

闽西仙云洞高分辨率石笋记录的东亚夏季风 CIS-8 事件及亚旋回特征*

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摘 要 基于福建仙云洞石笋 (XY2-10) 的 9 个高精度 ^{230}Th 年龄和 442 个氧同位素数据, 重建了 38.20—36.10 ka B. P. 平均分辨率达 5 yr 的东亚夏季风 (East Asian Summer Monsoon, EASM) 强度演变历史。福建仙云洞石笋 $\delta^{18}\text{O}$ 值在 CIS-8 (Chinese Interstadial 8) 时期整体呈现出稳定的偏负特征, 与同一时期中国季风区内葫芦洞、永兴洞、小白龙洞石笋 $\delta^{18}\text{O}$ 记录趋势较为一致, 但该石笋 $\delta^{18}\text{O}$ 记录的夏季风强度在 CIS-8 期间整体偏强的趋势, 与格陵兰冰芯 $\delta^{18}\text{O}$ 记录的降温趋势不同。分析表明, 在 CIS-8 事件期间, 南极变冷, 其通过增强南半球马斯克林高压 (Mascarene High, MH) 和越赤道气流, 使中国南方地区石笋 $\delta^{18}\text{O}$ 记录的 EASM 整体保持较强态势。此外, 仙云洞石笋 $\delta^{18}\text{O}$ 记录还揭示了 CIS-8 事件内部存在 21 次百年至十年际尺度的夏季风增强事件, 这与格陵兰 NEEM (Northern Greenland Eemian Ice Drilling) 冰芯 $\delta^{18}\text{O}$ 记录、阿拉伯海海盆岩心反照率记录的亚旋回事件相对应, 表明 EASM 增强 (减弱)、北高纬温度升高 (降低) 和赤道辐合带 (Intertropical Convergence Zone, ITCZ) 北移 (南移) 在百年至十年际尺度上存在紧密的联系, 而这种联系可能是源于北大西洋经向翻转环流 (Atlantic Meridional Overturning Circulation, AMOC) 变化引起的北半球高纬与低纬地区的快速海气耦合。

关键词 CIS-8 事件 石笋 东亚夏季风 福建仙云洞 亚旋回

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East Asian Summer Monsoon CIS-8 event and its sub-cycle features recorded by precisely-dated high-resolution stalagmite from Xianyun Cave, western Fujian Province, China

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Abstract The Greenland Interstadial 8 (GIS-8) event during Marine Isotope Stage 3 (MIS3) is characterized by significant warming at northern high latitudes. However, relatively few high-resolution

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geological records have been used to reveal its detailed structure and global response. In this study, nine high-precision ^{230}Th ages and 442 oxygen isotope ($\delta^{18}\text{O}$) data were measured from a stalagmite (XY2-10) collected from Xianyun Cave in Fujian Province. These data enable us to reconstruct the evolution of the East Asian Summer Monsoon (EASM) intensity with an average temporal resolution of 5 years over the period of 38.20–36.10 ka B. P. (Before Present, “Present” refers to 1950 AD), which covers the Chinese Interstadial 8 (CIS-8) event. The $\delta^{18}\text{O}$ time series exhibit a stable negative characteristic during the CIS-8 period, consistent with the trends observed in $\delta^{18}\text{O}$ records from other stalagmites in the Chinese monsoon region, such as those from Hulu Cave, Yongxing Cave, and Xiaobailong Cave. However, the strengthening trend in summer monsoon intensity recorded by the stalagmite in Xianyun Cave during CIS-8 contrasts with the cooling trend evident in the Greenland ice core $\delta^{18}\text{O}$ record. The analysis suggests that during CIS-8, enhanced cooling in Antarctica strengthened the Mascarene High and the transequatorial flow in the Southern Hemisphere, resulting in an overall stronger EASM in southern China, as reflected in the stalagmite $\delta^{18}\text{O}$ records. Our sub-decadal resolution record also identifies 21 centennial- to interdecadal-scale summer monsoon enhancement events within the CIS-8 interval. These events correlate well with corresponding events in the Greenland NEEM (Northern Greenland Eemian Ice Drilling) ice-core $\delta^{18}\text{O}$ record and the core albedo record from the Arabian Sea Basin. This correlation indicates that the EASM enhancement (weakening), warming (cooling) of northern high latitudes, and northward (southward) shift of the Intertropical Convergence Zone (ITCZ) are strongly linked on centennial- to interdecadal-scales. These connections are likely driven by rapid air-sea coupling mechanism, which is influenced by changes in the Atlantic Meridional Overturning Circulation (AMOC) in the North Atlantic.

Key words Chinese Interstadial 8 event, stalagmite, East Asian summer monsoon, Xianyun Cave of Fujian Province, sub-cycles

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1 概述

末次冰期深海氧同位素第 3 阶段 (Marine Isotope Stage 3, MIS3) 以一系列典型的千年尺度 Dansgaard-Oeschger (DO) 旋回为标志 (Dansgaard *et al.*, 1993; Hinnov *et al.*, 2002), 全球冰量、太阳辐射及 CO_2 浓度均处于中等水平 (McManus *et al.*, 1999; Sachs and Lehman, 1999), 北大西洋洋流不稳定, 易发生千年尺度气候震荡 (Dansgaard *et al.*, 1993)。格陵兰冰芯与中国季风区石笋分别记录了北半球高纬度地区 (后文简称“北高纬”) 温度快速变暖与东亚夏季风 (East Asian Summer Monsoon, EASM) 快速增强的气候突变事件, 分别被称为格陵兰间冰阶 (Greenland Intersta-

dials, GIS) 与中国间冰阶 (Chinese Interstadials, CIS) (Johnsen *et al.*, 1992; Cheng *et al.*, 2006)。研究发现, 千年时间尺度上 GIS 与 CIS 事件具有良好的——对应关系 (Wang *et al.*, 2001, 2005)。依据高分辨率的格陵兰冰芯记录发现在 GIS 事件内部存在百年至十年际尺度的亚旋回事件, 表明冰期中的暖事件气候变化也不稳定 (Capron *et al.*, 2010, 2012; Rasmussen *et al.*, 2014)。该冰芯记录中, 末次冰期千年尺度气候突变事件的亚旋回事件是否在亚洲季风区也存在, 对于理解气候突变事件的驱动机制具有重要意义。此外, CIS 事件在起始过程方面与格陵兰冰芯快速突变并不完全一致, 而是表现出类似南极冰芯缓慢变化的特征, 说明中国

