中更新世气候转型: 特征、机制和展望

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摘要 中更新世转型(mid-Pleistocene transition, MPT)的特征、机理及其影响一直是古气候研究的热点问题之一。通过综合分析全球代表性的地质记录, 揭示出海洋和陆地气候变化在中更新世(距今~1.2至~0.7 Ma)多表现为从准4万年到准10万年的主导周期转型, 但低纬地区水文气候的周期变化不显著。数值模拟研究表明, 地球轨道参数变动引起的太阳辐射变化可能是冰期-间冰期气候旋回的根本驱动, 而下垫面和大气CO₂浓度变化的反馈机制则触发了中更新世气候周期转型并放大冰期-间冰期的波动。因此, MPT是地球气候系统内外部多个因素共同作用的结果。未来研究一方面应加强中低纬地区水文循环变化研究, 关注中更新世气候转型影响的区域差异; 另一方面通过整合气候重建和模拟结果, 辨析区域气候变化响应差异的主要诱因。

关键词 中更新世转型(MPT), 冰期-间冰期旋回, 轨道要素, 气候系统反馈, 水文过程

20世纪40年代, 南斯拉夫科学家米兰科维奇提出地球轨道要素驱动气候变化的理论(简称米氏理论), 发现65°N附近夏季太阳辐射是驱动第四纪冰期-间冰期旋回的主要原因^[1]。米氏理论认为, 轨道参数包括偏心率(准400和100 ka周期)、地轴倾角(黄赤交角, 41 ka周期)和岁差(23和19 ka周期)的变化, 导致地球表面接收太阳辐射的时空配置发生周期性变化^[2], 而北半球高纬地区夏季太阳辐射同冰雪消长关系密切, 控制冰盖的前进和后退, 被认为是冰期-间冰期气候波动的关键诱因^[3]。全球大量地质记录揭示了冰期旋回与天文要素驱动的关系^[4-7], 数值模拟研究也对冰期旋回成因做了机理探讨^[8,9]。但迄今为止, 全球不同地质记录中气候变化周期与天文要素驱动和系统内部反馈的动力联系仍有很大争议, 尤其是中更新世全球气候变化主导周期从4万年变为10万年的过程, 无法通过米氏理论给出充分解释。

第四纪是距今260万年以来的地质时段, 表现为大幅气候波动和人类演化迁徙, 其中冰盖的周期性消长与全球气候变化和人类文明演进息息相关^[10]。在《Science》杂志2005年提出未来25年亟需解决的125个科学难题中, 提到“Something about the way the planet tilts, wobbles, and careens around the sun presumably brings on ice ages every 100000 years...”, 即“围绕太阳的行星倾斜和进动等过程或能引发冰期的10万年旋回”。10万年(即100 ka)气候周期的出现同中更新世转型密切相关, 仅凭天文轨道要素驱动无法合理解释第四纪气候周期的非稳态变化。丁仲礼^[11]总结了米氏理论遇到的挑战, 认为单一敏感区驱动机制难以解释冰期旋回的所有观察事实; 鹿化煜和王珏^[12]认为太阳辐射触发冰期旋回, 大气CO₂和冰冻圈反馈起重要放大作用; 汪品先^[13]指出低纬过程的岁差和偏心率周期对全球气候变化的重要性; Clark

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等人^[14]总结了中更新世气候转型的特征并提出风化层假说. 前人研究论述了冰期旋回和气候周期转型的变化特征和动力机制, 但关于高低纬气候变化的周期差异^[15], 以及不同地区或记录气候代用指标对冰期旋回和天文要素的差异性响应^[16], 尚未作深入探讨. 随着更多高分辨率海洋和湖相沉积的研究发现, 不同地区记录气候周期变化存有较大差异, 亟需从全球视角认识气候周期转型的特征和影响. 本文旨在回顾全球代表性地质记录, 重点从中更新世气候转型特征出发, 分析全球不同类型地质记录信号的异同, 强调中低纬不同指标记录的周期变化差异, 并结合数值模拟结果探讨转型机制的可能贡献, 以期获得关于中更新世气候转型特征和机理的综合认识.

