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Changing currents: a strategy for understanding and predicting the changing ocean circulation

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Within the context of UK marine science, we project a strategy for ocean circulation research over the next 20 years. We recommend a focus on three types of research: (i) sustained observations of the varying and evolving ocean circulation, (ii) careful analysis and interpretation of the observed climate changes for comparison with climate model projections, and (iii) the design and execution of focused field experiments to understand ocean processes that are not resolved in coupled climate models so as to be able to embed these processes realistically in the models. Within UK-sustained observations, we emphasize smart, cost-effective design of the observational network to extract maximum information from limited field resources. We encourage the incorporation of new sensors and new energy sources within the operational environment of UK-sustained observational programmes to bridge the gap that normally separates laboratory prototype from operational instrument. For interpreting the climate-change records obtained through a variety of national and international sustained observational programmes, creative and dedicated UK scientists should lead efforts to extract the meaningful signals and patterns of climate change and to interpret them so as to project future changes. For the process studies, individual scientists will need to work together in team environments to combine observational and process modelling results into effective improvements in the coupled climate models that will lead to more accurate climate predictions.

Keywords: strategic marine research; sustained observations; patterns of climate change; ocean processes

1. Introduction

Ocean circulation lies at the core of marine science. It is central to the physics, biology and chemistry of the ocean by setting the distribution of temperature, salinity, nutrients, trace elements and carbon. Its interaction with the atmosphere affects global weather patterns and moderates the climate of continental regions. Its interaction with bottom topography helps set sediment distribution. Its interaction with Arctic and Antarctic sea ice and glaciers

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defines the rate of melting. Patterns of ocean circulation determine the zones of active commercial fisheries, the regions of high and low ocean productivity, and consequently both the physical and biological pathways for air–sea gas exchange.

Marine research in the past 20 years has focused on defining the present-day ocean circulation. With the World Ocean Circulation Experiment (WOCE) during the 1990s, the global distribution of physical and chemical properties has been defined for the first time [1]. Western boundary currents have been measured in each ocean basin, and the strength of the circulation has been quantified [2,3]. From these measurements of ocean circulation, we begin to understand how biogeochemical distributions are set and how the ocean and atmosphere interact to determine the present climate [4].

The key issue for the next 20 years is to understand how the ocean circulation varies on interannual to decadal time scales and to quantify the impacts of varying ocean circulation on climate, biological productivity, the cryosphere, etc. In particular, a key scientific challenge is to understand how the circulation will change under changing thermohaline forcing associated with increased greenhouse gases in the atmosphere. It is widely expected that subpolar and polar regions will become much warmer with more precipitation, while tropical regions will become moderately warmer and have increased evaporation [5]. With changed equator to pole gradients, winds may strengthen or weaken. How will ocean circulation change?

Under evolving radiative forcing associated with increased carbon dioxide (CO_2) in the atmosphere, will there be stronger monsoons, fewer El Niño events, weakened Atlantic meridional overturning circulation? Presently, we have only rudimentary ideas on how the strength and structure of ocean circulation are set. If the ocean circulation changes, there will be substantial effects on the biology and chemistry of the ocean, on regional and global climate and on the melting of ice.

We know that there have been substantial changes in past climates owing to changing ocean circulation. For example, the glaciation of Antarctica occurred only when a circumpolar passage opened and the Antarctic Circumpolar Current (ACC) isolated the Antarctic continent [6]. The closure of Panama blocked tropical circulation and isolated Atlantic and Pacific ecosystems [7]. On more recent paleo time scales, varying Atlantic overturning circulation is linked to Northern Hemisphere ice-age cycles [8]. Changes in ocean circulation do have substantial effects.

We divide this strategy for understanding and predicting the changing ocean circulation into three activities: sustained observations of the varying and evolving ocean circulation, careful analysis and interpretation of the observed climate changes for comparison with climate model projections, and the design and execution of focused field experiments to understand ocean processes that are not resolved in coupled climate models so as to be able to embed these processes realistically in the models.

2. Background

Twenty years ago, marine observing systems were just beginning to be set up. The Tropical Ocean Global Atmosphere Tropical Atmosphere Ocean (TOGA-TAO) array in the tropical Pacific Ocean for observing and predicting El Niño events was the first large-scale open ocean observing system. The scientific imperative came from the failure of existing systems to detect, let alone predict, the strong 1982–1983 El Niño event [9]. The array's design drew upon increasingly reliable *in situ* instruments that had been proved and improved over the previous two decades, and the existence of satellite data telemetry. Systematic satellite altimetry measurements of global sea surface height variability started with Topex-Poseidon's launch in 1992, but with a heritage to the US Navy's Geosat mission and the National Aeronautics and Space Administration (NASA) Seasat mission in 1978. Building on established hydrographic sampling methods, the WOCE (1990–1998) set out to systematically sample the ocean from top to bottom across each ocean basin for the first time. To complement the traditional conductivity–temperature–depth and water sampling techniques, ocean sensors and platforms were developed, notably neutrally buoyant floats, surface drifters and acoustic current profilers [1,10]. It can be argued that the requirements of the WOCE accelerated the development and use of these technologies. After the WOCE, marine scientists have concentrated on maintaining regional and global observing systems such as the TAO array, Topex-Poseidon (now called Jason) and continued, repeat hydrographic sampling as well as building new observing systems such as Argo and Rapid to explore the scales of temporal and spatial variability throughout the ocean [11]. Systematic sampling from ships, satellites, floats and buoys is now contributing to the Global Ocean Observing System (GOOS) in an internationally coordinated way. This observing system has dual use, addressing fundamental scientific questions and underpinning essential societal services.

