Institution: Imperial College London

Unit of Assessment: 10 Mathematical Sciences

Title of case study: C10 - Forecasting Ocean Oil Spill movements, facilitating Oil Spill clean-ups

1. Summary of the impact (indicative maximum 100 words)

In the 1990s Dr D Moore, who has extensive experience in fluid dynamics, worked with collaborators at the US Naval Research Laboratory (NRL) on parallelising an ocean modelling code. This resulted in the Navy Layered Ocean Model (NLOM) and later the Hybrid Coordinate Ocean Model (HYCOM). NLOM and HYCOM, which were/are distributed through the NRL and HYCOM consortium, are open access ocean modelling codes that are used to forecast ocean currents. They have proved particularly impactful for the forecasting of ocean oil spills and the corresponding management of the environmental risk. NLOM and/or HYCOM have been used extensively in the Deepwater Horizon oil spill in 2010 as well as the Montara Well Release oil spill in Australia in 2009, providing valuable forecasts to assist with the response to the disasters.

2. Underpinning research (indicative maximum 500 words)

Dr Dan Moore worked extensively on fluid dynamics earlier in his career and had a large set of fluid dynamics code that was optimised for the, now obsolete, CRAY supercomputer. By the early 1990s he had the motivation to consider how to move large Computational Fluid Dynamics (CFD) programs from the CRAY environment to the Massively Parallel Computing Environment. Crucially, he had also established a research link with Dr. Alan Wallcraft, a former Imperial Mathematics PhD Student, who worked in the Ocean Modeling Division of the US Naval Research Laboratory (NRL). Moore had previously supplied numerical software in the 1980s (optimized for the CRAY supercomputer) for the NRL's numerical models of the Gulf of Mexico, and had worked with Dr. Wallcraft in the early 1990s trying to scale up the NRL's efforts from the Gulf of Mexico to the rest of the World's oceans (minus the Arctic Ocean).

From 1991 to present Moore spent every summer in the US working with Wallcraft on a real 'production' Ocean Modelling Code [2] (the Navy Layered Ocean Model: NLOM), trying out various ideas developed and tested at Imperial during the academic year to allow it to run efficiently on several hundred processors simultaneously. The collaboration resulted in paper [1]. This paper developed a scalable methodology for covering a two dimensional domain (such as the surface of the earth) with overlapping tiles. The fluid flow equations could be solved locally on each tile by a single processor. After each time step, each tile would exchange information with the adjacent overlapping tiles. This enabled flows to move through the tiles. Moore and Wallcraft devised an efficient mapping from this 2-D tiling to a 1-D striping to allow the Elliptic Equation for the surface pressure field to be solved by spectral methods on many processors simultaneously. The intention was to develop code that could work on any number of processors efficiently. This was achieved by using a standard numerical research computing language, FORTRAN, for all of the code and a standard mechanism for exchanging data between tiles, Message Passing Protocol MPI. This disconnected the Fluid Dynamics Code from the precise details of the computer it was running on. The number of processors to use and the exact details of the size and number of tiles were made as input data for the code to 'read' at the start of its run.

The concepts behind producing a scalable World Ocean model can be applied to both existing 2-D CFD codes and to the design of new codes. This tiling strategy was applied successfully to other NRL models such as the Polar Ice Prediction System (PIPS) and the Navy Coastal Model, NCOM. Moore continued his summer research associations with the Ocean Modelling Division of the NRL and worked on developing their current operational model: Hybrid Coordinate Ocean Model (HYCOM, [Journal of Marine Systems, Vol 65, Issue 1–4, 2007, p60–83]). This too uses the tiling concepts developed by Moore and Wallcraft in the mid-1990s to achieve efficient execution of several thousand processors simultaneously.

Key personnel:

- Dr Dan Moore, Reader in Computational Applied Mathematics, 1/9/1977-31/7/2011 and 1/10/2011- present, Mathematics Department, Imperial College.
- Dr Alan Wallcraft, Mathematics PhD Student 1977-1981, Imperial College, Computer Scientist Contractor 1981-1997, Planning Systems Inc, Computer Scientist, 1997-present, NRL- Stennis Space Center (NRL-SSC), USA

3. References to the research (* References that best indicate quality of underpinning research)

[1] * Wallcraft, Alan J. & Moore, Daniel R., "*The NRL layered ocean model*", Parallel Computing, 23, 2227-2242 (1997). DOI. [N.B. Author affiliation for DM is listed as Stennis Space Center but the research was carried out while DM was employed as a Reader in Computational Applied Mathematics at Imperial College London.]

[2] * Moore, D.R., Wallcraft, A.J., "*Formulation of the NRL Layered Ocean Model in spherical coordinates*", NRL Contractor Report 7323-96-0005 24 pp. (1998). DOI. [N.B. Author affiliation for DM and AW is listed as Planning Systems Inc (who paid for DM's visits to the NRL) but the research was carried out while DM was employed as a Reader in Computational Applied Mathematics at Imperial College London.]

