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末次冰期南海南部暴露的巽他陆架是大气碳汇?

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摘要:在约10万年的冰期-间冰期旋回中, 大气 CO_2 浓度与温度存在几乎同步的周期性变化; 间冰期的 CO_2 浓度约为 280×10^{-6} , 冰期逐渐下降, 至盛冰期达到最低(约 180×10^{-6}), 冰消期又快速回升。关于冰期大气 CO_2 的去向, 前人的许多研究表明, 冰期的海洋是个巨大的碳汇, 而陆地碳储量在冰期是下降的。从海洋和陆地碳库整体的变化来看, 似乎冰期大气 CO_2 浓度的下降完全可以用海洋碳库的增加来解释, 甚至陆地碳库还是大气的源。但通过分析各种地质证据与数值模拟结果, 发现末次冰期南海南部暴露的巽他陆架上分布着广阔的热带森林, 这意味着, 末次冰期暴露的巽他陆架可能具有较强的储碳能力, 与冰期陆地的碳源角色相反。因此, 为更准确了解碳循环与气候变化, 未来的研究需要对陆地碳库进行有效细分, 定量描述各区域在碳循环中的角色。

关键词:陆地碳库; 热带森林; 碳循环; 巽他陆架; 末次冰期

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The Sunda Shelf—A carbon sink during the last glacial period?

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Abstract: So far, the ice cores from Antarctica have provided a high-resolution record of atmospheric CO_2 concentration levels over the past 800000 years. A significant fact is that the atmospheric CO_2 concentration variation with respect to change in temperature is almost synchronous throughout these eight glacial-interglacial cycles, ranging from about 180×10^{-6} to 280×10^{-6} . While the terrestrial carbon pool is the source of atmospheric CO_2 , the deep ocean acts as the sink of the atmospheric CO_2 which could explain the reduction of atmospheric CO_2 concentration during the glacial period. However, lots of palynological and numerical simulated evidences reveal that tropical forest must have dominated the emerged Sunda Shelf in the South China Sea during the last glacial period (LGP), suggesting that the Sunda shelf may have played a role as an atmospheric carbon sink in the LGP. In order to better understand the carbon cycle and climate change, future research needs to subdivide the terrestrial carbon pool effectively with quantitative calculation.

Key words: terrestrial carbon pool; tropical forest; carbon cycle; Sunda shelf; Last glacial period

1 全球气候与碳循环变化背景

世界气象组织(WMO)最新发布的《温室气体公报》指出, 2016年大气 CO_2 全球平均水平已上升至 403.3×10^{-6} , 达到工业革命前(约公元1750年之前)水平的145%, 而最近一次大气 CO_2 达到如此高的水平已经是约3~5 Ma前的上新世中期。 CO_2 作为大气中最重要的温室气体, 对辐射强迫的

贡献极大, 并且人类活动造成大气温室气体的增加被认为是目前全球变暖的主要影响因子。在CMIP5(国际耦合模式对比计划)以及正在发展的CMIP6中, 未来大气 CO_2 代表性浓度路径RCP 8.5、RCP4.5以及RCP2.6(例如RCP8.5代表在2100年时辐射强迫相对1750年达到 8.5 W/m^2 的浓度路径)模拟结果表明, 不同的大气 CO_2 增加趋势将会造成全球范围内不同幅度的升温。可见, 预测大气 CO_2 浓度变化对于未来气候变化的预测和

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控制都十分重要。然而,要准确预测大气 CO_2 浓度的变化趋势,需要定量了解各个碳库的源、汇角色以及碳循环在地质历史时期上的演变。随着冰芯提取微小气泡等技术的成熟,目前通过冰芯气泡恢复的古大气 CO_2 浓度最长已达到约 80 万年以前^[1],显示了该时段大气 CO_2 的不同变率。十分瞩目的是,在这约 80 万年期间,大气 CO_2 浓度存在显著的十万年冰期-间冰期旋回特征;同时高分辨率冰芯记录显示 CO_2 浓度变化要略微领先于指示温度变化的氢同位素变化曲线^[2],这也暗示碳循环可能对气候变化起着重要的引领作用。

