青藏高原及周边地区冰川中吸光性杂质及其影响研究进展

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摘要 沉降到冰川表面的吸光性杂质(如黑碳、有机碳、粉尘等)对冰冻圈物质能量平衡具有重要影响. 青藏高原及周边地区是冰川分布集中区, 也是开展雪冰吸光性杂质对冰川消融影响研究的理想区域. 基于近几年青藏高原及周边地区雪冰中吸光性杂质特别是黑碳的研究成果, 综述了该区域雪冰中吸光性杂质的浓度水平与时空分布, 着重探讨了黑碳的主要来源, 阐明了吸光性杂质导致的辐射强迫及其对雪冰消融的影响, 并指出目前研究中存在的问题以及未来研究的主要方向. 目前, 该地区冰川中吸光性杂质的空间差异大, 同一冰川不同表面吸光性杂质分布特征研究匮乏; 雪冰中吸光性杂质在冰川表面的迁移、富集等过程研究亟待加强; 吸光性杂质对冰川反照率反馈以及冰川消融作用显著, 但评估结果仍存在较大的不确定性. 在未来, 雪冰中吸光性杂质的混合状态、生物地球化学循环过程与气候变化的协同影响等将是一个新的研究方向.

关键词 黑碳, 有机碳, 粉尘, 吸光性杂质, 冰川, 青藏高原

大气中的吸光性杂质主要指黑碳(black carbon, BC)、有机碳(organic carbon, OC)、粉尘(dust)等物质, 通过改变直接辐射强迫、与云的相互作用、雪冰反照率以及相关反馈机制, 显著影响大气与雪冰介质的能量平衡, 对地球的气候系统具有独特而重要的作用^[1-10], 被认为是除温室气体外最大的人为辐射强迫因子^[3,11,12].

黑碳是吸光性杂质的重要组成部分, 是含碳的化石燃料和生物质不完全燃烧的产物, 具有独特的物理化学性质, 如强烈吸收可见光(吸收截面(mass absorption cross-section, MAC)为 $5 \text{ m}^{-2} \text{ g}^{-1}$, 550 nm)、

耐高温(4000 K)、可聚合为稳定结构的团、不溶于水和大部分有机溶剂等^[1,3,13,14]. 现今全球BC排放量约为 7500 Gg a^{-1} , 绝大部分源于人类的生产生活排放(交通工具排放、工业用煤等), 其次为生物质燃烧(森林大火、秸秆焚烧等), 东亚和南亚排放量可达 2000 Gg a^{-1} ^[3], 成为全球大气黑碳研究的热点区域之一^[12].

雪冰中有机碳因测试方法的不同, 分为水溶性有机碳(water soluble organic carbon, WSOC, 利用总有机碳分析仪分析)和不溶性有机碳(water insoluble organic carbon, WISOC, 基于滤膜利用热光法分析), 这类物质主要源于腐殖质类物质、燃烧产物中的柏油

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物质、生物质气溶胶等, 具有较弱的吸光性(MAC小于 $1 \text{ m}^{-2} \text{ g}^{-1}$, 550 nm)^[3,15,16]. 与黑碳相比, 吸光性有机碳能够强烈吸收近紫外太阳辐射, 进而引起辐射强迫的改变, 增加碳质气溶胶的光吸收效率^[17,18].

粉尘是吸光性杂质的另外一种重要组分^[19,20], 主要源自沙漠干旱区以及土壤扬尘等^[21]. 粉尘具有较弱的吸光性(对亚洲粉尘而言MAC为 $0.009 \text{ m}^{-2} \text{ g}^{-1}$, 550 nm)并呈深色(更易吸收短波辐射), 因全球大气中粉尘载荷量巨大($\sim 1800 \text{ Tg a}^{-1}$), 所以由粉尘引起的辐射强迫也较为显著^[17,22,23].

沉降到冰川表面的吸光性杂质能够显著降低雪冰反照率, 进而导致雪冰消融增强^[24-29]. 长期的雪冰消融可能显著改变区域气候及大气环流模式^[9,24,30], 由此引起的水资源季节分配、水文过程等改变, 将深刻影响经济社会和人口的可持续发展^[31].

