Past summer upwelling events in the Gulf of Oman derived from a coral geochemical record

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We used a high-resolution oxygen isotope (δ18Ocoral), carbon isotope (δ13Ccoral) and Sr/Ca ratios measured in the skeleton of a reef-building coral, *Porites* sp., to reveal seasonal-scale upwelling events and their interannual variability in the Gulf of Oman. Our δ13Ccoral record shows sharp negative excursions in the summer, which correlate with known upwelling events. Using δ13Ccoral anomalies as a proxy for upwelling, we found 17 summer upwelling events occurred in the last 26 years. These anomalous negative excursions of δ13Ccoral result from upwelled water depleted in 13C (dissolved inorganic carbon) and decreased water-column transparency. We reconstructed biweekly SSTs from coral Sr/Ca ratios and the oxygen isotopic composition of seawater (δ18OSW) by subtracting the reconstructed Sr/Ca-SST from δ18Ocoral. Significant δ18OSW anomalies occur during major upwelling events. Our results suggest δ13Ccoral anomalies can be used as a proxy for seasonal upwelling intensity in the Gulf of Oman, which, driven by the Indian/Arabian Summer Monsoon, is subject to interannual variability.

The Gulf of Oman is located on the northeastern coast of the Arabian Peninsula and both the Arabian Sea and the Gulf of Oman are located in arid environments. The climate is dominated by the seasonal reversal of the Indian/Arabian Monsoon, which in turn governs the surface wind field of the Indian Ocean north of 10°S. The intensity and direction of the monsoon winds vary seasonally. During the southwest (SW) Monsoon develops during the boreal summer (from June to mid-September) and is characterized by strong airflow across the Arabian Sea that feeds moisture and rainfall to the Indian subcontinent.

The Indian/Arabian Summer Monsoon causes coastal upwelling bringing cooler temperatures, nitrified and saline water to the sea surface along the southern coast of the Arabian Peninsula. Upwelled water flows northward and affects the oceanic stratification of the Gulf of Oman through gyres and eddy systems that sweep into the Oman Sea1. The Northern Arabian Sea is therefore one of the most productive areas in the world2. The SW Monsoon is also the major climatic factor affecting the near-shore environment and areas of coral growth in Oman during the summer months3.

The high nutrient content of this water induces phytoplankton blooms. Satellite-based ocean color measurements show the temporal and spatial variability of the surface chlorophyll-a distribution along the coast of the Southern Arabian Peninsula4. In the Gulf of Oman, upwelling does not necessarily occur every summer5–7. In addition, observational records that allow us to understand the dynamics of upwelling events in the Gulf of Oman are scarce. Satellite based sea surface temperature (SST) in the Gulf of Oman did not reflect low SST excursions in summer measured by CTDs. (Fig. S1). Long-term and *in situ* records of primary production, salinity and temperature are necessary in order to understand upwelling events4. In this study, we used paleo-climatic reconstructions from coral geochemical records to provide a history of summer monsoon-driven upwelling variability in the Gulf of Oman.

