新仙女木(YD)事件区域特征及动力机制研究新进展

刘殿兵

南京师范大学地理科学学院,南京,210046

内容提要:新仙女木事件(Younger Dryas event, YD事件)为末次冰消期发生的快速降温事件,作为典型突变气候事件,它一直是国际古气候关注热点,其研究的开展促进和深化了科学界对千年尺度突变气候事件的理解和认识。近年来,随着高分辨率地质记录涌现,YD事件时空差异性日益突出。对比和认识这些区域之间事件细节结构及转型模式异同有助于甄别其相位关系,探讨不同环境快速重组对高、低纬突变气候事件的响应方式,进而验证早期驱动—响应假说,为其动力学机制建立及未来相似边界条件下气候预测提供基本地质证据和理论模型。本文从YD事件区域响应方式入手,通过总结和对比模拟研究及地质记录,对YD事件已有研究存在的争议进行回顾,提出有待加强的研究区域和未来研究方向。

关键词:YD事件;精细结构;转型方式;区域差异

新仙女木事件(Younger Dryas, YD事件)发生于距今12.9~11.5 ka BP期间(校正年龄),是末次冰期向全新世转换、急剧升温过程中一次快速降温事件。该事件以最初在丹麦Allerød冰缘带沉积物中发现的北极苔原植物仙女木(Dryas Octopetala)命名(Jensen, 1938),随后,广泛发现于北大西洋周围海相和陆相记录中(Johnsen et al., 1992; Dansgaard et al., 1993; Bond et al., 1993)。格陵兰冰芯圈闭的氮气同位素研究表明,在YD期间当地气温约下降15±3 ℃(Severinghaus et al., 1998)。此时,大气环流特征、水汽传输模式等发生剧变,大气粉尘浓度突增并呈"闪烁式"变化(Taylor et al., 1993),其它大气组分也呈现显著高频振荡(Mayewski et al., 1993)。该事件的结束约在10~20a内完成,格陵兰冰芯的冰雪累积速率在1~3a内增加近1倍(Alley et al., 1993),并呈阶段式变化特点(Taylor et al., 1997)。由于YD发生时正值全球普遍升温,如此大幅气温下降,导致地表环境突变,甚至使北美石器时代文化遭到毁坏,猛犸象、乳齿象等大型陆地动物群灭绝(Dalton, 2007)。特别在环北大西洋区,其爆发突然、气候变幅异常突出,成为突变气候事件研究的典型参考,因而关于YD细节过程及动力机制的研究,有助于认识气候快速变化基本规律及相似边界条件下的气候预测。

尽管已有研究总结了YD记录的区域响应及各种驱动假说(王建民和钟巍, 1994; Alley and Clark, 1999; Isarin and Renssen, 1999; 李潮流和康世昌, 2006),然而,受早期记录的年龄模式、分辨率、各代用指标环境意义及敏感性、区域环境等因素影响,关于该事件内部细节及转型方式尚存在诸多争议。近年来,随着高分辨率及高精度年龄模式的记录不断涌现,争议集中表现在以下几个方面:振荡模式的空间不一致;事件内部结构存在分歧;转型模式区域差异;驱动机制悬而未决。上述科学问题的深入研究和解决,将有助于进一步认识YD事件时空特征,在精细尺度上进行记录对比,揭示区域差异,进而理解其动力学机制。

1 YD事件区域响应特征

一般来说,在北半球中高纬,YD事件或同期的干旱/降温事件具有同相位特征(Alley and Clark, 1999),而在低纬及南半球表现不一。受两极气候"跷跷板"模式(Broecker, 1998)影响,对应于北半球降温,南极气温在YD期间呈上升趋势(Jouzel et

注:本文为国家自然科学基金(编号41172148),江苏高校优势学科建设工程资助项目,南京师范大学高层次人才科研启动基金项目(编号2011105XGQ0102)共同资助的成果。

收稿日期:2011-11-08;改回日期:2012-02-07;责任编辑:黄敏。

作者简介:刘殿兵,男,1972年生。讲师,主要从事洞穴古气候研究。电话:025-85891653。Email:ldb9921@njnu.edu.cn。

al., 1995; EPICA Community Members, 2006)。尽管早期研究认为南极罗斯海域 Taylor Dome 冰芯与南极大陆内部气候变化不一致,在 YD 期间,当地气温与北大西洋气候同步下降(Steig et al., 1998),但进一步研究表明该结论是由于采用错误的年龄模式所致(Mulvaney et al., 2000)。即便如此,仍有众多南半球地质证据清晰记录了 YD 事件期间气候的干/冷波动,如南美安第斯山脉在 YD 期间降温,形成大量冰帽(Clapperton et al., 1997),厄瓜多尔和巴塔哥尼亚冰川增长(Heine and Heine, 1996; Glasser et al., 2004)。两半球低纬环境变化极具争议性,如高海拔冰芯$\delta^{18}O$研究发现,昆仑山(杨志红等, 1997)和南半球玻利维亚热带气温(Thompson et al., 1998)在 YD 期间显著下降,新西兰冰川在 YD 期间曾经发生推进(Denton and Hendy, 1994),但同区众多地质记录并不支持 YD 事件的两半球同步性(Singer et al., 1998; Williams et al., 2005; Barrows et al., 2007)。孢粉研究显示,与北半球 YD 同期的新西兰冰进可能是降水增加导致冰雪累积速率增大结果(Singer et al., 1998),而当地温度并未下降,且这种冰进发生的时间显著晚于北半球 YD 事件(Barrows et al., 2007)。类似结论也得到东南亚石笋研究结果的支持(Partin et al., 2007; Griffiths et al., 2009),YD 期间该区域降雨量持续增大,说明低纬海洋的水文循环过程与高纬气候变化迥异。众多大洋研究表明 YD 期间两半球间海表温(SST)呈现此消彼长关系,如北大西洋温盐环流(THC)显著减弱(McManus et al., 2004),大范围 SST 下降(Zhao Meixun et al., 1995; Bard et al., 2000; Guilderson et al., 2001),而热带南大西洋暖水堆积,温度上升(Arz et al., 1999; Mulitza and Rühlemann, 2000; Weldeab et al., 2006)。但热带大洋水文环境独特,与南半球联系紧密,对 YD 响应的方式迥异。南中国海不饱和烃记录的 SST(Kienast et al., 2001)、热带南太平洋 Sr/Ca 重建的 SST(Corrège et al., 2004)、大西洋科里亚科洋盆 Ma/Ca 记录的 SST(Lea et al., 2003)与格陵兰气温变化一致,在 YD 期间显著降温。同时,"南极型"海温上升模式也在诸多记录中体现(Rühlemann et al., 1999; Visser et al., 2003; Stott et al., 2007)。Shakun 和 Carlson(2010)总结了全球末次盛冰期以来高分辨率地质记录,认为在北半球范围内,YD 期间气候异常的振幅随着纬度增加而增大,从某种程度上支持了高北纬驱动;南半球大多数记录呈现与北半球相反相位,反映了两半球气候"跷跷板"响应模式。由于他们总结的低纬记录多集中在大洋,气候突变事件受到海相沉积年龄模式、海水的混合等因素影响,上述结论尚需要内陆高分辨记录进一步验证。