青藏高原以及周边地区是中低纬度最大的冰川分布区, 被誉为“第三极”, 西起帕米尔和罕都库什地区, 东到我国的横断山地区, 北起昆仑山-祁连山, 南到喜马拉雅山脉, 覆盖面积约为 $5 \times 10^6 \text{ km}^2$, 平均海拔大于 4000 m , 冰川面积超过 100000 km^2 ^[32]. 目前冰川普遍退缩的事实与机理引发了广泛探讨^[33-35], 其中南亚和中亚地区化石燃料以及生物质燃烧产生的大量吸光性杂质, 对青藏高原冰冻圈环境产生重要影响, 吸光性杂质对冰川退缩的贡献备受关注^[9,22,36-39]. 在此背景下, 研究吸光性杂质随大气传输、沉降对青藏高原地区冰川加速消融的影响, 并由此加剧冰川变化具有重要意义. 研究内容主要围绕3个方面开展: (1) 实测雪冰中吸光性杂质浓度; (2) 量化冰川表面反照率与吸光性杂质的关系; (3) 模拟当前情景下雪冰中吸光性杂质变化所引起的气候效应.

目前, 研究工作主要集中于冰川积累区雪坑和冰芯中黑碳浓度水平及其对反照率的影响^[7,9,22,29], 而针对冰川不同表面(如新雪、老雪、裸冰)吸光性杂质的浓度及其对反照率的影响研究还很稀少, 仅在高原南部的念青唐古拉山脉的扎当冰川、中部的唐古拉小冬克玛底冰川等有相关报道^[26,40-42]. 受海拔高度、消融过程、局地排放等因素影响, 不同冰川甚至同一冰川不同表面雪冰中吸光性杂质空间分布存在巨大差异, 特别是在消融期, 这种差异所导致的冰川表面反照率的变化更加复杂^[38]. 冰川消融期雪冰中吸光性杂质的迁移、富集等过程尚缺乏细致的研究, 而消融期雪冰中黑碳存在显著富集现象^[28,29,40], 可明

显加速雪冰消融过程. 而对模型模拟而言, 月均值的黑碳浓度变化以及零星的观测仍显粗糙^[19]. 青藏高原雪冰中吸光性杂质研究主要针对黑碳, 其他吸光性杂质如粉尘、有机碳等涉及较少, 仅在数条冰川有相关研究^[40-42].

基于近几年的一系列研究(图1), 本文主要综述了青藏高原及周边地区雪冰中吸光性杂质特别是黑碳的时空分布和来源、吸光性杂质在冰川表面的迁移转化规律以及对冰川消融的影响, 指出了目前存在的问题以及亟待加强研究的方向.

1 吸光性杂质浓度水平

1.1 空间分布

20世纪80年代, 雪冰中黑碳研究开始于北极和南极地区, 并已经取得大量成果. 全球范围来看, 不同地区雪冰中黑碳浓度差异显著. 靠近北极点及亚北极地区黑碳浓度约为数个至十几个 ng g^{-1} , 如北极点地区约为 5 ng g^{-1} , 北冰洋低纬度地区约为 10 ng g^{-1} , 加拿大亚北极地区雪冰中黑碳浓度为 8 ng g^{-1} , 加拿大亚北极地区为 14 ng g^{-1} , 而在俄罗斯西部和东部雪冰中黑碳浓度可达 $21 \sim 34 \text{ ng g}^{-1}$, Svalbard地区雪冰中黑碳为 13 ng g^{-1} ^[43]. 由于受到人类活动的深刻影响, 中纬度不同地区雪冰中黑碳浓度差异也较大, 北美大部分地区降雪中黑碳浓度为十个至十几个 ng g^{-1} , 但不同季节(如春季粉尘输入较大时)或新降雪中黑碳浓度可高出一个数量级^[19]. 中国北方积雪中黑碳浓度差异巨大, 东北部靠近西伯利亚南缘地区黑碳浓度仅为 $50 \sim 150 \text{ ng g}^{-1}$, 而在东北重工业区黑碳浓度可达 $1000 \sim 2000 \text{ ng g}^{-1}$, 内蒙草原一带则为 $100 \sim 600 \text{ ng g}^{-1}$ ^[15,27].

