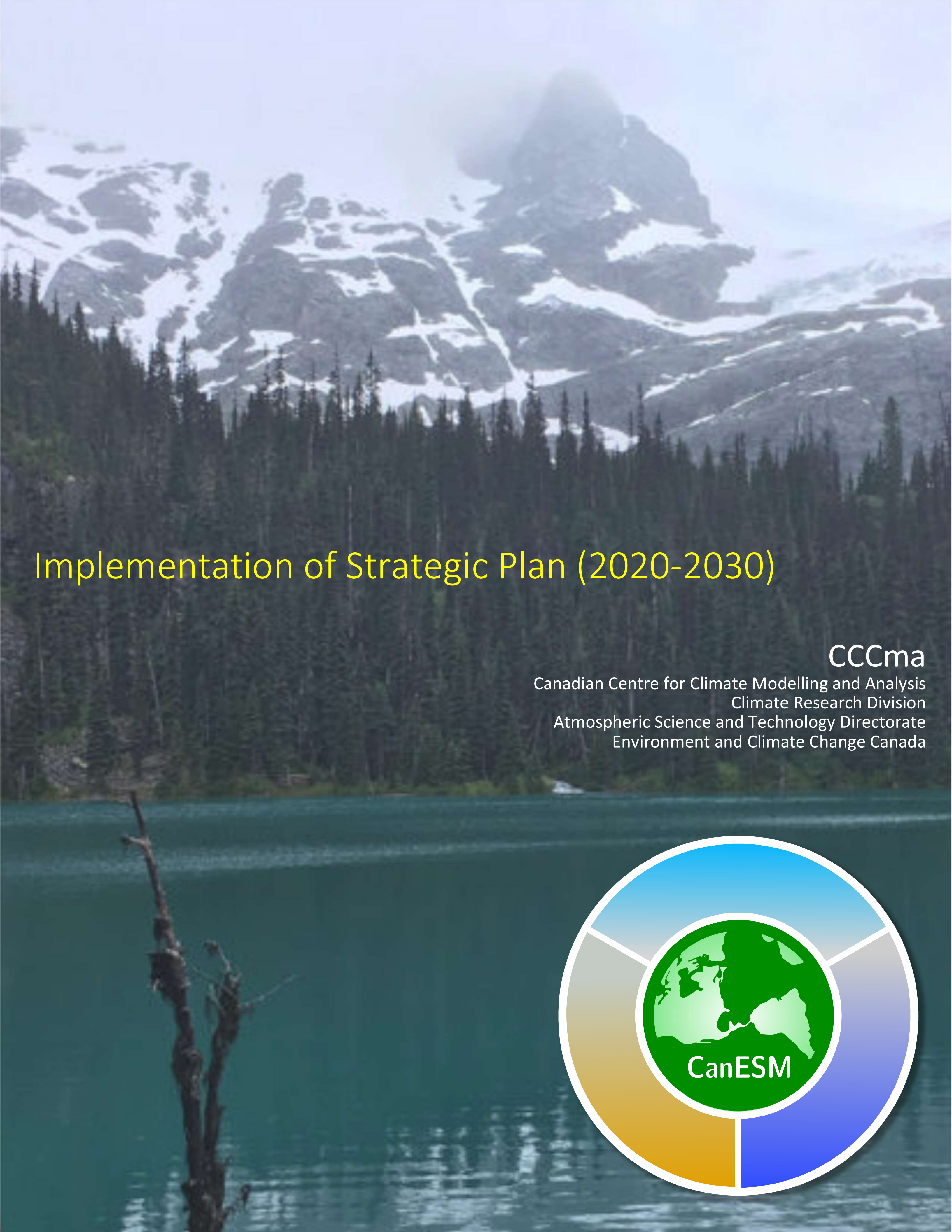

Implementation of Strategic Plan (2020-2030)

CCCma
Canadian Centre for Climate Modelling and Analysis
Climate Research Division
Atmospheric Science and Technology Directorate
Environment and Climate Change Canada

Context

In order to fulfill CCCma's mandate, this implementation plan was developed as the companion document to the CCCma strategic plan (2020–2030). This document is organized around CCCma research and development (R&D) themes and is supported by a set of concrete roadmaps to advance its work on the three time horizons of, near- (1-3 years), medium- (5-7 years) and long-term (10+ years).

The document summarizes the scientific and technical tasks and their associated milestones required to address emerging scientific understanding within strategic priority areas and to meet the goal of modernizing the foundation of Canada's Earth system modelling infrastructure, which underlies all scientific applications of the model.