2 事件内部结构分歧

YD 内部气候次级振荡及其结构研究取决于地质记录的分辨率和精细时标的建立,这种干冷背景下的气候不稳定性已经得到早期模拟研究的证实(Manabe and Stouffer., 1997, 2000)。GISP2 冰芯高分辨率$\delta^{18}O$记录显示,格陵兰气温在 YD 期间逐步回暖,并叠加了数次百年尺度次级旋回,变幅达 YD 整体振幅的 2/3,其极低温出现在 Allerød/YD 转换结束时段(Stuiver and Grootes, 2000)。尽管同区 GRIP 和 NGRIP 冰芯(Johnsen et al., 2001; Rasmussen et al., 2006)YD 内部升温趋势及极低温类似于 GISP2 记录,但内部细节不够详尽,且振幅上较弱,这种区域内差异可能由不同分辨率导致。冰芯 Ca^{2+} 等其它离子浓度在 YD 内部呈现出与气温类似趋势(Mayewski et al., 1997),指示冬季风强度降低和亚洲内陆干旱化程度在干/冷的 YD 内部逐步减轻,格陵兰当地气候逐渐向暖/湿方向转变。受分辨率影响,欧洲内陆湖泊揭示 YD 期间仅存在一次振幅异常突出(达到早全新世水平)的短暂回暖过程(von Grafenstein et al., 1999),其余时段当地气候保持稳定。后续研究进一步表明,在 YD 早期欧洲内陆表现为快速气候波动而晚期较为稳定(Brauer et al., 1999, 2008)。与此相反,北大西洋东北海洋沉积显示,YD 事件最后 300a 气候呈多次快速振荡而早期相对稳定(Ebbesen and Hald, 2004),这种气候变化模式也得到挪威湖泊记录最新研究的支持(Bakke et al., 2009)。

在中、低纬,大西洋西部海洋沉积的钛、铁(Haug et al., 2001)及灰度(Hughen et al., 1996, 2000)等指标显示热带气候存在一系列数十年尺度快速振荡,反映热带环境的不稳定性。同时,东太平洋圣·巴巴拉海盆水文状况也表现出快速波动特征(Hendy et al., 2002)。热带南太平洋 SST 在 YD 期间下降 4.5 ± 1.3℃,内部叠加了诸多高频变化,周期上类似于现代厄尔尼诺—南方涛动信号(Corrège et al., 2004)。中国南部玛尔湖研究发现在 YD 期间亚洲冬季风加强,且在 YD 早期存在大幅气候波动(Yancheva et al., 2007)。日本琵琶湖季节沉积

表明,尽管此时东亚沿海夏季温度变化微弱,但冬季温度和降水高频变化显著(Nakagawa et al., 2006)。

亚洲内陆黄土记录显示,YD 期间在总体干旱的背景下季风降雨存在一系列干/湿波动,强度约为 YD 事件整体振幅的 1/2 (Zhou Weijun et al., 2001),这种冷湿气候配置也见于其他研究(周卫健等,1996;萧家仪等,1998;周杰等,1999)。上述近海和大陆内部相似的气候响应方式,证实了 YD 内部极端干冷背景下气候的高度不稳定性,而其演化趋势和振幅差异可能与指标的气候意义有关,也可能反映区域差异。Ruth 等(2007)通过对比黄土中值粒径、磁化率、冰芯资料、葫芦洞石笋记录,也发现黄土记录的 YD 开始时间要早于石笋记录,因此,他们认为即便在亚洲夏季风系统内部,YD 事件也存在区域上的差异性。

3　转型模式区域特征

早期研究表明,不同记录不同代用指标所指示 YD 的结束呈现出快速特征,约在 10~20a 内完成,而 Allerød/YD 转换时间争议较大。目前关于该转换时间最为迅速的评估是来自德国湖泊的研究,纹泥统计结果表明,X 射线荧光扫描法获取的铁元素指示欧洲在 1a 内进入 YD 寒冷期(Brauer et al., 1999, 2008)。这种快速转换至今鲜见,目前仅在 YD 结束时段高纬水汽突变中见到(Alley et al., 1993; Steffensen et al., 2008),可能和北大西洋区较大的季节性变化有关(Denton et al., 2005),也可能受控于独特的"极地放大"(polar amplification)效应(Manabe and Stauffer, 1980)。GRIP (Johnsen et al., 2001)和 NGRIP(Rasmussen et al., 2006)冰芯年层时标显示,$\delta^{18}O$在约 200a 内完成 Allerød/YD 转换,而在 GISP2 冰芯(Meese et al., 1997)中约为 250a。热带大西洋科里亚科洋盆纹泥早期统计结果约为 200a(Hughen et al., 1996),而后期工作将其延长为 250a(Hughen et al., 2004)。基于年层时标的青天洞石笋记录表明,东亚季风的 Allerød/YD 转换表现出缓慢特征,约为 380a,至少比高北纬冰芯长 130a (Liu Dianbing et al., 2008)。末次冰消期,缓变转换方式也反映在其它中低纬石笋及海洋沉积记录中(Wang Yongjin et al., 2001; Sinha et al., 2005; Schefu et al., 2005; Vacco et al., 2005; Shakun et al., 2007)。可是,这些记录的时标多依赖测年点平均内插方法建立,其 100a 左右的测年误差尚不足以严格控制 Allerød/YD 转换时间,故具有年层序列的记录显得尤为重要。上述转型方式的区域差异,可能由各记录的年龄模式或转型起止时间界定不同造成,也有可能反映区域环境响应差异。总之,北大西洋海、陆气候响应方式不同尚需要其他区域,如低纬高分辨率研究验证。

已有成果显示,YD 结束在众多记录中表现极为快速,但不同指标转换细节差异显著。冰雪累积速率及过剩氘响应迅速,约在 1~3a 内进入早全新世(Alley et al., 1993; Steffensen et al., 2008),说明水汽对气候突变响应比较敏感。GRIP 冰芯过剩氘和粉尘浓度在不到 20a 内完成转换,而$\delta^{18}O$指示的气温历时约 50a,说明亚热带大西洋变化要早于高纬气温(Dansgaard et al., 1989)。同样,冰芯多参数对比研究也发现来自中纬源区的参数(如过剩氘、非海盐钙、各种微粒浓度)变化要早于北冰洋区各参数(δD、海盐钠、平均微粒粒径)约 15a(Taylor et al., 1997)。NGRIP 冰芯高分辨率数据(Steffensen et al., 2008; Thomas et al., 2009)进一步支持了上述结论,冰芯粉尘沉积的变化要早于格陵兰升温,说明低纬 ITCZ 对高北纬气候影响深远。同样来自冰芯包裹体的甲烷浓度和氮气、氩气同位素对比显示,$\delta^{15}N$指示的极地气温变化早于来自低纬的甲烷 0~30a(Severinghaus et al., 1998)。由于大气 CH_4浓度在北半球升温期增加快速,其来源仍存在较大争议(Chappellaz et al., 1993; Dällenbach et al., 2000; Kennett et al., 2000; van Huissteden, 2004; Schaefer et al., 2006; Fischer et al., 2008),且温度和重力对$\delta^{15}N$具有双重影响(Severinghaus et al., 1998),制约了温度与 CH_4 相位关系的精确解译。影响这些十年际尺度气候变化相位分析的主要因素是精确的时标以及各参数的敏感性、响应气候的方式,只有在精确时标的框架下,选择那些敏感性一致、响应气候方式类似(如同为温度、降水、大气环流等)的参数对比,才能真正解决高、低纬气候事件的相位问题。