4. Details of the impact (indicative maximum 750 words)

NLOM

The collaboration with Dr Alan Wallcraft at the NRL resulted in the NRL Layered Ocean Model (NLOM) - the world's first scalable portable ocean model. The model was released in 1995 and was available through the NRL [A]. The Navy Layered Ocean Model (NLOM) is a nearly global (72S to 65N) mesoscale ocean model. It was run successfully as the US Navy's Ocean Forecasting and Nowcasting system from 1995 until 28 Feb 2013 [A]. The model has 6 layers in the vertical direction and during its 18 year lifespan it increased its horizontal resolution from 1/8 of a degree to 1/32 of a degree. It changed hardware successfully every 3-5 years running efficiently and interchangeably on massively parallel computers (distributed memory - CM5, CRAY T3D/T3E, IBM SP2, SGI Power Challenge Array, Convex Exemplar), multi-processor shared memory computers (CRAY YMP/C90/T90, SGI Power Challenge, Convex Exemplar), or scalar computers (single processor workstations) [A, B].

NLOM is a layered model that covers regions of the ocean deeper than 200m. The complimentary Navy Coastal Ocean Model (NCOM) is maximised for shallow seas or continental shelves and when it hits deep water is patched onto NLOM. NLOM and NCOM are free and available software.

HYCOM

On 1/3/2013 NLOM was formally superceded by the Hybrid Coordinate Ocean Model (HYCOM) [C]. Earlier versions of HYCOM had been available, in addition to NLOM, for the previous decade. HYCOM is a sophisticated, high resolution system for simulating ocean physics and describes the effects of the tides, winds, earth's rotation, and many other factors on the flow of water. HYCOM produces daily 3D snapshots of oceanographic variables such as temperature, salinity, and current velocity and it runs daily at the Navy DoD Supercomputing Resource Center. As a hybrid model it, unlike NLOM, works in both deep and shallow waters.

The prediction systems produced by HYCOM are being transitioned for operational use by the US Navy at the Naval Oceanographic Office, the US Fleet Numerical Meteorology and Oceanography Centre and by NOAA at the National Centers for Environmental Prediction. Improved open-ocean nowcasts and forecasts are being applied to search and rescue operations, shipping routes, tracking of icebergs and major pollutants, commercial fisheries, etc [C].

Oil Spills

A major application of NLOM and HYCOM has been their use in tracking oil spills such as the Deepwater Horizon disaster in the Gulf of Mexico (2010), the Montara Well release in the Timor Sea (2009) and the Prestige Oil Tanker spill in the Bay of Biscay (2002). These models provide

valuable forecasts of where the oil will be carried by local ocean currents, which is of great assistance for deployment of clean-up vessels.

Deepwater Horizon: During the BP Deepwater Horizon disaster in 2010, the largest oil spill in US history, the Naval Oceanographic Office (NAVO) supplied the National Oceanic and Atmospheric Administration (NOAA) with daily trajectory forecasts. NOAA officially managed the response to the disaster, in conjunction with BP. Beginning on 21 April 2010, and lasting for 107 days, different forecasts were supplied to NOAO, three of which were NLOM, NCOM and HYCOM. Forecasts for 24 hours, 48 hours, and 72 hours were produced for surface oil in the nearshore to support daily response planning. These forecasts continued to be produced until no recoverable oil was seen in overflights of the area for about three weeks [D]. In mid-May, when a "tail" of oil was observed which created a potential pathway for oil to be transported to the Florida Keys, Cuba, or the Bahamas, forecasts began being produced for two regions: nearshore and offshore. The offshore forecasts also supported daily response planning, predicting where surface oil impacted by the Gulf current systems would be in the next 24, 48, and 72 hours. Weeks later, when recoverable oil was no longer observed in overflights or satellite analyses, the offshore forecasts were phased out. The archive of the daily oil spill forecast maps produced by NOAA [D] refer to models from NAVO/NRL (nearshore forecasts in May and June), NAVO/NCOM (offshore forecasts in May and June) and NRL/IASNFS (offshore forecasts in May and June) [D]. The NAVO/NRL models included NLOM and NCOM. NRL/IASNFS refers to the NRL Intra-Americas Sea Ocean Nowcast/Forecast System (IASNPS) which is a 1/24 degree (~6 km), 41-level sigma-z ocean model based on NCOM. The open boundary conditions for the model, which include sea surface elevation, transport, temperature, salinity and currents, are provided by NCOM [E].

There are many examples of the use of NLOM and HYCOM in forecasting the movement of the Deepwater Horizon oil spill. Many academic and private research institutions partnered NOAA in the response to the spill, contributing personnel, expertise and equipment [F]. Examples of the extensive use of HYCOM or NLOM by these institutions are provided by The Ocean Circulation Group (OCG) and the Optical Oceanography Laboratory at the University of South Florida [G], and the Deepwater Horizon Oil Spill Portal hosted by the Rutgers University Coastal Ocean Observation Lab [H]. Partners in the Rutgers University Coastal Ocean Observation Lab's response to the Deepwater spill included several US federal agencies such as the US Department of Homeland Security, Environmental Protection Agency, and the US Integrated Ocean Observing System (IOOS) [I]. The 'Deepwater Horizon Oil Spill Principal Investigator Workshop Final Report' from 2011, sponsored by the US National Science and Technology Council's Subcommittee on Ocean Science and Technology, credits HYCOM in reference to modelling the warm ocean current in the Gulf of Mexico [J].