1 中更新世转型(MPT)的研究简史

Shackleton和Opdyke^[4]根据赤道太平洋V28-239孔氧同位素记录($\delta^{18}\text{O}$)论证了深海 $\delta^{18}\text{O}$ 作为全球冰量变化的指标, 对理解古气候变化和冰期旋回做出了里程碑式的贡献. 1976年, 南印度洋两深海钻孔 $\delta^{18}\text{O}$ 的频谱分析发现450 ka以来的气候震荡存在显著的轨道周期^[5], 使米氏理论从统计学上得以证明. 随后, Pisias和Moore^[17]分析V28-239孔 $\delta^{18}\text{O}$ 记录的频谱随时间变化特征, 揭示出更新世气候主导周期的转变, 表现为中更新世(1.45~0.9 Ma)气候变化以对称的4万年周期为主, 到晚更新世(~0.9 Ma)出现了不对称的10万年主导周期, 被描述为中更新世转型(mid-

Pleistocene transition, MPT)^[18], 此外, 也有研究认为这种气候周期转变发生在早更新世(~1.4 Ma), 称为早-中更新世转型(early-middle Pleistocene transition, EMPT)^[19,20]. 值得注意的是, 虽然地球轨道要素中偏心率变化具有100 ka周期, 但它引起的太阳辐射变化很小(0.1%或极小^[3]), 难以解释中更新世气候的周期转型^[7], 引发了分别从地质记录和数值模拟角度研究中更新世转型特征和机理的热潮.

自20世纪90年代开始, 大量研究工作集中在重建更新世气候变化历史, 探索MPT发生的时间和特征. Berger等人^[21]根据南太平洋806站 $\delta^{18}\text{O}$ 记录认为气候周期在~0.9 Ma从41 ka转换到100 ka是突变的, 称作中更新世革命(mid-Pleistocene revolution, MPR), 引发了中更新世气候周期转型是渐变还是突变的争论. 例如, 南太平洋ODP1123孔重建的底层水温揭示是南极冰量突变引发的MPT^[22], 但日本浅海沉积的岩相和化石记录表明全球冰量在MPT时期是渐变的^[23]. 随着大量海洋和陆地记录的深入研究(图1), 尤其是反映大洋环流^[24]、全球冰量^[25]、海表温度^[14,26]、海平面^[27]、粉尘源区干旱化^[28]、东亚季风演化^[29]等的记录, 均表明全球气候在距今1.2~0.7 Ma从4万年逐渐转变为10万年周期.

2 MPT的时空特征

中更新气候转型开始以100 ka气候周期出现为标志, 结束时该周期主导且稳定. 因此, MPT的持续

图1 (网络版彩色)更新世气候变化代表性站点分布

Figure 1 (Color online) Location map showing representative sites of Pleistocene climate changes

时间和变化特征同100 ka周期密切相关。基于已有地质记录的代用指标变化揭示出MPT持续时间差异较大,跨度从1.5~0.5 Ma不等。北大西洋两钻孔的 $\delta^{18}\text{O}$ 及碳酸盐变化,揭示出100 ka周期早在~1.5 Ma就已出现^[30],而亚热带南大西洋多孔沉积磁化率^[31]和ODP1123孔的 $\delta^{18}\text{O}$ 和海表温度(sea surface temperature, SST)记录^[32]表明MPT开始于~0.9 Ma。关于MPT结束时间,多数记录表明在0.7~0.6 Ma,如北大西洋DSDP607^[33]和赤道东太平洋ODP677^[34]的冰量和温度信号,个别海洋记录揭示MPT到0.5~0.4 Ma才结束^[31,32]。全球大洋57个站点(LR04)深海 $\delta^{18}\text{O}$ 堆叠表明MPT发生在1.2~0.7 Ma^[14,25],这是目前被广泛接受的起止时间。

本文选取更新世以来24个代表性的气候记录,涵盖海洋、陆地黄土和湖泊沉积(图1, 站位信息和相

关文献见表1),代用指标包括 $\delta^{18}\text{O}$, $\delta^{13}\text{C}$, 海表温度(SST)等,用于讨论中更新世转型的空间特征。结果表明,大部分记录均出现了从41 ka到100 ka的主导周期转型,但地中海U1385和ODP967/968孔、中国南海ODP1143孔及埃利格格特根湖(下文简称埃利湖)的部分指标,在中更新世前后未见显著周期变化,冰期-间冰期的100 ka震荡也不明显。下面分高、中、低纬三个地区对不同记录揭示的周期转型特征进行简要描述。