青藏高原以及周边地区雪冰中黑碳研究虽然起步较晚, 但一批学者业已取得一系列成果, 提升了对该地区的认识. 实测研究发现, 冰川雪冰中黑碳的平均浓度则约为 50 ng g^{-1} , 较南北极地区偏高, 最高浓度出现在天山地区(消融期可达 3000 ng g^{-1}), 而喜马拉雅山地区则最低(16 ng g^{-1})^[7,28,44-46](图1). 不同冰川表面(如新雪区、老雪区、裸冰区)吸光性杂质分布特征研究发现, 天山科其喀尔冰川老雪中黑碳浓度为 2180 ng g^{-1} ^[47]. 帕米尔地区冰川中新雪的黑碳浓度较低(为 57 ng g^{-1})^[38], 这与慕士塔格峰冰川雪坑的浓度基本一个水平^[19]; 数天后老雪的浓度可达 175 ng g^{-1} ,

图1 青藏高原及周边地区冰川雪冰中吸光性杂质研究点以及黑碳含量分布图(圆圈大小代表黑碳含量多寡)

Figure 1 Location map of studies on light-absorbing impurities in snow/ice of glaciers and black carbon (BC) concentrations across the Tibetan Plateau and its surroundings (Circle size represents the concentrations of BC)

而强烈消融的雪中黑碳浓度更高(1110 ng g^{-1})^[38]. 高原西部的木吉冰川新雪中黑碳为 25 ng g^{-1} , 而老雪中则为 731 ng g^{-1} ^[29]. 高原北部祁连山老虎沟12号冰川表层老雪中黑碳含量约为 1785 ng g^{-1} ^[48], 而雪坑黑碳的含量则小于 40 ng g^{-1} ^[7]. 高原中部唐古拉小冬克玛底冰川新雪中黑碳浓度为 41.77 ng g^{-1} , 老雪中可达 247 ng g^{-1} ^[40], 而距离较近的各拉丹冬果曲冰川冰芯记录的黑碳仅为数个 ng g^{-1} ^[49]. 扎当冰川消融期(7~8月)老雪区和裸冰区中黑碳平均浓度为 258 ng g^{-1} , 显著高于新雪的浓度水平(52 ng g^{-1}), 且黑碳和粉尘随海拔升高而减小^[26]. 在珠穆朗玛峰南坡的Mera冰川也发现, 老雪中黑碳浓度达到 180 ng g^{-1} , 较之新雪以及冰芯($\sim 1.5 \text{ ng g}^{-1}$)显著偏高^[7,44,50]. 藏东南地区4条冰川的研究结果表明, 老雪以及裸冰中黑碳含量高出新雪以及冰芯黑碳含量1~2个数量级^[9,22,42]. 玉龙雪山白水河1号冰川也发现, 随着雪冰消融黑碳浓度呈增加趋势^[41]. 黑碳在不同类型雪冰中含量的差异, 特别是冰川消融区老雪中含量普遍高于雪坑/冰芯含量, 更新了我们对于同一条冰川不同区域表层雪中黑碳浓度的认识, 为评估黑碳对雪冰反照率以及消融的影响提供了新数据.

冰川表雪中黑碳的空间分布形式可能受到青藏高原地区大气碳质气溶胶分布的影响. 基于区域气

候模式RegCM4.3.4的模拟结果表明, 气溶胶中黑碳含量高值出现在喜马拉雅山脉以南; 中亚地区黑碳气溶胶含量要低于南亚地区, 但是仍高于高原腹地^[51]; WRF-Chem模拟结果亦给出了相近的趋势^[52]. RegCM4.3.4模拟的雪冰中黑碳含量在青藏高原边缘地区呈高值, 而高原腹地含量较低^[53], 其含量水平($40\sim 70 \mu\text{g m}^{-2}$)与冰川雪坑结果大致相当. 这种模拟趋势与实测数据仍有差异, 如模拟结果仍低估了扎当冰川黑碳的含量水平, 而高估了喜马拉雅地区表雪的黑碳含量. 特别是在高原腹地, 如小冬克玛底冰川以及扎当冰川, 由于受到雪冰类型(新雪、老雪、裸冰)的影响, 黑碳含量可能相差1~2个数量级; 而受制于模式分辨率(50 km)等影响, 模式结果目前还不能精确抓住该特征.

