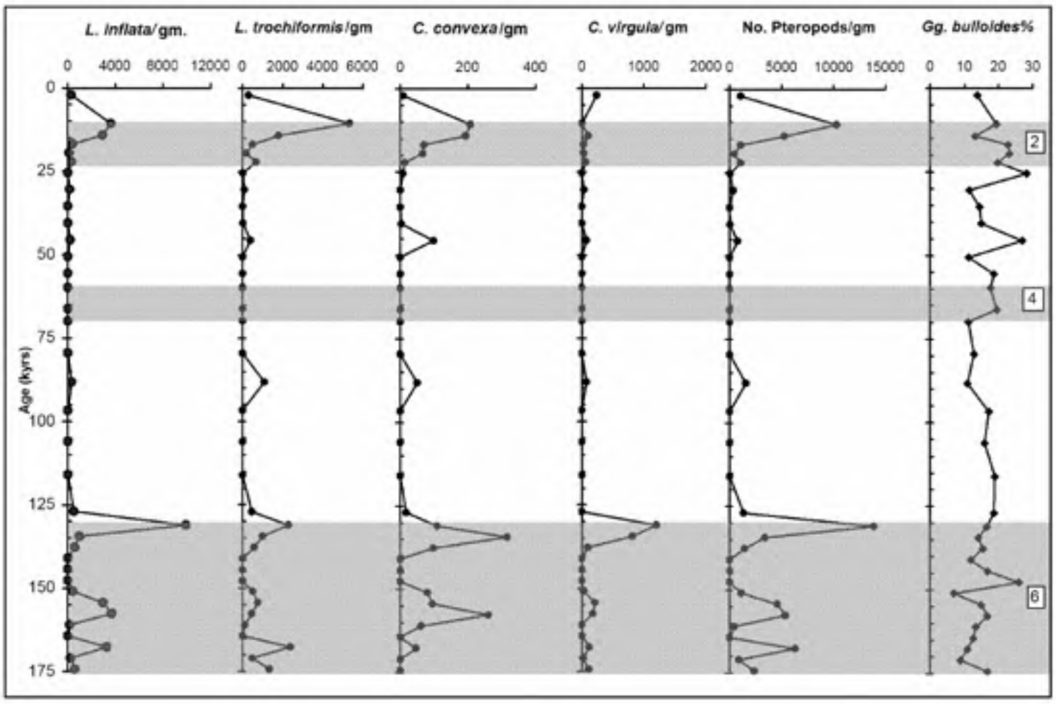

Figure 3. Down-core variations in numerical abundance (number of specimens/g dry sediment) of selected pteropod species, total number of pteropod shells/g dry sediment and relative abundance of planktic foraminifer, *Globigerina bulloides*. Grey bars with even numbers represent isotopic glacial intervals.

