Volcanoes above the Kuril-Kamchatka subduction zone, Russia. Credit: NASA Earth Observatory

COMPUTING THE EARTH FROM CORE TO CLOUDS

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The earth sciences have long contributed to driving advances in high performance computing. Weather forecasting was one of the earliest practical applications, back in the days when supercomputers had less computational power than the latest video game consoles and mobile phones (Fig. 1). By the time Japan began development of the Earth Simulator in the late 1990s, the scope had broadened to include climate modelling, the effects of global warming, and the dynamics of the earth's interior. When it launched in 2002, the Earth Simulator was the fastest supercomputer in the world and remained on top of the list for over two years. Of the top 10 fastest supercomputers today, 8 are lodged at institutions (across the USA, Japan, Germany and China) that conduct research related to earth and environmental sciences.

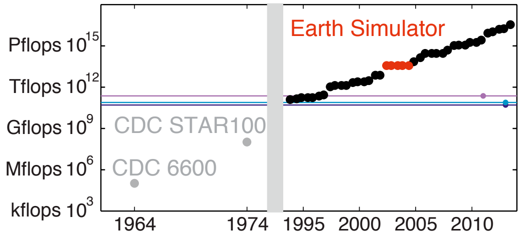

Figure 1. Exponential growth of computational power. Circles show the performance of the world's fastest supercomputers. Dots show the performance of a Sony Playstation 3 (purple), Apple iPhone 5s (turquoise) and Samsung Galaxy S4 (blue). Sources: www.top500org, en.wikipedia.org/wiki/History_of_supercomputing, www.phonearena.com

NUMERICAL MODELLING OF THE EARTH

Motions in the atmosphere, ocean and solid earth are inherently complicated. One has only to look around to appreciate the vastly different scales and forms these motions take, from ripples on a lake to cloud vortices to the migration of tectonic plates that spread, converge and slip past each other to form rift valleys, trenches and fault zones.

These motions are governed by physical laws that can be expressed as a multivariate system of equations representing the earth system. Interestingly, many of the equations (e.g., Navier-Stokes equations for fluids, wave equation, conservation laws) are common to the atmosphere, ocean, ice, mantle and core, but for each case, the terms that dominate or become negligible are different.

PAST, PRESENT AND FUTURE CLIMATE

The Norwegian Earth System Model (NorESM) is one such numerical model that represents as best it can the physics, thermodynamics, chemistry and biochemistry of the atmosphere, ocean, sea ice and land surface. A consortium of universities and research institutions in Bergen, Oslo and Tromsø share the massive job of maintaining, updating and improving NorESM.

Researchers at the University of Bergen and the Bjerknes Centre for Climate Research use NorESM to study a wide range of climates, from ice ages and past periods of extreme warmth to the global warming occurring today and continuing into the future.NorESM contributed climate simulations (Iversen et al. 2013) to the Coupled Model Intercomparison Project (CMIP5; cmip-pcmdi.llnl.gov/cmip5), and these were used in numerous studies cited in a report released in autumn 2013 by the Intergovernmental Panel on Climate Change (www.ipcc.ch). For these simulations, the atmosphere is sliced up into a grid with approximately 2° latitude-longitude boxes and 26 vertical levels, and the ocean is sliced into 1° boxes and 53 vertical levels. The 3-dimensional state of the atmosphere and ocean is then advanced forward in 30-minute time steps. A typical 100-year long simulation involves more than 3.7 million grid points and nearly 1.8 million time steps. NorESM ran on several hundred processors for a period of 9 months to complete the suite of simulations contributed to CMIP5, and produced about 70 TB of data. Figure 2 shows a NorESM estimate of how surface temperature may change by the end of this century following one possible future scenario. The model is given inputs of the external "forcings" for the period of interest, in this case changes in solar irradiance and estimated changes in atmospheric greenhouse gas concentrations and aerosols (this medium-high scenario stabilizes atmospheric carbon dioxide at 850 ppm, approximately 450 ppm higher than today, shortly after 2100). It is then run forward into the future with the various model components evolving and interacting freely.

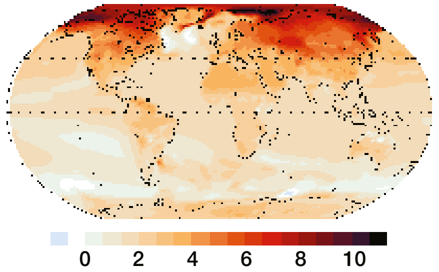

Figure 2. Map of surface warming in the decade 2090-2099 from a NorESM simulation of the RCP6.0 future scenario. Warming is relative to the 1961-1990 period.