青藏高原北部老虎沟冰川雪坑、表雪、附加冰中WSOC浓度分别为332, 229, 426 ng g^{-1} ^[54], 较青藏高原南部的唐古拉(217 ng g^{-1})和珠穆朗玛峰(153 ng g^{-1})地区偏高^[55]. 藏东南地区冰川中WISOC约为 230 ng g^{-1} ^[16], 比该地区冰芯记录的WISOC浓度偏高^[22], 可能与采样时段不同有关. 对雪坑而言, WSOC和WISOC的浓度均呈现北部高、南部低的特征, 最低值出现在喜马拉雅山脉的珠穆朗玛峰地区^[16,41]. 模拟的有机碳气溶胶的空间分布与黑碳较为一致, 在喜

马拉雅山脉以南呈高值,高原腹地较低^[51],与雪冰中有机碳的分布存在差异;特别是在高原北部,模式结果并没有表现出高值。

区域模式模拟结果显示,空间上,粉尘气溶胶高值区出现在距离干旱区(如塔克拉玛干沙漠、塔尔沙漠)较近的地区;而在冬季,羌塘高原地区也会出现高值;而高原西部地区粉尘气溶胶在夏季呈现较高含量^[53]。粉尘气溶胶时空分布的不同进而影响到其在冰川表面的沉降。雪冰研究结果发现,粉尘浓度主要体现出青藏高原北部以及天山等地区呈高值,喜马拉雅山脉雪冰中粉尘含量较低,表明粉尘源区对雪冰中粉尘沉降的显著影响^[44,56,57]。在粉尘浓度季节变化上,高原西部的慕士塔格冰川夏季呈高值^[56],而在高原中部和南部则表现为冬季呈高值的特征^[57]。表明主要受到粉尘来源以及降水等的影响。

整体上,雪冰中吸光性杂质在高原的分布因受到排放源区、局地地形、大气环流以及不同冰川表面等多种因素的影响,其浓度高原北部以及东南边缘较高。而针对同一冰川不同区域(如冰川积累区和消融区)雪冰中吸光性杂质的季节变化研究有待加强,特别是对于青藏高原北部毗邻的天山与阿尔泰山地区冰川不同区域的吸光性杂质分布特征研究亟待拓展。

1.2 黑碳历史变化

由于黑碳具有很强的稳定性,沉降到冰川后会累积,可反演人类活动、气候环境变化的关系等。南亚和中亚地区化石燃料以及生物质燃烧产生的黑碳,对青藏高原地区环境产生重要影响^[9,12]。工业革命以来珠穆朗玛峰和各拉丹冬冰芯中黑碳浓度均呈显著上升趋势,1975~2000年的浓度约为1975年之前浓度的3倍^[49,50](图2(a))。珠穆朗玛峰地区冰芯中粉尘自19世纪60年代以来略有下降,雪冰中黑碳的辐射强迫更为显著,表明通过控制减排黑碳可以有效地降低喜马拉雅山脉地区雪冰反照率和冰川消融^[50]。青藏高原冰芯记录还显示,20世纪50~60年代黑碳含量较高,但不同地区钻取的冰芯记录了黑碳含量不同的历史变化趋势,西风带气候区冰芯(慕士塔格)记录显示20世纪70年代以来黑碳含量较低,未出现明显的增长;而季风气候区冰芯记录无一例外显示20世纪80年代以来黑碳含量快速的增长趋势,这与青藏高原南部冰川较西北部冰川退缩快是相一致的^[9,22]。图2(b)显示了全球不同区域过去150年来的黑碳排放量历史^[58]。珠

图2 青藏高原地区冰芯记录的黑碳历史变化(a)以及全球不同区域黑碳的排放量(b)

Figure 2 Black carbon concentrations in ice cores from the Tibetan Plateau (a) and black carbon historical emissions (b)

穆朗玛峰东绒布、宁金岗桑以及作求普(南亚季风气候区)冰芯黑碳历史变化与南亚地区黑碳的排放量变化较为一致,而慕士塔格(西风带影响区)更多地受到中东地区黑碳排放的影响。结合雪冰微粒的Pb同位素^[59]、污染事件追踪^[60]、气团轨迹反演^[38]、碳同位素指纹信息^[61]等进一步佐证了南亚和中亚地区人类活动排放的大量污染物可对青藏高原及周边地区环境产生深刻影响。

