

November 2019

Spatiotemporal Pattern, Trend, and Influence of Glacier Change in Tibetan Plateau and Surroundings under Global Warming

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Recommended Citation

Ninglian, WANG; Tandong, YAO; Baiqing, XU; An'an, CHEN; and Weicai, WANG (2019) "Spatiotemporal Pattern, Trend, and Influence of Glacier Change in Tibetan Plateau and Surroundings under Global Warming," *Bulletin of Chinese Academy of Sciences (Chinese Version)*: Vol. 34 : Iss. 11 , Article 3.

DOI: <https://doi.org/10.16418/j.issn.1000-3045.2019.11.005>

Available at: <https://bulletinofcas.researchcommons.org/journal/vol34/iss11/3>

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Spatiotemporal Pattern, Trend, and Influence of Glacier Change in Tibetan Plateau and Surroundings under Global Warming

Abstract

Glaciers, an important part of Asia's water tower, are extremely sensitive to climate change. The study on the spatiotemporal pattern of the changes of the glaciers in the Tibetan Plateau and surroundings in the context of global warming is helpful to identify the main water storage and supply areas of Asian Water Towers, which is of great significance for the rational planning and utilization of water resources. Through comprehensive analysis, it was revealed that the "Karakoram anomaly" might expand in different degrees to the Western Kunlun Mountains and the Pamirs, while the glaciers in the other parts of the Tibetan Plateau and surroundings were in an accelerated melting state recently. Moreover, we also illuminated the influences of the changes of the glaciers over the past 50 years and in different climate scenarios in the future on the basin water resources and sea level rise, and pointed out that the glacier observation and investigation should be carried out systematically, and a climate-ice-hydrological processes coupling model should be set up, in order to accurately assess the glacier melt water resources, which is an important basis for the green silk road construction.

Keywords

Tibetan Plateau and surroundings; Asian Water Tower; arid region; glacier melt runoff; global warming; water resources

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全球变暖背景下青藏高原及周边地区 冰川变化的时空格局与趋势及影响

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摘要 作为“亚洲水塔”重要组成部分的冰川，对气候变化的响应极其敏感。研究全球变暖背景下青藏高原及周边地区冰川变化的时空格局特征，有助于识别“亚洲水塔”的主要储水与供水区域，这对水资源的合理规划与利用具有重要意义。文章通过综合分析，揭示出“喀喇昆仑异常”现象在昆仑山西部和帕米尔高原地区亦有不同程度的表现，分布在这些区域以外的青藏高原及周边地区山地冰川近期大多处于加速消融状态；同时，阐明了近50年来以及未来不同气候变化情景下青藏高原及周边地区冰川变化对流域水资源状况和海平面上升的影响；并指出，要系统开展青藏高原及周边地区冰川的调查与观测，建立气候-冰川-水文过程耦合模型，准确评估变化环境下的冰川水资源状况及其影响，以服务于中国社会经济发展和“绿色丝绸之路”建设。

关键词 青藏高原，亚洲水塔，干旱区，冰川融水径流，全球变暖，水资源

DOI 10.16418/j.issn.1000-3045.2019.11.005

虽然冰川位于偏远地区，但其变化会对区域水资源甚至全球环境带来重要的影响。地球上68.7%的淡水资源集中在冰川上，尽管南极冰盖和格陵兰冰盖的冰储量占地球总冰储量（2 776 万平方公里^[1,2]）的99.4%，其余0.6%的冰储量^①集中在山地冰川上，但是

山地冰川对气候变化的响应极为迅速^[4]，其变化带来的影响已受到科学界以及各国政府、社会各界的广泛关注。例如，最新研究表明近几十年来山地冰川物质损失对同期海平面上升的贡献达到25%—30%^[5]；欧亚发展银行密切关注气候变暖、冰雪消融对中亚水资源

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资助项目：第二次青藏高原综合科学考察研究（2019QZKK0201），中国科学院战略性先导科技专项（A类）（XDA20060201），国家重点研发计划（2017YFC0404302）