The geochemical proxies in coral skeletal carbonate provide a long-term history of environmental variation, with high time resolution (2 weeks to a month)8,9. Coral skeletal oxygen isotopes (δ18Ocoral) reflect SST and oxygen isotopes in seawater (δ18OSW)10,11. Coral skeletal Sr/Ca ratios are used as SST proxies12. Sea-surface salinity...
(SSS) is derived from $\delta^{18}O_{SW}$, which is generated by subtracting the temperature component (obtained from coral Sr/Ca) from $\delta^{18}O_{coral}$. Stable isotopes of carbon in coral skeletons ($\delta^{13}C_{coral}$) are influenced by kinetic isotopic fractionation, vital effects (photosynthesis and respiration) and the carbon isotopic composition of dissolved inorganic carbon in seawater ($\delta^{13}C_{DIC-SW}$)\(^{13-16}\). Coral skeletons are precipitated in isotopic disequilibrium with ambient seawater as a result of kinetic and vital effects. The kinetic effect selectively depletes $^{12}\text{C}$ and $^{16}\text{O}$ in coral skeletons and is particularly important when coral growth rates are very low ($< 4 \text{ mm per year}$)\(^{13, 14}\). Photosynthetic activities of zooxanthellae affect $\delta^{13}C_{coral}$ by changing the carbon isotopes in the internal dissolved inorganic carbon pool of the coral\(^{17}\). A 50% weakening of solar radiation induces a decrease of approximately 0.5‰ VPDB in $\delta^{13}C_{coral}$\(^{18}\). The amount of solar radiation received by the coral varies depending on incoming solar radiation, cloud cover and water transparency\(^{17, 19, 20}\). Upwelling can reduce water transparency and change the sea-surface $\delta^{13}C_{DIC-SW}$. Therefore, upwelling events should be registered by the coral via a decrease in $\delta^{13}C_{coral}$. We used a coral record from the Gulf of Oman to reconstruct the timing and frequency of upwelling events using high-resolution records of Sr/Ca ratios, $\delta^{18}O_{SW}$ and $\delta^{13}C_{coral}$ based on a 26-year-old coral core.

Results and Discussion

We determined $\delta^{18}O_{coral}$, $\delta^{13}C_{coral}$ and Sr/Ca ratios from 664 samples. Each powdered sample was split for paired stable isotope and Sr/Ca analysis. Sr/Ca ratios and $\delta^{18}O_{coral}$ showed 26 distinct annual cycles (Fig. 1a and b). The average of the Sr/Ca ratios was 9.28 (mmol $\times$ mol$^{-1}$), with values ranging from 8.98 to 9.56 (mmol $\times$ mol$^{-1}$). The $\delta^{14}O_{coral}$ averaged $-4.33$ (‰VPDB) and ranged from $-4.92$ to $-3.41$ (‰VPDB). We calculated the regression line between satellite SST and Oman coral Sr/Ca ratios using seasonal maxima and minima to avoid potential biases due to intra-seasonal age model uncertainties, as follows:

$$\text{Sr/Ca ratios (mmol} \times \text{mol}^{-1}) = -0.044 \pm 0.003 \text{SST} + 10.46 \pm 0.18. (r = -0.95; P < 0.01)$$

We established a regression line between satellite SST and $\delta^{18}O_{coral}$ assuming that $\delta^{18}O_{coral}$ reflect only SST variations, with the same $\delta^{18}O_{coral}$ samples with Sr/Ca ratios, as follows:
The correlation coefficient between $\delta^{18}$O_{coral} and Sr/Ca ratios was 0.77 ($P < 0.01$). $\delta^{18}$O$_{sw}$ were calculated by subtracting the temperature component (estimated from coral Sr/Ca ratios) from $\delta^{18}$O$_{coral}$ following the method proposed by Nurhati et al.\textsuperscript{21}. The slope of the $\delta^{18}$O$_{coral}$ - SST regression is $-0.104 \pm 0.005$‰/°C, which is too high to be consistent with published estimates\textsuperscript{12,13,22}. This suggests a significant contribution of $\delta^{18}$O$_{sw}$ to $\delta^{18}$O$_{coral}$. We therefore used the published regression slope of $-0.18 \pm 0.03$‰/°C\textsuperscript{12} to convert $\delta^{18}$O$_{coral}$ to SST, and our slope of $-0.044$ mmol × mol$^{-1}$/°C for SST estimation. The $\delta^{18}$O$_{sw}$ anomalies were calculated by applying a band-pass filter to remove the periodicity components longer than 2 years and subtracting the seasonal cycle. Relative changes of $\delta^{18}$O$_{sw}$ are on the order of ± 0.424‰/°SMOW (2σ). Anomalies above or below this threshold were marked as significant $\delta^{18}$O$_{sw}$ anomalies (Fig. 1c). The uncertainty of calculated $\delta^{18}$O$_{sw}$ is ± 0.113‰/°SMOW (following Nurhati et al.\textsuperscript{21}).