2 雪冰中吸光性杂质在冰川表面的迁移和富集

吸光性杂质沉降到雪冰表面之后,其浓度在雪层中的分布、与雪粒的包裹形态随着雪的老化、融化、再冻结等过程而发生变化^[62,63]。天山乌鲁木齐河源1

号冰川消融期雪冰黑碳浓度($\sim 3000 \text{ ng g}^{-1}$)要比未消融的夏季表雪($\sim 400 \text{ ng g}^{-1}$)高出一个数量级,表明雪冰消融导致黑碳的富集^[28]。该现象在青藏高原西部的木吉冰川也有发现^[29]。雪的融化过程不仅影响黑碳在雪层的分布和浓度,也改变黑碳与雪粒的混合状态,由于雪粒内部的物质大都亲水或者结合水分子形成水化物,雪粒表面水分子迁移和融水冲刷将可溶物几乎清除殆尽,而将黑碳等暴露于雪粒外,致使黑碳吸收辐射强力增强;而雪的老化也导致黑碳在表雪富集,增强了黑碳对反照率的影响^[3,29,64]。对高原中部的唐古拉小冬科玛底冰川研究发现,消融期内随雪坑深度减薄,吸光性杂质在雪层内会重复分布,高值主要出现在污化层以及发生强烈消融的层位,低值则主要出现在雪坑表层(新雪),其浓度相差1~2个数量级^[40]。

雪冰中黑碳不仅与大气环境中黑碳的浓度、沉降方式(干沉降或湿沉降)、及雪的升华、融化、再冻结过程有关,也与湿雪的比表面积、水膜厚度等影响有关,而如何精细量化雪冰中黑碳富集对反照率的影响,则必须进一步开展细致的观测实验。其他吸光性杂质如粉尘等的迁移转化过程对反照率的影响研究亦未有详细报道,粉尘与黑碳的相互影响及迁移、富集过程等的差异亟待加强。

3 黑碳和粉尘的来源

基于黑碳含量、大气传输模型和排放因子等对该地区黑碳的来源进行了研究。模拟结果显示,沉降到青藏高原的黑碳气溶胶主要来源于南亚地区:非季风期贡献可达50%左右,季风期贡献约为30%,并主要影响高原南部地区;人为源黑碳的影响可达30%~70%^[65-67]。而在帕米尔地区,人为源黑碳排放超过60%,且主要源于中亚和南亚地区^[38]。但上述研究还存在很大的不确定性,对黑碳的化石燃料和生物质燃烧的贡献不清楚,限制了减缓黑碳排放的政策制定。

碳氧同位素最近被证明是鉴定大气污染物来源的有效示踪物,尤其放射性碳同位素(^{14}C)被用于鉴定化石燃料和生物质燃烧对有机气溶胶和黑碳气溶胶的相对贡献^[61,68]。基于青藏高原以及周边地区雪冰中黑碳的 ^{14}C 研究发现,雪坑中黑碳的同位素组成在区域上具有显著差异,高原东北部(老虎沟12号冰川)雪冰中黑碳具有最大的化石燃料贡献,可达66%;高原中部(唐古拉小冬科玛底冰川)雪冰黑碳则主要

来源于生物质燃烧,其比例可达70%;喜马拉雅山脉南坡的Thorung冰川雪冰中黑碳的化石燃料贡献约为54%,与南亚地区的比率一致;显示从高原边缘到高原内部,生物质燃烧对黑碳的贡献逐渐增大^[61]。上述结果不仅明确界定了喜马拉雅山脉和青藏高原地区不同燃料对黑碳的贡献,可以为黑碳的大气传输模拟研究提供验证数据。

依据气团轨迹、Sr-Nd同位素等特征,定性诊断青藏高原粉尘主要来源于周边的干旱区以及高原自身^[9,21,57,59,69,70],但上述结果无法量化远源传输与局地源的贡献比例。由于青藏高原冰川沉积物中存储了大量的粉尘碳酸盐,其中的 ^{13}C 和 ^{14}C 可能记录了粉尘的源区及其传输与沉积特征。目前,还没有青藏高原本土碳酸盐的 ^{14}C 分析数据,粉尘重要源区塔克拉玛干沙漠也没有 ^{14}C 分析数据,还需要进一步分析以上沙尘源的同位素示踪值,才能反演冰川上的本地源和长距离传输粉尘的相对贡献。