4　驱动机制争议

大洋温盐环流(THC)一度被认为是突变气候的主要驱动因子(Broecker et al., 1990),该观点在古气候研究领域至今仍然占有主导地位。尽管 THC 理论在模型中得到检验,但在地质记录中却存在诸多分歧。古气候学界对大洋深层水形成的方式,如大洋盐度振荡作用(Broecker et al., 1990; Birchfield and Broecker,1990)、劳伦泰冰盖的累积—

崩溃模型(MacAyeal, 1993)、大洋水自由振荡和受驱变化(Sakai and Peltier, 1997)等,以及淡水注入区域(Teller et al., 2002; Tarasov and Peltier, 2005; Carlson et al., 2007)在认识上仍未统一。而且,该机制倡导者 Broecker (2006)在野外考察中未发现洪水留下的古河道地质证据(意即冰坝湖溃缺机制很难成立),因此, YD 突变事件是大洋还是大气驱动(Broecker, 2003)国际学术界尚未有定论。现代观测也证实,北欧暖冬和大西洋径向翻转流(Atlantic meridional overturning circulation, AMOC)无关,而和冰岛低压及随后形成的西风北移路径相关的驻波有关(Seager et al., 2002)。近年来,随着现代格陵兰冰盖快速溶解(Krabill et al., 1999),大量淡水注入北大西洋,深层水快速淡化(Dickson et al., 2002),而北大西洋 AMOC 依然活跃(Sy et al., 1997),全球气温有增无减。鉴于此,大气驱动(Brauer et al., 2008)、太阳活动作用(Renssen et al., 2000; Goslar et al., 2000)、赤道大洋水热传输作用(Cane, 1998)等各种假说逐步被提出。Berger (1990) 总结了触发 YD 事件的可能机制:①包括气候系统、大气 CO_2 含量和地面反照率在内的一系列正反馈;②大陆冰架的崩塌;③气候系统外驱动力,如太阳辐射、火山喷发和宇宙尘埃等因素的影响。尽管如此,对于 YD 事件的偶发性,一直很难从已有的机制模型中得到满意的解释。所以,Firestone 等(2007)提出"彗星撞击造成北美大型动物群灭绝和 YD 降温"。但是,模拟及地质证据表明,类似突变事件广泛存在于其它冰消期升温过程中(Sima et al., 2004; 陈仕涛等, 2006; Cheng Hai et al., 2009; Broecker et al., 2010)。神农架三宝洞 0.4 Ma 以来石笋$\delta^{18}O$记录显示,在最近几个终止点期间 YD 事件表现为冰消过程的"规则事件",似乎 Allerød—Bølling 表现为"突变升温"(Cheng Hai et al., 2009; Broecker et al., 2010)。因此,要从地球系统内、外更大的气候背景寻求其动力机制。通过不同区域气候响应模式精细对比,有望精确诊断高、低纬 YD 事件的相位关系并探求其动力联系。

5 讨论与展望

精确独立定年是认识区域气候突变事件之间因果关系的先决条件。已有研究显示,NGRIP 冰芯$\delta^{18}O$记录的 YD 事件持续约 1193 ± 39a(Rasmussen et al., 2006),而 GISP2 冰芯比 NGRIP 记录约长 70a (Meese et al., 1997),热带大西洋 Cariaco 海盆纹泥统计约为 1300a(Hughen et al., 2000),德国和波兰陆相湖泊纹泥统计约为 1090 ~ 1140a(Goslar et al., 2000; Litt et al., 2001)。上述差异反映不同记录对事件的开始和结束时间界定不同,也可能和各自测年误差有关,或许区域气候在本质上不同步。解决这些问题的关键是事件精细时标的建立及同区域多记录交互检验。

YD 事件精确时标的建立不仅具有重要的气候学意义,对^{14}C 年代学研究同样影响深远。指示放射性^{14}C 产生速率的大气^{14}C 浓度($\Delta^{14}C$)影响着^{14}C 年龄精度,且随时间发生变化。目前,基于树轮的大气 $\Delta^{14}C$ 重建仅达到 12.59 ka BP(Friedrich et al., 2004),尽管后续工作尝试将其延长到 26 ka BP (Reimer et al., 2004),甚至 50 ka BP(Reimer et al., 2009),但老于 12.59 ka BP 部分主要依赖海相沉积。这些记录本质上反映当地溶解无机碳中^{14}C 变化,而非直接指示大气 CO_2变化,且大洋碳储库年龄的不确定性势必影响大气 $\Delta^{14}C$ 重建的精度。YD 早期,Cariaco 海盆沉积记录显示,大气 $\Delta^{14}C$ 在 200a 内快速增加近 50 ± 10‰(Hughen et al., 1998),与碳圈循环模拟结果(30‰, Goslar et al., 1999)差异较大。大气 $\Delta^{14}C$ 浓度如此大幅变化可能因 13 ~ 12.5 ka BP 期间 Cariaco 盆地^{14}C 年龄偏轻造成 (Goslar et al., 2000),其它因素如海—气之间的气体交换速率变化可能也有贡献(Delaygue et al, 2003)。极为关键的是,YD 期间 Cariaco 盆地生物扰动强烈(Hughen et al., 1996),纹泥计数困难,难以准确界定 Allerød/YD 转型的时间(Hughen et al., 2004)。可见,精确时标的研建已成为关键。运用石笋同层位 AMS ^{14}C 和高精度 U/Th 年龄对比研究,已成功获取 50 ka 以来大气 $\Delta^{14}C$ 的浓度变化 (Beck et al., 2001; Weyhenmeyer et al., 2003; Hoffmann et al., 2010)。当洞穴围岩"老碳"贡献率保持不变时(Beck et al., 2001; Hoffmann et al., 2010),年纹层石笋成为大气 $\Delta^{14}C$ 重建的理想材料。

在区域气候子系统中,低纬季风为快速物理系统(Bordoni and Schneider, 2008),敏感地响应于海—气—冰等边界条件变化(An Zhisheng, 2000),同时,通过大气/洋流作用与南半球气候信号联系紧密(Pierrehumbert, 2000)。观测和地质记录显示,热带大西洋水汽循环和亚洲季风在数十年尺度上联系紧密(Latif, 2001; Dykoski et al, 2005)。所以,季风 YD 事件的研究具有独特的意义,可以此为"桥梁"考察高、低纬区域及南北半球气候突变行为及可能