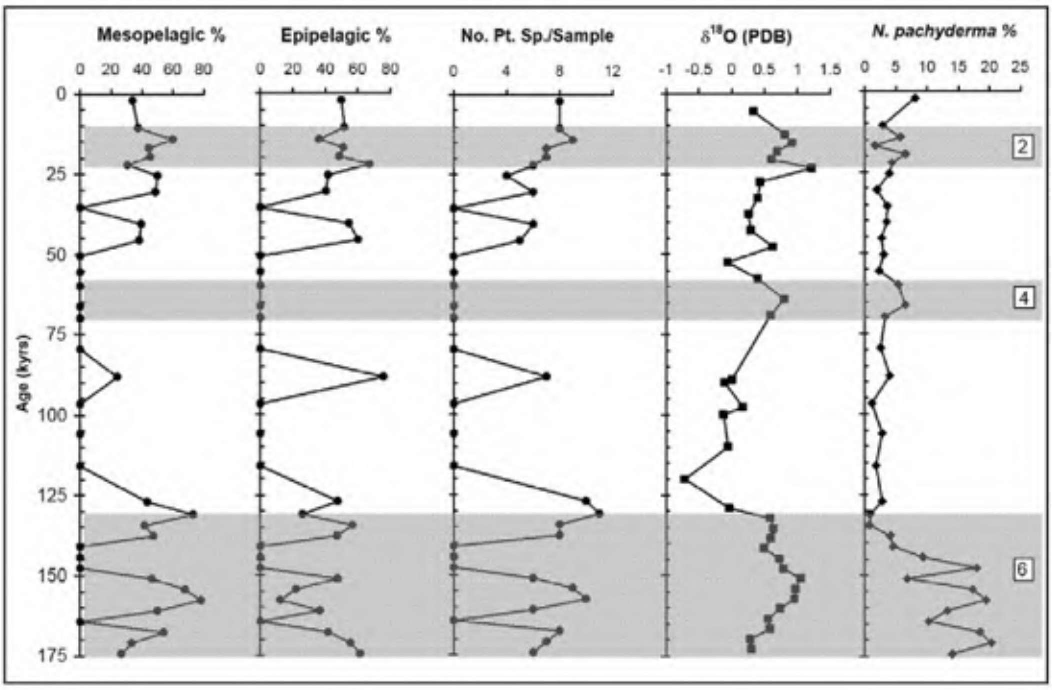

Figure 4. Down-core variations in relative abundance of mesopelagic and epipelagic pteropods, number of pteropod species in each sample, $\delta^{18}O$ measurements made on planktic foraminiferal species, *Neogloboquadrina dutertrei* (after Steens *et al.*[12]) and relative abundance of planktic foraminifer, *Neogloboquadrina pachyderma*.

to the mesopelagic group. Epipelagics are non-migratory species that live in the mixed layer, whereas mesopelagics are migratory species that inhabit the intermediate water mass and migrate diurnally. Transitions of isotope stages MIS 6/5 (~132 to 128 ka) and MIS 2/1 (~15–10 ka) are marked with peak abundances of about 10,000–14,000 specimens per gram dry sediment. Two more peaks of pteropod abundance have been observed during glacial

