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# 青藏高原及周边地区近期冰川状态失常与灾变风险

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**摘要** 青藏高原及周边地区是除南、北极地区之外全球最重要的冰川资源富集地. 近百年来, 青藏高原及周边地区冰川整体处于缓慢退缩状态, 但20世纪90年代以来, 这种状态发生了根本变化. 以东帕米尔-喀喇昆仑-西昆仑地区冰川相对稳定甚至部分冰川前进为特征的"喀喇昆仑异常"是青藏高原及周边地区冰川状态失常的一种表现形式; 而青藏高原东南地区冰川加速退缩则是这一地区冰川失常的另一种表现形式. 高海拔地区的异常升温是青藏高原及周边地区冰川状态失常的重要驱动力. 另外, 这种冰川状态失常还与气候变暖背景下的西风和季风大气环流过程有关. 随着全球变暖的加剧, 冰川状态失常直接导致冰崩、冰湖溃决等灾变风险的增加. 应对青藏高原及周边地区冰川状态失常的不利影响, 需要进一步加强冰川变化监测与研究, 加大冰川灾害防范力度.

**关键词** 冰川, 状态失常, 灾变风险, 青藏高原

作为"亚洲水塔"[1]的重要组成部分, 青藏高原及周边地区冰川对亚洲地区水资源压力的缓解具有重要意义[2], 特别为中国西部地区的水资源安全、生态安全和经济社会发展提供了重要保障. 因此, 全面认识青藏高原及周边地区冰川变化及其影响, 对阐明冰川与气候及人类活动的相互作用关系, 明确冰川未来变化趋势与提出应对措施具有重要的科学与社会意义.

据Randolph Glacier Inventory(RGI 6.0), 青藏高原及周边地区的冰川面积约$9.8\times10^4$ km$^2$[3]. 其中, 冰川分布面积最广的山系是昆仑山, 其次分别为念青唐古拉山和天山[4](图1(a)). 根据冰川发育的水热条件和物理性质, 青藏高原及周边地区冰川可分为海洋型冰川、亚大陆型冰川和极大陆型冰川. 在中国境内, 这3种类型的冰川分别约占总面积的22%, 46%和32%[4]. 根据中国第二次冰川编目(2004~2010年)统计, 中国境内面积超过0.01 km$^2$的冰川共有48571条, 总面积达51766 km$^2$, 总水储量约为$4\times10^{12}$ m$^3$[29]. 相当于长江4年的径流量, 年均融水径流量约为$6.2\times10^{10}$ m$^3$[30], 超过黄河的年径流量. 在中国西北内陆干旱区, 冰川融水占出山径流的25%~29%, 而在塔里木河则占40.3%左右[31]. 冰川融水对黄河、澜沧江、怒江、长江、雅鲁藏布江和印度河等各源区年径流的贡献分别为0.8%, 1.4%, 4.8%, 11%,

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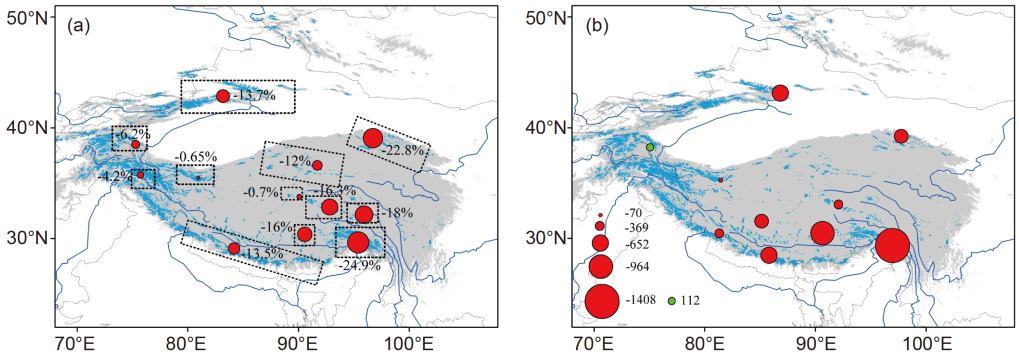



**图 1** 青藏高原及周边地区冰川的空间失常变化. (a) 青藏高原及周边地区冰川分布和1990年以来典型区域冰川面积变化空间特征(东帕米尔地区自1972年以来). 数据来源: 天山[5]、喀喇昆仑山[6,7]、西昆仑[8~11]、东昆仑[12]、祁连山[13~16]、唐古拉山[17~20]、喜马拉雅山地区[21]、念青唐古拉山[22,23]、藏东南[24,25]; (b) 2001~2018年青藏高原及周边地区不同山系代表性冰川多年平均物质平衡空间分布, 单位: mm w.e. 数据来源: 天山乌鲁木齐河源1号冰川[26]、小冬克玛底冰川1988~2015年[27,28]、小冬克玛底冰川2016~2018年以及其他冰川(第二次青藏高原综合科学考察研究队未发表的实测结果)

**Figure 1** Abnormal spatial pattern changes in the glaciers on the Tibetan Plateau and surroundings. (a) Distribution of glaciers on the Tibetan Plateau and surroundings and spatial pattern of glacier area changes in typical regions since 1990. Data sources: Tianshan[5], Karakoram[6,7], Western Kunlun mountain[8–11], Eastern Kunlun mountain[12], Qilianshan[13–16], Tanggula[17–20], Himalayan[21], Nyainqentanglha[22,23], and Southeast Tibetan Plateau[24,25]. (b) Spatial mass balance changes of observed glaciers during 2001–2018 over the Tibetan Plateau and surroundings (mm w.e.). Data sources: Urumqi No.1 glacier[26], Small Dongkemadi glacier[27,28], and other data from the unpublished results of the Second Tibetan Plateau Scientific Expedition and Research

11.6%, 48.2%[32].

