Development of the New Zealand Earth System Model: NZESM

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Abstract

The New Zealand Earth System Model (NZESM) is currently under development to help inform scientists, policy makers, climate-sensitive sectors of the economy, and the general public in New Zealand about climate change. The term 'climate model' is generally used to describe a computer model that incorporates physical aspects of the climate system such as atmospheric and oceanic fluid mechanics and thermodynam- ics. In addition, Earth System Models represent aspects of biology and chemistry such as marine biogeochemistry and atmospheric ozone chemistry. The development of the NZESM represents a step-change in model complexity for New Zealand science, and a major motivation for its development is to reduce Southern Hemisphere specific mod- elling problems such as the formation of Southern Ocean sea ice and Antarctic Bottom Water. The atmosphere, land surface, ocean and sea ice components of the model are already available in New Zealand. In the future, additional models representing (for ex- ample) ocean biogeochemistry and marine ice-sheets will also be added to the NZESM framework. Over the next 5 years, the NZESM will be run to produce hindcasts for the past 150 years and projections for up to 200 years into the future. Such experiments will ". . . enable New Zealanders to adapt, manage risk, and thrive in a changing climate", which is the mission statement of the Deep South National Science Challenge. Over the next decade, the NZESM will be used in Earth System science research throughout New Zealand, both in terms of pure science and via communication of its results to New Zealanders.

1. Introduction and motivation

Climate modelling has made very significant progress in recent decades, as documented in the five reports on climate change published by the Intergovernmental Panel on Climate Changethus far. Despite this progress however, the most recent IPCC report (IPCC, 2013) identifies several Southern Hemisphere specific shortcomings in climate model simulations that affect most or all contemporary climate models.

One example is the general underestimation of cloud cover over the Southern Ocean in IPCC fifth assessment report models. This and other examples are discussed in section 2.2. These shortcomings compromise the reliability of climate projections available to New Zealand. This has motivated the New Zealand Government to launch (as one of 11 National Science Challenges, NSCs) the Deep South NSC, whose mission is to inform the Government, climate-sensitive industries, e.g. agriculture and hydropower, and the general public with up-to-date climate projections that are not subject to those shortcomings. The Deep South NSC includes the development of the New Zealand Earth System Model. Here we provide a description of the current process and state of efforts to develop this model. Further information can be found on the official government websites of the NSCs (http://www.mbie.govt.nz/info-services/science-innovation/national-science-challenges) and the Deep South National Science Challenge itself (http://deepsouthchallenge.co.nz/).

The NZESM is based on the Unified Model (UM) framework which is supported by aninternational consortium led by the UK Met Office. Brown et al., (2012) provide a review of the development of the UM and Easterbrook and Johns, (2008) give an overview of the code development practises used at the Met Office. The UM has existed for several decades and is 'unified' across time and spatial scales, whilst maintaining a common dynamical core. It has different configurations suitable for weather forecasting at short timescales and high resolution as well as at coarse-resolution. These latter configurations can be applied to the simulation of century-to-millennium-scale climate and Earth System change. One of the first tasks for the NZESM will be to produce climate simulations for the period 1850-2200. This will serve the dual purposes of validating the model against observations for the hindcast section of the simulations (1850-present) as well as giving scientific and policy relevant information to New Zealanders as to what changes may be expected to occur in the coming decades and centuries (present-2200).

The National Institute of Water and Atmospheric Research (NIWA) has been using the UK Met Office Unified Model framework for over 20 years and is now a 'core' model development partner in the Unified Model Consortium. The United Kingdom Earth System Model (UKESM, on which the NZESM is based) is a joint development between the Met Office and the UK Natural Environment Research Council, NERC (www.nerc.ac.uk), with components being developed at several different research centres around the UK.

The IPCC's reports detail the current best understanding of the climate system [(PCC, 2013). Warming of the atmosphere alone however only represents one aspect of human interference with the climate. To quote the Intergovernmental Panel on Climate Change: "Warming of the climate system is unequivocal". Other human impacts involve, for example, atmospheric aerosol loading (known as 'global dimming' reviewed in (Ramanathan and Carmichael, 2008) and stratospheric ozone depletion, causing the 'ozone hole', (Erickson et al., 2015). Both of these processes are explicitly represented in the NZESM. It is this additional complexity that distinguishes an Earth System Model (McGuffie and Henderson-Sellers, 2005) from a climate model.

The Deep South NSC builds on but also transforms the pre-existing research landscape in New Zealand. It funds some observations of the climate system, but these observational activities are now informing the formulation of the NZESM. It also establishes the NZESM in New Zealand, for which there is no precedent. NZESM simulations will in due course complement international climate model data in informing a well-established regional climate modelling activity based at NIWA. The regional climate model data will be taken up by a variety of climate change Impacts & Implications projects. This line of activity continues, albeit with an adjusted remit that accounts for the presence of some other NSCs, the Climate Change Impacts & Implications (CCII) project which MBIE has sponsored for several years and which is running out at the end of 2016.

This paper firstly reviews the background of climate modelling in and with reference to New Zealand, and then moves on to a discussion of the major components making up NZESM intended to inform future users. The document ends with an outlook to research which will be performed with the NZESM over the coming years, and how New Zealand will be in a position to contribute to ongoing international climate research efforts, possibly including those led by the IPCC.

The Deep South NSC is hoping to make a difference to resolving these outstanding problems in global climate science and they define development projects of the NZESM. Further details and examples of Southern Hemisphere climate biases are given in Section 2.

2. Climate modelling in New Zealand

2.1 History

Research with climate models in New Zealand has been taking place for over two decades (Mullan et al., 1993). Early papers detail the initial installation and validation of the Met Office modelling framework in New Zealand (Bhaskaran et al., 1999), the development of a high resolution regional climate simulation framework over the New Zealand region (Bhaskaran et al., 2002) and the effect of El Nino˜ Southern Oscillation (ENSO) on Southern Hemisphere climate (Bhaskaran and Mullan, 2003). Other studies describe more recent developments to the high-resolution regional climate models at NIWA (Ackerley et al., 2012, Drost et al., 2007), the simulation of New Zealand's climate 6000 years ago (Ackerley et al., 2013), and the simulation of extreme weather events in New Zealand (Harrington et al., 2014; Rosier et al., 2015).