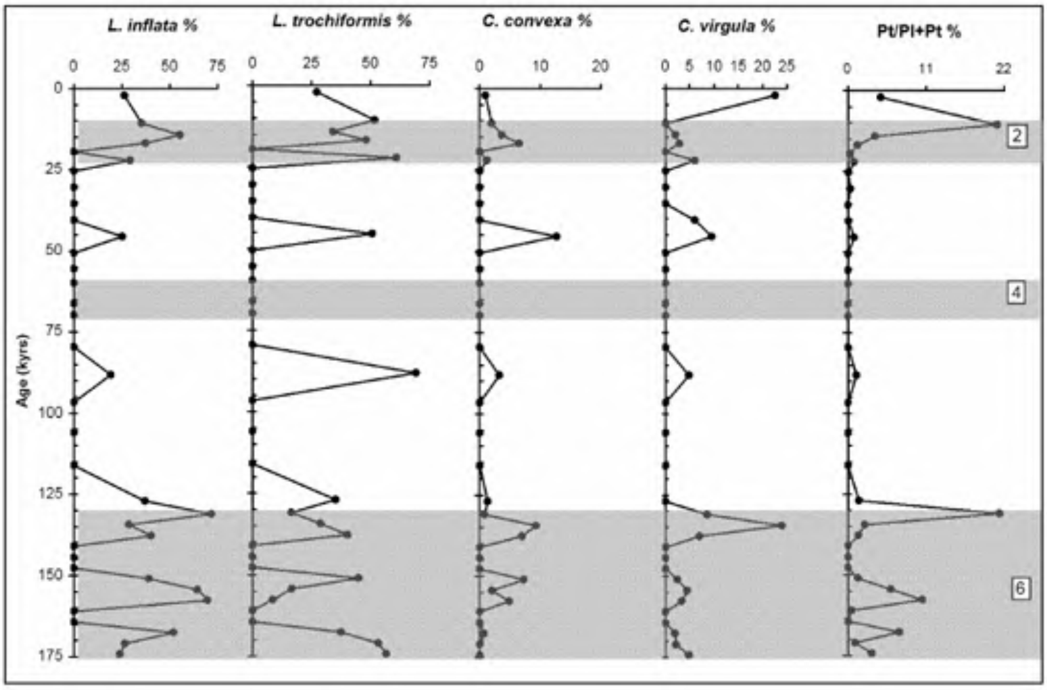

Figure 5. Down-core variations in relative abundance of selected pteropod species and ratio of pteropods vs pteropods and planktic foraminifers (*Pt*/*Pl* + *Pt*%).

stage MIS 6 at ~168 ka and ~158–150 ka. Intervals of increased pteropod abundance are also marked with higher faunal diversity and increased percentages of mesopelagic pteropods (Figure 4). The above intervals are also characterized by higher planktic $\delta^{18}O$ values and higher abundances of *N. pachyderma* (Figure 4). Abundance per gram dry sediment and relative abundance of four most common pteropod species are presented in Figures 3 and 4, comprising >80% of the total faunal assemblage. The mesopelagic *Limacina inflata* is the most dominant species during MIS 6/5 transition. It also occurs abundantly at ~168 ka and ~150–158 ka intervals. Another mesopelagic species, *Clio convexa* is marked with abundance peaks during these intervals (Figure 3). The epipelagic *Limacina trochiformis* is marked with maximum dominance during MIS 2/1 transition and also shows distinct abundances at ~174, ~85 and ~24 ka. *Creseis virgula*, an epipelagic species shows significant increase in abundance (about 1500 specimens per gram dry sediment) at the end of MIS 6 (Figure 3). In general, the intervals of higher total abundance of pteropods also correspond with the increased ratios of pteropod vs planktic foraminiferal tests (Figure 5).

The absolute abundance of pteropods (specimens per gram dry sediment) is mainly influenced by their production within the water column, deposition vs dissolution ratio of shells and sediment accumulation rate (dilution effect)[11]. A strong positive correlation has been reported between production of pteropods and surface-water productivity in the open ocean[13,14]. Singh *et al.*[11] have recorded maximum abundance of total pteropods in the Arabian Sea sediments of low primary-productivity regions. However, flux study in the northeastern Arabian Sea does not show any close relationship between pteropod abundance and surface-water productivity[15]. Thus, some other factors in addition to surface-water productivity control the pteropod distribution. The pteropod species recorded in the present study are tolerant to a wide range of salinity, as they are also distributed in both low- and high-salinity waters[3,10]. Aragonite preservation appears to have major influence on the pteropod content of relatively deeper sediments and intervals of higher pteropod abundance indicate better aragonite preservation.

Aragonite shells of the pteropods dissolve rapidly within the CO_2-rich waters of the OMZ during sinking through the water column. In general, the ACD, therefore, lies nearly at the middle of the OMZ, preventing good pteropod deposition at ODP site 728A, which lies just below the OMZ. Thus, it is suggested that variation in the abundance of pteropod shells should be related to the changing strength of the OMZ in the NW Arabian Sea. Reichart *et al.*[16] have reported that high pteropod preservation index values are associated with low values of C_{org} during glacial intervals due to low surface-water productivity. Thus, intervals of prominent peak of pteropod abundance represent substantial deepening of the ACD and weakened OMZ in the NW Arabian Sea, possibly due to low surface-water productivity combined with intense rate of thermocline ventilation. The lowering of the ACD in the northern Arabian Sea suggests that the local OMZ has been significantly reduced in intensity during several periods because of a more intense convective turnover[16]. Intense winter mixing results in a weakening of the OMZ and a reduction of the nutrient concentration in the sub-surface waters. During the glacial period, intensified winter monsoonal winds could have increased excess evaporation over freshwater input over much of the Arabian Sea, thereby resulting in an increase in sea surface salinity (SSS). The combined effect of decreased sea surface temperature and high SSS has increased the sea surface densities, thereby promoting deep water mixing in the northern part of Arabian Sea during the glacial periods[17].