Simultaneously, 20 years ago, ocean circulation models started to be joined to atmosphere models to create coupled climate models that could be used to make projections of how climate might evolve [12]. These climate model projections are sensitive to small changes in ocean circulation over long time scales. For example, early coupled models required flux adjustment to maintain realistic sea surface temperature (SST) patterns: seasonal cycles in SST could be modelled reasonably well, but small errors in annual average air–sea heat exchange in the models led to unrealistic SST patterns over decadal time scales that corrupted climate projections unless a flux adjustment was made in the coupled model [13]. The Hadley Centre model HadCM3 was the first coupled climate model that could make realistic simulations without flux adjustments over century time scales [14]. For the past 20 years, marine scientists have been refining coupled climate models, improving their horizontal resolution, developing parametrizations for unresolved processes and improving the representation of key components such as radiation and air–sea exchanges, so that the models now produce decadal projections that appear realistic [5].

Climate change is the central scientific issue for our time. We are presently conducting a global climate experiment by putting CO_2 into the atmosphere, effectively doubling the amount of CO_2 over about a 100 year time scale [15]. Fundamental physical arguments predict that the atmosphere and ocean will warm by several degrees. Beyond that, we are uncertain how large and how fast the warming will be, what the regional patterns will be and what other changes will happen as the world warms. To date, the ocean has taken up about 40 per cent of the additional CO_2 put into the atmosphere [16] and ultimately we expect that the ocean will accumulate almost all of the added CO_2 owing to its capacity to store CO_2 in the deep ocean. Studies of ocean temperature show that the ocean has gained more than 90 per cent of the heat gained by the global system over the past 50 years and the ocean warming is spreading from the upper 700 m into progressively deeper layers [17].

We have coupled ocean–atmosphere climate models that predict the course of climate change, and Intergovernmental Panel on Climate Change reports periodically summarize the areas where these models agree and where they disagree on the details of future climate [5]. We also have studies of warm events in the paleo record, which may be analogues for the high carbon world, but the coupled climate models have not yet been able to model these events [18]. A central focus for marine science in the next 20 years is to observe the patterns of climate change in the ocean, to interpret the observations to understand the process of climate change and to improve our ability to accurately predict the course of climate change globally and regionally in order to help society to adapt to global change.

3. Sustained observations of the varying and evolving ocean

Long-term global monitoring of ocean properties and circulation is the key to understanding climate change and to developing our ability to predict future changes. First, long time series establish the amplitude of variability on subannual, seasonal and interannual time scales against which climate change on decadal periods can be assessed. For example, if decadal change exceeds the amplitude of subannual and seasonal variability, the change would have to be considered substantial and robust. More sophisticated statistical analysis would undoubtedly show a significant change at smaller amplitudes, but the key is that the background variability must be quantified. Similarly, monitoring establishes the spatial pattern of decadal changes that are essential for assessing the mechanisms of change. Is the warming larger in equatorial or polar regions? By how much? Comparing the spatial patterns of decadal change against model projections with and without anthropogenic forcing will establish whether the decadal changes are the result of natural long-term variability or due to anthropogenically driven changes.

To document the size and structure of changes in ocean circulation, sustained observations are needed of physical, chemical and biological properties: temperature, salinity, sea level, oxygen, nitrate, CO_2, phytoplankton, etc. We are fortunate at present to have international projects that are providing not only the sustained observations, but also the functional components that provide products to researchers and other users. Taking data from international efforts such as the Argo network of over 3000 profiling floats that monitor temperature, salinity and soon oxygen on a global basis from surface to 2000 m depth, and altimetric satellites that monitor sea surface height globally since 1992, integrative initiatives such as the Global Ocean Data Assimilation Experiment (GODAE) link these observations with numerical weather-prediction centres, data assimilation and assembly centres, and data and product servers, to provide a global analysis of the time-varying ocean circulation starting about 20 years ago. These analyses improve each year as new observations accumulate. Such systems representing ocean conditions over the past 20 years complement the global sea-level network, with time series extending back 100 years and more, and the historical set of high-quality repeat hydrographic sections extending back to the Challenger Expedition [19] in the 1870s. We are thus able to monitor changes in temperature, salinity, CO_2 and biogeochemical properties, including nitrate, phosphate and silica.

UK marine scientists contribute to and rely on international monitoring efforts such as WOCE (now the Global Ocean Ship-based Hydrographic Investigations Program (GOSHIP)), Topex-Poseidon-Jason, TAO, Argo and other elements of GOOS. UK scientists also lead some critical sustained observation programmes: the continuous plankton recorder (CPR) network of lines to monitor the variability in phytoplankton abundance and species over the past 50 years represents a unique time series of biological measurements [20]; the Rapid measurements of the Atlantic meridional overturning circulation and its components at 26° N is the only programme monitoring on a continuous basis the overturning circulation on a basin-scale basis (figure 1, [21]); long-term biogeochemical monitoring of the highly productive region at the Porcupine Abyssal Plain (PAP) site [22] and the range of planktonic ecosystems traversed by the Atlantic Meridional Transect (AMT) programme [23] complement the monitoring of oligotrophic conditions around Bermuda (Bermuda Atlantic Time-series Study (BATS) site [24]) and Hawaii (Hawaii Ocean Time-series (HOT) site [25]). The collection of global sea-level measurements by the UK's Permanent Service for Mean Sea Level (PSMSL) provides a unique and valuable database for calculating the change in sea level with time [26].

For sustained observations, physical oceanographers now have a substantial toolbox of instruments that meet their basic needs for the measurement of temperature, salinity and currents. Robust and reliable instruments for these parameters are available for long-term deployment, for example, on moorings and on autonomous vehicles such as gliders. Energy and cost budgets, rather than fundamental technological barriers or concerns over longevity and calibration, hold back development of additional sensors such as current profilers on profiling floats. Breakthroughs in affordable, reliable, safe power sources such as lithium carbon monofluoride primary batteries, with specific energies up to double the best currently available, would be of immediate and widespread benefit. Energy consumption, and the challenges of multivariate calibration and cross-sensitivities are the key issues holding back chemical sensors based on optical properties, e.g. for dissolved nitrate. Consumer electronics is likely to continue to drive innovation in efficient, short-wavelength solid-state light sources into the ultraviolet. When such light sources down to 200 nm become available, optical nitrate sensors are likely to become more prevalent.