4 雪冰中吸光性杂质对雪冰反照率、辐射强迫以及冰川消融的影响

雪冰中微量的黑碳浓度引起的反照率降低及反馈作用,导致全球平均的雪冰黑碳辐射强迫达 $+0.04 \text{ W m}^{-2}$,其中人类活动排放的黑碳沉降到雪冰上引起的辐射强迫达 $+0.035 \text{ W m}^{-2}$ ^[3,6]。利用不同模型与方法研究的喜马拉雅-青藏高原地区雪冰中黑碳引起的辐射强迫差异较大(图3),如Flanner等人^[24]评估整个地区的平均辐射强迫为 1.5 W m^{-2} ,春季可达 $10\sim 20 \text{ W m}^{-2}$;而GEOS-Chem模型模拟的青藏高原年均雪冰黑碳平均辐射强迫为 2.9 W m^{-2} ^[71]。Qian等人^[72]指出,春季青藏高原雪冰中黑碳可能导致的辐射强迫约为 $5\sim 25 \text{ W m}^{-2}$,最大值出现在4月或者5月消融期开始时段。Kopacz等人^[67]计算的喜马拉雅-青藏高原地区的黑碳的瞬时辐射强迫为 $5\sim 15 \text{ W m}^{-2}$,最大值出现在夏季,最小值则出现在冬季。Ji等人^[66]模拟的结果表明,高原西部季风期雪冰中黑碳引起的辐射强迫为 $3\sim 4.5 \text{ W m}^{-2}$;非季风期喜马拉雅山脉以及藏东南地区黑碳-雪冰辐射强迫为 $5\sim 6 \text{ W m}^{-2}$ 。Ming等人^[25]利用冰川积累区雪坑黑碳浓度计算引起的辐射强迫为 6 W m^{-2} ,对反照率降低的影响约为5%,与Yasunari等人^[74]模拟的结果($4.2\%\sim 5.1\%$)较为接近。而在夏季消融期(无新雪覆盖),SNICAR模型模拟的雪冰黑碳对反照率的降低达36%^[26]。高原中部地区,

图3 实测和模拟的青藏高原及周边地区雪冰中黑碳-辐射强迫效应(BC RF)(*, 未发表数据)

Figure 3 Observed and simulated BC-radiative forcing (BC RF) in snow over the Tibetan Plateau and its surroundings (*, unpublished data)

黑碳和粉尘对反照率降低的贡献可达52%和25%^[40], 表明相对于粉尘而言, 黑碳是导致冰川消融的主要因子. 而在高原东南部, 黑碳对反照率降低的贡献约为4.6%^[41]. Ming等人^[45]研究珠穆朗玛峰雪冰发现, 夏季黑碳的辐射强迫约为 4.5 W m^{-2} , 而Ménégoz等人^[73]模拟的喜马拉雅山区辐射强迫约为 $1\sim3 \text{ W m}^{-2}$. 因受黑碳与雪粒形状、混合状态、包裹层形态等影响, 导致不同区域黑碳对雪冰反照率的影响差异可达数倍.

雪冰中粉尘对反照率降低的贡献也较大, 特别

是当粉尘与黑碳具有较高的比值时, 或者当反照率降低到0.7以下时, 粉尘对雪冰反照率的降低作用显著^[5,23,26], 黑碳的贡献仅约占1/3^[27]. 喜马拉雅山脉南坡Mera冰川冬春季雪冰中黑碳对反照率降低的影响可达6%~10%, 由此导致的瞬时辐射强迫为 $75\sim120 \text{ W m}^{-2}$; 而粉尘可导致40%~42%的反照率降低, 瞬时辐射强迫可达 $488\sim525 \text{ W m}^{-2}$ ^[44]. 在青藏高原中部地区, 冬季雪冰中黑碳和粉尘对反照率降低的贡献分别为11%和28%^[25]; 而在夏季冰川强烈消融期, 粉尘对反

照率降低的贡献可达58%，平均辐射强迫为 $1.1\sim 8.6\text{ W m}^{-2}$ ^[26]。研究还发现，扎当冰川黑碳和粉尘浓度随海拔升高逐渐减小，而反照率则逐渐增大；当冰川表面被新降雪覆盖时，黑碳对反照率降低的影响较大；冰川处于强烈消融状态时（表面为老雪或裸冰），粉尘引起的反照率降低达56%，较黑碳引起的反照率降低（28%）明显偏大；SNICAR模型模拟的粉尘导致的平均辐射强迫可达 $1.1\sim 8.6\text{ W m}^{-2}$ ，说明粉尘是引起扎当冰川消融的重要组分^[26]。而对于小冬克玛底冰川而言，黑碳对反照率降低的影响要大于粉尘^[40]。对于不同类型冰川区消融期内雪冰中吸光性杂质的迁移、富集、转化等过程对反照率影响的差异鲜有研究，特别是消融期开始后吸光性杂质的短时间尺度变化过程对反照率的影响尚属空白。