低纬海洋地区站点记录的温度、碳循环和冰量信号均出现中更新世气候转型,在~1 Ma前后出现100 ka变化周期。如东赤道太平洋ODP677的 $\delta^{18}\text{O}$ 和 $\delta^{13}\text{C}$ ^[24,34]、暖池核心区MD97-2140的 $\delta^{18}\text{O}$ 和SST^[35]、赤道大西洋ODP1077的SST^[53]、热带印度洋ODP722的 $\delta^{18}\text{O}$ 和SST^[55,56]、中国南海南部ODP1143的 $\delta^{18}\text{O}$ 和 $\delta^{13}\text{C}$ ^[36,37]等。然而,南海ODP1143孔反映亚洲夏季

表1 各站点指标信息

Table 1 Core locations and palaeoclimate proxies of those sites

位置	站点	经纬度	代用指标 ^{a)}	参考文献
西太平洋暖池	V28-239	3°05'N, 159°E	$\delta^{18}\text{O}$	[4]
西太平洋暖池	MD97-2140	2°02'N, 141°46'E	$\delta^{18}\text{O}$, SST	[35]
中国南海	ODP1143	9°22'N, 113°17'E	$\delta^{18}\text{O}$, SST, $\delta^{13}\text{C}$, Hm/Gt	[36~39]
北太平洋	ODP882	50°21'N, 167°35'E	SST	[40]
东北太平洋	ODP1012	32°17'N, 118°24'W	$\delta^{18}\text{O}$, SST, $\delta^{15}\text{N}$	[41]
赤道东太平洋	ODP849	0°11'N, 110°31'W	$\delta^{18}\text{O}$, SST, $\delta^{13}\text{C}$	[42,43]
赤道东太平洋	ODP677	1°12'N, 83°44'W	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$	[24,34]
南太平洋	ODP1123	41°47'S, 171°30'W	$\delta^{18}\text{O}$, SST, $\delta^{13}\text{C}$	[32,44]
北大西洋	ODP982	57°31'N, 15°52'W	$\delta^{18}\text{O}$, SST	[45]
北大西洋	DSDP607	41°N, 32°58'W	$\delta^{18}\text{O}$, SST, $\delta^{13}\text{C}$	[33]
东大西洋	ODP659	18°05'N, 21°02'W	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$	[46,47]
西地中海	U1385	37°34'N, 10°8'W	$\delta^{18}\text{O}$, L*, Ca/Ti	[48]
东地中海	ODP967/968	34°N, 33°E	$\delta^{18}\text{O}$, Ti/Al	[49,50]
西大西洋	ODP1058	32°N, 72°W	$\delta^{18}\text{O}$	[51]
赤道西大西洋	ODP925	4°12'N, 43°29'W	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$	[52]
赤道东大西洋	ODP1077	5°11'S, 10°26'E	SST	[53]
南大西洋	ODP1090	42°55'S, 8°54'E	$\delta^{18}\text{O}$, SST	[54]
北印度洋	ODP722	16°37'N, 59°48'E	$\delta^{18}\text{O}$, SST	[55,56]
北印度洋	ODP758	5°23'N, 90°21'E	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$	[57]
塔吉克斯坦	Chashmanigar黄土	38°24'N, 69°5'E	GS, MS	[58]
中国北方	西峰/灵台黄土	35°N, 107°E	GS, MS	[59]
中国西南	鹤庆古湖	26°34'N, 100°1'E	ISM index	[60]
俄罗斯东北部	埃利湖	67°3'N, 172°E	MS, Si/Ti	[61]
俄罗斯南部	贝加尔湖	53°42'N, 108°31'E	BioSi	[62]

a) SST, 海表温度; Hm/Gt, 赤铁矿/针铁矿; L*, 亮度; GS, 粒度; MS, 磁化率; ISM index, 印度夏季风指数; BioSi, 生物硅

风强度的赤铁矿/针铁矿(Hm/Gt),在晚更新世却呈现23 ka主导周期^[38,39],不同于该孔其他指标的100 ka周期.同一地区不同指标的周期差异反映高低纬气候过程的不同影响,受高纬冰盖影响显著的指标呈现类似的主导周期转型,而反映低纬亚洲季风过程的化学风化信号,受太阳辐射影响以岁差周期为主,不具有类似全球的MPT特征.

