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山地冰川演化与冰湖发育相互作用机制

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摘 要: 冰川-冰湖耦合过程是冰冻圈物质与能量循环的重要组成部分,系统刻画冰川演化与冰湖发育过程的相互作用机制,对于完善冰冻圈科学理论体系和认知冰川作用区变化规律、水循环模式和灾害效应具有重要意义。本文立足山地冰川演化和冰湖发育过程,系统归纳了冰川-冰湖相互作用研究进展,剖析了冰川作用与冰湖发育耦合机制及相关模型的应用,并对现有冰川演化与冰湖发育过程耦合机制研究存在的不足与挑战进行解析和总结。冰川-冰湖耦合过程的深入研究有助于提高数值模拟的可信度与精度,为评估冰川-冰湖耦合过程影响、建立灾害监测预警体系和采取适应性措施提供数据与理论基础。

关键词: 冰川; 冰湖; 湖盆; 水文机制; 冰川动态
中图分类号: P343.6+3 **文献标志码:** A **文章编号:** 1000-0240(2022)03-1041-12

0 引言

末次冰盛期以来山地冰川显著退缩[1-2],全球山地冰川作用区大量冰湖形成和扩张[3-7],影响着冰川作用区及其下游生态、环境和社区生活[8-11]。冰湖作为冰冻圈水文学的重要组成部分,与冰川相互作用并参与和改变区域水循环过程[12-13]。研究表明,冰湖对冰川动力学过程和消融特征影响显著,引起冰流速率、物质平衡等发生变化[14-16],而冰湖溃决事件灾害链更与冰川跃动联系密切[17-18],冰湖的迅速变化将对冰川演化发挥不可或缺的作用。

冰川形成于固态降水的积累与演化,受气候、地形、几何形态等要素的综合作用塑造了丰富的冰川地貌类型[9,19-20]。冰湖形成于冰川作用区洼地,以冰川水系为纽带耦合冰川进行能量流动与物质交换。考虑到冰湖发育受制于冰川作用产生的湖盆地形和冰川作用区的产汇流机制,从冰川演化角度解构冰湖形成机理更能反映冰湖本质(图1)。近年冰川演化模拟逐渐从经验模型和一阶近似模型向充分考虑温度场、底部滑动和物质运输等影响因素的综合高阶动力学模型转变[21-22];另一方面,冰湖又反作用于冰川动态(图1),深刻影响着冰川数值模拟的发展和完善,理解冰川-冰湖耦合机制将促进冰冻圈尺度的综合数值模拟完备。

本文系统归纳了现有冰川-冰湖耦合过程机理研究成果,探讨了当前研究中存在的不足与挑战及未来研究趋势,有助于增进冰冻圈水文过程和灾害效应认识,完善冰冻圈科学理论体系。

1 冰湖湖盆发育机制

湖盆是地表相对封闭的可蓄水洼池。冰川作用区在重力和外营力共同驱动下,各地表环境要素相互作用,发生侵蚀、搬运、沉积、消融等过程,外在形式表示为塑造地貌和物质运输,为冰湖发育提供多元地形条件[8,19]。冰湖母冰川周边环境地形因子控制冰川作用过程和冰湖发育[23],并制约湖盆特征(如位置、面积等)[24]。

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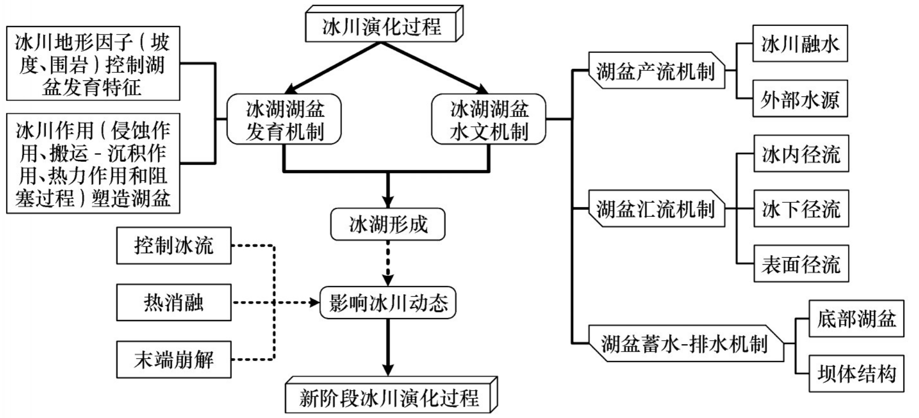

图1 冰川演化与冰湖发育耦合机制

Fig. 1 Coupling mechanism between glacial evolution and glacial lake development

1.1 地形控制因子

冰川通过坡度、下伏基岩等地形因子影响冰湖湖盆形成,利于湖盆发育的优势地形分布决定了冰湖分异。冰川坡度控制冰川动力学进而影响冰湖发育,主要表现为冰川地形(表面坡度)和山谷形态(底部地形);冰川围岩参与冰川作用过程,直接塑造和构成冰湖湖盆地形。

