From spaceborne observations to physical-based simulation for ice dynamics and permafrost deformation at Pan Third Pole and Greenland by using multi-source remote sensing data (ID. 95439)

Liming Jiang[1, 2], Stephen Livingstone[3], Andrew Sole[3], Gang Li[4], Zhuoqi Chen[4], Xi Lu[1, 5], Yuxuan Wu[1, 2], Zhida Xu[1, 2], Zhiping Jiao[1, 2], Xiaoen Li[1, 2], Yi Liu[1, 2], Xiaoguang Pang[1, 2], Yanting Mao[4]

[1] State Key Laboratory of Geodesy and Earth's Dynamics, Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences, Wuhan 430077, China.

[2] College of Earth and Planetary Science, University of Chinese Academy of Sciences, Beijing 100049, China.

[3] School of Geography & Planning, University of Sheffield, Sheffield, S10 2TN, UK.

[4] School of Geospatial Engineering and Science, Sun Yat-sen University, Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai 519082, China

[5] School of Geography and Sustainable Development, University of St Andrews, St Andrews, UK

This Dragon 6 project aims to advance understanding of cryospheric change under global warming by integrating multi-source satellite observations with process-based modelling across the Greenland Ice Sheet and the Pan Third Pole region. By linking observation-driven analysis with physical modelling, the resulting framework improves quantitative understanding and enhances predictive capability of ice dynamics and permafrost deformation.

Methodologically, advanced techniques based on Sentinel-1 synthetic aperture radar (SAR) and multi-sensor datasets are developed for key cryospheric processes. For glacier surface melting detection, dual-polarized SAR backscatter and the polarimetric decomposition features are combined with ensemble learning methods to detect the melt conditions, achieving an overall accuracy of ~80%. The fusion of Sentinel-1 SAR and Sentinel-2 optical velocity products significantly improves summer velocity coverage (by 18–57%) and reduces underestimation of near-terminus mass discharge by up to 20%. In addition, a novel multiple aperture coherence (MAC) approach is proposed for mapping landfast sea ice by exploiting sub-aperture phase stability, enabling robust discrimination between stable landfast ice and dynamic sea ice under challenging conditions such as strong winds and rough sea states, while overcoming limitations of repeat-pass InSAR and/or only backscatter coefficient.

Novel methods for retrieving key glacier physical parameters are developed. To address the difficulty of traditional ground-penetrating radar techniques in detecting the ice-bed interface of water-rich glacier, a stochastic dispersive medium model based on finite-difference time-domain (FDTD) simulations is constructed, together with a particle swarm optimization (PSO)-based corrected trimmed mean CFAR (CTM-CFAR) detector. For Bayi Glacier and 23k glacier on the Tibetan Plateau, the PSO-CTM-CFAR method reduced the ice thickness measurement error by approximately 30% compared with traditional methods. A novel method combining remote sensing albedo and differencing Digital Elevation Models (DEM) to estimate glacier annual mass balance is also developed, achieving a high accuracy (RMSE ~495 mm w.e., an ~11%

improvement over existing methods) and demonstrating strong potential for large-scale applications.

For glacier systems, the project investigates two complementary domains: the Greenland Ice Sheet and mountain glaciers in the Pan Third Pole region. For Greenland, a high-resolution and internally consistent dataset of ice front positions (Greenland Terminus Position Dataset, GrTPD) is developed, comprising 19,171 delineations for 465 glaciers from 2002 to 2021 with seasonal coverage. The dataset shows high geometric fidelity (mean average minimum distance of 86 m relative to alternative products like TermPicks) and provides a benchmark for algorithm validation and large-scale analysis of terminus variability. Combined with multi-source velocity and geometric observations, it enables improved characterization of outlet glacier dynamics and associated mass transport. For mountain glaciers in the Pan Third Pole region, the project investigates glacier–proglacial lake interactions and their influence on glacier dynamics. Results show that, compared with land-terminating glaciers, lake-terminating glaciers exhibit, on average, ~32% higher surface velocities and ~41% greater thinning rates. These effects display pronounced spatial heterogeneity and temporal evolution, particularly in the eastern Himalayas, central Himalayas, and the Nyainqentanglha Mountains, highlighting the important role of proglacial lake processes in mountain glacier retreat.

For permafrost systems, the project independently investigates deformation processes across the Qinghai–Tibet Plateau. Based on Sentinel-1 SAR data and time-series InSAR analysis, long-term subsidence and seasonal deformation patterns are characterized at regional scale. Results show that the mean long-term deformation rate in permafrost regions is -2.46 mm yr^{-1}, significantly higher than in seasonally frozen ground (-0.54 mm yr^{-1}). Spatial variability is jointly controlled by permafrost thermal stability, solar radiation, and precipitation. Areas with pronounced seasonal deformation are mainly concentrated in low-relief regions and around lakes and rivers, reflecting the important role of active-layer hydrology.

Building on the observation-based datasets, high-temporal-resolution constraints are incorporated into physical modelling. Ice-flow simulations using the Ice-sheet and Sea-level System Model (ISSM), constrained by sub-monthly terminus positions, show that frontal retreat explains more than 76% of velocity variability in Greenland's fastest glacier, Jakobshavn Isbræ. Remaining model–observation misfit extending tens of kilometres inland is strongly linked to variations in height above flotation and associated effective pressure changes. By incorporating these processes through parameterized basal shear stress adjustments, velocity misfits are reduced by over 90%, highlighting the importance of coupling terminus dynamics with basal processes.