2.2 Divergence of the NZESM from the UKESM

The New Zealand community is too small to support a new, independent Earth System Model on its own. Having our own climate modelling and model development activity will help grow understanding within New Zealand of the limitations of the current generation of climate models. New Zealand has well-developed expertise in high-latitude climate physics and the aim of the community is to contribute to large scale international climate modelling projects. The Deep South NSC is concentrating its efforts on a few selected model development topics, which are well-known and longstanding biases of particular relevance in the Southern Hemisphere (this list is subject to some extension and change as the Deep South NSC evolves):

1. Aerosol-cloud-radiation linkages over the Southern Ocean, e.g. (Ceppi et al., 2012). The 5th Assessment Report (AR5) of IPCC identified that cloud coverage over the Southern Ocean was generally underes-timated, resulting in a significant overestimation of solar heating of the ocean surface, with adverse consequences for ocean and atmosphere dynamics and sea ice. The hemi-spheric asymmetry of this problem suggests that the cause may be because aerosols in the Southern Ocean differ from those found, for example, in the Arctic.
2. Sea ice physics, e.g. (Zunz et al., 2013). Antarctic sea ice was poorly simulated by models contributing to AR5. Maximum and minimum extent, as well as the seasonal evolution, zonal asymmetries, and total ice volume, vary a lot across the AR5 models, with none of the models coming sufficiently close to the

observed sea ice extent. This behaviour may be linked to the above-mentioned problems with clouds, but also sea ice physics itself and coupling with the ocean are likely contributing factors. Conse-quences include an erroneous placement of the storm track and occurrence of errors in the frequency and severity of southerly cold-air outbreaks affecting New Zealand.

3. Antarctic Bottom Water (AABW) formation, e.g.(Heuze´ et al., 2013). AABW is cold, saline water rejected by sea ice formation, which then descends down the Antarctic continental shelf into the abyss where it defines the temperature and heat content of the deepest part of the global ocean. In models, the difficulty with AABW formation is the small-scale nature of the process, requiring high-resolution hydrodynamical modelling that is currently not feasible on a global scale. Consequences include errors in the ocean stratification and heat content, which can affect the ocean's response to global warming and may also be linked to sea-surface temperature errors alluded to above.

All of these problems contribute to biases in the simulation of present-day climate, but can also affect the sensitivity of climate to anthropogenic climate forcing.

Fundamentally, the NZESM over time may diverge in the formulation of the above model components but will remain closely 'related' to its parent model, the UKESM. This intermodel similarity is both common and necessary throughout the climate and Earth System model development community for pragmatic reasons. These models are made up of hundreds of thousands of lines of code and consist of many different sub-models (atmosphere, ocean, sea ice, etc) which in turn require large teams of subject experts. The New Zealand community is simply too small to support this effort alone and the country's resources are hence better spent on improving aspects of the model's formulation as well as configuration software development.

Development of the Norwegian Earth System Model, the NorESM (Bentsen et al., 2013) could be considered as a similar initiative in the Northern Hemisphere,where an already established Earth System model is used as a platform from which to build their own. In the case of the NorESM, the platform is the Community Earth System Model (CESM) (Gent et al., 2011) which was developed over several years and has contributed to the Coupled Model Intercomparison Project, CMIP5, and AR5. This is expressed in thewords of (Bentsen et al., 2013) as follows:

> *Despite the nationally coordinated effort, Norway has insufficient expertise andmanpower to develop, test, verify and maintain a complete Earth System Model.For this reason, NorESM is based on the Community Climate System Model version 4 operated at the National Center for Atmospheric Research on behalf of the Community Climate System Model (CCSM)/Community Earth System Model (CESM) project of the University Corporation for Atmospheric Research.*

The NZESM will continue to be hosted on the Met Office Science Repository Service (code.metoffice.gov.uk) for the foreseeable future. Any scientific or computational advances made in the development of the model will be made available for inclusion in the UKESM, and vice versa. There is thus no risk that the two models will diverge to