The sustained observation programmes should be improved and enhanced whenever possible: more and deeper Argo floats (currently limited to a profiling depth of 2000 m, which means that the half of the ocean deeper than 2000 m is not sampled) with oxygen and biogeochemical sensors, longer Rapid and PAP mooring deployments, additional CPR lines to provide greater spatial coverage, etc. Present sustained observation programmes will be improved through implementation of new sensors, new technologies. New sensors typify much of the development activity within research laboratories, where a diversity of approach to the sensing problems can be studied. It can be argued that there are few important gaps in the spectrum of parameters being investigated through

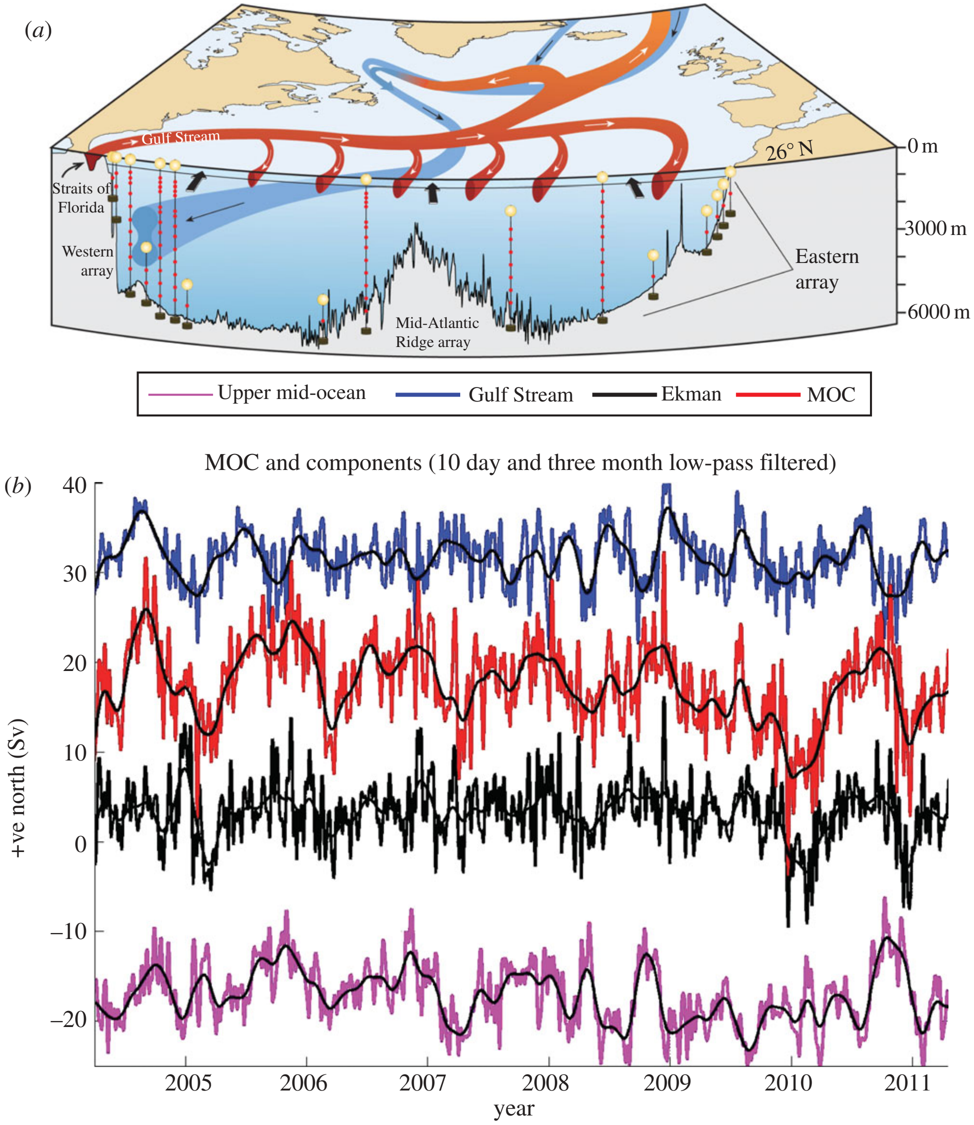

Figure 1. (*a*) Schematic of North Atlantic circulation with the Rapid monitoring array at 26° N. From http://www.noc.soton.ac.uk/rapidmoc/. (*b*) Gulf Stream (blue curves), meridional overturning circulation (MOC; red curves), Ekman (black curves) and Upper mid-ocean (purple curves) transports (10 day and 3 month, low-pass filtered) April 2004 to March 2011 as measured by the Rapid array. Transports are in Sverdrups ($1\,\mathrm{Sv} = 10^6\,\mathrm{m}^3\,\mathrm{s}^{-1}$). From http://www.noc.soton.ac.uk/rapidmoc/ [21].

laboratory-based sensor development programmes. In contrast, there is currently a gap between these laboratory devices and sustained application in the ocean by a broad community of users. This problem is not unique to marine science; it also exists in areas such as space instrumentation and defence. Directed action to bridge the so-called valley of death between proof-of-principle prototype and a qualified instrument in the actual operating environment must receive more attention. We argue that UK marine scientists and technologists should work together to bridge this gap, putting new sensors or new energy sources on Rapid instruments or instruments at the PAP Site, on UK Argo floats, on the CPR and on UK gliders to establish the new technologies as operational improvements to the sustained observations.

Additional sustained observations should be proposed or enhanced in critical locations of changing ocean circulation: regular monitoring of the flow of the ACC through Drake Passage using autonomous long-range underwater vehicles or deep gliders; more ocean time series in different biogeochemical provinces to complement established stations at Bermuda, Hawaii, PAP sites; complete monitoring of the overflows across the Greenland–Scotland Ridge, etc. Presently, UK marine scientists are actively planning to monitor the overturning circulation in both the North Atlantic and in the South Atlantic using new technologies. Here too in the smart, cost-effective design of sustained observational programmes, UK scientists can have a key role in future development of sustained observations. For example, based on physical principles, the Rapid programme can monitor the Atlantic meridional overturning circulation at 26° N using a combination of a disused subsea cable, and eastern and western boundary moorings, obviating the initial impulse to fill the ocean with moorings. While it is relatively easy for the UK to monitor Atlantic sites, it is essential that the UK also contribute significantly to international efforts to monitor critical remote regions such as the Southern Ocean, which appears to be warming faster than other regions and where the UK has long-standing scientific interests.