中纬地区记录表现为复杂的空间特征,大部分海洋记录多见明显周期转型,如北大西洋DSDP607^[33]、南大西洋ODP1090^[54]和南太平洋ODP1123^[32,44]等站位的温度和冰量信号.与非洲季风关系密切的地中海地区,ODP967/968孔 $\delta^{18}\text{O}$ 记录^[49]表现出同LR04海洋 $\delta^{18}\text{O}$ 记录类似的MPT特征,然而该孔的Ti/Al^[49](反映风尘和河流输入差异)和地中海西海岸U1385孔的亮度^[48](与有机质和水热条件有关),在更新世始终以23 ka周期主导,反映了低纬季风过程主导的水文气候变化.类似的现象除海洋外,在湖相沉积中也有显著表现.例如,日本琵琶湖~450 ka最冷月和最热月均温以100 ka周期为主,而代表东亚季风强度的夏季降水和季节性温差表现为强19~23 ka周期^[63].代表性湖泊记录还包括中国西南鹤庆古湖^[60]和俄罗斯贝加尔湖^[62],虽在~1.2 Ma均出现100 ka周期成分,但鹤庆湖的印度夏季风指数(ISM index)中的100 ka周期成分明显弱于贝加尔湖的生物硅含量(BioSi)(图2(b)).中纬陆地记录包括塔吉克斯坦Chashmanigar剖面^[58]和中国西峰/灵台剖面^[59]的黄土,其粒度和磁化率记录类似全球气候存在中更新世转型特征.值得注意的是,同样反映东亚和印度季风变化的石笋对冰量的响应差异较大,葫芦/三宝洞石笋 $\delta^{18}\text{O}$ 记录以显著的岁差周期为主^[64,65],而云南石笋记录表现为岁差和明显的冰期-间冰期波动的混合周期^[66],说明即使是同一载体的代用指标变化,其古气候指示意义也可能存在空间差异.

高纬地区的气候变化主要受两极冰盖控制,如北大西洋ODP982^[45]和北太平洋ODP882^[40]的SST和 $\delta^{18}\text{O}$ 等变化都出现100 ka主导周期,表现为显著MPT.然而,俄罗斯东北部埃利湖的Si/Ti(反映湖泊初级生产力强度)和磁化率(反映磁铁矿溶解的氧化还原条件)在整个更新世中表现为混合的岁差-倾角周期强迫,无明显周期转型^[61,67].

为了确认MPT前后的周期差异,本文选取65°N 7月太阳辐射和部分地质记录对比,包括全球海洋、亚

热带季风和中高纬水文记录等,分两个时段(2~1.2和0.8~0 Ma)进行频谱分析(图2).在2~1.2 Ma阶段,全球海洋指标和鹤庆湖的印度夏季风指数(ISM index)都以强41 ka周期为主,东亚季风黄土磁化率变化的41 ka周期存在但较弱,贝加尔湖生物硅记录(BioSi)以41 ka周期主导而埃利湖磁化率变化则表现为23~41 ka混合周期.到0.8~0 Ma时期,除埃利湖外6个记录都出现100 ka主导周期,其中鹤庆湖的100 ka周期成分相对较弱;埃利湖MS表现为23 ka的主导周期.总的来说,贝加尔湖和全球海洋记录最接近,埃利湖差异最大,中国黄土和鹤庆湖介于两者之间.太阳辐射在整个2 Ma以来都以19 ka和23 ka周期为主,中更新世过渡期无周期变化,但偏心率对岁差幅度的调制在MPT前后略有区别^[69].

