

中国季风区石笋记录揭示的太阳活动对千年尺度气候突变事件的驱动作用

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摘 要

末次冰期(LGP)气候状态非常不稳定, 发生了一系列千年尺度气候突变事件, 主要包括海因里希事件(H事件)和Dansgaard-Oeschger事件(DO事件), 关于其驱动机制的讨论一直是古气候学界关注的焦点话题。本文基于亚洲季风区石笋氧同位素记录, 结合大西洋经向翻转环流(AMOC)强度、热带辐合带(ITCZ)位置及 ^{10}Be 重建的太阳活动等多种代用指标, 探讨了深海氧同位素(MIS) 3阶段千年尺度气候突变事件的驱动机制与全球关联性。研究表明, 亚洲夏季风(ASM)变化与北高纬气候存在显著的遥相关关系, AMOC增强可引起格陵兰变暖、ITCZ北移及ASM增强。更为重要的是, 石笋 $\delta^{18}\text{O}$ 序列与太阳活动记录在结构与相位上表现出高度相似性, 指示太阳活动可能是千年尺度气候突变事件的潜在驱动源。进一步分析表明, 太阳活动可能通过调制北大西洋海气环流、热储过程及气候背景状态, 进而影响到AMOC的稳定性及大气-海冰-海洋耦合动力学, 导致DO事件的发生。本研究强调了太阳活动在触发和放大千年尺度气候振荡中的潜在作用, 为理解冰期气候突变机制提供了多指标集成分析的新视角。

关键词

末次冰期, 千年尺度气候突变事件, 亚洲夏季风, 石笋, 太阳活动

Driving Role of Solar Activity in Millennial-Scale Abrupt Climate Events as Revealed by Stalagmite Records from the Chinese Monsoon Region

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Abstract

The climate during the Last Glacial Period (LGP) was highly unstable, marked by a series of millennial-scale abrupt climate change events, primarily including Heinrich events (H events) and Dansgaard-Oeschger events (DO events). The discussion on their driving mechanisms has been a focal topic in the paleoclimatology community. This study, based on speleothem oxygen isotope records from the Asian monsoon region, integrates multiple proxy indicators such as the strength of the Atlantic Meridional Overturning Circulation (AMOC), the position of the Intertropical Convergence Zone (ITCZ), and solar activity reconstructed from ^{10}Be , to explore the driving mechanisms and global connectivity of millennial-scale abrupt climate change events during Marine Isotope Stage (MIS) 3. Research indicates a significant teleconnection between the variability of the Asian Summer Monsoon (ASM) and high-latitude Northern Hemisphere climate. Strengthening of the AMOC can lead to warming in Greenland, northward displacement of the ITCZ, and intensification of the ASM. More importantly, the speleothem $\delta^{18}\text{O}$ record and solar activity records exhibit high structural and phase similarities, indicating that solar activity may be a potential driver of millennial-scale abrupt climate change events. Further analysis suggests that solar activity could modulate the North Atlantic air-sea circulation, heat storage processes, and background climate state, thereby influencing the stability of the AMOC and the coupled dynamics of the atmosphere-ice-ocean system, leading to the occurrence of DO events. This study highlights the potential role of solar activity in triggering and amplifying millennial-scale climate oscillations, providing a new perspective for understanding the mechanisms of glacial climate abrupt changes through a multi-proxy integrated analysis.

Keywords

The Last Glacial Period, Millennial-Scale Abrupt Climate Change Events, Asian Summer Monsoon, Stalagmite, Solar Activity