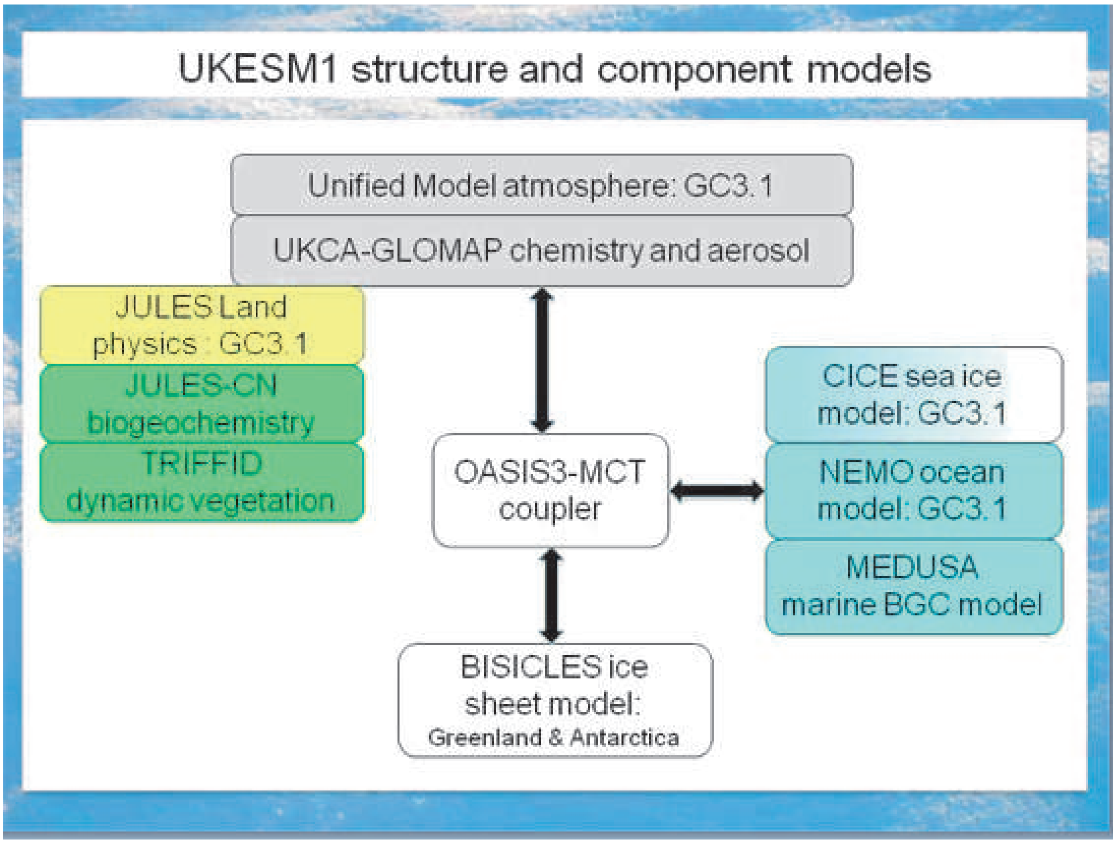

Figure 1: Structural relationships between the sub-models of the Met Office-NERC developed UKESM, upon which the NZESM is based. The arrows indicate that the different model components components communicate with each other via the OASIS coupler. Figure used with permission from Professor Colin Jones, head of the UKESM project.

such an extent that these advances cannot be shared in the future.

3 .Model development

The NZESM is being developed alongside the United Kingdom Earth System Model, UKESM, which is itself a co-development between the Met Office and the UK Natural Environment Research Council, NERC. Much of the first five years will be devoted to porting and validating the global coupled (GC) configuration of the UM. The first stage of the project also entails running long historical (past 150 years) and future (next 200 years) simulations. The historical simulation will be evaluated against reanalysis and (where possible) observational data and the future simulations will be evaluated with respect to this hindcast period and tosteady state controls.

The NZESM will contain these following sub-models (Figure 1):

1. Global Atmosphere, GA, e.g. (Walters et al., 2014).
2. Global Ocean, GO, e.g. (Megann et al., 2014).
3. Global Sea Ice, GSI, e.g. (Rae et al., 2015).
4. Global Land GL, e.g. (Walters et al., 2014).
5. The UK Chemistry & Aerosols (UKCA) module, e.g. (Morgenstern et al., 2009).
6. Marine ice-sheets, BISICLES, (Cornford et al., 2013).
7. Ocean biogeochemistry, MEDUSA, (Yool et al., 2013).

The Global Coupled model configurations (e.g. GC3.1 described in Figure 1) are made up of the combination of atmosphere, land surface, ocean and sea ice models. This is denoted in Figure 1 by the presence of the text 'GC3.1'. Each of these sub-models have their own numbering system describing their state of development. An example of this, given in (Williams et al., 2015), is that GC2 is defined as the combination of GA6.0, GL6.0, GO5.0 and GSI6.0). With reference to figure 1, the 'Unified Model atmosphere' and 'UKCA-GLOMAP' models are collectively known as the Global Atmosphere (GA), 'JULES' and 'TRIFFID' represent the Global Land (GL), the NEMO ocean model is the Global Ocean (GO) component and the CICE sea ice model is the Global Sea Ice (GSI) sub-model. Therefore, the Global Coupled model with the addition of UKCA atmospheric chemistry, MEDUSA biogeochemistry and BISICLES marine ice sheet are collectively known as the Earth System model.

The acronyms used in Figure 1 are now defined: UKCA, United Kingdom Chemistryand Aerosols; GLOMAP, Global Model of Aerosol Processes; JULES, Joint UK Land Environment Simulator; JULES-CN, JULES-Carbon Nitrogen; TRIFFID, Top-down Representation of Interactive Foliage and Flora Including Dynamics; OASIS3-MCT, OASIS version 3-Model Coupling Toolkit (e.g. Valcke, (2013); BISICLES, Berkeley Ice Sheet Initiative for Climate Extremes; NEMO, Nucleus for European Modelling of the Ocean; CICE, the Los Alamos Sea Ice Model; MEDUSA, Model of Ecosystem Dynamics, nutrient Utilisation, Sequestration and Acidification.

4. Results and future research

4.1. *Results*

At the time of writing (November 2016), the GC3 configuration has been ported to the NIWA HPC (High Performance Computer) and a 10 year coupled atmosphere – ocean – sea ice simulation starting in September 1978 has been run. It should be noted here that the results presented here should not be taken as indicative of the final results of the NZESM or its parent model, the UKESM. The reason for this is that, at the time of writing, the final model configuration has not been finalised or 'frozen'. Further documentation papers will follow in due course. The results that follow are to indicate to the reader that the model development process is well underway in New Zealand and that the annual mean preliminary results gained from a short coupled run are in line with the expected results from various different observational sources.

Figure 2 shows simulated and observed land surface air temperature and total precipitation. The temperature observations are described in (Jones et al., 1999) and the observational precipitation is the CMAP dataset. CMAP stands for CPC Merged Analysis of Precipitation; CPC is the Climate Prediction Centre of the National Oceanic and Atmospheric Administration of the USA (Xie and Arkin, 1997). In both of these cases the model data has been regridded onto the native grid of the respective observational dataset. In the ocean data shown below, all data have been regridded onto global 1^o grids from their native NEMO 'tripolar' grid (Xu et al., 2015). The simulated precipitation values shown in Figure 2 are in agreement with the large-scale features presented in (Williams et al., 2015), for example the Inter-Tropical and South Pacific convergence zones.

