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极地冰盖空天遥感监测:进展与展望

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摘 要:极地冰盖物质损失是全球海平面上升的重要来源,空天遥感技术已成为揭示其变化与失稳过程的主要手段。围绕冰盖/冰架系统过程、内部结构和物质平衡3个方面,系统梳理国内外尤其是国内科学界利用卫星及航空遥感技术在冰盖运动、融化、裂隙、粒雪含水层、冰下湖、接地线和质量平衡变化等要素监测中的进展。空天遥感监测结果表明,格陵兰冰盖物质损失主要受表面消融与溢出冰川加速流出所主导,南极冰盖物质损失则以冰架底部融化、接地线退缩驱动的动力失稳为驱动。现有遥感产品在时空分辨率和误差控制方面仍存在明显不足,内部融水迁移、冰下水系、底部通道及裂隙三维结构仍难以被连续、大范围监测。未来应加强多源遥感协同反演与立体透视探测,完善过程观测至物质平衡估算的不确定性传递,推动空天遥感从冰盖现状监测向失稳过程诊断与风险评估发展。

关键词:极地冰盖;空天遥感;冰盖失稳;内部结构;物质平衡;冰架

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Spaceborne and Airborne Remote Sensing of Polar Ice-Sheet: Advances and Prospects

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Abstract: Polar ice-sheet mass loss is an important contributor to global sea-level rise, and spaceborne and airborne remote sensing has become the primary means of observing its evolution and instability. This paper systematically reviews advances made by the international community, with particular emphasis on contributions from the Chinese scientific community. The remote-sensing monitoring of ice sheets and ice shelves is reviewed from three aspects, including ice-sheet/ice-shelf system processes, internal structure, and mass balance. Spaceborne optical imagery, synthetic aperture radar, microwave observations, satellite altimetry and gravimetry, together with airborne remote sensing, have enabled observations of ice flow, surface and basal melting, fractures, firn aquifers, subglacial lakes, grounding lines, and ice-mass change. Remote-sensing observations show that the Greenland Ice Sheet mass loss is mainly controlled by surface ablation and accelerated discharge from outlet-glaciers, whereas the Antarctic Ice Sheet mass loss is pri-

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marily driven by dynamic instability associated with ice-shelf basal melting and grounding-line retreat. Current remote-sensing products remain limited in terms of spatiotemporal resolution and uncertainty control, while englacial meltwater transport, subglacial hydrological systems, basal channels, and three-dimensional fracture structures remain difficult to monitor continuously and over large spatial scales. Future efforts should strengthen multi-source remote-sensing synergistic retrievals and three-dimensional observations, improve uncertainty propagation from process observations to mass-balance estimates, and advance spaceborne and airborne remote sensing from monitoring the current state of ice sheets toward diagnosing instability processes and assessing associated risks.

Key words: polar ice sheet; spaceborne and airborne remote sensing; ice-sheet instability; internal structure; mass balance; ice shelf

极地冰盖作为地球气候系统中最关键的调节器与全球最大的淡水资源库,其动态变化深刻影响着全球海平面、大洋环流与气候系统格局(图1)。南极冰盖面积约1 400万km^2,储存着足以抬升全球海平面约58 m的冰量;格陵兰冰盖面积约180万km^2,其完全融化将导致海平面上升约7.4 m。自20世纪90年代中期以来,格陵兰冰盖加速消融、持续退缩并减薄,南极冰架崩解与底部融化加剧导致内陆冰体加速流入海洋,极地冰盖物质损失已成为全球海平面上升的主要贡献者[1-3]。

卫星遥感已成为极地冰盖研究最核心的技术手段,在冰盖冰架系统过程、内部结构与物质平衡等方面取得了系统性进展。航空遥感作为卫星观测的重要补充与验证手段,在极地冰盖研究中同样发挥着不可替代的作用。美国国家航空航天局(National Aeronautics and Space Administration, NASA)于2009年启动冰桥计划(Operation IceBridge, OIB),利用机载激光雷达、冰穿透雷达等载荷系统获取了极地冰盖表面地形、粒雪含水层、冰下基岩地形、接地线位置及冰厚等关键参数[4]。中国雪鹰601固定翼飞机自2015年起投入南极考察,集成了冰雷达、航空重力仪、磁力仪、激光高度计等探测设备,在伊丽莎白公主地等关键区域开展了系统性的航空地球物理调查[5]。

近年来,以无人机为代表的近地遥感平台发展迅速,能够以厘米级空间分辨率获取高精度三维地形数据,在冰架微地形精细刻画、裂隙深度提取、表面水系动态监测及冰崖崩解过程定量评估中展现出独特优势[6]。本文旨在系统梳理极地冰盖关键过程与稳定性的空天基遥感监测现状,以期为深入开展冰架稳定性评估与演化预测提供科学支撑。

1 极地冰盖/冰架系统过程遥感监测

极地冰盖的物质损失受大气和海洋变暖的共同驱动,其主要过程涵盖了多界面的复杂作用。在表面,剧烈的表面融化促使融水下渗,形成内部的含水层与掩埋湖[7];在底部,温暖洋流引发冰架剧烈的底部融化,并伴随着复杂的冰下水文系统演变[8];在动力学方面,底部融化导致接地线退缩并削弱冰架的支撑效应,进而引发内陆冰盖运动加速、冰体结构损伤加剧,以及边缘冰山的剧烈崩解[8]。为全面评估这些多界面的动态演变,空天基遥感已成为当前最核心的监测手段,不同类型的传感器针对特定过程发挥着不可替代的作用。在动力学与结构损伤方面,基于光学与合成孔径雷达(synthetic aperture radar, SAR)影像,现已实现全南极与格陵兰冰盖流速场(运动)、裂隙(损伤)的高精度制图以及崩解过程的连续监测[9-12];在表面融化方面,星载微波辐射计、散射计与SAR通过识别液态水导致的亮温与后向散射突变,实现了两极冰盖融化范围、持续时间及融化通量的长期连续监测[13-15];在水文与内部结构方面,结合光学与SAR影像已成功在冰盖尺度监测水文系统的演化[16],同时雷达测深与高度计等探测手段能够穿透冰体,识别内部的等时层、含水层与掩埋湖,并实现对接地线迁移及底部融化速率的高精度精细化评估。