修改稿收到日期：2019年10月10日

① 16万平方公里（冰量），相当于每年全球河川入海径流量3.8万平方公里（水量）^[3]的3.8倍。

的影响^[6]等。“水塔”一词已被广泛用来强调山地对下游邻近地区提供淡水资源的重要性，在全球范围内广泛分布的山地尤其是干旱半干旱地区的山地是“水塔”的主要分布区域^[7,8]，青藏高原及周边地区也即第三极地区^②被称为“亚洲水塔”^[9]。高耸的地势使得这里成为地球上中低纬度冰川最发育的地区。因此，充分认识这一地区冰川变化及其影响，有助于理解“亚洲水塔”对区域水资源和区域经济社会发展的重要性。本文以目前所获得的观测资料和相关的研究资料为基础，试图揭示这一地区冰川近期变化的总体特征与趋势，并阐明其变化对水资源和海平面变化的影响。

1 青藏高原及周边地区不同流域冰川的分布状况

冰川编目资料是研究冰川空间分布的关键。全球冰川编目研究工作早在国际地球物理年（1957—1958年）时就已经提出，但前期进展非常缓慢。随着遥感技术的发展与应用，1995年美国科学家发起了GLIMS（Global Land Ice Measurements from Space）计划，冰川编目工作得到了前所未有的发展^[10]。我国自20世纪70年代末期以来，先后2次系统性地完成了我国冰川的编目工作^[11,12]。根据美国国家雪冰数据中心最新版本的全球冰川编目资料（Randolph v.6.0）^[2]，在21世纪第1个10年时期青藏高原及周边地区冰川共有97 760条，面积为98 739.7平方公里，冰储量约为7 481立方公里^[5]，分别约占全球山地冰川（冰帽）总数量（215 547条，包括格陵兰边缘区域和南极及其周边区域）的45.4%、总面积（705 738.8平方公里）的14.0%和总冰储量（161 543立方公里）的4.6%。如果在全球山地冰川（冰帽）中不将格陵兰边缘区域和南极及其周边区域的冰川（冰帽）计算在

内，那么青藏高原及周边地区冰川的面积和储量将分别占全球山地冰川的20.4%和7.6%。

冰川在不同流域的分布情况，是冰川水资源状况评价的重要基础。依据全球冰川编目资料^[2]和青藏高原及周边地区的流域界线，我们统计了青藏高原及周边地区不同流域的冰川分布情况（表1）。结果表明，印度河流域分布的冰川数量最多、面积最大，达22 431条，总计27 267.2平方公里，占青藏高原及周边地区冰川总数量的22.95%、总面积的27.61%；其次是塔里木河流域，该流域分布的冰川面积占青

表1 青藏高原及周边地区不同流域冰川分布情况统计

流域名称	冰川数量 (条)	冰川面积 (km ²)	面积占比 (%)
鄂毕河流域*	2 224	1 133.8	1.15
锡尔河流域**	5 082	2 827.8	2.86
阿姆河流域**	13 059	11 005.6	11.15
伊犁河流域**	3 166	2 353.7	2.38
准噶尔内流区**	3 118	1 767.3	1.79
塔里木河流域**	15 798	20 350.8	20.61
吐哈盆地内流区**	367	164.9	0.17
河西内流区**	2 056	1 076.1	1.09
青藏高原内流区**	6 319	7 309.2	7.40
柴达木内流区**	2 074	1 707.4	1.73
印度河流域*	22 431	27 267.2	27.61
恒河流域*	6 698	7 952.0	8.05
雅鲁藏布江流域*	11 561	10 563.3	10.70
怒江*	2 149	1 270.7	1.29
澜沧江流域*	436	200.2	0.20
长江流域*	1 063	1 663.8	1.69
黄河流域*	159	125.9	0.13
合计	97 760	98 739.7	100

注：*外流域，**内流域

② 即以青藏高原为核心的亚洲高山集中分布区，包括青藏高原及其周边山地以及帕米尔高原、天山山脉和阿尔泰山。

高原及周边地区冰川总面积的 20.61%；再次是阿姆河流域，其分布的冰川面积占青藏高原及周边地区冰川总面积的 11.15%；黄河流域分布的冰川面积最小，仅 125.9 平方公里，占青藏高原及周边地区冰川总面积的 0.13%。另外，统计结果还表明，青藏高原及周边地区外流水系分布的冰川面积（50 176.9 平方公里）较内流水系分布的冰川面积（48 562.8 平方公里）大，这很可能意味着外流水系是水汽进入青藏高原及周边地区的主要通道。换句话说，青藏高原及周边地区冰川的分布除受地形影响外，还受到水汽来源方向的影响。