的联系。洞穴石笋作为亚洲内陆重要陆相材料，其氧同位素指标日益成熟，气候意义比较明确（一般解释为夏季风强度变化）。亚洲季风区多个洞穴监测结果表明，洞穴滴水对外部大气降水响应时间不超过 2 个月甚至更短（李彬等，2000；周运超等，2004；Johnson et al.，2006；Ban Fengmei et al.，2008；罗维均和王世杰，2008），意即洞穴滴水对外部大气降水的响应时间很短，不影响其季节性变化，而仅削弱其同位素变化的幅度。已有亚洲石笋研究清晰记录了 YD 事件期间的夏季风急剧衰减（Wang Yongjin et al.，2001；Yuan Daoxian et al.，2004；Dykoski et al.，2005；Sinha et al.，2005；Liu Dianbing et al.，2008；Yang Yan et al.，2010），并发现 YD 开始季风慢速转型特征。目前所采用的 U/Th 测年手段可获得理想的年龄精度，若石笋材料连续发育清晰年层，可进一步精确控制季风事件的相对时标，进而实现区域内、外高分辨率地质记录精确对比。因此，季风 YD 事件年际时标的建立对进一步验证热带大西洋纹泥时标具有极其重要的参考价值，将有助于提高大气 $\Delta^{14}C$ 重建精度及促进 ^{14}C 年代学的研究。

参　考　文　献 / References

陈仕涛，汪永进，孔兴功，刘殿兵，Cheng Hai，Edwards R L. 2006. 倒数第三次冰消期亚洲季风气候可能的类 Younger Dryas 事件. 中国科学（D 辑），36(5)：445 ～ 452.

李彬，袁道先，林玉石，覃嘉铭，张美良. 2000. 桂林地区降水、洞穴滴水及现代洞穴碳酸盐氧碳同位素研究及其环境意义. 中国科学（D 辑），30 (1)：81 ～ 87.

李潮流，康世昌. 2006. 全球新仙女木事件的恢复及其触发机制研究进展. 冰川冻土，28 (4)：568 ～ 576.

罗维均，王世杰. 2008. 贵州凉风洞大气降水—土壤水—滴水的 $\delta^{18}O$ 信号传递及其意义. 科学通报，53 (17)：2071 ～ 2076.

王建民，钟巍. 1994. 晚冰期新仙女木事件的研究历史及现状. 冰川冻土，16(4)：371 ～ 379.

萧家仪，王建，安芷生，吴锡浩，周卫建. 1998. 南岭东部新仙女木事件的孢粉学证据. 植物学报，40(11)：1079 ~ 1082.

杨志红，姚檀栋，皇翠兰，孙维贞. 1997. 古里雅冰芯中的新仙女木期事件记录. 科学通报，42(18)：1975 ~ 1978.

周杰，周卫健，陈惠忠，薛祥煦，Gerald Nanson. 1999. 新仙女木时期东亚夏季风降水不稳定的证据. 科学通报，44(2)：205 ～ 208.

周卫健，李小强，董光荣，Porter S C，Stuiver M，Donahue D，Jull A J T. 1996. 新仙女木期沙漠/黄土过渡带高分辨率泥炭记录—东亚季风颤动的实例. 中国科学（D 辑），26(2)：118 ～ 224.

周运超，王世杰，谢兴能，罗维均，黎廷宇. 2004. 贵州 4 个洞穴滴水对大气降雨响应的动力学及其意义. 科学通报，49(21)：2220 ～ 2227.

Alley R B，Meese D A，Shuman C A，Gow A J，Taylor K C，Grootes P M，White J W C，Ram M，Waddington E D，Mayewski P A，Zielinski G A. 1993. Abrupt increase in snow accumulation at the end of the Younger Dryas event. Nature，362：527 ～ 529.

Alley R B，Clark P U. 1999. The delaciation of the northern hemisphere：A global perspective. Annual Reviews of Earth and Planetary Science，27：149 ～ 182.

An ZhiSheng. 2000. The history and variability of the East Asian paleomonsoon climate. Quaternary Science Reviews，19：171 ～ 187.

Arz H W，P tzold J，Wefer G. 1999. The deglacial history of the western tropical Atlantic as inferred from high resolution stable isotope records off northeastern Brazil. Earth and Planetary Science Letters，167：105 ~ 117.

Bakke J，Lie Ø，Heegaard E，Dokken T，Haug，G H，Birks H H，Dulski P，Nilsen T. 2009. Rapid oceanic and atmospheric changes during the Younger Dryas cold period. Nature GeoScience，2：202 ～ 205.

Ban Fengmei，Pan Genxiong，Zhu Jian，Cai Binggui，Tan Ming. 2008. Temporal and spatial variations in the discharge and dissolved organic carbon of drip waters in Beijing Shihua Cave，China . Hydrological Progresses，22：3749 ～ 3758.

Bard E，Rostek F，Turon J-L，Gendreau S. 2000. Hydrological impact of Heinrich events in the subtropical northeast Atlantic. Science，289：1321 ~ 1324.

Barrows T T，Lehman S J，Fifield L K，De Deckker P. 2007. Absence of cooling in New Zealand and the adjacent ocean during the Younger Dryas chronozone. Science，318：86 ～ 89.

Beck J W，Richards D A，Edwards R L，Silverman B W，Smart P L，Donahue，D J，Hererra-Osterheld S，Burr G S，Calsoyas L，Jull A J T，Biddulph D. 2001. Extremely large variations of atmospheric ^{14}C concentration during the last glacial period. Science，292：2453 ～ 2458.

Berger W H. 1990. The Younger Dryas cold spell——a quest for causes. Palaeogeography，Palaeoclimatology，Palaeoecology，89：219 ～ 237.

Birchfield G E，Broecker W S. 1990. A salt oscillator in the glacial northern Atlantic? II：A "scale analysis" model. Paleoceanography，5：835 ～ 843.

Bond G，Broecker W，Johnsen S，McManus J，Labeyrie L，Jouzel J，Bonani G. 1993. Correlations between climate records from North Atlantic sediments and Greenland ice. Nature，365：143 ～ 147.

Bordoni S，Schneider T. 2008. Monsoons as eddy-mediated regime transitions of the tropical overturning circulation. Nature GeoScience，1：515 ～ 519.

Brauer A，Endres C，G nter C，Litt T，Stebich M，Negendank J F W. 1999. High resolution sediment and vegetation responses to Younger Dryas climate change in varved lake sediments from Meerfelder Maar，Germany. Quaternary Science Reviews，18：321 ~ 329.

Brauer A，Haug G H，Dulski P，Sigman D M，Negendank J W. 2008. An abrupt wind shift in western Europe at the onset of the Younger Dryas cold period. Nature GeoScience，1：520 ～ 523.

Broecker W S，Bond G，Klas M，Bonani G. Wolfli W. 1990. A salt oscillator in the glacial Atlantic? 1. The concept. Paleoceanography，5：835 ～ 843.