埃利湖磁化率和其他指标(特别是邻近的贝加尔湖)的周期差异,可能与区域气候的主控因子有关.埃利湖磁化率变化表征环境中保存的磁性矿物浓度,与湖泊覆盖冰川时间和温度有关,主要受地区辐射调控^[61];而贝加尔湖生物硅的环境意义存在多个说法,与水热分层平衡^[70]或冰融水^[71]有关,或受冰盖影响更大.Hinnov^[67]认为埃利湖和贝加尔湖相比更远离北半球大陆冰盖,气候受控于岁差和倾角混合的辐射强迫;贝加尔湖靠近欧亚大陆内陆所以受北半球冰盖影响更大^[19,67].

为进一步理清中更新世转型特征和持续时间的区域差异,对部分有代表性的地质记录进行小波分析,首先通过带通滤波获得这些指标的100, 41和23 ka周期成分,然后累加获得新的曲线后进行连续小波变化,清晰地辨析出3个周期成分随时间的变化特征(图3).这些记录的中更新世转型大致可以分为3种类型:(1) MPT特征明显,表现为在1.2~0.7 Ma记录从41 ka到100 ka的主导周期转换,无明显或很弱23 ka周期(图3(a), (b), (d));(2) MPT特征不明显,如鹤庆的印度夏季风信号(图3(c)),中更新世后100 ka周期存在但不显著, MPT持续时间在1.2~0.7 Ma;(3) 无显著的MPT,如地中海和俄罗斯东北部的埃利湖记录,100 ka周期强度明显弱于41和23 ka混合周期(图3(e)).

3 MPT的可能机制

什么因素引发了全球多数地区的气候变化周期从4万年变为10万年?已有观点从外强迫驱动和内部反馈过程进行探讨,外强迫是轨道要素引起的太阳

图 2 更新世气候变化代表性记录(a)及对应的周期变化(b). (a) 中分别为 65°N 7 月太阳辐射^[68], 全球深海 $\delta^{18}\text{O}$ ^[25], 全球平均表面温度 (GAST)^[26], 全球海平面相对高度(RSL)^[27], 中国西峰/灵台黄土磁化率^[59], 鹤庆古湖印度夏季风指数^[60], 贝加尔湖生物硅含量^[62], 埃利湖沉积物磁化率^[61]. 黄色阴影区为MPT. (b) 灰色阴影从左至右分别表示 100, 41, 23 和 19 ka周期成分, 红色为 2~1.2 Ma的频谱, 深蓝色为 0.8~0 Ma 的频谱, 其中, 由于记录本身时间跨度差异, 贝加尔湖早更新世时段为 1.8~1.2 Ma, 鹤庆中更新世以后时段为 0.8~0.125 Ma

Figure 2 Eight representative time series of Pleistocene climate changes (a) and the corresponding spectral results (b). (a) Mean July insolation at 65°N^[68], global marine $\delta^{18}\text{O}$ stack^[25], global average surface temperature (GAST) as temperature deviation^[26], global relative sea-level (RSL)^[27], stacked MS from Xifeng/Lingtai sections^[59], ISM index from Heqing Basin^[60], BioSi from Lake Baikal^[62], MS from Lake El'gygytgyn^[61]. Yellow bar denotes the MPT. (b) Grey bars indicate the spectral peaks at 100, 41, 23 and 19 ka bands, respectively. Spectral results are presented for two time intervals (red: 2~1.2 Ma, dark blue: 0.8~0 Ma). Note that Lake Baikal before the MPT is from 1.8 to 1.2 Ma, and Heqing Basin ISM index after the MPT is from 0.8 to 0.125 Ma

辐射变化, 反馈机制主要包括大气 CO_2 浓度和下垫面变化。

Imbrie等人^[7]在20世纪90年代提出了气候系统对轨道要素存在非线性响应, 奠定了轨道观点的基础。后来不同观点认为轨道参数中的偏心率、地轴倾角和岁差都可能导致气候周期变化(图4(a))。有研究发现气候震荡受偏心率相位调控, 但强偏心率通过调整岁差幅度会改变气候系统内部反馈^[69]。地轴倾角也是气候周期改变的原因^[77,78], 冰盖变厚时气候状态容易发生“跳跃”, 2~3个倾角周期产生1个100 ka旋回^[77]。最近模型^[79]仅使用65°N夏半年辐射变化就准

