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# 快速升温下的北极径流变化及其驱动机制综述

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**摘要:** 全球快速升温背景下,多年冻土广泛发育的北极流域水文情势发生显著变化,不仅改变了该地区的生态环境,也对全球气候系统和社会经济带来了深远影响。因此,北极流域水文过程研究已成为当前国际科学界关注的前沿热点问题。本文通过梳理国内外相关文献,系统回顾并总结了北极主要流域的径流时空变化及其驱动机制的研究成果与最新进展;详细分析了欧亚大陆和北美地区的径流变化规律与时空差异;深入探讨了快速升温下降水变化(降水量、雨/雪组分比例)和冻土退化对北极流域径流的直接与间接作用机制。尽管当前北极水文研究在数据积累和科学认识方面取得了重要进展,但仍面临地面观测站点稀少以及气候、积雪/冻土、水文之间响应难以定量等挑战。因此,建立完善的北极流域观测网络并发展具有北极特色的寒区水文模型,是深入理解北极水系统快速变化的基础,也是应对北极地区水灾害风险和提升水资源管理能力的关键所在。

**关键词:** 北极放大;水文情势;气候变暖;冻土退化;净降水
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## 1 引言

北极地区是全球气候变化最为剧烈的地区之一。1979—2021年北极地区的升温速度(0.73 ℃/10a)是全球其他区域的4倍[1],这一现象被称为“北极放大”效应(Arctic Amplification, AA)[2-3]。北极放大效应加速海冰融化并导致反照率降低,进而形成对气候的正反馈效应[3-7]。北极放大效应不仅直接改变了极地海洋、海冰、积雪/冻土、冰川与冰盖等极地系统要素[8-9],而且对北极地区生态环境[10-13],乃至北半球中高纬度地区[14-15]以及全球的大气圈[16-18]、水圈[19]、生物圈[20]和人类经济社会[21-22]产生深远影响。越来越多的研究表明,近年来北半球频发的极端气候与水文事件,诸如高温、热浪、干旱、强降水、洪涝等,均与北极放大具有密切的关联[23-24]。

从水循环的视角来看,持续快速的气候变暖促进北极地区的陆气交互作用,增加大气水汽含量[25],引起降水、蒸发和径流的显著增加[26-31],指示北极地区的水循环正在加剧[32]。由于河流是连接陆地和海洋的重要通道,伴随着北极河流径流量的增加,输送到

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北冰洋的淡水、泥沙以及其他陆源溶解物和颗粒物的通量也在显著增加[33-36]，从而对北冰洋的温度、盐度、海冰甚至海洋环流产生影响[37-42]，进一步导致海洋与大气之间能量交换增强，形成北极放大的正反馈效应。

北冰洋占世界大洋面积的3.6%，体积仅占1%，但汇集了全球11%的地表径流量[43]。这主要归因于北极地区河流众多（图1），其流域面积约为22.5×10$^6$ km$^2$，占全球陆地面积的15%[30]，是北冰洋面积的1.5倍[44]。随着气候变暖，北极地区的地表径流量整体上显著增加[45]，但不同流域之间以及不同季节内的北极河流径流量变化存在显著差异。本文将从水文地理学的视角[46]来综合分析快速增暖背景下北极流域径流变化的主要特征，以及径流变化背后的关键机制。

## 2 北极流域概况及研究历程回顾

北极地区的大河主要分布在欧亚大陆和北美地区。其中，欧亚大陆上的北极河流主要分布在俄罗斯境内（图1），自西向东主要包括北德维纳河（Northern Dvina）、伯朝拉