冰川表面坡度平缓为局部洼地的形成和汇流提供条件,坡度陡峭表明蓄水区域有限及冰流、径流速度相对较快,不利于滞水过程。如喜马拉雅山中段波曲流域,受陡峭地形阶地限制2010—2017年冰湖面积增幅较1970—2010年明显放缓,且扩张潜力较小[25]。相较于整体坡度差异,冰川积累区和消融区之间的表面坡度差异是引起冰湖形成的关键响应因素,更为陡峭的积累区平均坡度在物质平衡线附近切变,导致冰川末端低流速和高消融率,为冰湖发育提供有利条件[24,26]。

冰川底部地形随着冰湖扩张、融合逐渐成为冰湖的载体,决定着冰湖的最终发育形态。坡度梯度较大的底部地形为冰湖湖盆形成提供了场所,而过于均一坡度的冰下地形不利于储存冰下径流。对比研究喜马拉雅山西段拉达克地区同一流域的Dulung冰川和Chilung冰川纵向山谷剖面发现,Dulung冰川末端山谷第一段(5.4°)呈现出比Chilung冰川末端山谷第一段(4°)更陡峭的坡度,Dulung冰川末端山谷第二段底部地形趋于平缓并在第二段末端受冰碛坝阻挡成湖,而Chilung冰川遵循冰川坡度总体趋势,未形成利于冰湖发育的湖盆地形[24](图2)。

冰川围岩是承担冰川作用的载体,不同地表质地结构在冰流驱动下表现出不同种类的冰川作用过程。冰床基岩不同程度的侵蚀塑造出不同类型

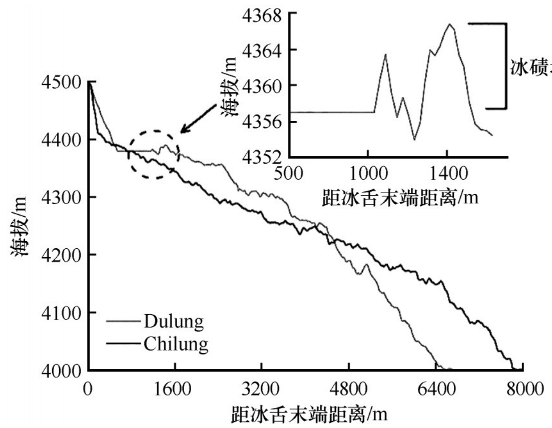

图2 Dulung冰川和Chilung冰川底部地形剖面[24]

Fig. 2 Basal topographic profile of Dulung Glacier and Chilung Glacier[24]

的冰下地貌,如较为坚固的基岩颗粒(如砾石)被底部冰川冰携带在冰床上运动和改造冰川则表现为冰川刻蚀,仅在底部冰床留下刻槽,而较为松散的冰川底部基岩结构在巨厚冰盖或冰川作用下则表现为冰川过量下蚀作用,形成有利于冰湖发育的下伏地形。两侧基岩在冰川运动过程中多表现为搬运、沉积过程,受冰川侵蚀而剥离基岩的碎屑,随冰川作用运输并以冰碛的形式参与冰湖湖盆构成。考虑到坝体稳定性,冰川侵蚀作用塑造的冰湖存在时间一般较冰碛湖更长[25]。

1.2 冰川侵蚀成湖

冰川侵蚀作用是冰川发育和运动过程中对围岩各类侵蚀作用的总称,不同类型的冰川侵蚀作用塑造了不同深度、位置、形态特征的冰蚀洼地湖盆。底部和冰内岩屑的对冰床、两侧谷壁不同程度的改造表现为刨蚀、掘蚀;冰川底部冰川冰与凸出冰床岩石冻结成块或冰川冰嵌入冰床基岩节理和裂隙

中，而随冰川运动拔起带入冰层中称拔蚀；冰川深切下伏地层发生过量下蚀作用，冰川作用于特殊的下覆地质、地貌部位（如岩性差异导致抗侵蚀能力的差异），形成远超冰川其他部分长期、稳定侵蚀深度的侵蚀盆地或槽谷[27]。冰川侵蚀作用形成的冰湖完全出露地表需要表面冰川完全消融，因而目前该类作用形成的冰湖多为第四纪冰川侵蚀作用的产物，表现为冰缘湖形式。其中，山地冰川溯源和下蚀侵蚀形成的围椅状凹地称为冰斗，冰斗冰川消退后冰斗底部出露为湖盆，称为冰斗湖；冰川对冰床侵蚀作用（磨蚀、刨蚀、过量下蚀作用等）形成的沟谷地貌[9]，冰川消退后出露成两侧陡直而底部宽平的"U"形山谷，为发育冰川槽谷湖提供条件[28]。