The pteropod spikes have been observed at the transitions from glacial to interglacial (MIS 6/5 and MIS 2/1), whereas most of the interglacial intervals have no or rare pteropod shells. A similar pattern was also recorded in the Gulf of Aden where interglacial stages (MIS 13 to MIS 1) were almost devoid of pteropod shells[18]. However, pteropod spikes occur at all transitions from glacial to interglacial stages, with a maximum during MIS 6. The interval of MIS 6 shows intense surface-water cooling as reflected in the increased values of planktic $\delta^{18}O$ and dominant occurrences of temperate planktic foraminifer, *N. pachyderma* (Figure 4). Also, the glacial/interglacial preservation pattern supports the Murray Ridge records[4,16] which show pteropod spikes at transitions from glacial to interglacial (MIS 6/5, 4/3 and 2/1). The pteropod spike across the MIS 2/1 transition is mainly contributed by the epipelagic form, *L. trochiformis* whereas the mesopelagic *L. inflata* contributes dominantly to the pteropod spike during MIS 6/5 transition. Thus, this difference in pteropod abundance may possibly be due to a relatively more intensified monsoon-driven surface productivity during MIS 2/1 transition than across the MIS 6/5 transition, which is also evident with the relative increase in the abundance of *G. bulloides*, a well-known planktic foraminifer of high surface productivity region (Figure 3). However, ventilation of the OMZ was significantly more to allow better pteropod preservation during both these transitions. Thus, the breakdown in the OMZ conditions may be mainly due to enhanced deep-winter mixing instead of decreased surface productivity.

The mesopelagic pteropod assemblages show a decrease in abundance during periods of more intense and vertically more extended OMZ in the Red Sea[19]. Almogi-Labin *et al.*[10,19] suggested that a more intense and vertically more extended OMZ would be responsible for the elimination of *L. inflata* and other mesopelagic pteropods. They (op. cit.) also reported that the peaks of abundance of *L. inflata*, the most common mesopelagic pteropods during the Holocene, are associated with a well-aerated OMZ. *L. trochiformis* and *C. virgula* are epipelagic species living in the mixed layer with small-scale vertical migrations[20]. *L. trochiformis* and *C. virgula* together constitute a major portion of the epipelagic group. Studies have revealed that these species are only confined to the upper 50–100 m, with *C. virgula* being a somewhat shallower mixed-layer dweller[10,19,21]. Thus, the changing abundances of these two epipelagic species may be divided into the intervals with *L. trochiformis* dominance reflecting a thicker mixed layer and with *C. virgula* dominance reflecting shallower mixed layer. Changing position of the mixed layer may be in response to the variations within an overall humid climatic phase.

The intensity of the monsoon during interglacial and interstadial stages is high, which results into enhanced upwelling and surface productivity off Somalia and Oman[22,23]. In general, total abundance of pteropods shows an almost reverse trend with the abundance of *G. bulloides* reflecting opposite relation with surface water productivity, which is mainly influenced by the strength of the SW monsoon. The increased influx and remineralization of organic matter has resulted in high DIC concentrations in the subsurface waters, thus reducing the pH and dissolving the aragonite[24]. However, during the intervals of weak SW monsoon upwelling, induced surface-water productivity becomes low, which increases the pteropod preservation due to higher pH in the intermediate and bottom waters. Intervals with relatively low pteropod abundances but higher abundances of epipelagic forms reflect relatively strong OMZ. The higher strength of the OMZ is possibly due to monsoon-led surface-water productivity and reduced deep-winter mixing, which cause dissolution of major pteropod population due to decline in pore water pH. However, the absence or poor pteropod preservation in the NW Arabian Sea and other upwelling regions suggests that dissolution and not the lack of supply is responsible for the low pteropod abundance or its absence in the higher productivity regions[25,26].