2 近 50 年来冰川变化的时空格局及其原因

广义的冰川变化研究，包括冰川物理属性^③、冰川化学成分^④以及冰川侵蚀、沉积地貌过程的变化等多个方面。现代冰川变化研究，大多考虑冰川变化与气候、水文过程之间的关联，因此更多地关注冰川平衡线高度、面积、物质平衡、长度、积累区范围以及冰川温度等方面的研究。考虑到目前青藏高原及周边地区冰川观测与研究资料的限制，这里仅对冰川平衡线高度、面积、物质平衡这 3 个要素过去几十年的变化进行分析和讨论，并在宏观尺度上对青藏高原及周边地区冰川面积和物质平衡变化的空间格局特征进行系统综合分析。

2.1 冰川平衡线高度变化

冰川平衡线高度是冰川上年物质积累与年物质损耗相等位置处的海拔高度。冰川前进、退缩或消亡的命运直接由冰川平衡线高度变化决定。相对于冰川稳定态或物质平衡为零时的平衡线高度而言，如果平衡线高度升高，那么冰川就会因消融增强而退缩，而且当冰川平衡线高度升高并超过冰川顶部时，冰川将会

最终消亡；反之，如果平衡线高度下降，冰川就会因物质积累增多而前进。与冰川的其他特征参数（如长度、面积等）变化相比，平衡线高度变化是气候变化最直接的反映。冰川平衡线高度只能通过实地观测和计算才能获得。

在全球范围内，具有 50 年以上长期连续观测记录的冰川其数量不足 40 条。在整个青藏高原及周边地区，只有天山乌鲁木齐河源 1 号冰川和图尤克苏冰川、祁连山七一冰川和阿尔泰山小阿特鲁冰川等少数几条监测冰川具有长期的观测记录。这些监测冰川的观测结果表明，近几十年来它们的平衡线高度均呈上升趋势。例如，乌鲁木齐河源 1 号冰川和图尤克苏冰川的平衡线高度在 1960—2013 年时期分别升高了约 116 米和 80 米^[13]，小阿特鲁冰川平衡线高度在 1983—2007 年时期升高了约 142 米^[13]，七一冰川平衡线高度在过去 50 年间的上升量超过了 250 米^[14]，并且 2016 年其平衡线高度接近该冰川的顶部。由于青藏高原及周边地区监测冰川的数量极其有限，目前无法获得该区域平衡线高度变化的空间特征。今后应该在青藏高原及周边地区不同山区开展冰川监测工作，同时利用遥感资料开展冰川雪线高度的重建工作，以充分揭示青藏高原及周边地区平衡线高度/雪线高度的时空变化特征，为高海拔气候变化重建和冰川变化原因分析提供科学基础。

2.2 冰川面积变化

冰川面积是衡量一个地区冰川发育状况的重要指标，也是计算冰川物质平衡或冰川消融量的关键参数。早期，主要依据测量和地形图来获得一个区域的冰川覆盖范围。随着航空遥感资料和卫星遥感资料在冰川学研究中的应用，使得快速获取空间大范围内冰川面积资料成为可能。

③ 包括：温度、成冰过程、形态（长度、面积、体积等）、积累、消融、物质平衡、雪线/平衡线高度、光学特征、电磁学特征、力学性质、结构、构造、组成等。

④ 包括：水同位素组成、可溶性化学物质组成、不可溶物质组成、pH 值等。

目前,许多研究者利用不同时期的遥感资料以及冰川编目资料等,对近几十年来青藏高原及周边地区不同山区的冰川面积变化进行了研究。例如,基于我国两次冰川编目资料,揭示出20世纪70年代至21世纪第1个10年时期,我国冰川面积减少了约18%^[12,15]。考虑到不同研究者的研究时段存在一定的差异,为了便于对青藏高原及周边地区不同区域冰川面积变化进行对比分析,我们对收集到的不同地区的冰川面积变化资料^[12,16-39],进行年变化速率计算,以揭示青藏高原及周边地区冰川面积变化的空间格局。从图1可以看出,过去40年间青藏高原及周边地区冰川经历了普遍的萎缩态势,但不同区域冰川萎缩的速率存在显著差异。北部的阿尔泰山、中天山和东天山以及青藏高原东部和南部的冰川萎缩速率明显较大,而羌塘高原、西昆仑山、喀喇昆仑山、帕米尔高原和西天山的冰川萎缩速率明显较小,尤其是喀喇昆仑山地区的冰川面积几乎处于不变的状态,此即为“喀喇昆仑异常”现象(即20世纪末在全球冰川普遍处于