近百年来, 青藏高原及周边地区冰川整体处于缓慢退缩状态. 但近几十年来随着升温加剧, 这一地区的冰川表现出快速退缩特征. 根据第二次中国冰川编目与第一次冰川编目(20世纪60~80年代)数据对比, 中国境内冰川储量减少约20%, 面积缩小约17.7%[29]. 其中, 冰川物质损失的主体是面积小于1 $km^2$的小型冰川. 升温加剧和冰川快速退缩导致青藏高原及周边地区冰川灾害频发, 甚至发生冰崩等新型灾害, 使得这一地区冰川灾变风险突显.

## 1 青藏高原及周边地区冰川整体处于失常状态

卫星遥感资料和实地观测研究均显示, 在全球变暖背景下, 目前青藏高原及周边地区冰川无论是空间变化格局还是时间变化上均表现出状态失常特征; 而且, 冰川系统内部也表现出失常的变化.

青藏高原及周边地区冰川状态失常首先主要表现在空间变化格局上. 通过系统分析青藏高原及周边地区现有的冰川面积、末端位置、物质平衡变化数据, 发现1990~2010年这一地区冰川变化呈现明显的空间差异[33]. 具体表现为: 青藏高原东南(简称藏东南)地区冰量亏损及面积萎缩幅度最大(图1), 其次为喜马拉雅山南缘; 在青藏高原腹地冰川面积和长度退缩幅度相对较小, 冰川物质亏损相对较弱; 而在帕米尔-喀喇昆仑-西昆仑地区冰川退缩程度最小(图1), 部分冰川甚至前进, 表现出微弱的物质盈余. 最新的冰川物质平衡观测结果(2005~2018年)也显示, 位于季风区的藏东南(帕隆12号、帕隆94号、帕隆390号和24K)与过渡区唐古拉山附近(小冬克玛底、羌塘1号南支和羌塘1号北支), 多条代表性冰川区域多年平均物质平衡分别为−1408和−366 mm w.e(w.e., 水当量, 余同). 而在西风区的慕士塔格地区(慕士塔格15号), 代表性冰川多年平均物质平衡为+112 mm w.e., 表现出显著的空间变化格局失常的特征(图1(b)).

2000和2016年ASTER DEM获得的两期青藏高原及周边地区冰川厚度变化的空间分布特征, 也揭示了这一地区的冰川变化呈现明显的空间差异. 较明显的冰量亏损发生在喜马拉雅山东侧的藏东南地区(物质平衡亏损高达−0.62 ± 0.23 m w.e./a)、横断山区及天山等地区, 而在西昆仑地区冰川呈现出微弱的正平衡及冰量增加的趋势[34]. 青藏高原及周边地区冰川变化的这种空间差异性改变了原有的空间变化格局.

典型地区的冰川面积变化也指示了青藏高原及周边地区冰川变化趋势存在显著区域差异. 20世纪90年代以来, 位于高原西北昆仑山脉的冰川面积减少趋势很微弱, 该山脉南坡冰川面积甚至逐渐增加(图2(a))[14~16,35], 而唐古拉山冬克玛底地区的冰川面积表现出加速萎缩趋势(图2(b))[25,36]. 可见, 这两个地区冰川面积变化在同一时间出现拐点, 但其后的趋势截然

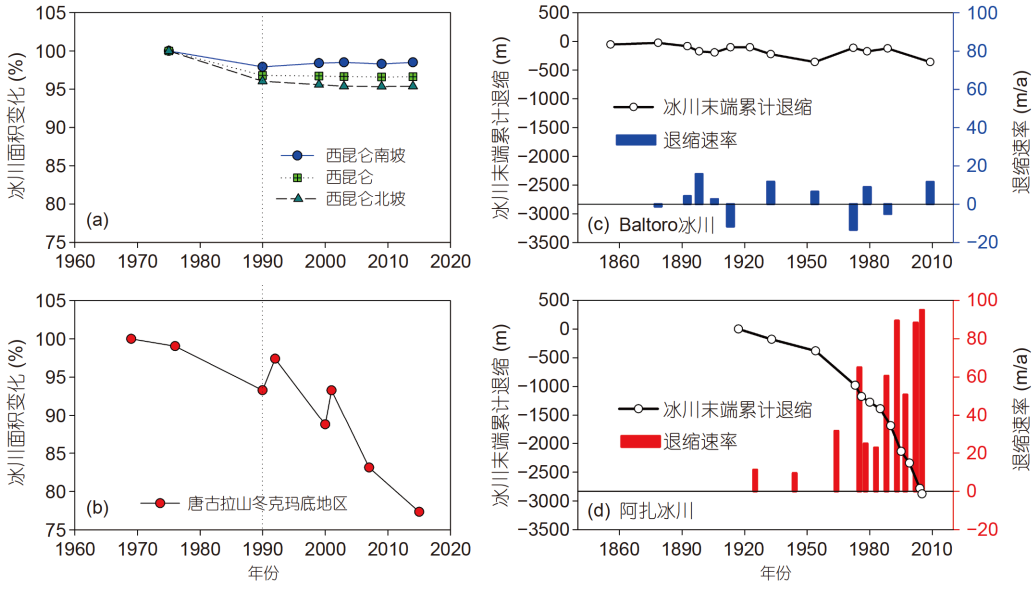



**图 2** (网络版彩色)西昆仑(a)与唐古拉冬克玛底地区(b)冰川面积变化的趋势对比; 喀喇昆仑山西北部Baltoro冰川(c)和藏东南阿扎冰川(d)末端累计退缩(折线图)与退缩速率变化(柱状图)对比

**Figure 2** (Color online) Glacier area changes in the western Kunlun mountains (a) and Dongkemadi regions (the Tanggula mountains) (b); the cumulative retreat (line) and retreat rates of Baltoro glacier (c) in the northwest of the Karakorum mountains and the Ata Glacier (d) in southeastern Tibet (histogram)

相反.