Summarizing, aragonite (pteropod) preservation appears to be influenced by the changing strength of the OMZ, providing a proxy to understand the history of the OMZ fluctuations in the NW Arabian Sea. Most of the examined section (mainly interglacial intervals) is marked with either absence or low pteropod abundances, indicating rapid aragonite dissolution due to the development of strong OMZ. The strength of the OMZ increases most likely in response to higher organic matter influx due to increased SW monsoon-led upwelling and surface-water productivity. However, few distinct pteropod spikes have been identified during the last ~175 kyrs, suggesting increased aragonite preservation. Increased pteropod preservation mainly during glacial periods and glacial/interglacial transitions suggests substantially weakened OMZ and relatively deep ACD. This explains that the significant ventilation of deep water due to increased deep winter mixing causes less intense OMZ during periods of reduced summer monsoon.

1. Millero, F. J., *Chemical Oceanography*, CRC Press, Boca Raton, 1996, pp. 1–469.
2. Morse, J. W. and Arvidson, R. S., The dissolution kinetics of major sedimentary carbonate minerals. *Earth Sci. Rev.*, 2002, **58**, 51–84.

3. Rottman, M. L., Dissolution of planktonic foraminifera and pteropods in South China Sea sediments. *J. Foraminiferal Res.*, 1979, **9**, 41–49.
4. You, Y. and Tomczak, M., Thermocline circulation and ventilation in the Indian Ocean derived from water mass analyses. *Deep-Sea Res. I*, 1993, **40**, 13–56.
5. Wyrtki, K., Physical oceanography of the Indian Ocean. In *The Biology of the Indian Ocean* (ed. Zeitschel, B.), Springer, Berlin, 1973, pp. 18–36.
6. Reid, J. L., On the total geostrophic circulation of the Indian Ocean: Flow patterns, tracers and transports. *Prog. Oceanogr.*, 2003, **56**, 137–186.
7. Klöcker, R., Ganssen G., Jung Simon, J. A., Kroon, D. and Henrich, R., Late Quaternary millennial-scale variability in pelagic aragonite preservation off Somalia. *Mar. Micropaleontol.*, 2006, **59**, 171–183.
8. Schmiedl, G. and Leuschner, D. C., Oxygenation changes in the deep western Arabian Sea during the last 190,000 years: Productivity versus deep water circulation. *Palaeoceanography*, 2005, **20**, PA2008, doi: 10.2029/2004PA001044.
9. Ishikawa, S. and Oda, M., Reconstruction of Indian monsoon variability over the past 230,000 years: Planktic foraminiferal evidence from the NW Arabian Sea open-ocean upwelling area. *Mar. Micropaleontol.*, 2007, **63**, 143–154.
10. Almogi-Labin, A., Hemleben, C. and Meischner, D., Carbonate preservation and climatic changes in the central Red Sea during the last 380 kyr as recorded by pteropods. *Mar. Micropaleontol.*, 1998, **33**, 87–107.
11. Singh, A. D., Nisha, N. R. and Joydas, T. V., Distribution patterns of Recent pteropods in surface sediments of the western continental shelf of India. *J. Micropalaeontol.*, 2005, **24**, 39–54.
12. Steens, T. N. F., Kroon, D., ten Kate, W. G. and Sprenger, A., Late Quaternary periodicities of oxygen isotope ratios, calcium carbonate contents, and magnetic susceptibilities of western Arabian Sea Margin Hole 728A. In *Proceedings ODP*, *Scientific Results* (eds Prell, W. L. *et al.*), College Station, Texas, 1991, vol. 117, pp. 309–320.
13. Deuser, W. G., Seasonal and interannual variation in deep-water particle fluxes in the Sargasso Sea and their relation to surface hydrography. *Deep-Sea Res.*, 1986, **33**, 225–247.
14. Almogi-Labin, A., Hemleben, C. and Deuser, W. G., Seasonal variations in the flux of euthecosomatous pteropods collected in deep sediment trap in the Sargasso Sea. *Deep-Sea Res.*, 1986, **35**, 441–464.