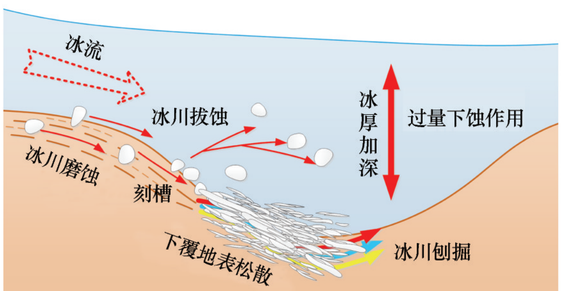

图 3　冰川侵蚀作用成湖

Fig. 3　Glacial lake formation of glacier erosion

冰川侵蚀作用（尤其是过量下蚀作用）形成的冰湖，其坝体与湖盆均由冰床基岩组成，结构较为稳定，冰湖存在时间较长，位置相对固定[29-30]。冰川退缩背景下该类作用形成的湖盆将逐渐出露地表，因而成为目前冰冻圈领域预估未来潜在冰湖形成、发展研究的热点[31-32]。早期研究将该类冰湖形成位置判别机制定性为冰面坡度阈值<5°[33]，随着定量化模拟冰厚成为可能，基于浅冰近似模型及其改进模型（如GlabTop模型）对冰床地形重建并表现出较高的精度，被广泛应用于山地冰冻圈和极地冰盖用于生成"无冰川DEM"，实现对潜在冰床湖盆位置的识别[27,30,34-37]。

1.3　冰川搬运-沉积成湖

冰川搬运作用是冰川运动过程中将冻结在冰川中的碎屑物质迁移到另一位置的过程，冰川消融或载荷能力降低导致冰体携带的碎屑物质堆积（沉积）[19]（图4）。受制于不同冰川搬运-沉积过程形成的冰碛堆积表现为不同类型的冰湖湖盆坝体：前推式冰碛坝、嵌入式冰碛坝、倾倒式冰碛坝、冰核式冰碛坝，坝体高度由数米至超过100 m不等，坝体颗粒

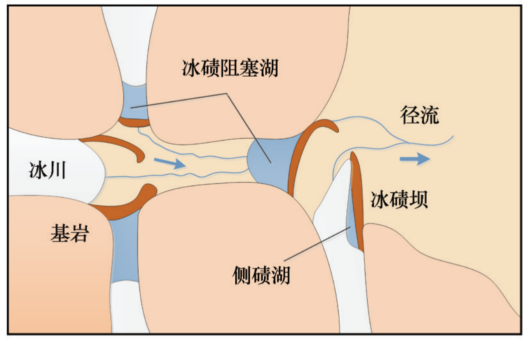

图 4　冰川搬运-沉积作用成湖[38]

Fig. 4　Glacial lake formation of glacier transport and sedimentation[38]

胶结程度和分选差异较大[23]。

冰川搬运-沉积作用在安第斯山脉、兴都库什-喜马拉雅山脉、天山、北美科迪勒拉山系西部等高山地区的广泛存在塑造了大量的冰碛阻塞湖[39]，该类型湖泊在冰湖总量中占较大比重，并随气候变化持续增加和扩张[40]。因其较高的不稳定性成为学术界冰湖溃决机理的主要研究对象，并构建了一系列经验模型、分析模型和数值模型对触发机制、溃口的产生和发展以及洪水演进路线进行模拟[39,41-43]。受地表起伏、破碎度、覆被类型等要素的综合影响[44]，冰川作用区偶发的冰（雪/岩）崩、泥石流等灾害性事件导致大量的冰川和山体碎屑物质被携带运输，最终在下游沉积下来，阻塞河谷、冰川融水等形成堰塞湖[44]。成湖过程中的破坏力对下游居民、社区和道路、桥梁、水电站等基础设施存在显著的潜在危害[44-45]，且常以灾害链的形式出现[45-47]。

1.4　冰川热力成湖

冰川热力作用过程通过能量转换机制控制冰川运动状态、塑造冰川作用区地表形态，为冰湖湖盆提供了广泛发育的温床，主要表现为热喀斯特作用和冰川消融[8]（图5）。冰川冰面、冰内和冰下的热力状况差异所导致的冰体差异消融在塑造冰川喀斯特的地表营力中扮演了重要角色，热融作用引起的地面沉降、塌陷在冰川不同位置塑造热喀斯特湖盆[19-20]，埋藏于冰碛中的死冰融化沉陷而形成冰碛垄热融湖；而冰内水系通道的堵-溃和冻-融过程使得汇入冰内水系或冰内管壁的融水因冰川内部存在裂隙、管道或洞穴而聚集，通过长时间的累积形成冰内湖[49]；冰下湖在格陵兰冰盖冰缘地带的分布和海洋性山岳冰川小规模存在的可能性归因于其活跃的水文状况和发育的冰下水系通道，反映了热