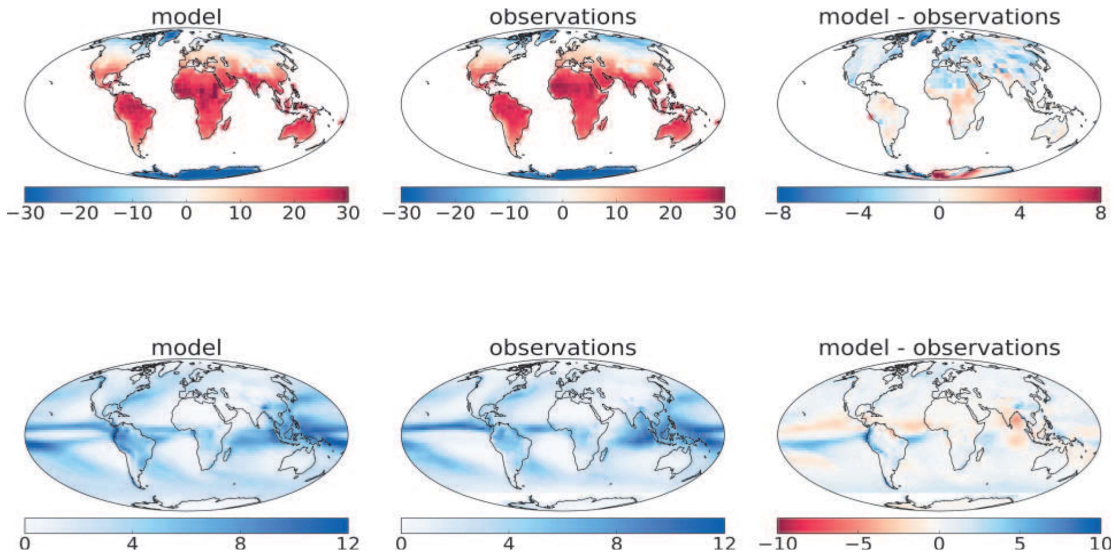

Figure 2. Simulated and observed land surface air temperatures (in degrees Celsius) and to-tal precipitation (in millimetres per day). The temperature and precipitation datasets are from Jones et al (1999) and Xie and Arkin (1997) respectively. The temperature data represents the observed annual mean for the period 1961 - 1990 and the precipitation data is the decadal mean starting in January 1979.

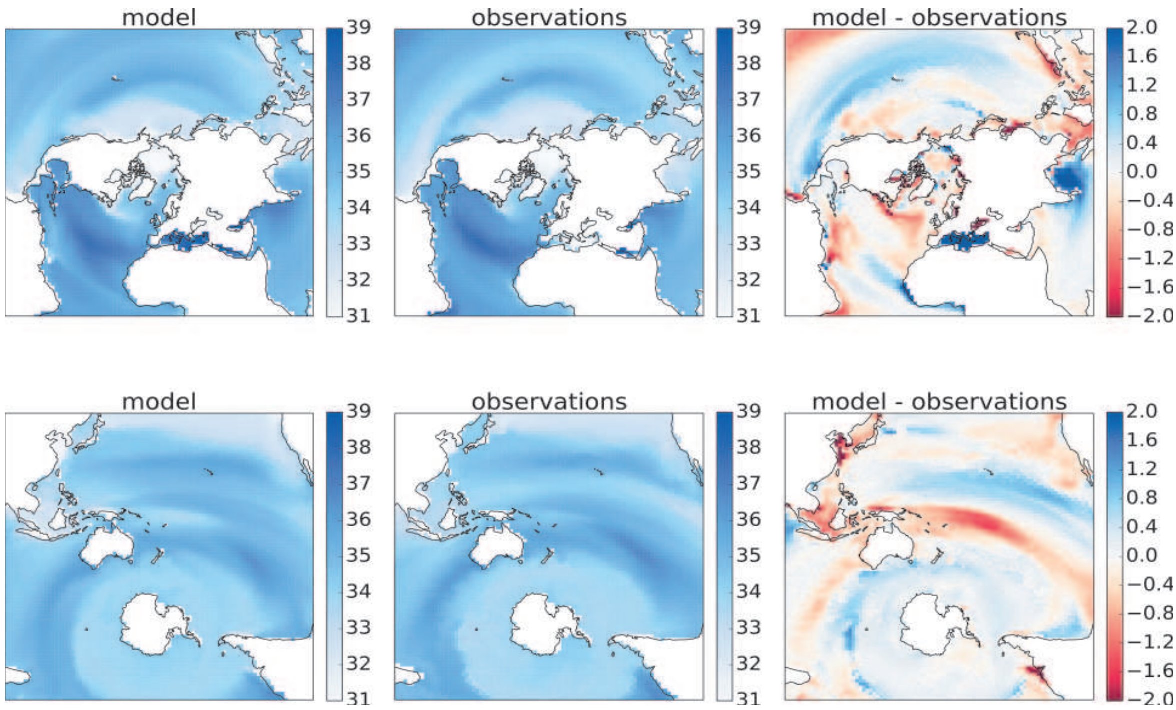

Figure 3: Annual mean simulated and observed sea surface salinity values in Practical Salinity Units (PSU). The observed dataset is from Balmaseda et al. (2013).

