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青藏高原大气和雪冰黑碳的空间分布特征

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摘 要:青藏高原为亚洲主要河流提供水资源。青藏高原周边地区排放的黑碳气溶胶经大气环流可被传输至高原内部,并沉降到雪冰表面,对降水和冰川物质平衡产生重要影响。回顾近十几年来青藏高原大气和雪冰黑碳空间分布特征。结果表明:青藏高原大气黑碳浓度在空间分布上呈现出由外围向内部逐渐降低、由低海拔向高海拔指数降低的趋势;从季节变化看,西风气候区大气黑碳浓度夏季出现高值,季风气候区则冬、春季出现高值;青藏高原雪冰黑碳含量具有同大气黑碳浓度相一致的季节变化特征,并在空间分布上呈现出由南向北增加、由低海拔向高海拔降低的趋势。

关键词:黑碳;空间分布;季节变化;大气;雪冰;气溶胶;排放;青藏高原

中图分类号:X131.1;P427.2 **文献标志码**:A

Spatial Distribution Characteristics of Atmosphere and Snow Black Carbons in Qinghai-Tibet Plateau

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Abstract: Qinghai-Tibet Plateau is the source of major rivers in Asia. Black carbon (BC) aerosol emits from surrounding regions can be transported to the inner Qinghai-Tibet Plateau by atmospheric circulation and consequently deposited in snow, which can significantly influence precipitation and mass balance of glaciers. Spatial distribution of atmosphere and snow black carbons in Qinghai-Tibet Plateau was reviewed. The results show that the concentrations of atmosphere black carbon gradually decrease from the outside to the inner of Qinghai-Tibet Plateau, and exponentially decrease with the increase of elevation; the concentrations of atmosphere black carbon in the westerly region of Qinghai-Tibet Plateau show high values in summer and low values in winter, whereas those in the monsoon region present high values in winter and spring seasons, and low values in summer; the contents of snow black carbon have the same seasonal characteristics of the concentrations of atmosphere black carbon, and decrease from the southern to the northern part of Qinghai-Tibet Plateau, and linearly decrease with the increase of elevation.

Key words: black carbon; spatial distribution; seasonal variation; atmosphere; snow; aerosol; emission; Qinghai-Tibet Plateau

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0 引 言

青藏高原被誉为亚洲"水塔",拥有除南、北两极之外最多的冰川储备,其冰川融水是亚洲众多河流的重要淡水补给,与全球 60%人口的生活生产息息相关[1]。然而,青藏高原周边地区人口密集,能源结构和燃烧技术相对落后。包括黑碳(BC)气溶胶在内的污染物不但对人类健康造成危害[2],同时也会产生一系列的气候环境效应,特别是对区域地-气辐射收支、降水时空分布和冰川物质平衡的影响[3-5],引起了国际社会的广泛关注[6-7]。