The average $\delta^{18}$O$_{coral}$ was $-1.62$‰/$\text{VPDB}$ and ranged from $-3.28$ to $+0.29$‰/$\text{VPDB}$. The $\delta^{18}$O$_{coral}$ also showed clear seasonal variation (Fig. 1d) and distinct short-term negative anomalies (Fig. 1d). The $\delta^{18}$O$_{coral}$ analysis was performed to avoid contamination from organic matter. We measured each CO$_2$ gas sample 6 times using a dual inlet system loaded on a MAT251. Analytical precision of the $\delta^{18}$O$_{coral}$ (standard deviations) were below 0.05‰.

Growth rate disturbances and anomalous-colored annual band were not observed on X-ray photographs and coral cores. Therefore, the variations of $\delta^{13}$C$_{coral}$ were assumed to reflect environmental changes rather than the coral growth disturbances\textsuperscript{23}.

The interpretations of $\delta^{13}$C$_{coral}$ has been debated about what the $\delta^{13}$C$_{coral}$ values are reflecting\textsuperscript{10,13-16,24,25}. The main factors influence that can influence $\delta^{13}$C$_{coral}$ include: (1) kinetic effect and vital effect, (2) solar radiation, (3) water-column transparency, (4) variation of photosynthetic activity caused by the seasonal solar radiation cycle. At inter-annual resolution, the $\delta^{18}$O$_{coral}$ values showed a weak negative correlation with the $\delta^{18}$O$_{coral}$ record (r = -0.317, n = 634, P < 0.001: Fig. S2a). Summer $\delta^{18}$O$_{coral}$ did not correlate significantly with $\delta^{18}$O$_{coral}$ (r = 0.140, n = 181, P > 0.05: Fig. S2a). Winter $\delta^{18}$O$_{coral}$ had no significant correlation with winter $\delta^{18}$O$_{coral}$ (r = 0.04, P > 0.05, n = 159: Fig. S2b). The extension rates show that the Oman coral grew very quickly, on average 25.1 mm/year with a range between 19 to 31.5 mm. These values were considerably lower than the critical value estimated for kinetic isotopic fractionation effects (4 mm/year)\textsuperscript{14}.

Previous studies reported $\delta^{13}$C$_{coral}$ on seasonal and inter-annual variations are attributable to solar radiation\textsuperscript{17,26}. To investigate the processes driving these $\delta^{13}$C$_{coral}$ fluctuations, we compared $\delta^{13}$C$_{coral}$ with satellite-based outgoing longwave radiation (OLR) (Fig. S3a) which reflect cloud cover. For a comparison of $\delta^{13}$C$_{coral}$ with monthly-resolved OLR data, biweekly resolved $\delta^{13}$C$_{coral}$ data were resampled at a monthly resolution using the software AnalySeries (version 2.0.8)\textsuperscript{27}. The $\delta^{13}$C$_{coral}$ were compared with OLR, and we calculated the correlation coefficients between these time series. $\delta^{13}$C$_{coral}$ without anomalous $\delta^{13}$C$_{coral}$ excursions positively correlated with OLR at a significant level (r = 0.411, P < 0.01, n = 302: Fig. S3a and S3b). A significant correlation appeared between the mean seasonal cycle of $\delta^{13}$C$_{coral}$ and OLR averaged over the past 26 years (r = 0.702, P = 0.01, n = 12: Fig. S3c and d). The positive correlations between $\delta^{13}$C$_{coral}$ and OLR (Fig. S2b and S2d) suggest that $\delta^{13}$C$_{coral}$ captured the variation of photosynthetic activity caused by the seasonal solar radiation cycle. At inter-annual resolution, the 15 month-moving average profile of $\delta^{13}$C$_{coral}$ positively correlate with that of OLR (r = 0.347, P < 0.01, n = 303: Fig. S4a and S4b). The duration of low OLR and coeval $\delta^{13}$C$_{coral}$ decreased from 1992 to 1993. We propose that insolation and OLR had decreased in globally as a result of up-stirred volcanic aerosol from the eruption of Mount Pinatubo, the Philippines in June 1991\textsuperscript{28}. Low $\delta^{13}$C$_{coral}$ from 1992 to 1993 would be influenced by decreasing insolation which resulted from the volcanic eruption of Mount Pinatubo.

