SPECIAL PROJECT PROGRESS REPORT

Progress Reports should be 2 to 10 pages in length, depending on importance of the project. All the following mandatory information needs to be provided.

Reporting year	July 2014 – July 2015
Project Title:	The use of imprecise arithmetic to increase resolution in atmospheric models
Computer Project Account:	spgbtpia
Principal Investigator(s):	Prof. Tim Palmer, Dr Peter Düben Co-Investigators: Andrew Dawson, David MacLeod, Stephen Jeffress, Aneesh Subramanian
Affiliation:	University of Oxford
Name of ECMWF scientist(s) collaborating to the project (if applicable)	Dr Glenn Carver, Dr Martin Leutbecher, Dr Filip Vana, Dr Antje Weisheimer
Start date of the project:	01.01.2014
Expected end date:	31.12.2016

Computer resources allocated/used for the current year and the previous one

(if applicable)

Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	5,000,000	4,390,234	10,000,000	3,472,848
Data storage capacity	(Gbytes)				

Summary of project objectives
(10 lines max)

The aim of this project is to study the limits and prospects of the use of imprecise hardware in a global atmosphere model (IFS). In particular, we want to investigate the potential use of inexact hardware and reduced precision floating point arithmetic in a model of the global atmosphere. The use of inexact hardware has the potential to reduce the computational cost significantly, due to a reduced energy demand and/or an increase in performance. A reduction of computing cost allows higher computing power within the same budget for computing facilities. Higher computing power allows higher resolution and the resolution in state-of-the-art atmospheric simulations is still far from being adequate. If the results of this project show that it is possible to use inexact hardware to perform large parts of the computation of an atmosphere model, this project might lead to a fundamental change in future computing hardware used for weather and climate modelling.

Summary of problems encountered (if any)
(20 lines max)

None.

Summary of results of the current year (from July of previous year to June of current year)
This section should comprise 1 to 8 pages and can be replaced by a short summary plus an existing scientific report on the project

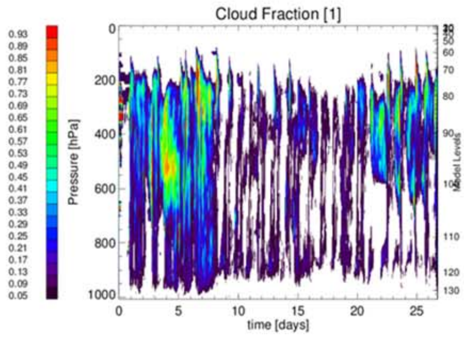
We have enabled a version of the OpenIFS model to run with single precision instead of double precision. The use of single precision is much cheaper compared to the use of double precision since the amount of data that needs to be stored in memory and cache and transported between processors is reduced by a factor of two. Processing of vectorised loops is twice as fast as well.
These tests were successful in that results between the double precision and the single precision model are very similar. We tested the performance of the single precision simulations at different resolutions and for different lengths of simulations and results were promising for all simulations. We also performed ten-day forecasts with twenty ensemble members at T399 resolution for more than 40 initial dates. Results are almost identical between single and double precision simulations except for a change of the forecast quality for geopotenial height in the tropics that should be investigated further. Single precision has now been included into the new cycle of the IFS model and Filip Vana has taken over the work to identify problems and advantages of the single precision setup and to test if single precision will be an interesting alternative for the operational forecast at ECMWF.