由生物质和化石燃料燃烧排放的黑碳气溶胶对辐射具有极强的吸收作用,进而对地球系统的能量收支和分布具有重要影响,是气候环境变化不可忽视的影响因子[8-10]。首先,黑碳气溶胶悬浮在大气中可吸收更多来自太阳和地表的辐射能,对空气柱产生加热作用[11-12]。大气环流模型模拟显示,南亚黑碳气溶胶吸收辐射对大气的加热作用可使喜马拉雅山脉南麓、印度恒河平原上空 2~5 km 大气层升温 0.6 ℃,这可能是过去 50 年来喜马拉雅地区比全球平均增温快 1 倍的原因之一。另有研究发现,青藏高原积雪变化的空间分布特征同大气黑碳分布具有紧密的联系,模拟结果显示大气黑碳可使青藏高原地区升温 1.3 ℃[13]。其次,黑碳气溶胶可作为云凝结核,改变云滴微物理特性[14-15],降低云反照率,加热云滴及其周围环境,使云滴蒸发,减少云中液态水含量[16],抑制有效降水[11,17]。另外,沉降在积雪和冰川表面的黑碳能够显著改变冰雪表面的反照率[18],在冰雪下垫面产生正辐射强迫,进而导致近地表气温升高。但近期有研究指出,青藏高原某些地区沙尘对雪冰表面反照率及辐射强迫的影响显著高于黑碳所产生的影响[19]。Hansen 等的模拟结果显示,在 1880~2002 年间,海冰和雪中的黑碳所产生的地表正辐射强迫可使全球地表平均升温 0.17 ℃[20]。Jacobson 认为燃烧排放的黑碳和有机碳在 10 年中可使近地表温度上升 0.27 ℃[21]。Flanner 等使用 SNICAR 模型模拟的结果显示,青藏高原雪冰黑碳所引起的瞬时强迫最大可达 20 W·m^{-2}[22]。由此可见:黑碳可通过加热大气和降低雪冰表面反照率使区域气候变暖,诱发冰川、积雪融化;同时,黑碳可抑制季风活动和改变降水的时空分配[23-24],进而造成冰川物质平衡负增长。因此,青藏高原黑碳气溶胶不但影响区域气候和水循环过程,也会改变青藏高原冰川物质平衡。

综上所述,黑碳气溶胶的这些气候环境效应使其成为青藏高原冰川变化的重要影响因子。青藏高原大气和雪冰黑碳的观测及其空间分布特征对黑碳气溶胶在青藏高原区域气候环境变化研究中具有非常重要的意义。本文重点对青藏高原大气黑碳浓度和雪冰黑碳含量的空间分布特征进行了系统分析和整理。

1 大气黑碳浓度的空间分布

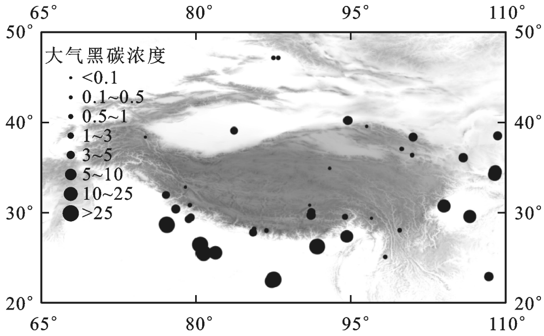
青藏高原地区海拔 3 000 m 以上区域大气黑碳平均浓度为(0.49±0.88)μg·m^{-3}[25-46],海拔4 000 m 以上区域大气黑碳平均浓度为(0.15±0.10)μg·m^{-3}[25,30,33-34,38-40,42-44,46]。青藏高原大气黑碳浓度高于南极(0.05~20 ng·m^{-3})[47-48],但低于北极(1~10 μg·m^{-3})[18],这表明青藏高原大气受人为活动影响较小。一般而言,青藏高原高海拔地区大气黑碳浓度低于低海拔地区,偏远区域低于人口密集的城市。此外,青藏高原大气黑碳季节变化特征也表现出明显的气候区差异[49]。

1.1 由外围向内部

图 1 汇总了青藏高原及周边地区大气黑碳浓度观测结果。由图 1 可以看出,大气黑碳浓度由高原外部向高原内部呈现出降低趋势。在海拔 3 000 m 以下的南亚,受人为排放影响较大的城镇、乡村地区大气黑碳平均浓度为(15.91±9.18)μg·m^{-3}[40,48-54],受人为排放影响较小的偏远地区大气黑碳平均浓度为(1.02±0.30)μg·m^{-3}[37-39,50,55-62];中国中西部乡村地区大气黑碳平均浓度为(3.93±0.21)μg·m^{-3}[27],而在中西部偏远地区则为(0.66±0.63)μg·m^{-3}[27,29,63-64]。值得指出的是,南亚受人为排放较小的偏远地区通常也是位于喜马拉雅山脉南侧海拔较高的地区(约 2 000 m)。在人口相对密集、排放较为强烈的城市(如拉萨),大气黑碳浓度相对于青藏高原内陆其他地区高出 1 到 2 个数量级[27-28]。虽然在旅游旺季来源于青藏高原本地的人类活动影响排放增加[30,65],但整体而言,由于青藏高原地势高耸、人口稀薄,大气黑碳浓度接近本底值。这也说明尽管南亚排放的污染物可在印度季风的作用下被传输至青藏高原内陆区域[30,65-66],但喜马拉雅高耸的山脉可以有效地阻挡大部分黑碳气溶胶向高原内部输入。