1.1 冰盖运动过程

冰盖流动是重力作用下冰体物质由内陆向海岸带呈放射状运动的过程。监测冰盖流速是衡量冰盖稳定性、定量评估海平面上升占比的重要手段之一[17]。SAR与光学卫星影像是目前用于构建全域、长时序流速场的基础数据源。合成孔径雷达差分干涉测量(differential interferometric synthetic aperture radar, D-InSAR)技术可以

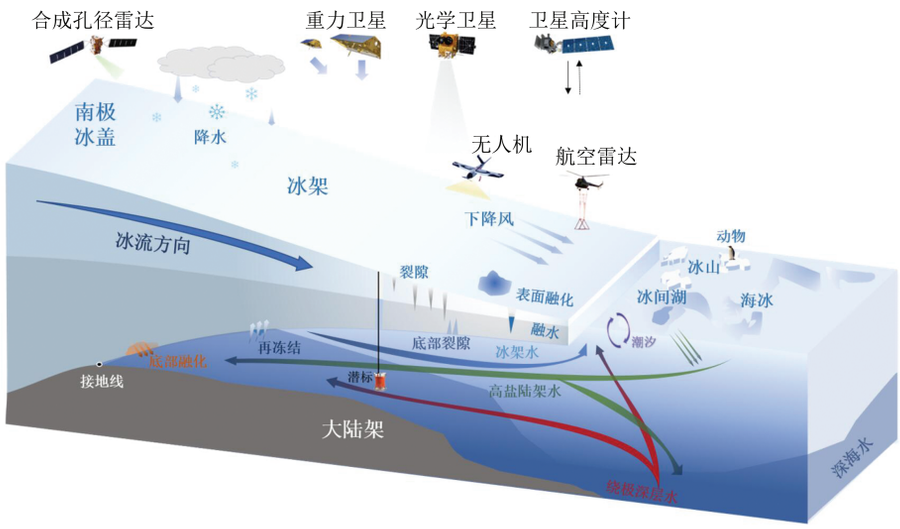


图 1　极地冰盖冰架系统示意图

Fig. 1　Schematic Diagram of the Polar Ice Sheet and Ice Shelf System

厘米级精度提取流速,但受限于表面冻融、卫星重复周期、相位解缠困难等,其主要用于冰盖内陆慢速区提取[18]。偏移量追踪基于影像模板匹配方法或其频率变体,同时适用于SAR与光学影像,其应用范围更广[19]。国外多家机构基于近年来广泛且规律获取的Sentinel-1、Landsat系列等制作并发布了长期、年及更精细时间分辨率的南北极冰盖流速场拼接产品,如NASA资助的MEaSUREs计划下设的多个冰流速制图项目(GrIMP、its_live等[20-21])、欧洲空间局资助的哥白尼气候变化服务(C3S)[22]、丹麦与格陵兰地质调查局资助的PROMICE项目[23]等。格陵兰冰盖的卫星影像覆盖更为丰富,其年或更精细时间分辨率流速产品较南极冰盖更为完整。冰盖流速提取需处理大量影像数据,且算法耗时巨大,导致这些产品的空间分辨率通常为数百米,远低于原始卫星影像分辨率。

中国目前在全南极高分辨率年尺度冰流速制图[24]、D-InSAR高流速区域监测[25]、SAR与光学影像提取流速融合[26]、基于早期返回式卫星影像的冰盖流速提取[27]等方面取得了显著成果。极地冰盖遥感影像受极夜、夏季冰盖表面冻融等影响,单一数据源无法完成全时空域的流速提取。如SAR影像在冰盖渗浸带及湿雪带发生日周期冻融变化后,其散射特征变化不能满足偏移量估计算法要求,可以采用光学影像进行补充。仅以2022年7月5日—17日的Sentinel-1 SAR影像为数据源,图2展示了格陵兰冰盖排冰量较大的数条冰川的GrIMP流速场产品与Sentinel-2补充后的流速场[26]。返回式卫星影像如ARGON等是少有可构建20世纪60—80年代南极冰盖流速场及冰通量的数据源。文献[28]发展了多层影像密集匹配框架,重建了南极历史冰流速场,并对东南极流速过估进行了改正。

1.2　冰盖表面融化过程

全球气候变暖导致冰盖表面融化持续增强,产生的大量融水通过降低冰雪反照率、诱发冰架水力压裂及促进冰流加速等过程影响冰盖稳定性[3,29-31]。由于微波亮温和后向散射特征对雪层液态水含量变化高度敏感,星载微波遥感成为冰盖表面融化监测的核心手段[32-33]。研究主要利用主被动微波传感器,结合经验阈值、时序分析和机器学习等方法,实现冰盖融化发生、持续时间及空间范围监测,揭示了近年来两极冰盖融化范围扩大及持续时间延长的变化规律[34-39]。然而,冻融状态监测难以定量表征融化强度及融水产生量。近期,文献[13-14]基于SSM/I数据首次实现了两极冰盖融化通量的长期逐日监测,揭示了格陵兰冰盖融化持续增强及东南极逐渐成为新的融化热点等关键变化特征,如图3所示。

冰盖表面融化产生的液态融水在粒雪层中渗流、滞留和再冻结,当孔隙储水能力达到饱和或渗透受阻时,将在冰面低洼区域汇聚形成冰面湖,并通过降低表面反照率进一步增强局地融化,广泛分布于格陵兰冰盖,南极相对较少[40-42]。由于冰面湖与周围冰雪具有明显的光谱差异性,光学遥感已成为其监测的主要技术手段[43-44]。研究主要利用中分辨率成像光谱仪(moderateresolution imaging spectroradiometer, MODIS)、Landsat、Sentinel-2和WorldView等星载光学遥感数据,并结合无人

