Institution: University of Reading

Unit of Assessment: 10 Mathematical Sciences

Title of case study: Ocean and climate forecasting improved by developments in data assimilation

1. Summary of the impact

Ocean circulation accounts for much of the energy that drives weather and climate systems; errors in the representation of the ocean circulation in computational models affect the validity of forecasts of the dynamics of the ocean and atmosphere on daily, seasonal and decadal time scales. Research undertaken by the University of Reading investigated systematic model errors that resulted from data assimilation schemes embedded in the key processes used to predict ocean circulation. The researchers developed a new bias correction technique for use in ocean data assimilation that alleviates these errors. This has led to significant improvements in the accuracy of the forecasts of ocean dynamics. The technique has been implemented by the Met Office and by the European Centre for Medium Range Weather Forecasting (ECMWF) in their forecasting systems, resulting in major improvements to the prediction of the weather and climate from oceanic and atmospheric models. The assimilation technique is also leading to better use of expensively acquired satellite and in-situ data and improving ocean and atmosphere forecasts used by shipping and civil aviation, energy providers, insurance companies, the agriculture and fishing communities, food suppliers and the general public. The impact of the correction procedure is also important for anticipating and mitigating hazardous weather conditions and the effects of long-term climate change.

2. Underpinning research

Data assimilation techniques are used to improve predictions from computational models. A numerical model can never completely describe the complex physical processes underlying the behaviour of a real world dynamical system. Data assimilation combines current estimates of state variables such as temperature, pressure, humidity, and wind speed from the model with physical observations of the ocean and atmosphere in order to improve forecasts and reduce uncertainty in the forecast accuracy. Mathematically, the assimilation problem is an ill-posed inverse problem, matching model data to observations, that requires regularization and is solved using cycled variational methods or sequential filter methods. In addition to improving forecasts from the model, data assimilation can also be used to identify systematic bias errors within the model, highlighting where the model forecasts are consistently incorrect in relation to physical observations. Researchers at Reading have demonstrated that where systematic errors exist in a model, these can be overcome by using a correction term within the data assimilation scheme and have established a sound mathematical basis for this approach. As a result of the new assimilation scheme, the final model outputs are corrected for the inherent model errors.

Data assimilation schemes in the early 1990s assumed that models were perfect and ignored systematic errors in the model. Between 1993 and 1997, A K Griffith, an EPSRC PhD student† at Reading, holding a CASE Award with the Met Office, and Prof N K Nichols at Reading, investigated the significant effects of systematic errors on generic data assimilation schemes using simplified models of atmospheric motion. They developed methods to correct for these errors within the assimilation process and provided a strong mathematical foundation for these methods based on control theory. These results were presented at the Newton Institute meeting on the Mathematics of Atmosphere and Ocean Dynamics (http://bit.ly/18kXE19). After the meeting, Dr M J Bell from the Met Office (at the time manager of the Met Office Forecast Ocean Assimilation Model team, now Head of the National Centre for Ocean Forecasting) proposed that Reading should extend the method to oceanic models. From 1997 – 2000, in conjunction with the Met Office, M J Martin, a NERC CASE student‡ at Reading, and Prof Nichols, also at Reading, investigated the extension and application of the new correction method to estimating model bias errors in oceanic

systems.

Under previous data assimilation schemes, spurious ocean circulation occurred when thermal and wind data with systematic errors near the equator were assimilated into oceanic models. In the work carried out during the second studentship, Nichols and Martin, together with Bell, acting as Martin's industrial supervisor, developed a method for correcting the bias error in the pressure gradient of existing oceanic models. The correction of the bias error, using the model and observation differences, improves the model dynamics by reducing or eliminating spurious deep ocean overturning circulations and restoring temperature and salinity balances in the ocean system. The technique relies on state augmentation, in which the data assimilation scheme is used to find both the ocean state variables and the model bias errors. The bias correction scheme, as well as correcting temperature and density imbalances leading to the spurious circulation, also improves the estimated horizontal velocities in the forecast, particularly the strength and positioning of the equatorial undercurrent near the ocean surface in the tropics. This is especially important for seasonal forecasting, which is dependent on the correct simulation of the El Niño Southern Oscillation cycle, the cause of extreme weather (floods and droughts) in many regions of the world. The bias correction used in the ocean forecast model, coupled with the forecast model of the atmosphere, then ensures that the dynamical adjustment of the system to the assimilated data does not interfere with forecast skill.

† A K Griffith - Data assimilation for numerical weather prediction using control theory, EPSRC CASE Studentship (1993 – 1997) – University of Reading PhD, (1997) http://bit.ly/1ahHeb7
‡ M J Martin - Data assimilation in ocean circulation models with systematic errors, NERC CASE Studentship (1997 - 2000) – University of Reading PhD, (2000) http://bit.ly/1ahHWoX

3. References to the research

Early paper: (20 citations, 48 Google Scholar) Griffith & Nichols, Adjoint methods in data assimilation for estimating model error, Flow, Turbulence and Combustion, 65, (2000), 469-488; DOI:10.1023/A:1011454109203

Main research paper: (43 citations, 81 Google Scholar) Bell, Martin & Nichols, Assimilation of data into an ocean model with systematic errors near the equator, Quarterly J. of the Royal Met Soc, 130, (2004), 873-893; DOI: 10.1256/qj.02.109

Papers of Griffith & Nichols (2000) and Bell, Martin & Nichols (2004) cited in: Dee, Bias and Data Assimilation, Quarterly J. of the Royal Met Soc, 131, (2005), 3323-3343. (122 citations)