1.2 海拔变化

青藏高原大气黑碳主要来源于高原外部低海拔区域的排放。研究表明,在西风和印度季风作用下,

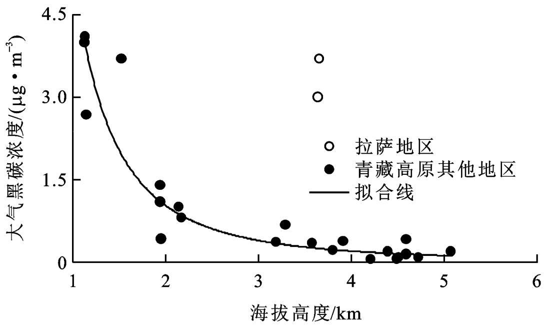


大气黑碳浓度单位为 $\mu g \cdot m^{-3}$；数据引自文献[25]～[65]

图 1　青藏高原及周边地区大气黑碳浓度空间分布

Fig. 1　Spatial Distribution of Concentration of Atmosphere Black Carbon over Qinghai-Tibet Plateau and Surrounding Area

青藏高原黑碳主要来源于中亚—东欧和南亚[5,67-68]。在大气黑碳传输过程中，受青藏高原的机械抬升作用，大气黑碳浓度由低海拔向高海拔呈现出指数降低的变化趋势(图 2)。此外，由图 2 可以看出，尽管拉萨海拔较高，但受当地人为排放影响，大气黑碳浓度显著高于青藏高原其他地区。



数据引自文献[25]～[65]

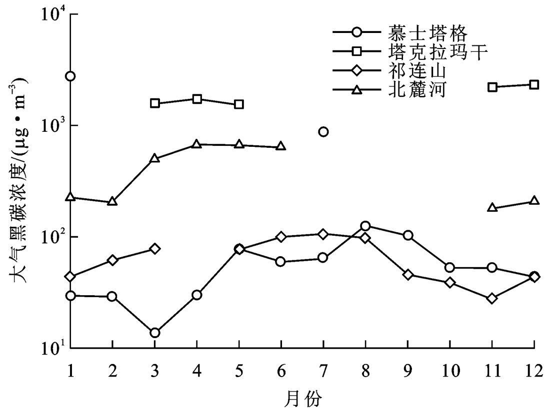
图 2　大气黑碳浓度随海拔高度的变化

Fig. 2　Variations of Concentration of Atmosphere Black Carbon Corresponding to Elevation

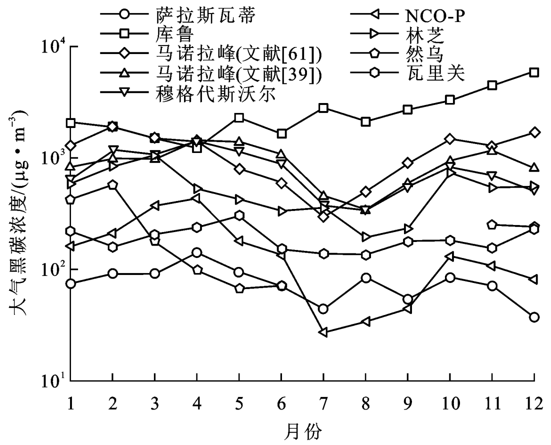
1.3　季节变化

青藏高原大气黑碳浓度的季节变化受排放源、大气环流和当地沉降条件等因素影响。在受人为活动影响较大的城市，大气黑碳浓度在冬、春季出现最高值，这主要来源于当地居民燃烧煤、牲畜粪便等致使黑碳排放量增加，同时干燥的区域气候条件不利于大气颗粒物沉降；在较为偏远的地区，大气黑碳浓度季节变化主要取决于大气环流和当地沉降条件。本文仅讨论受人为活动影响较小的观测点大气黑碳浓度的季节变化。