季风区气候会受到南半球气候的强有力调控 (Rohling *et al.*, 2003; Cai *et al.*, 2006; Chen *et al.*, 2016; Wu *et al.*, 2020)。

GIS-8 事件在格陵兰冰芯 $\delta^{18}\text{O}$ 记录中的持续时间接近 1700 yr, 振幅达 4‰ (Andersen *et al.*, 2006), 是 MIS3 阶段最典型的 GIS 事件之一。中国季风区的三星洞、小白龙洞、雾露洞、葫芦洞和永兴洞石笋 $\delta^{18}\text{O}$ 记录都捕捉到了 CIS-8 事件 (Cai *et al.*, 2006; 何尧启和姜修洋, 2012; Duan *et al.*, 2014; Cheng *et al.*, 2016; Liang *et al.*, 2022)。其中, 西南雾露洞石笋 $\delta^{18}\text{O}$ 记录的 CIS-8 事件开始与南极冰芯 $\delta^{18}\text{O}$ 记录存在着类似的缓慢变化特征, 说明中国季风区在 CIS-8 事件初始时受到与南极温度相关的南半球水汽输送的影响 (Duan *et al.*, 2014)。贵州三星洞石笋 $\delta^{18}\text{O}$ 记录显示 CIS-8 内部还存在 4 次亚旋回事件, 在定年误差范围内分别与格陵兰 NGRIP 冰芯 $\delta^{18}\text{O}$ 记录及 Cariaco 海盆沉积物反射比记录一一对应, 表明亚洲夏季风与北极温度、赤道辐合带 (Intertropical Convergence Zone, ITCZ) 位置在千年至百年尺度上存在遥相关 (何尧启和姜修洋, 2012)。然而, 上述石笋记录的氧同位素分辨率较低, 且位于中国西南地区或长江中下游地区。因此, 为了更准确地还原 EASM 在 CIS-8 时期的时空变化特征, 了解其与南、北极气候的联系, 有必要获取更多区域高精度定年的高分辨率古气候记录并对其进行更深入的研究。

文中选取位于东亚季风区前沿地带的中国东南地区福建仙云洞的 1 根石笋 (编号 XY2-10), 通过精确的 ^{230}Th 测年和氧同位素测试, 重建了中国东南地区 38.20—36.10 ka B. P. 期间平均分辨率达 5 yr 的东亚夏季风时间演化序列, 揭示出中国东南地区 CIS-8 事件期间 EASM 的变化特征。通过与已发表的古气候记录对比, 探讨其内部特征及可能存在的驱动机制。

2 研究区域概况、材料与方法

石笋样品采自福建西部龙岩市连城县城东南 15 km 处的仙云洞 (25° 33' N, 116° 59' E) (图 1-A), 洞口海拔约为 968 m。仙云洞所在的连城县处于浙闽丘陵, 受典型的东亚夏季风影响, 地形因素兼具山地气候特征, 全年气候温和, 降水充沛。距仙云洞 59 km 的永安气象站自 1989 至

2018 年年平均气温为 20 °C, 平均降水量 1552 mm, 5—9 月份降水量约占全年总降水量的 60% (图 1-C)。溶洞发育于二叠系栖霞组石灰岩中, 自洞口向内呈阶梯状下延, 全长 2470 m (张富强等, 2018)。洞穴封闭性较好, 洞内实测气温为 17.5 °C, 湿度常年接近 100%。洞内有若干大小不等的洞厅, 滴水点众多, 次生碳酸盐发育良好。洞穴上覆土壤为黄壤, 植被繁茂, 主要以毛竹林、林下草本植物为主。

样品 XY2-10 采自仙云洞右支洞的中部大厅 (图 1-B), 整体外形呈圆柱状, 长 532 mm, 底部直径约为 58 mm (图 2-A)。将石笋沿着中心生长轴切开、抛光, 抛光面光滑且无溶孔。在距顶部 41 mm、70 mm 及 515 mm 处分别存在 1 个风化层面, 有可能为沉积间断。