Theme 1 Canadian Earth System Modelling Activities

The Canadian Earth System Model (CanESM) is the foundation of ECCC's climate modelling enterprise. It is formed by the coupling of component models for the atmosphere, ocean and land, which are developed to represent the full spectrum of physical, biological and chemical processes. Earth System Modelling (ESM) activities involve, the maintenance of operational versions of the CanESM for science applications; the assembly and evaluation of new CanESM versions derived from updated and improved component model versions; and the oversight of major changes of CanESM software and hardware infrastructure required to support future developments in its component models and downstream modelling systems (e.g. seasonal to decadal prediction system CanSIPS).

Development of future versions of CanESM can be divided into two complimentary streams: **Stream 1:** *The physical improvement of CanESM*. In the near- to medium-term, this involves continued development related to the tunings, physical parameterizations, and resolution of the component models of the atmosphere, ocean, and land. In the medium- to long-term, the full atmospheric chemistry model will be integrated into, and optimized within, the CanESM.

Stream 2: *The maintenance and structural improvement of CanESM.* In the near- to medium-term, this involves the oversight of CanESM science applications; the wholesale replacement of major components such as the CanAM spectral dynamical core with the GEM dynamical core; and an upgrade of the Canadian Coupler (CanCPL) with a new community system coupler, such as the National Unified Operational Prediction Capability on the Earth System Model Framework (NUOPC/ESMF). In the medium- to long-term, this involves the adoption of a collaborative approach to development, application and analysis by producing a version of CanESM that can run on any computing platform. This type of approach would facilitate improved scientific collaboration across government departments and agencies, the Canadian academic, and the international climate communities.

Theme 2 Technical Development Activities

The Technical Development Committee (TDC) oversees and coordinates all of the technical and computing infrastructure required to support the development, application, and analysis of CanESM. Technical support activities also have an ongoing compute-platform element whereby the CCCma IMIT team provides maintenance of IT equipment including Linux laptops, local servers, High Performance Computing (HPC) system accounts including quotas, and act as liaison with Shared Services Canada (SSC). This also includes key collaboration platforms, such as the Earth System Grid Federation (ESGF), File Transfer Protocol (FTP) and open data servers.

In the near-term, creating a modern standards compliant model and diagnostics code base, which is robust efficient and portable, is one of CCCma's key priorities. In parallel, the underlying tools and software used to run the model and diagnostics on HPC platforms (i.e. sequencing) require a major overhaul to align with modern best practices, and to ensure maintainability. The modernization plan will focus on adopting open standards and community tools wherever possible. The goals of this effort are to make the CanESM and tools codebases highly portable - to enable easier maintenance, further align CCCma expertise with the community, and broaden both internal and external collaboration. It is also vital that the tools and codebases are made flexible enough to adapt to new and emerging chip and machine architectures. Part of these efforts will involve support for the adoption of major new model components, including the GEM dynamical core, ocean model component (NEMO4), and a community coupler.

In the medium- to long-term, the TDC will play the central role in maintaining a production-ready modelling system, and in facilitating model development. This ongoing maintenance work spans version control systems and repositories, sequencing tools, and metadata handling. This ongoing maintenance and the broader modernization effort will be bookended by the phases of the WCRP Coupled Model Intercomparison Project (CMIP), which is the major coordinating science activity in support of the IPCC climate assessment reports. Phase 7 of CMIP (CMIP7) will provide a focus for key technical activities including, optimization of model throughput, capturing provenance, ensuring reproducibility, preparation of an extensive model output to conform to the CMIP7 data requests, and detailed handling and publication of the resulting datasets.

Theme 3 Atmospheric Modelling Activities

Models of atmospheric processes, or parameterizations, are substantial and critical components of Earth system models. As these models are increasingly being called upon to answer more diverse science-policy questions with greater specificity, their parameterizations must be continuously developed and improved to more realistically simulate physical processes in ever-increasing detail. Development of CanAM, the atmospheric component of CanESM, can be divided into three interconnected areas, *physical processes*, *chemistry and short lived climate forcings*, and *regional climate modelling*.

In the near- to medium-term, plans for significant development of physical processes include, the move to 4-stream radiative transfer in the troposphere and lower stratosphere; an improved, community, non-local thermodynamic equilibrium radiative transfer code for the upper-stratosphere and mesosphere; updated microphysics and subgrid-scale statistical properties of the prognostic cloud scheme; an updated deep convective scheme designed to interact with shallow convection through a predator-prey modelling approach; and, a new turbulent kinetic energy scheme for the boundary layer. These physical processes will be coupled with parameterizations of aerosols and gas-phase chemistry in the troposphere and stratosphere, including ozone, aerosol emissions and aerosol microphysics modelling using PAM (aerosol microphysics scheme). Also in the near-term, CanAM physics will be coupled with the GEM dynamical core. This will improve efficiency and scalability of CanAM dynamics to allow higher resolution and will provide a common dynamical model for global and regional climate modelling. In the same timeframe, the regional climate modelling capability will use improved versions of CanESM to develop and configure the model for a range of downscaling applications including seasonal to decadal predictions and longer-term future projections of climate change.

