第11卷 第1期
1999年3月
湖 泊 科 学
JOURNAL OF LAKE SCIENCES
Vol.11, No.1
Mar., 1999

全球大陆末次盛冰期气候和植被研究进展

于 革　　张恩楼
(中国科学院南京地理与湖泊研究所湖泊沉积与环境开放实验室,南京 210008)

提　要　末次盛冰期(LGM)是太阳辐射异常处于极低值、北半球第四纪冰流规模处于峰值、两万年来距人类环境最近但与现代气候有着巨大反差的特殊时期.70年代以来由于新资料不断积累、气候模拟技术发展、海洋大陆冰流各圈层的相关和偶合、传统的气候指标和新的气候指标的认识和应用、以及区域性和全球性的国际合作,在LGM古气候环境领域已经取得了巨大进展.本文根据数个国际LGM合作计划研究成果,综述90年代以来全球对LGM研究方法途径和大陆古气候植被研究成果,并对其前景提出雏议.

关键词　末次盛冰期　全球大陆　古温度　古降水　古植被
分类号　P532

世界上地质历史时期最后一次冰期的命名因地而异,在北美东部称为威斯康星冰期(Wisconsin),在西欧称为威赫塞尔冰期(Weicheselian),在阿尔卑斯山地称为玉木冰期(Würm),在我国西部山地称为晚大理冰期或玉木冰期[1].70年代初Dreimanis和Goldthwait提出末次盛冰期(Last Glacial Maximum,简作LGM),包括晚更新世晚期距今14000a至22000a[2],作为地质史上的末次冰期的最盛时期.自1979年Peterson等人[3]首次对LGM(18000aBP^{14}C年,或21000aBP天文年)古气候环境进行研究以来,围绕这段特殊时期的气候与环境,已有众多地球环境学科学者参与研究并成为国际合作计划和项目的热点.

18000aBP^{14}C年太阳辐射异常处于极低值,而冰流规模处于峰值,造成了LGM极端寒冷时期[4-6].LGM已经被认为是两万年来距人类环境最近、但是一个与现代有着巨大反差的气候时期.由于LGM集中了重建地球实验场和反演极端寒冷气候环境、测试地球轨道、冰流驱动机制和下垫面反馈作用、预测未来气候环境变化关键时段和参照点,LGM的气候和环境始终是全球变化研究中的重要课题.20多年来,仅全球规模的围绕LGM气候环境研究的专题研究计划从未间断,从70年代末集中地质资料研究的CLIMAP(Climate, Long-range Investigation, Mapping and Prediction Project,长期气候调查、制图和预测计划)[7]到80年代末资料与模型结合的COHMAP(Cooperative Holocene Mapping Project,全球全新世制图计划)[5];90年代初又从单一气候模型研究转为大气环流、海洋环流和下垫面不同圈层的模型耦合研究,同时从模型研究转为结合地质资料与模型相互对比验证的综合研究,如TEMPO(Testing Earth System Models with Palaeoenvironmental-Observations,古环境资料测试地球系统模型计划)[8],PMIP(Palaeoclimate Modelling Intercomparison Project,古气候模型对比计划)[9],BIOME6000(Global Palaeo-Vegetation Project,全球古植被计划)[10]等重大国际合作计划.

本文根据近期国际文献资料,并结合作者参加的国际PMIP,TEMPO和BIOME6000项

---

* 中国科学院1997年度"百人计划"资助.收稿日期:1998-09-11.于革,女,1957年生,研究员.

目研究，试图综述90年代以来国际LGM古气候和植被环境研究的方法和成果，并对其前景及发展提出雏议，希望促进中国与国际全球变化合作研究的同步进展.

1 研究LGM气候环境方法途径的进展

近20年来由于新资料积累、现代技术发展、区域性和全球性的国际合作，通过模型和类比对气候指标的定性化，使得研究LGM古气候环境的手段不断更新，研究领域不断拓宽.

(1) 对传统气候指标的认识和定性解释大大改进.对北半球第四纪冰流分布、规模和海面波动幅度的认识更为精确可靠[11].对气候指标认识可以区分出年际和季节变化，能够更好地理解以往似乎矛盾的现象.80年代后期，人们对LGM时期地中海地区广泛分布的干草原和同期出现的高湖面现象感到难以解释.当认识到花粉信息反映生长季节植物有效水分状况[12-13]，而湖泊变化反映了全年平均水量条件[14]，对该地区的冬季和夏季的不同湿度状况和大气环流季节变化有了重新认识.此外，地质资料转换气候参数的方法和技术也得到不断提高改进，例如应用在花粉资料中的多指标校正法[15]，CO_2浓度对山地森林线变化的关系[16]并应用于生态模型中[17]，冰川平衡线与温度和降水等多元气候参数定量关系[18]，以及海洋性冰川变化对海面温度的反馈作用模式[19-20].