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1. 引言

末次冰期(Last Glacial Period, 简称 LGP, 115~11.5 ka BP)是距今最近的一次冰期, 气候状态非常不稳定, 发生了一系列千年尺度气候突变事件, 主要包括海因里希事件(Heinrich events, 简称 H 事件)和 Dansgaard-Oeschger 旋回(简称 DO 事件) [1]-[7]。H 事件是指在北大西洋深海沉积物中发现的六次大规模的冰漂碎屑层(Ice-Rafted Detritus, 简称 IRD), 展示出低频高幅的变化特点, 对全球气候产生了重大影响 [1][4][7]。DO 事件是指在格陵兰冰芯氧同位素记录中首次识别出的大规模、冷暖迅速交替的气候突变事件, 指示了格陵兰地区温度的变化[3], 包括格陵兰冰阶(Greenland Stadials, 简称 GS)和间冰阶(Greenland Interstadials, 简称 GIS) [5]。亚洲夏季风(Asian Summer Monsoon, 简称 ASM)千年尺度气候突变事件和格陵兰地区的温度变化具有良好的对应关系[8], 与之对应的是中国石笋记录的中国冰阶(Chinese Stadials, 简称 CS)和中国间冰阶(Chinese Interstadials, 简称 CIS) [9]。自从这些事件在北高纬地区发现以来, 南极冰芯[10] [11]、黄土[12]、深海沉积物[13]和洞穴沉积物记录[8] [14]等其他载体中也呈现出类似的气候波动印迹, 但不同载体中记录的气候突变事件在特征和结构变化方面存在显著差异, 这引起了古气候学界

对其驱动机制的激烈探讨。特别是在深海氧同位素(Marine Isotope Stages, 简称 MIS) 3 阶段(30~60 ka BP), DO 事件呈现出高频大幅的特点, 是研究者关注的热点时段[15]-[17]。

目前主流观点认为, 千年尺度气候突变事件与大西洋经向翻转环流(Atlantic Meridional Overturning Circulation, 简称 AMOC)强度变化有关, AMOC 强度变化会导致全球热量的重新分配[18]-[21], 引起热带辐合带(Intertropical Convergence Zone, 简称 ITCZ)的南北移动[13], 进而影响全球气候模式。但是, 随着越来越多高分辨率记录的出现, 这些事件显示出的某些特征与这一假设不符。例如, 通常需要淡水扰动触发 AMOC 强度的变化[22], 但实际上淡水输入可能发生在气候突变之后[23]。南极冰芯记录观察到的 DO 事件在结构特征上与格陵兰冰芯记录存在显著差异, 表现为更加缓慢渐进[16], 并且得到了南半球记录和低纬地区记录的支持, 表明南极气候变化可能在全球范围广泛存在[24]-[27]。此外, 热带水文气候变化[28]、火山活动[29]、太阳活动[30]等因素也逐渐显示出重要作用。因此, 末次冰期关于千年尺度气候突变事件的驱动机制仍是一个激烈争论的话题, 需要结合更多不同地区高分辨率的多种代用指标记录进行更深入地分析。本文试图结合石笋以及其他古气候数据, 通过将石笋氧同位素记录与其他气候代用指标记录进行对比, 寻找千年尺度气候突变事件可能的驱动机制以及全球气候变化之间的联系。

2. 研究区域及材料

2.1. 研究区域

亚洲季风区是全球最典型的季风区之一, 是大气环流的重要组成部分, 生活着数十亿人口, 可以通过西风带、厄尔尼诺-南方涛动(El Niño-Southern Oscillation, 简称 ENSO)以及跨赤道气流与北高纬地区、热带海洋和南极气候产生联系[8] [31] [32]。因此, 亚洲季风区是连接全球气候变化的纽带, 既受全球气候变化的深刻影响, 又是气候变化的重要参与者。在亚洲季风区千年尺度气候突变事件的早期研究中, 南京葫芦洞高分辨率石笋记录中显示出千年尺度上亚洲季风和北大西洋气候的紧密耦合, 突出了北高纬驱动对千年尺度气候突变事件的影响[8], 后续也有多条记录显示亚洲季风和北高纬的遥相关[33] [34]。然而, 随着越来越多高精度定年和高分辨率石笋记录的出现, 反映出亚洲季风区 CIS 事件与格陵兰地区 GIS 事件的变化特征与结构存在显著差异[25] [35] [36]。因此, 亚洲季风区千年尺度气候突变事件的驱动机制及其如何响应全球气候变化仍需进一步探讨。