代表性冰川的长度变化同样指示了青藏高原及周边地区冰川变化趋势存在显著空间差异. 自1860年以来的大部分时段, 喀喇昆仑山西北部Baltoro冰川表现出一定的退缩, 且退缩速率较低, 但部分时段该冰川前进明显[37~39](图2(c)); 而位于藏东南的阿扎冰川自1917年以来出现持续退缩的趋势, 而且退缩速率越来越大[9](图2(d)).

在时间上, 青藏高原及周边地区冰川状态失常主要表现在冰川储量亏损速率上. 近50年来, 青藏高原及周边地区冰川处于物质负平衡态. 但这一亏损过程不断加剧, 尤其自20世纪90年代以来发生明显的变化: 之前处于亏损的冰川, 亏损幅度逐渐增大; 处于盈余的冰川, 大多数由盈余转为亏损状态, 且亏损程度越来越大. 据估算, 仅在2003~2009年间, 整个青藏高原冰川储量的损耗速率达−15.6±10.1 Gt/a[40].

典型地区的卫星遥感资料显示了这种加速退缩特征. 在念青唐古拉山西段, 冰川面积的退缩率从1979~1991年的4.43 $km^2$/a增大到1991~2011年的7.04 $km^2$/a[28,41~45]. 在唐古拉山布加岗日地区, 冰川退缩率在1988~1994年为0.84 $km^2$/a, 1999~2006年增加到1.24 $km^2$/a, 而在2006~2013年间进一步增加到1.48 $km^2$/a, 表现出加速退缩趋势[23]. 通过分析最近40年来的卫星遥感图像发现, 2000~2016年喜马拉雅山地区冰川物质亏损速率为−0.43±0.14 m w.e./a, 是1975~2000年亏损速率(−0.22±0.13 m w.e./a)的2倍[46].

典型代表性冰川的物质平衡变化也证实了1990年以来青藏高原及周边地区冰川加速亏损的趋势. 天山乌鲁木齐河源1号冰川、七一冰川、抗物热冰川和小冬克玛底冰川是我国具有长期观测的典型代表性冰川. 另外, 慕士塔格15号冰川也具有较长的观测序列. 在1990年之前, 七一冰川呈现出正平衡状态[9]; 但在1990年以后, 乌鲁木齐河源1号冰川、七一冰川、抗物热冰川和小冬克玛底等4条冰川则均表现出负平衡状态, 且近期这些冰川物质亏损趋势加剧(图3). 其中, 青藏高原监测时间最长和最连续的小冬克玛底冰川1989~2010年平均物质平衡为−0.23 m w.e./a, 2000~2010年平均物质亏损量为1989~1999年期间平均值的3倍. 另外, 慕士塔格15号冰川在2000年表现出明显的物质正平衡, 但在2010年物质正平衡偏也有所减缓(图3).

极高海拔地区的冰芯记录也指示了冰量加速亏损的特征. 念青唐古拉冰川和各拉丹东冰川两根冰芯记录结果显示, 念青唐古拉冰川和各拉丹东冰川分别自20世纪50和80年代以来没有物质净积累. 这些结果表明, 在过去30~60年间, 冰芯钻取点的冰量亏损率超过每年几百毫米水当量[49].

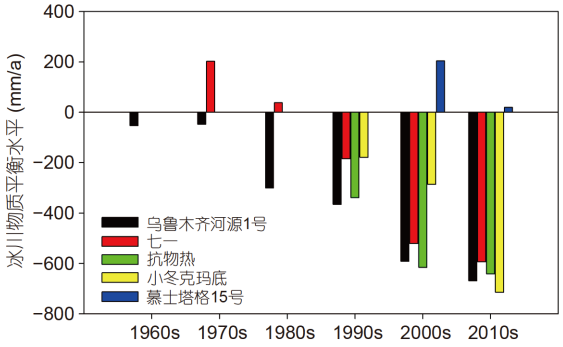



**图 3** 典型代表性冰川的物质平衡变化[9,32~34,47,48]. 抗物热、小冬克玛底、慕士塔格15号等冰川2010年以来部分年代的数据, 来源于第二次青藏高原综合科学考察研究队未发表的实测结果

**Figure 3** Changes in the mass balance of typical glacier[9,32~34,47,48]. The data on the glaciers in the 2010s, such as Kangwure, Small Dongkemadi and Muztagata No. 15, are derived from the unpublished results of the Second Tibetan Plateau Scientific Expedition and Research

模型模拟也进一步表明青藏高原及周边地区冰川亏损加速. 在喜马拉雅山西段的纳木那尼冰川, 根据近期的实地冰川观测和物质平衡模拟, 重建了1973~2014年的冰川平衡线高度和物质平衡变化. 结果表明, 即使在海拔6000 m处, 近期的冰川物质亏损也达到了年均0.73 m w.e., 平衡线高度从1974~1989年约5969 m急剧上升到1990~2014年约6193 m[50].