(2) 运用和发展新的气候指标.利用地层中的古地下水(old underground water)测定惰性气体(Ne, Ar, Kr, Xe)含量，模拟地下水与汇水区地温关系，并与古气温和降水相关[21-22].通过对洞穴沉积物碳酸盐稳定同位素古气候研究，建立碳酸盐生长速率与气候相关而转换温度[23]，进而利用碳酸盐氧同位素与温度关系[24]，配合其他指标过滤温度和降水气候信号变化[25].

(3) 地域覆盖面更宽.大陆钻孔和各种古气候资料的获得，填补了许多以往气候变化关键地区的空白点.全球性古气候资料以数据库形式综合并系统化，为重新认识LGM气候特征和变化规律提供了更多的空间信息和更宽阔的视野.欧洲、北美、非洲、俄罗斯等地区的古湖泊数据库[26-28]，北美、欧洲等地区花粉数据库[6]在研究LGM专题中发挥了重要作用.目前，BIOME6000综合的LGM花粉资料已经覆盖到北美、欧洲、非洲、大洋州、俄罗斯、中国、日本等世界大陆大部分地区[29].

(4) 高精度的地质记录研究.来自格陵兰冰芯[30]、深海氧同位素[31]、湖泊沉积[32-33]、黄土沉积[34-36]等连续的高精度地质证据，提供了长尺度气候变化记录，使LGM气候重建更为精细可靠，从而能够有效避免由于仅采用峰谷曲线形状对比，而把LGM与短期降温(例如北大西洋Heinrick事件)的错误对应.

(5) 由于计算机技术发展和大气环流模型(GCM)的改进，使古气候模拟更为先进可靠.GCM可运行十年循环，全球规模的气候模型精度提高到1个经纬度网格，陆地与大气交换系统更接近现实[37]，如大气环流模型耦合或驱动的海洋动力模型[38]、与大气环流模型耦合的生物圈模型[39]、水文模型[40]以及气候系统中不同成分参与的模型[41].全球20个模型组织参加的PMIP计划集中对LGM模拟[9]，避免以往模型各自为营、模型结果各异而又无法检验的局面，大大提高了人类模拟气候的整体水平.

(6) 测年方法和技术的进步.通过珊瑚礁碳酸盐和树轮有机碳的分析，对晚更新世以来的

时间序列中的大气 CO_2 浓度的变化研究,认识到^{14}C 年代与天文年代的差异[42-43].末次盛冰期的峰值用^{14}C 年代测定为 18000aBP,而对应天文年代是 21000aBP,两者相差 3000a[42].由于 AMS^{14}C 年代技术的应用,克服了微量样品测试的限制,从而大大提高年代测定的精度.这使在时间序列中重建 LGM 古气候的边界条件更为精确,LGM 横向区域的气候记录对比更为可靠.

(7) 在 80 年代认识地球轨道变动造成的太阳辐射变化和冰流消长变化的动力机制基础上,通过冰芯研究进一步揭示大气成分(CO_2、CH_4、N_2O)浓度变化和生物化学循环参与对气候系统的耦合作用,进而对 LGM 诱发成因提出了新的解释[44],认识到大气温室气体和浓度变化可能是诱发气候变化的重要因子[45-46].通过对 LGM 以来的快速气候震荡和短期温度变化的研究[31,42,47],对百年尺度气候系统的稳定性和大气与海洋冰流系统的耦合、气候发展的预测能力产生了巨大影响.人类不断认识到地球下垫面包括海洋、高纬冰流和海冰、大陆植被和土壤对气候系统的巨大反馈作用以及引起的气候效应.

2　LGM 大陆气候环境

LGM 最戏剧性的变化是北半球位于北美和北欧的第四纪冰流,估计冰流最大厚度达 3500-4000m[7],巨大的冰流吸收海洋水体 $50\times10^6-50\times10^6$ km^3[48],由此造成世界性海洋水面下降 120m 以上[49].在我国,施雅风等根据冰川雪线等综合地质资料估计 LGM 海面下降幅度大于 140m 以上[50].巨大的冰流造成地壳重压而下陷 700-800m[51].LGM 大陆面积增加,区域性风场强度增大,地表侵蚀加强.根据深海钻孔 LGM 层的风积物研究,北太平洋西风带风力强度增加了 20%,北太平洋和北大西洋信风带风力强度分别增加了 30% 和 50%[52-54].强大的风力同时也造成大气中尘埃浓度增高[55].宇宙尘埃有所增加,^{10}Be 和^{14}C 浓度相应增加 20%[56].相比之下,大气成分 CO_2 浓度降低.根据格陵兰和南极冰流冰芯测定,CO_2 浓度为 190-200$\mu g\cdot g^{-1}$[45],比工业革命前 CO_2 浓度(280$\mu g\cdot g^{-1}$)约低 30%,CH_4 含量则是现代的一半[57].下面就 90 年代以来对 LGM 大陆温湿状况和植被状况的研究进展予以介绍.