CO_2 浓度的冰期旋回现象启发我们思考:盛冰期相比间冰期减少的 $(80\sim 100)\times 10^{-6}$ CO_2 到底去向何方?前人围绕这个问题展开了大量研究,许多证据表明冰期减少的大气 CO_2 大部分被海洋通过生物碳泵或碳酸盐泵等所吸收,尽管在各海区的碳汇能力以及定量上存在分歧,但海洋作为冰期强大的碳汇没有争议^[3];与海洋碳库相反,由于冰期欧亚大陆中高纬度地区苔原、冰盖的扩张等,大部分研究认为陆地总碳储量是下降的,也就是说陆地碳库不仅不能解释冰期大气 CO_2 的降低,而且还是大气的碳源^[4],也因此以往人们对陆地碳库的重视程度不如海洋碳库。但前期不同研究对末次盛冰期 (Last Glacial Maximum, LGM) 陆地碳储量的估计却相差很大,与工业革命前期 (Pre-industrial Period, PI) 相比它的变化幅度 (LGM-PI) 在 $+20\sim -1350$ Gt 不等^[5,6],这些不同方法的估测范围几乎达到了现代陆地碳总量的一半^[7];近年来根据稳定碳同位素守恒等方法的有效校正^[8-10],剔除了个别不合理的估测,变化幅度 (LGM-PI) 也依然在 $-300\sim -1100$ Gt,相比自然状态下只有 $399\sim 593$ Gt 的大气碳储量,仍是非常巨大的误差。

除此之外,陆地碳库及陆地生物圈在冰期对碳循环的影响远非“大气碳源”如此简单概括,实际上陆地生物圈不仅在季节、年际等短时间尺度上可以通过植物呼吸、光合作用等途径调控大气 CO_2 浓度的分布和变化,在亚轨道尺度、轨道尺度上陆地碳库的源、汇分布也相差甚远。例如,在 LGM,全球海平面下降导致巽他陆架的大面积出露^[11,12],这是在冰期增加的陆地碳库。而且,土壤碳库在陆地碳库中占主要部分,现代东南亚有丰富且季节分布均匀的降水,非常适宜于泥炭地的发展,占热带泥炭体积高达 77%^[13]。因此,冰期巽他陆架可能在碳循环中占有比现代更重要的地位,并且极大可能与冰期陆地

整体释放 CO_2 的趋势相反,充当大气碳汇。下文将主要从冰期海平面变化、植被变化等方面进一步综合论证以上观点,为日后的定量研究工作提供参考。

2 冰期海平面变化与巽他陆架

在现代,来自卫星遥感、数值模拟等的结果表明北半球中高纬度陆地生态系统是巨大的碳汇,对陆地碳汇的贡献超过 90%,固定了大部分“去向不明”的 CO_2 ^[14];而热带地区由于大量森林遭受砍伐,从前人们认为这既导致碳排放、又降低了它吸收碳的能力。但近年来大气 CO_2 垂直分布的实测结果表明,大多数大气输送模式由于不能很好地描述大气中的对流及暴风雨活动,模拟结果差,实际上热带的碳汇能力是远被低估的^[15]。现代全球生物量中,森林占据了 92%,其中有 2/3 位于热带^[16];陆地初级生产力 (Gross Primary Production, GPP) 最高的区域也是热带^[17],可见热带森林在碳收支中的地位十分重要。其中,亚马逊雨林是全球最大、物种最为丰富的热带雨林,拥有全球热带森林的 49%;其余热带森林分布在刚果盆地和东南亚,分别各占全球的 1/4^[18]。当然,除了地上生物量碳之外,土壤碳库在陆地中占有更大的分量,即使在土壤碳密度相对低的热带,其土壤碳储量也是地上生物量碳的 1 倍以上,北半球中高纬土壤含碳量更是极高^[19],但总的碳储量仍是热带森林占有最大比重^[20]。在冰期,尽管陆地总碳量比间冰期要低,但热带森林碳库所占全球陆地碳库的比重却是增大的^[20]。

与南美亚马逊盆地、非洲刚果盆地不同的是,如今的东南亚是“海洋性大陆”,并且巽他陆架上爪哇岛、马来半岛、苏门答腊岛、中南半岛、婆罗洲等这些岛屿之间的水域深度大部分不超过 70m^[21] (图 1),陆架具有极小的坡度,被称为“亚洲大浅滩”。巽他陆架的这些特点使其对海平面变化的反应非常敏感,轻微的海平面下降就能导致海岸线的大幅向外迁移。在末次盛冰期,多个珊瑚礁记录的综合分析结果显示巽他陆架海平面低于现代多达 116m,暴露出海面的陆架面积与周围岛屿的总和相当,形成人们常说的“巽他古陆”;而且在末次冰期超过 90% 的时间里,巽他陆架海平面也低于现代大约 50m^[22] (图 2)。也就是说,在冰期-间冰期约 10 万年的周期性旋回当中,大部分时候巽他陆架都处于暴露状态,如今的“海洋性大陆”状态才是短暂的。