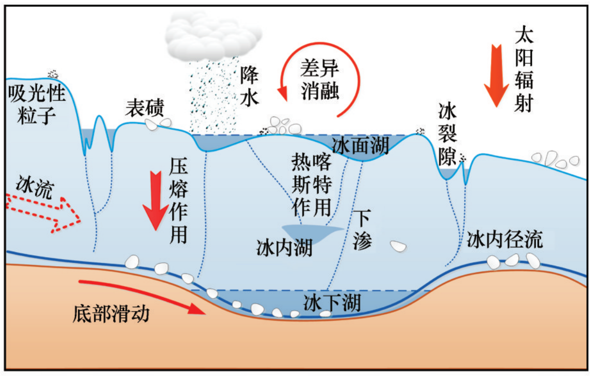

图5 冰川-冰湖热力耦合机制

Fig. 5 Thermal coupling mechanism of glacier and glacial lake

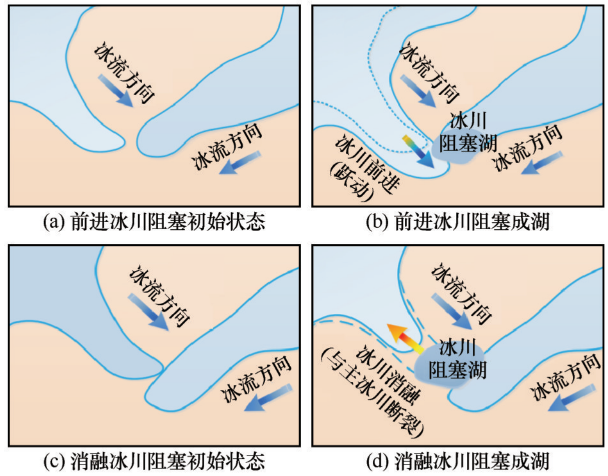

图6 冰川阻塞湖形成过程:前进冰川阻塞(a)~(b);消融冰川阻塞(c)~(d)

Fig. 6 Ice-blocked lake formation process: advancing glacier dammed (a)~(b); ablating glacier dammed (c)~(d)

喀斯特作用的活跃[28,50-51]。研究表明,全新世末次冰盛期消退期间热喀斯特湖曾在西伯利亚和阿拉斯加的广大地区发育[52]。

表碛、吸光性粒子、水体和微生物等对地表反照率的正反馈改变冰川能量循环,促进冰川表面差异消融,使得冰面凹陷形成湖盆底部为冰体的冰面湖[23,28,53]。冰面湖是许多其他类型湖泊的前身,喜马拉雅山地区的Ngozumpa冰川探地雷达调查结果揭示了同一底部湖盆表面多个冰面湖的扩张、加深、融合最终发育为冰碛湖、冰川侵蚀湖这一过程[54]。早期冰面湖数值模拟概念上仅包括表碛覆盖对冰川物质平衡的影响,近期基于自由对流原理构建的物质-能量平衡模型解释了冰面湖与大气和冰川之间的耦合机制[55]。

1.5 冰川阻塞成湖

冰川底部滑动和跃动状态下冰流显著前进[8,56-57],可能迅速阻塞河谷或另一支冰流形成坝体,为冰湖湖盆发育提供条件[58][图6(a)~(b)],叶尔羌河流域的克亚吉尔特索湖典型地反映出该类冰湖形成的特征[59]。末次冰期全球范围内冰川前进发育陆地冰盖阻塞河流水系,形成巨大的冰川阻塞湖[60];冰川快速退缩过程中的差异消融导致支冰川退却与主冰川分离,而另一支冰流或主冰川冰流经过阻塞成为冰坝,为冰川阻塞湖发育构建湖盆[图6(c)~(d)]。天山地区伊力尔切克冰川麦茨巴赫湖具有显著的支冰川快速退缩被主冰川阻塞成湖特征[61],该类冰湖在羌塘高原内部也有分布,且较为稳定[28]。

2 冰湖湖盆水文机制

冰湖湖盆为蓄水提供了有利的地形条件,大气降水、季节性融水、冰川径流等多元水源的综合作用使得洼地最终发育成湖[8,62]。冰湖湖盆的产-汇流机制描述了湖泊水源的产生与汇集[8,63-64],降水、冰川和冻土等水循环要素为冰湖提供了广泛而丰富的补给(图7)。不同类型冰湖各水源组分贡献比差异显著(如冰斗湖相较冰面湖降水补给占比更大),且冰川产流是冰川表面气象要素和冰川物理性质综合作用的结果[8,64]。本文围绕冰川产-汇流对冰湖湖盆的产-汇流机制进行论述,反映出冰川作用下的冰湖水文过程。此外,冰湖蓄水-排水机制决定了冰湖动态和最终形态[23,49](图7)。