2.1　古气温和地表热力状况

根据化石花粉和大植物化石、地下水中惰性气体、洞穴堆积氧同位素测定等综合方法恢复的 LGM 年最冷月温度[58],在热带岛屿和低地降温幅度是 2-5K,热带高海拔山地约为 5-9K.中低纬地区两个最大降温幅度(超过 10K)的地区,分布在北半球亚热带的中国东部(8-13K)和北美佛罗里达地区(8-15K).高纬度地区的年降温幅度在北美和北欧冰流外围超过 10K.一般北半球大陆的最冷月温度比年均温度变幅要大,主要反映 LGM 冬季大陆冰流和大陆冷气团从高纬极地向低纬热带地区的扩张,造成极端严寒气候.

CLIMAP 曾预测 LGM 热带海面温度比现代降低 1.5K,部分海区(南太平洋)甚至比现代升温[7].近年来研究表明 LGM 热带海洋降温为 2-5K[59,60],不仅远低于 CLIMAP 估计,而且不存在比现代温暖的热带海洋[61].根据最近对全球海洋表面温度的研究[62],南大洋 LGM 降温幅度在 1-2K,低纬度热带海洋在 4K 以内;而中纬度海区北太平洋为 2-4K.与陆地降温幅度对比,大陆降温是海洋的 1.5-2 倍,这与通过模型和现代类比对 LGM 模拟结果一致[63],表明冰流和裸露陆地等大陆下垫面特性加剧了 LGM 降温效应,而海洋相对是大陆的热源.这

影响到比现代夏季更小的海陆温差，可能是中低纬海陆季风萎缩的重要原因.

2.2 湿度状况和大气环流

全球第四纪湖泊数据库提供了LGM湖泊水位变化资料，可用来定性恢复地表降水和湿度状况[14,64]. 利用花粉和大植物定性恢复的植物生长期有效水分，能够提供夏季水分状况[65]. 这些气候指标的综合研究[58]表明，全球大部分地区，包括加勒比海地区、热带非洲、美洲赤道地区、中国东部、大洋州等地区比现代干旱. 在北美西南部、安第斯山地和太平洋赤道山地岛屿LGM时期比现代湿润[58]. 地中海地区的高湖面反映了LGM比现代更加潮湿的气候条件[66]. 中亚和中国青藏高原比现代潮湿，地表水量条件呈现正平衡状况[67].

LGM降水和湿度空间分布反映了大气环流的变化. 北美劳伦兹冰流和北欧斯堪的那维亚冰流在LGM时产生强大的冰流高压，诱导冰流反气旋发展，形成西风带分支. 南支西风气流以比现代更南的位置进入北美和欧洲，导致美国西南部、地中海地区和中亚比现代多雨、更湿润[5,66]. 高海拔的湿润状况可能由于低温严寒造成极端低的蒸发条件[58,67]. 全球热带地区大部分低地比现代干旱，反映LGM大陆度增加、海陆水分循环减弱、年降水普遍减少的特征.

中国黄土资料提供的风成沉积记录，通过岩石学、古生物学和地球化学的研究能够恢复地表湿度并指示风场方向和强度. 研究结果表明LGM中国东部和中部比现代干旱，反映了冬季风的强盛和夏季风的萎缩[34-36]. 夏季风北界向东南退缩10个纬度以上[68].

2.3 植被迁移和树线变化

以花粉为基本资料的重建全球古植被计划自1994年实施以来，经数百名国际学者包括我国在内的第四纪花粉学、古植物和环境学等领域进行合作，4年来在综合和重建晚第四纪古植物和制图方面已经取得了可观的成果[69-72]. 该研究利用世界各地不同植被带表土花粉资料对现代植被和气候的对应关系，进行花粉植被模拟，能够改进和克服花粉与植物、植物与地带性植被关系中的一些不确定因素. 从重建LGM北半球大陆植被的综合成果来看，在欧亚和北美大陆中纬度地带为大片的草原和荒漠植被，在欧亚大陆西岸欧洲平原取代了现在的针阔叶混交林，在大陆东岸的我国华北平原取代了温带落叶阔叶林[70]. 现代分布在50°N以北的泰加林在LGM时大面积减少，被苔原植被所取代. 东亚地区大面积的亚热带植被向南迁移，退缩北回归线以南. 地带性植被迁移幅度最大在中国东部[71]和北美东部[72]，温带森林向南退缩达500－800km.