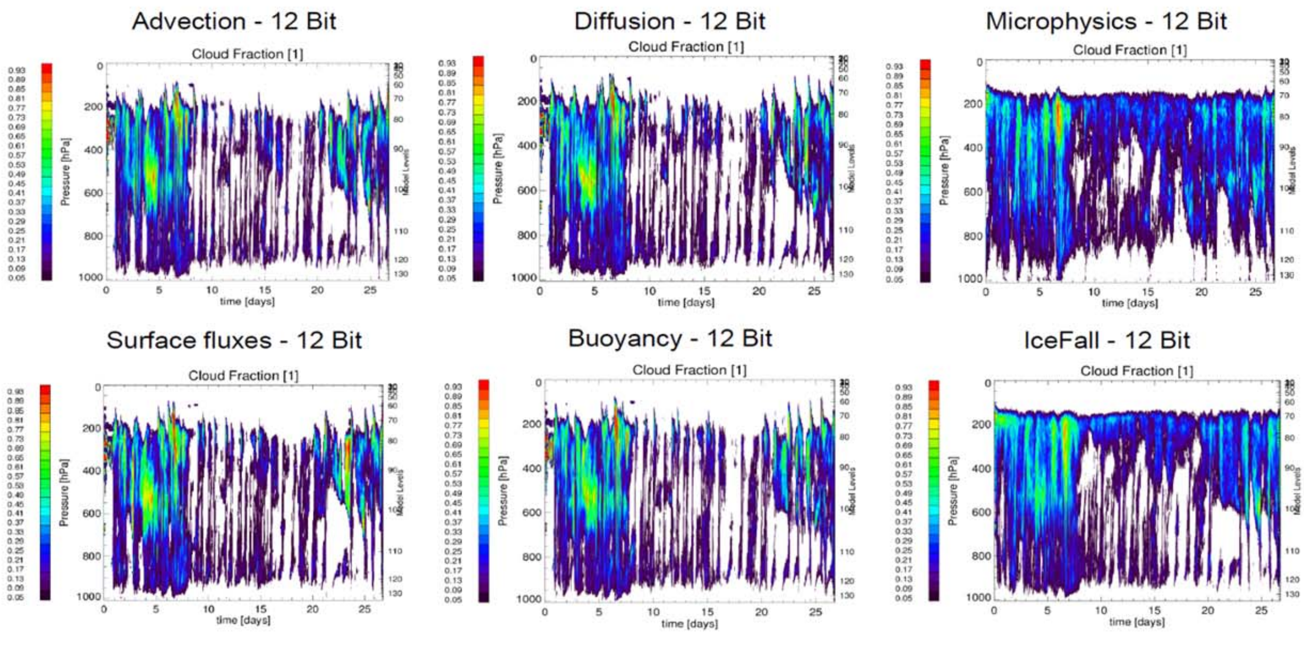
To study a stronger reduction of precision beyond single precision in simulations of IFS and the global atmosphere we started to introduce an emulator for reduced numerical precision into parts of OpenIFS and IFS. The emulator was developed in Oxford and is working with type declarations and overloaded operators to allow the emulation of reduced precision in large parts of a model which is as big as IFS, with hundreds of thousands of lines of code, with only a limited amount of changes in the model code. To this end, real number declarations are replaced by declaration of a predefined type at the beginning of subroutines and modules. Thereafter, all operations that are performed with theses types are described by the library of the emulator. This allows changes in the precision of floating point operations. The precision level that is used can also be changed locally.

At the moment we investigate the use of reduced precision in three different parts of the IFS model setup:

1. We reduce precision for the integration of the cloud-resolving model (CRM), which is used in a super-parameterised version of IFS. Here, the CRM is a limited area model with one horizontal and the vertical dimension, which is run within each grid-cell of the global simulation using the prognostic parameters of the global model simulation as boundary conditions. The CRM is introduced to represent sub-grid-scale dynamics down to cloud-resolving scale and to represent convective processes. This setup has been tested in the US NCAR climate model before and allowed improvements in the representation of the tropics and in particular the Maddan-Julian-Oscillation and the diurnal cycle in convection globally. The CRM computations in IFS increase the computational cost of the entire model simulation substantially. However, since the impact of the CRM on the global simulation is only via averaged values, we expect rounding errors of reduced precision hardware to be of minor importance. We also expect that a larger number of columns in the CRM, that may be possible if cheap reduced precision hardware is used, will improve the model simulations. The emulator for reduced precision is already introduced into the model setup of the CRM and first results are promising.