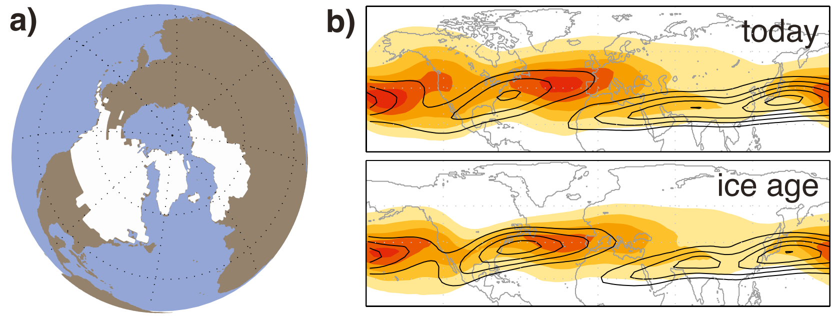

Figure 3. Climate of the last ice age. (a) Maximum extent of Northern Hemisphere ice sheets according to the ICE-5G reconstruction (Peltier, 2004). (b) Simulated winter storm tracks (shading showing eddy kinetic energy at 200 hPa) and atmospheric jet streams (contours showing westerly wind at 250 hPa, 10 ms-1 starting at 30 ms -1) in present climate and ice age climate (modified from Li and Battisti, 2008).

NorESM predicts warmer temperatures almost everywhere on the globe, with more pronounced warming towards the North Pole and over continents. Regions where sea ice disappears become over 10°C warmer than they today. While no single climate model is perfect, results such as this are remarkably consistent. If we continue along this scenario, the IPCC climate models agree that the world will likely warm by at least 2°C by the end of the century, though the warming will be neither uniform nor smooth due to regional and interannual-to-decadal variations (IPCC AR5, 2013).

Climate models can project us forward into possible future worlds, but they can just as easily take us back in time. During the last ice age, massive ice sheets blanketed North America and Scandinavia (Fig. 3a), reaching heights of over 3 km at their maximum extent around 21,000 years ago. One can find geologic records of ice age climate in deep ocean sediments, lake sediments and ice cores drilled from Greenland and Antarctica (Fig. 4). The records are often discontinuous, tricky to interpret and fraught with dating uncertainties, so we turn to climate models to fill the gaps. Studying such periods helps deepen our understanding of the wide range of climate conditions Earth can experience.

To simulate the last ice age, the model is given estimated forcing inputs for the past instead of the future – in this case, reduced concentrations of atmospheric greenhouse gases and aerosols, the appropriate solar irradiance, altered continental coastlines to account for lower sea levels, and our best guess for the extent and height of the ice sheets. Figure 3b shows an example of output from this type of simulation performed using NorESM's atmospheric component. Compared to today, the model simulates a weaker and southward-shifted North Atlantic storm track during the ice age (Li and Battisti, 2008). Since it is this storm track that coastal Norway owes much of its rainfall to, the result suggests that Bergen might have been considerably less rainy back then (though also considerably colder)! The altered storm track is likely related to the presence of the North American ice sheet and the internal dynamics of atmospheric jet streams (Pausata et al., 2009; Li and Wettstein, 2012).

STRUCTURE OF THE SOLID EARTH

NorESM includes the earth system components that are important for simulating climate, from the top of the atmosphere to the ocean abyss, but stops short of the solid earth.

The term "solid" is in fact misleading, because this part of the Earth is anything but constant and unyielding. The tectonic plates of the lithosphere glide along at speeds of 5-10 cm/year, the underlying mantle convects on time scales of millions of years, and at the centre of it all lies the core, where flow patterns in the outer liquid shell create a dynamo that is believed to generate the Earth's magnetic field. The time scales of these motions are so long that they are mostly negligible if you are interested in climate, but certainly not if you are interested in phenomena such as earthquakes, volcanoes, seafloor spreading, subduction processes and magnetic reversals.

SUBDUCTION ZONES

Subduction zones are a growing research focus at the Department of Earth Science at UiB, and they illustrate well how computational approaches can be used in solid earth sciences. Subduction is a process by which, when two tectonic plates converge, one moves under the other and plunges into the underlying mantle (Fig. 5a). Regions where subduction occurs include the northwestern coast of North America, the eastern coast of Japan and the south-western coast of Indonesia. Subduction zones are often associated with powerful megathrust earthquakes, explosive volcanism and orogenesis (mountain building).