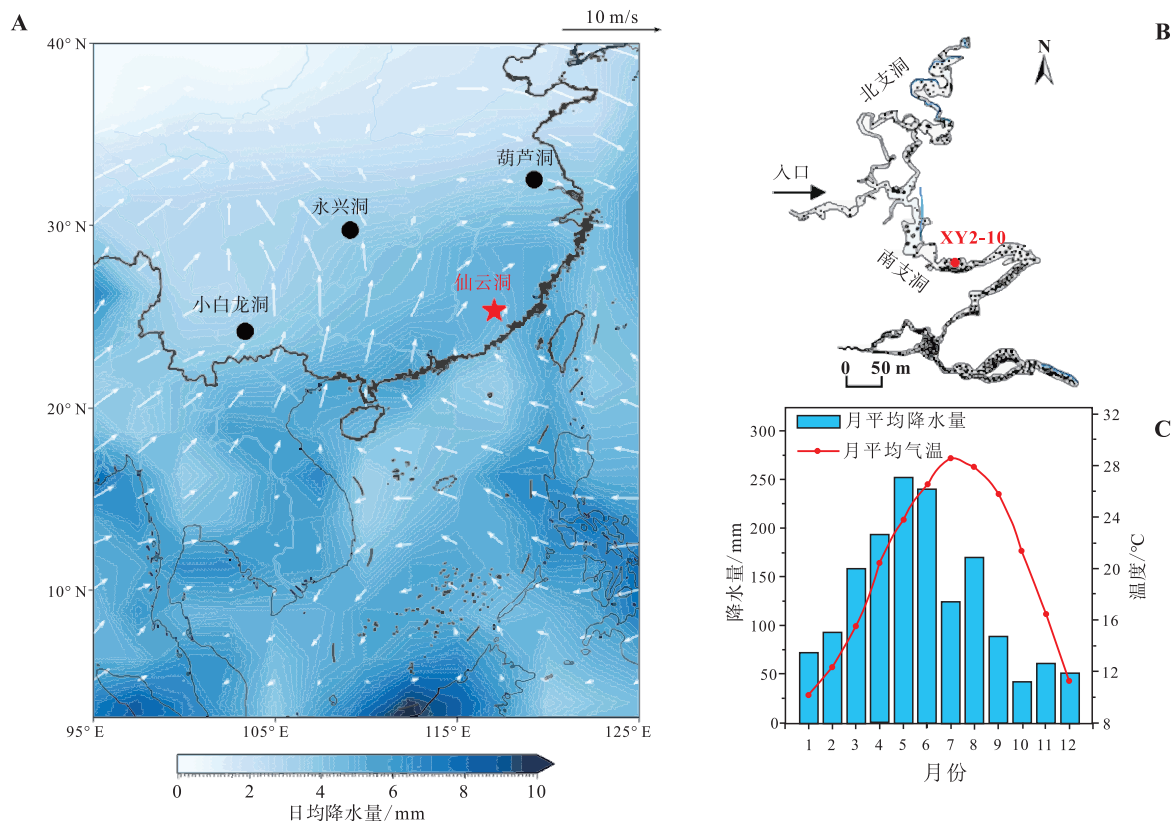
在石笋抛光面上, 使用直径为 0.5 mm 的牙钻, 沿生长轴钻取 11 个样品用于 ^{230}Th 定年。化学前处理和分析方法参照 Shen 等 (2012), 分析仪器为 MC-ICP-MS Neptune, 在台湾大学高精度质谱与环境变迁实验室 (HISPEC) 完成测试。

使用直径为 0.3 mm 的牙钻, 沿生长轴方向, 每间隔 1 mm 采集 1 个氧同位素样品, 共获取 442 个样品进行稳定同位素测试。每 9 个样品插入 1 个标准样品 (NBS-19), 通过碳酸盐自动进样装置 Kiel-IV 与 Finnigan MAT-253 Plus 型质谱仪联机测试完成。氧同位素样品的采集与测试工作在福建师范大学地理科学学院稳定同位素实验室完成。

3 结果

3.1 U/Th 年代

表 1 给出了 XY2-10 石笋在 41~530 mm 层段的 11 个 U-Th 实测年龄以及误差范围 ($\pm 2\sigma$)。定年结果显示, XY2-10 石笋 ^{238}U 含量高 (8.7~29.0 $\mu\text{g/g}$), ^{232}Th 含量低 (33.5~12924.1 pg/g), 测年误差为 13~104 a, 测年精度高。结合定年结果和岩性特征分析, 认为在 70 mm、515 mm 处可能存在沉积间断 (图 2-A)。文中主要分析距顶部 70~511 mm 的石笋层段。在研究层段, 根据 9 个 ^{230}Th 定年点, 采用线性内插方法, 建立了年龄—深度模型 (图 2-B), 由此构建了 38.20—36.10 ka B. P. 分辨率达 5 yr 的氧同位素序列, 该时段生长速率



A—1960—2020 年区域日均降水量（蓝色梯度）及 850 hPa 矢量风（白色箭头），红色五角星代表仙云洞的地理位置，黑色点分别代表葫芦洞、永兴洞和小白龙洞的位置；B—仙云洞洞穴平面示意图（改自张富强等，2018），红色点代表 XY2-10 的采样点位置；C—1989—2018 年永安气象站月平均温度及降水量，数据来源于 <https://data.cma.cn/>

图 1 福建龙岩仙云洞洞穴示意图及永安气象站月平均温度、降水量

Fig. 1 Sketch map of Xianyun Cave of Longyan area, and average temperature and precipitation per month of Yong'an weather station in Fujian Province