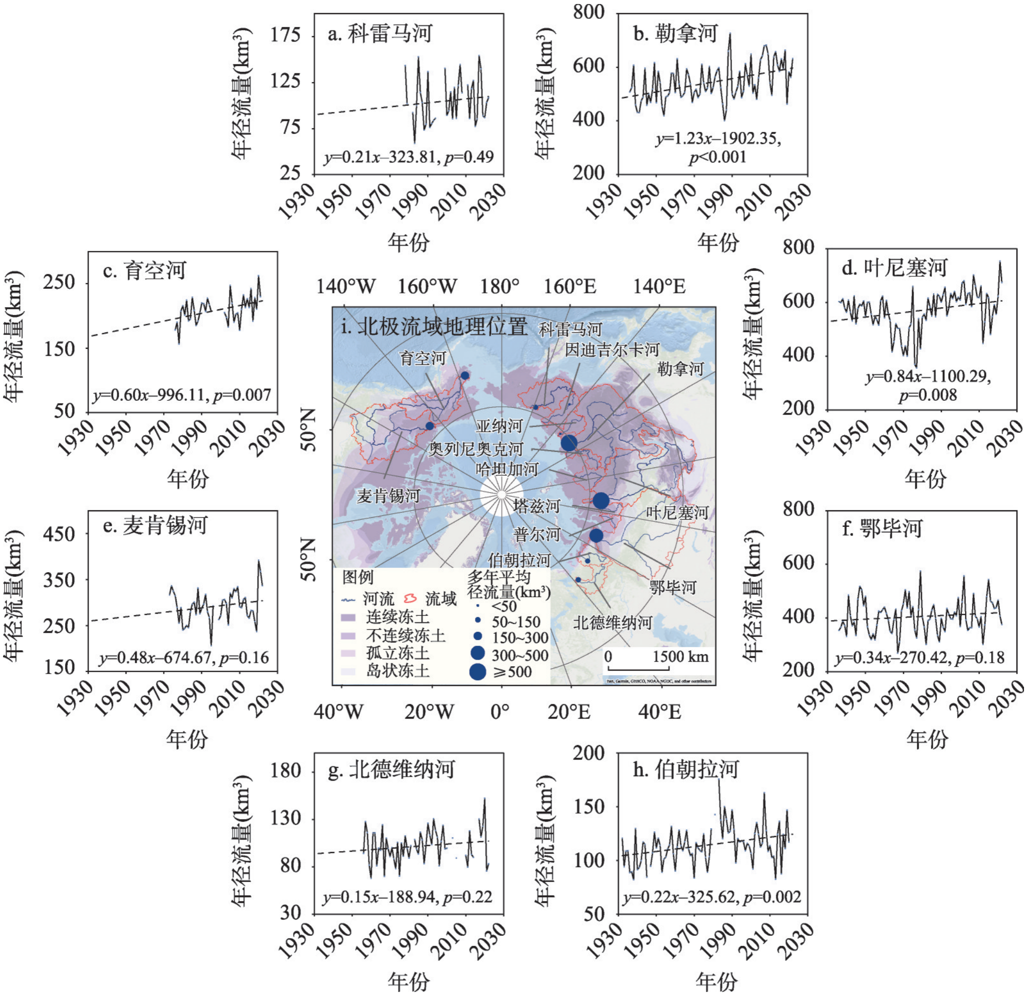



图1　北极流域地理位置分布及主要河流的年径流变化

Fig. 1 Geographic distribution of Arctic river basins and temporal changes in annual runoff from major rivers

河（Pechora）、鄂毕河（Ob）、普尔河（Pur）、塔兹河（Taz）、叶尼塞河（Yenisei）、哈坦加河（Khatanga）、奥列尼奥克河（Olenek）、勒拿河（Lena）、亚纳河（Yana）、因迪吉尔卡河（Indigirka）和科雷马河（Kolyma）。在北极地区的6条最大河流中，其中4条河流（鄂毕河、叶尼塞河、勒拿河、科雷马河）位于欧亚大陆的西伯利亚地区（表1）。从俄罗斯境内流入北冰洋的多年平均河流径流量为2922 $km^3$，约占北冰洋的河流径流总汇入量的55.6%[47]。

**表1 北极地区主要河流的径流观测信息[52]**

**Tab. 1 Runoff observation of major rivers in the Arctic region [52]**

| 河流 | 水文站纬度 (°N) | 水文站经度 (°) | 多年平均径流量 ($km^3$) | 流域面积 ($10^6$ $km^2$) | 径流观测时段 |
|---|---|---|---|---|---|
| 鄂毕河 | 66.63 | 66.60 E | 405 | 2.95 | 1936—2022年 |
| 叶尼塞河 | 67.43 | 86.48 E | 570 | 2.44 | 1936—2022年 |
| 勒拿河 | 70.68 | 127.39 E | 544 | 2.43 | 1936—2022年 |
| 科雷马河 | 67.47 | 153.69 E | 105 | 0.65 | 1978—2022年 |
| 育空河 | 61.93 | 162.88 W | 209 | 0.83 | 1976—2021年 |
| 麦肯锡河 | 67.45 | 133.74 W | 292 | 1.75 | 1973—2022年 |
| 北德维纳河 | 64.13 | 41.92 E | 102 | 0.35 | 1956—2022年 |
| 伯朝拉河 | 65.42 | 52.28 E | 114 | 0.25 | 1932—2020年 |
| 普尔河 | 67.01 | 78.22 E | 168 | 0.11 | 2018—2022年5—10月 |
| 奥列尼奥克河 | 71.85 | 123.65 E | 42 | 0.22 | 1991—2022年 |
| 亚纳河 | 70.77 | 136.08 E | 33 | 0.24 | 1978—2022年 |