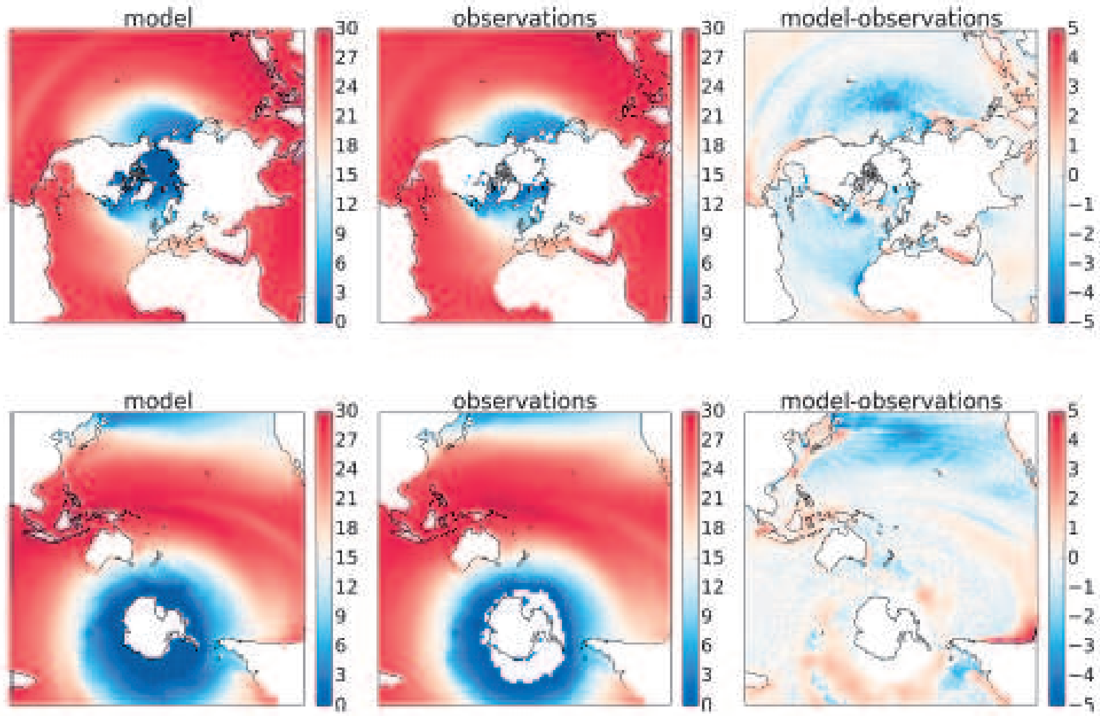

Figure 4. Annual mean simulated and observed sea surface temperature values in degrees Celsius. The observed dataset is from Rayner et al., (2013).

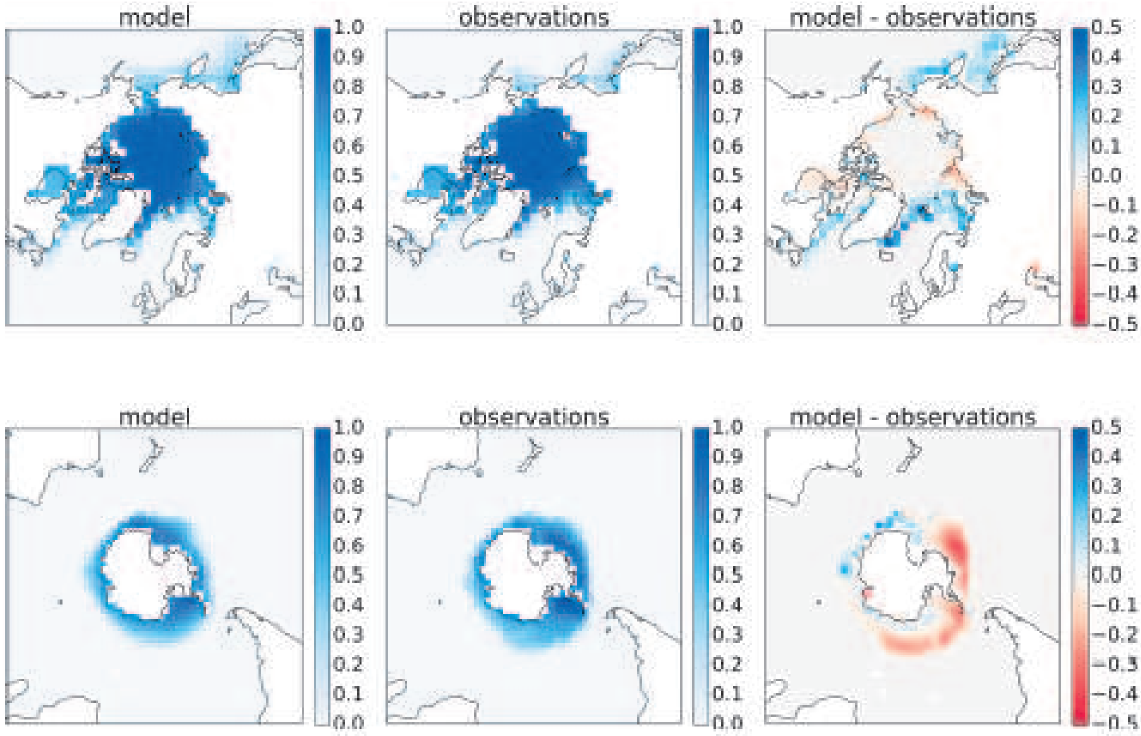

Figure 5. Annual mean simulated and observed sea ice extent, plotted here as the fractional concentration in each grid cell. The observed dataset is from Rayner et al., (2013).

Figure 3 shows ocean surface salinity maps for the NZESM and for a reanalysis product from the European Centre for Medium Range Weather Forecasts (ECMWF). These data can be freely downloaded from the ECMWF website and are described in (Balmaseda et al., 2013). The results in Figure 3 are centred on the North Pole and on New Zealand for the Northern and Southern Hemispheres respectively. The agreement between these sets of simulated and observed results is striking, especially since these results are not finalised, as mentioned above.

The observational comparison shown in Figures 4 and 5 is with the observational dataset of Rayner et al., (2003) and again shows encouraging results. From these preliminary simulations, it appears that the longstanding warm bias in the Southern Ocean persists. The Southern Ocean warm bias is well known and is a feature of several climate models used in the fifth Coupled Model Intercomparison Project (Wang et al., 2015). The agreement between observed and simulated sea ice extents currently shows better agreement in the Northern Hemisphere. This is clearly an important consideration to the New Zealand Earth System Modellingcommunity and work is underway to understand this discrepancy in the preliminary results.