确预测出过去几百万年的每个冰消期, 发现~1 Ma前气候受倾角强迫产生41 ka周期, 之后冰消所需的辐射阈值变高使间冰期“跳跃”。而中国石笋记录65万年以来季风变化的主要冰消期都被4或5个岁差所分隔, 认为岁差影响北半球夏季辐射是冰盖变化的初始诱因^[65]。轨道驱动观点遵循了米氏理论的原则并强调冰盖消长对太阳辐射变化的非线性过程, 但该假说也受到其他机理的挑战, 因为气候系统内部的反馈过程显然对中更新世转型和100 ka周期的出现起着非常重要的作用^[14]。

“大气 CO_2 驱动”观点在20世纪90年代后逐渐受

图3 5个更新世气候变化序列的小波分析结果. (a) 全球深海 $\delta^{18}\text{O}$ 堆栈^[25]; (b) 中国西峰/灵台黄土序列磁化率^[59]; (c) 鹤庆古湖印度夏季风指数^[60]; (d) 贝加尔湖生物硅含量^[62]; (e) 埃利湖沉积物磁化率^[61]

Figure 3 Wavelet results of five representative time series of Pleistocene climate changes. (a) Global marine $\delta^{18}\text{O}$ stack^[25]; (b) stacked MS from Xifeng/Lingtai sections^[59]; (c) stacked ISM index from Heqing Basin^[60]; (d) BioSi from Lake Baikal^[62]; (e) MS from Lake El'gygytyn^[61]

到重视. 早期气候记录认为高原抬升等地质进程影响大气 CO_2 低于某阈值时打破北半球夏季暖气候, 使冰川积累^[24]. 数值模拟结果也发现, 间冰期时高 CO_2

浓度下辐射增强少许就能融化北半球冰盖, 而 CO_2 降低后冰川在辐射最大值(高偏心率、高倾角、低气候岁差)时才融化^[9]. 后来研究注意到东方站 CO_2 的100 ka

图 4 100 ka冰期旋回出现的机制假说. (a) 地轴倾角(红色)、偏心率(灰色)和气候岁差(深蓝色)^[68], 石笋 $\delta^{18}\text{O}$ (浅蓝色)^[65]. (b) 南极冰芯大气 CO_2 (橘色)^[72], 全球海洋 $\delta^{18}\text{O}$ 中的冰量信号(浅绿色)^[73], 东方站冰芯 $\delta^{18}\text{O}$ 中的冰量信号(深绿色)^[74], “十字”符号标记气候不同步时期, 灰色阴影对应4次主要冰消期. (c) 有无风化层和大气 CO_2 含量对北半球冰量的影响^[75], CO_2 为200 ppm(1 ppm=1 $\mu\text{L/L}$, 下同)时所有大陆覆盖厚沉积即风化层(黑色); 大陆实际情况下 CO_2 固定200 ppm(紫色), CO_2 固定280 ppm(青色), 阴影为模拟实际情况. (d) 不同时期的冰冻圈对北半球冰盖影响的模型^[76], 左为2.53 Ma时的冰川下垫面, 冰川下覆盖厚的风化层, 冰盖较薄, 右为0.78 Ma时的冰川下垫面, 风化层被冰川磨蚀, 冰盖不易运动并积累变厚

Figure 4 Hypothesis of the forcing mechanisms driving the onset of 100-ka ice cycles. (a) Obliquity (red), eccentricity (grey) and climatic precession (dark blue)^[68], the composite speleothem $\delta^{18}\text{O}$ (light blue)^[65]; (b) atmospheric CO_2 composite (orange)^[72], ice volume obtained by marine $\delta^{18}\text{O}$ (light green)^[73], ice volume obtained by Vostok air $\delta^{18}\text{O}$ (dark green)^[74], crossed symbols mark asynchronous periods, grey shaded bars denote the timing of glacial terminations; (c) simulated ice volume variations in different experiments^[75]: all continents covered by thick sediments (black) with constant CO_2 (200 ppm), a CO_2 concentration of 200 ppm (violet) and 280 ppm (cyan) with realistic sediment mask, the shading denotes baseline experiment; (d) cross section of ice sheet and bedrock at two different times^[76], left: all sediments originate from the initial regolith layer and shallow-ice flows during 2.53 Ma; right: sufficient erosion of the regolith to begin exposing crystalline bedrock then ice sheet grows during 0.78 Ma

