Sub-grid cloud parametrization issues in the Met Office Unified Model: A tale of several grey zones

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1 Introduction

Clouds form an important part of the weather and climate system. When running and developing a seamless forecasting system such as the Met Office Unified model (Brown et al., 2012) it is important to accurately represent the existence of clouds on a range of time and space scales. It is within clouds that precipitation forms, the forecasting of which is important on spatial scales ranging from individual river catchments to countries and from timescale ranging from hours to decades. Clouds also affect the large-scale circulation due to the release of latent heat associated with condensation (and the latent cooling due to evaporation). Clouds also interact with solar and terrestrial radiation, strongly modulating the temperature experienced at the surface, which is a key component of weather forecasts. The interaction of cloud and radiation also affects the earth's radiative balance and is important to represent accurately when carrying out climate simulations.

2 The Met Office Unified Model and its range of horizontal grid-lengths

At present the Met Office Unified Model (MetUM) forms the basis of our next generation of climate model (Hewitt et al., 2011), which will be run using grid-lengths between 60 and 150 km depending on the application. The MetUM is also run operationally as a global deterministic and ensemble forecast model (Walters et al., 2011) using a grid-length of around 25 km and 40 km respectively. The MetUM is also run as a limited-area model over the North Atlantic and western Europe using a grid-length of 12 km. Over the United Kingdom we run deterministic forecasts using nested domains with grid-lengths of 4 km and 1.5 km and an ensemble with a grid-length of 2.2 km. These higher resolution models are configured in a similar manner to the models described by Lean et al. (2008). For the purposes of parametrization development and for comparison against observational case studies, the MetUM can also be run using a grid-length down to 100 m (e.g. Price et al., 2011).

As computer power increases, and higher and higher resolution models become affordable for different purposes, it is important to consider not only how clouds are represented within the models used for numerical weather prediction and climate-change studies, but also how the representation of clouds is influenced by the representation of other processes (such as convection), which are themselves dealt with differently at different resolution. This is a theme that we will return to later, when discussing "grey zones".

3 On the need for cloud parametrization schemes

The general circulation models (GCMs) used for climate-change studies and for numerical weather prediction (NWP) are run with grid-lengths that mean that cloud predictions would be very unrealistic if the model was formulated to only create cloud once the grid-box mean humidity reached the grid-box-mean value of saturation. The reason why this would be unrealistic is because in the atmosphere there are many processes that lead to variations in temperature, humidity and pressure on scales much smaller than the grid-length of the model. As a result of these sub-grid-scale fluctuations, the local value of humidity can exceed the local value of saturation humidity. This leads to the formation of sub-grid-scale cloud despite the grid-box mean value of humidity being below the grid-box-mean saturation value (Fig. 1).

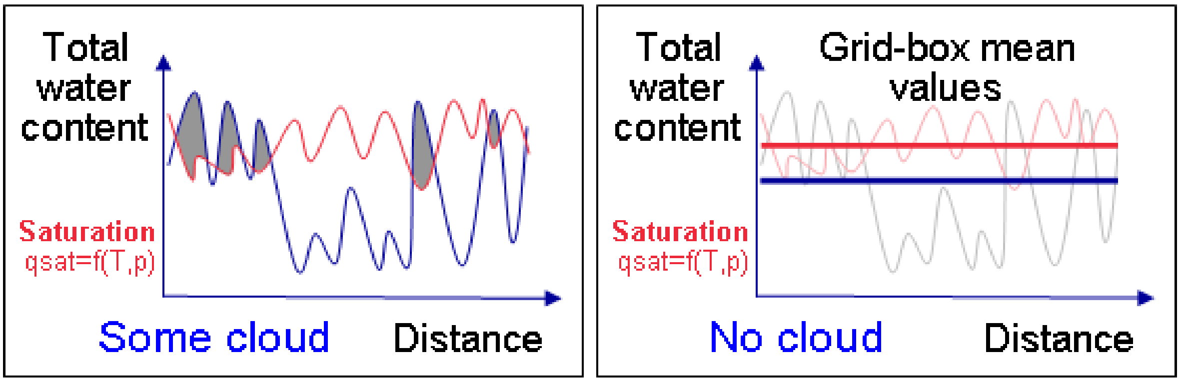

Figure 1: Schematic illustration of the variability of total water content and saturation mixing ratio within a grid-box. Within the grid box, there are places where the local value of total humidity exceeds the local value of saturation and hence there should be some cloud present and a non-zero fractional cloud cover (on the left). However if the occurrence of cloud is simply inferred from the grid-box-mean humidity and grid-box-mean value of saturations then no cloud will be present in the model since the relative humidity is below 100% (on the right).