Enhancement of established programmes and adding new sustained observations are competitive processes; all are worthwhile, but only the most persuasive cases are likely to attract long-term support. What is most important is that at the very least, the UK maintains the scientifically rational sustained observational programmes we have. Their long time series are increasingly valuable as each year provides new events, better representation of the background variability and evidence for climate changes that can be used to challenge models. It should be as difficult to stop an existing monitoring programme as it is to initiate a new monitoring programme. A primary focus of UK marine science must be to continue and to enhance sustained observations of the evolving ocean circulation.

4. Careful analysis and interpretation of climate changes

In the next 20 years, we will begin to know the results of the global climate experiment we are presently performing. A key scientific issue is to document the magnitude and pattern of climate change in the ocean clearly. How deep do the changes penetrate? Where are they largest? Where do they originate and how do they spread? Next we want to use the magnitude and pattern of climate change to elucidate the mechanisms of change well enough to develop hypotheses for future change that can be tested against continuing observations. Finally, we want to compare the clearest patterns of actual climate change with coupled climate model projections in order to improve climate model capabilities for predicting future climate change.

Given the existence of a network of sustained ocean observations, careful analysis and interpretation of climate changes are fundamentally down to individual scientific initiative. They can be done by small teams of marine scientists working with publicly available sustained observations and coupled climate model outputs. One caveat is that the funding process must encourage scientists to document the changes carefully and think about what they mean. It is the careful documentation and thinking that are essential (see Wust [27, p. 20] which concludes with the statements: 'The first step of oceanographic activity must be the observational work at sea with all the pleasures of exploration, oceanographical measurements and visits to strange coasts. The second step is the numerical evaluation of the data …. But in the further development of oceanography, the expensive collection of the mass of data cannot be regarded as the main task of expeditions. Complete analysis of the data must not be pushed farther and farther into the background. The third step, the complete interpretation of the data that will provide the new results anticipated for the central problems of the expeditions, is the most tedious of all, but it brings the greatest progress and satisfaction. It is the duty of able oceanographers to complete the analysis and interpretation of the tremendous amount of new data and to set high standards for the publication of the results, as was done by the great expeditions in the past. Such tasks are time-consuming and also expensive. However, the scientific value of an expedition … depends on the quality and the completeness of the results published in extensive expedition reports').

Too often there is an opinion that the sustained observations will speak for themselves, whereas it is always the case that careful analysis and synthesis are required to extract maximum information. One need only consider the example of changing sea level where open ocean sea-level rise needs to be made consistent with coastal sea-level changes (which sometimes show decreasing sea level) and the thermal expansion effect needs to be separated out (figure 2, [26]). Dedicated scientific effort is needed to extract meaningful results from the sustained observations. This critical work will certainly be done over the next 20 years. UK marine scientists should be leaders in interpreting the global climate-change record. Proposal assessment must encourage such careful analysis and synthesis and must take into account the capabilities and track records of the scientists doing such work [31].

Within UK-led sustained observational programmes, there should be an embedded analysis and synthesis effort of international quality. Careful examination and use of new observations for important scientific objectives lead to improved quality control of the observations and to improvements in future observations. For example, the PSMSL in Liverpool has traditionally not only led the UK sea-level network and archived global sea-level time series, but has also taken a leading international role in analysing global sea-level trends. Involvement of PSMSL scientists in the global analysis means that the tide gauge network quickly incorporates new technological advances, any glitches in tide records are removed and quality-control issues with other countries' sea levels are identified and corrected (for example, the Greeks traditionally measured sea level positive downward) so that analysis of sensitive global sea-level trends has minimal possible error. Similarly for Rapid, the scientific analysis of the new observations embedded within the operational measurement programme has meant that sampling strategies (how many instruments, what parameters, how