Since the disaster, there have been numerous publications detailing the events and the response, many of which credit HYCOM for hydrodynamic modelling [K]. There have also been several books published, again crediting HYCOM [L] or NCOM, NLOM and HYCOM [M].

Montara Well Release: The Montara oil spill was an oil and gas leak and subsequent slick that took place in the Montara oil field in the Timor Sea, off the northern coast of Western Australia. It is considered one of Australia's worst oil disasters. The slick was released following a blowout from the Montara wellhead platform in Aug 2009, and continued leaking until early Nov 2009 (in total 74 days), when the leak was stopped by pumping mud into the well and the wellbore cemented thus "capping" the blowout. NLOM, NCOM and HYCOM were used to assess the spill [N,O].

5. Sources to corroborate the impact (indicative maximum of 10 references)

[A] NRL Global NLOM website, http://www7320.nrlssc.navy.mil/global_nlom/ (archived at https://www.imperial.ac.uk/ref/webarchive/8mf on 8/7/13)
[B] Office of Naval Research NLOM page (archived at https://www.imperial.ac.uk/ref/webarchive/9mf on 8/7/13)
[C] HYCOM webpage, http://hycom.org/ (archived at https://www.imperial.ac.uk/ref/webarchive/0mf on 8/7/13) and http://hycom.org/about

(archived at https://www.imperial.ac.uk/ref/webarchive/bnf on 8/7/13)
[D] NOAA Deepwater Horizon archive, Oil Trajectory Maps, http://www.noaa.gov/deepwaterhorizon/maps/traj_maps.html (archived at https://www.imperial.ac.uk/ref/webarchive/lnf on 9/7/13)
[E] IASNFS webpage, http://www7320.nrlssc.navy.mil/IASNFS_WWW/IASNFS_intro.html (archived at https://www.imperial.ac.uk/ref/webarchive/mnf on 9/7/13)
[F] NOAA Deepwater Horizon Archive - About the response, http://www.noaa.gov/deepwaterhorizon/about/index.html (archived at https://www.imperial.ac.uk/ref/webarchive/cnf on 8/7/13)
[G] OCG Deepwater Horizon webpage, http://ocg6.marine.usf.edu/~liu/oil.html (archived at https://www.imperial.ac.uk/ref/webarchive/dnf on 8/7/13) and OCG HYCOM forecast http://ocg6.marine.usf.edu/~liu/Drifters/latest_gomhycom.htm (archived at https://www.imperial.ac.uk/ref/webarchive/fnf on 8/7/13)
[H] IOOS/Rutgers University Deepwater Horizon Blog, http://rucool.marine.rutgers.edu/deepwater/category/deepwater-blog/ (see 28, 25, 23, 22 July) (archived at https://www.imperial.ac.uk/ref/webarchive/gnf on 8/7/13) and http://rucool.marine.rutgers.edu/deepwater/2010/06/another-amazing-hycom-forecast/ (archived at https://www.imperial.ac.uk/ref/webarchive/hnf on 8/7/13), http://rucool.marine.rutgers.edu/deepwater/2010/06/surface-analysis-hycom-is-back/ (archived at https://www.imperial.ac.uk/ref/webarchive/jnf on 8/7/13)
[I] IOOS/Rutgers University Deepwater Horizon Oil Spill Portal, http://rucool.marine.rutgers.edu/deepwater/ (archived at https://www.imperial.ac.uk/ref/webarchive/knf on 8/7/13),
[J] Deepwater Horizon Oil Spill Principal Investigator Workshop Oct 25-26, 2011 - Final Report (available here)
[K] Selected publications using HYCOM and/or NLOM for Deepwater Horizon analysis: DOI-1, DOI-2, DOI-3, PDF-1
[L] 'Monitoring and Modeling the Deepwater Horizon Oil Spill: A Record Breaking Enterprise', Yonggang Liu, Amy MacFadyen, Zhen-Gang Ji, Robert H. Weisberg, Wiley, 2 May 2013, ISBN13 9781118671825 (available here)
[M] 'Oil Spill Science and Technology', Mervin Fingas, Gulf Professional Publishing, 3 Dec 2010, ISBN13 9781856179447 (available here)
[N] B.A. Brushett, B.A. King, and C.J. Lemckert, "Evaluation of met-ocean forecast data effectiveness for tracking drifters deployed during operational oil spill response in Australian waters", Journal of Coastal Research, 2011, SPI 64, pp 991-994 (available here)
[O] 'Ocean nowcasting and forecasting for the Montara oil spill', Brassington and King, 2010, http://www.cawcr.gov.au/staff/gbb/presentations/agu_ocean_sciences_2010_brassington.pdf (archived here)