根据花粉和大植物化石恢复的LGM时期山地植被带，在低纬度山地树线比现代平均下降430m，赤道地区平均下降320m[58]. LGM树线最大下降幅度在中美洲山地，比现代下降了670m. 植被模拟表明，CO_2持续降低会造成生物量大幅度减少而使得森林难以生长[73]. 当LGM时期的CO_2浓度为$190\mu g \cdot g^{-1}$时，树线可降低数百米[17]. LGM山地树线在垂直高度上大幅度下降，指示了LGM温度大幅度降低，与模型结果一致[16]，反映了LGM时期大气CO_2浓度降低可能是造成热带山地气温降低、树线下降的重要原因之一.

3 前景展望

LGM研究已经在全球范围内综合和重建气候与环境方面取得重大成果，它将进一步为全球变化研究提供了一系列科学基础和依据. 在今后气候模型和植被模型发展、认识和评价CO_2

等大气成分对气候变化的影响和作用、对千年尺度气候变化原因等方面的研究中，其资料和成果将发挥出重要的作用．

(1) 古气候模型下垫面及其反射率状况．TEMPO 计划对目前气候环境变化和预测主要通过大气环流模型进行古气候模拟，仍然有待于地质资料提供当时的冰流规模、大陆面积、植被状况以及海洋、海冰温度等边界条件，这些模拟的结果也极需要地质资料的验证[6]．确定气候模型的边界条件，提供末次盛冰期下垫面状况，进一步发展定量方法，把点状分布资料转化为空间网格数据模式．

(2) 大气尘降源地及其运移、扩散的空间途径．最近 IGAC①计划中的核心项目将集中研究汽溶胶特性及其对辐射的影响，但目前对大气降尘源地及其运移、扩散的空间途径知之甚少，这已成为众多模型亟待解决的热点．LGM 的花粉源地和传播资料，对大气尘降模型中源地和传播路径设计和模拟有潜在的应用价值．LGM 地表状况也能够对尘降模型的模拟进行补充和验证．

(3) 植物碳循环和大气 CO_2 浓度变化．大气中稀有气体和气汽溶胶的研究将在连接 GAIM－PAGES②—IGAC 三项国际合作计划中成为一个新起点，其中核心问题之一是重建 CO_2 和 CH_4 在晚冰期和早全新世时间序列上的突然变化以及成因机制[42]．由于大气 CO_2 浓度变化的参与使全球生物圈模型趋向于更加复杂和完善[73,74]．进一步对各个地区 LGM 花粉资料进行全球性的综合和系统化，将充实生物圈模型设计的边界条件并能够对其输出结果进行检验，同时也是对 GCTE 计划③中的核心项目“全球植物功能型”研究的重要贡献．

围绕大气圈与植被圈、海洋圈的耦合是否是诱发冰期的主要原因，植物和 CO_2、CH_4 对气候变化的作用和反馈等关键问题，有关科学家将进一步致力于：(a) 建立大气圈、海洋圈、陆地生物圈等各种地球系统模型，以解决大气稀有气体源和全球碳循环在气候变化中的作用和机制；(b) 采用观测资料和数据对这些模型模拟的结果，进行对比和检验．而目前对 LGM 研究所积累的资料和成果能够应用在湿地演化和消亡、CH_4 源地发展、不同时期植物量与 CO_2 浓度变化等问题上，对分析陆地生态将发挥重要作用，并进一步为探索气候变化的动力机制作出重要贡献．

(4) 千年尺度的气候变化动力机制．高分辨率陆相地质记录表明，全球气候在百年至千年尺度上有着强烈变动[75,76]，高分辨率的海洋钻孔记录也表明了相似的变化[77,78]．一些研究者通过对比海陆气候是否有着同步的相关变化，提出高阶位轨道频率、海洋热盐循环对晚冰期一些突发性变化的可能性提出一些假设性解释[78,79]．引起千年尺度气候变化的动力机制目前还难以掌握，下一个 PAGES 的“全新世气候系统的相互作用”课题将对此集中研究．因此把 LGM 资料与模型的研究应用到时间序列上，对恢复百年至千年尺度上整个全新世植被变化，将起到关键作用．

致谢　施雅风先生对我国末次盛冰期的冰川、雪线等研究对世界有独特的贡献，在第四纪气候和环境变化领域中是我国重要的卓越领袖．该文稿根据于革近年来参加的国际末次盛冰

---

① IGAC 是 International Global Atmosphere Chemistry 缩写，国际全球大气化学计划．

② GAIM 是 Global Analysis, Interpretation and Modelling 缩写，全球分析解释和模拟计划．PAGES 是 Past Golbal Changes 缩写，过去全球变化．

③ GCTE 是 Global Change and Terresterial Ecosystem 缩写，全球变化和陆地生态系统计划．

期合作研究成果，由张恩楼协助整理文献资料，编撰成此文．谨此向施先生对该领域研究的关心和支持表示衷心感谢，并向参与合作的众多从事国际第四纪气候环境专家致谢．

参 考 文 献

1 施雅风．我国西部山地晚更新世玉木冰期探讨．见：施雅风著．地理环境与冰川研究．北京：科学出版社，1998．457－481

2 Dreimanis A, Goldthwait RP. Wisconsin glaciation in the Hurron, Erie, and Ontario lobes. In: Black RF ed. The Wisconsinan Stage. Boulder: Geology Society of America, 1973. 71－106