Broecker W S. 1998. Paleocean circulation during the last deglaciation：a bipolar seesaw? Paleoceanography，13：119 ～ 121.

Broecker W S. 2003. Does the trigger for abrupt climate change reside in the ocean or in the atmosphere? Science，300：1519 ～ 1522.

Broecker W S. 2006. Was the Younger Dryas was triggered by a flood?

Science, 312: 1146 ~ 1148.

Broecker W S, Denton G H, Edwards R L, Cheng Hai, Alley R B, Putnam A E. 2010. Putting the Younger Dryas cold event into context. Quaternary Science Reviews, 29: 1078 ~ 1081.

Cane M. 1998. A role for the tropical Pacific. Science, 282: 59 ~ 61.

Carlson A E, Clark P U, Haley B A, Klinkhammer G P, Simmons K, Brook E J, Meissner K J. 2007. Geochemical proxies of North American freshwater routing during the Younger Dryas cold event. The Proceedings of the National Academy of Sciences of the United States of America, 104: 6556 ~ 6561.

Chappellaz J A, Fung I Y, Thompson A M. 1993. The atmospheric CH_4 increase since the Last Glacial Maximum. Tellus, 45B: 228 ~ 241.

Cheng Hai, Edwards R L, Broecker W S, Denton G H, Kong Xinggong, Wang Yongjin, Zhang Rong, Wang Xianfeng. 2009. Ice age terminations. Science, 326: 248 ~ 252.

Clapperton C M, Hall M, Mothes P, Hole M J, Still J W, Helmens K F, Kuhry P, Gemmell A M D. 1997. A Younger Dryas icecap in the Ecuadorian Andes. Quaternary Rearch, 47: 13 ~ 28.

Corrège T, Gagan M K, Beck J W, Burr G S, Cabioch G, Cornec F L. 2004. Interdecadal variation in the extent of South Pacific tropical waters during the Younger Dryas event. Nature, 428: 927 ~ 929.

Dällenbach A, Blunier T, Fl ckiger J, Stauffer B, Chappellaz J, Raynaud D. 2000. Changes in the atmospheric CH_4 gradient between Greenland and Antarctica during the Last Glacial and the transition to the Holocene. Geophysical Research Letters, 27: 1005 ~ 1008.

Dalton R. 2007. Blast in the past? Nature, 447: 256 ~ 257.

Dansgaard W, White J W C, Johnsen S J. 1989. The abrupt termination of the Younger Dryas climate event. Nature, 339: 532 ~ 534.

Dansgaard W, Johnsen S J, Clausen H B, Dahl-Jensen D, Gundestrup N S, Hammer C U, Hvidberg C S, Steffensen J P, Sveinbj rnsdottir A E, Jouzel J, Bond G. 1993. Evidence for general instability of past climate from a 250-kyr ice-core record. Nature, 364: 218 ~ 220.

Delaygue G T, Stocker F, Joos F, Plattner G-K. 2003. Simulation of atmospheric radiocarbon during abrupt oceanic circulation changes: trying to reconcile models and reconstructions. *Quaternary Science Reviews*, 22, 1647 ~ 1658.

Denton G H, Hendy C H. 1994. Younger Dryas age advance of Franz-Josef Glacier in the Southern Alps of New Zealand. Science, 264: 1434 ~ 1437.

Denton G H, Alley R B, Comer G C, Broecker W S. 2005. The role of seasonality in abrupt climate change. Quaternary Science Reviews, 24: 1159 ~ 1182.

Dickson B, Yashayaev I, Meinche J, Turrell B, Dye S, Holfort J. 2002. Rapid freshening of the deep North Atlantic Ocean over the past four decades. Nature, 416: 832 ~ 837.

Dykoski C A, Edwards R L, Cheng Hai, Yuan Daoxian, Cai Yanjun, Zhang Meiliang, Lin Yushi, Qing Jiaming, An Zhisheng, Revenaugh J. 2005. A high-resolution, absolute-dated Holocene and deglacial Asian monsoon record from Dongge Cave, China. Earth and Planetary Science Letters, 233: 71 ~ 86.

Ebbesen H, Hald M. 2004. Unstable Younger Dryas climate in the northeast North Atlantic. Geology, 32: 673 ~ 676.

EPICA Community Members. 2006. One-to-one coupling of glacial climate variability in Greenland and Antarctica. Nature, 444: 195 ~ 198.

Firestone R B, West A, Kennett J P, Becker L, Bunch T E, Revay Z S, Schultz P H, Belgya T, Kennett D J, Erlandson J M, Dickenson O J, Goodyear A C, Harris R S, Howward G A, Kloosterman J B, Lechler P, Mayewski P A, Montgomery J, Poreda R, Darrah T, Que Hee S S, Smith A R, Stich A, Topping W, Wittke J H, Wolbach W S. 2007. Evidence for an extraterrestrial impact 12,900 years ago that contributed to the megafaunal extinctions and the Younger Dryas cooling. Proceedings of the National Academy of Sciences of the United States of America, 104: 16016 ~ 16021.

Fischer H, Behrens M, Bock M, Richter U, Schmitt J, Loulergue L, Chappellaz J, Spahni R, Blunier T, Leuenberger M, Stocker T F. 2008. Changing boreal methane sources and constant biomass burning during the last termination. Nature, 452: 864 ~ 867.

Friedrich M, Remmele S, Kromer B, Hoffmann J, Spurk M, Kaiser K F, Orcel C, K ppers M. 2004. The 12,460-year Hohenheim oak and pine tree-ring chronology from Central Europe—— A unique annual record for radiocarbon calibration and palaeo-environment reconstructions. Radiocarbon, 46: 1111 ~ 1122.

Glasser N F, Harrison S, Winchester V, Aniya M. 2004. Late Pleistocene and Holocene palaeoclimate and glacier fluctuations in Patagonia. Global and Planetary Change, 43: 79 ~ 101.

Goslar T, Wohlfarth B, Bj rck S, Possnert G, Bj rck J. 1999. Variations of atmospheric ^{14}C concentrations over the Allerød—Younger Dryas transition. Climate Dynamics, 15: 29 ~ 42.

Goslar T, Arnold M, Tisnerat-Laborde N, Czernik J, Wiöckowski K. 2000. Variations of Younger Dryas atmospheric radiocarbon explicable without ocean circulation changes. Nature, 403: 877 ~ 880.

Griffiths M L, Drysdale R N, Gagan M K, Zhao Jianxing, Ayliffe L K, Hellstrom J C, Hantoro W S, Frisia S, Feng Y-X, Cartwright I, St. Pierre E, Fischer M J, Suwargadi B W. 2009. Increasing Australian—Indonesian monsoon rainfall linked to early Holocene sea-level rise. Nature GeoScience, 2: 636 ~ 639.

Guilderson T P, Fairbanks R G, Rubenstone J L. 2001. Tropical Atlantic coral oxygen isotopes: Glacial—interglacial sea surface temperatures and climate change. Marine Geology, 172: 75 ~ 89.