In the medium- to long-term, CanAM developments ensure that CanESM has the necessary capacity to address Canada-relevant climate change issues for applications that include, the next phase of Canada's Changing Climate Report, CCCR2.0; the use of CanRCM for operational regional downscaling of the seasonal-to-decadal forecast system, CanSIPS; and the fully interactive coupling of CanRCM with the regional ocean system, CanTODS, to produce a coupled Regional Earth System Model, CanRESM. Additionally, these CanAM developments will support major international modelling activities such as, CORDEX, for regional climate downscaling; CMIP7, which feeds into IPCC assessments; CCMI, which feeds into the WMO Scientific Assessments of Ozone; and the AMAP assessment, which depends critically on improved modelling of black carbon and methane in the Arctic. In addition to these specific applications of CanESM, atmospheric model development will further improve CCCma's ability to simulate the past and future climate in both the troposphere and stratosphere; simulate interactions between climate and air pollution; and to investigate mitigation efforts such as climate engineering.

Theme 4 Ocean Modelling Activities

The ocean is a key component of CanESM due to its ability to absorb and retain vast quantities of heat and carbon relative to the land and atmosphere. It is a central player in determining the strength and distribution of warming over Canada. Obtaining the correct temporal rate and spatial structure of warming over Canada depends on the quality of ocean currents and temperatures simulated by CanNEMO as well as the physical robustness of the carbon biogeochemistry modelled by CanOE. The continuous development and improvement of CanNEMO and CanOE is, therefore, crucial for improving climate predictions over Canada.

In the near-term, key priorities include the investigation and reduction of uncertainties in projections of physical and biogeochemical ocean states through collaboration with world leading ocean-climate centres and participation in CMIP6 and CMIP6-endorsed MIPs, including the Flux-Anomaly-Forced Model Intercomparison Project (FAFMIP), Ocean Model Intercomparison Project (OMIP) and other ocean-focused MIPs; upgrading the sea-ice from LIM2 to LIM3 and including biogeochemistry; upgrading the NEMO version in CanNEMO from NEMO3 to NEMO4 including CanOE biogeochemistry; developing and testing a high-resolution 1/4-degree CanNEMO; the introduction of ocean emissions of N_2O, as an additional potential greenhouse gas source in Canadian waters; and the initial development of a coastal regional modelling system, CanTODS, in collaboration with DFO scientists.

In the medium-term, key priorities include the support and ongoing maintenance of two operational versions of CanESM based on the 1-degree and 1/4-degree CanNEMO ocean models, which are tuned and validated against observations for CCCR2.0 and CMIP7; an operational version of CanTODS used to produce an ensemble of downscaled biogeochemical climate projections, spanning parent ESM, realization and scenario uncertainty; and, an evaluation of the utility of CanTODS for the downscaling of biogeochemistry in CanSIPS, the seasonal prediction system.

In the long-term, as part of the Canadian Earth system modelling framework to produce Canadian-focused climate predictions and projections, CanRCM and CanTODS will be coupled to form CanRESM in the identical manner that CanAM and CanNEMO are coupled to form global CanESM. In this way, CanESM and CanRESM will operate seamlessly over global and regional spatial scales.

Theme 5 Land Surface Modelling Activities

Sophisticated land surface models are an essential component of ESMs providing physical representations of terrestrial ecosystems and carbon sources and sinks. To date, all versions of CanESM have employed independent models to parameterize physical (CLASS) and carbon biogeochemistry (CTEM) land surface processes and have employed minimal coupling between them. Over the past five years, a new land surface scheme, CLASSIC, has been developed to tightly integrate both physical and biogeochemistry processes into a single parameterization. CLASSIC is currently a "stand—alone" model, having been developed outside of CanESM and driven by, and validated against, observational datasets.

In the near-term, key priorities include solving the technical and scientific issues related to bringing CLASSIC into CanESM so that it may serve as its operational land surface scheme; testing of CLASSIC's nitrogen cycle in CanESM; testing and tuning of CLASSIC for increased CanESM resolutions of 1-degree including peatland processes; and, a detailed analysis of CLASSIC's performance against other land surface models contributing to the Global Carbon Project (GCP).