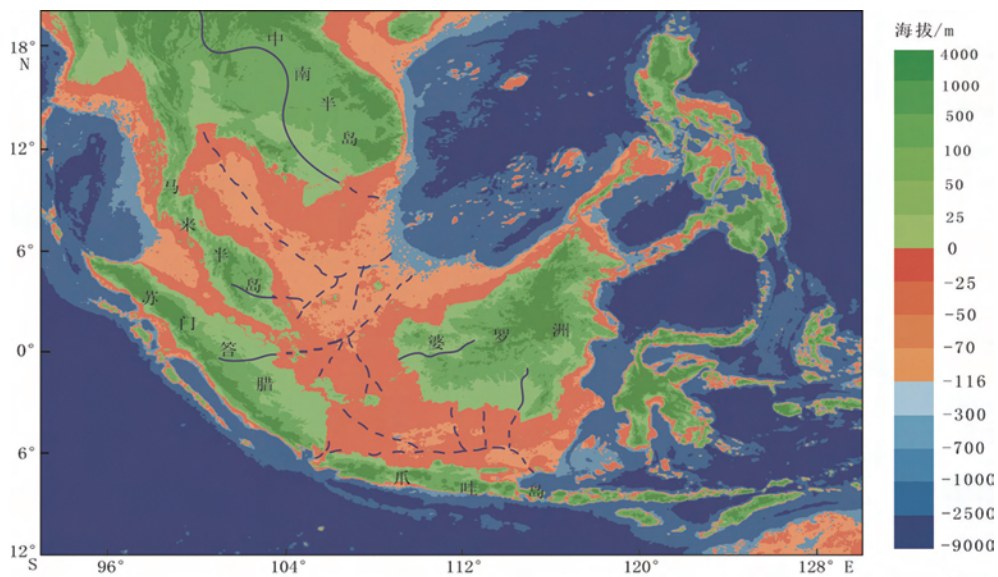


图 1 巽他陆架地形与河流
(蓝色虚线代表巽他陆架暴露后发育的河流^[23,24];地形数据来源:NOAA 全球地形数据 ETOPO1(doi:10.7289/V5C8276M))
Fig.1 Topography and paleo-rivers of Sunda Shelf
Topography data from ETOPO1 (doi:10.7289/V5C8276M) and paleo-river data from references^[23,24]

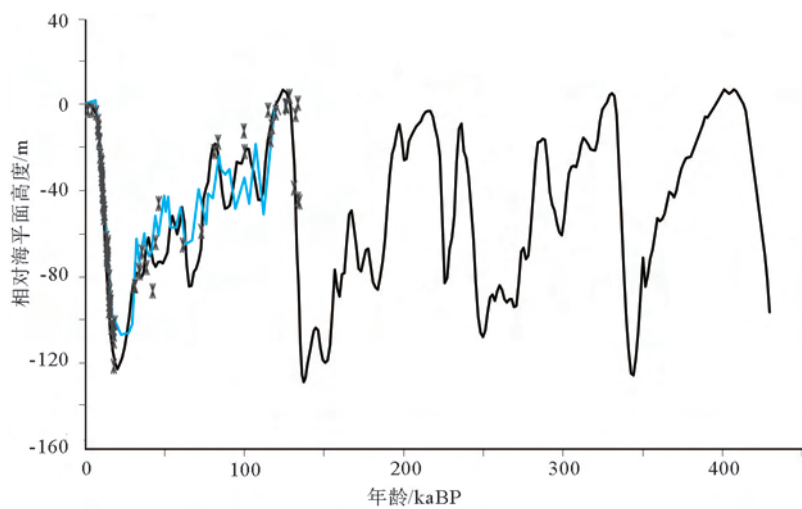


图 2 相对海平面变化
(浅蓝色实线为巽他陆架海平面变化模拟重建^[22],黑色星号和实线分别为珊瑚记录和有孔虫 $\delta^{18}\text{O}$ 重建的复合海平面变化^[25])
Fig.2 Relative sea level changes
(The blue line is Sunda Shelf's relative sea level history including the local hydro-isostatic^[22], the black crosses are coral reef records, and the black line is a composite sea level curve derived from foraminifer $\delta^{18}\text{O}$ ^[25])