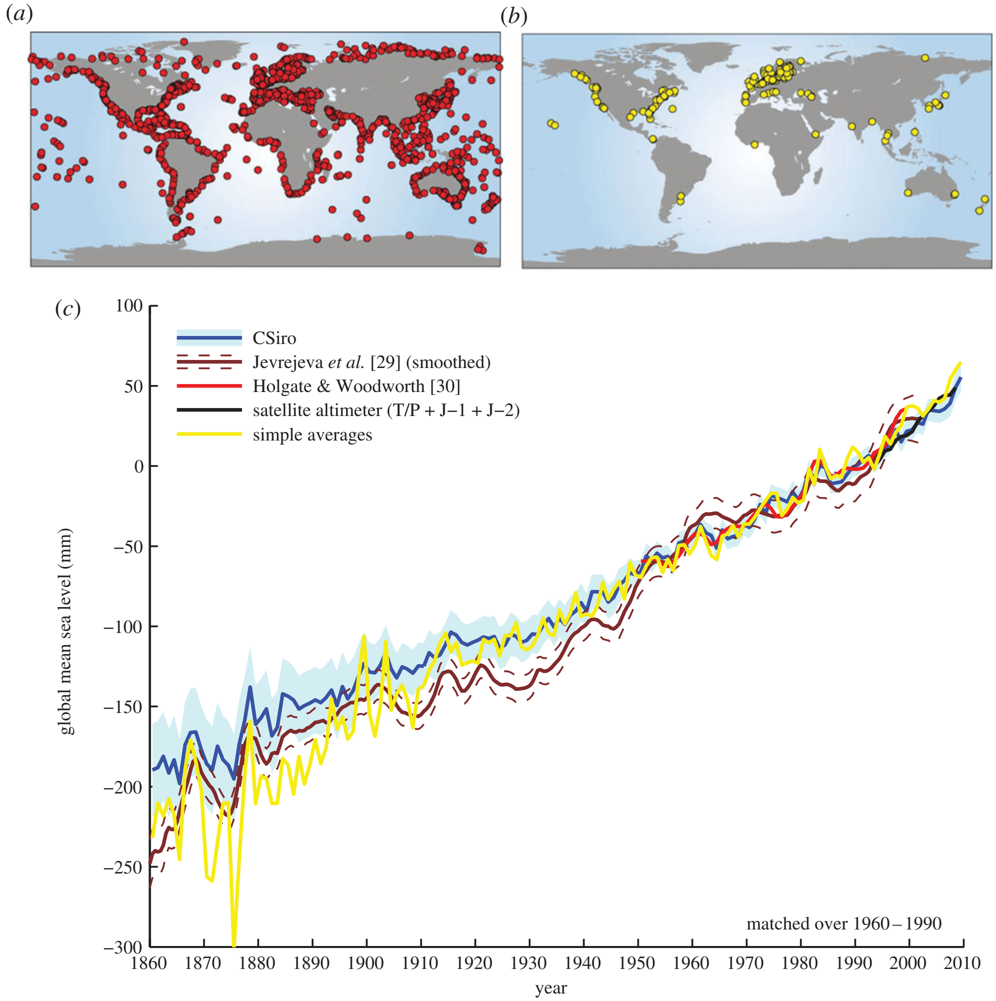

Figure 2. (*a*) Stations represented in the dataset of the Permanent Service for Mean Sea Level (PSMSL). (*b*) Stations with long records containing more than 60 years of data are shown in yellow. Reproduced with permission from Woodworth *et al.* [26]. (*c*) Global average sea level from 1860 to 2009 (in blue) derived from the reconstruction method of Church & White ([28] denoted CSiro) compared with the estimates of Jevrejeva *et al.* ([29] brown), Holgate & Woodworth ([30], red), and from a simple average of tide-gauge data (yellow). All of these estimates are based entirely or largely on PSMSL tide-gauge data. The satellite altimeter record is shown in black, T/P refers to Topex-Poseidon, J-1 refers to Jason 1 and J-2 refers to Jason 2. All series are set to have the same average value over 1960–1990, and the reconstruction is set to zero in 1990. Reproduced with permission from Woodworth *et al.* [26].

fast the sampling, where the moorings should be placed) are quickly modified to improve the quality of the publicly available time series for the Atlantic meridional overturning circulation.

Thus, while analysis of global trends and patterns can be analysed using publicly available datasets by small teams of scientists anywhere in the world, it is critical for UK-led sustained observational programmes to have embedded within them an analysis and synthesis effort of international quality. For the benefit of the sustained observations, the acquisition of measurements should not be separated physically or financially from serious scientific analysis of the observations. Again, programme and proposal assessment must ensure that international quality analysis efforts are embedded within sustained observations led by UK scientists.

5. Key processes

Coupled climate models rely fundamentally on embedding all important processes that affect long-term variability in climate. Many of these processes are of small spatial scale; so they must be parametrized in terms of the larger spatial-scale properties resolved in the models. The classic problem is how to parametrize eddy fluxes in coarse resolution climate models. Inaccuracies in parametrizing eddy fluxes led to large inaccuracies in long-term climate simulations in early models [12]. Present models use the Gent–McWilliams parametrization of eddy effects that has made recent climate model simulations more realistic and stable [32]. But we know this parametrization is not universal, and it does not work uniformly everywhere; hence, inaccuracies are still being introduced into model simulations over long time scales [33].

There are many such small-scale processes in the ocean that can affect climate over century time scales. To improve the ability of coupled climate models to make accurate climate projections, concentrated studies are needed to understand these small-scale processes well enough so they can be accurately included in climate models. Typically, these studies would involve fieldwork and analysis coupled with model studies as well as testing various ways to include the small-scale processes in coupled climate models. Here, we describe serious gaps in our understanding of ocean circulation and its interaction with the atmosphere, land and ice forms that should be addressed by marine scientists over the next 20 years. Some process experiments have been started; some are being actively planned. These experiments are larger than a single investigator and small team can address. They will require national and international collaboration and coordination for a concerted approach to improve our understanding of how the ocean works.

(a) *Deep-water formation*

We do not understand what sets the size and strength of the thermohaline circulation in the ocean. This is a multi-faceted problem that is often broken into components: how much deep water is formed? What sets the stratification in the ocean? How does new deep water mix and move and ultimately return to the surface ocean? How will these processes change under global warming and associated changes in thermohaline forcing?

Let us start with deep-water formation. How much deep water is formed during a severe winter? A climate model with 50 km horizontal grid must make deep water over a 50 × 50 km grid cell, but observations of deep wintertime convection indicate that deep-water formation occurs on horizontal scales of 10 km or less. Does a severe winter produce a larger volume of new deep water or a constant volume of denser deep water? We cannot expect the climate model to provide an answer and process models of convection depend on lateral mixing and how fast the deep water leaves the convection region. We suggest that a field experiment with associated process modelling is required to answer the fundamental question of how much deep water is formed. The Mediterranean regularly makes deep water, and we would suggest that new long endurance autonomous platforms and sensors could be deployed for the winter season over several years to measure the variability in deep-water formation. For example, in 2005–2006, a severe winter over the northwestern Mediterranean led to the formation of a huge volume of new and denser deep water [34]. Given air–sea buoyancy loss over the winter, could we predict how much deep water should be formed? And would such predictions work for subsequent winters of varying severity?