We calculated the $\delta^{13}$C$_{coral}$ anomaly ($\delta^{13}$C$_{anomaly}$) by removing the 15 month-moving average (31 bi-weekly data point) after subtracting the averaged seasonal cycle of $\delta^{13}$C$_{coral}$. The threshold for $\delta^{13}$C$_{coral}$ anomalous excursions was determined as a standard deviation of 1σ: ± 0.343‰/$\text{VPDB}$. In summer, the anomalous negative excursion of the $\delta^{13}$C$_{anomaly}$ occurred 17 times in summer, while 1 anomalous negative excursion occurred in the spring of 1993 (Fig. 1f). Anomalous positive $\delta^{13}$C$_{anomaly}$ excursions were also observed prior to summer negative $\delta^{13}$C$_{anomaly}$ excursions. The $\delta^{13}$C$_{anomaly}$ had no significant correlation with OLR anomaly calculated by same procedure (r = 0.05, P > 0.3 Fig. S4c and S4d), suggesting that anomalous negative excursions of $\delta^{13}$C$_{anomaly}$ in the summer (AN-13C) would not be generated from OLR variations.

We examined the timing of the AN-13C with the compiled evidence of each past upwelling event documented from in situ and satellite observations (Fig. 1f and g). Abrupt SST decreasing events in summer were revealed in 1987–1989\textsuperscript{29} and 2000\textsuperscript{30} from satellite SST data, in 1994, 1994, 2001, 200, 2002\textsuperscript{50} (Fig. S5) and 1990\textsuperscript{31} based on in situ SST data, and 2010 based on our vertical seawater temperature profile (Fig. S6). The vertical profile of seawater temperature deduced by temperature sensors attached to the diving gear of local volunteer divers in 2010, also suggest that the thermocline was closer to the surface during summer upwelling events (Fig. S6). In addition, Al-Azri et al.\textsuperscript{1} had measured chlorophyll-a concentrations, nutrients, phytoplankton density and SST in Fahal Island (23.67°N, 58.5°E) and Bandar Al Khayran (23.51°N, 58.72°E: near to our coral sample site). From July to September 2004, upwelling was observed as increasing chlorophyll-a concentrations and phytoplankton density as well as decreasing SST\textsuperscript{1}. In August 2005, SST decreased for 1 month, while other parameters did not change\textsuperscript{1}. Al-Azri et al., 2012 reported that in situ chlorophyll-a and satellite based SST suggested that upwelling also occurred in July, 2008\textsuperscript{8}. The satellite observations (SeaWiFS and MODIS at 24°N, 58°E from Asia-Pacific Data Research Center\textsuperscript{25}) from 1997 to 2013 suggested that chlorophyll-a concentrations in the Gulf of Oman increased in August 2000, September 2004 and August 2008 (Fig. S7). In other upwelling years, chlorophyll-a
Therefore, the numbers of the days for upwelling periods were defined as the duration of SST lower than 26.5 °C. δ13C anomaly values of no upwelling years (0 days) was estimated from in situ δ13C from the Arabian Sea 18 and the value of δ13C in isotopic equilibrium between coral carbonate and seawater 24. δ13C from the Gulf of Oman in the Arabian Sea, while the associated Ekman transport creates strong upwelling along the coastal margins, bringing cold, nutrient-rich water to the surface 4, 5. This upwelled water has indirect impacts on concentrations in satellite data were not available to compare with AN-δ13C due to the lack of satellite data in summer. Based on these in situ and satellite datasets, past upwelling events occurred in 1982 29, 1988 29, 1989 29, 1990 31, 1992 5, 1994 6, 2000–2002 29, 2004 1, 2008 7 and 2010 (Fig. 1g). The AN-δ13C corresponds with these past upwelling events.