青藏高原南部至东南部区域，受季风影响显著，气候湿润、季风盛行的夏季降水量高，在此称之为季风气候区；青藏高原西北部和内陆北部地区，常年受西风急流影响，降水少，气候干燥，在此称之为西风气候区。已有研究显示：西风气候区大气黑碳浓度呈现出夏季较高的趋势(如慕士塔格、塔克拉玛干、祁连山和北麓河)；季风气候区则呈现夏季较低的季节变化特征(如萨拉斯瓦蒂、库鲁、马诺拉峰、穆格代斯沃尔、NCO-P、林芝、然乌和瓦里关)[25-64](图 3、4)。西风气候区大气黑碳浓度的高值主要同大气边界层活动活跃、地表污染物传输增强相关联；季风气候区则主要与区域季节性降水增强、大气污染物湿沉降增加相关。



(a)　西风气候区



(b)　季风气候区

数据引自文献[25]～[64]

图 3　大气黑碳月平均浓度季节变化

Fig. 3　Seasonal Variations of Monthly Mean Concentrations of Atmosphere Black Carbon

2　雪冰黑碳含量的空间分布

同两极相比，青藏高原雪冰黑碳含量(质量分数，下同)略高($(45\sim50)\times10^{-9}$)。北极地区雪冰黑碳含量为 30×10^{-9}[69]，格陵兰地区为 3.0×10^{-9}[20]，而南极雪冰黑碳仅为 0.2×10^{-9}[18]。在水平方向上，青藏高原雪冰黑碳含量由南向北呈现微弱增加趋势；在垂直方向上则呈现出随海拔升高而