In addition to this coupled model, work is ongoing to assess and further improve the new cloud microphysics scheme of (Furtado et al., 2016) with the aim to improve the representation of mixed-phase clouds in weather and climate models and hence improve the Southern Hemisphere radiation bias mentioned earlier. The latest Met Office-NERC coupled ocean-sea ice model, GO6 – GSI8 has been ported in order to study the oceanic environment ofNew Zealand at high resolution (with prescribed atmospheric forcing) and work is underway at NIWA and The University of Canterbury to develop a new sea ice parameterisation. This parameterisation will add a prognostic joint sea ice thickness and floe size distribution which evolves according to floe-size dependent thermodynamics and fracture by ocean surface waves.

4.1.1 Run speed

Table 1 shows run speeds for the different configurations of the Unified Model atmosphere model currently being run by the NZESM project scientists. The coupled model results shown in this paper are for a coupled atmosphere – ocean – sea ice model and use 16 8 (east-west north-south) processors for the atmosphere component and 9 8 processors in total for the ocean and sea ice components. The ocean and sea ice components run using a common executable and hence do not require their own respective processors. The total number of processors used therefore is 200 and the run speed for this configuration is approximately 0.7 simulation years per day. All run speeds given in this section of the paper do not take the time taken to queue for resources on the High Performance Computer into account.

The computer architecture used (‘FitzRoy’ at NIWA, Wellington) is an IBM Power6 machine. FitzRoy is due to be replaced in 2017 and due to advances in computer processor architecture a per-core speed up (in terms of number of floating point operations per second) of the order of 400% is expected. Also a large increase in the number of available processing elements (PEs) is anticipated, meaning larger simulations and/or larger ensembles of simulations can be produced.

Configuration	N96 (offline oxidants	N96 (Strat Trop)	N216 (Strat Trop)
16 x 8	0.6	0.28	–
16 x 16	0.99	0.54	–
32 x 16	1.38	0.87	0.15
32 x 28	2.84	1.41	0.22

Table 1: Run speeds in years of simulation per real day for different processors configurations of the NZESM atmosphere component forced with prescribed sea surface temperatures and sea ice extents. The processor configurations describe the number of processors used in each direction (i.e. latitude or longitude) of the simulation. The two configurations marked with dashes could not be run since memory could not be allocated to run so many processes on a small number of processors. The run speed of these configurations would in any case have been prohibitively slow to obtain useful results in a realistic time frame. The terms N96 and N216 refer to the low and high resolution configurations of the Unified Model atmosphere component of the NZESM and are explained in section 4.2. The term 'StratTrop' refers to Stratosphere - Troposphere chemistry simulation capability, as opposed to simpler 'offline oxidants' chemistry calculations.

4.2 Next steps

Forthcoming simulations to be performed with the NZESM include the following:

1. Coupled atmosphere – ocean – sea ice – atmospheric chemistry simulations for 150 years into the past (so-called hindcast simulations) and future simulations for the next 200 years.
2. The use of different 'perturbed physics' configurations, e.g., (Stainforth et al., 2005; Murphy et al., 2004; Frame et al., 2009) of the NZESM to explore the effect of parameter uncertainty on climate in New Zealand in the coming decade, for example in changes to extreme weather events. The related weather@home project has been recently described in (Black et al., 2016).
3. As well as the perturbed physics approach used in the previous point, ensembles will also be run using different initial conditions. This will enable the study of the effect of chaos in determining a simulations trajectory through time and will be of particular interest in the study of seasonal to decadal climate.
4. Reduced complexity configurations will be used to produce perturbed ensembles (e.g. for studying climate extremes) which will be too expensive to run using the full NZESM.

In this final point, an example of a reduced complexity configuration is the ability of the Unified Model to be run in 'single column' mode, for example (Lock et al. (2000). Such a configuration can be used to target processes that essentially occur in a vertical column only, such as radiation, the boundary-layer scheme, or fast chemistry. The single column model is useful for testing new parameterisations of cloud processes for example and will be of increasing use as the NZESM diverges from the UKESM in the coming years. In terms of model resolution, the NZESM is being developed in two main resolutions; N96–ORCA1 and N216–ORCA025. In these configurations, the ‘N’ refers to the number of atmospheric waves which can be resolved at a particular grid spacing and N96 (N216) corresponds to a horizontal resolution of 1.875 1.25 (0.83 0.55). The ‘ORCA’ numbers refer to the approximate horizontal resolution of the ocean model in degrees.

Specific research using the NZESM, which will also contribute towards UKESM development include the following:

- Improvements to the modelling of sea ice and its interaction with the ocean. This is especially relevant to the global community due to the current interest in the increase in Antarctic sea ice extent, e.g. (Turner et al., 2009).
- Use of historical weather and climate information to validate NZESM hindcast simu-lations over the New Zealand region. Improving cloud and aerosol microphysics as mentioned above.
- Use of high-resolution ocean model simulations, based on local grid refinement tech-niques facilitated by AGRIF (Adaptive Grid Refinement In Fortran, (Debreu et al., 2007)) to improve the process-based understanding of particular areas of interest to the Deep South NSC. These areas include high southern latitude seas with a significant effect on Antarctic Bottom Water (AABW) formation for example.
- Atmospheric chemistry, including the simulation of the stratospheric ozone layer and tropospheric composition.

The Deep South NSC has a significant education and outreach component and NZESM development is already cont-ributing towards this, for example as part of the Victoria University course Antarctica Online (http://cce.victoria.ac.nz/courses/443-antarctica-online). As part of this course, data visualisations were used throughout a video interview with the first author to illustrate Earth System Modelling and its uses in the study of Antarctic climate to students without an academic background in the Earth or physical sciences.

5. Conclusions.

Preliminary results presented here show that the NZESM is producing results for its atmospheric, oceanic and sea ice components which indicate technical functionality and a degree of realism which will be better characterized in a thorough validation of the model which has not been performed yet.