The possible controlling factors of the AN-δ13C with upwelling events are: (1) decreasing water-column transparency 33, (2) variations of δ13C in isotopic equilibrium between water-column and δ13CDIC-SW. Heterotrophic feeding would also be the controlling factor of negative δ13Ccoral with upwelling events. A study 35 reported that corals feeding 13C-depleted zooplankton decreased their δ13Ccoral. The coral records from the Gulf of Aqaba, Red Sea suggested that increasing heterotrophy with upwelling decreased δ13Ccoral for an approximately half a year. Afterwards, δ13Ccoral could be increased by the preferential uptake of 13C by zooplankton at the sea surface 46. In the western Indonesian coast, it was reported that δ13Ccoral increased by approximately 2.2‰VPDB after large phytoplankton blooms due to upwelling 46.

We propose the following mechanism to explain the short-term negative peaks in the δ13Ccoral: 1. Upwelling events bring deep, cold and nutrient-rich water with low δ13CDIC-SW to the surface in summer. Upwelling events cause unusually high nutrient conditions in the Gulf of Oman. Photosynthesis activities in zooxanthella would be emphasized in eutrophic conditions and temporarily increased δ13Ccoral. 2. Lower δ13CDIC-SW from the deep sea decreases δ13Ccoral. 3. Phyttoplankton blooms arise from a nutrient supply to the sea surface. 4. Phytoplankton primarily depletes 12CO2-SW. Active phytoplankton photosynthesis increases 13CO2-SW. 5. δ13Ccoral increases with the restoration of δ13CDIC-SW.

We compared the AN-δ13C minima with the upwelling periods (number of the days) in summer (Figs 2a, S5 and S6). In situ daily to weekly SST data in 1992, 1994, 2001, 2002 and 2010 revealed that SST during upwelling events was as same as winter SST (23.5 °C), and daily fluctuations of SST in upwelling periods ranged within 3 °C. Therefore, the numbers of the days for upwelling periods were defined as the duration of SST lower than 26.5 °C in summer. δ13Ccoral values of no upwelling years (0 days) was estimated from in situ δ13C DIC-SW in the Arabian Sea (+1.32‰VPDB at 0–10 m depth in non-upwelling seasons 29) and the value of δ13C in isotopic equilibrium between coral carbonate and seawater 37. The AN-δ13C minima were correlated to the upwelling periods as below. Upwelling periods (days) = −87.16 ± 16.40 × AN-δ13C minima (‰VPDB) ± 4.92 ± 9.45 (r = −0.937, P < 0.05; Fig. 2a).

Then, past upwelling periods in the year with no in situ SST data were reconstructed from each AN-δ13C using this equation (Fig. 2b). The estimated uncertainty for reconstructed upwelling periods was 12.66 days (1σ) including the analytical precision of δ13Ccoral, the intercept and the slope of this equation. In 1987, 2006, 2008 and 2009, each upwelling period was extremely long, over 120 days (Fig. 2b). In those years, coral extension rates were emphasized in eutrophic conditions and temporarily increased δ13Ccoral. Sr/Ca ratios showed 1-month increasing (cooling) in summer except in 1994, 2001, 2002, 2006, and 2009, however, these did not correspond to reconstructed upwelling events. In non-AN-δ13C (upwelling) years (1989, 1991, 1997–1998, 2003, 2007, 2011–2012), the δ18OSW anomaly was low in summer. Upwelling events in the Gulf of Oman are driven by the SW Monsoon, which causes strong seasonal winds parallel to the coast of Southern Oman in the Arabian Sea, while the associated Ekman transport creates strong upwelling along the coastal margins, bringing cold, nutrient-rich water to the surface 4, 5. This upwelled water has indirect impacts on
corals and reef areas farther north through gyres and eddy systems that sweep into the Oman Sea. In addition, upwelling may be influenced by vertical seawater density, depending on SST and SSS. The δ18O anomaly record suggested that deep seawater did not reach the sea surface as low-density water masses might form a cap on the sea surface in the Gulf of Oman.