北美地区主要发育两大北极河流，即育空河和麦肯锡河（图1）。麦肯锡河是加拿大境内最长的河流，流域面积为175万 $km^2$，约占加拿大陆地总面积的20%，其多年平均径流量为292 $km^3$（图1、表1）。研究表明，多年冻土约占麦肯锡河流域面积的75%[48-50]，且流域内分布众多大型湖泊，如大熊湖、大奴湖等。育空河位于加拿大西北部和阿拉斯加中部，是北美地区的主要河流之一，流域面积约为83万 $km^2$，多年平均径流量为209 $km^3$（表1）。育空河流域几乎全部被多年冻土覆盖（覆盖率约96%），其中连续型和不连续型多年冻土约占一半[49-50]。育空河流域的地表径流主要来自于冰雪融水和大气降水[51]。

北极河流水文情势变化的野外观测最早开始于20世纪初[47]。其中鄂毕河、叶尼塞河、勒拿河和伯朝拉河的径流观测记录甚至可追溯至20世纪30年代（表1）。当前，Arctic Great Rivers Observatory研究团队实时整编北极大河流域日径流观测数据（https://arcticgreatrivers.org），为研究北极河流径流变化提供了数据基础[52]。

自21世纪初以来，全球科学家开始关注北极地区径流变化及其背后的物理机制[30-31, 53]。表2列出了1912—2018年间北极流域地表径流的不同估算结果。值得注意的是，由于不同学者关注的流域范围不同（从局部区域的5.26×$10^6$ $km^2$至全流域的24.20×$10^6$ $km^2$），选取的研究时段和研究方法也存在差异，由此得到的多年平均径流深介于200~234 mm之间不等。近年来，北极流域径流观测与模拟的研究手段不断改进，从早期单一的水文观测数据整编，发展到当前基于水文气象数据及水文模型的径流量估算[30, 44, 54]。研究数据也从传统的水文监测[55]，扩展至气象卫星监测[44]与遥感大数据[56]相结合等。

**表2 北极地区地表径流量评估汇总表**

**Tab. 2 Summary of various assessment values of surface river runoff in the Arctic region**

| 序号 | 汇流面积 ($10^6$ $km^2$) | 多年平均径流量 ($km^3$) | 多年平均径流深 (mm) | 研究时段 | 研究方法 | 文献来源 |
|---|---|---|---|---|---|---|
| 1 | 12.9 | 2603 | 202 | 1912—1995年 | 观测 | [57] |
| 2 | 24.2 | 4749 | 212 | 1960—1989年 | 观测+分析 | [55] |
| 3 | 9.1 | 1932 | 212 | 1936—1999年 | 观测 | [31] |
| 4 | 16.9 | 3658 | 216 | – | 观测+模型 | [58] |
| 5 | 18.9 | 4314 | 228 | 1921—1999年 | 观测+分析 | [44] |
| 6 | 23.7 | 5250 | 222 | 1921—1999年 | 观测+分析 | [44] |
| 7 | 11.4 | 2310 | 203 | 1940—1990年 | 观测 | [59] |
| 8 | 16.4 | 3596 | 219 | 1979—1999年 | 模型 | [54] |
| 9 | 8.8 | 1796 | 204 | 1936—2006年 | 观测 | [60] |
| 10 | 12.1 | 2420 | 200 | 1964—2000年 | 观测 | [61] |
| 11 | 15.8 | 3162 | 200 | 1980—1999年 | 模型 | [62] |
| 12 | 16.7 | 3730 | 223 | 2003—2005年 | GRACE卫星 | [56] |
| 13 | 19.0 | 4300 | 226 | 1936—2006年 | 观测+模型 | [63] |
| 14 | 5.26 | 1154 | 219 | 1964—2013年 | 观测 | [64] |
| 15 | 11.3 | 2310 | 204 | 1970—2017年 | 观测 | [65] |
| 16 | 13.5 | 2996 | 221 | 1975—2015年 | 观测+分析 | [66] |
| 17 | 22.1 | 5169 | 234 | 1984—2018年 | 模型 | [30] |

# 3 北极流域径流变化特征

欧亚大陆河流径流量占北极地区总径流量的65.8%，而北美地区河流径流量占比为34.2%[30]。近年来，北极地区河流径流总量显著增加[29, 31, 67-69]，但欧亚大陆地区的河流径流增加量显著高于北美地区[30, 32]，表明欧亚大陆地区和北美地区的径流变化存在一定的差异。此外，近来的研究更加关注冬季径流的变化。尽管北极流域冬季径流量在全年径流中的占比低，但随着全球变暖的加速，其增加速率远超全年径流[70-73]，指示了北极寒区流域多年冻土退化及地下径流系统对环境变化的快速响应。下文将具体从年径流和冬季径流两个方面来探讨北极流域径流的变化特征。