How does the newly formed deep water escape the formation region? Surely, the amount and properties of deep water depend on how fast the newly formed deep water leaves the formation region. If the newly formed deep water stays around the formation site, then a smaller volume of denser deep waters should be formed. But if the deep water quickly escapes, then more deep water with densities close to present deep-water density will be formed. Experience in the Mediterranean suggests that a boundary current carries the deep water away [35]. Evidence from the Labrador Sea is presently confusing as float trajectories suggest no direct flow in the deep western boundary current but rather some kind of injection into the mid-ocean circulation and subsequent southward flow along the Mid-Atlantic Ridge [36]. For the formation of North Atlantic deep water in the Nordic Seas, the new deep water must cross the Greenland–Scotland Ridge into the greater North Atlantic. If more deep-water is formed, how does that affect the deep stratification in the Nordic Seas and the amount of deep water overflowing the Ridge and the modification of deep-water properties due to mixing and entrainment as the deep water cascades down over the ridge crest? So there are at least three mechanisms for the escape of new deep water from its formation region. Can we understand these mechanisms well enough to embed them in coupled climate models?

(*b*) *Mixing*

Ultimately, the dense deep waters formed in high latitudes in wintertime must return to the surface layers of the ocean. Present understanding suggests that this return can occur either as a direct aspiration of the deep waters along isopycnals across the ACC, so there is little modification in the density of the deep water as it returns to the surface layers, or slowly as a result of small-scale mixing that transforms deep water into warmer less-dense waters that rise and then return to the formation regions. Both mechanisms rely on mixing. The aspiration of deep water across the ACC probably relies on isopycnal mixing due to eddies rather than direct southward and upward flow due to upwelling (because zonally averaged mean southward flow across the ACC is constrained to be small owing to its ageostrophic character). Small-scale mixing is associated ultimately with mechanical energy input by winds and tides; so it can occur on more global scales.

Neither eddy mixing nor small-scale mixing are well represented in coupled climate models. Arguably, the way in which these mixing effects are represented in climate models will have a large effect on climate projections over century time scales. If model mixing returns the deep waters to the surface an order

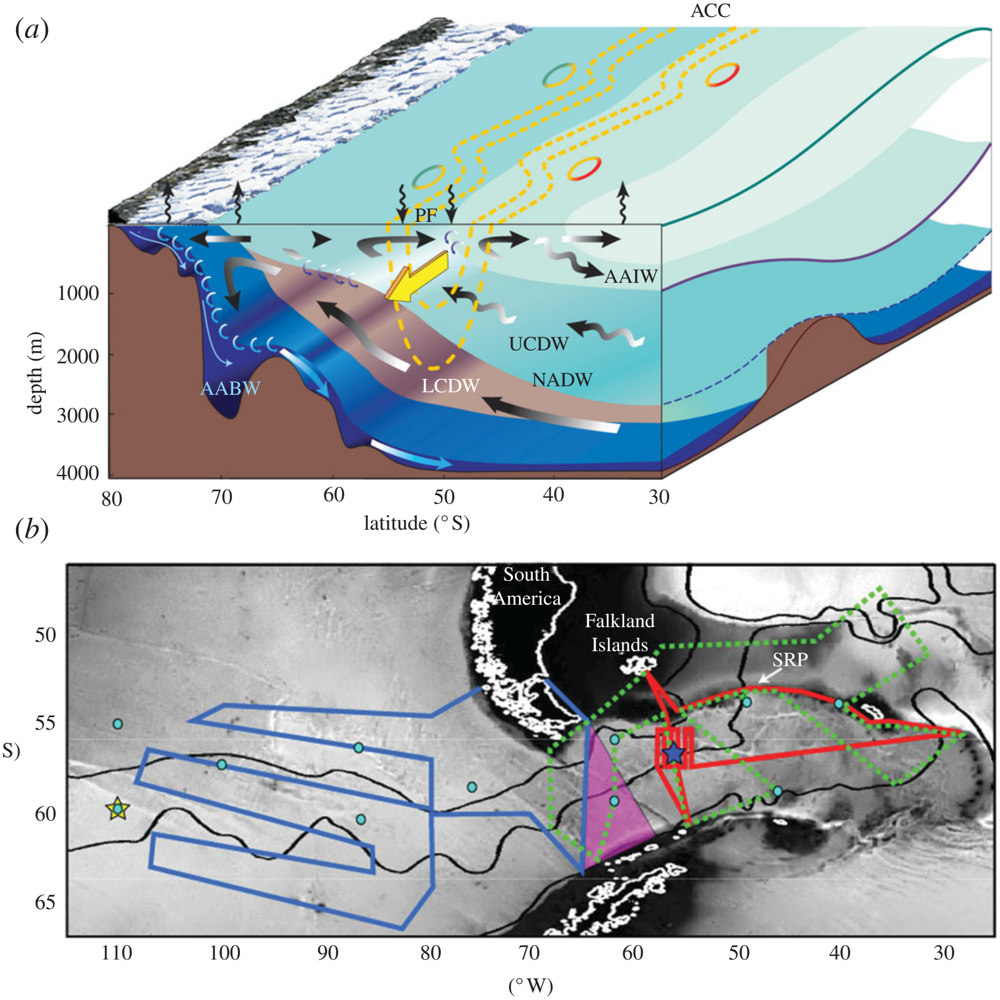

Figure 3. (*a*) Schematic of the present paradigm of the Southern Ocean limb of the meridional overturning circulation. The isopycnal upwelling of upper and lower circumpolar deep water (UCDW and LCDW, with sources in the North Atlantic) is supported by mean geostrophic mass fluxes below the level of topographic obstacles to the ACC and by mesoscale eddy-driven mass fluxes at mid-depth. The upwelled water changes density through air–sea–ice interaction. It then returns northward in the wind-driven Ekman layer to form Antarctic intermediate water (AAIW), and as Antarctic bottom water (AABW) in mean geostrophic flows. Reproduced with permission from Olbers and Visbeck ([37], fig. 1). (*b*) Schematic tracks of the US DIMES expedition 2 (blue, solid), UK DIMES expedition 2 (red, solid) and UK DIMES expedition 3 (green, dashed). The envelope of tracks of the three US Drake Passage transects is shaded in magenta. The yellow star indicates the tracer deployment location and cyan dots show positions of US sound sources. The blue star marks the location of the UK mooring cluster. The grey shading indicates the bathymetry; the climatological locations of the subAntarctic front, polar front and southern boundary of the ACC are indicated by the black lines from north to south; SRP, Shag Rocks Passage. Reproduced with permission from Naveira Garabato *et al.* [38].