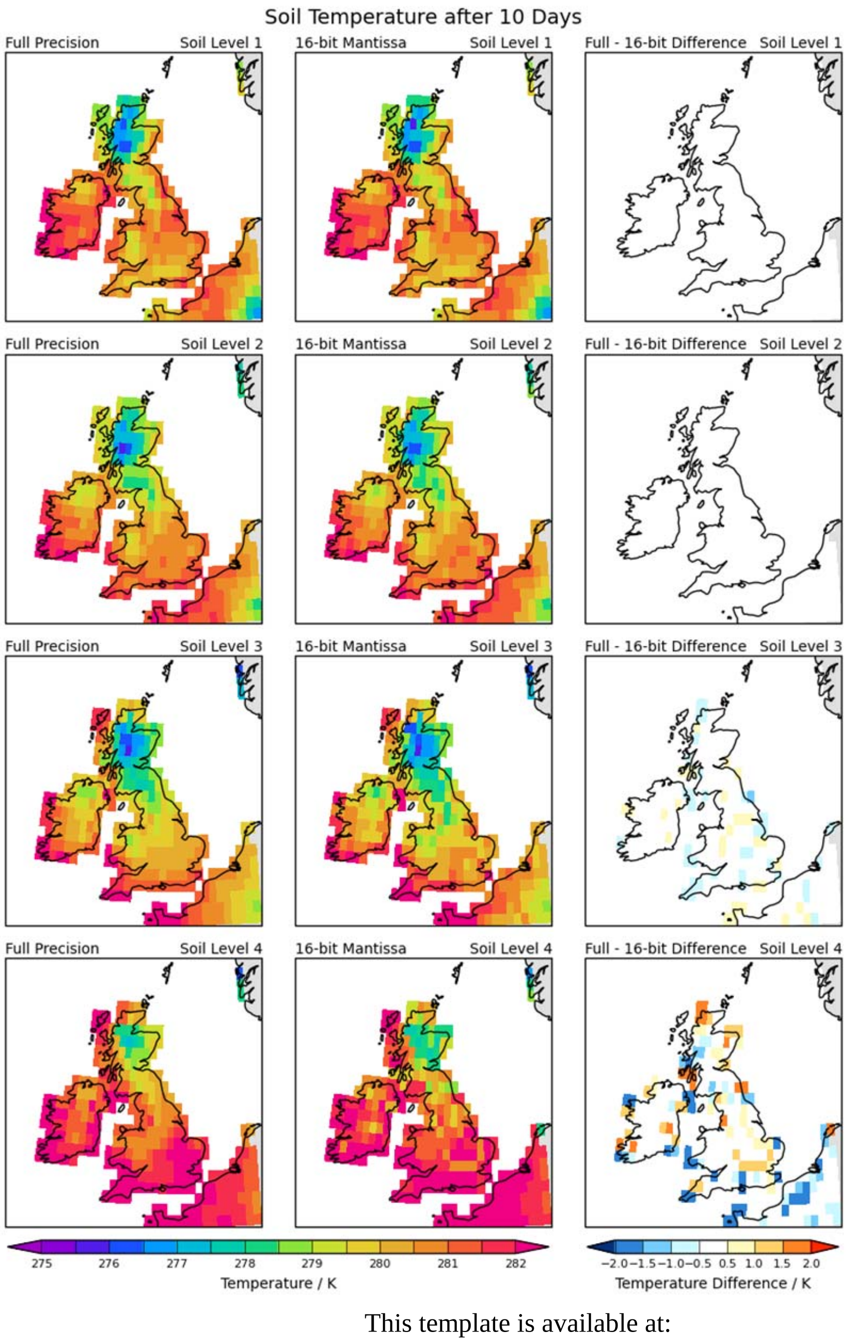
   To save computing power in a first approach, we have been testing the CRM with reduced





precision in a Single Column Model of IFS Physics. The figures above show preliminary results of the mean cloud fraction in the column produced by the CRM (the double precision control simulation is shown on the top). We reduce the precision of various components of the CRM to test the sensitivity of convection in the model to the computational accuracy of these physical processes. Currently, we observe that the convection in the model is most sensitive to the microphysics parameterization (including the ice fall parametrisation). Reducing precision on the computation of advection, diffusion, surface fluxes or buoyancy doesn't impact the convection and clouds in the model much. We further plan to test this in the IFS GCM on the Cray XC-30 Machines with our allocated resources to study the impact of these reduced precision computations on global fields. We expect a speed up in computation of the CRM at every time step in the model, which has promise in solving the convection problem for GCMs. We will also compare model simulations at different spatial resolution and numerical precision to study the trade-off between resolution and precision and to check if a model simulation that is using a higher resolution for the CRM but lower numerical precision will show better results compared to a simulation in double precision at lower resolution.

2. We also introduced the emulator for reduced precision into the land surface scheme of IFS. Similar to the cloud-resolving model in super-parametrisation, the land-surface scheme is



independent between grid-cells and uses the prognostic values of the global simulation as boundary conditions. The exact values of the prognostic fields of the surface scheme appear to have only a small impact for short-term forecasts of IFS and only field values at the surface interact with the global atmosphere model. Therefore, we expect that numerical precision can be reduced significantly for many quantities in the surface scheme with no strong impact on the global simulation. We introduced the emulator for reduced numerical precision into the surface scheme and we are now testing the impact on model quality if precision is reduced. To save computing power, we have started the investigation with a stand-alone version of the land surface scheme. The Figure above shows preliminary results of a snapshot of soil temperature over the UK for a ten day forecast at the four soil levels for the double precision model (left) and a model that is using 16 bits for the significand of floating point numbers (middle), as well as the difference between the two (right). While there are still differences visible for lower levels that need to be addressed, differences at the surface level—which interacts with the atmosphere model—are very small.

