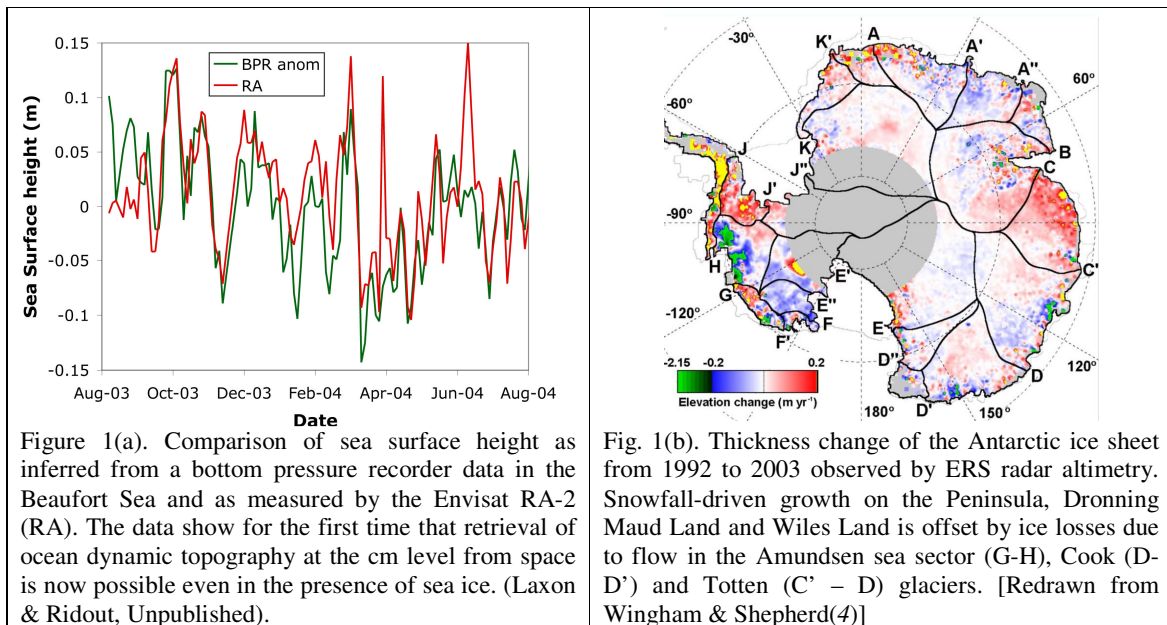


**THE CRYOSPHERE AND POLAR OCEANS:  
THEME 5 OF THE NATIONAL CENTRE FOR EARTH OBSERVATION (NCEO)**  
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**1. SUMMARY OF THE PROPOSAL**

‘The Cryosphere and Polar Oceans’ is aimed at resolving uncertainties in future climate and sea-level arising from the large-scale behaviour of the cryosphere. It will bring together satellite data, particularly geodetic measurements from altimetry, interferometry, and gravimetry, allied with numerical models, to: (i) quantify and understand recent mass changes in the marine and land cryosphere; (ii) provide constraints on models of Arctic Ocean circulation and global sea level rise; (iii) make model predictions of changes in the cryosphere over the 21<sup>st</sup> century; (iv) maintain and extend a UK national capability in polar geodesy, and (v) provide to NCEO Theme 1: ‘EO for Climate Diagnosis & Prediction’, and more widely, new model components for coupled, global climate modelling and large-scale data sets for its evaluation. This proposal answers to the 2007 – 2012 NERC Strategy demand for quantifying polar change through improved observations. It builds on the wider NERC-supported programmes of the Centre for Polar Observation and Modelling (CPOM) that integrates the work of the theme with that of the UK HEIs, NERC Centre Surveys and the Hadley Centre, the European Space Agency (ESA), particularly through our scientific leadership of the CryoSat-2 mission, and the wider international community. Our objectives answer to the needs identified by the International Panel on Climate Change(1,2), and the Arctic Climate Impact Assessment(3). The work is also timely in responding to the International Polar Year (2007-2009) objective to determine the environmental status of the polar regions. The proposal is organised as follows: §2 describes the importance of the cryosphere in the climate system and its present uncertainties; §3 describes objectives of the three science sub-themes, ‘The Arctic Ocean-Ice System’, ‘Ice Sheets and Sea Level’ and ‘Polar Geodesy’, and summarises related CPOM programmes; the organisation of the work is described in §4 together with its schedule and deliverables; § 5 describes the resources needed to perform the work; and finally §6 provides references.