2.1 湖盆产流机制

冰川消融和外部水源进入冰川水文系统共同作用于冰湖湖盆产流机制。冰川表面消融受太阳辐射影响表现出显著的时空差异,冰内和冰床因形变或滑动产生摩擦引起的消融较为稳定[8]。表碛覆盖、吸光性粒子(如碳质气溶胶)、冰崖和冰川微生物群落等因子直接或间接影响冰川表面反照率、湍流热通量和局部热平流等,导致冰川表面消融特征非线性分布[65],加剧差异消融[23,53,66-74];不同介质之间的热传导和压力等要素引起的冰熔点变化促进冰川融水形成[13,55,75-76]。

大气降水(降雨、固态降水消融)、冻土消融、地下水等冰川作用区外部水文因子是冰川径流的重要组分,并随冰川径流补给入湖参与冰湖水文过程[8,64]。降水和冰川融水的共同作用引起青藏高原冰川补给湖总蓄水量在1990—2013年上升84%[62],全球升温情景下的降水变化将持续深刻影响冰湖

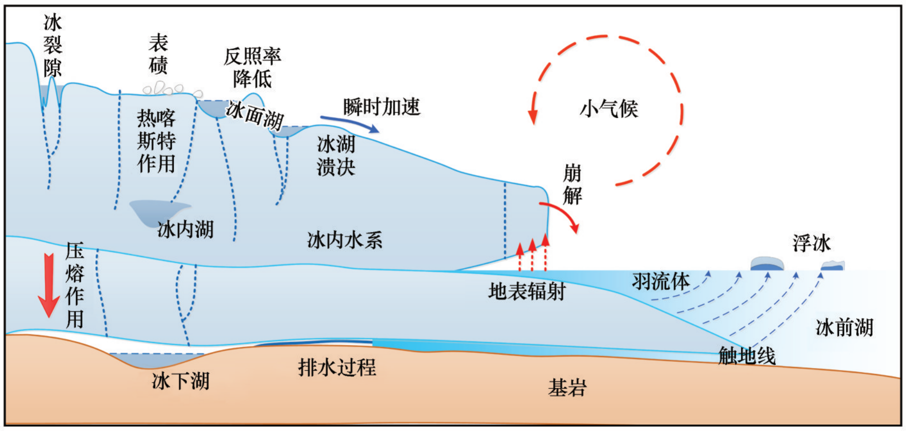

图7　冰湖发育对冰川动态的影响

Fig. 7　Effects of glacial lake development on glacial dynamics

水量[66]，蒸发加剧导致的区域性小气候降水增加和固态降水比重下降[77]，将促进冰川径流量增长和冰湖发育。

学术界正致力于开展流域水文模型和综合冰冻圈水文模型，基于物质-能量平衡模型和统计学原理考虑复杂地形上的风、湍流、粒雪等参数，以野外工作站仪器、无人机和卫星遥感数据为模型的补充，对地表反照率、积雪和冰川的物质平衡和再分布、集水区径流等进行模拟[73,78-79]，建立综合性冰川产流机制模型。

2.2　湖盆汇流机制

冰川汇流普遍存在于冰川水文系统，塑造了树枝状、扇形、羽状等多样径流形态，冰湖湖盆辐合汇集汇流路径水源而成湖。冰川水系入湖补给冰湖路径本质上取决于水势梯度和水流阻力之间的平衡[8]，水势梯度反映了水文系统的流向，地表可表征为海拔高度和质量的函数，水体流动方式表现为占据表面凹陷，而冰川内部受压力、海拔变化等因素的复杂影响致使水流汇集于被高水势环绕的低水势区域[80]；水流阻力取决于水流温度与黏度的关系和水系通道特性（如通道粗糙度，横截面积等）[8]。

不同位置冰川汇流的水势梯度和水流阻力差异表现出不同的汇流特征[64,81]。冰川表面径流受制于坡度沿最大梯度方向汇集，同时为保持表面径流的持续存在而下切侵蚀速率超过相邻冰面消融速率[80]。冰上排水系统因积雪与裸冰渗透率差异沿积雪孔隙下渗，并在冰面形成饱和水层后沿坡度流动，使表面汇流过程滞后[82]；冰内径流反映了表面水体（冰川融水、大气降水等）经由裂隙或垂直通道与冰床建立水文联系[83-84]。冰川表面径流水压剪切作用是冰内径流产生的主因，且随水流进入管道导致管壁融化使管道直径扩大[8]；冰下径流存在形态主要为管道式和分布式，其存在形态体现了汇流特征，分布式向管道式转变表明汇流水源增加，反之则表现为管道式向分布式转变[85-86]。