Young scientist contributions include the development of SAR-based algorithms, multi-source data fusion, retrieval of key glacier parameters, and integration of observation-derived constraints into process-based modelling. By advancing Earth observation and its integration with physical modelling, the project aims to facilitate a transition from observation-driven analysis to process-based understanding, providing new insights into cryosphere dynamics and supporting improved projections of climate-driven changes in polar and high-altitude environments.

中文版：

本项目旨在通过融合多源卫星观测与过程驱动的物理模型，深化对全球变暖背景下冰冻圈变化的认识，研究区域涵盖格陵兰冰盖与泛第三极地区。通过将观测驱动分析与物理建模相结合，所构建的一体化框架有效提升了对冰川动力学与多年冻土形变过程的定量认知能力与预测能力。

在方法发展方面，项目基于 Sentinel-1 合成孔径雷达（SAR）及多源遥感数据，发展多种面向冰冻圈关键过程的先进技术。针对冰川表面融化过程，融合双极化 SAR 后向散射特征与极化分解参数，结合集成学习方法，实现融化状态识别，整体精度约为80%。通过融合 Sentinel-1 雷达与 Sentinel-2 光学冰流速度产品，显著提升夏季速度场覆盖率（提高18%–57%），并降低冰川末端区域物质通量低估（最高可达 20%）。此外，提出基于多孔径相干性（Multiple Aperture Coherence, MAC）的陆缘固着冰识别方法，通过利用子孔径相位稳定性，在强风及海面粗糙等复杂条件下实现对稳定陆缘冰与动态海冰的鲁棒区分，有效克服传统重轨 InSAR 方法及仅依赖后向散射系数方法的局限性。

在冰川关键物理参数反演方面，项目进一步发展冰厚与质量平衡估算方法。针对高含水冰体条件下传统探地雷达难以识别冰-基底界面的难题，构建基于有限差分时域（FDTD）的随机色散介质模型，并结合粒子群优化（PSO）的改进恒虚警检测算法（CTM-CFAR），实现冰-基底界面的高精度识别。在青藏高原八一冰川与 23K 冰川的应用表明，该方法相比传统方法可降低约 30%的冰厚测量误差。同时，提出融合遥感反照率与数字高程模型（DEM）差分数据的年质量平衡估算方法，在全球范围内验证表明，其均方根误差约为495 mm w.e.，较现有方法精度提升约 11%，展现出良好的大尺度应用潜力。

在冰川系统方面，项目针对两个互补的冰川体系开展研究：格陵兰冰盖与泛第三极山地冰川。针对格陵兰冰盖，构建了高分辨率且内部一致的冰川前缘位置数据集（Greenland Terminus Position Dataset, GrTPD），涵盖 2002–2021 年期间 465 条冰川共 19,171 条前缘位置记录，并实现季节尺度观测。该数据集具有较高几何精度（相对于 TermPicks 数据集的平均最小距离为 86 m），可作为自动识别算法验证及冰川前缘变化大尺度分析的重要基准。结合多源速度与几何观测数据，该数据集显著提升了对溢出冰川动力学及物质输送过程的刻画能力。针对泛第三极山地冰川，重点分析冰川-冰湖相互作用及其对冰流动力学的影响。结果表明，相较于陆地终止型冰川，冰湖终止型冰川流速平均提高约32%，变薄速率增加约41%，且在东喜马拉雅、中喜马拉雅及念青唐古拉山等区域表现出显著的空间异质性与时间演化特征，凸显了冰湖过程在山地冰川退缩中的重要作用。

在多年冻土系统方面，项目针对青藏高原开展独立观测与过程分析。基于Sentinel-1 SAR 数据和时序 InSAR 方法，系统刻画了区域尺度长期沉降与季节性形变特征。结果显示，多年冻土区平均长期形变速率为-2.46 mm yr^{-1}，显著高于季节性冻土区（-0.54 mm yr^{-1}），其空间分布受冻土热稳定性、太阳辐射及降水等因子共同控制。季节性形变较大的区域主要集中于低地形区域及湖泊、河流周边，反映活动层水文过程对地表形变的重要调控作用。

在物理模拟方面，项目将高时间分辨率观测数据引入冰流动力学模型。基于冰盖与海平面系统模型（Ice-sheet and Sea-level System Model, ISSM），并结合亚月尺度冰川前缘位置约束，模拟结果表明冰川前缘退缩可解释格陵兰最快冰川——Jakobshavn Isbræ——超过 76%的流速变化。模型与观测之间在上游数十公里范围内仍存在一定偏差，该偏差与浮力高度变化及其引起的有效压力变化密切相关。通过引入基底剪切应力参数化，流速误差降低超过 90%，凸显了冰川前缘过程与底部动力学耦合作用的重要性。

青年学者在本项目中主要承担 SAR 算法开发、多源数据融合、冰川关键参数反演及观测约束与物理模型耦合研究等工作。通过推进地球观测技术与物理建模的深度融合，本项目致力于推动从“观测驱动分析”向“过程机理建模”的转变，为冰冻圈动力学研究提供新的科学认知，并为气候变化背景下极地与高山地区冰冻圈演化的预测提供有力支撑。

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