By contributing to the development of the UKESM in southern high-latitude processes, best use is made of the relatively small resources (by international standards) available to climate modelling in the Deep South NSC. The specialist skills and interests of Deep South researchers also complement those of the other UKESM-supporting institutes and provide expertise in Southern Hemisphere processes. The purpose of this publication has been to outline the ongoing development of the NZESM and as well as the framework of climate and Earth System modelling research in this country within which the Deep South NSC is operating.

New Zealand has some well-established expertise in global climate modelling. The development of the NZESM is an ambitious project aiming to achieve a step change in

Earth System modelling capability for the country. Apart from the technical benefits, the project provides a significant opportunity to engage with a variety of different communities and the general public, guided by the mission statement of the Deep South National Science Challenge: "To enable New Zealanders to adapt, manage risk, and thrive in a changing climate".

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Appendix is on next page

Appendix. Technical details

A.1. NZESM simulation workflow; a worked example.

In this section the model 'runtime' workflow of a typical coupled model is described. Figure A.1 shows an example Graphical Cylc, GCylc, window and Cylc itself is described in more detail below in section A.3.1.

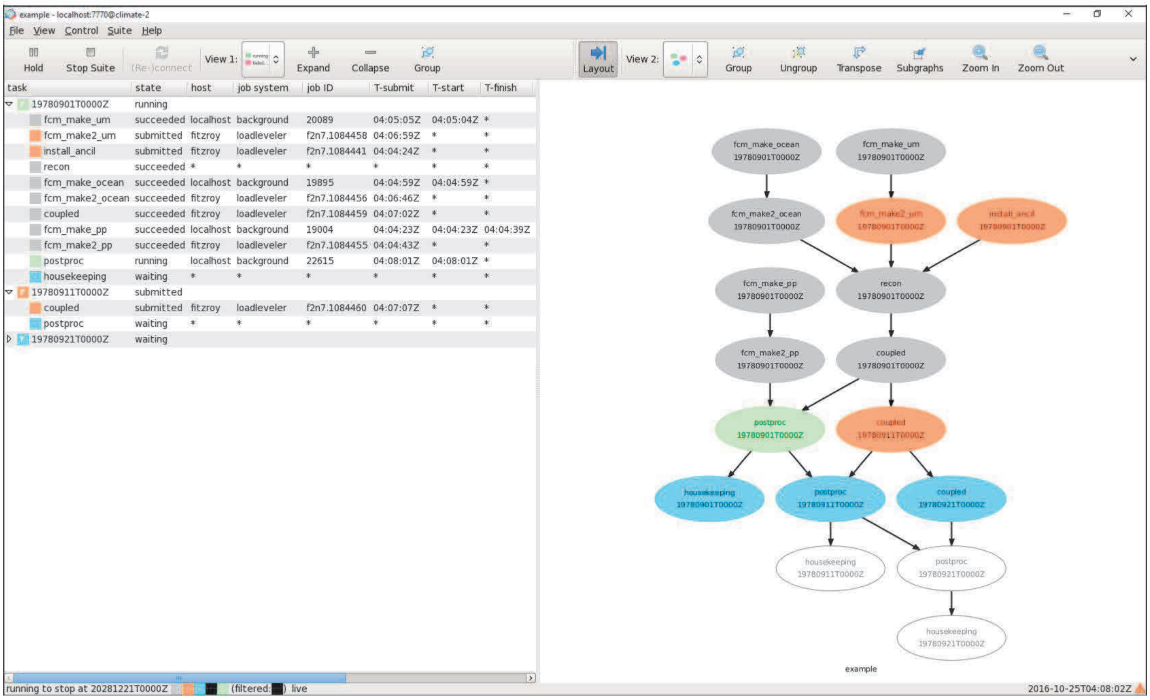

Figure A.1: A GCylc window showing 'text' (left) and 'graph' views (right) of a coupled atmosphere – ocean – sea ice simulation. The two panels show the same information but in different visual formats and are here shown using a high-contrast colour differentiation scheme designed for colour blind users. Each ellipse represents a different task to be computed by the HPC and in this example, the 'coupled' task represents the coupled atmosphere – ocean – sea ice system (GA, GO and GSI respectively).

A.1.1. FCM Make tasks

In Figure A.1 there are six FCM Make tasks; fcm_make_um, fcm_make2_um, fcm_make_ocean, fcm_make2_ocean, fcm_make_pp and fcm_make2_pp. The abbreviations um and pp here stand for Unified Model and Postprocessing respectively and since the workflows of the individual pairs of tasks are essentially the same, the generic task pairs will be referred to as make and make2 in this section. The left and right hand sides of Figure A.1 show the same information in different ways and it can be seen that the MAKE tasks are all run on the LOCALHOST machine which the user aunches the suite from and the make2 tasks are run on FITZROY which, at the time of writing, is the name of the High Performance supercomputer on which the NZESM is run. The MAKE tasks involve extraction of code from a user's personal filespace, from a local code mirror or from the remote central code repository (located physically in the UK). This code will typically involve the 'trunk' or 'master copy' of the code repository in question, plus a number of scientific or technical development branches. These branches are normally merged into the trunk of the code as the model development continues through time.

The MAKE tasks then subsequently merge the code. This merging is necessary since each branch to the trunk is essentially a complete copy of all the constituent text files, whilst usually only a very small number of files will be changed in each branch. After the MAKE tasks have done the extraction and merging of code, the MAKE2 tasks then pre-process and compile the code to produce the executable used at runtime.

There is no a priori reason for the MAKE and MAKE2 tasks to be run on different machines, however due to limited support for some open-source software packages on Fitzroy's IBM AIX operating system, it is easier to run the make task on the auxiliary post-processing servers (Red Hat Linux).