冰川汇流机制的复杂性使得不同汇流类型的数值模拟方法存在较大差异。冰面汇流机制模拟以格网形式进行量化，并考虑积雪覆盖对汇流滞后进行修正[86]；冰内汇流通过水流连续性方程描述，并将复杂的裂隙和垂直管道理想化为垂直通道、表面和底部裂隙通道[87]；出于对压力重要性考虑，冰下汇流模拟引入电压模型类比[85]，进而考虑地下水分量[87]。由于冰川水系密切连通，综合考虑冰川汇流机制的冰川动力学模型逐步得到发展，以量化冰川动态和冰川水文[88]。

2.3　湖盆蓄水-排水机制

冰湖湖盆底部和坝体结构控制了湖泊演变过程，湖盆构成有效的不透水屏障情况下，坝体最低高程决定了冰湖最高水位与排水基准面[8,23]。基岩结构的冰湖湖盆底部使得下渗过程难以发生，冰湖对冰川径流持续接纳直到水位超过坝体最低高度才会因漫顶而触发排水事件（该过程可能造成坝体破坏而引起蓄水条件的变化）[13,81]；若坝体由相对松散的冰碛物构成且结构不稳定，冰湖水压作用下管涌频发，导致冰湖排水和溃坝[23]，冰下湖的周期性排水事件推测与其坝体部分由冰川沉积物构成有关[89]；形成于冰川表面以冰体为底部湖盆的冰湖蓄水过程具有相当的不稳定性，冰裂隙和冰内径流的产生使得冰面湖与冰内水文系统连接成为可能，当湖泊与低水势区域之间建立起高效的水力连接，便

触发排水过程[39,90-91]。而当冰水通道排水事件结束，冰流瞬态加速过程终止，冰川流速回归正常阈值，蠕变重新主导冰湖湖盆底部运动形式，冰水通道迅速闭合，封闭的不透水湖盆开始新一轮蓄水-排水周期[8,92]；前进冰川阻塞湖因坝体由跃动冰川的冰川冰组成，不稳定性高，易受热消融而引起溃决，一般存在时间较短[8]。其补给方式依靠于拦截另一支冰流融水，当冰川融水蓄积达到一定水深（或水压）时，易形成周期性突发洪水[58]；而冰川消融断裂形成的冰川阻塞湖虽坝体由冰川冰构成，但其物质平衡趋于稳而较稳固，不易溃决[28]。天山地区伊力尔切克冰川麦茨巴赫湖由于季节性冰川消融，蓄水成湖、溃决并随冰川运动排水通道闭合而再次成湖，表现出特有的周期性而频繁发生溃决事件，协合拉水文站水文记录数据分析表明，1956年以来麦兹巴赫湖洪水次数高达50余次[61]。

3 冰湖对冰川动态的影响

冰湖演化对冰川动态存在广泛而深刻的影响，关键作用机制包括：控制冰流[16]、调节热消融过程[66,69]、促进末端崩解[93-96]（图7）。冰川物质平衡模型逐步将这些要素纳入考虑从而实现综合、全面的数值模拟，许多极地应用场景的理论和模型成果也正迁移到山地冰冻圈，用于探究冰川-冰湖耦合机制[97-98]。

3.1 冰湖-冰流控制作用

冰湖水动力学对控制冰流具有重要意义，主要表现为排水事件作用下的冰流瞬态加速、基底摩擦力调节和触地线迁移。受制于冰川热力学过程，冰面湖表现出季节性变化与生消过程不稳定，并经常伴随着快速排水过程、末端崩解和冰湖溃决[3,12,69]，而冰下湖也存在周期性地储存和释放大量湖水的现象[50]，均可能招致冰川瞬时加速和冰流量增加；湖水经由冰裂隙和冰水通道下渗使得底部摩擦减小可能引起基底滑动和跃动[81,99-100]，而湖泊排水事件导致的底部摩擦力减小，由于长期维持这个高效的局部蓄水-排水网络所需的汇流区域将覆盖到距离冰湖相当范围的冰川床，可能增加该区域基底阻力，引起冰流速度减缓甚至停滞[50,76,92]；冰川末端水下冰体触地线的迁移是控制冰流的关键因素，向下倾斜的触地线虽无法达到随遇平衡但仍可处于有限的稳态，而触地线后退引起的转变为向上倾斜形态将导致冰川末端的不稳定[101-104]。