为 0.13~0.30 mm/yr (图 2-C)。

3.2 石笋氧同位素记录

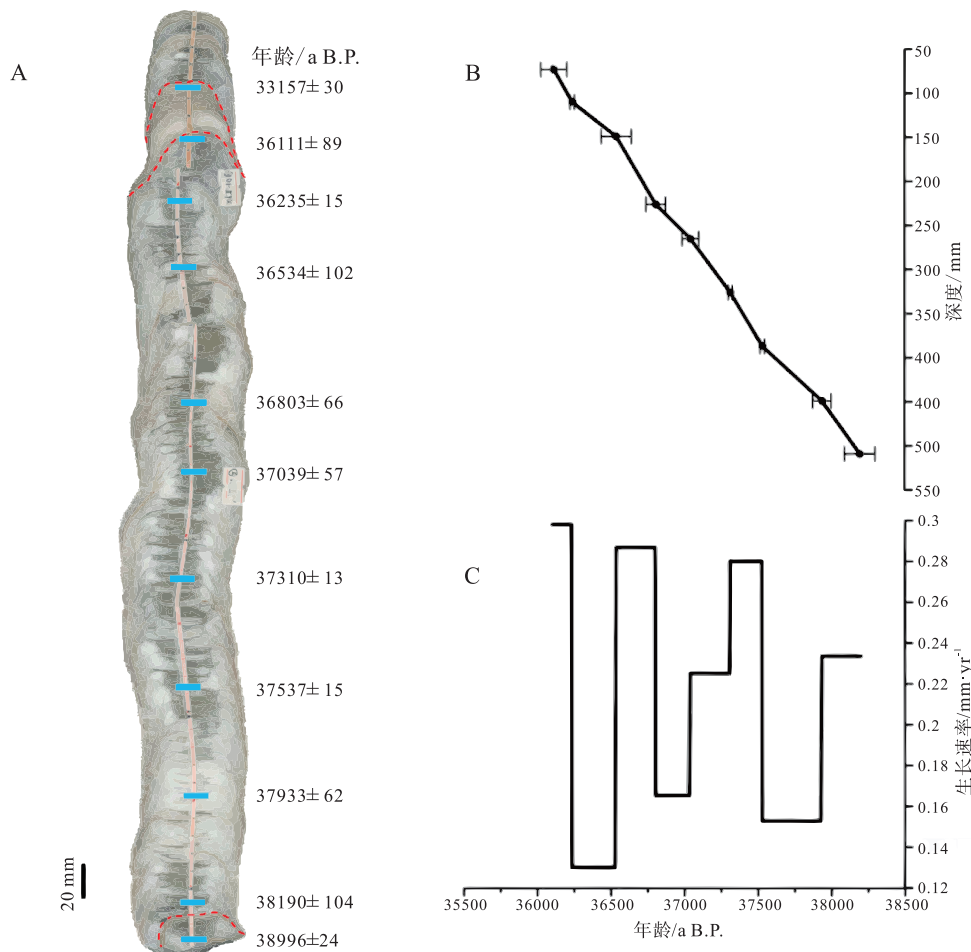
图 3 给出了覆盖 CIS-8 及间断面下海因里希冰阶 4 (Heinrich Stadial 4, HS4) 时期的仙云洞 XY2-10 及已发表的同一洞穴 XY-1 (Zhang *et al.*, 2021) 石笋氧同位素记录随时间演化序列。由图 3 可以看出, XY2-10 与 XY-1 氧同位素在重叠生长时段重现性较好, 说明 XY2-10 没有发生显著的动力分馏。在 HS4 时期, XY2-10 石笋氧同位素在 -7.43‰ ~ -7.08‰ 之间波动, 平均值为 -7.24‰ 。CIS-8 事件时期, 氧同位素整体在 -8.65‰ ~ -7.30‰ 之间波动, 平均值为 -8.13‰ 。整个 CIS-8 时段 XY2-10 氧同位素值较为偏负, 相比于 HS4 时期偏负约 1‰ , 与同一时期 XY-1 石笋氧同位素振幅相一致。38.19±0.10 ka B.P. 左右 XY2-10 石笋氧同位素快速负偏, 时间上与 XY-1 石笋

氧同位素记录的 CIS-8 开始时快速负偏在定年误差范围内一致。2 支石笋精确地标定了 CIS-8 事件开始时间为 38.19±0.10 ka B.P., 这与由葫芦洞校正的格陵兰冰芯 GICC05 (Greenland Ice Core Chronology 2005, GICC05) 时标下 CIS-8 的开始时间 (38.34±0.07 ka B.P.) (Cheng *et al.*, 2021) 及永兴洞 (38.18 ka B.P.) (Liang *et al.*, 2022)、小白龙洞 (38.21 ka B.P.) (Cai *et al.*, 2006)、雾露洞 (38.27 ka B.P.) (Duan *et al.*, 2014) 记录的 CIS-8 事件开始时间在定年误差范围内一致。38.19—36.29 ka B.P., 氧同位素呈稳定的水平波动, 并叠加了众多百年至十年际尺度的震荡。自 36.29 ka B.P. 开始, 石笋 $\delta^{18}\text{O}$ 值迅速偏正, 直到 36.19 ka B.P. 达到极大值之后趋于稳定波动。根据气候突变过程中间点的位置, 标定 CIS-8 事件的结束时间为 36.24±0.02 ka B.P.。CIS-8 事件的持续时间为 2 ka 左右。

表 1 福建龙岩仙云洞 XY2-10 石笋 ²³⁰Th 年龄分析结果
Table 1 ²³⁰Th dating results for stalagmite XY2-10 from Xianyun Cave of Longyan area, Fujian Province

样品编号 深度/mm	²³⁸ U ^a / μg·g ⁻¹	²³² Th / pg·g ⁻¹	$\delta^{234}\text{U}$ 测量值 ^a	$\delta^{234}\text{U}$ (校正值) ^b	$[\frac{^{230}\text{Th}}{^{238}\text{U}}]$ (活度比) ^c	$[\frac{^{230}\text{Th}}{^{232}\text{Th}}]$ ^d / μg·g ⁻¹	²³⁰ Th 年龄/yr (未校正)	²³⁰ Th 年龄/yr (校正值) ^{e,e'}	年龄/a B. P.
XY2-10-41	8.722±0.0004	12924.1±80.4	1413.3±0.4	1552.3±0.4	0.65125±0.00049	7246±45	33246±29	33231±30	33157±30
XY2-10-73	18.981±0.0226	1739.7±7.3	1399.9±3.0	1550.3±3.3	0.69728±0.00119	125436±547	36177±89	36176±89	36111±89
XY2-10-110	19.625±0.0011	58.6±72.7	1360.0±0.4	1506.7±0.5	0.68764±0.00022	3799201±4718819	36309±15	36309±15	36235±15
XY2-10-149	23.727±0.0383	152.4±13.9	1355.4±3.7	1502.9±4.1	0.69116±0.00126	1774237±161319	36607±102	36607±102	36534±102
XY2-10-226	27.185±0.0229	76.3±13.2	1363.9±1.9	1513.4±2.2	0.69813±0.00091	4100810±710641	36875±66	36875±66	36803±66
XY2-10-265	29.608±0.0273	515.5±13.7	1374.7±2.0	1526.4±2.3	0.70528±0.00071	667942±17695	37111±57	37111±57	37039±57
XY2-10-326	26.339±0.0015	147.5±83.5	1376.2±0.4	1529.3±0.4	0.71022±0.00018	2091107±1183322	37384±13	37384±13	37310±13
XY2-10-387	20.788±0.0012	140.2±74.1	1372.7±0.4	1526.4±0.5	0.71274±0.00021	1742326±921214	37601±15	37601±15	37527±15
XY2-10-449	21.949±0.0221	33.5±12.5	1364.2±2.1	1518.6±2.3	0.71672±0.00079	7748831±2887942	38005±62	38005±62	37933±62
XY2-10-509	23.449±0.0310	1622.3±7.6	1355.9±3.6	1510.5±4.0	0.71821±0.00127	171162±828	38255±104	38255±104	38190±104
XY2-10-530	17.124±0.0011	696.6±120.2	1339.7±0.5	1495.8±0.6	0.72624±0.00035	294362±50806	39071±24	39070±24	38996±24