A.1.2. Ancillary file installation

The INSTALL_ANCIL task defines locations and names of ancillary files to be used by the model at runtime. These ancillary files are boundary conditions used by the model. An example of this type of boundary condition is the provision of sea surface temperatures and sea ice extent in a model which does not use a dynamic ocean or sea ice model.

A.1.3. Reconfiguration

Reconfiguration (the RECON) task is the process by which data is processed to enable a simulation to start from a set of appropriate boundary conditions. The files used to start or restart a model run are often called 'model state dump' files. The reconfiguration contains a large amount of complex functionality which is outside the scope of this paper and the interested reader is referred to the relevant Unified Model Documentation Paper (Sharp and Mancell, 2016). Some of the most relevant aspects of the reconfiguration for NZESM development are as follows:

1) The ability to initialise prognostic variables to constants or to a 'missing data indi-cator'. A missing data indicator can be interpreted as 'not a number' (NaN) since it does not have a physical presence. For example the 1000hPa isobar often does not exist over very high terrain.
2) Using an interpolation scheme to use a model state dump file of a different resolu-tion to start a model run.
3) Using fields from an ancillary file to initialise a model field or fields.
4) Initialising data from NetCDF (Network Common Data Form) files and the Met Office's own file formats.

A.1.4. Running the coupled model

In this example of a coupled model containing atmosphere, ocean and sea ice models, all three are contained within the coupled task in Figure A.1. Within this task, all three submodels (GA, GO and GSI) all run together and are physically coupled to one another (e.g. exchanging information about the sea surface temperature to the atmosphere) using the OASIS framework (Valcke, (2013). In this task, the model's output files are written and any climatological mean quantities are calculated using the Storage Handling and Diagnostic System (STASH) submodel (Barnes, 2016). As can be seen in Figure A.1, each COUPLED task runs for ten days before automatically submitting the following one. This resubmission is done using the Cylc 'workflow engine'.

A.1.5. Postprocessing and housekeeping
Housekeeping tasks include the deletion or archiving of temporary files and folders which are needed to store information regarding simulation debugging in the event of a run failure. A further example concerns 'intermediate files', which are written by one task and used by another, but which are not part of the final set of products. These are often much larger than temporary files. If the experiment is long enough (or runs indefinitely, as in operational systems) these files will rapidly take up valuable user disk quota space. Housekeeping tasks can also move results to an archive to save them being overwritten or accidentally deleted by a future run of the same suite. In a Cylc suite (which all NZESM simulations are), housekeeping tasks should be part of the workflow to avoid the need for manual cleanup, or to avoid using too much disk space.

A frequently used postprocessing task (postproc in Figure A.1) used in coupled models is the building of global files for data output from the NEMO ocean model. NEMO by default gives one output file per processor (CPU) used and these must be combined into global fields to enable data analysis to take place.

A.2. Centralised version control with MOSRS

The Met Office Science Repository Service (MOSRS) provides a way for different modelling groups in the UM Consortium to collaborate using the same code base in real time. NIWA has a local copy of this code which is automatically updated ('mirrored') several times per day. Many projects are supported and enabled through MOSRS and each project uses a Trac (https://trac.edgewall.org/) Wiki and ticketing system to give users the ability to assign errors and upgrade requests to specific users or 'code owners'. MOSRS is accessible through a web browser and furthermore gives the ability to visualise code changes across version-controlled revisions. Users who are interested in accessing MOSRS for use with the NZESM should contact the lead author for further information.

A.3. Open source configuration software

A.3.1. Cylc
Cylc is a workflow engine that orchestrates the execution of suites of interdependent tasks. In particular, it can generate continuous (ongoing) workflows of cycling (repeating) tasks, in which tasks in one cycle may depend on those in previous cycles. This cycling capability is essential in climate and weather research and operations, and related activities such as weather-driven environmental prediction. The cycling of atmospheric models is driven by the need to split long model integrations into

short chunks to fit queue limits in shared HPC environments, and - in real time prediction systems – by the availability of real time data. Each model run depends on the previous run and has its own associated preprocessing, postprocessing and housekeeping tasks. Additionally, at start up a series of tasks has to run to extract the model source code from a revision control repository and build it, and to install many other files needed during the run. Cylc is used to run research and operational weather prediction and related systems at NIWA, Met Office (UK), and other institutions. It can routinely manage workflows of several thousands of tasks per cycle. Cylc was originally developed at NIWA. It is now an Open Source collaboration between NIWA, Met Office, and others; and is available from GitHub, https://cylc.github.io/cylc/.

A.3.2. FCM

The Flexible Configuration Management (FCM) is an environment for Fortran code management and version control. It is an open Source system developed by the UK Met Office and is also available from GitHub, https://github.com/metomi/fcm. FCM consists of wrappers around the standard Subversion suite of version control utilities and also includes a separate system for extracting and building scientific code bases, FCM Make, which is not present in standard Subversion.

Good code management and revision control is essential for collaborative development of a large code base such as a coupled Earth System Model. A branch and merge development model is used: new features and fixes are developed on branches to avoid interfering with the work of others, and merged into the trunk once completed.

A.3.3. Rose

Rose is "a framework for managing and running meteorological suites". (http://metomi.github.io/rose/doc/rose.html.) It is an Open Source system developed by the UK Met Office and available from GitHub. Rose uses Cylc as its workflow engine. Rose includes suite storage and discovery on the network, to facilitate shared suite development (with FCM), a generic configuration system for complex scientific applications and various utilities for working with suites. The configuration system for suites and tasks consists of a generic GUI, ROSE CONFIG-EDIT, that is driven by simple human readable config files (for all model input parameters etc.) and optional metadata to control display and place constraints on entered data. This can provide a full-featured GUI for configuring suites and tasks without any need for custom GUI programming. At run time, "app config files" are processed to create and install files, generate environment variables and Fortran namelists, and to execute the task job. A utility, Rose Bush, (soon to be migrated to Cylc) provides a modern searchable, filterable, web interface for quick access to thousands of task job logs from a suite run.

References are included above in main section.

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