周期分量同偏心率相位一致并早于冰心 $\delta^{18}\text{O}$ 的冰量信号几千年变化(图4(b)), 认为全球碳循环通过 CO_2 影响高纬温度进而产生100 ka冰量周期^[74], 但 CO_2 和全球海洋 $\delta^{18}\text{O}$ 中冰量信号的同步性难以解释. 关于 CO_2 观点存在较多争议, 因为难以分辨 CO_2 和气候变化的因果关系, 更多观点认为 CO_2 不能驱动MPT, 但能放大大气候震荡的幅度^[80,81].

“下垫面变化”包括大冰盖、岩石圈和大洋环流三类不同观点. Abe-Ouchi等人^[80]建立了气候-冰盖模型研究大冰盖对气候系统的非线性响应, 发现间冰期时气候发生正反馈使北半球冰川一直积累, 大冰盖形成后出现负反馈并快速崩塌产生100 ka不对称周期. 南极冰盖扩大使南极底层水输出增强, 通过大西洋经向翻转流影响北大西洋深层水, 形成稳定的深

海环境和增强生物生产力^[82,83],或长期冷却使南极东部冰盖增长至大陆架外产生易消融的海洋性冰川^[84],导致气候不对称长周期的出现。“岩石圈观点”源自20世纪80年代的冰盖-基岩模型^[85],后被Clark等人^[14,76]深化(图4(d)),认为冰盖底部风化层变化影响冰川的稳定性,当风化层被剥蚀露出基岩面时摩擦阻力增大,冰川积累形成大冰盖。大洋环流观点源自Broecker等人^[86,87],温盐环流使大洋碳库形成“生物泵”^[87]降低大气CO₂而影响全球气候,而Denton^[88]质疑温盐环流驱动的可能性并模拟出无环流时气候的100 ka周期。“下垫面驱动”观点强调了地球圈层系统对气候的影响,从全新的角度看待冰盖消长及其对全球气候的影响,但这派观点多以模拟结果为主,缺少足够的地质记录证据。

目前更多模型倾向将多个因素结合模拟,Ganopolski和Calov^[75]模拟了轨道强迫、大气CO₂、风化层等因素对北半球冰量的影响(图4(c))。CO₂高浓度时气候受倾角和岁差调控,无100 ka周期,低浓度(200 ppm)时100 ka周期变强且幅度变大;当北半球覆盖风化层时即使低CO₂浓度也不产生100 ka周期,即北美冰盖下部陆相沉积消失和大气CO₂降低共同影响了冰川对轨道强迫的敏感性。总的来说,气候-冰冻圈系统对轨道强迫的非线性响应和内部反馈过程结合,引发了中更新世气候转型和100 ka冰期旋回的出现。这类模型从全球视角考虑了多种要素和气候响应,但随着区域高分辨率地质记录的出现,尤其是低纬水文信号揭示出不显著的MPT,亟需利用高分辨率气候模型从区域气候差异的角度全面理解MPT的主控因素。

4 结论与展望

因为中更新世气候转型同100 ka气候周期出现

密切相关,前人研究多集中于其周期变化特征、持续时间及全球影响。随着全球不同类型地质记录的研究深入和数值模拟手段的运用,逐渐理清了中更新世转型的时空特征及其与100 ka冰期旋回出现的可能机理。中更新世转型是一个全球性的气候事件,大多数海洋记录在距今1.2~0.7 Ma有明显从41 ka向100 ka的周期转变,但地中海、中国南海和东亚季风区与水文气候变化相关的代用指标变化表现出较强23 ka岁差信号。对中更新世气候转型及相关的100 ka冰期旋回的诱因,从单一轨道要素驱动机制逐渐趋向于气候系统内外部因子共同作用的机理探索,并尝试利用数值模拟区分各要素的相对贡献和动力过程。简言之,地球轨道参数影响高纬地区太阳辐射变化,可能是地球冰期-间冰期气候旋回的根本驱动,地表过程和气候系统内部反馈会触发气候周期转型并放大地球气候的100 ka周期。