In future investigations we will also compare the influence of the rounding error forcing to the influence of stochastic parametrisation schemes that are introduced and tested in the land-surface scheme at the moment.

3. We are in the process to introduce the emulator for reduced precision into the cloud scheme of IFS. The module cloudsc generates about 7.5% of the computational cost of high resolution simulations with IFS but consists of less than 3000 lines of code. It is therefore a promising candidate to start investigations with reduced precision in IFS. Furthermore, a study of the cloud scheme will allow a direct comparison between physical parametrisation schemes (and potentially stochastic parametrisation schemes) and the rounding errors that are generated by reduced precision hardware. We already started to implement the emulator into the cloud scheme and hope that we can start with simulations soon.

We have also performed tests with reduced numerical precision in toy models such as Lorenz'95 and a C-grid shallow water model to find the best way to identify the lowest precision level that can be used in different parts of model simulations. To this end, we investigated how a reduction in precision will influence the quality of short- and long-term simulations and how to relate errors due to reduced precision with model errors. Our simulations showed that the minimal level of precision that should be used is similar in short and long-term simulations and we argue that simulations of only a small number of timesteps (e.g. 50) can provide valuable information about the minimal level of accuracy that can be used in both weather and climate-type forecasts. This result is consistent with the approach of seamless predictions in atmospheric modelling for which short-term simulations over days, weeks or seasons (initial value problems) are used to understand and improve long-term climate simulations (boundary-value problems). Trial-and-error tests can be avoided for expensive integrations if only short-term simulations are evaluated in a first approach to reduced precision. However, we find that it is important to evaluate each reduced-precision simulation parameter against its own reference value, if the model simulation is evaluated after only a small number of timesteps. This is necessary since interactions between different quantities will need an appropriate amount of time to propagate perturbations. We also performed tests to automatize the search for the right level of precision that can be used in a C-grid model. Preliminary results suggest that this can be done comparably easily, using the emulator for reduced precision.
Furthermore, we also studied how rounding errors due to reduced numerical precision compare to stochastic forcings of a stochastic parametrisation scheme in simulations of the 1D Burgers equations. Results show that a comparison between the magnitude of the rounding error forcing and the magnitude of the random forcing of stochastic parametrisation schemes, that are typically

motivated by sub-grid-scale variability, is very useful to identify the magnitude of the rounding error forcing that can be used—and therefore the minimal level of precision—with no strong reduction in quality for earth-system models.

All of these studies provide useful knowledge for our attempt to “fine-grain” the levels of precision to be used in the three different parts of the IFS model that are under consideration (listed above). The finer the precision level can be adjusted to application needs (one precision level for the entire model, module, subroutine, line of code or individual parameter), the stronger precision can be reduced and more information can be gained about the information content of different variables and bad coding habits.

List of publications/reports from the project with complete references

P. D. Düben, S. Dolaptchiev, 2015: Rounding errors may be beneficial for simulations of atmospheric flow: Results from the forced 1D Burgers equation, *Theoretical and Computational Fluid Dynamics*, in print

P. D. Düben and T. N. Palmer, 2014: Benchmark Tests for Numerical Weather Forecasts on Inexact Hardware, *Mon. Wea. Rev.*, **142**, 3809–3829

P. D. Düben, H. McNamara and T.N. Palmer, 2014: The use of imprecise processing to improve accuracy in weather & climate prediction, *Journal of Computational Physics*, 271, 2-18

Summary of plans for the continuation of the project

(10 lines max)

We want to continue tests with the single precision version of IFS and pursue our investigations on the use of reduced precision in super-parametrisation, the land surface scheme and the cloud scheme. We will identify the minimal level of precision that can be used in different parts of the model with no strong degradation in results and compare the impact of reduced numerical precision with the forcing of stochastic parametrisation schemes.

We will also start to emulate the use of inexact hardware within other (cost-intensive parts) parts of the OpenIFS model. We will try to apply the approach of scale separation, which has shown to be very efficient in a spectral dynamical core, in the spectral part of the OpenIFS model as well as for the Legendre transformation. This will need more work on the emulator for reduced precision to allow an automatized search for the right precision level.