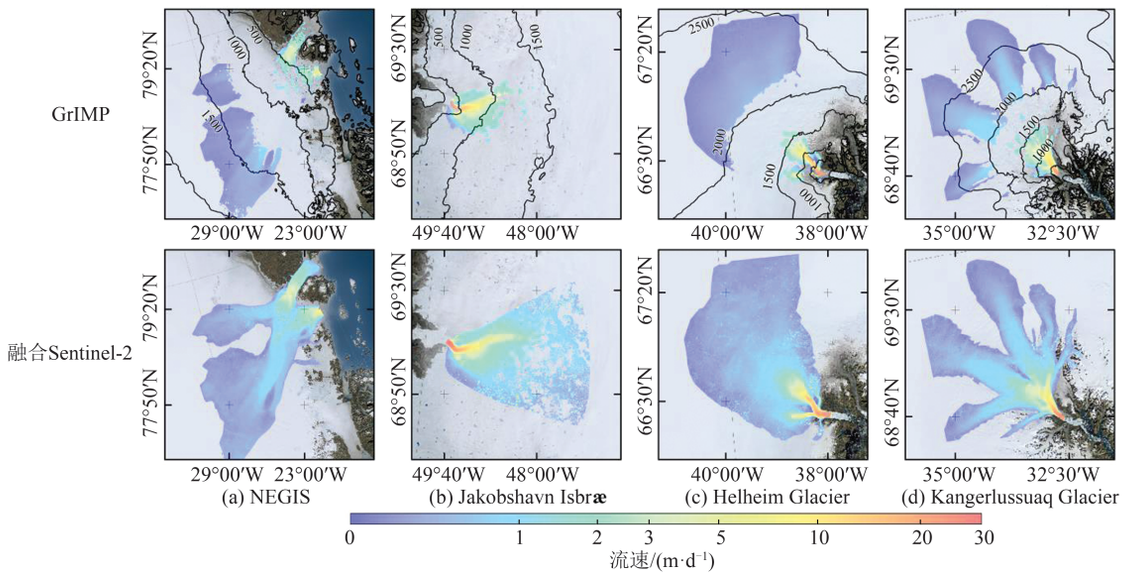


图2 GrIMP流速场及采用Sentinel-2影像补全后流速场对比示例

Fig. 2 Examples of GrIMP Ice Velocity Field and the Ice Velocity Field After Gap-Filling with Sentinel-2 Images

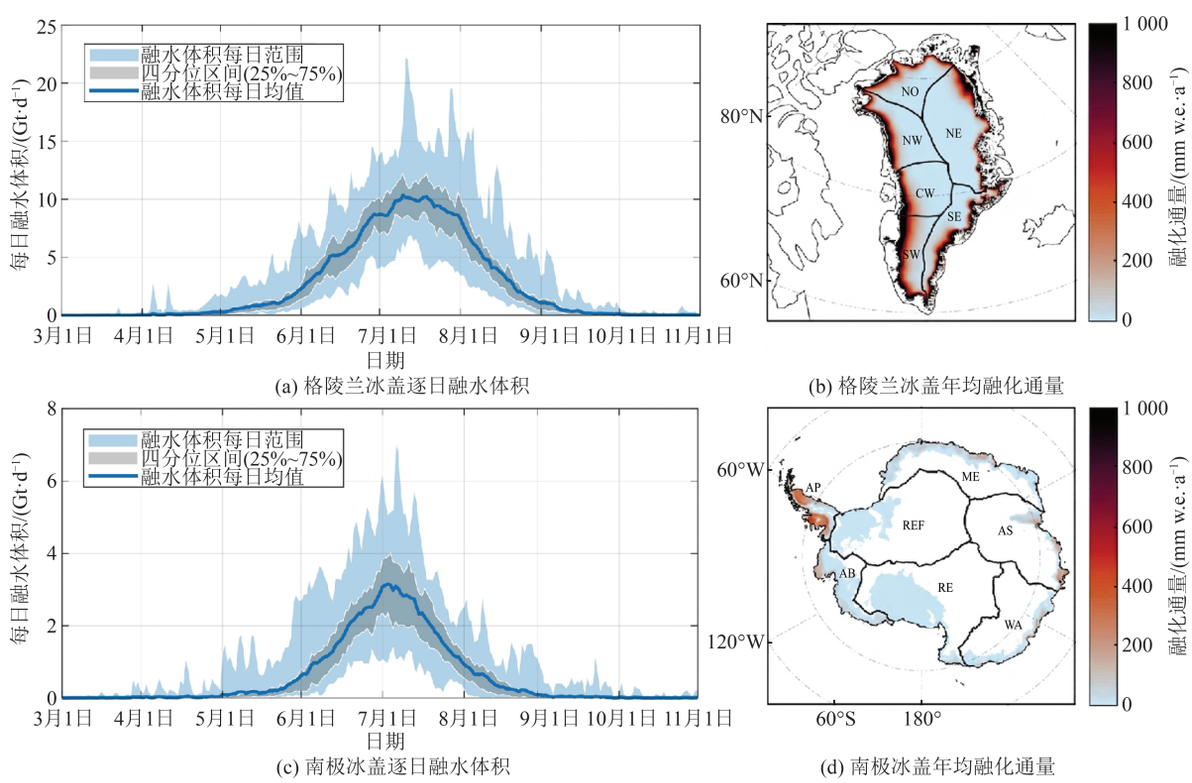


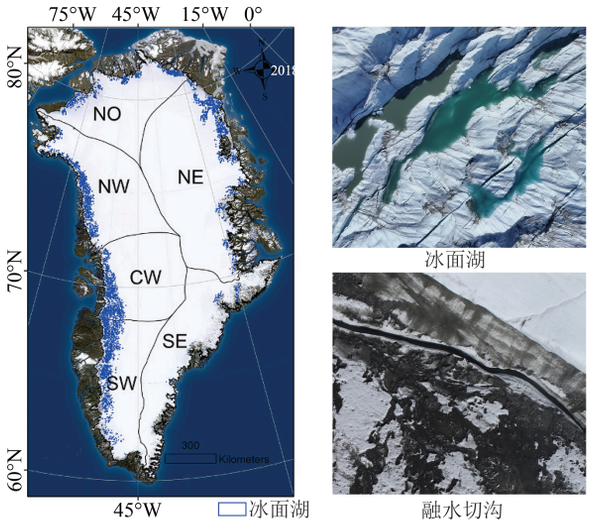
图3 1992—2022年格陵兰冰盖和南极冰盖表面融化遥感监测结果

Fig. 3 Satellite-Derived Surface Melt over the Greenland Ice Sheet and the Antarctic Ice Sheet from1992 to 2022

机高分辨率光学观测开展局地验证,结合人工解译、光谱阈值和机器学习等方法,实现冰面湖范围及演化过程监测,揭示了其与气候、地形及冰盖动力过程之间的关系[44-50]。最新研究联合多源光学数据,实现了格陵兰冰盖冰面湖的大范围连续监测。卫星与无人机监测结果表明,格陵兰冰面水系高度发育,主要分布在西部与东北部,降雪较高的西南部几乎不发育冰面湖[16](图4)。