注：^a 样品编号 XY2-10 后的数字为距顶深度（单位：mm）；
²³⁰Th 衰变常数是 $9.1705 \times 10^{-6} \text{ yr}^{-1}$ ，²³⁴U 是 $2.8221 \times 10^{-6} \text{ yr}^{-1}$ （Cheng *et al.*, 2013），²³⁸U 是 $1.55125 \times 10^{-10} \text{ yr}^{-1}$ （Jaffey *et al.*, 1971）；
^a $[\frac{^{238}\text{U}}{^{232}\text{Th}}] = [\frac{^{235}\text{U}}{^{232}\text{Th}}] \times 137.818 (\pm 0.65\%)$ （Hiess *et al.*, 2012）； $\delta^{234}\text{U} = ([\frac{^{234}\text{U}}{^{238}\text{U}}]_{\text{活度比}} - 1) \times 1000$ ；
^b $\delta^{234}\text{U}$ 初始值校正，例如， $\delta^{234}\text{U} = \delta^{234}\text{U}_{\text{测量值}} \times e^{\lambda^{234}T}$ ， T 是校正年龄；
^c $[\frac{^{230}\text{Th}}{^{238}\text{U}}]_{\text{活度比}} = 1 - e^{-\lambda^{230}T} + (\delta^{234}\text{U}_{\text{测量值}}/1000) [\lambda^{230}/(\lambda^{230} - \lambda^{234})]$ （ $1 - e^{-(\lambda^{230} - \lambda^{234})T}$ ）， T 是年龄；
^d 碎屑 ²³⁰Th 污染程度用 $[\frac{^{230}\text{Th}}{^{232}\text{Th}}]$ 原子比而不是活度比来表示；
^e 使用估算的原子 ²³⁰Th/²³²Th 比值 4（±2）×10⁻⁶ 计算样品的年龄校正；
测年平均误差为 2σ；
B. P.（Before Present）指相对于公元 1950 年。



A—仙云洞 XY2-10 石笋抛光面，红色虚线为 41 mm、70 mm、515 mm 处的沉积间断，蓝色长方形代表测年点，并标注了测年点年龄和误差；B—用线性内插法建立的 XY2-10 石笋年龄-深度模式图，黑点和误差棒分别代表实测年龄及对应的 2σ 误差，黑色线为年龄模式；C—XY2-10 石笋年龄-生长速率模型

图 2 福建龙岩仙云洞 XY2-10 石笋的抛光面、年龄-深度模式和生长速率图

Fig. 2 Polished surface, age-depth pattern and growth rate of stalagmite XY2-10 in Xianyun Cave of Longyan area, Fujian Province