of magnitude too fast or too slow, then the model projections over decadal time scales will be increasingly inaccurate. There is presently an international experiment (Diapycnal and Isopynal Mixing Experiment in the Southern Ocean; DIMES) going on in the Southern Ocean led by UK scientists to quantify isopycnal (lateral) and diapycnal (vertical) mixing (figure 3, [38]). The Southern Ocean is an ideal location for studying mixing because most of the global wind input mechanical energy for mixing is injected there, and it is a region of strong eddy activity and associated isopycnal mixing. A central issue following DIMES will be to assess how much of the vertical mixing associated with winds is done locally in the Southern Ocean either, in mid water column or near the ocean bottom topography. If most of the vertical mixing is done in the Southern Ocean, it may be possible to adjust coupled climate models to represent Southern Ocean mixing more accurately to improve long-term climate projections.

(*c*) *Ocean stratification*

The balance between the amount of intermediate and deep waters formed and the amount of mixing that returns deep waters to the surface sets the ocean stratification. If more deep water is formed than can be mixed back to the surface, then the ocean stratification will increase. If less deep water is formed, one expects that the mixing will decrease the stratification. Imbalance in the two processes then should show up in models as changes in ocean stratification over long-term climate runs. For example, some coupled climate model simulations exhibit a Southern Ocean that is too warm, too buoyant compared with present observations [39]. This perhaps suggests that the models have too much mixing relative to their deep-water formation. This is not to criticise any particular models but to point out that changes in ocean stratification can be used to diagnose problems in model representation of key processes. Monitoring the evolution of ocean stratification also gives evidence for how the balance between water mass formation and mixing is evolving over time. For example, a stronger or weaker northward penetration of Antarctic bottom water (AABW) into the Atlantic, Indian and Pacific Oceans probably indicates changing AABW formation if abyssal mixing has remained relatively constant.

(*d*) *Freezing and melting of sea ice*

As Arctic Ocean sea ice declines, it is critical to understand the processes of freezing and melting of sea ice in order to predict the evolution of Arctic circulation. Freezing of sea ice extrudes salt into the surface ocean that leads to downward mixing. In the present Arctic, where freezing occurs primarily on the periphery of the permanent ice cover, the depth of this mixing is limited by subsurface stratification associated with fresher halocline waters that have been advected in under the sea ice. If the Arctic becomes largely ice free in summer, large-scale wintertime freezing of sea ice might initially erode the fresh halocline waters, later leading to deep wintertime mixing that might even culminate in open Arctic Ocean deep-water formation. A key process study is needed to understand how deeply the extruded salt from sea ice penetrates and how much the low saline halocline stratification is being eroded locally near the ice edge.

In the spring and summer, melting of sea ice deposits a layer of fresh water on the surface. A key issue here is where this fresh water layer goes. If it merely mixes vertically down to 50 m or so, then the wintertime freezing may just return this freshwater layer to its normal salinity. But if the freshwater deposited from melting is able to get away from the ice edge, then the melting–freezing cycle will lead to continual injection of salty, dense water downward to erode the fresh halocline. If we look to the situation of Antarctic sea ice, the salt extrusion associated with freezing leads to the formation of AABW, while the fresh surface waters resulting from melting move northward in the wind-driven Ekman layer and ultimately form relatively fresh Antarctic intermediate water (AAIW) that subducts and carries an enormous supply of nutrients equatorward into the lower thermoclines of the Atlantic, Indian and Pacific Oceans [40]. Will the Arctic evolve into a similar system as it becomes ice free in summer? Process studies into both freezing and melting of Arctic sea ice are key to understanding how deep the extruded salt penetrates during freezing and where the fresh surface waters from melting sea ice go. We are fortunate now to have gliders that can be sent to survey the properties of the ice edge during both the freezing and melting phases of the annual cycle.

(e) Impact of changing ocean circulation on glaciers

For climate projections, a key process involves the interaction of ocean circulation with glaciers. Warming ocean waters are increasingly able to melt glaciers where they extend out over the sea and also at their grounding lines [41]. Melting at the grounding line may lubricate the base of the glacier, enabling it to flow faster into the sea. Thus, we particularly need process studies under the glacier and near the grounding line [42]. When warmer waters flow under the glacier up to the grounding line, how much faster does the glacier move? Relating the speed of glacier movement to warmer water should enable coupled climate models to embed glacier processes more accurately into long-term projections of climate change.

(f) Biological productivity

As SST and dissolved CO_2 increase, we need to understand the impact on biological processes such as primary production, respiration and export. At high latitudes, ocean productivity has a seasonal cycle with phytoplankton growth in spring associated with light and nutrient availability, then subsequent species succession and grazing by zooplankton followed by population decline. Much of the upper ocean primary production is respired back to CO_2, but a small proportion is exported downward below the thermocline. This process of ‘export production’ helps sequester CO_2 from the atmosphere into the deep ocean, and the balance between primary production and respiration influences the amount of carbon sequestered. It is generally taken that export production is balanced by new production each year associated with renewal of nutrients into the surface layers. Fundamental questions include how primary production and plankton community structure influence export, respiration and sequestration of carbon, and how primary production, export production, respiration and new production independently vary as the climate changes.

Several studies suggest that increasing temperature causes a disproportionately greater increase in plankton respiration than in production, with the prediction that by 2100, biological processes will take up 21 per cent less atmospheric CO_2 than today [43]. Increasing temperature is also associated with phytoplankton producing more dissolved organic carbon rather than particulate organic carbon, meaning that less carbon is exported through passive sinking and more is respired in the surface layers [44]. The depth at which sinking particles of carbon are respired back to CO_2 is dependent on temperature, dissolved oxygen concentration and stratification. Modelling studies have shown that a modest change in this depth can have a substantial impact on atmospheric CO_2 concentrations [45]. In a warmer world, the general expectation is that phytoplankton size will decrease, and because sinking rate is dependent on size, export will decrease and respiration will increase [46,47]. Sinking rate is also dependent on 'ballast' minerals such as calcium carbonate and opal produced by phytoplankton such as coccolithophores and diatoms, respectively. Increasing CO_2, leading to reduced pH and decreasing seawater calcium carbonate saturation state, is expected to lead to reduced export and increased respiration in surface layers [48,49].