退缩状态时,喀喇昆仑冰川出现前进的现象)^[40]。另外,图1还表明“喀喇昆仑异常”现象很可能在昆仑山西部和帕米尔高原地区亦有程度不同的表现。因此,进一步的研究应从西风与季风的相互作用,解释产生这种空间差异特征的原因^[41]。

2.3 冰川物质平衡变化

一条冰川的物质平衡是指该冰川在某一时段内(通常为1年)以固态降水为主的物质积累量和以消融为主的物质支出量之间的差值,即某一时段内冰川物质的收支状况。在某一研究时段内,如果冰川物质平衡是正值,则表明该冰川物质处于积累状态,冰川会增厚或前进;如果冰川物质平衡是负值,则表明该冰川物质处于亏损状态,冰川会减薄或退缩。冰川物质平衡的研究方法有冰川学方法(野外观测法和模型计算法)、水文学方法、大地测量学方法和重力测量法等。目前,山地冰川物质平衡研究常用的方法是野外观测方法和大地测量学方法。

图2是青藏高原及周边地区不同地区基于大地测

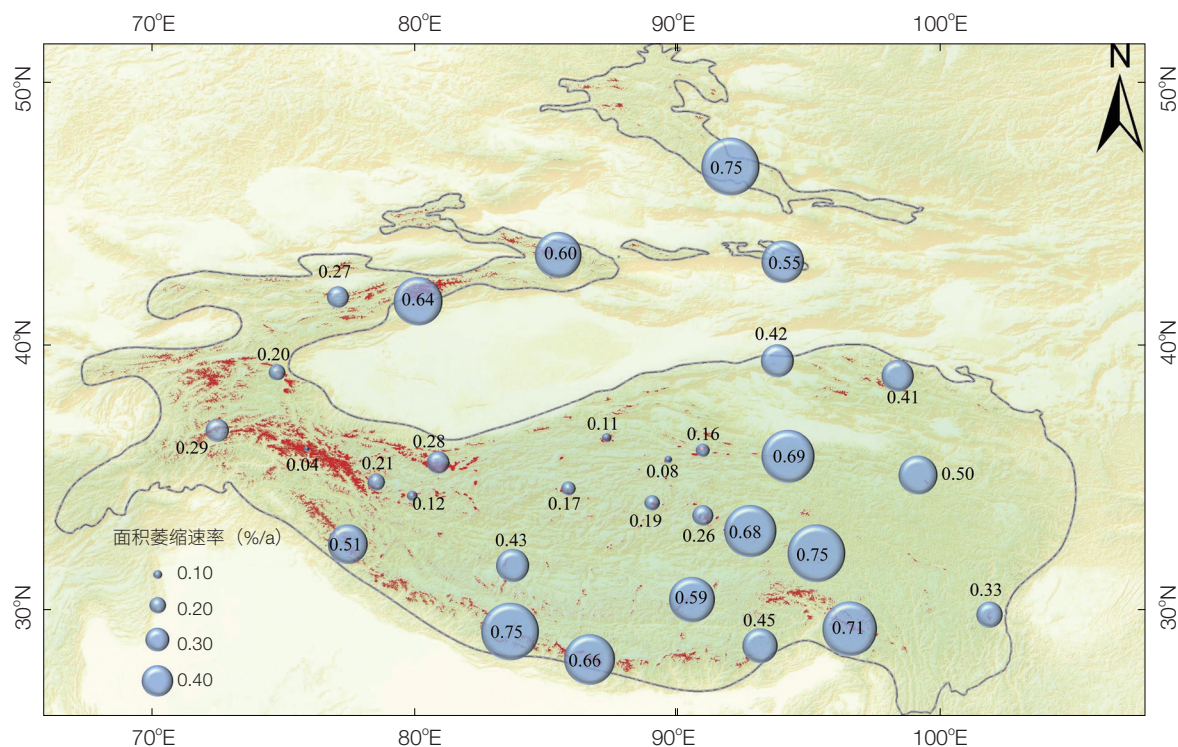


图1 近40年来青藏高原及周边地区不同区域冰川面积萎缩速率
综合文献资料[12,16-39]绘制

量学方法获取的冰川物质平衡和监测冰川物质平衡的综合对比图。为了研究近 50 年青藏高原及周边地区冰川物质平衡的变化趋势,我们将收集到的冰川物质平衡资料^[20,25,38,42-63],大致以 2000 年左右为界分成前、后两个时段,以分析其近期变化与前期变化之间的差异。结果表明,阿尔泰山、天山东部、青藏高原东部和南部地区的冰川其物质不仅亏损量大,而且基本都处于加速亏损状态,其中藏东南地区尤为显著,其近期的冰川物质亏损速率大于每年 0.6 米水当量;天山西部冰川的物质亏损量也较大,但近期亏损速率呈减小趋势;喀喇昆仑山、西昆仑山和帕米尔高原地区的冰川,其物质平衡水平普遍偏低,近期冰川物质大多处于积累状态(这进一步说明“喀喇昆仑异常”现象不局限于喀喇昆仑地区),即使物质处于亏损状态的冰川,其近期亏损速率亦呈减少趋势。