Haug G H, Hughen K A, Sigman D M, Peterson L C, Rö hl U. 2001. Southward migration of the intertropical convergence zone through the Holocene. Science, 293: 1304 ~ 1308.

Heine K, Heine J T. 1996. Late Glacial climatic fluctuations in Ecuador: Glacier retreat during the Younger Dryas Time. Arctic and Alpine Research, 28: 496 ~ 501.

Hendy I L, Kennett J P, Roark E B, Ingram B L. 2002. Apparent synchroneity of submillennial scale climate events between Greenland and Santa Barbara Basin, Califonia from 30 ~ 10 ka. Quaternary Science Reviews, 21: 1167 ~ 1184.

Hoffmann D L, Beck J W, Richards D A, Smart P L, Singarayer J S, Ketchmark T, Hawkesworth C J. 2010. Towards radiocarbon calibration beyond 28 ka using speleothems from the Bahamas. Earth and Planetary Science Letters, 289: 1 ~ 10.

Hughen K A, Overpeck J T, Peterson L C, Trummbore S. 1996. Rapid climate changes in the tropical Atlantic region during the last deglaciation. Nature, 380: 51 ~ 54.

Hughen K A, Overpeck J T, Lehman S J, Kashgarian M, Southon J, Peterson L C, Alley R, Sigman D M. 1998. Deglacial changes in ocean circulation from an extended radiocarbon calibration. Nature, 391: 65 ~ 68.

Hughen K A, Southon J R, Lehman J R, Overpeck J T. 2000. Synchronous Radiocarbon and Climate Shifts during the Last

Deglaciation. Science, 290: 1951 ~ 1954.

Hughen K A, Southon J R, Bertrand C J H, Frantz B, Zermeõo P. 2004. Cariaco Basin calibration update: Revisions to calendar and ^{14}C chronologies for core PL07-58PC. Radiocarbon, 46: 1161 ~ 1187.

Isarin R F B, Renssen H. 1999. Reconstructing and modeling Late Weichselian climates: the Younger Dryas in Europe as a case study. Earth-Science Reviews, 48: 1 ~ 38.

Jensen K. 1938. Some west Baltic pollen diagrams. Quartar, 1: 124 ~ 139.

Johnsen S J, Clausen H B, Dansgaard W, Fuhrer K, Gundestrup N, Hammer C U, Iversen P, Jouzel J, Stauffer B, Steffensen J P. 1992. Irregular glacial interstadials recorded in a new Greenland ice core. Nature, 359: 311 ~ 313.

Johnsen S, Dahl-Jensen D, Gundestrup N, Steffensen J, Clausen H, Miller H, Masson- Delmotte V, Sveinbjörnsdottir A, White J. 2001. Oxygen isotope and palaeotemperature records from six Greenland ice-core stations: Camp Century, Dye-3, GRIP, GISP2, Renland and NorthGRIP. Journal of Quaternary Science, 16: 299 ~ 307.

Johnson K R, Hu Chaoyong, Belshaw N S, Henderson G M. 2006. Seasonal trace-element and stable-isotope variations in a Chinese speleothem: The potential for high-resolution paleomonsoon reconstruction. Earth and Planetary Science Letters, 244: 394 ~ 407.

Jouzel J, Vaikmae R, Petit, J R, Martin M, Duclos Y, Stievenard M, Lorius C, Toots M, Mèliéres M A, Burckle L H, Barkov N I, Kotlyakov V M. 1995. The two-step shape and timing of the last deglaciation in Antarctica. Climate Dynamics, 11: 151 ~ 161.

Kennett J P, Cannariato K G, Hendy I L, Behl R J. 2000. Carbon isotopic evidence for methane ydrate instability during Quaternary Interstadials. Science, 288: 128 ~ 133.

Kienast M, Steinke S, Stattegger K, Calvert S E. 2001. Syncronous tropical South China Sea SST change and Greenland warming during deglaciation. Science, 291: 2132 ~ 2134.

Krabill W, Frederick E, Manizade S, Martin C, Sonntag J, Swift R, Thomas R, Wright W, Yungel J. 1999. Rapid thinning of parts of the southern Greenland ice sheet. Science, 283: 1522 ~ 1524.

Latif M. 2001. Tropical Pacific/Atlantic Ocean interactions at multi-decadal time scales. Geophysical Research Letters, 28: 539 ~ 542.

Lea D W, Pak D K, Peterson L C, Hughen K A. 2003. Synchroneity of tropical and high-latitude Atlantic temperatures over the last glacial termination. Science, 301: 1361 ~ 1364.

Litt T, Brauer A, Goslar T, Merkt J, Balaga K, Müller H, Ralska-Jasiewiczowa M, Stebich M, Negendank J F W. 2001. Correlation and synchronization of Lateglacial continental sequences in northern central Europe based on annually laminated lacustrine sediments. Quaternary Science Reviews, 20: 1233 ~ 1249.

Liu Dianbing, Wang Yongjin, Cheng Hai, Edwards R L, Kong Xinggong, Wang Xianfeng, Wu Jiangying, Chen Shitao. 2008. A detailed comparison of Asian Monsoon intensity and Greenland temperature during the Allerød and Younger Dryas events. Earth and Planetary Science Letters, 272: 691 ~ 697.

MacAyeal D R. 1993. Binge/purge oscillations of the Laurentide ice sheet as a cause of the North Atlantic ' s Heinrich events. Paleoceanography, 8: 775 ~ 784.

Manabe S, Stouffer R J. 1980. Sensitivity of a global climate model to an increase of CO_2 concentration in the atmosphere. Journal of Geophysical Research, 85: 5529 ~ 5554.

Manabe S, Stouffer R. 1997. Coupled ocean—atmosphere model response to freshwater input: Comparison to Younger Dryas event. Paleoceanography, 12: 321 ~ 336.

Manabe S, Stouffer R. 2000. Study of abrupt climate change by a coupled ocean—atmosphere model. Quaternary Science Reviews, 19: 285 ~ 299.

Mayewski P A, Meeker L D, Whitlow S, Twickler M S, Morrison M C, Alley R B, Bloomfield P, Taylor K. 1993. The atmosphere during the Younger Dryas. Science, 261: 195 ~ 197.

Mayewski P A, Meeker L D, Twickler M S, Whitlow S, Yang Qinzhao, Lyons W B, Prentice M. 1997. Major features and forcing of high-latitude northern hemisphere atmospheric circulation using a 110, 000-year-long glaciochemical series. Journal of Geophysical Research 102: 26345 ~ 26366.

McManus J F, Francois R, Gherardi J-M, Keigwin L D, Brown-Leger S. 2004. Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes. Nature, 428: 834 ~ 837.

Meese D A, Gow A J, Alley R B, Zielinski G A, Grootes P M, Ram M, Taylor K C, Mayewski P A, Bolzan J F. 1997. The Greenland ice sheet project 2 depth—age scale: methods and results. Journal of Geophysical Research, 102: 26411 ~ 26423.

Mulitza S, R hlemann C. 2000. African monsoonal precipitation modulated by interhemispheric temperature gradients. Quaternary Resarch, 53: 270 ~ 274.