1.3 冰架底部融化过程

冰架底部融化是连接海洋强迫与冰盖动力变化的关键过程,持续监测其时空变化对评估冰架稳定性具有重要意义。由于冰架腔体环境封闭且现场观测困难,空天遥感已成为开展大范围、长时序底部融化监测的主要技术手段。冰架底部融化率的遥感估算主要基于质量守恒与静力平衡关系。早期研究多利用ERS、Envisat和



(a) 2019年格陵兰冰盖冰面湖最大范围

(b) 航空遥感观测的格陵兰冰盖冰面水体(郑雷拍摄于2026年5月24日)

图4　格陵兰冰盖冰面水体分布遥感监测

Fig. 4　Remote Sensing Monitoring Results of Supraglacial Lakes on the Greenland Ice Sheet

ICESat等沿轨测高数据获取冰架表面高程变化,并结合粒雪压实、表面物质平衡、冰流速度和厚度变化,反演底部融化或冻结的空间分布。随着CryoSat-2雷达测高、ICESat-2光子计数激光测高和多时相数字高程模型(digital elevation model, DEM)的应用,监测方式逐步由稀疏沿轨估算发展到高分辨率连续制图和长时序变化分析[51]。文献[52]基于CryoSat-2引入拉格朗日框架,改善了东南极Shackleton冰架高程变化场的空间连续性,并降低了底部融化率估算的不确定性。文献[53]进一步利用ICESat-2和拉格朗日方法,构建2019—2023年阿蒙森海6个主要冰架的季度底部融化率序列,揭示了融化率的空间异质性及不同冰架年际变化的协同性。但该方法依赖多种辅助数据和静力平衡假设,雷达波穿透、粒雪变化、冰流速度散度及接地线附近复杂地形误差均会传递至融化率结果。预计随着高重访激光与雷达测高、多时相DEM及智能反演技术的发展,底部融化遥感监测将由离散高程变化反演逐步迈向高时空分辨率、三维连续和近实时监测。

1.4　冰盖损伤过程探测

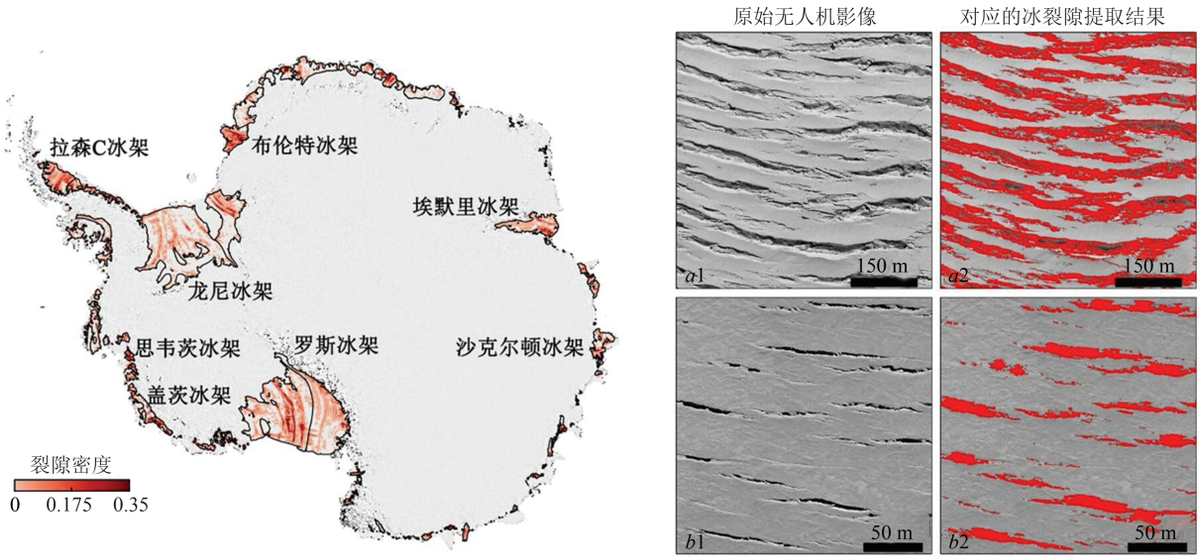
冰盖损伤过程主要表现为冰体结构的破裂、变形和弱化,是冰架崩解和冰流加速的重要前兆[54]。与表面融化或流速变化相比,损伤具有更强的空间非均匀性和突发性,常集中在冰架前缘、侧向剪切边界、底部通道上方、接地线附近以及受海底隆起控制的应力集中区,其最直观的遥感表征通常为冰面裂隙[55-56]。光学遥感、SAR和激光测高为裂隙识别与演化监测提供了长期、宽覆盖和多尺度观测能力。MODIS和Landsat等不同分辨率光学影像均被用于提取裂隙长度、密度和扩展速率[57]。文献[58]将ResUNet应用于2004年、2009年和2014年MOA影像,完成环南极冰架表面裂隙分布及演化制图,推动裂隙研究由局部案例分析向大陆尺度多时相自动制图发展。Sentinel-1和RADARSAT等SAR数据则能够在极夜和多云条件下识别裂隙形态变化,并追踪其与冰流剪切带、接地线和冰架前缘变化之间的关系。激光测高则为裂隙垂向结构观测提供了新手段,文献[59]利用ICESat数据开展裂隙位置和深度探测,文献[60]进一步基于ICESat-2光子数据提出LCSF-ice算法,实现裂隙深度和宽度的自动提取,为裂隙三维特征重建提供了技术基础。

近年来,基于深度学习的遥感影像裂隙自动提取方法快速发展,使裂隙识别从人工判读和局部区域案例分析逐步转向大范围、长时序和半自动化制图[58,61]。无人机低空摄影测量则可获取厘米级裂隙影像和局地三维地形,如图5所示,其中$a1$和$b1$为原始无人机影像,$a2$和$b2$为对应的冰裂隙提取结果。该技术可以为卫星尺度裂隙三维分析提供重要补充,但受续航能力、气象条件和作业范围限制,尚难开展大范围连续监测。未来研究应加强基于裂隙长度、密度、深度和扩展速率等指标的冰盖损伤标准化表达,建立裂隙三维几何、冰体损伤状态和冰盖稳定性之间的定量联系,从而提高对冰架崩解临界状态的识别能力。