对比图 1 和 2,可以发现青藏高原及周边地区冰川物质平衡变化的空间格局与冰川面积变化的空间格局具有很好的一致性,即冰川物质亏损速率增大的地区,其冰川面积的

萎缩速率就大,冰川物质亏损速率减小(或物质平衡处于正值)的地区,其冰川面积的萎缩速率就小。这也说明了不同方法、不同资料所获得的青藏高原及周边地区冰川变化空间格局的可比性与一致性。

2.4 冰川变化的原因

冰川变化不仅受到气温变化的影响,而且受到降水量变化的影响。近几十年来,青藏高原及周边地区绝大部分地区都经历了显著的变暖。1955—1996 年,青藏高原气温上升速率为 $0.16^{\circ}\text{C}/10\text{ a}$,大大高于同期北半球气温的上升速率($0.054^{\circ}\text{C}/10\text{ a}$);而且 1998—2013 年,青藏高原气温的上升速率达到 $0.25^{\circ}\text{C}/10\text{ a}$ ^[64]。这是造成青藏高原大部分地区冰川物质亏损速率加速的直接原因。天山地区 1960—2014 年的增温率达 $0.30^{\circ}\text{C}/10\text{ a}$,其中东、中天山区的增温率高达 $0.45^{\circ}\text{C}/10\text{ a}$ ^[65]。这是天山中、东部地区冰川面积萎缩率较天山西部地区大的关键原因。另外,气象观测资料表明,近几十年来青藏高原南部和东部地区降水量呈弱的减少趋势^[66,67],这也进一步加强了