15. Schulz, H., von Rad, U. and Ittekkot, V., Planktic foraminifera, particle flux and oceanic productivity off Pakistan, NE Arabian Sea; modern analogues and application to the paleoclimatic record. In *The Tectonic and Climatic Evolution of the Arabian Sea Region* (eds Clift, P. D. *et al.*), Geological Society of London, Special Publication, 2002, pp. 499–516.
16. Reichart, G. J., den Dulk, M., Visser, H. J., van der Weijden, C. H. and Zachariasse, W. J., A 225 kyr record of dust supply and the oxygen minimum zone from the Murray Ridge (northern Arabian Sea). *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 1997, **134**, 149–169.
17. Reichart, G. J., Nortier, J., Versteegh, G. J. M. and Zachariasse, W. J., Periodical breakdown of the Arabian Sea oxygen minimum zone caused by deep convective mixing. In *The Tectonic and Climatic Evolution of the Arabian Sea Region* (eds Clift, P. D. *et al.*), Geological Society of London, Special Publication, 2002, pp. 407–420.
18. Almogi-Labin, A., Schmiedl, G., Hemleben, C., Siman-Tov, R., Segl, M. and Meischner, D., The influence of the northeast winter monsoon on productivity changes in the Gulf of Aden, NW Arabian Sea, during the last 530 ka as recorded by the benthic foraminifera. *Mar. Micropaleontol.*, 2000, **40**, 295–319.
19. Almogi-Labin, A., Hemleben, C., Meischner, D. and Erlenkeuser, H., Paleoenvironmental events during the last 13,000 years in the Central Red Sea as recorded by pteropods. *Palaeoceanography*, 1991, **6**, 83–98.
20. Bé, A. W. H. and Gilmer, R. W., A zoographic and taxonomic review of euthecosomatous pteropods. In *Oceanic Micropaleontology* (ed. Ramsay, A. T. S.), Academic Press, London, 1977, vol. 1, pp. 733–808.
21. Jasper, J. P. and Deuser, W. G., Annual cycles of mass flux and isotopic composition of pteropod shells settling into the deep Sargasso Sea. *Deep-Sea Res.*, 1993, **40**, 653–669.
22. Reichart, G. J., Lourens, L. J. and Zachariasse, W. J., Temporal variability in the northern Arabian Sea Oxygen Minimum Zone (OMZ) during the last 225,000 years. *Palaeoceanography*, 1998, **13**, 607–621.
23. Altabet, M. A., Higginson, D. and Murray, D., The effect of millennial scale changes in Arabian Sea denitrification on atmospheric CO_2. *Nature*, 2002, **415**, 159–162.
24. Millero, F. J., Degler, E. A., O'Sullivan, D. W., Goyet, C. and Eischeid, G., The carbon dioxide system in the Arabian Sea. *Deep-Sea Res. II*, 1998, **45**, 2225–2252.
25. Berger, W. H., Deep-sea carbonate: Pteropod distribution and the Aragonite Compensation Depth. *Deep-Sea Res.*, 1978, **25**, 447–452.
26. Gerhardt, S. and Henrich, R., Shell preservation of *Limacina inflata* (Pteropoda) in surface sediments from the Central and South Atlantic Ocean: A new proxy to determine aragonite saturation state of water masses. *Deep-Sea Res. I*, 2001, **48**, 2051–2071.

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Nitrogen isotopes in chondrules: Signatures of precursors and formation processes

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Nitrogen isotope abundance of 68 individual chondrules separated from six ordinary, two carbonaceous and two enstatite chondrites has been analysed. N composition of chondrules from ordinary and carbonaceous chondrites generally shows large variation and differs from that of their host. This large range of N composition suggests the presence of different N components in their precursors. Chondrules from the enstatite chondrites on the other hand show N isotopic composition similar to that of their host, suggesting precursors with similar N components for both chon-

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