除了在空间格局和时间变化上出现失常外, 青藏高原及周边地区冰川状态失常还表现在冰川系统内部变化. 冰川系统内部变化失常最显著标志是冰川系统内部结构变化. 青藏高原及周边地区相对稳定的极大陆型冰川比例越来越少, 而亚大陆型冰川比例不断增大. 冰川强烈消融, 使得冰川表面经历不同的破碎化过程: 开始形成冰面湖, 随之发育冰面河道, 然后在冰川表面广泛发育冰裂隙, 导致冰川表面破碎(图4). 冰面融水渗透加强, 造成冰川内部加速液化, 从而改变了冰川表面形态和冰内相态结构, 加剧了冰川不稳定性[51,52].

冰川系统内部变化失常的另一明显特征是运动速度持续减小. 根据100万对光学卫星图像, 对青藏高原及周边地区2000~2017年期间所有冰川的冰流变化进行分析[53], 发现在11个研究区域中只有2个区域(喀喇昆仑山和昆仑山)的冰川运动速度有所增加, 尤其以喀喇昆仑区域的冰川增速显著, 高达+0.8 ± 0.3 m/(10 a); 而其他9个区域的冰川均表现出异常的持续减速, 并伴有冰体减薄, 其中以念青唐古拉山东段附近藏东南的冰川运动速度降速最为显著, 达到−6.4 ± 0.2 m/(10 a).

## 2 青藏高原及周边地区冰川状态失常的原因

冰川是气候的产物, 对气候变化非常敏感. 由于受冰川发育条件及其物理性质的影响, 青藏高原及周边地区不同类型冰川对气候变化(气温和降水)的响应过程和强度呈现明显的空间差异. 近年来, 随着地面观测资料的积累和模型模拟能力的提升, 对青藏高原及周边地区不同区域代表性冰川能量-物质平衡过程及其气候敏感性进行了定量分析. 综合青藏高原及周边地区14条不同类型冰川的研究结果发现, 藏东南、喜马拉雅山、念青唐古拉山、祁连山及西天山等诸多地区的冰川对于气温变化均非常敏感, 仅高原内陆地区和西昆仑山及东帕米尔地区为数不多的冰川对于气温的

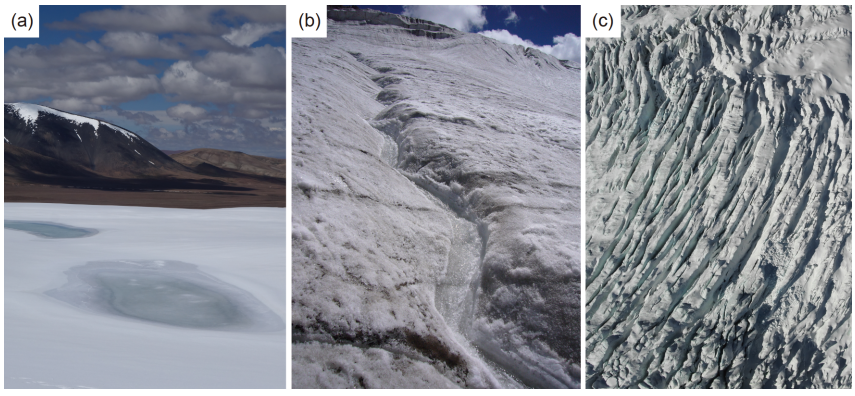



**图 4** 普若岗日冰原上形成的冰面湖(a, 赵华标摄于2017年7月)、念青唐古拉山中习冰川消融区表面发育的冰面河道(b, 余武生摄于2009年9月)和藏东南帕隆4号冰川表面破碎(c, 杨威摄于2017年12月)

**Figure 4** The ice-faced lake formed on the Puruogang icefield (a, photographed by Huabiao Zhao in July 2017), the ice-faced river developed on the surface of the ablation zone of the Zhongxi glacier in the Nyainqentanglha Mountains (b, photographed by Wusheng Yu in September 2009), and the broken surface of the Parlung No. 4 glacier in southeastern Tibet (c, photographed by Wei Yang in December 2017)

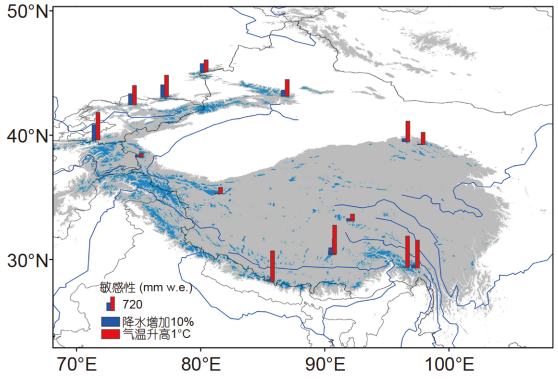



**图 5** 青藏高原及周边地区代表性冰川对气温(+1°C)和降水变化(+10%)的敏感性空间分布[55~67]

**Figure 5** Spatial distribution of sensitivity of representative glaciers to temperature (+1°C) and precipitation (+10%) on the Tibetan Plateau and surroundings[55~67]

敏感程度相对较弱[54~56](图5). 由此可见, 青藏高原及周边地区的温度变化是这一地区冰川退缩的决定性因素.

气候变暖在青藏高原及周边地区等高海拔地区表现更为突出[68,69]. 基于青藏高原91个气象台站的观测结果显示, 1970~2014年青藏高原年平均气温升温率达0.35°C/10 a, 约是全球同期平均升温率的2倍[70,71]. 特别是20世纪90年代以来, 这一地区经历了异常显著的升温. 高海拔地区的异常升温是青藏高原及周边地区冰川状态失常的重要驱动力.