3 Peterson GM, Webb T Ⅲ, Kutzbach JE, *et al*. The continental record of environmental conditions at 18000 yr B.P. An initial evaluation. *Quaternary Res*, 1979, **12**: 47－82

4 Burger AL, Imrie J, Hays JD, *et al*. Milankovitch and Climate. Dordrecht: Reidel, 1987. 895

5 COHMAP Members. Chimatic changes of the 18000 yars: observations and model simulations. *Science*, 1988, 241: 1043－1052

6 Wright Jr HE, Kutzbach JE, Webb T Ⅲ, *et al*. Global climates since the Last Glacial Maximum. Minneapolis: University of Minnesota Press, 1993. 569

7 CLIMAP Project Members. Seasonal reconstructions of the Earth's surface at the Last Glacial Maximum. Geological Society of America Map Chart Serise 36, 1981

8 TEMPO. The potential role of vegetation feedbacks in the climate sensitivity of high-latitude regions: a case study at 6000 years before present. *Glo Biogeoch Cycles*, 1996, **10**: 727－735

9 Joussaume S, Taylor KE. Status of the Paleoclimate Modeling Intercomparison Project (PMIP). In: Proceedings of the First International AMIP Scientific Conference (Monterey, California, USA 15－19 May 1995). *WCRP Report*, 1995, **92**: 425－430

10 Prentice IC, Webb Ⅲ T. BIOME 6000: towards a global palaeovegetation data set. *Glo Change Newslet*, 1994, **19**: 8－9

11 Peltier WR. Ice age paleotopogrphy. *Science*, 1994, **265**: 195－201

12 Prentice IC, Guiot J, Harrison SP. Mediterranean vegetation, lake levels and palaeoclimate at the Last Glacial Maximum. *Nature*, 1992, **360**: 658－670

13 Sykes MT, Prentice IC, Cramer W. A bicolimatic model for the potential distributions of north European tree species under present and future climates. *J Biogeog*, 1996, **32**: 203－233

14 Harrison SP, Digerfeldt G. European lakes as palaeohydrological and palaecolimatic indicators. *Quaternary Sci Rev*, 1996, **12**: 233－248

15 Guiot J. Structural characteristics of proxy data and methods for quantitative climate reconstruction. *Palaklimaforschung*, 1991, **6**: 271－284

16 Street-Perrott FA, Huang YS, Perrott RA, *et al*. Impact of lower atmospheric carbon dioxide on tropical mountain ecosystems. *Science*, 1997, **278**: 1422－1426

17 Jolly D, Haxeltine A. Effect of low glacial atmospheric CO_2 on tropical African mountain vegetation. *Science*, 1997, **276**: 786－787

18 Hostetler SW, Clark PU. Climatic controls of western US glaciers at the Last Glacial Maximum. *Quaternary Sci Rev*, 1997, 16: 505－511

19 Diaz HF, Graham NE. Recent changes in tropical freezing heights and the role of sea surface temperature. *Nature*, 1996, **383**: 152－155

20 Crowley TJ, Baum SK. Effect of vegetation on an ice-age climate mode simulation. *J Geophy Res*, 1997, **102**: 16463－16480

21 Stute M, Schlosser P, Clark JF, *et al*. Paleotemperatures in the Southwestern United States derived form noble gas measurements in groundwater. *Science*, 1992, **256**: 1000－1003

22 Stute M, Schlisser P. Principles and applications of the noble gas paleothermometre. *Grophy Monograph*, 1993, **78**: 89－100

23 Brood GA, Cowart JB, Brandt SA, *et al*. Quaternary climatic change in southern and eastern Africa during the last 300 ka: the evidence from caves in Somalia and the Transvaal region of South Africa. *Zeitschrift Geomorphologie NF Suppl*, 1997, **108**: 15 - 48

24 Fischer MJ, Gale SJ, Heijnis H, *et al*. Low latitude speleothems and palaeoclimatic reconstruction. *Karst Waters Inst Spce Pub*, 1996, 2: 62 - 64

25 Bar-Matthews M, Ayalon A, Kaufman A. Late Quaternary paleoclimate in the eastern Mediterranean rgion from stable isotope analysis of speleothems at Soreq Cave, Israel. *Quaternary Res*, 1997, **47**: 155 - 168

26 Street-Perrott FA, Marchand DS, Roberts N, *et al*. Global lake-level variations form 18000 to 0 years ago: a palaeoclimatic analysis. US DOE/ER/60304-H1 TR046. US Department of Energy, Technical Report. 1989. 144