2.2. 研究材料

本文以石笋为载体进行研究, 作为洞穴次生碳酸盐沉积物, 石笋由含钙离子与碳酸根离子的洞穴滴水在洞底沉积形成。当水体中碳酸钙达到过饱和状态时, 碳酸盐矿物逐年析出沉淀, 并在形成过程中详细记录了古气候信息[37]。利用石笋定量重建古气候具有以下显著优势: (1) 空间分布广泛(全球岩溶区约占陆地面积的 15%, 在岩溶发育区普遍存在洞穴石笋沉积) [38]; (2) 测年精度高(基于 U-Th 和 U-Pb 法定年技术可获取高精度绝对年代框架) [39] [40]; (3) 气候代用指标丰富(涵盖碳氧同位素、微量元素、生长速率、磁学参数等); (4) 记录连续性强、时间跨度大(单根石笋可跨越漫长地质时段, 多石笋拼接可构建数十万年连续序列)[32]; (5) 相互对比性强(同时代和不同区域的石笋皆可对比); (6) 采样成本较低。以上优势使得石笋逐渐成为继冰芯、黄土、深海沉积物之后古气候研究的第四大支柱。

3. 石笋氧同位素的气候意义

石笋氧同位素($\delta^{18}\text{O}$)是利用石笋重建古气候领域运用最为广泛的代用指标。根据 Hendy (1971)的同位素分馏平衡理论[41], 石笋 $\delta^{18}\text{O}$ 信号主要受控于洞内滴水的 $\delta^{18}\text{O}$ 组成及洞穴环境温度, 而目前研究的洞穴大多都是封闭洞穴, 洞内温度较为稳定, 因此石笋 $\delta^{18}\text{O}$ 信号主要承袭滴水 $\delta^{18}\text{O}$ 特征。鉴于洞穴滴水直