季风与西风协同作用导致青藏高原及周边地区的降水[9]或水汽输送量[72]产生显著的空间差异, 进而影响这一地区的冰川变化空间格局. 冰芯净积累量记录可以反映高海拔降水量的变化, 青藏高原不同区域近500年来冰芯净积累量记录, 揭示高原南、北表现出显著的反位相变化[73]. 进入20世纪后, 高原北部冰芯净积累量表现出一定的增加趋势, 而高原南部冰芯净积累量呈较显著的降低趋势, 这与该时段印度季风减弱而西风增强有关. 青藏高原东南部树轮同位素的研究结果表明印度季风自1740年以来逐渐减弱[74], 相应的大气相对湿度呈降低趋势[75]. 1979~2018年的GPCP降水数据显示, 藏东南地区降水表现出显著的降低趋势, 而帕米尔-喀喇昆仑地区降水呈现一定的增长趋势(图6). 地面观测站点的资料也表明, 相对湿润的高原东部和南部在1984~2006年的降水呈现一定的下降趋势, 而在相对干旱的高原中部和北部降水有增加趋势[76]. 最近的水汽追踪研究进一步表明, 青藏高原以南乃至孟加拉湾地区的水汽被输送到青藏高原, 丰沛的水汽被直接输送到喀喇昆仑地区, 导致该地区形成较大降水[72]. 由于喀喇昆仑山的气温变化幅度较慢, 而降水特别是降雪增加明显, 使得喀喇昆仑山的冰川处于相对稳定状态[77]. 相反, 青藏高原南部地区降水呈现降低趋势[72]. 由于季风与西风的协同作用导致降水和水汽输

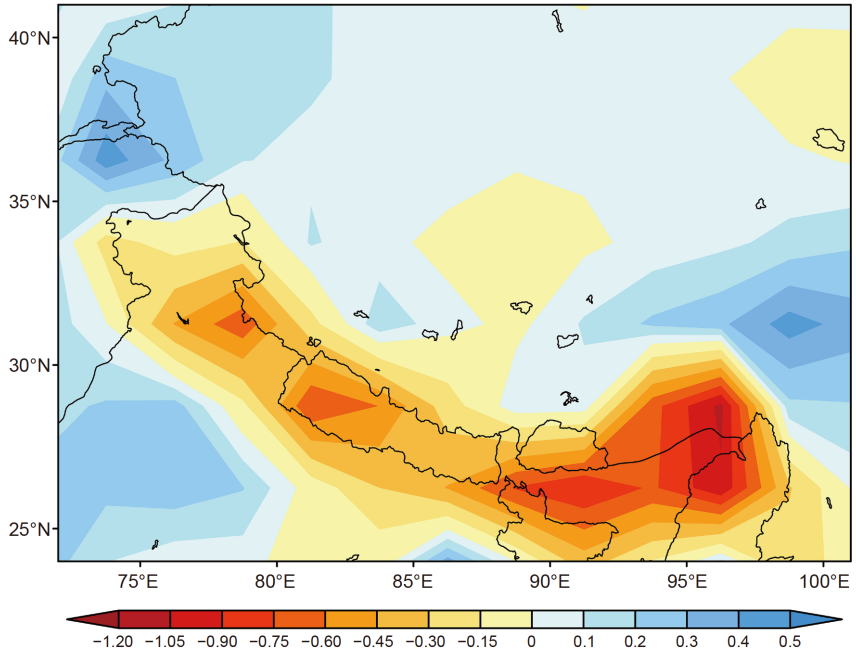



**图 6** 青藏高原及周边地区降水变化格局. 基于GPCP降水资料1990~2018年平均值与1979~1990年平均值的差值, 单位: mm/d

**Figure 6** Precipitation change pattern on the Tibetan Plateau and surroundings. The difference between the average value of GPCP from 1990 to 2018 and the average value from 1979 to 1990. Unit: mm/d

送量出现明显的空间差异, 进而使得藏东南地区冰川消融加剧, 而喀喇昆仑地区冰川出现稳定, 甚至部分冰川出现前进. 因此, 在青藏高原及周边地区冰川作用区气温普遍升高的趋势下, 水汽和降水(尤其降雪)的异常增加能够调节冰川变化的速率甚至方向, 从而导致青藏高原及周边地区冰川空间状态失常.

青藏高原及周边地区冰川变化与人类活动的增强有密切关系. 喜马拉雅山南侧的南亚地区人口众多, 存在严重的人为气溶胶污染排放. 冬春季节爆发的南亚大气棕色云能够将黑碳物质输送至青藏高原南部和东南部[78]. 在非季风期(10月~次年4月), 青藏高原61%的黑碳来自于南亚地区的人为排放[79]. 20世纪80年代中期以来, 南亚地区黑碳排放使得青藏高原南部冰川中黑碳含量持续增加[80]. 黑碳增加将降低冰川反照率, 从而促进冰川强烈消融. 喜马拉雅山脉南坡雅拉(Yala)冰川的研究表明, 表雪中黑碳对反照率降低的影响可达2%~5%[81]. 模拟结果显示, 在青藏高原中部的小冬克玛底冰川, 黑碳导致的雪冰消融量约占该冰川总消融量的9%~23%. 在藏东南地区4条冰川的观测结果显示, 对新雪而言, 虽然黑碳对冰川消融量的贡献率小于5%; 但黑碳在消融过程中会发生富集, 富集的黑碳对冰川消融量贡献率可提高至15%[82,83].

另外, 冰川系统自反馈作用也对冰川变化产生较大的影响. 气候变暖也会使冰川本身的属性发生变化, 进而加速冰川消融. 主要包括:

(1) 冰面反照率下降. 冰川消融的主要能量来源是短波辐射[84], 因此冰川表面的反照率很大程度上决定了冰川消融速率. 据观测, 消融区裸露冰面的反照率远低于积累区雪面的反照率[85]. 在气候变暖的背景下, 随着冰川消融区面积逐渐增加, 冰川整体反照率逐渐减小, 增强了辐射加热, 从而造成冰川表面消融强度进一步增加. 由此可见, 冰面反照率下降是导致冰川物质亏损加速的一个重要原因.