4 讨论

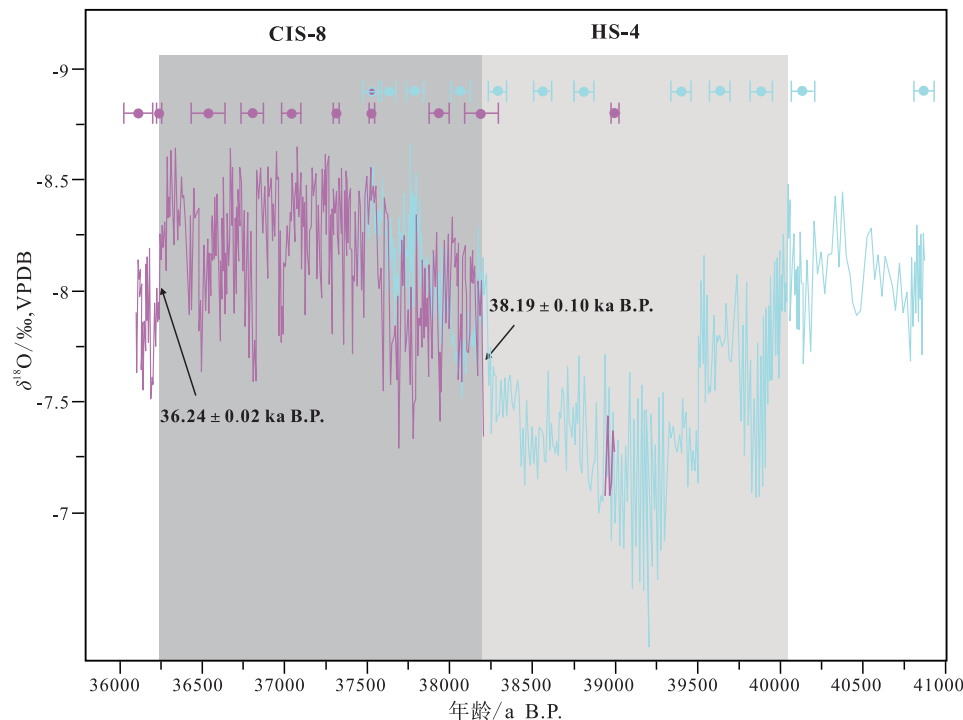
4.1 仙云洞石笋氧同位素指示意义

研究认为，中国石笋 $\delta^{18}\text{O}$ 在轨道至百年时间尺度上反映了平均气候状态下的夏季风强度或大尺度范围内水汽整体运移状况 (Liu *et al.*, 2014; Cheng *et al.*, 2016)，但目前对于夏季风强度的解释存在不同认识，例如夏季降水量与全年降水量的比值 (Wang *et al.*, 2001; Zhang *et al.*, 2020)、水汽源变化 (Tan, 2014)、传输路径上雨除效应强度 (Yuan *et al.*, 2004; Ruan *et al.*, 2019) 等。针对中国东南地区的石笋 $\delta^{18}\text{O}$ 记录，前人研究表明其在十年至年际时间尺度上主要受控于厄尔尼诺/南方涛动 (El Niño-Southern Oscillation, ENSO) 调

控的夏季/非夏季降水比例 (Zhang *et al.*, 2018a, 2018b; Lu *et al.*, 2021)。最近，Qiu 等 (2023) 基于福建西部玉华洞 11 yr 的现代监测，认为与 ENSO 有关的上游对流和雨除效应调控了中国东南地区年际至季节降水 $\delta^{18}\text{O}$ 值。据此，结合先前的解释 (Qiu *et al.*, 2022, 2024; Zhang *et al.*, 2024)，笔者认为中国东南地区仙云洞石笋 $\delta^{18}\text{O}$ 在千年至百年时间尺度上反映了大尺度环流和降水变化的信号，即 EASM 的强度。当 $\delta^{18}\text{O}$ 值越正 (负)，EASM 越弱 (强)。

4.2 CIS-8 事件特征及演化机制

GIS-8 事件在格陵兰冰芯记录中呈现快速升温—持续降温—快速降温的“锯齿状”变化模式 (Dansgaard *et al.*, 1993; Wolff *et al.*, 2010)，表明



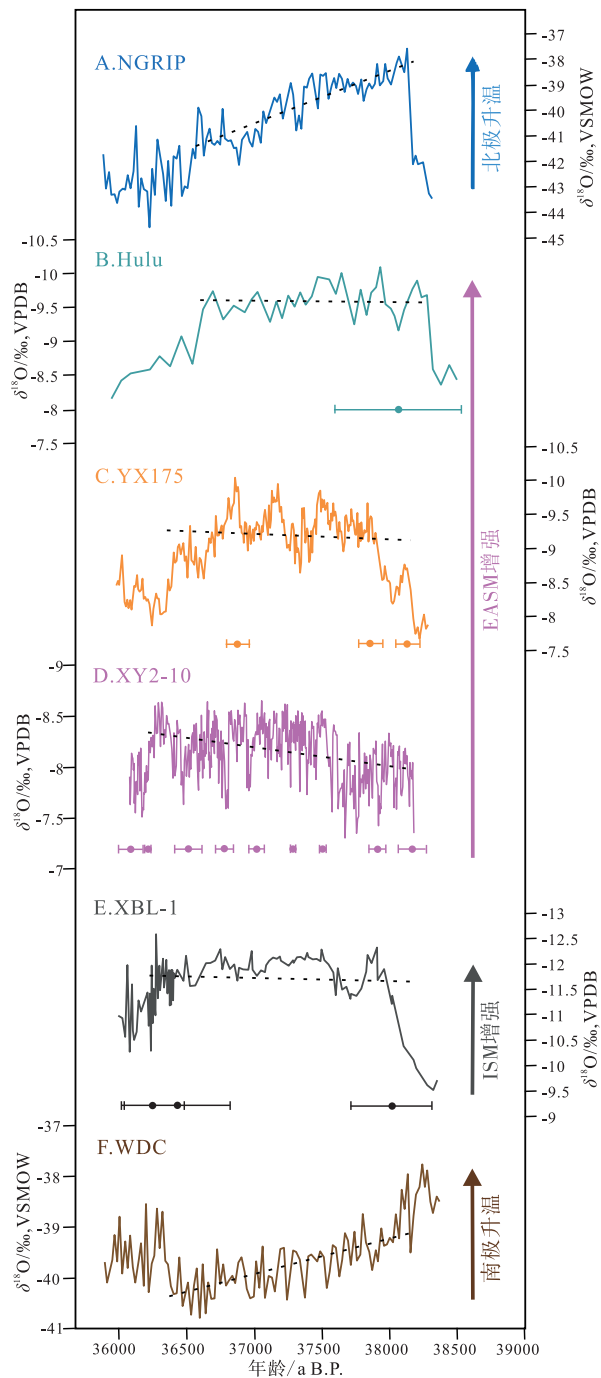
紫色代表仙云洞 XY2-10 石笋 $\delta^{18}\text{O}$ 记录(本研究); 蓝色代表仙云洞 XY-1 石笋 $\delta^{18}\text{O}$ 记录(Zhang *et al.*, 2021)。误差棒代表年龄误差, 阴影部分表示 CIS 及 HS 事件, 黑色箭头指示事件开始和结束时间

图 3 福建龙岩仙云洞 XY2-10 与 XY-1 石笋 $\delta^{18}\text{O}$ 记录

Fig. 3 $\delta^{18}\text{O}$ records of stalagmites from XY2-10 and XY-1 of Xianyun Cave of Longyan area, Fujian Province