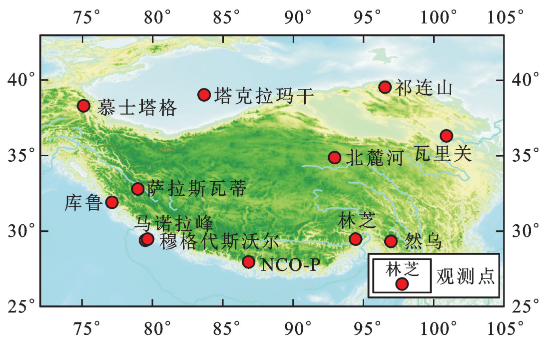


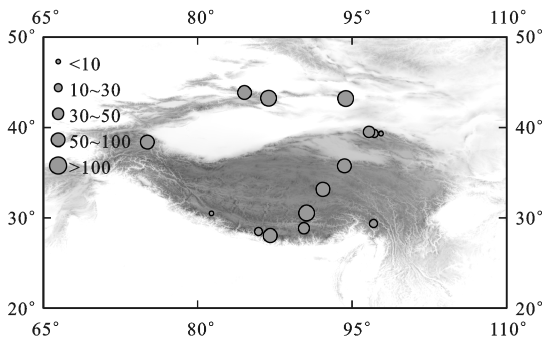
图4　观测点地理位置

Fig. 4　Locations of Observation Sites

降低的趋势。

2.1　区域分布

青藏高原雪冰黑碳含量具有较大的空间分布差异(图5)。纳木那尼冰川表雪的雪冰黑碳含量仅为4.3×10^{-9},而在乌鲁木齐1号冰川表雪的雪冰黑碳含量达155.5×10^{-9},二者相差2个数量级。从表1可以看出:各区域平均雪冰黑碳含量从小到大依次为藏东南地区、喜马拉雅山地区、祁连山地区、帕米尔高原地区、青藏高原中部地区、天山山脉地区;青藏高原雪冰黑碳含量在纬度梯度上呈现出由南向北升高的趋势(图6)。南亚密集的人类活动排放是青藏高原大气和雪冰黑碳的重要来源,而雪冰黑碳含量在纬度上的这种变化趋势表明,雪冰黑碳含量不但同大气环流和排放源相关,同时也与当地的降水量紧密相关。在青藏高原季风气候区年降雪量比西风气候区高,特别典型的是在藏东南地区年降雪量可达3.5 m[70],而在帕米尔高原地区年降雪量约为0.6 m[71]。在青藏高原纬度相对较低、受季风降水影响较大的区域,降水量显著高于青藏高原内陆和北部区域,这对雪冰黑碳具有"稀释作用",使得雪冰



雪冰黑碳含量单位为10^{-9};数据引自文献[3]、[5]、[63]、[68]、[72]~[79]

图5　雪冰黑碳含量空间分布

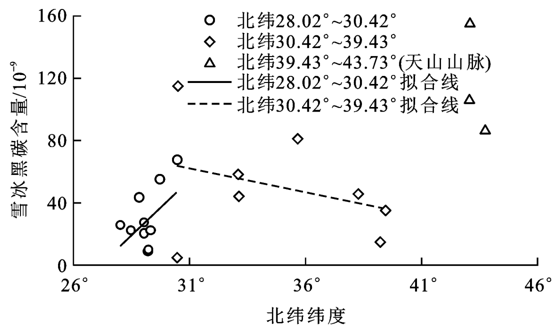
Fig. 5　Spatial Distribution of Contents of Snow Black Carbon

黑碳含量呈现较低值。随着纬度升高,季风带来的降水所产生的"稀释作用"逐渐减弱,雪冰黑碳含量随之升高。从本文调查数据来看,在北纬30.42°以南区域,雪冰黑碳含量随纬度增加而升高;而在北纬30.45°以北区域,随南亚季风输送能力减弱,雪冰黑碳含量呈现出下降趋势;天山山脉雪冰黑碳同青藏高原其他地区相比具有更高的含量,这很可能缘于其四周为地表干旱的荒漠,地表对底层大气的加热作用使得大气对流活动加强,可更有效地将地表黑碳传输至高空大气,进而形成天山山脉雪冰黑碳含量高值区(图6)。

表1　青藏高原各区域雪冰黑碳平均含量

Tab. 1　Mean Contents of Snow Black Carbon in Different Regions of Qinghai-Tibet Plateau

地区	雪冰黑碳平均含量/10^{-9}	数据来源
藏东南	9.0	[5]、[79]
喜马拉雅山	17.1	[3]、[5]、[73]、[76]、[77]
祁连山	21.2	[73]、[74]
帕米尔高原	45.8	[5]、[73]
青藏高原中部	63.6	[5]、[73]~[77]
天山山脉	116.5	[74]、[75]、[77]



天山山脉纬度范围较窄,观测数据较少,未标出拟合线;数据引自文献[3]、[5]、[70]、[73]~[77]

图6　雪冰黑碳含量纬度变化

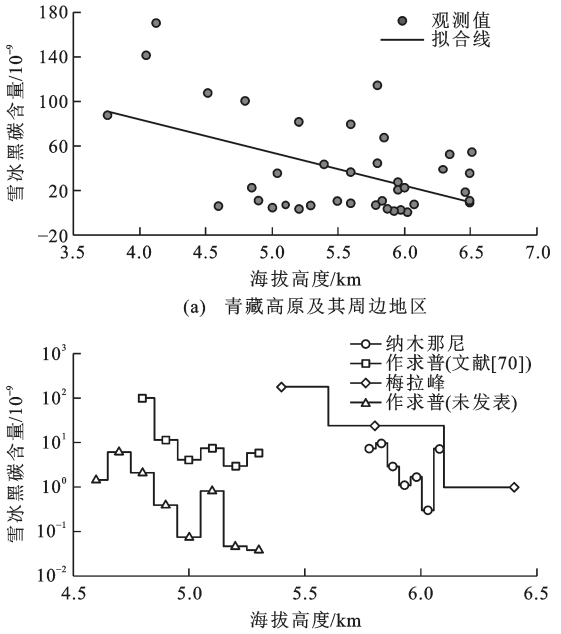
Fig. 6　Variations of Contents of Snow Black Carbon Corresponding to Latitude