27 Tarasov PE, Pushenko MY, Harrison SP, *et al*. Lake status records from the former Soviet Union and Mongolia: Documentation of the Second Version of the Database. Boulder: NOAA Paleoclimatology Publications Series Report 5, 1996: 224

28 Yu G, Harrison SP. Lake status records from Europe: Data base documentation. Boulder: NOAA paleoclimatology Publications Series Report 3, 1995: 451

29 Prentice IC, Webb Ⅲ T. BIOME 6000: reconstructing global mid-Holocene vegetation patterns from palaeoecological records. *J Biogeog*, 1998, in press

30 Dansgaard W, Johnsen SJ, Clausen HB, *et al*. Evidence for general instability of past climate from a 250-kyr ice-core record. *Nature*, 1993, **364**: 218 - 220

31 Johnsen SJ, Clausen HB, Dansgaard W, *et al*. Irregular glacial interstadials recorded in a new Greenland ice core. *Nature*, 1992, **359**: 311 - 313

32 Grimm EC, Jacobson GL, Watts WA, *et al*. A 50 000-year record of climate oscillations fron Florida and its temporal correlation with the Heinrich events. *Science*, 1993, **261**: 198 - 200

33 Watts WA, Allen JRM, Huntley B. Vegetation history and palaeoclimate of the Last Glacial Period at Lago Grande di Monticchio, southern Italy. *Quaternary Sci Rev*, 1996, 15: 113 - 132

34 Porter SC, An Z. Correlation between climate events in the North Atlantic and China during the last glaciation. *Nature*, 1995, **375**: 305 - 308

35 Guo ZT, Liu TS, Gouiot J, *et al*. High frequency pulses of east Asian monsoon climate in the last two glaciations: link with the Northe Atlantic. *Clim Dyn*, 1996, **12**: 701-709

36 Chen FH, Bloemendal J, Wang JM, *et al*. High-resolution multi-proxy climate records from Chinese loess: evidence for rapid climatic changes over the last 75 kyr. *Palaeogeog Palaeoclim Palaeoecol*, 1997, **130**: 323 - 335

37 Houhtton JT, Meira Filho LG, Callander BA, *et al*. Climate Change 1995: The Science of Climate Change. Cambridge: Cambridge University Press, 1996

38 Kutzbach JE, Liu Z. Response of the African monsoon to orbital forcing and ocean feedbacks in the middle Holocene. *Science*, 1997, **278**: 440 - 443

39 Foley J, Ramankutty N, Pollard D, *et al*. Coupling a dynamic biosphere model with an atmospheric general circulation model. *Glo Change Biol*, 1998, in press

40 Coe MT. Simulating continental surface water: An application to Hlolcene Northern Africa. *J Climate*, 1997, **10**: 1680 - 1689

41 Ganopolski A, Rahmstorf S, Petoukhov V, *et al*. Simulation of modern and glacial climates with a coupled global model of intermediate complexity. *Nature*, 1998, **391**: 351 - 356

42 Bard E, Arnold M, Fairbanks RG, *et al*. Calibration of the ^{14}C timescale over the past 30000 years using mass spectrometric U-Th ages from Barbados corals. *Nature*, 1990, **345**: 405 - 410

43 Kutzbach JE, Guetter PJ, Behling P, *et al*. Simulated climatic changes: Results of the COHMAP climate-model experiments. In: Wright HE, Kutzbach Jr JE Webb Ⅲ T, *et al*. eds. Global climates since the Last Glacial Maximum. Minneapolis: University of Minnesota Press, 1993, 24 - 93

44 Lorius C, Oeschger H. Palaeo-perspectives: reducing uncertainties in global change? *Ambio*, 1994, **23**: 30 - 36

45 Barnola JM, Raynaud D, Korotkevich YS, *et al*. Vostok ice core: a 160 000 year record of atmospheric CO_2. *Nature*, 1992, **360**:408 - 414

46 Leuenberger M, Siegenthaler U. Ice age atmospheric concentration of nitrous oxide from an Antarctic ice core. *Nature*, 1992, **360**:449 - 451

47 Bond G, Broecker WS, Johnsen SJ, *et al*. Correlations between climate records form North Atlantic sediments and Greenland ice. *Nature*, 1993, **365**:143 - 147

48 Hughes TJ. The last great ice sheets: a global view. In: Denton H, Hughes TJ eds. The last great ice sheets. New York: John Wiley. 1981.263 - 317

49 Fairbanks RG. A 17000-year glacio-eustatic sea level record: influence of glacial melting rates on Younger Dryas event and deep ocean circulation. *Nature*, 1989, **342**:637 - 642

50 施雅风，王靖泰．中国晚第四纪的气候、冰川和海平面的变化．见：施雅风著．地理环境与冰川研究．北京：科学出版社，1998.247 - 256

51 Peltier WR. Glacial isotasy, mantle viscosity, and Pleistocene climate change. In: Ruddiman WF, Wrignt HE eds. North America and adjacent oceans during the last deglaciation. Boulder: Geololgy Society of America, 1987.155 - 182