**2.SCIENTIFIC BACKGROUND TO THE THEME**

The cryosphere is a source of great uncertainty in the global evolution of climate change. Climate models predict a polar amplification of global warming as a consequence of ice-albedo feedback(5) .

Model results indicate that changes in sea ice are responsible for 37% of the global temperature rise resulting from a doubling of CO<sub>2</sub>(6) . The disappearance of Arctic sea ice this century could prompt the release of a further 100,000 km<sup>3</sup> of freshwater stored in the Arctic Ocean and its sea ice cover(7) , with additional increases from the Greenland ice sheet (of some 300 to 2000 km<sup>3</sup> yr<sup>-1</sup> in (8)) and river inputs(of some 1000 km<sup>3</sup> yr<sup>-1</sup> in (9)). Combined, these sources are thought sufficient to disrupt the North-Atlantic meridional overturning circulation(10) and affect European winter climate. While models predict ocean thermal expansion to be the largest source of 21<sup>st</sup> century sea level rise, the past decade of satellite observations has also revealed that the principle mechanisms of mass loss from the ice sheets of Antarctica and Greenland are not represented in the present generation of coupled climate models, to the extent it is not possible to even quantify the uncertainty of the ice sheets' future contribution to sea level (IPCC 2007).

*Arctic temperatures* have increased by almost a factor of two greater than the global average over the last century(2) with the majority of models implicating the retreat and thinning of sea ice in this trend(11) . Satellite evidence has revealed a 23% decrease(12) in summer ice extent since 1979 and submarine data suggest that sea ice has thinned by 40% in the central Arctic in the last 30 years(13) . Although trends in ice extent are significant, the significance of trends in thickness is highly uncertain due to limited spatial and temporal sampling(12,14) . The paucity of data on ice thickness make the source of its variability uncertain. Model results suggest dynamic processes dominate(15) whilst observations show a thermodynamic control for the inter-annual variability of ice thickness averaged across the Arctic(16) . Global climate model predictions of both the recent(17) and future(18) rate of decline of sea ice area differ by more than a factor of 2. The determination of sea ice mass balance remains critical for change detection, improving model prediction and quantification of freshwater transport.

The Arctic Ocean receives 7000 km<sup>3</sup> yr<sup>-1</sup> of freshwater from precipitation, rivers and Pacific inflow which is stored before ultimately being exported through the Fram Strait into the Greenland-Iceland-Norwegian (GIN) Seas and through the Canadian Archipelago into the Labrador Seas, and ultimately to the North Atlantic(19). Although the freshwater input to the Arctic is relatively well known, the mechanisms of storage and transport of fresh water in, and through, the Arctic in both sea ice and the 200 m thick 'halocline' layer, is poorly known, and relies primarily on numerical models of the Arctic Ocean. However models disagree on even the sign of the mean ocean circulation in the Arctic, and estimates of the kinetic energy in the surface layer varies by an order of magnitude(20). A related, but poorly known, quantity is the sea level rise in the Arctic which is not only important for determining its contribution to global sea level rise, but also, when combined with bottom pressure measurements, as an indicator of salinity or temperature changes within Arctic Ocean(21) .