A great deal of knowledge about subduction zones comes from seismic images of these regions. The concept is similar to how radiologists make medical scans, but instead of using energy from X-rays or ultrasonic waves to see into your body, seismologists use energy from earthquakes to see into the Earth. Earthquakes are one of the few sources that create enough energy to illuminate structures deep (hundreds to thousands of kilometres) inside the Earth.

Seismometers that detect ground motion are deployed above a subduction zone of interest, then left in place for months to years, waiting for an adequate number of earthquakes to pass through the subduction zone, sample its structure, and be recorded as seismic waveforms (Fig. 5b). Usually, the earthquakes are so distant and the ground motions so small that someone standing next to a seismometer would not notice any shaking. Using a range of data processing and imaging techniques (Bostock et al., 2001; Rondenay 2009), we can then decode the surface motions to create images of the subduction zone structure below (Fig. 5c; see also Rondenay et al., 2008). To do so, we must have knowledge of both the forward model (i.e., given a physical system with certain properties, what are the expected observations?) and its inverse (i.e., given a set of observations, what are the properties of the physical system that produced it?).

The vertical profile shown in Fig. 5c could be considered the current state of the art in terms of subduction zone imaging, but the inverse method used to make it oversimplifies the problem. It assumes that elastic waves travelling through the earth only interact with earth structure in one way – by diffracting when they encounter a sudden irregularity. However, we know that the wiggles in a seismic waveform derive from a much wider range of interactions. The waves are accelerated and slowed down, attenuated and absorbed, bent and straightened, as well as focused and defocused by structures of all shapes and sizes.

Figure 4. Ice core from Greenland. Source: NEEM ice core drilling project, www.neem.ku.dk (Sepp Kipfstuhl)

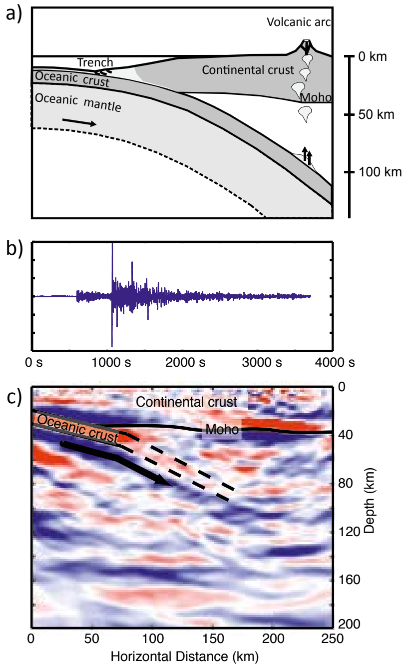

Figure 5. Subduction zone imaging. (a) Schematic diagram of a typical subduction zone (modified from Hyndman and Peacock, 2003). (b) Example of seismic waveform of a distant earthquake recorded by a seismometer. (c) High-resolution image of the Cascadia subduction zone across Oregon, USA obtained by 2-D inversion of scattered seismic waves (modified from Rondenay et al., 2008). Colour scale represents perturbations in seismic velocity relative to a reference background velocity, with red/blue denoting slow/fast velocities.

A new class of seismic imaging methods aims to account for many of these interactions.These "Full Waveform Inversion" (FWI) methods (Tromp et al., 2008; Virieux and Operto, 2009) attempt to deduce the structure of the subsurface (the observations). Whereas the image shown in Fig. 5c was generated on a PC in just a few minutes, FWI methods are much more computationally demanding. The forward model must be run over and over, both to set up the framework for the inversion and to help guide the search for the optimal solution. Researchers at UiB are currently implementing and applying FWI methods not only to subduction zones, but also to petroleum exploration and reservoir characterization.

FUTURE PERSPECTIVES

Over the last half-century, high performance computing has proved itself as essential a tool for the earth sciences as weather balloons and rock hammers. Today, scientists strive to gather more and better observations, to consider physical processes in increasingly realistic ways, to make fewer simplifying assumptions. The ever-expanding volume of data, quality of data and complexity of models ensures a continuing and growing demand for supercomputing in the field. Topics such as those described here highlight some of the vibrant areas of research that will surely make use of the supercomputing facilities for years to come.

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Cloud vortex streets off the Cape Verde Islands, Terra MODIS image from 5 January 2005 Photo: visibleearth.nasa.gov