Observations suggest that the primary productivity of the Gulf of Oman is subject to inter-annual variability, but long-term observational records are lacking. Our new δ13C coral record captured past upwelling events and their periods in the Gulf of Oman for 26 years. Thus, coral skeletal archives fill an important gap in the observational record and have great potential for increasing our understanding of the upwelling mechanisms in the Gulf of Oman. Moreover, it is possible to reconstruct past SST, SSS and upwelling frequency/intensity during the Holocene (from 0 to 10 ka) by applying the same methods to fossil corals from the Arabian Peninsula.

Methods

Coral sampling. On February 23, 2013, we drilled a Porites sp. coral colony in the Gulf of Oman (23°30′ N, 58°45′ E; Fig. 3a and b). This Porites colony was living at a 2 m water depth in a small bay (Bandar Khayran) south of Muscat. There was no dry-riverbed (locally name: wadi) nearby; thus, we excluded the influence of occasional plumes of freshwater from coastal runoff at the site. In total, the coral core was 71 cm long. On the sampling date, we measured in situ SST and SSS at 24.3 °C and 38.2 PSU (practical salinity unit). Meteorological records from the weather station at Seeb Airport (23.60°N, 58.30°E) showed low precipitation rates, with less than 14.0 mm/month (the monthly average precipitation climatology for the past 23 years was 0.28–14.0 mm/month; GHCN-Monthly ver. 2). For coral proxy calibration, we used Advanced Very High Resolution Radiometer (AVHRR) satellite SST data, SODA satellite SSS data (http://iri.columbia.edu: Fig. 3c) and OLR data (https://climexp.knmi.nl: Fig. 3c) during past 26 years (data from https://climexp.knmi.nl/). Error bars indicate climatology deviation (1σ).

Subsampling. The coral core was sliced into 5-mm-thick slabs. We took X-radiographs of the coral slabs to identify the coral growth axis (Fig. 4). We prepared ledges of 1.5 mm in thickness along the maximum growth axis and obtained coral powder at a resolution of 0.5 mm for geochemical analysis.

Oxygen and carbon isotope measurements. The coral powder was weighed, and 100 μg (±20 μg) were taken for oxygen and carbon stable isotope analysis. The sample powder was reacted with 100% H3PO4 at 70 °C in an automated carbonate preparation device (Kiel II). The δ13C coral and δ18O coral were analyzed with a Finnigan MAT251 stable isotope ratio mass spectrometer system installed at Hokkaido University. Analytical errors for δ13C coral and δ18O coral were determined to be 0.08 and 0.07‰, respectively, based on replicate measurements of the NBS-19 standard (1σ, n = 40).
Trace element measurements. We measured Sr/Ca ratios with a SPECTRO CIROS CCD SOP inductively coupled plasma optical emission spectrophotometer installed at Kiel University following a combination of methods described by Schrag et al. and de Villiers et al. Approximately 250 μg of coral powder was dissolved in 4 mL of HNO₃. The sample solution for the measurement of trace elements was prepared via serial dilution with 2% HNO₃ for a Ca concentration of ca. 8 ppm. Analytical precision of the Sr/Ca determinations was 0.07% RSD or 0.01 mmol ⋅ mol⁻¹ (1σ).

Data analysis. We used the coral Sr/Ca ratios to develop an age model for all proxies. Minima and maxima of the coral Sr/Ca ratios were chosen as anchor points and tied to the maxima and minima of SST, respectively. To obtain a time series with equidistant time steps, we resampled the proxy data at a biweekly resolution using the AnalySeries software, version 2.0.8. Annual extension rates were estimated from the distance (in mm) between the winter anchor points in each sclerochronological year.

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Author Contributions
T.W. and M.P. designed the project. T.W., A.Y., M.P. M.R.C. collected samples. T.K.W., A.Y. and D.G.-S. analyzed the samples. T.K.W. wrote the manuscript. All authors helped with the interpretation of the data and writing the manuscript.

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