The large uncertainties in model predictions of the Arctic Ocean and its ice cover leave open the question of its role in a warming climate. The paucity of data on ice thickness and Arctic Ocean hydrography continue to hamper efforts to reduce, or even quantify, the uncertainties in model predictions. Quantitative, pan-Arctic data which can be brought to bear on these problems can only be provided from space. 'The Cryosphere and Polar Oceans' will provide unique decadal timescale data, and errors, on ice thickness and sea surface height required to address these issues(16,22). It will build on the current UK experience in the geodesy of ice-covered oceans and exploit the new *in-situ* observations to be provided during the International Polar Year (IPY) and new satellite missions, in particular CryoSat-2(23) . These data will be combined with a state-of-the-art ocean-ice model to determine the evolution of the Arctic Ocean in recent decades, and to enable the transfer of new, fully-tested model physics to the wider global climate modelling community.

*Our knowledge of the land cryosphere* contribution to sea level has been transformed in recent years through time-series of measurements from satellite-borne microwave radars that extend over a decade. In 1992, sparse, ground-based measurements allowed the Antarctic contribution to account for either all of the non-steric component of 20<sup>th</sup> century sea-level rise (~ 1.5 mm yr<sup>-1</sup>) or, alternatively, leave a shortfall of some 1000 Gt yr<sup>-1</sup> in the ocean mass budget(24) . Since 1998, however, successive

satellite-based estimates have been undertaken. A review of these(25) concluded that the present Antarctic and Greenland contribution to sea level rise is in fact small (some  $0.35 \text{ mm yr}^{-1}$  of the present rise of  $3.0 \text{ mm yr}^{-1}$ ). Equally, it has become apparent that the mass losses are dominated not by melting (although this has increased in Greenland and the Antarctic Peninsula) but by flow. In Antarctica and Greenland, ice streams, few in number but accounting for some  $600 \text{ Gt yr}^{-1}$  of the discharge, are transporting ice to the ocean faster than snowfall replaces it inland. In addition to the well-established thinning of the West Antarctic, Amundsen sector ice streams(26, 27) it is now known that the Totten and Cook glaciers in East Antarctica are undergoing inland thinning (e.g. Fig. 1(b)). In Greenland, substantial(28) though variable(29) increases in flow of coastal glaciers have been observed since 2000.

The discovery that flow dominates ice sheet losses to the ocean makes prediction of the future contribution uncertain (underlined by the IPCC's(2) inability to quantify it). The causes of the changes in flow are not known. The marine-terminated West Antarctic ice sheet (WAIS) may be geometrically unstable, a possibility given new theoretical impetus by Schoof(30) and the thinning East Antarctic ice streams have a similar geometry. Equally, the simultaneous drawdown of internally-decoupled flows make external forcing from the ocean (through ice shelf melting at or near the grounding line resulting in increased longitudinal stresses inland) equally likely(31-34). In Greenland, the observed accelerations are linked with calving events(35,36) that may be related to atmospheric or oceanographic forcing. In addition there is evidence(37) that increased sub-aerial melt is reaching the bed and is affecting flow rates deep into the ice sheet interior(37,38). Nor is simply uncertain causes that limit predictions of future changes. Present coupled climate models do not capture the actual ice streams responsible for the losses, the higher order stresses involved in their flow, or the details of their basal hydrology. The detailed treatment of the mechanics at the grounding line also remains uncertain(39).

Because present predictive capability is limited, continued observation is essential to maintain to the wider community a best estimate of the trend, and to elucidate the cause(s) of the flow imbalances. These are central aims of 'The Cryosphere and Polar Oceans'. Equally, process models that contain higher-order stresses, basal hydraulics, calving and ocean-ice coupling, and which answer to the unprecedented spatial and temporal detail of the satellite observations, have been developed (33). Such models, while remaining some way from generating ice streams *ab initio*, do allow with data assimilation insight into the detailed stress state of the actual Antarctic and Greenland ice streams of greatest concern and, through their wider application, are the most reliable basis today for prediction over the next century. This too is the aim of 'The Cryosphere and Polar Oceans'.