北高纬温度在 CIS-8 事件开始后持续降低直至事件结束(图 4-A)。图 4-D 代表的 XY2-10 石笋 $\delta^{18}\text{O}$ 序列在 CIS-8 完全开始后呈现出持续偏负的特征, 说明仙云洞石笋记录的东亚夏季风强度在事件期间是逐渐增强的, 这与北高纬温度变化趋势不一致。将中国季风区不同石笋记录的 CIS-8 事件氧同位素变化序列进行对比, 发现虽然各石笋 $\delta^{18}\text{O}$ 记录变化细节存在一定差异, 这可能与样品的氧同位素分辨率及定年精度不同有关, 也可能是受局地气候的影响或者由石笋记录的信噪比不同引起, 但在事件整体变化趋势上, 可以较为明显地看出葫芦洞(图 4-B)和小白龙洞(图 4-E)石笋 $\delta^{18}\text{O}$ 值在 CIS8 事件期间始终较为偏负, 永兴洞(图 4-C)和仙云洞(图 4-D)类似, 表现出明显的负偏趋势, 说明中国季风区石笋记录的 EASM 整体较为强劲。已有研究表明, 石笋记录的 EASM 在千年尺度上响应北高纬气候强迫(Wang *et al.*, 2001; Cheng *et al.*, 2009), 但地理空间和影响因素的区域差异性可能会使低纬夏季风和北高纬温度在 CIS 变化模式上呈现出不同的变化特征(Han *et al.*, 2016;

Duan *et al.*, 2018)。因此, CIS-8 时期 EASM 强度与北高纬温度不一致的整体变化趋势, 可能暗示了其他驱动力的作用。将仙云洞石笋 $\delta^{18}\text{O}$ 记录(图 4-D)与南极冰芯 WDC 的 $\delta^{18}\text{O}$ 记录(图 4-F)进行比较, 南极冰芯表现出的持续变冷与 EASM 的整体较强趋势在反相位关系下具有更强的一致性。从中国石笋、黄土与南极冰芯、南半球湖泊等古气候地质证据的对比中已经发现, EASM 作为全球气候系统的一个组成部分, 充当了北半球和南半球气候相互作用的“桥梁”角色, 会受到南半球气候“推力”的影响(An, 2000, 2015; Rohling *et al.*, 2009)。当 CIS-8 开始后, 南高纬地区温度持续降低, 加大了南半球温度梯度, 这会导致马斯克林高压(Mascarene High, MH)的增强。而 MH 对东亚夏季风环流有重要引导作用, MH 的增强会改变对流层低层大气环流, 增强跨赤道的索马里急流, 使南印度洋水汽更多输送至东亚地区, 从而加强 EASM(Xue *et al.*, 2004; Cai *et al.*, 2006; 崔英方等, 2011; Chen *et al.*, 2016; Wu *et al.*, 2020)。因此, 虽然北高纬地区温度在 CIS-8 时期逐渐降



A—北格陵兰冰芯 NGRIP $\delta^{18}\text{O}$ (North Greenland Ice Core Project members, 2004) 在 GICC05 时标下的记录 (Andersen *et al.*, 2006); B—葫芦洞石笋 $\delta^{18}\text{O}$ 记录 (Cheng *et al.*, 2016); C—永兴洞 YX175 石笋 $\delta^{18}\text{O}$ 记录 (Liang *et al.*, 2022); D—仙云洞 XY2-10 石笋 $\delta^{18}\text{O}$ 记录 (本研究); E—小白龙洞 $\delta^{18}\text{O}$ 记录 (Cai *et al.*, 2006); F—WDC 冰芯 (WAIS Divide Project Members, 2015) 在 WD2014 时标下的记录 (Buizert *et al.*, 2015)。误差棒表示测年误差, 虚线为线性拟合的趋势线

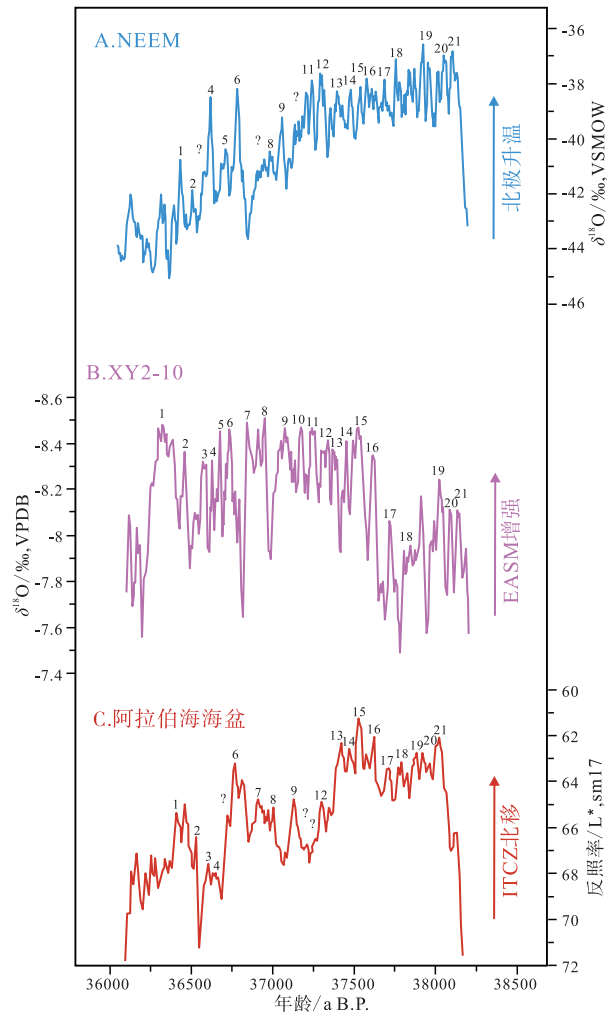
图 4 福建龙岩仙云洞石笋 $\delta^{18}\text{O}$ 记录的 CIS-8 事件与其他记录对比

Fig. 4 Comparison of CIS-8 event recorded by stalagmite $\delta^{18}\text{O}$ in Xianyun Cave of Longyan area, Fujian Province with other records