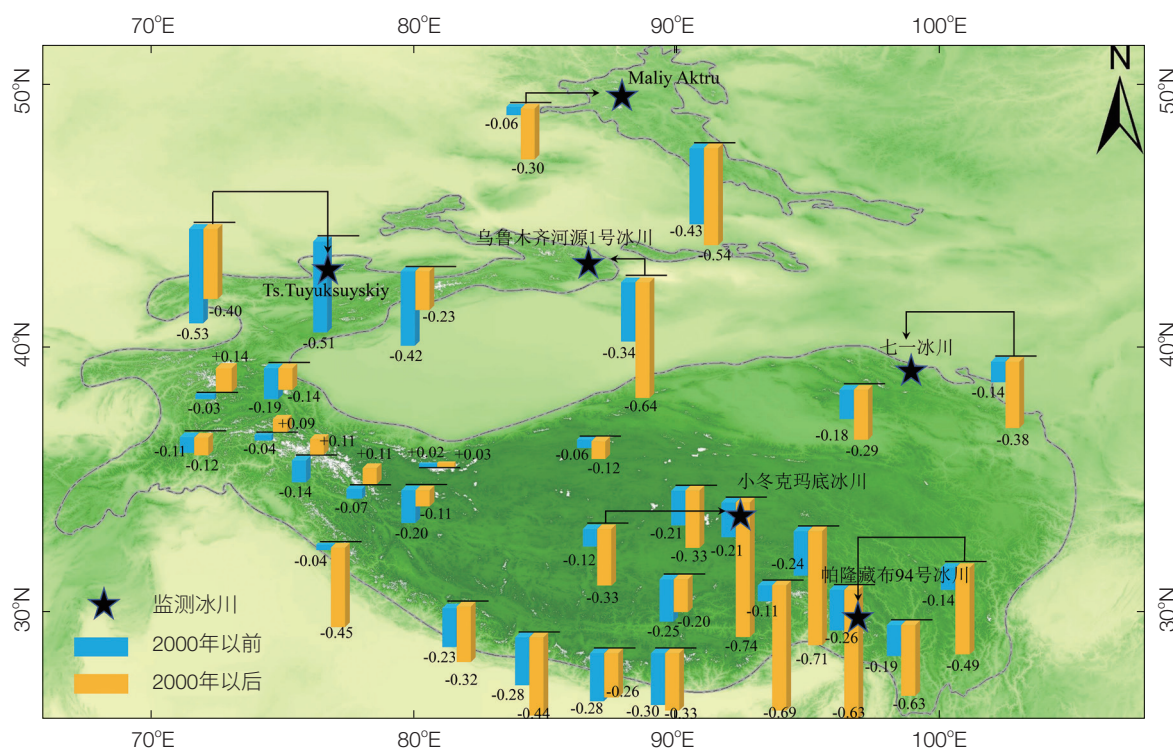


图 2 20 世纪 70 年代以来不同时段青藏高原及周边地区冰川物质平衡变化
综合文献资料 [20,25,38,42-63] 绘制,单位:米水当量/每年

这些地区冰川的退缩趋势。相关研究表明,青藏高原西北部地区(尤其是喀喇昆仑地区)近几十年来不仅气温有所降低^[66],而且降水量呈增加趋势^[68-70],这是导致“喀喇昆仑异常”现象发生的主要影响因素。

3 冰川变化对水资源及海平面变化的影响

冰川被誉为“固体水库”,是青藏高原及周边地区水塔的重要组成部分。在我国西北干旱地区和中亚干旱区,高山冰川融水对河川径流起到“削峰填谷”的作用,即:在干旱年份,冰川消融量增大,对河川径流的补给增强,从而缓解下游地区的干旱;在湿润年份,冰川消融减弱,对河川径流的补给减少,从而使河川径流量的变化趋于平缓。例如,印度河流域正常年份7月的冰川融水对同期径流的贡献约为53%,但在干旱年份可达63%^[71]。然而,冰川的这种作用随着流域内冰川规模的变化而发生变化。因此,揭示冰川变化对水资源的影响,对于干旱地区水资源的合理规划与利用具有重要的意义。另外,鉴于全球山地冰川变化对海平面上升的重要影响,以及青藏高原及周边地区冰川作为全球山地冰川的重要组成部分,因此,认识青藏高原及周边地区冰川变化对海平面的影响,将有助于理解青藏高原及周边地区冰川在全球变化研究中的作用。

3.1 青藏高原及周边地区冰川的未来变化

关于流域尺度或区域尺度冰川变化的预测,目前大多利用冰川学的相关模型来进行计算。最近的一项研究表明,在未来全球升温 1.5°C 的情况下(相当于典型浓度排放路径RCP2.6情景下的升温),青藏高原及周边地区将升温 $2.1^{\circ}\text{C}\pm 0.1^{\circ}\text{C}$,这将导致到21世纪末青藏高原及周边地区冰川的冰储量减少到目前的 $64\%\pm 7\%$,面积减少到目前的 $64\%\pm 8\%$ ^[72]。在极端排放情景下(RCP8.5),到21世纪末青藏高原及周边地区冰川的冰储量和面积将分别减少到目前的 $36\%\pm 5\%$ 和 $32\%\pm 5\%$ ^[72]。未来全球升温 2°C 情况

下全球山地冰川冰量变化的预估结果表明,到21世纪末全球山地冰川冰储量将减少 $64\%\pm 5\%$,青藏高原及周边地区冰川冰储量减少比例在中亚地区达到 $80\%\pm 7\%$,在青藏高原西部地区高达 $98\%\pm 1\%$ ^[73]。基于不同气候条件下冰川变化的经验关系,对我国冰川未来变化的预估结果表明,在未来2030年、2070年和2100年气温分别上升 0.4°C — 1.2°C 、 1.2°C — 2.7°C 和 2.1°C — 4.0°C 情况下,届时我国冰川面积将分别减少12%、28%和45%^[74]。由此可见,不同预估结果之间还存在一定的差异,今后应在预估方法、模型等方面进行进一步的完善,以降低预估的不确定性。