1.5　冰架崩解过程

冰架崩解产生冰山是南极冰架质量损失的主要方式之一,其造成的质量损失约占南极冰架净质量损失总量的1/2[62-63]。崩解并非孤立事件,而是冰架长期损伤累积的结果[64-65]:海洋驱动的冰架底部融化引起冰架减薄并改变应力分布[51,66-67],表面融水可能通过水力压裂促进裂隙向下扩展,冰流拉伸、剪切及冰架弯曲则推动裂隙和裂谷持续发育[61,65,68-69],当裂谷贯穿冰架或结构强度不足以维持前缘稳定时,潮汐、海浪和海冰变化等外部扰动可触发冰架崩解[70-72]。

目前,相关研究主要依赖数值模拟和遥感观测。数值模型用于模拟冰架应力、裂隙扩展及前缘进退过程[73-76]。遥感观测则主要依赖光学和SAR影像,可直接提取冰架前缘位置、裂隙演化和崩解面积。现有监测已由单一冰架[77-78]扩展至区域[79-81]及环南极尺度,文献[11]基于Envisat ASAR



(a) 南极冰架裂隙密度分布 (b) 无人机影像上的冰裂隙及其提取结果

图5 南极冰架裂隙空间分布

Fig. 5 Spatial Distribution of Crevasses Across the Antarctic Ice Shelf

影像估算了环南极冰架崩解通量,并指出海洋驱动的冰架减薄能够增强冰山崩解并造成冰架退缩;文献[12]融合Envisat ASAR、MODIS、Landsat 8和Sentinel-1等多源光学与SAR影像,建立了2005—2020年环南极冰山崩解数据集(图6)。

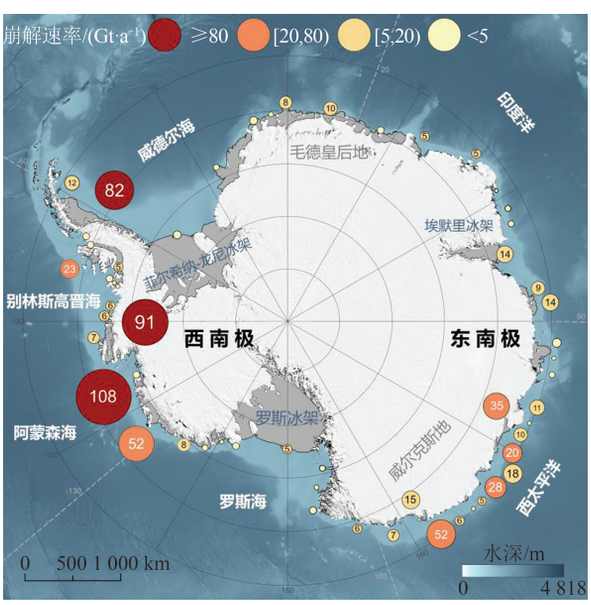


图6 2005-08—2020-08南极冰架平均崩解速率的空间分布[12]

Fig. 6 Spatial Distribution of Average Calving Rate of Antarctic Ice Shelves from August 2005 to August 2020[12]

2 冰盖内部结构空天遥感透视

与表面过程相比,冰盖内部结构具有隐蔽性强和直接观测困难等特点,其变化不仅影响冰盖物质储存与能量传递,也可通过改变冰体强度、冰下水文和接地状态进一步作用于冰流动力学与稳定性。近年来,卫星微波、激光测高、机载冰雷达及多源遥感融合方法不断拓展冰盖空天基遥感的透视能力,使粒雪含水层、掩埋湖、内部等时层、冰下湖及接地带等关键结构能够由局地探测逐步向区域乃至冰盖尺度识别发展。被动微波遥感已成功探测格陵兰冰盖与威尔金斯冰架中粒雪含水层的范围与埋藏深度[82-83];深度学习方法也被应用于冰盖等时层与掩埋湖的系统性识别[16,84];基于卫星测高与InSAR的接地线与冰架底部融化率产品已实现全南极覆盖[85-86]。

2.1 粒雪含水层

随着表面融化增强,部分融水可在粒雪孔隙中长期滞留,形成粒雪含水层。其范围和埋藏深度直接反映粒雪层对融水的储存能力,并影响融水再冻结、向深部迁移及后续水文过程,是认识冰盖近表层水文结构的重要参数。粒雪含水层主要依靠机载冰雷达进行探测。OIB机载雷达利用液态水与干雪之间显著的介电性质差异,在雷达回波剖面中识别含水层界面[83,87]。这些观测首次较为直接地揭示了粒雪含水层的垂向结构,但受航线分布限制,难以获得冰盖尺度的连续空间信息。

随着Sentinel-1、ASCAT和SMAP等微波卫星资料的应用,粒雪含水层监测逐步由机载航线探测扩展到区域和冰盖尺度[88-91]。近期研究中,文献[82]进一步将OIB机载雷达获得的含水层位置和埋深作为标定数据,与主、被动微波遥感观测相结合,利用多层回归模型同时反演粒雪含

水层的空间范围与埋藏深度。结果表明,格陵兰冰盖和威尔金斯冰架均存在大范围粒雪含水层,其平均埋藏深度约为 13 m(图 7)。这一进展使卫星遥感由过去主要判断含水层是否存在,进一步发展到对其埋藏深度的定量刻画,为分析粒雪储水能力及其年际变化提供了新的观测基础,但目前埋藏深度反演仍较依赖有限的机载雷达样本,大范围、连续的年际变化监测能力仍有待提高。