此外,青藏高原典型气候区的雪冰黑碳含量具有同大气黑碳浓度相一致的季节性变化特征。在典型的季风气候区(藏东南)冰芯记录中,黑碳呈现出显著的冬、春季高,夏季低的季节变化特征[5,70];而在典型的西风气候区(东帕米尔高原)冰芯记录中,黑碳呈现出夏季高、冬季低的季节变化特征[76]。在藏东南地区,冰芯黑碳冬、春季高值反映了南亚大气棕色云的爆发以及西风带南支和南亚季风的输送,而夏季黑碳低值则反映了充沛的季风降水对区域大气环境的清洁作用以及对雪冰黑碳的"稀

释作用”；在东帕米尔高原地区，冰芯黑碳夏季高值反映了夏季中亚地区频繁的大气对流活动对地表黑碳更有效的输送[43,72]，而冬季低值则反映了较弱的大气对流活动。

2.2　沿海拔梯度的变化

青藏高原雪冰黑碳含量在海拔高度 3 500～6 500 m 范围内表现出显著地随海拔升高而降低的趋势[图 7(a)]。对于同一条冰川，表雪的雪冰黑碳含量同样具有随海拔升高而降低的变化特征[图 7(b)]。雪冰黑碳含量的这种沿海拔梯度分布特征主要由排放源的空间距离和污染物大气动力学传输高度决定。另外，在冰川低海拔区，随着积雪消融增强，融水流失，具有憎水特性的黑碳被保留在残留的雪中，由此形成富集。黑碳沉积后在表雪中的富集作用可使雪冰黑碳含量增长约 20 倍，极值可达 90 倍[5,75]。雪冰黑碳的这种沉积后作用可显著加强雪冰黑碳含量沿海拔增高而降低的空间分布特征。



(a)　青藏高原及其周边地区

(b)　同一条冰川

数据引自文献[3]、[5]、[70]、[73]～[77]

图 7　不同海拔高度雪冰黑碳含量变化

Fig. 7　Variations of Contents of Snow Black Carbon Corresponding to Elevation

3　结　语

(1)青藏高原大气黑碳浓度呈现出由外向内降低的趋势，体现出青藏高原周边低海拔地区人为活动排放向高原内陆传输的结果；另外，在青藏高原地势机械阻挡和抬升作用下，大气黑碳浓度呈现出由低海拔向高海拔指数降低的趋势。

(2)在青藏高原受人为活动较小的偏远地区，大气黑碳浓度的季节性变化主要取决于大气环流和区域降水条件。季风气候区由于夏季降水显著增强，大气黑碳浓度呈现出冬、春季高，夏季较低的季节变化特征；西风气候区则由于春、夏季近地表垂直对流活动加强，大气传输效率增加，大气黑碳浓度呈现出春、夏季较高，冬季较低的季节变化特征。

(3)青藏高原雪冰黑碳含量在纬度梯度上主要受降水条件影响，表现出由南至北含量升高的空间变化特征；而在海拔梯度上则主要受控于传输距离和传输高度，雪冰黑碳含量表现出随海拔升高而降低的特征，同时低海拔地区黑碳沉积后的富集作用可显著加强这种雪冰黑碳含量沿海拔增高而降低的分布特征。

(4)冰芯和表雪中雪冰黑碳含量具有与大气黑碳浓度相一致的季节变化特征，即季风气候区雪冰黑碳含量在冬、春季出现高值，西风气候区则在春、夏季出现高值。

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