低, 但是南极降温引起的自南向北更强的越赤道气流会增强亚洲夏季风强度, 从而削弱了北高纬地区气候对中国季风区的影响, 使得 EASM 呈现出整体较强的趋势。

4.3 CIS-8 时期百年至十年际尺度气候亚旋回事件

高分辨率的格陵兰 NEEM 冰芯 (Gkinis *et al.*, 2021) 与阿拉伯海海盆岩心 (Deplazes *et al.*, 2013), 不仅记录了 CIS-8 千年尺度气候振荡, 更揭示出事件内的亚旋回震荡特征。对格陵兰 NEEM 冰芯 $\delta^{18}\text{O}$ 、阿拉伯海海盆岩心反照率及 XY2-10 石笋 $\delta^{18}\text{O}$ 记录分别进行 6 点、6 点及 4 点滑动平均处理以达到相近分辨率后进行对比, 结果如图 5 所示。由图 5 可以看出, EASM 在长期趋势上未响应 ITCZ 南移及北高纬地区变冷信号, 这也在一定程度上说明了 EASM 还受到南半球越赤道气流的调控, 因此 3 个记录在整体变化趋势上并未显示出完全一致的变化特征。而在百年至十年际时间尺度上, 平滑后的石笋 $\delta^{18}\text{O}$ 发生了 21 次明显负偏 (图 5-B), 指示了东亚季风区共发生了 21 次季风增强的亚旋回事件, 这与格陵兰冰芯 $\delta^{18}\text{O}$ 正偏指示的北极温度升高 (图 5-A) 和阿拉伯海海盆岩心反照率降低指示的 ITCZ 北移 (图 5-C) 相对应。研究发现, 全新世 (张春霞等, 2010)、末次冰消期 (姜修洋等, 2015) 及末次冰期其他 CIS 事件中 (Liu *et al.*, 2010; 王晓艳等, 2015; 车印平等, 2020), 也存在这种百年至十年际时间尺度高低纬联系。而末次冰期气候不稳定背景下的 MIS3 时期, 海气耦合系统可能会放大微弱气候信号, 导致大气系统随机共振, 引起高低纬一致变化 (刘殿兵等, 2008; Ganopolski and Rahmstorf, 2002; Willeit *et al.*, 2024)。整个 CIS-8 期间, 大气 CO_2 浓度下降, 冰盖体积减小, 这可能使北大西洋经向翻转环流 (Atlantic Meridional Overturning Circulation, AMOC) 的活动敏感性增强 (Arz *et al.*, 2007; Bauska *et al.*, 2021; Sun *et al.*, 2022)。因此, 这一时期北高纬地区冰量的短时间变化可能会引起北大西洋淡水注入发生变化, 并影响到北大西洋北部深层水的形成, 从而导致 AMOC 增强 (减弱) (Rahmstorf, 2002), 北高纬地区的气温升高 (降低)。这一认识一方面会使指示数十年时间尺



A—格陵兰冰芯 NEEM $\delta^{18}\text{O}$ (Gkinis *et al.*, 2021) 在 GICC05 时标下的 6 点平滑记录 (Andersen *et al.*, 2006); B—仙云洞石笋 $\delta^{18}\text{O}$ 的 4 点平滑记录; C—阿拉伯海海盆岩心反照率 4 点平滑记录 (Deplazes *et al.*, 2013)。曲线上方数字表示 21 次亚旋回事件

图 5 福建龙岩仙云洞石笋 $\delta^{18}\text{O}$ 记录与高低纬地区气候记录平滑后对比

Fig. 5 Comparison between smoothed $\delta^{18}\text{O}$ record of stalagmite in Xianyun Cave, Longyan, Fujian Province and climate records at high and low latitudes regions

度上北大西洋海温非周期性波动的大西洋年代际变率 (Atlantic Multidecadal Variability, AMV) 正 (负) 位相转变 (Zhang and Delworth, 2005; Sutton *et al.*, 2018; Zhang *et al.*, 2019), 从而引起南、北半球海洋温度梯度异常, 哈德莱环流圈与 ITCZ 位置北 (南) 移; 另一方面会经北半球西风将北高纬地区气候信号向低纬传递, 最终导致东亚夏季风强度增强 (减弱) (Broccoli *et al.*, 2006; Cosford *et al.*, 2008; Schneider *et al.*, 2014; Guo *et al.*,

2024; 丁一汇等, 2020; 姜大膀等, 2024)。因此, 东亚季风 CIS-8 内部百年至十年际尺度的亚旋回特征可能是受到 AMOC 变化引起的北高纬与低纬地区的快速海气耦合影响。

5 结论

本研究基于福建西部仙云洞石笋 9 个高精度 ^{230}Th 年龄和 442 个氧同位素分析, 获得了 38.20—36.10 ka B.P. 平均分辨率达 5 yr 的 CIS-8 时期东亚夏季风强度变化信息。

1) CIS-8 时期, 仙云洞石笋 XY2-10 的 $\delta^{18}\text{O}$ 值整体表现出稳定的负偏趋势, 与同一时期中国季风区葫芦洞、永兴洞、小白龙洞石笋 $\delta^{18}\text{O}$ 记录相似, 说明空间尺度上中国南方地区石笋记录的 EASM 在事件期间整体较为强劲, 这可能是由于南极变冷, 南半球马斯克林高压和越赤道气流增强, 进而加强了 EASM。

2) 高分辨率的仙云洞石笋 $\delta^{18}\text{O}$ 记录揭示出 CIS-8 事件内存在 21 个 EASM 增强的亚旋回气候事件, 这与格陵兰 NEEM 冰芯及阿拉伯海海盆岩心反照率记录有相对应的关系。表明在末次冰期典型 CIS 季风增强事件气候背景下, 受到北大西洋气候波动的影响, EASM 在百年至十年际尺度上具有不稳定的强弱变化, 这可能源于 AMOC 变化引起的北大西洋海温异常经海气耦合系统将北高纬信号传递至低纬地区。

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