## 3.1 年径流变化特征

据Peterson等[31]的研究，1936—1999年欧亚大陆6条大河（北德维纳河、伯朝拉河、鄂毕河、叶尼塞河、勒拿河、科雷马河）的年径流量增加了约7%，为128 $km^3$。然而，自1980年代快速升温以来，这6条河流的径流量增速有所加快，1981—2011年6条河流年径流量增加12%[32]。这一地区大河的径流虽都在显著增加，但各条河流径流量变化的速率存在较大差异（图1）。根据Wang等[53]的研究，1936—2019年鄂毕河和叶尼塞河的年径流量增加约7%~8%，而勒拿河的径流量同期增加达22%。

北美地区径流量变化的早期研究发现，1975—2015年麦肯锡河和育空河的年径流量增加了9%[32]。最新观测数据也显示，1975—2022年北美地区这两大北极河流年径流量呈现增加趋势（图1），与前人的研究结果一致[30, 45, 74]。值得注意的是，2010—2019年麦肯锡河的径流量呈现下降趋势，然而在2020年出现了急剧的增加，育空河在同一时期则持

续显著增加。根据径流观测数据，1976—2021年虽然育空河的年径流量小于麦肯锡河，但其增长速率却高于麦肯锡河（图1）。

### 3.2 冬季径流变化特征

北极河流径流变化的另一个典型特征是冬季径流量显著增加。北极地区冬季持续半年，从11月到次年4月[75-76]。由于寒冷地区冬季降水通常以积雪形式存在，冬季地表径流量极低，且主要来源于基流[77]。以北美地区的麦肯锡河和育空河为例，其冬季径流量仅占全年总径流量的21%和15%。

1980—2009年鄂毕河、叶尼塞河、勒拿河和麦肯锡河在12月至次年2月间的总径流量增加1.3%[78]。1980—2019年勒拿河、科雷马河、育空河和麦肯锡河的冬季径流量分别增加了43%、72%、16%和16%，为年均径流增幅的1.7~5.2倍[72]。此外，相比于1936—1975年，1976—2015年期间欧亚大陆地区的北德维纳河、伯朝拉河、鄂毕河，以及西西伯利亚北部的河流和拉普捷夫海流域西部的河流，冬季径流量增加了15%~40%[47]。而同期叶尼塞河、勒拿河和科雷马河的冬季径流量增加更为明显，分别为68%、47%和174%[47]。值得注意的是，小流域的冬季径流变化通常更为显著，如1995—2019年叶尼塞河上游流域冬季径流增加了80%，而同期的年径流量仅增加7%[71]。

## 4 快速升温下的北极径流变化驱动

北极流域径流过程能够直接和间接地受到气候变化的影响[79]，如降水的变化[80-81]、积雪量及消融模式的变化[82-83]，以及多年冻土退化[53, 84-85]等。此外，诸如水库的修建[86-87]和调蓄[47, 88]等人类活动也极大地影响径流在年内的季节分配[89]，导致河流冬季和夏季径流量发生显著变化[90-91]。然而，对于北极大河的年径流量而言，人类活动的影响相对较小[89]，其变化主要受到气候变化的影响。

从水文学的视角来看，降水和气温是影响流域水文过程及年径流量变化的关键气象要素。基于温度、降雨双参数弹性系数分析发现，北极河流年径流量的增加主要是由降水增加导致的[53]（图2a）。值得注意的是，在全球干旱半干旱区，升温通常带来流域的蒸散发量增加，进而导致地表径流量减少[92]。与之相反，在北极寒区流域，升温常常伴随流域冬季径流量的增加（图2b）[53]。这主要与升温导致的北极流域多年冻土退化密切相关。本文将聚焦北极气候变化，从净降水量变化、积雪情势变化、降水相态转化、多年冻土退化4个方面（图3），探讨快速升温背景下北极径流变化背后的水文学机制。