3.2 冰川变化对水资源的影响

在流域尺度上,冰川对于水资源的重要性评价主要包括3个方面,即:固体冰储量、冰川融水量或冰川融水对出山径流的贡献,以及气候变暖情况下冰川融水径流峰值的出现时间(融水径流峰值出现之前,冰川融水径流处于增加趋势,之后冰川融水径流将处于减少趋势)。前文已经介绍了青藏高原及周边地区冰川的冰储量,而且我国2次冰川编目也已经给出了我国不同时期的冰川的冰储量状况(即20世纪70年代时约为5600立方公里^[11],2010年前后为4494立方公里^[12])。因此,此处仅就气候变暖情况下青藏高原及周边地区冰川变化对融水径流的影响予以说明。

最近对我国冰川融水径流的估算结果表明,我国冰川每年的融水径流总量为629.56亿立方米^[75],较以前的估算值(604.65亿立方米^[76],主要依据1990年之前资料计算)略高,这反映了过去气候变暖背景下冰川融水径流的增加趋势。基于月尺度的度日模型对1961—2006年时期塔里木河流域各水系冰川物质平衡和融水径流序列进行了重建,结果表明:塔里木河流域多年平均冰川融水径流量为144.16亿立方米,冰川融水对河流径流的贡献在1990年之后明显增大;1991—2006年冰川融水对河流径流的补给

比例由 1961—1990 年的 41.5% 增加到 46.5%；塔里木河流域出山径流年际变化与冰川融水径流年际变化过程基本一致，并均呈上升趋势；河流径流量增加量中约 3/4 以上源于冰川消融增强的贡献^[77]。1961—2006 年河西内陆河流域各河流冰川融水径流都呈增加趋势，冰川融水补给率从 1961—1990 年的 15.1% 增加到 1990 年之后的 19.4%^[78]。对石羊河冰川融水径流过去变化的重建和未来不同气候情景下的预测结果表明，1961—2008 年冰川融水径流以每年 7 900 立方米的速度增长，之后冰川产流量呈下降趋势。因此，该流域融水径流在 21 世纪初已经到达峰值，即拐点已经产生，是目前我国冰川融水径流被发现已经达到峰值的唯一流域^[79]。表 2 列出了在未来气候变暖情景下青藏高原及周边地区主要河流冰川融水径流峰值的出现时间。从该表可以看出，青藏高原及周边地区大部分河流冰川融水径流峰值的出现时间将多在 20 世纪 30—40 年代。这意味着应尽早开展冰川融水径流变化对下

游地区的影响与适应性对策研究。

3.3 冰川变化对海平面的影响

若地球气候变冷，大洋中蒸发的水汽会通过水循环过程抵达高纬度和高海拔地区，并以固态降水的形式保存在冰川上，补给冰川并使冰川扩张，导致陆地冰量增加，大洋水减少，海平面下降；反之，若地球气候变暖，陆地上冰川消退融化，大量融水流入大洋，使海平面上升。目前，全球变暖导致的冰川消融退缩，是影响海平面上升不可忽视的重要因素。

如果全球山地冰川全部融化，可导致海平面上升约 0.43 ± 0.06 米^[86]，其中青藏高原及周边地区冰川的贡献约占此上升量的 5.6%。基于冰川观测资料和模型模拟计算，估计出 1902—2009 年全球山地冰川物质损失使海平面上升约 114±5 毫米，其中青藏高原及周边地区冰川物质损失导致的海平面上升量约为 19 ± 0.6 毫米^[87]；2006—2016 年，全球山地冰川每年的物质损失使海平面上升约 0.92 ± 0.39 毫米，其中青藏高原及周