Mulvaney R, R thlisberger R, Wolff, E W, Sommer S, Schwander J, Hutterli M A, Jouzel J. 2000. The transition from the last glacial period in inland and near-costal Antarctica. Geophysical Research Letters, 27: 2673 ~ 2676.

Nakagawa T, Tarasov P E, Kitagawa H, Yasuda Y, Gotanda K. 2006. Seasonally specific responses of the East Asian monsoon to deglacial climate changes. Geology, 34: 521 ~ 524.

Partin J W, Cobb K M, Adkins J F, Clark B, Fernandez D P. 2007. Millennial-scale trends in west Pacific warm pool hydrology since the Last Glacial Maximum. Nature, 449: 452 ~ 456.

Pierrehumbert R T. 2000. Climate Change and the Tropical Pacific: The Sleeping Dragon Wakes. Proceedings of the National Academy of Sciences of the United States of America, 97: 1355 ~ 1358.

Rasmussen S O, Andersen K K, Svensson A M, Steffensen J P, Vinther B M, Clausen H B, Siggaard-Andersen M-L, Johnsen S J, Larsen L B, Dahl-Jensen D, Bigler M, R thlisberger R, Fischer H, Goto-Azuma K, Hansson M E, Ruth U. 2006. A new Greenland ice core chronology for the last glacial termination. Journal of Geophysical Research, 111, D06102, doi: 10.1029/2005JD006079.

Reimer P J, Baillie M G L, Bard E, Bayliss A, Beck J W, Blackwell P G, Buck C E, Burr G S, Cutler K B, Damon P E, Edwards R L, Fairbanks R G, Friedrich M, Guilderson T P, Herring C, Hughen K A, Kromer B, McCormac F G, Manning S W, Ramsey C B, Reimer P J, Reimer R W, Remmele S, Southon J R, Stuiver M, Talamo S, Taylor F W, van der Plicht J, Weyhenmeyer C E. 2004. IntCal04 Terrestrial radiocarbon age calibration, 0 ~ 26 cal kyr BP. Radiocarbon, 46: 1029 ~ 1058.

Reimer P J, Baillie M G L, Bard E, Bayliss A, Beck J W, Blackwell P G, Ramsey C B, Buck C E, Burr G S, Edwards R L, Friedrich M, Grootes P M, Guilderson T P, Hajdas I, Heaton T J, Hogg A G, Hughen K A, Kaiser K F, Kromer B, McCormac F G, Manning S

W, Reimer R W, Richards D A, Southon J R, Talamo S, Turney C S M, van der Plicht J, Weyhenmeyer C E. 2009. Intcal09 and Marine09 radiocarbon age calibration curves, 0 ~ 50,000 years cal BP. Radiocarbon, 51: 1111 ~ 1150.

Renssen H, van Geel B, van der Plicht J, Magny M. 2000. Reduced solar activity as a trigger for the start of the Younger Dryas? Quaternary International, 68 ~ 71: 373 ~ 383.

R hlemann C S, Mulitza P, M ller M, Wefer G, Zahn R. 1999. Warming of the tropical Atlantic Ocean and slowdown of thermohaline circulation during the last deglaciation. Nature, 402: 511 ~ 514.

Ruth U, Bigler M, R thlisberger R, Siggaard-Andersen M-L, Kipfstuhl S, Goto-Azuma K, Hansson M E, Johnsen S J, Lu Huayu, Steffensen J P. 2007. Ice core evidence for a very tight link between North Atlantic and east Asian glacial climate. Geophysical Research Letters, 34, L03706, doi: 10.1029/2006GL027876.

Sakai K, Peltier W R. 1997. Dansgaard Oeschger oscillations in a coupled atmosphere ocean climate model. Journal of Climate, 10: 949 ~ 970.

Schaefer H, Whiticar M J, Brook E J, Petrenko V V, Ferretti D F, Severinghaus J P. 2006. Ice record of $\delta^{13}C$ for atmospheric CH_4 across the Younger Dryas—Preboreal transition. Science, 313: 1109 ~ 1112.

Schefu E, Schouten S, Schneider R R. 2005. Climatic controls on central African hydrology during the past 20,000 years. Nature, 437: 1003 ~ 1006.

Seager B R, Battisti D S, Yin J, Gordon N, Naik N, Clement A C, Cane M A. 2002. Is the Gulf Stream responsible for Europe's mild Europe? Quarterly Journal of the Royal Meteorological Society, 128: 2563 ~ 2586.

Severinghaus J P, Sowers T, Brook E J, Alley R B, Bender M L. 1998. Timing of abrupt climate change at the end of the Younger Dryas interval from thermally fractionated gases in polar ice. Nature, 391: 141 ~ 146.

Shakun J D, Burns S J, Fleitmann D, Kramers J, Matter A, Al-Subbary A. 2007. A high-resolution, absolute-dated deglacial speleothem record of Indian Ocean climate from Socotra Island, Yemen. Earth and Planetery Science Letters, 259: 442 ~ 456.

Shakun J D, Carlson A E. 2010. A global perspective on Last Glacial Maximum to Holocene climate change. Quaternary Science Reviews, 29: 1801 ~ 1816.

Sima A, Paul A, Schulz M. 2004. The Younger Dryas——an intrinsic feature of late Pleistocene climate change at millennial timescales. Earth Planetary Science Letters, 222: 741 ~ 750.

Singer C, Shulmeister J, McLea B. 1998. Evidence against a significant Younger Dryas cooling event in New Zealand. Science, 281: 812 ~ 814.

Sinha A, Cannariato K G, Li H-C, You C-F, Cheng Hai, Edwards R L, Singh I B. 2005. Variability of southwest Indian summer monsoon precipitation during the Bølling—Allerød. Geology, 33: 813 ~ 816.

Steig E J, Brook E J, White J W C, Sucher C M, Bender M L, Lehman S J, Morse D L, Waddington E D, Clow G D. 1998. Synchronous climate changes in Antarctica and the North Atlantic. Science, 282: 92 ~ 95.

Steffensen J P, Andersen K K, Bigler M, Clausen H, Dahl-Jensen D, Fischer H, Goto-Azuma K, Hansson M, Johnsen S J, Jouzel J, Masson-Delmotte V, Popp T, Rasmussen S O, R thlisberger R, Ruth U, Stauffer B, Siggaard-Andersen M-L, Sveinbj rnsd ttir E, Svensson A, White J W C. 2008. High-resolution Greenland ice core data show abrupt limate change happens in few years. Science, 321: 680 ~ 684.

Stott L, Timmermann A, Thunell R. 2007. Southern Hemisphere and deep-sea warming led deglacial atmospheric CO_2 rise and tropical warming. Science, 318: 435 ~ 438.

Stuiver M, Grootes P M. 2000. GISP2 oxygen isotope ratios. Quaternary Research, 53: 277 ~ 284.

Sy A, Rhein M, Lazier J R N, Koltermann K P, Meincke J, Putzka A, Bersch M. 1997. Surprisingly rapid spreading of newly formed intermediate waters across the North Atlantic Ocean. Nature, 386: 675 ~ 679.