3.2 冰湖-热消融调节机制

冰湖对冰川热消融机制影响与冰湖蓄水机制总体一致，作用表面反照率、冰内热传导和冰熔点控制物质平衡。冰面湖湖水较低的反照率吸收更多入射太阳辐射，表现出加速冰川融化的正反馈[66,69]，消融速率可达到厚表碛的10倍[105]，湖水温度日变化曲线呈“V”形，反映了湖水的分层和交换、混合过程，及对冰川消融的非线性影响[106]。冰面湖渗入冰层发生再冻结作用释放潜热造成局部升温导致负物质平衡[107-108]，再次促进冰面湖形成，触发正反馈机制[12]；冰面湖下渗和冰内湖、冰下湖连通形成冰内水文体系，通过热传导耦合冰川导致冰川负平衡加剧[13]，表面水体吸收的更多太阳辐射向下伏冰体传导促进了冰内能量传输的活跃[55]。冰前湖的冰-水界面是控制水上部分消融特征的关键要素，在冰川末端与冰面接触处往往形成凹槽（图7），水体较高的温度向冰川末端传输热量，同时末端受水面的长波辐射影响，促进局部消融[109]。此外，较厚冰层的巨大压力使得压熔点降低，导致底部冰川冰融化并加剧冰川物质损失[75-76]。

入湖冰川水下部分冰体消融还受冰湖及周边地形辐射、浮力、几何形态、热量交换等要素综合影响。湖水温度升高和冰内径流量增长将加快消融速率[110-111]；冰下径流入湖受浮力作用上升，冰湖表面相对温暖的湖水对流至湖底，促进水下部分消融而再次释放融水，形成正反馈，该过程作用范围称为羽流体，羽流体不同形态、体积也影响着水下部分消融速率[97,110]；触地线垂直截面冰通量与冰厚正相关，触地线后退，对应垂直截面冰厚增加冰通量变大，导致冰川减薄和触地线持续后退，形成正反馈机制[101-104]；冰川末端水下部分的几何形态也会导致差异化物质平衡[112]；冰川末端崩解入湖引起水温降低将暂时性表现出减缓消融的负反馈[92]。此外，冰湖经由冰内水系相互作用[113]，未来气候变化过程将进一步强化冰川表面和内部水文系统间的连通性，冰湖-热消融调节机制对冰川动态将施加更为持续而强烈的影响[12]。

3.3 冰湖-末端崩解过程

气候变化引起的冰冻圈物质负平衡加剧将导致末端崩解风险随排水量增加而增大[114-115]。伴随冰面湖季节性变化与生消过程的快速排水过程和冰湖溃决可能触发末端崩解[3,12,69]；冰-水界面施加在冰川末端的水压差异所形成的小凹陷一定程度

上引起了末端形态学特征变化，进而影响冰川物质平衡和冰川几何形状演化，冰川末端的持续内切将改变冰川动力学特征，促进冰川退缩，增加末端崩解风险，末端崩解入湖会影响冰湖稳定性，并可能造成涌浪和冰湖溃决[93-96]。

4　结论与展望

冰川-冰湖耦合过程影响着冰川作用区及其周边地区生态环境、水资源循环模式和灾害效应，成为当前冰冻圈领域的一个重要科学议题。本文依据冰湖形成直接因素和主导因素视角，从冰川作用原理出发，系统性地总结了冰川演化成湖作用和冰湖演化对冰川动态影响机理和数值模拟研究进展，主要结论如下：

（1）冰川作用区水-能转换过程机理研究为构建冰川-冰湖-灾害理论体系奠定基础。冰川作用区的水循环过程深刻影响着冰川行为，是冰川侵蚀和碎屑物搬运-沉积过程的能量来源和直接驱动因素，并以产、汇流机制为中继与冰湖动态相连接。冰川、冰湖为主体的机理研究大量开展为完善冰冻圈科学体系和理解冰冻圈各要素相互作用机制提供了必要的理论支撑和依据，而对冰川作用区水-能转换过程机理的进一步探究意味着不依赖于某一研究对象为主体的冰冻圈水文过程的综合理解，对于构建完整的冰川-冰湖-灾害理论体系具有重要意义。

（2）冰川-冰湖相互作用机制完善为综合化数值模拟提供支撑，促进模型性能优化与应用。随着数理基础的完善与硬件性能发展，冰川-冰湖耦合过程模拟逐渐从经验模型和一阶近似模型向高阶动力学模型转变和发展，并逐步将表碛覆盖、冰内径流、触地线等参数纳入考虑。但冰川-冰湖耦合过程的各个组成部分均表现出复杂的响应机制，且该系统与周边环境存在物质、能量交换而非孤立，当前的数值模拟仍未能综合地反映和量化水-能转换过程函数中的分量，基于物质-能量平衡原理的综合水文模型开发对于认知水循环模式和评估灾害效应具有重要价值。