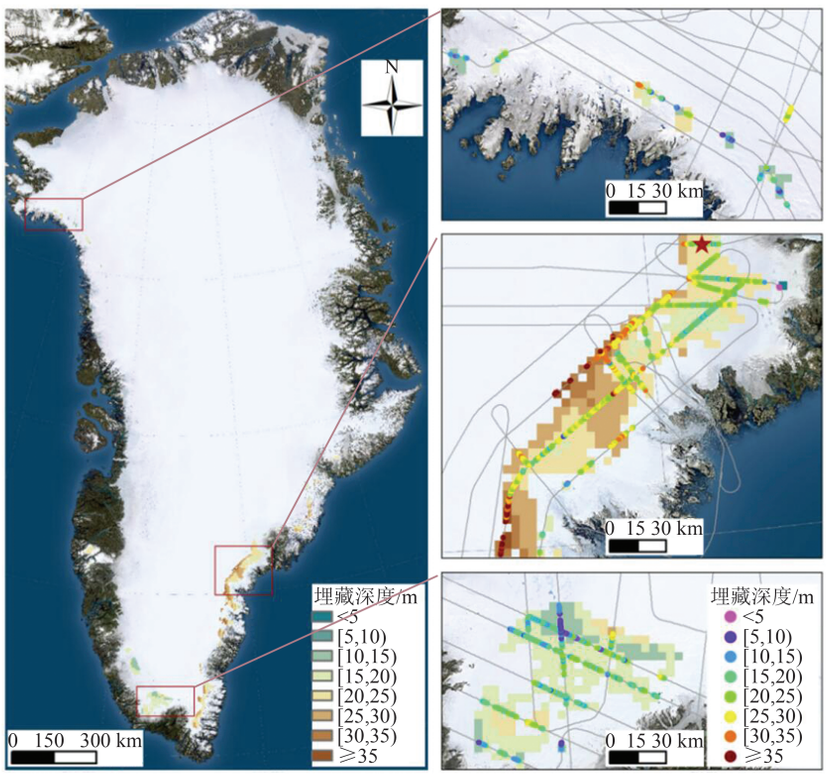


图 7　2017 年格陵兰冰盖粒雪含水层分布

Fig. 7　Distribution of the Firn Aquifer in the Greenland Ice Sheet in 2017

2.2　冰盖掩埋湖

部分夏季冰面湖在冻结季节并未完全冻结,而是在雪层覆盖下形成掩埋湖,持续储存液态融水,并通过影响冰盖内部热力结构、融水输运及后续融化过程影响冰盖稳定性[92-94]。这些湖被积雪覆盖,传统可见光遥感难以直接识别掩埋湖,而微波雷达能够穿透干雪层,对液态融水与周围粒雪介电特性差异具有较高敏感性,因此成为掩埋湖监测的主要遥感手段[95-97]。

早期研究主要依托 OIB 机载雷达及现场观测,对掩埋湖内部结构和形成机制进行了验证[92,98]。随着 Sentinel-1 SAR 数据的广泛应用,利用阈值分割、图像分割及机器学习等方法,逐步实现了冰盖掩埋湖的更大范围识别[75,99-102]。文献[16]联合可见光与 SAR 影像,发现约 13% 的格陵兰冰盖夏季冰面湖在冬季不会完全冻结,而是形成掩埋湖,并揭示了掩埋湖的空间分布、季节演化及其与表面融化、降雪和粒雪结构之间的耦合关系,为揭示冬季融水储存对冰盖稳定性的影响提供了新的遥感观测手段。2017—2022 年格陵兰冰盖的掩埋湖遥感监测结果如图 8 所示。

2.3　冰盖等时层

深霜层是由雪变质作用形成的低密度、粗粒内部层,通常出现在温度梯度大于 20 K/m 的条件下[103-104]。在南极冰盖,夏季强日照驱动其广泛发育[105],季节敏感性使其成为理想的地层等时标记,可追溯冰盖历史演变,对了解南极冰盖的积累率与物质平衡具有重要意义[106-107]。深霜等时层的研究早期依赖原位雪剖面观测,但成本高昂,时空覆盖有限[108-109]。数值模型如 SNOWPACK 可模拟雪层剖面并理论定位等时层,但实际对比表明其模拟能力不足,受限于高质量大气与雪面数据观测匮乏及参数化方案缺陷[110-111]。

OIB 机载雪雷达通过捕捉粒雪层内部反射水平获取深霜等时层信息[4,112],如图 9 所示,其中 2015 年雪雷达数据缺失。近年来,冰雷达内部层理提取已由逐层追踪发展到多尺度学习、CNN-RNN、迁移学习和语义分割等自动识别方法[113-117],显著提高了层理检测效率与精度。但是

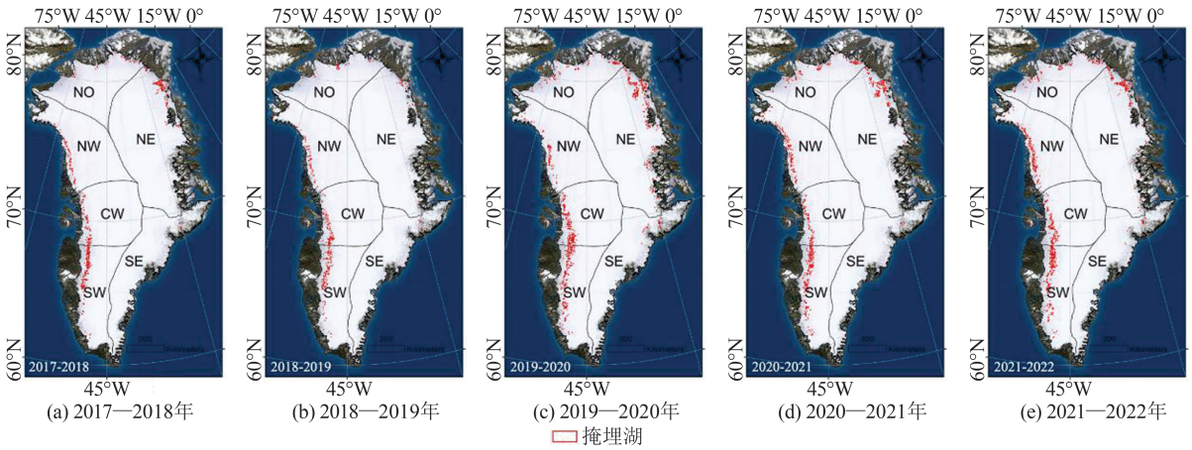


图8 2017－2022年格陵兰冰盖掩埋湖遥感监测结果

Fig. 8 Remote Sensing Monitoring Results of the Buried Lakes on the Greenland Ice Sheet from 2017 to 2022