基于以上分析,我们思考:既然在现代的“海洋性大陆”状态下,东南亚热带森林比例就已经等于非洲的刚果盆地,那么在冰期它是否能超过刚果雨林、成为全球第二热带雨林?甚至在末次盛冰期陆地面积达到现代两倍的时候,与现代的“地球之肺”——亚马逊热带雨林相匹敌?而且,值得注意的是,早在接近一个世纪之前就已经有科学家提出冰期巽他陆架存在古巽他河^[24](图 1),后来又发现了

古湄南河、湄公河与巴南河等,尤其是古湄南河,推测其流量可与长江相比,这些河流的出现十分有利于热带森林和泥炭地的发展^[26]。当然,冰期气候状态与现代相差很大,温度、降水量都有不同程度的降低^[27],因此冰期热带森林可能会有不同程度的减少,若草原扩张,固碳量必定不如热带雨林。但也有研究表明热带某些地区的碳密度在冰期时甚至高于目前值^[28],这可能是由于这些地区降水量变化不

大、温度降低导致的。Anderegg 等人^[29]基于遥感数据的分析也发现,陆地碳汇的年代际变率受到热带地区的夜晚温度影响,可能是通过温度降低导致呼吸作用减弱而实现的。因此,冰期植被的准确重建对于陆地碳库的估测来说意义就非常重大。上文认为冰期巽他陆架可能作为大气碳汇的猜测,除考虑到陆地面积增大以外,很大程度上也基于巽他陆架在冰期可能具有可观的植被和土壤碳密度。因此,下文将根据孢粉化石、古生物等地质记录以及数值模拟结果,分析末次冰期巽他陆架最有可能的植被分布,以考量巽他陆架在冰期碳循环中究竟充当着怎样的角色。

3 末次冰期巽他陆架植被分布的争议

冰期暴露的巽他陆架究竟能否维持热带森林或被萨瓦纳(Savanna)草原覆盖,是个争论已久的问题。早在 20 世纪 90 年代,Heaney^[23]就根据孢粉化石记录提出东南亚在冰期出现“草原通道(Savanna Corridor)”的假说,即在巽他陆架的中部——北起泰国南部、南至爪哇岛以东,都被萨瓦纳草原所覆盖。冰期是否存在“草原通道”又是巽他陆架古植被恢复研究中争议最大的问题,但海陆变化使得这里

的孢粉化石记录的解释变得十分复杂,基本上只能通过其他替代性指标来推测其冰期植被分布。Bird 等人^[30]也通过收集物种、沉积物等几种证据,表示支持末次冰期存在“草原通道”的观点(图 3)。

但是,在所谓“草原通道”所持续的短时间内是否能形成生物隔离是存疑的,如 Silk 等人^[31]的证据表明,如今马来半岛、苏门答腊与东边的婆罗洲出现的显著物种差异是受到了土壤因素影响,因此东西两侧的物种差异不能作为“草原通道”曾经存在的证据;从爪哇海的泥炭沉积记录来看,森林也可能在间冰期海平面上升之前就已经存在^[32];以冰期马来半岛几乎不出现森林栖息物种为证据而支持草原扩张的说法^[33],以及部分基于洞穴沉积物中蝙蝠粪便的碳同位素来推测草原扩张的研究^[34],也得不到孢粉化石记录的支持,低地雨林孢粉成分在末次冰期仍占主要地位,只有在末次盛冰期热带低地雨林面积才有所缩小,而禾本科花粉只在澳洲北部出现了明显增多(图 4)。这些来自陆地、海洋的孢粉证据表明,末次冰期暴露的巽他陆架上并没有出现大面积的草原扩张,而且仍然以森林占主导地位。