（3）开展集成气候变化要素的冰川-冰湖耦合过程模拟，明晰冰冻圈未来演化，服务高寒区风险战略长期规划。气候变化作用于冰川并导致冰湖分异，冰川演化与冰湖发育特征受制于大气强迫的驱动动量、能量平衡过程。决策者对制定风险战略和采取适应性措施长期规划的考虑对未来气候情景下的冰川-冰湖耦合动态提出要求，冰川-冰湖耦合过程对不同环流模式下大气强迫的响应是当前研究们亟需思考的又一重要议题。

总之，冰川作用下的冰湖发育过程是各要素综合作用的结果，近年在冰川-冰湖耦合机理研究和数值模拟均取得了较为显著的进展，从单一、定性研究向高阶、定量研究转变，方法逐步综合化、复杂化。但冰川-冰湖-灾害理论体系仍不完善，数值模拟仍未综合反映各组分。对冰川-冰湖耦合过程机理认知的推进，将为数值模拟完善和模型精度与可信度提高构筑理论支撑，为评估冰川作用区及周边地区对气候变化的响应、水资源循环模式及灾害效应奠定理论基础。

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The interaction mechanisms between mountain glacier evolution and glacial lake development

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Abstract: The coupling process of the glacier and glacial lake is a significant component of the cryosphere material and energy cycle, and it's crucial for improving the theoretical system of cryosphere science and recognizing the changing pattern of glacierized region, water cycle model, and disaster effect to depict the interaction mechanism between glacier evolution and glacial lake development, systematically. Establishing the mountain glacier evolution and glacial lake development process, this paper systematically summarizes the research advance of the coupling process of the glacier and glacial lake, profiles the coupling mechanism of glaciation and glacial lake development and the application of relevant models, and analyzes and summarizes the shortcomings and challenges of the present research on the coupling mechanism of glacier evolution and glacial lake development. The results suggest that the environmental topographic factors around the glacial lake parent glacier dominate the glaciation process and glacial lake development, and constrain the characteristics of the lake basin. Glacier slope (surface slope, bottom topography) controls glacier dynamics and influences glacial lake differentiation; the surrounding rocks participate in the glaciation process and directly constitute the glacial lake basin; glacier erosion, transport, deposition, and ablation processes shape the landform and material transportation to provide multiple topographic conditions for glacial lake development. The glacial lake basin receives water from all components of the environment, which makes the depressions eventually develop into lakes. The runoff generation and concentration mechanism is closely related to the glacier runoff yield and concentration, where glacier ablation and external water sources enter the glacier hydrological system, and the glacial lake basin converges and collects water from the glacial sink path to form glacial lakes; the bottom of the glacial lake basin and the dam structure formed by different glaciation control the glacial lake storage and discharge mechanism, which determines the glacial lake dynamics and final development form. There are extensive and profound effects of glacial lake evolution on glacier dynamics. Glacial lake hydrodynamics control glacier ice flow, as manifested by the transient acceleration of ice flow under the impact of drainage events, regulation of basal friction, and migration of grounding lines; glacial lakes act on surface albedo, intra-ice heat transfer, and ice melting point to control mass balance and influence glacier thermal ablation mechanisms. The ablation of the submerged part of the ice body of the incoming glacier is also influenced by a combination of elements such as topographic radiation, buoyancy, geometry, and heat exchange in the glacial lake and its surrounding landscapes; changes in terminal morphological features caused by rapid glacial lake drainage processes, glacial lake outbursts, and water pressure differences at the ice-water interface may trigger glacial terminal disintegration. The improvement of glacier-glacial lake interaction mechanism provides support for integrated numerical simulation and promotes model performance optimization and application. The simulation of coupled glacier-glacial lake process in the background of continuous improvement of mathematical foundation and development of hardware performance gradually changes and develops from empirical model and first-order approximation model to higher-order dynamics model, and gradually takes the parameters of debris coverage, intra-ice runoff, and grounding line into consideration, and the method is gradually integrated and complicated. In summary, the glacial lake development process under glaciation is the comprehensive effect of various elements. Relatively significant progress has been made in recent years in glacier-glacial lake coupling mechanism research and numerical simulation, from single, qualitative research to higher-order, quantitative research, and the methods are gradually integrated and complicated. However, the theoretical system of glacier-glacier-lake-hazard is still not well developed, and the numerical simulations still do not reflect all components integratingly. Exploring the knowledge of the mechanism of the glacier-glacier lake coupling process will build the theoretical support for the improvement of numerical simulation and the enhancement of model accuracy and credibility, which will contribute to the enhancement of the credibility and accuracy of numerical simulation and to the provision of data and theoretical basis for assessing the impact of glacier-glacier-lake coupling process, establishing disaster monitoring and early warning system and taking adaptive measures.

Key words: glaciers; glacial lake; lake basin; hydrological mechanism; glacier dynamics

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