区域气候模拟结果显示，青藏高原地区黑碳/粉尘-雪冰辐射效应可导致近地面增温 $0.1\sim 1.5\text{ }^{\circ}\text{C}$ ，雪水当量减少 $5\sim 25\text{ mm}$ ^[53,66]。基于黑碳和粉尘对雪冰反照率的影响，模拟评估结果表明，帕米尔地区4条冰川表雪中黑碳对冰川消融的贡献可达6.3%，对应于冰川消融速率可提升 0.8 mm d^{-1} ^[38]。祁连山老虎沟12号冰川消融期雪冰中黑碳和粉尘对反照率降低的贡献约为15%~40%，由此导致的冰川消融量约为 $200\sim 400\text{ mm w.e.}$ （water equivalent），可占总消融量的20%~40%（未发表数据）。喜马拉雅山脉南坡Yala冰川的观测结果表明，若表层雪（2 cm）中黑碳浓度为 $26.0\sim 68.2\text{ ng g}^{-1}$ ，则对反照率降低的影响可达2.0%~5.2%，可导致冰川径流增加约 $70\sim 204\text{ mm}$ ，该结果尚不包括雪的老化、粉尘以及反照率反馈机制等的影响^[74]。而藏东南地区4条冰川的结果表明，老雪黑碳和粉尘对冰川消融量的贡献可达15%，约为 350 mm w.e. ；对新雪而言，其贡献率小于5%^[42]。过去40年来，青藏高原冰川物质损失量约为 $450\text{ km}^3\text{ w.e.}$ ^[35,75]，则吸光性杂质对冰川损失量的贡献可达 $20\sim 80\text{ km}^3$ 。

关于雪冰中有机碳吸光性的研究还较少。在高原北部的老虎沟12号冰川研究中发现，WSOC导致的辐射强迫为 0.43 W m^{-2} ^[54]。对扎当冰川而言，WISOC对反照率的影响超过了黑碳影响的20%，引起的辐射强迫约为 $0.81\sim 1.34\text{ W m}^{-2}$ ；在新雪覆盖条件下，WISOC对辐射强迫的影响甚至达到了粉尘影响的72.3%^[76]。藏东南作求普冰芯研究表明，WISOC导致的辐射强迫从1956~1979年的 0.2 W m^{-2} 增加到2006年的 0.84 W m^{-2} ，分别占黑碳辐射强迫的27%和

43%^[22]。虽然雪冰中的有机碳吸光能力（ $\sim 1.3\text{ m}^2\text{ g}^{-1}$ ）相对于黑碳较弱，但是所引起的雪冰表面反照率降低以及冰川消融等效应不容忽视。

综上所述，雪冰中吸光性杂质的存在会显著改变雪冰反照率，影响雪冰消融，进而会对气候以及水文过程产生反馈。然而，目前基于观测与模拟的雪冰中吸光性杂质对雪冰消融的影响仍存在较大差异，与不同时间、不同地区的吸光性杂质的沉降速率及雪的积累率存在较大差异有关，在模型输入时很难将两者完全匹配^[19,66]，特别是对雪冰中不同吸光性杂质的迁移、富集、转化等过程（如物质与雪的混合状况、物质的淋洗/清除效率等）的认识尚不完全清楚^[24,28,29,40]。因此，青藏高原不同地区（如季风区和西风影响区）和不同冰川表面（如老雪区、新雪区、裸冰区）雪冰中高分辨率的吸光性杂质的观测与分析势在必行，特别是消融期开始后吸光性杂质在短时间尺度内的变化过程差异对于模型的改进至关重要，可为我们全面认识吸光性杂质对青藏高原不同地区冰川消融影响的机制提供科学依据。

5 研究展望

青藏高原被誉为“亚洲水塔”，是亚洲许多大河的发源地，冰川融水是亚洲极其重要的水资源。大气气溶胶中的吸光性杂质随大气环流传入高原^[12,65,77]，然后通过干、湿沉降到冰川、积雪表面，降低雪冰表面反照率，提高雪冰对太阳辐射的吸收效率，近期研究认为吸光性杂质是冰冻圈（冰川、积雪等）加速消融的重要原因之一^[9,19,36,40]。但是，目前关于吸光性杂质对青藏高原雪冰消融的影响和定量评估研究才刚刚起步，对一些关键过程的认识不甚清楚，如雪冰中吸光性杂质的混合形貌特征（特别是黑碳的包裹层效应）、吸光性杂质的来源（近源和远源、人为源和自然源）、在雪冰表面的时空分布特征和生物地球化学及富集过程等。已开发的能量平衡模型虽然在理论上考虑了吸光性杂质的能量吸收效应，但并不能实现模型与吸光性杂质参量的耦合^[19]，如何建立包含吸光性杂质的能量平衡模块，定量评估吸光性杂质对冰川和积雪消融的影响仍是一个迫切需要解决的问题。