此外,许多数值模拟的研究也合理地重建了末次冰期巽他陆架的植被分布。Canon 等人^[57]利用大气环流模式、结合古生物记录约束的方法,表明末

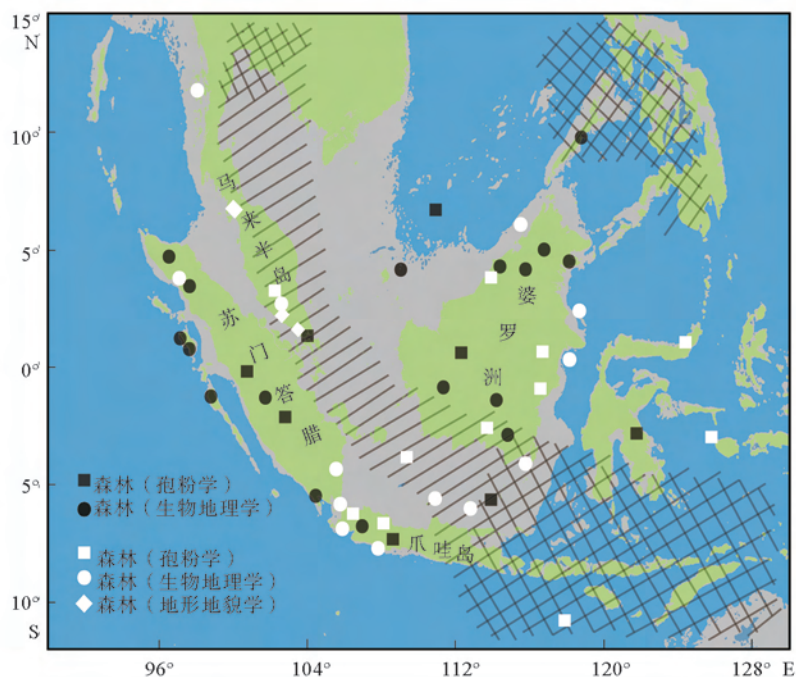


图 3 LGM 巽他陆架植被分布

(“/”表示末次盛冰期“草原通道”,“×”表示现代草原,根据文献[23,30]修改)

Fig.3 Vegetation map of Sunda Shelf during the LGM

(modified after references [23,30])

根本上来说是通过模拟古代的气候状况,在假设气候-植被关系与现代一致的基础上,根据气候来重建植被和碳库,因此提高模拟古气候状况的可信度,是重建真实陆地碳库的必要条件。

首先,在模式的选择上,应当选择最能合理模拟东南亚气候的模式,例如 Cannon 在模拟 LGM 巽他陆架植被分布时就采取了能有效模拟 ENSO 模态的海气耦合模式^[57],因为巽他陆架正是处于赤道西太平洋暖池的关键区域,当然印尼穿越流也是需要考虑的因素。同时,笔者认为,在冰期巽他陆架的植被和碳库模拟当中,需要有针对性地原理上对争议最大的所谓“草原通道”进行分析。Heaney 最先提出巽他陆架在冰期存在“草原通道”假设是基于当冰期海温降低、蒸发减弱,再加上陆架暴露、沿海陆地面积减少导致季风带来的水汽减少,从而导致了草本植物的扩张,因此这个“草原通道”也是位于冰期巽他陆架的内陆地区,呈南北向分布^[23]。尽管许多地质证据都指向不存在“草原通道”的说法,但如今数值模式对 LGM 降水的模拟结果仍然存在分

歧,个别模式结果还显示巽他陆架在末次盛冰期降水增多(图 5)。德国的 MPI-ESM-P 模式能模拟出“草原通道”这种南北向分布的降水减少带状特征,而这个模式最突出的特点之一是它包含了动态植被模块,即模式中植被是可变的,并且包含植被-气候的相互作用过程。尽管我们尚未知道正确的答案,但冰期巽他陆架内陆地区是否因为远离海洋、季风降水减少而出现“草原通道”确实是值得我们思考的方向,植被与气候的相互作用也是今后研究需要加强的问题。

其次,建立值得信赖的气候-植被关系也十分重要。在现代东南亚-澳洲大陆,800~2000mm 的年降水量和大约 6 个月的旱季是促进萨瓦纳发育的主要因素^[62],戴璐^[35]从植物学角度分析了全球各地影响萨瓦纳草原发育的气候因素,指出降水量对萨瓦纳分布的主导作用,包括年均降水量和降水量的季节变化(图 4)。冰期禾本科花粉明显增多的区域,就是以现代降水季节性强的区域为中心扩张。而现代 Sunda-Sahul 陆架的萨瓦纳草原只有在澳洲