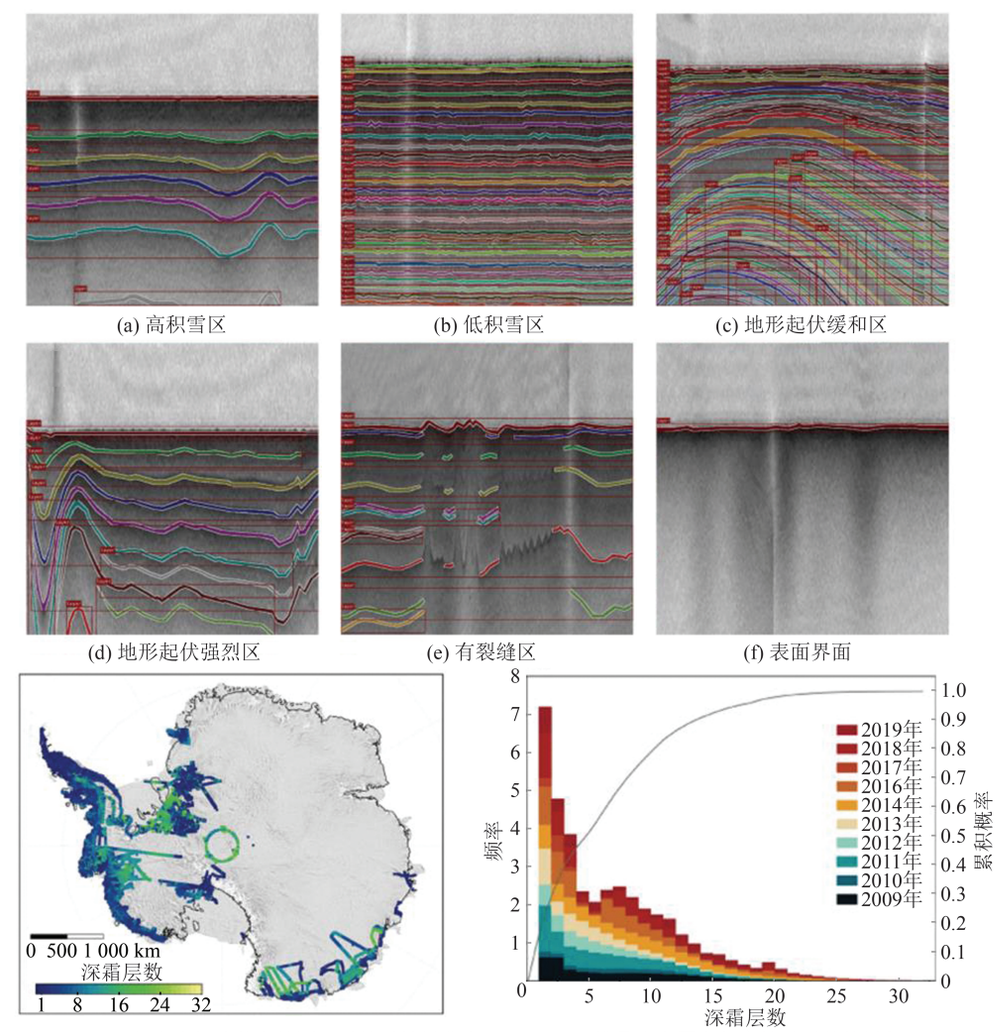


图9 深霜等时层的典型样本及其在南极冰盖上的分布

Fig. 9 Typical Samples and Distribution of Deep Frost Isochrons on the Antarctic Ice Sheet

现有方法仍存在误差累积、先验假设依赖、层间分离不完整及跨区域泛化不足等问题,尚难实现复杂内部层理的连续追踪与统一编号。现有方法在自动化、层间区分及泛化能力方面仍存在明显瓶颈。文献[84]基于实例分割与自注意力机制,开发了深霜等时层自动跟踪算法,实现层位自动提取与索引,系统揭示了南极冰盖深霜层的空间分布格局(图9),丰富了物质平衡原位观测数据。

2.4　冰下水文系统

冰下水文系统影响着冰床润滑、冰流速度以及冰架接地线附近的淡水输入,是理解冰盖不稳定性的核心内部过程之一[118]。其中,冰下湖是冰盖底部水体储存、连通与释放的重要载体,广泛分布于两极冰盖底部,也是空天遥感能够识别和持续监测的主要冰下水文对象。传统冰下湖研究主要依赖冰雷达、地震和钻探等观测方法,但极地冰盖范围巨大、环境恶劣,直接观测难以形成连续的时空覆盖。空天遥感的发展使冰下湖研究从“静态湖泊识别”逐步转向“活跃冰下湖动态监测”。早期冰雷达主要依据冰-水界面的强镜面反射识别冰下湖,雷达测高则利用异常冰面升降发现湖泊排水及湖间连通。ICESat 重复轨道激光测高进一步揭示了冰下湖在数月至数年尺度上的蓄排水过程,使湖泊边界、体积变化和级联水文网络能够被量化。此后,CryoSat-2 雷达测高和 ICESat-2 光子计数激光测高进一步提高了观测覆盖、时间连续性和空间细节。文献[119]融合多时相 ArcticDEM 与 ICESat-2 数据,重建了格陵兰东北部 Flade Isblink 冰下湖 2012—2021 年的冰面高程和体积变化序列,展示了高分辨率 DEM 与卫星测高协同开展活跃冰下湖长期监测的能力。当前主要限制在于遥感观测结果多反映冰下水文活动导致的冰面升降响应,却难以直接连续监测湖泊水量变化、排水通道几何形态与冰下融水流动过程。未来需融合卫星测高、多源 DEM、冰雷达、重力卫星和数值水文模型,构建活跃冰下湖水文过程的多尺度监测框架,并将其纳入冰盖动力和海平面预测模型。

2.5　冰盖接地线

接地线是指内陆冰盖和与漂浮冰架的物理边界,直接控制着冰通量,是评估海洋冰盖不稳定性、计算质量收支以及驱动冰动力学模型的核心参数[120]。然而,接地线本质上属于冰下特征,直接探测极为困难。当前遥感研究主要通过识别接地带(grounding zone,GZ)的表面代理特征来间接推断接地线位置,主要包括潮汐弯曲的陆向极限(Point F)、静水平衡的陆向极限(Point H)以及表面坡度突变点(Point Ib)。

目前国际上已发布近 10 种全南极接地线产品[86]。2018 年发射的 ICESat-2 卫星为接地线监测带来了革命性进展。文献[121]利用 ICESat-2 数据开发了全自动化算法,成功绘制了首个覆盖全南极的高分辨率 GZ 产品,包含 Point F,Point H 和 Point Ib(图 10)。该产品不仅有效填补了 D-InSAR 的覆盖空白,还精确捕捉到了阿蒙森海、罗斯冰架以及东南极 Wilkes Land 的长期接地线加速退缩的趋势。此外,ICESat-2 的高密度数据还揭示了潮汐调制下的短期接地线迁移现象及冰下海洋通道的动态变化,为理解冰-海洋相互作用提供了新视角。文献[122]完成了 1992—2009 年 5 种主流接地线产品的精度评估,发现 9.5% 的南极接地线表现出后退或前进的趋势,其中后退最快的区域为松岛冰川(544±51 m/a),前进最快的区域为默茨冰川(304±16 m/a)。结果表明,西南极冰盖的接地线有显著的后退趋势,而东南极除托滕冰架区域外的冰盖接地线介于平衡和轻微前进趋势之间。