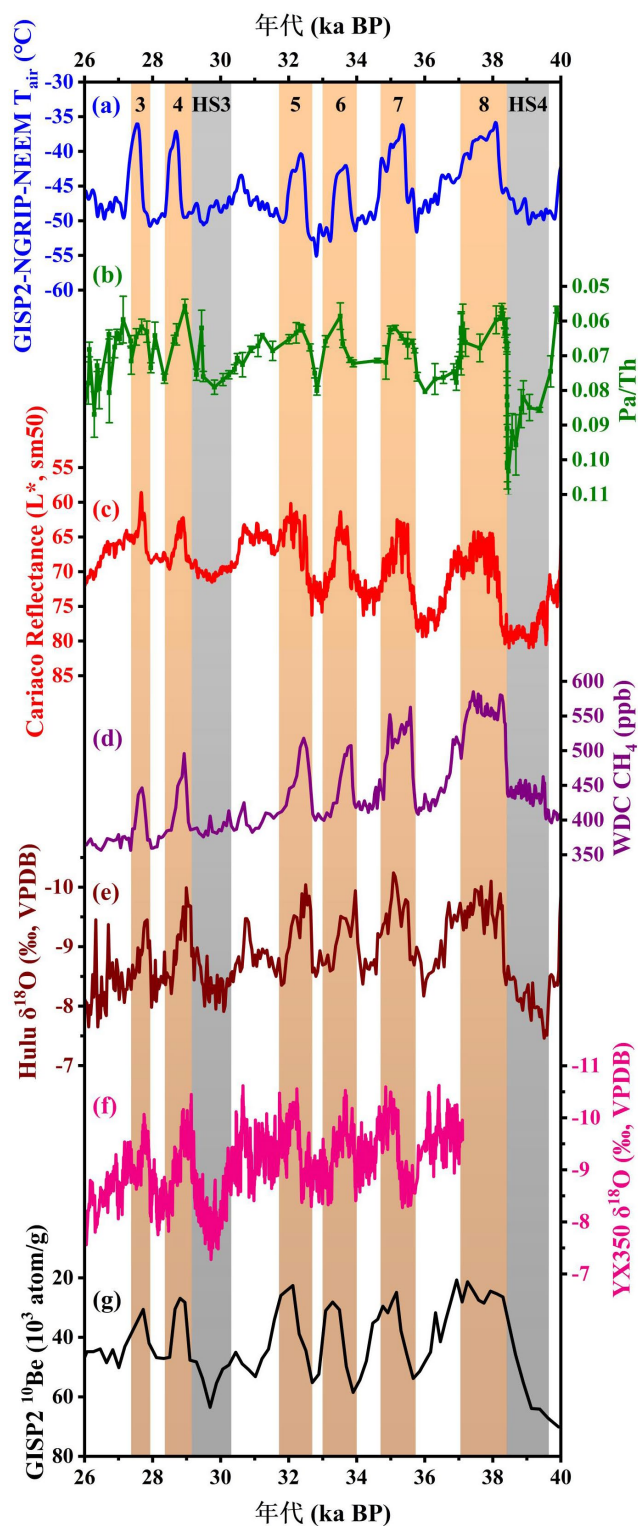
接响应大气降水 $\delta^{18}\text{O}$ 变化, 石笋序列实质上记录了古大气降水同位素组成, 进而指示了古季风的演化趋势。此气候代用指标的有效性已在亚洲季风区多个记录中得到广泛验证。但是, 在石笋 $\delta^{18}\text{O}$ 的具体气候意义上仍存在争议: 反映夏/冬降水比例变化[8]; 反映水汽输送路径上水汽剩余比例的变化[42]; 反映印度夏季风区局地降水变化[43][44]; “环流效应”[45]等。尽管石笋 $\delta^{18}\text{O}$ 的气候意义充满多种解释, 但是在轨道-千年尺度上, 中国季风区石笋 $\delta^{18}\text{O}$ 紧密追踪 ASM 强度的变化, 即石笋 $\delta^{18}\text{O}$ 偏负对应于 ASM 增强, 反之则对应于 ASM 减弱, 这得到了此区域众多洞穴记录的支持[9][32][33][46]。因此, 石笋 $\delta^{18}\text{O}$ 可以作为反映 ASM 强度变化的可靠指标。

4. 太阳活动对千年尺度气候突变事件的潜在驱动作用

许多研究表明, 太阳活动对全球气候变化具有显著影响, 可能是气候变化的关键驱动因素[47]-[51]。太阳活动的代用指标包括太阳黑子数、大气 $\Delta^{14}\text{C}$ 和 ^{10}Be 。虽然太阳黑子记录在时间上有局限性, 但宇宙成因放射性核素(如 ^{14}C 和 ^{10}Be)提供了超出器测记录的太阳活动变化历史[52]-[55]。由于 $\Delta^{14}\text{C}$ 不仅反映太阳活动变化, 而且还体现了碳循环和海洋环流的信息[53][56], 所以在重建太阳活动上具有不确定性。而 ^{10}Be 记录作为可靠的太阳活动记录指标, 在重建太阳活动变化方面具有显著优势。因此, 我们将亚洲季风区石笋记录、 ^{10}Be 重建的太阳活动记录以及其他与千年尺度气候突变事件相关的古气候记录放在同一个框架进行对比, 试图寻找其背后的影响因素。

如图 1 所示, 在 MIS3 中晚期, 南京葫芦洞(图 1(e)) [8]和湖北永兴洞(图 1(f)) [7]石笋 $\delta^{18}\text{O}$ 记录清晰地捕捉到了 DO3-8 及 HS3-4 等千年尺度气候突变事件, 显示出千年尺度上亚洲气候和北高纬气候的遥相关。AMOC 的增强(图 1(b))导致格陵兰地区温度升高(图 1(a)), 引起全球热量的重新分配和 ITCZ 的南北移动(图 1(c)), 从而增强了 ASM。值得注意的是, 通过对比利用 ^{10}Be 重建的太阳活动记录(图 1(g)), 我们发现石笋 $\delta^{18}\text{O}$ 记录与其存在较高的相似性, 太阳活动峰值期对应于 ASM 增强(即 DO 事件), 反之亦然。因此, 如此高的相似性表明太阳活动可能通过某种方式驱动着千年尺度气候突变事件, 深刻影响着事件本身的特征和结构变化。