Tarasov L, Peltier W R. 2005. Arctic freshwater forcing of the Younger Dryas cold reversal. Nature, 435: 662 ~ 665.

Teller J T, Leverington D W, Mann J D. 2002. Freshwater outbursts to the oceans from glacial Lake Agassiz and their role in climate change during the last deglaciation. Quaternary Science Reviews, 21: 879 ~ 887.

Thomas E R, Wolff E W, Mulvaney R, Johnsen S J, Steffensen J P, Arrowsmith C. 2009. Anatomy of a Dansgaard—Oeschger warming transition: High-resolution analysis of the North Greenland Ice Core Project ice core. Journal of Geophysical Research, 114, D08102, doi: 10.1029/2008JD011215.

Thompson L G, Davis M E, Mosley-Thompson E, Sowers T A, Henderson K A, Zagorodnov V S, Lin P N, Mikhalenko V N, Campen R K, Bolzan J F, Cole-Dai J, Francou B. 1998. A 25, 000-year tropical climate history from Bolivian ice cores. Science, 282: 1858 ~ 1864.

Taylor K C, Lamorey G W, Doyle G A, Alley R B, Grootes P M, Mayewski P A, White J W C, Barlow L K. 1993. The flickering switch' of late Pleistocene climate change. Nature, 361: 432 ~ 435.

Taylor K C, Mayewski P A, Alley R B, Brook E J, Gow A J, Grootes P M, Meese D A, Saltzman E S, Severinghaus J P, Twickler M S, White J W C, Whitlow S, Zielinski A A. 1997. The Holocene——Younger Dryas transition recorded at Summit, Greenland. Science, 278: 825 ~ 827.

Vacco D A, Clark P U, Mix A C, Cheng Hai, Edwards R L. 2005. A speleothem record of Younger Dryas cooling from the Klamath Mountains, Oregon, USA. Quaternary Research, 64: 249 ~ 256.

van Huissteden J. 2004. Methane emission from northern wetlands in Europe during Oxygen Isotope Stage 3. Quaternary Science Reviews, 23: 1989 ~ 2005.

Visser K, Thunell R, Stott L. 2003. Magnitude and timing of temperature change in the Indo—Pacific warm pool during deglaciation. Nature, 421: 152 ~ 155.

von Grafenstein U, Erlenkeuser H, Brauer A, Jouzel J, johnsen S J. 1999. A mid-European decadal isotope—climate record from 15, 500 to 5000 years BP. Science, 284: 1654 ~ 1657.

Wang Yongjin, Cheng Hai, Edwards R L, An Zhisheng, Wu Jiangying, Shen Chuanchou, Dorale J A. 2001. A high-resolution absolute-dated Late Pleistocene monsoon record from Hulu Cave, China. Science, 294: 2345 ~ 2348.

Weldeab S, Schneider R R, K llinga M. 2006. Deglacial sea surface temperature and salinity increase in the western tropical Atlantic in synchrony with high latitude climate instabilities. Earth and Planetary Science Letters, 241: 699 ~ 706.

Weyhenmeyer C E, Burns S J, Fleitmann D, Kramers J D, Matter A, Waber H N, Reimer P J. 2003. Changes in atmospheric ^{14}C between 55 and 42 ky BP recorded in a stalagmite from Socotra Island, Indian Ocean. EOS Transactions 84(46): Fall Meeting Supplement, 32B ~ 0298.

Williams P M, King D N T, Zhao Jianxiang, Collerson K D. 2005. Late Pleistocene to Holocene composite speleothem ^{18}O and ^{13}C chronologies from South Island, New Zealand——did a global Younger Dryas really exist? Earth and Planetary Science Letters, 230: 301 ~ 317.

Yancheva G, Nowaczyk N R, Mingram J, Dulski P, Schettler G, Negendank J F W, Liu Jiaqi, Sigman D M, Peterson L C, Haug G H. 2007. Influence of the intertropical convergence zone on the East Asian monsoon. Nature, 445: 74 ~ 77.

Yang Yan, Yuan Daoxian, Cheng Hai, Zhang Meiliang, Qin Jiaming, Lin Yushi, Zhu Xiaoyan, Edwards R L. 2010. Precise dating of abrupt shifts in the Asian monsoon during the last deglaciation based on stalagmite data from Yamen Cave, Guizhou Province, China. Science in China(Series D, Earth Sciences), 53: 633 ~ 641.

Yuan Daoxian, Cheng Hai, Edwards R L, Dykoski C A, Kelly M J, Zhang Meiliang, Qing Jiaming, Lin Yushi, Wang Yongjin, Wu Jiangying, Dorale J A, An Zhisheng, Cai Yanjun. 2004. Timing, duration, and transitions of the last interglacial Asian monsoon. Science, 304: 575 ~ 578.

Zhao Meixun, Beveridge N A S, Shackleton N J, Sarthein M, Eglinton G. 1995. Molecular stratigraphy of cores off northwest Africa: Sea-surface temperature history over the last 80 ka. Paleoceanography, 10: 661 ~ 675.

Zhou Weijian, Head M J, An Zhisheng, De Deckker P, Liu Zhengyu, Liu Xiaodong, Lu Xuefeng, Donahue D, Jull A J T, Beck J W. 2001. Terrestrial evidence for a spatial structure of tropical-polar interconnections during the Younger Dryas episode. Earth and Planetary Science Letters, 191: 231 ~ 239.

Recent Progress on Studies of the Spatial Structure and Dynamics for the Younger Dryas Event

LIU Dianbing

College of Geography Science, *Nanjing Normal University*, *Nanjing*, 210046

Abstract: As a prototype of abrupt climate changes, the Younger Dryas (YD) event occurred during the last deglaciation, when the Northern Hemispheric temperatures decreased significantly. This event, a focus of interest in the paleoclimate studies, has promoted the understanding of millennial-scale climate changes. Currently, increasing high-resolution records identified a spatio-temporal heterogeneity for the YD event. Knowledge of the structure and transitional pattern for these spatial expressions helps to determine the phase relationship between them, and further understand how reorganization of regional environments responses to rapid climate changes at the low- and high-latitudes. Thus, the previous hypotheses of trigger-response can be tested to deduce a physical interpretation for the YD and present a basis for climate prediction under the similar boundary conditions. By summarizing and comparing the modeling studies and geologic records, this review focuses on the regional responses and the current debates for YD event, and then presents some areas and directions to be further studied. Increasing high-resolution records identified a spatio-temporal heterogeneity for the Younger Dryas (YD) event. Knowledge of the structure and transitional pattern for these spatial expressions helps to determine the phase relationship between them, and further understand how reorganization of regional environments response to rapid climate changes at the low- and high-latitudes. Thus, the previous hypotheses of trigger-response can be tested to deduce a physical interpretation for the YD and present a basis for climate prediction under the similar boundary conditions.

Key words: the Younger Dryas Event; detailed structure; transitional pattern; regional discrepancy