大量研究从全球和动力视角分析了中更新世气候转型的特点和机理,随着更多区域高分辨率工作的开展,有限证据表明低纬水文循环变化似乎受高纬冰盖影响相对较小,中更新世气候转型对不同区域和不同气候要素的差异影响仍不清楚。因此,未来一方面需加强区域气候响应尤其是水文循环变化差异的研究,辨析北半球冰盖扩张对中低纬气候的影响;另一方面多利用高分辨率气候模型分析中低纬水文气候变化特征,通过区分天文要素和下垫面变化的不同影响,探索中更新世转型的主要诱因。最后,地质记录-数值结合是研究气候自然变率和机理及预估未来变化趋势的关键^[89],判断当前温暖期的持续时间不仅要考虑过去典型温暖期的历史相似型,还需准确评估高CO₂浓度背景下气候变化的敏感性差异,这对预测当前温暖间冰期还会持续多久至关重要。

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Summary for “中更新世气候转型: 特征、机制和展望”

Mid-Pleistocene climate transition: Characteristic, mechanism and perspective

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Milankovich theory suggested that orbitally induced summer insolation change at high-latitude region of Northern Hemisphere played a key role in driving the ice cycles during the Pleistocene. However, a significant shift of the Pleistocene climate from 41-ka to 100-ka cycles (namely mid-Pleistocene transition, MPT) cannot be simply attributed to the astronomical forcing due to insignificant insolation change induced by eccentricity forcing. Here we summarized multiple proxies generated from the ocean and land to address Pleistocene climate changes such as global ice volume, sea surface temperature, sea level, aridity of dust sources, and monsoon-related hydrological cycles. The temporal and spatial characteristics of the MPT phenomenon, in terms of the timing, duration, amplitudes and frequencies, were addressed using spectral and wavelet results. Most records reveal that the MPT was commenced as the onset of the ~100-ka cycles at ~1.2 Ma, and ended by the establishment of the dominant 100-ka cycles at ~0.7 Ma. However, some hydroclimatic proxies from the Mediterranean Sea, South China Sea and Chinese caves show a relatively strong 23-ka cycles during the middle to late Pleistocene. Such a difference may be attributable to varied sensitivity of proxy indicators to the insolation and glacial forcing. Globally, temperature and sea level signals that are affected by changing ice volume usually demonstrate a distinctive and consistent MPT. By contrast, regional hydroclimatic proxies at mid-to-low latitudes are likely dominated by the precession cycles (i.e. high-resolution, absolutely dated Chinese speleothem records).

The MPT associated with the onset of ~100-ka cycles has inspired the paleocommunities to address its driving mechanism from both data and model perspectives. Several hypotheses have been proposed to explain the MPT in the past two decades, including nonlinear response to external forcing and complicated internal feedbacks. The nonlinear response to the astronomical forcing including eccentricity (100-ka cycle), interplay between obliquity (41-ka cycle) and precession (23- and 19-ka cycles) can produce the 100-ka ice-age cycles. However, model results suggest that the MPT and subsequent “100 ka world” are likely caused by changes in atmospheric CO₂ concentration, bedrock exposure or ocean circulations. Taking these different hypotheses together, it was suggested that the solar insolation caused by changing Earth's orbital parameters as external forcing, drives the glacial-interglacial climate cycles, whilst the nonlinear responses to atmospheric CO₂ decrease and to different regolith boundary conditions as internal feedbacks have played key roles in triggering the climate transition and amplifying the glacial-interglacial oscillations.

While most proxies from the land and ocean demonstrate a remarkable MPT from 41- to 100-ka cycles, regional high-resolution proxy records indicated that hydroclimatic changes at mid-to-low latitudes exhibit insignificant MPT and weak ~100-ka cycles after the MPT. In the future, more data assimilation should be focused on the hydroclimatic changes particularly in monsoon-affected regions to decipher the diverse responses in a regional scale. Meanwhile, simulations using high-resolution regional climate system models should be performed to quantify the responses of different climate parameters to external forcing and internal feedback. Through intensively data-model comparison, new insights into past climate variability and dynamics will permit a better projection of future climate change under the global warming context.

mid-Pleistocene transition, glacial cycles, orbital forcing, climate system feedbacks, hydroclimatic process

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