52 Sarnthein M, Tetzlaff G, Koopman B, *et al*. Glacial and interglacial wind regimes over the eastern subtropical Atlantic and north-west Africa. *Nature*, 1981, **293**:193 - 196

53 Janecek TR, Rea DK. Quaternary fluctuations in the northern hemisphere trade winds and westerlies. *Quaternary Res*, 1985, **24**:150 - 163

54 Hooghiemstra H, Bechler A, Beug HJ. Isopollen maps for 18 000 years BP of the Atlantic offshore of Northwest African: evidence for paleowind circulation. *Paleoocean*, 1987, **2**:561 - 582

55 Hammer CU, Clausen HB, Dansgaard W, *et al*. Continuous inpurity analysis along Dye 3 deep core. In: Langway CC, Oeschger H, Dansgaard W eds. Greenland ice core: geophysics, geochemistry, and environment. Washington DC: American Geophysics Union, 1985.90 - 94

56 Beer J. Information on past solar activity and geomagnetism fron ^{10}Be in Camp Century ice core. *Nature*, 1988, **331**:675 - 680

57 Stauffer B, Lochbronner E, Oeschger H, *et al*. Methane concentration in the glacial atmosphere was only half that of the pre-industrial Holocene. *Nature*, 1988, **332**:812 - 814

58 Point S, Harrison SP, Prentice C, *et al*. Tropical climates at the last glacial maximum: a new synthesis of terrestrial data, I. Vegetation, lake-levels and geochemistry. *Clim Dyn*, 1998, in press

59 Anderson DM, Webb RS. Ice-age tropics revised. *Nature*, 1994, **367**:23 - 24

60 Bard E, Rostek F, Sonzogni C, *et al*. Comparing temperatures of the glacial ocean quantified with the alkenone method and simulated by numerical models. PAGES Open Science Conference Abstracts, 1998.20

61 Webb RS, Rind DH Lehman SJ, et al. Influence of ocean heat transport on the climate of the Last Glacial Maximum. *Nature*, 1997, **385**:695 - 699

62 Muller PJ, Kirst G, Ruhland G, *et al*. Calibration of the alkenone paleotemperature index Uk37 based on coretops from the eastern South Altantic and global ocean (60°N-60°S). *Geochem Cosmochem Acta*, 1998, in press

63 Joussaume S, Taylor KE, Braconnot P, *et al*. Climate changes of LGM: results of 18 simulations from the Paleoclimate Modeling Intercomparison Project (PMIP). *Clim Dyn*, 1998, in press

64 Yu G. Lake-level records and palaeoclimates of northern Eurasia. *Lundqua*, 1996, **37**:1 - 17

65 Prentice IC, Cramer W, Harrison SP, *et al*. A global biome model based on plant physiology and dominance, soil properties and climate. *J Biogeog*, 1992, **19**:117 - 134

66 Harrison SP, Yu G, Tarasov P., Late Quaternary lake-level records from northern Eurasia. *Quaternary Res*, 1996, **45**:138 - 159

67 Qin B, Yu G. implications of lake level fluctuations at 6ka and 18ka in mainland Asia. *Glo Planet Change*, 1996, **18**:59 - 72

68 Winkle M, Wang PK. The late-Quaternary vegetation and climate of China. In: Wright HE, Kutzbach Jr JE, Webb Ⅲ T,

et al. eds. Global Climates since the Last Glacial Maximum. Minneapolis: University of Minnesota press, 1993.221－259

69 Peyron O, Guiot J, Cheddadi R, *et al*. Climate reconstruction in Europe for 18 000 yr BP from pollen data. *Quaternary Res*, 1998, **49**: 183－196

70 Tarasov PE, Webb T Ⅲ, Andreev AA, *et al*. Present-day and mid-Holocene biomes recontructed from pollen and plant macrofossil data from the former Soviet Union and Mongolia. *J Biogeog*, 1998, in press

71 Yu G, Chen XD, Ni J, *et al*. Pollen-based biome reconstructions for China at 6ka and 18ka. *J Biogeog*, 1998, in press

72 Summers RL, Williams JW, Webb T Ⅲ. Applying plant functional types to construct biome maps from eastern North American pollen data: comparison with model results. *Quaternary Sci Rev*, 1998, in press

73 Haxeltine A, Prentice IC. BIOME 3: An equilibrium terrestrial biosphere model based on ecophysiological constrains, resource available, and competition among plant functional types. *Glo Biogeoch Cycles*, 1996, **10**: 7175－7162

74 Foley JA, Prentice IC, Ramankutty N, *et al*. An integrated biosphere model of land surface processes, terrestrial carbon balance, and vegetation dynamics. *Glo Biogeoch Cycles*, 1996, **10**: 603－628