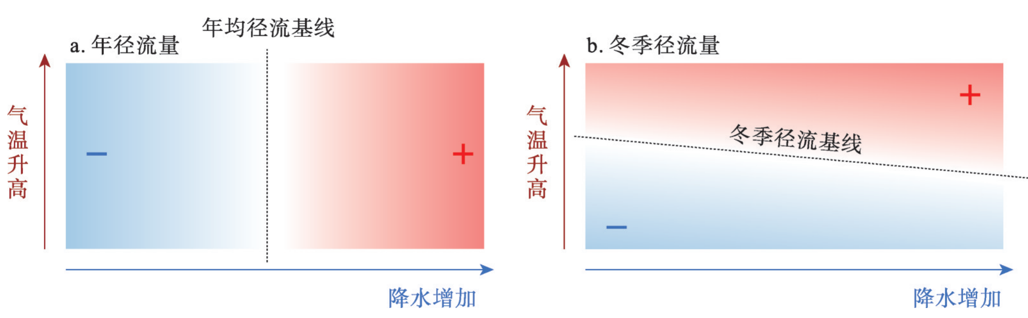
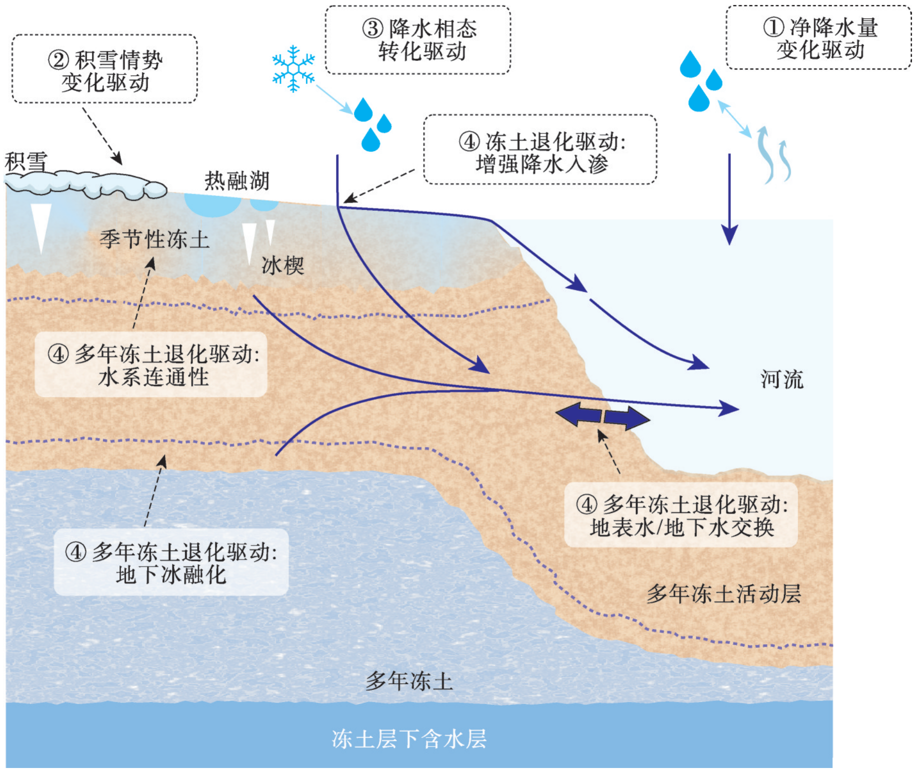



图2 北极流域年径流量和冬季径流量对气温与降水变化的响应

Fig. 2 Schematic diagram illustrating the response of annual runoff and winter runoff in the Arctic basin to changes in temperature and precipitation




注：修改自Liu等[72]。

图3　北极流域径流过程变化的主要驱动示意图

Fig. 3　The schematic diagram depicting the key drivers that predominantly influence hydrological processes within the Arctic river basin

### 4.1 净降水量变化驱动

受气候变化的影响，包括鄂毕河、叶尼塞河、勒拿河、麦肯锡河等在内的北极流域正在变得更加温暖和湿润[93-94]。随着气温升高，北极地区蒸发量增加[95]，其中冬季[29]和多年冻土区[96]的增速更为显著，这导致了大气中的水汽含量增加。根据克劳修斯—克拉贝龙方程（Clausius-Clapeyron relation），温度每升高1 ℃，大气水分含量约增加7%[97]，进而带来降水增加[98]。1979—2017年北极陆地降水的增速为(0.10±0.05) (mm/d)/100 a[99]，同期西伯利亚三大流域的年降水增速可达0.25 (mm/d)/100 a [100]。研究证实，北极地区降水对升温的敏感系数为4.5% /℃[27]，其中西伯利亚东部的平均和极端降水在秋季的增加趋势接近热力学约束的8% /℃[99]。根据气候模型的模拟结果显示，在未来持续升温的背景下，北极地区的降水增加速度和幅度将远远超过先前的预估结果[26]。至21世纪末（2091—2100年），北极地区的降水量将增加50%~60%，显著高于全球平均水平[101-102]。

从水量平衡的角度来看，一个流域的径流变化主要取决于降水与蒸发。当前北极陆地的降水量增速远大于蒸发量增速，引起北极流域净降水量（降水量与蒸发量之差）增加，进而导致河流径流量增多[29]。1980—2017年鄂毕河年降水量增速为1.27 mm/a，而年蒸发量的增速仅为0.54 mm/a，导致径流量在同期以0.54 mm/a的速率持续增加[103]。Berezovskaya等[80]利用1936—1998年的降水与径流观测数据，证实了西伯利亚勒拿河流域径流量与降水量呈现同步增加的态势。在未来更加温暖和湿润的气候条件下，麦肯锡

河、勒拿河和叶尼塞河等北极河流的径流量将在整个21世纪持续增加[94]。模型预测，到21世纪末北极地区的净降水量将达到2318~2734 $km^3/a$，远高于之前的预估结果[104]。因此，随着快速升温的影响，北极流域径流量可能将持续增加。