In the medium- to long-term, new and improved CLASSIC processes will be developed and evaluated within the CanESM framework. These include, excess ground ice; high latitude Plant Functional Types; ground water; plant hydraulics; and processes related to land use change. These improvements will additionally support high-profile international modelling activities such as CMIP7 related land-focused MIPs (e.g., Fire Model Intercomparison Project) and GCP.

Theme 6 Seasonal to Decadal Prediction Activities

Seasonal to decadal prediction (S2D) research is one of CCCma's priority areas, providing initialized climate forecast products to Canadians, and furthering understanding of the predictability of the Earth system. This activity leads directly to the implementation of operational climate prediction systems run by the Meteorological Service of Canada (MSC), and so involves intensive intra-departmental collaboration and strict adherence to a set of ISO quality assurance standards.

In the near-term, ECCC's seasonal hindcasts and forecasts from CanSIPSv2 and decadal hindcasts and forecasts from CanCM4 and CanESM5.0 will be analyzed. Applications explored will include S2D prediction of regional sea level variations impacting coastal communities, soil moisture variations bearing on drought and flooding potential, and additional climatic indices impacting agriculture, and air quality.

New products with demonstrated value will be distributed on the Canadian Climate Data and Scenarios (CCDS) and/or Canadian Centre for Climate Services (CCCS) sites. New interactive analysis tools, running on the HPC system, will be developed to provide diagnostic capabilities assisting research and development, as well as real-time monitoring of operational S2D forecasts. CCCma will continue to participate in international research initiatives such as one to examine the predictability of atmospheric CO_2 variations and impacts of COVID-19 related emission reductions on the global carbon cycle.

In the medium- to long-term, advanced CCCma models with increased atmospheric and ocean resolution will be applied to S2D prediction, and improved initialization methods will be implemented. Still higher resolution predictions for Canada's coastal oceans will be derived from CanTODS downscaling in collaboration with DFO scientists. The inclusion of biogeochemistry in CanTODS will further support decision making related to the conservation and management of living marine resources. Additional sector-specific S2D forecast products, which take end-user needs into account through stakeholder engagement, will be developed and delivered through CCDS and/or CCCS. Additionally, the suite of S2D products will be enhanced to include user-relevant information such as probabilities of extreme events and exceedance probabilities for user-specified thresholds. Diagnostic capabilities will be expanded through an interactive "climate forecast engine" that provides specialized forecast information in response to queries from users and could potentially be packaged as a public resource.

For the seasonal to interannual prediction system, CanSIPS, there will be ongoing close collaboration with MRD and MSC on operational implementation and evaluation. Decadal predictions are not yet run operationally (rather they are run as part of CCCma's research activities), but discussions will be initiated in the medium- term to explore the potential transition of a mature system to MSC operations.

Theme 7 Applications and Analysis Activities

Applications of Canada's Earth System Model, and analysis of its results, are essential for addressing and understanding emerging scientific issues, informing future model improvement, and supporting climate service applications. In the near-term, the focus will be on analysis of CanESM5.0 to understand its key biases including the reasons for its high climate sensitivity. This analysis will inform future model development and will be documented in peer-reviewed publications and technical reports. Additionally, in the near-term, CCCma will continue to carry out and publish studies on emerging science questions which include the climate effects of COVID-19 disruption; attribution of global and Canadian temperature and hydrological change; the influence of forcing uncertainty on projections; Arctic amplification; and, short-lived climate forcers and their impact on Arctic climate.

In the medium- to long-term, in addition to the investigation of emerging science issues, CCCma will engage in new activities to support climate service applications. For example, CanESM5.0 projections will be downscaled to high resolution over Canada and provided to partners for use in impact assessment and adaptation planning. Approaches to using observational constraints to improve climate projections over Canada will be investigated and tested as well as approaches to separating forced changes and internal variability in projections. The detection of potential climate responses to mitigation policies, both nationally and internationally, will also be examined. With additional investment, interactions between climate change, air quality, and health will be explored with Health Canada, and a quasi-operational system for the attribution of extreme events will be developed to inform efforts related to disaster risk reduction. Finally, we will further develop capacity to analyze climate impacts of geoengineering approaches on Canadian and global climate.

Conclusion

CCCma is well positioned to provide the best possible scientific basis for informing decision-making in Canada through achieving these milestones, which are fully aligned with the seven priorities described in the strategic plan. However, the realization of these milestones is only possible with new and focused investments in key *technical* and *scientific* capacity.