Use in ECMWF system: (19 citations, 28 Google Scholar) Balmaseda, Dee, Vidard & Anderson, A multivariate treatment of bias for sequential data assimilation: Application to the tropical oceans, Quarterly J. of the Royal Met Soc. 133: (2007), 167-179; DOI: 10.1002/qj.12

Use in Met Office system: (9 citations, 89 Google Scholar) Martin, Hines & Bell, Data assimilation in the FOAM operational short-range ocean forecasting system: a description of the scheme and its impact, Quarterly J of the Royal Met Soc, 133, (2007), 981-995; DOI: 10.1002/qj.74

4. Details of the impact

Models of ocean circulation, in conjunction with numerical weather prediction models, are essential in forecasting over long time periods, from one week to many decades, because ocean transport accounts for much of the energy that drives weather and climate systems. The initial beneficiaries of the research are forecasters using oceanic models, since the correction reduces or eliminates spurious overturning circulations and other imbalances caused in previous data assimilation schemes by systematic model errors.

Between 2000 and 2004, the correction for the pressure gradient term developed by Nichols and Martin, together with Bell, was successfully implemented into the Met Office's Forecast Ocean Assimilation Model (FOAM). FOAM forms its operational ocean forecasting system. Significant improvements in the accuracy of the ocean forecasts were achieved as a result of incorporating the error correction process into FOAM. Results showing the impact of the pressure correction on the ocean assimilation are shown in Bell et al (2004). At the end of 2008 the FOAM system was transitioned to use a different core component for its ocean model. This new component is NEMO (Nucleus for European Modelling of the Oceans - http://www.nemo-ocean.eu/), a community ocean modelling system for oceanographic research, operational oceanography, seasonal forecasting and climate studies. The significant impact of Reading's pressure bias correction technique on the accuracy of forecasting continued to be recognised and the correction technique was again implemented into the FOAM data assimilation system using NEMO. This system is used for producing short-range forecasts of the ocean and sea-ice state (out to 7 days), and is now also used directly to initialise the ocean component of seasonal forecasts.

In addition to the Met Office implementation, the correction technique was also adopted by ECMWF and incorporated into their ocean assimilation system, resulting in improved predictions of ocean circulation. ECMWF also built on the original correction method of Reading, extending the scheme to allow for temporal variations in the bias error. Between 2008 and 2009, the ECMWF also transitioned to NEMO as the ocean modelling element of its forecasting system and the pressure bias correction technique was again found to be an important component needed for assimilation with the new ocean model.

In practice ocean and weather forecasting assimilation systems have been used separately to provide input data to each other, but recently data assimilation systems for coupled oceanic and atmospheric models have been under development at ECMWF and the Met Office. Although it was expected that for coupled models, the pressure correction technique might not be required, it was found that the bias error correction scheme is still needed to avoid spurious ocean dynamics and maintain balances in the coupled systems.

Forecasting systems, such as those relying on the correction schemes developed by the University of Reading, require a vast quantity of input data collected from satellites, ocean buoys, aircraft and shipping, radiosondes, and radar, as well as ground stations. These data are assimilated into complex multi-scale models of the ocean and atmosphere. Improvements to data assimilation techniques, such as those developed at Reading, enable better use of this expensively acquired data to give more accurate weather and climate predictions. Good forecasts enable good planning and the research on data assimilation at Reading continues to bring significant benefits to the whole community.

Accurate seasonal forecasts, extending for a decade or more, are particularly important for understanding the effects of climate change and in developing strategies for living with changes in our environment as well as for mitigating hazardous conditions that may arise, such as flooding, drought, intense rainfall, heavy snow and ice, or excessive temperatures. Improvement in the accuracy of ocean, weather and climate forecasting has impacts on economic, commercial and organisational elements of society as well as on the environment. The development from the University Reading, and the improvement in accuracy it has allowed, has made an important contribution to such advances.

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

Need for use with new NEMO model in Met Office system: Lea, Drecourt, Haines & Martin, Ocean altimeter assimilation with observational- and model-bias correction, Quarterly J of the Royal Met Soc, 134, (2008), 1761-1774; DOI: 10.1002/qj.320.

Main paper stating the implementation of bias correction scheme in new Met Office-NEMO system: Storkey, Blockley, Furner, Guiavarc'h, Lea, Martin, Barciela, Hines, Hyder & Siddorn, Forecasting the ocean state using NEMO: The new FOAM system, Journal of Operational Oceanography, 3, (2010), 3-15.

ECMWF Newsletter article stating that a bias correction scheme of the type used in their previous system needs to be put into the new DA scheme NEMOVAR: Mogenson, Balmaseda, Weaver, Martin & Vidard, NEMOVAR: A variational data assimilation system for the NEMO ocean model, ECMWF Newsletter No. 120 – Summer 2009, (2009) pp17-21. http://www.ecmwf.int/publications/newsletters/pdf/120.pdf

Pages 2, 18 and 34 of the following notes describe the use of the bias correction scheme: Mogensen, Data assimilation in the ocean, ECMWF Training Course slides (2010). http://bit.ly/1faaI15

Page 17 of the following ECMWF publication refers to the incorporation of the bias correction based on the original work: Mogensen, Balmaseda & Weaver, The NEMOVAR ocean data assimilation system as implemented in the ECMWF ocean analysis for System 4, ECMWF Technical Memorandum 668, (2012). http://bit.ly/17Wixks

Foam system description: http://www.ncof.co.uk/FOAM-System-Description.html, (2011).