### 4.2 积雪情势变化驱动

积雪作为大气圈和冰冻圈的关键要素之一[105]，也是重要的水文变量。气候变暖对北极地区的积雪分布、积雪量和积雪融化时间等产生显著影响[106-109]。1970—2010年北半球3—4月积雪覆盖面积明显缩小，减少速率达80万 $km^2/10$ a [110]。同时，1992—2016年北半球年均积雪量呈显著下降趋势（197.2 $km^3/10$ a），总计减少约13%[111]。此外，1960—2000年北极大部分地区均出现积雪期缩短、春季融雪时间提前的现象[112-113]。以1979—2009年为例，北极地区的积雪日数和雪水当量分别以−2.49 d/10 a和−0.17 cm/10 a的速率减少[114]。

在全球变暖的背景下，积雪变化对河流径流过程产生显著影响[115-116]。在春季融雪期，北极四大流域（鄂毕河、叶尼塞河、勒拿河、育空河）的河流径流量与积雪面积呈显著相关，积雪面积越大，径流量越低；随着积雪面积减少，河流径流量呈增加趋势[82-83, 117]。通过对叶尼塞河融雪径流的进一步研究发现，在融雪初期，河流径流量减少，而在融雪后期，河流径流量增加[91]。此外，随着全球升温，积雪融化时间提前，导致河流的径流峰值从夏季提前到春季[118]。受融雪时间提前的影响，欧亚大陆北极河流5月份的流量显著增加[119-120]。根据未来情景预估，至21世纪末，北极地区春季积雪面积可能减少10%~35%，积雪深度和雪水当量也相应减少[121]，积雪情势变化对北极径流的影响仍将持续。

### 4.3 降水相态转化驱动

降水相态（即降雨和降雪）的转变能够直接影响流域径流的形成[81, 122]。伴随北极升温，更多降雪在到达地表前就已融化，特别是在夏季和秋季[101]。已有研究证实，北极地区降雪向降雨的相态转变，导致秋季至冬季的河流径流量增加[123]。预计到2091—2100年，降雨将成为北极地区的主要降水形式[124]。伴随着积雪融化提前、积雪日数减少和降雨增多[109, 123]，北极地区出现春汛提前、地表径流增加等现象[125-126]，导致区域径流从“融雪—径流主导型”向“降雨—径流主导型”的转变[101]。

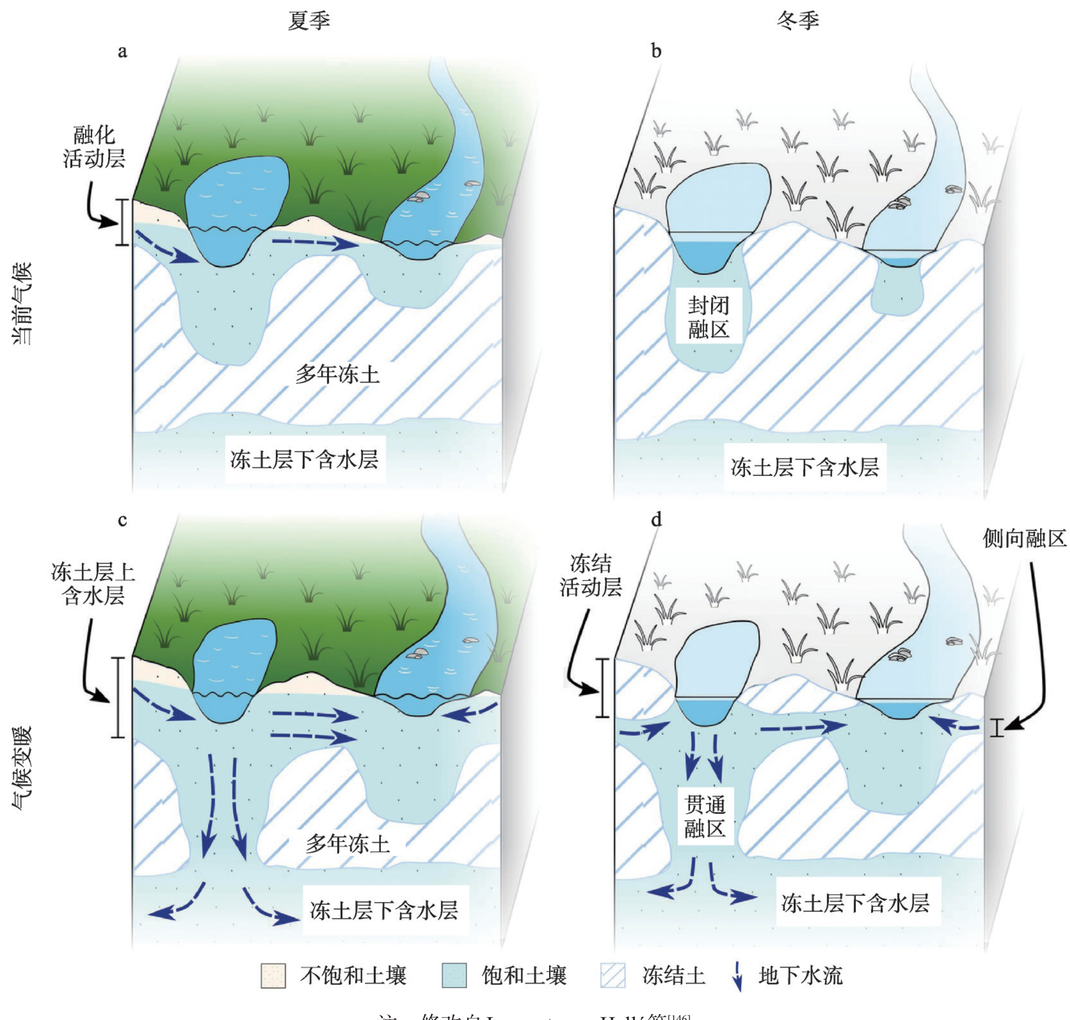
降雪向降雨相态的转变还将进一步加速多年冻土退化，并影响径流过程。通过增强地表感热传递，降水入渗导致多年冻土中的地下冰融化（图3），增加了地下水向河流的补给量[127]。阿拉斯加的野外观测数据表明，降雨量每增加1 cm，多年冻土退化深度将增加(0.7±0.1) cm[128]。在富含冻土冰的西伯利亚苔原区，夏季降雨量每增加10 cm，冻土融化深度将增加35%，且该影响在随后两年内还将持续存在[129]。观测与模拟研究结果表明，降雨对多年冻土退化的贡献与升温相当[130]，并共同影响径流过程。然而，降雨—冻土退化—地表/地下径流之间的响应关系仍难以定量。