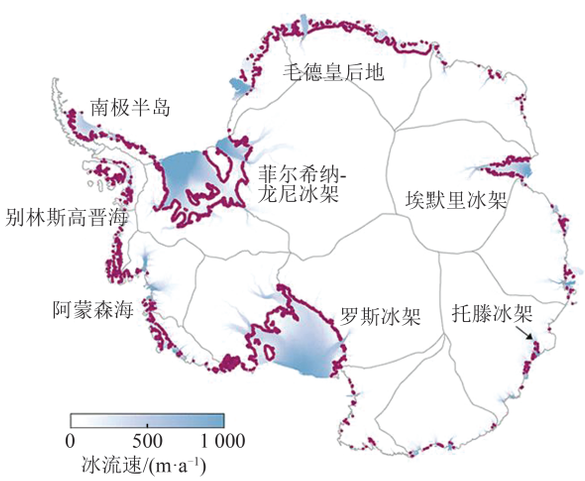


图 10　基于 ICESat-2 的南极冰盖接地带特征空间分布

Fig. 10　Spatial Distribution of ICESat-2-Derived Grounding Zone Features of the Antarctic Ice Sheet

3　两极冰盖物质平衡遥感估算

冰盖物质平衡是一定时期内冰盖质量收入与支出的净差,综合反映降雪积累、表面融化与径流、底部融化以及接地线处固体冰通量等过程,是衡量冰盖稳定状态及其海平面贡献的核心指标。由于两极冰盖范围广阔且地面观测稀疏,卫星遥感已成为获取全冰盖物质平衡长时序变化的主要手段。目前主要包括卫星测高、卫星重力、输入-输出和融合约束 4 类估算方法[1,123]。

卫星测高通过重复观测冰面高程变化反演体积变化,是刻画物质变化空间格局的主要技术。雷达测高由 ERS-1/2、Envisat 发展至 CryoSat-2,并从传统脉冲拓展到合成孔径和干涉模式;激光测高则由 ICESat 发展至光子计数体制的 ICESat-2,提高了沿轨采样密度和高程精度。结

合重复轨道、交叉点和平面拟合,以及粒雪压实与密度模型,可将高程变化转换为质量变化。文献[124]统一处理ICESat与ICESat-2观测,实现了两极冰盖2003—2019年高程和质量变化的连续估算。但测高法易受雷达波穿透、地形坡度、粒雪压实和密度转换影响,误差在冰盖边缘和降雪异常区更为突出。卫星重力测量则提供了不依赖密度转换的直接质量观测,GRACE及GRACE-FO实现了两极冰盖月尺度质量变化反演,球谐滤波和质量集中块方法的发展进一步改善了条带噪声、信号泄漏和流域尺度质量分配问题。卫星重力法空间分辨率较低,冰后均衡调整和海陆信号泄漏会直接影响结果。输入-输出法利用区域气候模式估算表面物质平衡,并结合光学或SAR冰流速、冰厚和接地线位置计算固体冰排放,能够区分表面与冰动力过程的贡献。文献[2]重建了南极冰盖数十年的质量收支;文献[125]改进接地线处冰通量计算,实现逐年、逐流域评估并单独估算岛屿冰通量;文献[126]进一步融合年际冰流速度、最新冰厚和延拓至2020年的表面物质平衡序列,完成2000—2020年南极冰盖质量收支评估。该方法能够分解质量收支过程,但依赖表面物质平衡模型、冰厚、接地线和通量门设置,各输入数据的偏差可能在通量计算中累积。

上述3类物质平衡估算方法的观测对象、时空尺度和误差来源不同,因此多源融合估算成为提高可靠性的关键方向。融合约束法通过同化多源遥感观测与数值模型开展联合反演,例如利用GRACE/GRACE-FO质量变化约束冰流模型,利用ICESat-2高程变化校正区域气候或粒雪模型,并进一步融合SAR流速等数据,从而弥补单一数据的尺度局限,提升物质平衡估算的时空连续性与物理一致性[127]。国际冰盖物质平衡比较计划通过统一分区、时间基准和误差表达形成综合序列[123];文献[128]汇集国内8家机构的16套估算结果,采用自适应数据聚合窗口和两步协调方法,获得1996—2021年南极冰盖综合物质平衡序列。融合约束法虽可降低方法间的随机差异,但依赖输入结果的不确定度表征与权重设计,难以自动消除多方法共有的系统偏差。

4 总结与展望

近30年来,空天遥感推动极地冰盖研究由局地、间断的表面变化观测,逐步发展为涵盖表面过程、内部结构、冰下环境、动力边界和物质平衡的多尺度监测体系。光学影像与SAR已广泛用于冰流速度、裂隙发育、冰架前缘迁移和冰山崩解监测,主、被动微波遥感由冻融状态识别进一步拓展到融化通量、粒雪含水层和掩埋水体反演,卫星测高与重力观测则为冰面高程、冰架底部融化、活跃冰下湖、接地带迁移及质量变化估算提供了重要依据。机载冰雷达、激光测量、重力探测和航空遥感进一步弥补了卫星在冰盖内部层理、冰厚、冰下地形以及裂隙三维形态等方面观测的不足。随着多源观测的联合应用,冰盖遥感已经不再局限于几何形态与边界变化描述,而开始向融化量、冰通量、底部融化率和质量变化等关键参数的定量反演发展。

未来,空天遥感技术应更加面向海平面变化预测中的关键不确定性和冰盖快速失稳等前沿科学问题,构建多源、同步、连续且可交叉验证的综合观测体系。依托多星座光学和SAR卫星、激光与雷达测高、微波辐射计、重力卫星及机载冰雷达,并联合GNSS、地基雷达、地震阵列、冰下探测和海洋观测,提高关键区域的观测重访频率和空间分辨率。多源协同反演的重点由二维表面变化进一步转向融水储量、裂隙深度与连通性、内部层理、冰下湖水量、基底水系和冰-海界面等三维参数,实现从“看见冰盖变化”向“透视冰盖内部、解释失稳机制并预测未来演化”的转变。极地冰盖多尺度物理过程遥感透视探测已被列为遥感科学与技术领域的前沿科学问题之一,凸显了冰盖内部结构与关键过程三维探测的重要性。

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