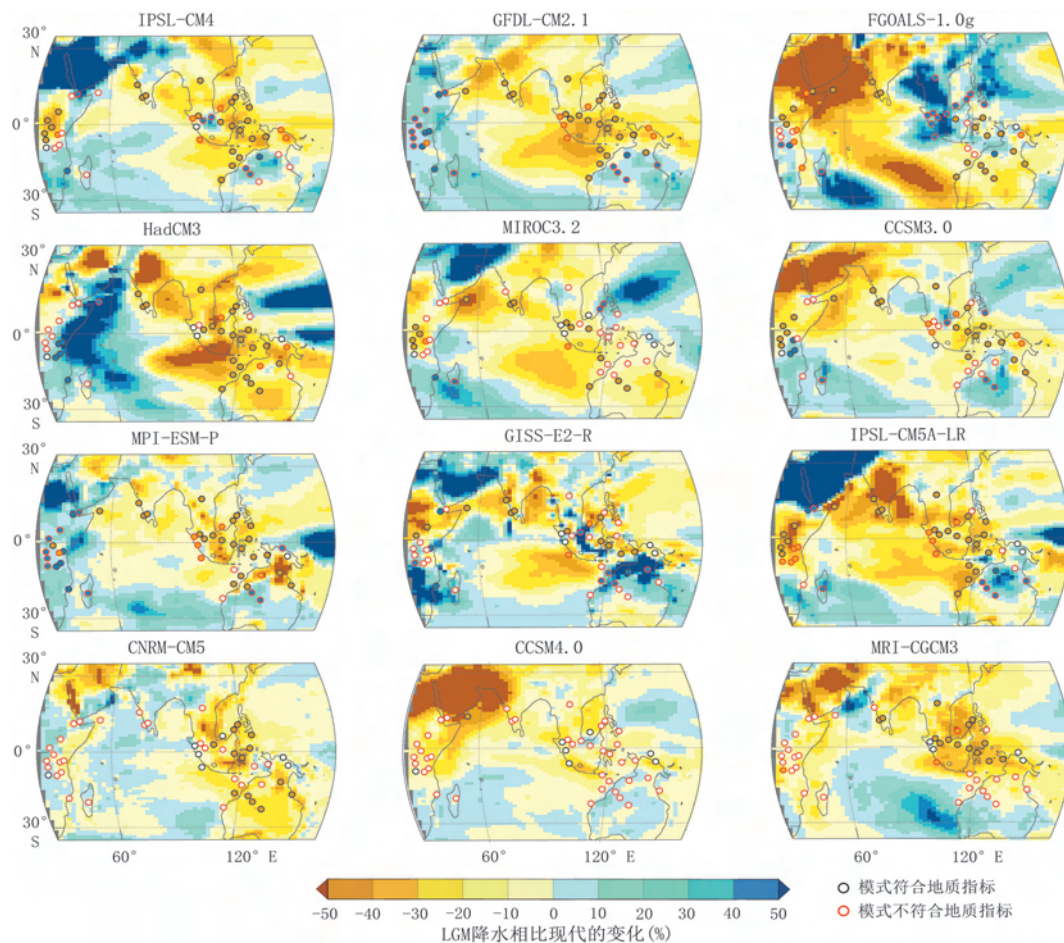


图 5 LGM 降水变化的模拟结果(根据文献[61]改绘)

Fig.5 Proxy-model synthesis of LGM rainfall changes(modified after reference [61])

北部才出现,在低纬度地区是不存在的^[63],这也为本文认为冰期巽他陆架没有出现草原扩张提供了佐证。此外,亚马逊盆地的植被和降水量变化也存在类似的情形^[64]:现代亚马逊盆地东部的“干旱走廊(Dry Corridor)”在冰期变得更干旱^[65],亚马逊西部雨林即使在末次盛冰期降水量也几乎与间冰期相当^[66,67]。但降水量降低到何种程度才会出现草原大量扩张,这是个尚未解决的问题。尽管亚马逊雨林的“干旱走廊”降水量在冰期确实下降了许多,地质证据却表明即使在年降水量最低的末次盛冰期此处也依然是被森林覆盖^[65]。因此,要准确地重建古代的植被分布,我们首先必须认清影响植被变化的气候、水文和土壤等因素,了解哪些因子发生变化、达到何种程度的变化才会导致植被变化;以及在气候逐渐变化的背景下是否会出现植被覆盖的突变可能也是我们需要深入研究的问题^[68]。

5 结论与展望

本文基于地质证据与数值模拟结果,从植被变化角度论证了末次冰期南海南部暴露的巽他陆架可能会具有极强的储碳能力,甚至与冰期陆地整体释放大气 CO₂ 的角色相反。这令我们意识到,巽他陆架或其他陆架在不同地质历史时期的淹没或暴露可能会导致它们的碳循环角色发生变化。我们未来的研究应对陆地碳库进行有效细分,应定量描述各区域在碳循环中的角色。而孢粉化石记录是植被重建、碳循环研究中极为有效的手段,但在这个可能相当于冰期“地球之肺”的巽他陆架上,孢粉记录还较为匮乏,相对比北美洲、欧洲孢粉数据库更是十分稀少,因此,未来还应给予东南亚孢粉研究工作充分的重视。

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