此外，雪冰中碳质气溶胶的生物可利用性研究发现，WSOC与 Ca^{2+} 具有很好的相关性，表明粉尘对冰川区的碳质气溶胶贡献作用较大，但是异养微生物活动对雪冰吸光性杂质的迁移富集等的影响不可

忽视^[54,78]. 格陵兰冰盖最新研究发现, 雪冰中微生物以及藻类等活动可以显著影响反照率, 进而引起雪冰消融加速^[79,80]. 南极冰川表面以及冰尘的微生物种群研究也发现其对光合有效辐射具有显著作用,

进而能够影响消融期的生态系统生产力^[81]. 在气候变化背景下, 这种生物过程与雪冰物理过程是如何相互作用, 也将成为青藏高原雪冰中吸光性杂质未来研究的一个突破点.

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Summary for “青藏高原及周边地区冰川中吸光性杂质及其影响研究进展”

Research progress of light-absorbing impurities in glaciers of the Tibetan Plateau and its surroundings

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Light-absorbing impurities (LAIs, including black carbon, organic carbon, and dust) deposited on glacier surface can have strong effects on mass and energy balance of the cryosphere. Widespread with amount of glaciers, the Tibetan Plateau (TP) is considered to be an ideal region to study the impact of LAIs to glacier melt. Based on recent studies of LAIs in glacial snow of the TP, we summarized the research progress of LAIs in glacial snow, including their concentrations and spatial distributions, especially focusing on discussion of sources of black carbon, and documenting the albedo reduction and radiative forcing caused by LAIs. Additionally, we identified research gaps and suggested future research directions. At present, spatial distribution of LAIs in glacial snow and ice from TP and its surroundings exist a significant difference due to natural/anthropogenic emission sources, local topography, atmospheric transportation, and different glacial surface (e.g., fresh snow, aged snow, granular ice, bare ice). In general, higher concentrations of BC occurred in the northern and southern regions; LAIs in aged snow or granular ice were higher by 1–2 order of magnitude than that in the fresh snow or snowpit. Characteristics of LAIs from different glacial surfaces were still limited especially in Tianshan regions, which need to be further studies. Since Industrial Revolution, BC in ice cores increased in recent decades which may be likely caused by increasing emissions of fossil fuel combustion and biomass burning in the South Asia and Central Asia. The process of snowmelt can enrich the BC concentrations in surface and change the mixture of BC with snow grains, which will further enhance the albedo reduction. Studies on post-deposition processes of other LAIs and their effects on snow surface albedo are urgent to be strengthened. Simulation results indicated that BC aerosol of the southern TP mainly originated from the South Asia, which can contributed to approximately 50% in non-monsoon season and 30% in monsoon season; anthropogenic sourced BC can contributed to 30%–70%. However, studies on enrichment and transport processes of LAIs in glacial surface snow still should be emphasized. Although LAIs initiated powerful snow albedo feedbacks and glacier melt, estimation of this effect was associated with a large uncertainty. Based snow ice and aerosol radiation (SNICAR) model, effects of BC and dust on albedo reduction were estimated to be less than 10% in the southern TP and more than 25% in the central and northern TP influencing by snow types. Simulation of BC on albedo effects were affected by mixture of BC, coatings with other components, and snow grains, which lead to different radiative forcing in different regions. For aged snow or granular ice, effects of BC and dust can give localized instantaneous radiative forcing to about near or more than 100 W m^{-2} ; for fresh or snowpit, BC and dust can result in a minor radiative forcing (mostly less than 10 W m^{-2}). These effects of LAIs on albedo reduction and radiative forcing enhanced glacier melt, which will further affect the hydrological processes. Estimation represented that LAIs in snow can lead to approximately 15% of the total glacier melt in the southeast TP and 6.3% increasing glacier melt in the Pamir regions. However, there still existed differences between the observations and simulations of LAIs in snow, which was mostly related to the different deposition flux and snow accumulation. In the future, mixing state of LAIs in snow, and their synergistic effects of biogeochemical process and climate change will be a new research direction.

black carbon, organic carbon, dust, light-absorbing impurities (LAIs), glacier, Tibetan Plateau

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