(2) 冰内温度上升. 冰川的冰体温度反映了冰川的冷储, 并与冰川融化过程密切相关. 冰温高的冰川对气候变化的响应较冰温低的冰川更为敏感, 如海洋型冰川对气候变暖的响应远比大陆型冰川敏感(图5), 其根本原因就在于海洋型冰川冰体温度高, 接近于融点. 乌鲁木齐河源1号冰川钻孔温度观测发现从1986~2001年, 冰温增加了0.9°C(0.06°C/a); 2001~2006年增加了0.4°C(0.08°C/a), 表现出加速升温趋势; 而2006~2012年增温有所放缓, 仅增加了0.2°C(0.04°C/a). 数值模拟研究结果表明, 活动层冰温若增加0.5°C, 表面消融会增加10%左右[52]. 由于冰体温度升高, 冰川对气候变化的敏感性增加, 同样幅度的气温升高, 会引起更多的物质亏损. 因此, 冰川的冰体温度升高在冰川加速消融过程中扮演重要角色, 它是气温升高的累积效应.

(3) 冰面破碎化. 冰川表面破碎化是由冰川强烈消融引起的, 在海洋型冰川上表现极为显著(图4(c)). 近年来随着气温的不断升高, 大陆型冰川上也出现破碎化趋势. 冰面破碎化一方面导致冰川的有效消融面积增大, 加速冰川消融; 另一方面冰面融水更容易进入冰川内部, 而冰川融水的出现可增加孔隙水压, 继而使冰内强度和有效应力降低[8], 热量更易渗入冰川更深处, 从而加剧冰川消融. 冰面破碎化不仅是海洋型冰川, 也是其他类型冰川发生加速消融的原因之一, 但这一机理尚需进一步定量研究.

(4) 冰川运动速度变化. 冰川由上至下的不断运动, 将冰体带入不同的水热条件带, 从而对冰川物质平衡产生影响. 冰川运动速度的异常变化将从以下两个方面加速冰川消融: 首先, 气候变暖导致冰川厚度减薄, 冰体运动速度异常减缓[53], 造成消融区冰川的物质补给减少, 进而导致冰川末端区域冰体减薄. 其次, 近年来部分地区冰川上部的运动异常加速, 导致冰川跃动事件显著增加. 在冰川跃动部分的上游, 积累的冰量超过消耗的水量, 在下游则是收入的冰量少于支出的冰量. 这个差别逐渐扩大, 直到应力松弛性卸荷, 表现为冰川的整体性受到破坏及冰川流速的急剧增加, 断裂面增大[8], 造成冰川上部冰体的异常快速下移. 这种冰川跃动行为直接导致消融区的冰体急剧增加, 从而导致短期内冰川加速消融.

## 3 青藏高原及周边地区冰川状态失常的灾变风险

冰川加速退缩与消融使得冰川融水在短期内增加[86], 但在长期趋势上冰川融水会减少甚至枯竭, 导致区域水资源短缺和生态环境风险增加. 同时, 冰川失常变化导致冰川不稳定性增强, 灾害风险加剧.

首先, 冰川加速退缩与消融引起的青藏高原及周边地区冰川融水径流增加, 在达到拐点变化以后将出现长期缺水的生态风险. 从近期看, 气候变暖背景下冰川的加速消融导致冰川融水增加, 一方面将会提供更多的水资源, 有利于下游的区域发展; 但另一方面也会因流量增加而导致融水季节洪水事件增多. 从长期看,

随着冰川的持续亏损, 冰川储量逐步减少, 冰川融水径流最终将减少甚至消失[87,88]. 在温室气体中等排放情景下, 中国大部分冰川补给河流在2050年前后冰川融水径流达到峰值, 之后融水径流将减少. 新疆部分河流冰川融水径流可能已经出现拐点, 未来融水径流将持续下降[89,90].

其次, 冰川状态失常正加剧灾变风险. 青藏高原及周边地区冰川过程伴随各种灾害风险. 随着气候变暖加剧和冰川的失常, 导致了前所未有的新灾害——冰崩. 顾名思义, 冰崩是指冰川突然崩解而垮塌的现象. 冰崩的发生会诱发一连串的次生灾害, 形成灾害链, 从而延长和放大了灾害后果. 典型的灾害链表现为: 冰崩导致滑坡、冰碛物碎屑流、冰湖溃决、洪水、泥石流、生态系统破坏、下游道路与桥梁及村庄的毁坏、人员伤亡和财产损失(图7(a)). 这是一个从冰冻圈开始, 影响到岩石圈、水圈、生物圈、人类圈的灾害链, 也是一种新型的巨灾过程. 2016年7月17日和9月21日, 西藏阿里地区的阿汝53和50号冰川先后发生了冰崩事件, 形成冰崩灾害链. 53号冰川的冰崩扇直接冲入阿汝错, 造成浪高20 m的巨大“湖啸”, 将湖水向对岸前推了约240 m, 留下了清晰的冲刷痕迹. 引起湖泊水位的上涨达9 m, 破坏力极强, 造成9名当地居民死亡、数百头牲畜被埋和优质草场毁坏[51]. 2018年10月17日和29日, 青藏高原东南部地区色东普流域内连续两次发生冰崩堵塞雅鲁藏布江事件, 造成主河道在米林县派镇加拉村下游7 km处形成堰塞湖(图7(b)), 最大蓄水量分别达