Time-series observations of phytoplankton production, respiration and export production are needed to address these fundamental questions. Algorithms exist to derive phytoplankton production from satellite sensors for ocean colour and to derive export production from satellite SST, but these are poorly constrained owing to the lack of *in situ* data. A priority is to maintain the satellite missions for ocean colour and to develop the algorithms against *in situ* observations. Present procedures to measure *in situ* production are labour intensive, but new sensors are under development for fluorescence, dissolved oxygen and optical backscatter for gliders and moorings that would allow year-round determination of depth-resolved production and respiration. Export production can be estimated via sediment traps and thorium isotopes. Intensive fieldwork at a site like the PAP location is needed to quantify primary and export production and respiration and their interannual variability over at least a decade.

Production is controlled by the availability of nutrients (and sunlight); so new production is fuelled by the arrival of new nutrients into the surface layer. In the open ocean, arrival of nutrients may be primarily due to upwelling, either direct or eddy driven, and these supply mechanisms are thought to be constrained by vertical stratification. Surface warming due to increased atmospheric CO_2 may increase upper ocean stratification, thus reducing transport of dissolved oxygen from the surface to depth (increasing midwater deoxygenation) and decreasing nutrient supply from below [50]. With the prospect of nitrate sensors becoming available for gliders, a process experiment to examine how the physical processes of upwelling and mixing bring nutrients into the surface layers through the year is needed to quantify new production. If the experiment could be undertaken in locations with contrasting vertical stratification, it may be possible to unravel how new and export production depend on stratification; so we could embed these processes in coupled climate models to project how productivity will evolve in a changing climate.

(*g*) *Shelf-slope exchange*

The boundary between the deep-ocean circulation and the continental shelf circulation is a region of strong topographic control where the flow mainly follows bathymetric contours. How the flow crosses the contours, either from the deep ocean to the shelf or from the shelf to the deep ocean is a complex scientific problem. Upwelling where wind is favourable is a mechanism for bringing ocean waters into the coastal zone. But how the coastal zone exports waters offshore is not well understood. Such export is key to getting fresh river waters away from the coast as well as for exporting nutrients and pollutants offshore. Is the export done by tidal mixing at the shelf edge or by vigorous eddies in the alongshelf currents at the shelf edge? Sizeable field programmes to quantify the contributions from various mechanisms are needed to be able to model the exchange in ocean circulation models. Arguably, the shelf-slope exchange has the major effect on near-shore circulation (e.g. residence time for freshwater, nutrients, pollutants) than on the deep ocean. But to the extent that the exchange affects the ocean circulation, the small-scale processes need to be accurately embedded in coupled climate models. A major study is now underway on the northwest UK shelf-slope exchange that should provide initial assessments of the exchange processes and how they can be modelled (http://www.smi.ac.uk/fastnet).

(h) *Summary of key scientific issues*

We have tried to identify key scientific issues associated with gaps in our understanding of ocean circulation and how it will evolve in a changing climate. They do not represent an exhaustive list, in a sense the choice is personal to the authors, and other scientists can and should add key problems to this list. But the overarching idea is that there are fundamental gaps in our understanding of ocean circulation that affect our ability to make accurate projections of climate change. Each represents an interesting, fundamental scientific problem with slow but substantial long-term effects on the evolving climate. As listed here, the problems are inherently of smaller spatial scale than can be explicitly resolved in today's coupled climate models. Thus, making progress on each of the problems should allow technical improvements to be made in coupled climate models to reduce uncertainty in their climate projections on 100 year time scales. That each of the problems need to be addressed initially by a combination of fieldwork and process modelling followed by testing of ways to embed the process in coupled climate models stresses that these are strategic research problems requiring concerted attack by a substantial group of scientists. In our view, it is not likely that substantial progress can be made by a single scientist and small team.

6. Conclusions

Our strategy for UK marine science in terms of ocean circulation research for the next 20 years is to focus on three types of research: (i) sustained observations of the varying and evolving ocean circulation, (ii) careful analysis and interpretation of the observed climate changes for comparison with climate model projections, and (iii) the design and execution of focused field experiments to understand ocean processes that are not resolved in coupled climate models so as to be able to embed these processes realistically in the models.

Within sustained observations, the UK has a lead role in monitoring the Atlantic meridional overturning circulation, in CPR surveys of phytoplankton distribution and abundance, in monitoring global sea level. These activities must be continued, as they are scientifically rational and their long time series are increasingly valuable. Within these established programmes, we emphasize the development and application of new technologies, putting new instruments into the real-world operating environment. In developing new sustained observations, we emphasize smart cost-effective design of sampling strategies.

There are other international sustained observational programmes where careful analysis and interpretation of the evolving changes in ocean circulation and comparison with coupled climate model projections will lead to understanding the causes and effects of climate change and help us to develop better predictions of climate change. We expect creative and careful UK marine scientists to be leaders in interpreting the global climate-change records, whatever the source of the records.

Finally, there are many fundamental processes in ocean circulation and its interaction with the atmosphere that we do not fully understand. These processes are not well resolved in coupled climate models and their subtle effects, perhaps small over short time scales, are likely to be substantial over century time scales, especially if they are not embedded properly in the models. Here, we identify some of these processes: deep-water formation, mixing, ocean stratification, freezing and melting of sea ice, biological productivity, shelf-slope exchange. To seriously address each of these processes will require scientific teams to carry out extensive fieldwork and process modelling followed by testing of how the results can be embedded in climate models. Brilliant scientists will be required to work in a team environment to address these strategic research issues.

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