表 2 青藏高原及周边地区主要河流冰川融水补给比例以及未来不同气候情景下融水径流峰值出现年代

水系	冰川融水对出山径流的贡献 (%)	融水径流峰值年代 (RCP2.6)	融水径流峰值年代 (RCP4.5)	融水径流峰值年代 (RCP8.5)	参考文献
鄂毕河	-	2004±10	2004±14	2006±27	[81]
巴尔喀什流域	21	2030±7	2051±12	2049±20	[81,85]
咸海流域	15—30	2030±5	2051±14	2044±15	[81,84]
塔里木河	40.2	2030±8	2051±13	2058±15	[81,83]
疏勒河	32.8	2010—2030	2010-2025	-	[80,83]
黑河	8.2	-	-	-	[83]
石羊河	3.7	2000—2009	-	-	[79,83]
黄河	1.9	2029±6	2051±17	2043±20	[81,83]
长江	18.8	2028±15	2028±13	2044±19	[81,83]
澜沧江	0.9	2029±17	2049±20	2043±23	[81,82]
怒江	8.3	2028±11	2049±19	2043±19	[81,82]
雅鲁藏布江	15.9	2030±18	2049±18	2049±30	[81,82]
恒河	11.5	2028±19	2044±21	2053±32	[81,82]
印度河	40.6	2029±10	2045±17	2064±19	[81,82]

边地区冰川的贡献约为 4.2%^[5]。在未来典型浓度排放路径 RCP2.6、RCP4.5 和 RCP8.5 情景下,到 21 世纪末全球山地冰川物质损失可引起海平面上升量分别为 79±24 毫米、108±28 毫米和 157±31 毫米,其中青藏高原及周边地区冰川的贡献分别约为 13.4%、13.6% 和 11.4%^[88]。海平面上升会对低地国家、海岸侵蚀、海水入侵、沿海生态环境等带来严重的影响。因此,冰川变化在全球变化研究中的远程效应应该引起足够重视。

4 结语

冰川不仅是“亚洲水塔”的重要组成部分,而且在中亚干旱区水资源供应方面具有重要的调节功能,使下游绿洲地区在干旱年份具有稳定的水源供给,从而保障了绿洲地区的生态安全和社会经济发展。然而,由于对该区域冰川缺乏系统性调查与研究,从而使关于该区域冰储量的估算结果存在较大的差异。尽管在我国冰川编目资料中给出了冰储量估算结果,但缺乏方法性探讨与不确定性评估,加之亚洲其他地区的冰川编目资料中还缺乏冰储量估算数据,因此需要发展冰储量估算方法,并利用多源高分辨率遥感数据及时获得空间大范围的冰川变化资料,为水资源评价与规划服务,并分析冰川变化对下游绿洲、湖泊及海平面等的影响。另外,由于青藏高原及周边地区监测冰川数量极其有限,同时也缺乏高海拔气象观测数据,因此青藏高原及周边地区不同流域冰川融水资源的估算结果之间存在很大差异^[89]。鉴于此,亟待开展青藏高原及周边地区冰川系统的强化监测,并建立基于遥感资料的气候-冰川-水文过程耦合模型,以准确评估变化环境下的冰川水资源状况及其影响,服务于中国社会经济发展和“绿色丝绸之路”建设。

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Spatiotemporal Pattern, Trend, and Influence of Glacier Change in Tibetan Plateau and Surroundings under Global Warming

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Abstract Glaciers, an important part of Asia's water tower, are extremely sensitive to climate change. The study on the spatiotemporal pattern of the changes of the glaciers in the Tibetan Plateau and surroundings in the context of global warming is helpful to identify the main water storage and supply areas of Asian Water Towers, which is of great significance for the rational planning and utilization of water resources. Through comprehensive analysis, it was revealed that the "Karakoram anomaly" might expand in different degrees to the Western Kunlun Mountains and the Pamirs, while the glaciers in the other parts of the Tibetan Plateau and surroundings were in an accelerated melting state recently. Moreover, we also illuminated the influences of the changes of the glaciers over the past 50 years and in different climate scenarios in the future on the basin water resources and sea level rise, and pointed out that the glacier observation and investigation should be carried out systematically, and a climate-ice-hydrological processes coupling model should be set up, in order to accurately assess the glacier melt water resources, which is an important basis for the green silk road construction.

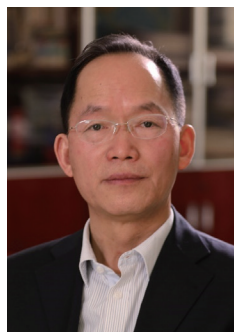
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Keywords Tibetan Plateau and surroundings, Asian Water Tower, arid region, glacier melt runoff, global warming, water resources



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■ 责任编辑：文彦杰

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