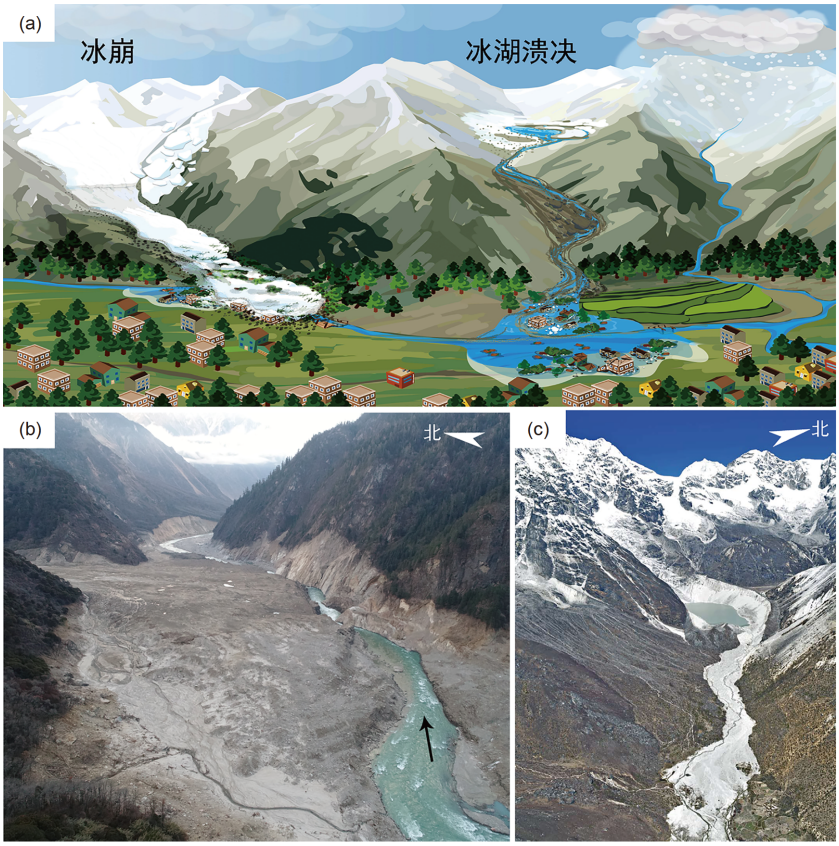



**图 7** 冰崩与冰湖溃决灾害风险示意图(a, 第二次青藏高原综合科学考察研究队绘制)及青藏高原及周边地区冰川灾害案例(b), (c). (b) 2018年10月16日藏东南米林县色东普流域色东9~15号冰川(29°44′51.53″N, 94°56′14.31″E)发生冰崩, 冰崩发生后导致雅鲁藏布江“堵江”事件发生(杨威摄于2019年1月), 图中黑色箭头表示河流流向; (c) 1985年尼泊尔Dig Tsho(27°52′25″N, 86°35′37″E)发生冰湖溃决事件后的鸟瞰图, 该事件造成超过2000多万元的损失, 并影响下游地区数月之久[91]. 照片来源: 国际山地综合发展中心(International Centre for Integrated Mountain Development), 摄于2009年4月24日

**Figure 7** Schematic diagram of ice avalanche and glacial lake outburst disaster risks (a, produced by the Second Tibetan Plateau Scientific Expedition and Research) and examples of glacier disasters on the Tibetan Plateau and surroundings (b), (c). (b) Ice avalanche occurred on October 16th, 2018, at Sedong 9–15 glaciers (29°44′51.53″N, 94°56′14.31″E) in the Sedongpu basin, Milin, southeastern Tibetan Plateau (photographed by Wei Yang). This ice avalanche resulted in blockage of the Yarlung Zangbo River. (c) Bird's-eye view of the glacier outburst disaster in 1985, Dig Tsho, Nepal. This disaster resulted in more than 20 million property losses and impacted the downstream area for several months[91]. Photographed by ICIMOD, April 24, 2009

$6.05\times10^8$和$3.26\times10^8$ $m^3$(第二次青藏高原综合科学考察研究队未发表的科考报告). 藏东南两次冰崩导致的冰碛物碎屑流、堵江、堰塞湖及其溃决洪水等连锁过程, 严重影响下游地区水利设施、道路桥梁和人民生命财产安全.

再者, 随着气候变暖, 特别是冰川中动力系统的不稳定性加剧, 导致冰川发生急剧加速移动的灾害——冰川跃动. 据2015年5月15日中国新闻网报道(http://www.chinanews.com/sh/2015/05-15/7279700.shtml), 2015年4月17日前几日, 公格尔九别峰东侧的克拉牙依拉克冰川西支突然发生跃动, 冰川快速前进12 km, 造成阿克陶县70户牧民房屋受损, 上百头牲畜失踪, 1000公顷草场被掩埋[92,93].

最后, 气候变暖和冰川状态失常还伴随着另一种灾害风险——冰湖溃决. 冰湖溃决是高山冰川作用区常见的自然灾害之一, 而且往往引发山区洪水和泥石流[8,94]. 全球气候变暖导致的冰川加速消融使得冰湖数量增加, 面积增大. 冰湖溃决洪水灾害主要发生在喜马拉雅山、喀喇昆仑山、天山和念青唐古拉山东段[8]. 喜马拉雅地区面积大于0.0081 $km^2$的冰湖数量, 从1990年的4549个增加到2015年的4950个, 冰湖面积增大了约14%[95,96]. 在中国境内的青藏高原, 有210个冰湖威胁到人类定居点, 其中具有极高危险性的冰湖有30个, 集中分布在喜马拉雅山中段的吉隆县、聂拉木县和定日县[97]. 2013年7月5日, 西藏嘉黎县然则日阿错冰湖溃决, 造成了人员失踪和房屋、桥梁、道路被毁[98].