### 4.4 多年冻土退化驱动

北极流域的重要特征之一是广泛分布多年冻土。在全球升温的背景下，多年冻土正在加速退化[131-134]，表现为多年冻土温度升高、面积减少、冻土活动层厚度增加，以及季节性冻土融化期延长且冻结期缩短等[135]。欧亚大陆和北美地区的575个多年冻土观测孔监测数据显示，多年冻土温度自20世纪70年代起开始上升[136-137]，仅在2007—2016年全球多年冻土升温了(0.29±0.12) °C[10]。加拿大西北部1 $km^2$区域的遥感监测显示，1947—2008年多年冻土面积从0.70 $km^2$减少到0.43 $km^2$ [138]。此外，20世纪70年代起冻土活动层也发生快速变化，至2013年鄂毕河、叶尼塞河和勒拿河流域的冻土活动层体积分别增加了28 $km^3$、142 $km^3$和228 $km^3$ [135]。模拟结果显示，当全球地表温度升高1.5 ℃时，在

RCP2.6（2027—2036年）、RCP4.5（2026—2035年）和RCP8.5（2023—2032年）情景下，多年冻土退化面积将分别达到23.6%、24.1%、25.6%[139]。由此可见，在全球持续升温背景下，多年冻土正在快速退化。

多年冻土退化可以通过改变活动层厚度、土壤含水量和地下径流量（即基流量）[140]，以及地表水和地下水之间的交换强度等[84, 141-143]，对流域径流过程产生直接或间接的影响。在多年冻土退化的过程中，一方面，地下冰不断融化，增加了地下水储量和含水层导水性[85, 144-145]，增强了地表水与地下水之间的连通性与交换强度[146-147]，从而导致地下水向河流排泄的水量（即基流量）持续增加（图4）[148]。特别是在多年冻土覆盖率较高的流域，活动层更厚、地下水储存能力更强，从而有利于增加地表径流[135]。另一方面，多年冻土退化还能够通过改变河流形态[149]和地貌形态（如热融喀斯特、热融滑坡和滑塌等）[150-152]，影响流域水流路径和水系连通性[153]，部分地表水甚至通过贯通融区渗漏至地下含水层（图4），从而导致湖泊等地表水体的干涸[84, 146]，影响流域水文过程。此




注：修改自Lamontagne-Hallé等[146]。

图4　当前气候及未来升温背景下的夏季与冬季水文过程及其对多年冻土退化的响应

Fig. 4　Conceptual hydrogeologic permafrost systems under the present climate conditions and its potential changes in a warmer climate for summer and winter