太阳活动已被证明能够影响气候系统中的关键组成部分, 如温度、风、降水和海洋环流[57]。研究表明, 由于太阳活动导致的紫外线(UV)辐射变化会驱动中层大气和平流层上部的温度变化。这些变化会导致平流层风模式的改变, 进而向下传播并影响北大西洋地区的大气循环和热量储存过程[58]-[60]。此外, 一些学者提出, 太阳活动的周期性变化会导致北半球冰盖融化引起的淡水通量的变化[61][62]。由于 AMOC 是海洋热盐环流的重要组成部分, 其变异性受到热通量和淡水通量强迫的显著影响[63]-[65], 因此我们认为太阳活动变化导致的北大西洋海气环流、热储存过程和淡水通量的变化, 将显著影响 AMOC 的强度和稳定性。值得注意的是, 太阳活动可能不会直接引起气候突变事件, 而是作为一种外部强迫, 调节 AMOC 的振荡, 然后 AMOC 放大这些气候信号并通过海洋环流向全球传输。此外, 太阳活动的变化扰动了北大西洋地区的背景气候状态。在 DO 事件的变率研究中, 一些模型研究表明, DO 事件是一种“自发”的气候振荡, 在北大西洋地区气候背景条件改变的情况下, 可以通过大气-海冰-海洋耦合动力学生成[17][66]。最近的一项研究提出了一个以北大西洋地区 AMOC 和海冰变化为中心的气候-冰盖系统的自维持振荡框架, 该框架受到背景气候条件的调节。这个框架表明, DO 旋回可能代表一种在大气-海冰-海洋系统内部生成的现象, 通过 AMOC 变化对冰架稳定性和冰流动的影响与冰盖动力学相关联。在这个框架中, 气候变化、二氧化碳浓度和冰盖的变化为北大西洋地区 AMOC 和海冰覆盖变化提供了负反馈, 导致海冰退缩和 AMOC 恢复到间冰期条件[67]。因此, 由太阳活动变化驱动的背景气候条件的改变, 可能通过北大西洋地区大气-海冰-海洋耦合动力学的影响, 产生类似于 DO 事件的内部振荡。



注：(a) 格陵兰地区气温变化记录[68]；(b) AMOC 强度变化记录[19] [20]；(c) ITCZ 位置变化记录[13]；(d)甲烷变化记录[69]；(e) 南京葫芦洞石笋 $\delta^{18}\text{O}$ 记录[8]；(f) 湖北永兴洞石笋 $\delta^{18}\text{O}$ 记录[7]；(g) ^{10}Be 重建的太阳活动记录[55]；黄色阴影代表 DO 事件，灰色阴影代表 H 事件。

Figure 1. Comparison of Chinese stalagmite oxygen isotope records with solar activity records and other paleoclimate proxies.
图 1. 中国石笋氧同位素记录与太阳活动记录以及其他古气候记录对比

5. 结论

本文以石笋为研究载体, 通过对比不同古气候记录, 分析了亚洲季风区千年尺度气候突变事件背后的驱动机制及全球气候变化之间的联系。研究发现, 在 MIS3 中晚期, ASM 和北高纬气候具有紧密联系, 增强的 AMOC 导致格陵兰地区的变暖、ITCZ 的北移及 ASM 的增强。此外, 亚洲季风区石笋 $\delta^{18}\text{O}$ 记录与重建的太阳活动记录之间具有高度相似性, 表明太阳活动对千年尺度气候突变事件存在着驱动作用, 可能是通过影响北大西洋地区海气环流、热储过程及气候背景条件所实现的。综上所述, 在讨论千年尺度气候突变事件的驱动机制时, 应充分考虑太阳活动的潜在重要作用。

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