75 Jacobson GL. Webb Ⅲ T, Grimm EC. Patterns and rates of vegetation change during the deglaciation of eastern north America.. In: Ruddiman WF, Wright HE Jr. eds. North America and adjacent oceans during the last deglaciation, Boulder: Geological Society of America, The Geology of North America v. K-3, 1987.277－287

76 Berglund BE, Barnekow L, Hammarlund D, *et al*. Holocene forest dynamics and climate changes in the Abisko area, northern Sweden－the Sonesson model of vegetation history reconsidered and comfirmed. *Ecol Bul*, 1996, **45**: 15－30

77 Koc N, Schrader H. Surface sediment diatom distribution and Holocene paleotemperature variations in the Greenland, Iceland and Norwegian Sea. *Paleocean*, 1990, **5**: 557－580

78 Sarnthein M, Jansen E, Weinelt M. Variations in Atlantic surface ocean Paleoceangraphy, 50°－80°: a time-slice record over the last 30000 years. *Paleocean*, 1995, **10**: 1063－1094

79 Bjock S, Kromer B, Johnsen S, *et al*. Synchronized terrestrial atmospheric deglacial records around the North Atlantic. *Science*, 1996, **274**: 1155－1159

Newly-Studies on Global Continental Climate and Terrestrial Yegetation during the LGM

YU Ge　　ZHANG Enlou

(*Lake Sedimentation and Environment Lab.*, *Nanjing Institute of Geography and Limnology*, *CAS*, *Nanjing* 210008)

Abstract

Climate in the last glacial maximum (LGM) is characterized by of the lowest anomaly of orbital forcing-induced insolation, but the greatest volume of Quaternary ice sheets in the northern hemisphere during the last 20000 years. Advaces in data collection, palaeoclimate modelling, land-sea-ice correlation, interpretation of classical proxies and development of new proxies, and international cooperations for the LGM since the last published synthesis of terrestrial palaeodata of the beginning of the 70s have prompted a new evaluation of palaeoclimate and paleovegetations. The paper attempts to review recent international publications, syntheses the results of a few of undergoing international cooperation projects, and provides preliminary highlights for the outlooks.

LGM boundary conditions can now be specified with greater confidence and precision than was possible when the first simulations of LGM land climates were performed in the end of the 1980s. Palaeoclimate modelling has advanced considerably, due to the availability of faster computers and the progressive refinement of atmospheric models. Simulations including coupling to dynamical ocean models and biosphere models can be now undertaken. Modelling intercomparsion and therefore data-modelling comparsion can be undergoing in a global scale within the PMIP project. Acquisition of terrestrial palaeodata has continued, and in particular there have been major efforts to obtain proxy records form sediment cores in previously data-sparse regions. Dating accuracy has also been improved thanks to the increasing use of AMS for ^{14}C-dating small samples of material of identifiably terrestrial origin. Data syntheses have been carried out on a rigorous basis, starting with the Global Lake Level Data Base and the regional pollen and lake-level data compilations carried out within the COHMAP project and continuing through the IGBP-sponsored BIOME 6000 prject, which includes the compilation of pollen records for the LGM and their translation into palaeobiomes using a standard methodology. Understanding and interpreting of the classical proxy data sources have been improved greatly. Multiproxy calibration methods have developed, and new proxy data sources have been developed, including the noble gas thermometer in groundwater and $\delta^{18}O$ in speleothems as records of mean annual temperatures on land. Understanding of the temporal context of the LGM has changed drastically, due to the recognition of large, synchronous climate fluctuations during the glacial stages in high-resolution climate records from Greenland ice, marine foraminiferal records, terrestrial pollen records and loess.

Cold-month temperature of LGM was estimated form pollen and plant macrofossil-based elevation shifts of vegetation belts and horizontal displacements of biomes, noble gases in gronudwater and $\delta^{18}O$ in speleothems. Cold-month anomalies ranged from -2 K at low elevations in Indonesia and the southern Pacific through -6 to -8K at many high-elevation sites to -8 to -15K in eastern China and the southeastern USA. Qualitative estimates of plant-available moisture from palaeoecological data and regional water balance from lake-level data, indicate LGM conditions wetter than present in westrn USA and the circum-Mediterranean region, likely associated with southward displacement of the jet stream, and at high elevations of Tibetan plateau and high mountains of Pacific islands where the effect of cooling on evaporative demands may have been decisive. The rest large lands of the world, both moisture indices show drier then present conditions elsewhere. These results are consistent with a colder than present ocean surface producing a weaker hydrological cycle and more arid continents.

Developments of LGM studies in recent years have created further opportunities for exploiting a series of research projects such as International Global Atmospheric Chemistry, Global Analysis, Interpretation and Modelling, Global Changes and Terrestrial Ecosystem in global change science.

Key Words LGM, global continents, palaeotemperature, palaeopreciptation, palaeovegetation