外，冻土退化可以通过影响植被生长状况[154-156]和演替过程[157]，改变地表辐射平衡及蒸散发通量[155, 158]，进而影响流域径流过程。

# 5 挑战与展望

北极升温带来的“放大效应”通过改变物质和能量交换，深刻影响着全球水文循环过程。然而，由于北极地区的海冰、积雪、多年冻土、冰川等多个水文要素之间的相互作用[8]，水文系统对气候变暖的响应异常复杂[159]，给北极水文研究带来巨大的挑战。尽管遥感监测和模型等研究方法的快速发展在很大程度上弥补数据缺失的不足，但仍需要与地面观测数据（特别是径流观测数据）相结合，并相互补充验证。因此，地面观测成为北极地区环境和水文变化研究的一个关键问题[160]。然而，由于北极地区地广人稀且气候条件极端恶劣，地面观测工作异常艰难，获取到的观测数据十分有限且难以连续。据Shiklomanov等[44]的统计，北美和俄罗斯地区的北极水文观测站点数量在1985年前后达到峰值（超过3000个），但随后开始减少，尤其受苏联解体的影响，到2000年站点数量甚至减少了38%。此后，在2008年的全球金融危机影响下，可用的北极地区地面观测站点进一步减少[99]。由此导致的地面观测数据缺失严重影响了北极观测数据的连续性。以叶尼塞河流域为例，其径流观测数据先后存在长达13年（1963—1965年、1968—1974年及1977—1979年）的数据缺失[78]。加上观测方法自身的局限性，所获取的径流数据通常还会存在3%~6%的误差[161]，增加了观测结果的不确定性。对北极河流而言，由于河水在冬季结冰，冬季的日尺度径流观测数据的误差尤为显著[162]。因此，地面站点观测数据的数量和质量极大地限制了对径流变化及其对气候变暖响应的量化分析[163]。此外，诸如水库调蓄、农业灌溉等人类活动也对北极流域的径流季节性变化产生影响[60, 90]，增加了北极水文过程研究的复杂性。综上所述，建立起北极流域径流及相关环境要素（如温度、降水、多年冻土、人类活动等）的动态监测网络，是当前北极水文过程研究所面临的重要挑战。

多年冻土作为指示气候临界点的重要指标之一[164-165]，正经历快速升温与退化。多年冻土的退化会导致流域的退水过程减缓，进而影响流域的径流过程。其中，地下径流作为与多年冻土退化紧密相关的径流组分，既直接受多年冻土退化的影响，又反向作用于多年冻土退化过程，使其成为极地环境快速变化的重要驱动因素[166-167]。从水文科学发展的角度来看，寒区径流和地下水如何随气候变暖而改变（如冰川消融和多年冻土融化），仍然是水文学中未解决的23个重要科学问题之一[168]。同时，多年冻土退化的水文效应也是冰冻圈科学与地球系统科学研究的核心问题之一[84]。然而，由于多年冻土与水文系统之间的相互作用极为复杂，并且随着多年冻土状态的变化而发生改变，加之多年冻土空间分布及其含冰量存在显著的时空差异，目前尚无法准确识别并量化多年冻土退化在水文过程中的作用。此外，由于难以对多年冻土变化进行高密度的实时监测，对多年冻土区水文过程的准确模拟和预测始终存在观测手段和数据等方面的限制，导致目前对多年冻土退化的水文效应的认识仍然不足，更难以进行更为深入和准确的定量分析[145]。因此，加强对北极多年冻土区的监测[169]，发展耦合冻融过程的寒区地下水模型[146]，量化多年冻土退化对径流变化的影响和贡献，揭示多年冻土退化对水文过程的影响机制，将成为未来极地水文学研究的重要方向。

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# Arctic runoff changes and their driving mechanisms under rapid warming: A review

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**Abstract:** Under the background of rapid global warming, the hydrological regime in the Arctic river basins, where permafrost is widely developed, has changed significantly. These changes not only altered the local ecological environment, but also had far-reaching impacts on the global climate system and socio-economy. Therefore, the study of hydrological processes in Arctic river basins has become a hot-spot issue at the forefront of the international scientific community. Based on a thorough review and critical analysis of domestic and international literature, this paper systematically summarizes the research findings and latest progress on the spatial and temporal changes of the runoff of major Arctic rivers, as well as the driving mechanisms behind these variations. In addition, the patterns and spatiotemporal differences in runoff changes between Eurasia and North America were analyzed in detail. Furthermore, the direct and indirect effects of precipitation changes (e.g., precipitation amount, rain/snowfall fractions) and permafrost degradation on Arctic runoff are thoroughly examined. Despite significant progress in data accumulation and scientific understanding in current Arctic hydrological research, considerable challenges persist, such as the scarcity of ground observations and the difficulty of quantitatively assessing the interactions among climate, snow/permafrost, and hydrological processes. Thus, establishing a robust observation network in the Arctic river basins and developing cold region hydrological models with account for the Arctic specifics are fundamental for gaining in-depth insights into the rapid changes occurring in the Arctic hydrological system. This is also crucial for addressing the risks of water-related disasters and enhancing water resource management in the Arctic region.

**Keywords:** Arctic amplification; hydrological regime; climate warming; permafrost degradation; net precipitation