## 4 总结与展望

冰川加速退缩与消融是全球性环境问题, 而青藏高原及周边地区冰川的失常变化与当地及下游居民生活息息相关, 成为国内外关注的热点和焦点. 最近研究结果表明, 青藏高原及周边冰川变化的前景很不乐观, 预计冰川面积减少至当前一半所需的时间将提前约10年[99]. 而且预测认为, 未来全球温度升高1.5 ℃情景下, 青藏高原地区将升温约2.1 ℃. 这种异常升温趋势将加速青藏高原及周边地区冰川的消融, 预计在RCP4.5, RCP6.0和RCP8.5情景下, 青藏高原及周边地区冰川将分别减少49%, 51%和64%[100]. 这些预测结果引发了人们对青藏高原及周边地区冰川命运和人类面临更大灾害风险的担忧. 但是这些预测由于缺乏大量的冰川实地观测证据支撑, 还存在很大的不确定性.

青藏高原及周边地区冰川观测已涉及冰川的各种类型, 监测手段包括实地观测和遥感监测. 但是, 受观测手段和地理条件的限制, 目前该地区的冰川观测仍以传统方式为主, 而且覆盖范围非常有限, 特别是对新出现的冰川灾害监测才刚起步. 在全球气候快速变暖背景下, 该地区的冰川观测体系需要进一步增强和升级. 在更全面的观测体系下, 开展更广泛的观测研究, 揭示青藏高原及周边地区冰川动态变化过程, 明确冰川-气候-水文之间的定量联系, 深化冰川对气候变化响应机理的科学认识, 提高该地区冰川未来变化情景预测的准确度. 另外, 需要加强冰川灾害监测, 揭示冰川失常变化的致灾机理, 从而为该地区防灾减灾规划及灾害风险管理提供科学依据[101].

为了应对冰川加速退缩与消融, 世界各国, 尤其是青藏高原周边国家应树立“命运共同体”理念, 落实《京都议定书》和《巴黎协定》气候治理责任, 加强合作, 积极探索绿色低碳可持续发展道路, 充分掌握该地区冰川变化的水资源效应, 加大冰川灾害防范力度, 推进青藏高原及周边地区环境保护和生态屏障建设.

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## 补充材料

**图S1** 青藏高原及周边地区代表性冰川分布图

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Summary for “青藏高原及周边地区近期冰川状态失常与灾变风险”

# Glacier anomalies and relevant disaster risks on the Tibetan Plateau and surroundings

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The Tibetan Plateau and its surroundings contain the largest number of glaciers outside the polar regions. In the past 100 years, the glaciers on the Tibetan Plateau and its surrounding areas have been retreating slowly. Since the 1990s, however, the state of glaciers has undergone abnormal changes. Compared with the data derived from the First Chinese Glacier Inventory (CGI) (1960s−1980s), the glacier volume in China decreased by approximately 20% and the glacier area was reduced by approximately 17.7%, based on the data derived from the Second CGI. In particular, the glacier mass loss of the small glaciers was characterized by an area less than 1 $km^2$ and was more intensive than that of lager glaciers. Abnormal changes in the glaciers on the Tibetan Plateau and the surrounding areas are mainly reflected by the spatial pattern. Through the systematic analysis of the data on glacier area, terminal position, and mass balance changes, it was found that the glacier changes in the region experienced obvious spatial heterogeneity from 1990 to 2010.

The “Karakoram glacier anomaly” in the eastern Pamir, Karakoram, and western Kunlun regions has exhibited slight mass stability or even glacier advance. However, the glaciers on the southeastern Tibetan Plateau experienced the most intensive and accelerated shrinkage. On the evaluated timescale, the state of glaciers on the Tibetan Plateau and its surroundings has undergone abnormal changes regarding the loss rate of glacier volume. In the past 50 years, most of the glaciers have had a negative mass balance. Moreover, the mass loss process has intensified, especially since the 1990s. It is estimated that the loss rate of glacier volume from the Tibetan Plateau was as large as $-15.6 \pm 10.1$ Gt/a between 2003 and 2009. In addition to the abnormal changes in spatial patterns and temporal changes, the glaciers exhibited an abnormal change within the glacial system. The most significant variability within the glacier system was the abnormal change in the structure of glacier ice. Another abnormal change within the glacier system was that the glaciers showed a sustained slowdown concomitant with ice thinning. Abnormal warming at high altitudes is an important driver of abnormal changes in glaciers on the Tibetan Plateau and its surroundings. Moreover, these contrasting glacier behaviors on the Tibetan Plateau and surroundings are related to atmospheric circulation processes, especially interactions between the westerlies and the Indian Summer Monsoon. In addition, changes in glaciers on the Tibetan Plateau and its surroundings are closely related to the enhancement of human activities. The South Asian region on the southern slope of the Himalayas acts as a main source of severe anthropogenic aerosol emissions, especially that of black carbon. The black carbon transported from South Asia to the glaciers reduces the glacier's albedo and thus accelerates glacier melting. As global warming intensifies, the abnormal glacier status will likely lead to more hazards, such as ice collapse and glacial lake outburst floods. To reduce the potential glacial risks on the Tibetan Plateau and surroundings, it is necessary to further strengthen the abilities of glacier monitoring and disaster prevention.

**glacier, anomalies, disaster risks, Tibetan Plateau**

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