The purpose of a cloud parametrization scheme is to determine the fraction of the grid-box that is covered by cloud and the liquid and ice water content of the clouds. These are then used by the model's microphysics scheme to calculate the impact of the clouds on the creation and evolution of precipitation particles and by the radiation scheme to calculate the impact of the clouds on the solar and terrestrial radiation traversing the atmosphere.

An example of a simple cloud scheme would be one that has a critical value of grid-box mean relative humidity (RH_{crit}), above which cloud cover starts to increase from zero. The details of the formulation of the scheme would determine the rate at which cloud cover increases as relative humidity (RH) increased. In Fig. 2 we consider a scheme where the cloud cover reaches 50% when the grid-box-mean RH reaches 100 %. So this means that although the grid-box-mean value of RH may be 100 % half of the grid-box is has a larger value (and hence is cloudy) and half of the grid-box has a lower value and hence is cloud-free. Our simple cloud scheme produces overcast skies once the grid-box-mean RH reaches $2.0 - RH_{crit}$. Assuming saturation adjustment would mean that cloud would form when the RH reached 100%.

4 Sub-grid variability and its dependence on grid-length

As the resolution is increased and the model's grid boxes get smaller, one might expect that there would be less and less variability in each box. Eventually, given a small enough grid-box, one could assume that

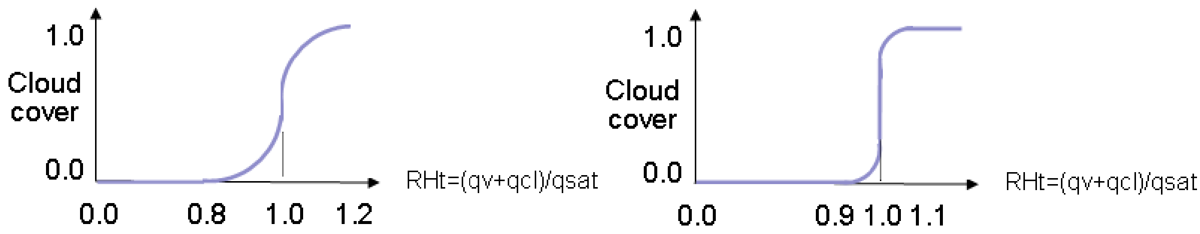

Figure 2: Schematic of a simple cloud scheme that starts producing cloud cover once the grid-box-mean relative humidity rises above a certain critical value of 0.8 (on the left) and 0.9 (on the right). The concept of a critical relative humidity is closely tied to the concept of sub-grid-scale variability. A critical relative humidity of 0.9 means that the grid-box-mean relative humidity must reach 0.9 before any of the fluctuations about this mean lead to the local moisture content exceeding the local saturation value. A critical relative humidity of 0.8 implies more variability in sub-grid-scale humidity. As the grid-boxes get smaller, one might expect the critical relative humidity to tend towards 1.0.

the grid-box was perfectly homogeneous. In this case, there would no longer be a need to have a cloud parametrization scheme, and instead one could simply assume that the grid-box was either completely cloudy or completely clear, with no option of partial cloud cover.

This change in the sub-grid variability as the grid box gets smaller could be represented by the critical relative humidity increasing and tending towards 100% as the grid-box size gets smaller.

By analysing in-situ data collected by research aircraft, considering different length flight legs, calculating the leg-averaged thermodynamic properties and comparing them to the individual thermodynamic measurements one can estimate RH_{crit} as a function of grid-box size (Fig. 5, Ian Boutle, pers. comm.). These data suggest a value of $RH_{crit} = 0.95$ for horizontal grid-lengths of 1.5 km. The observational data are well described by a linear fit in log space. Extrapolation of the fit suggests that RH_{crit} reaches 1.00 when the grid-box is around 180 m (Ian Boutle, pers. comm.). This would suggest that when running a model with a grid-length of around 100 m, one could use an all-or-nothing cloud scheme, but that something more sophisticated is required when the grid-length is 200 m or larger.

One question that arises from this is how much the variation in *vertical* grid-length impacts the value that RH_{crit} should have. This is particularly important since many GCMs used a stretched grid in the vertical, and have small grid-spacing near the surface that increases smoothly the further one gets from the ground. It may be that observational data from tethered balloons or instrumented masts could be used to to infer how RH_{crit} should vary with vertical resolution. Analysis of data from LES could also be of use in this context.

5 The cloud schemes in the Met Office Unified Model

There are two cloud schemes available in the Met Office Unified Model and both are used in current operational model configurations. The Smith (1990) cloud scheme was used in all our models until July 2010 and is still used in our limited area, smaller grid-length, model configurations. The prognostic cloud and prognostic condensate cloud scheme (PC2, Wilson et al., 2008) has been incorporated into the development version of the climate model (which will form the basis of the HadGEM configuration submitted to the next Intergovernmental Panel on Climate Change (IPCC) assessment). PC2 is also used in the global forecast model (both in the deterministic model and in the ensemble prediction system).

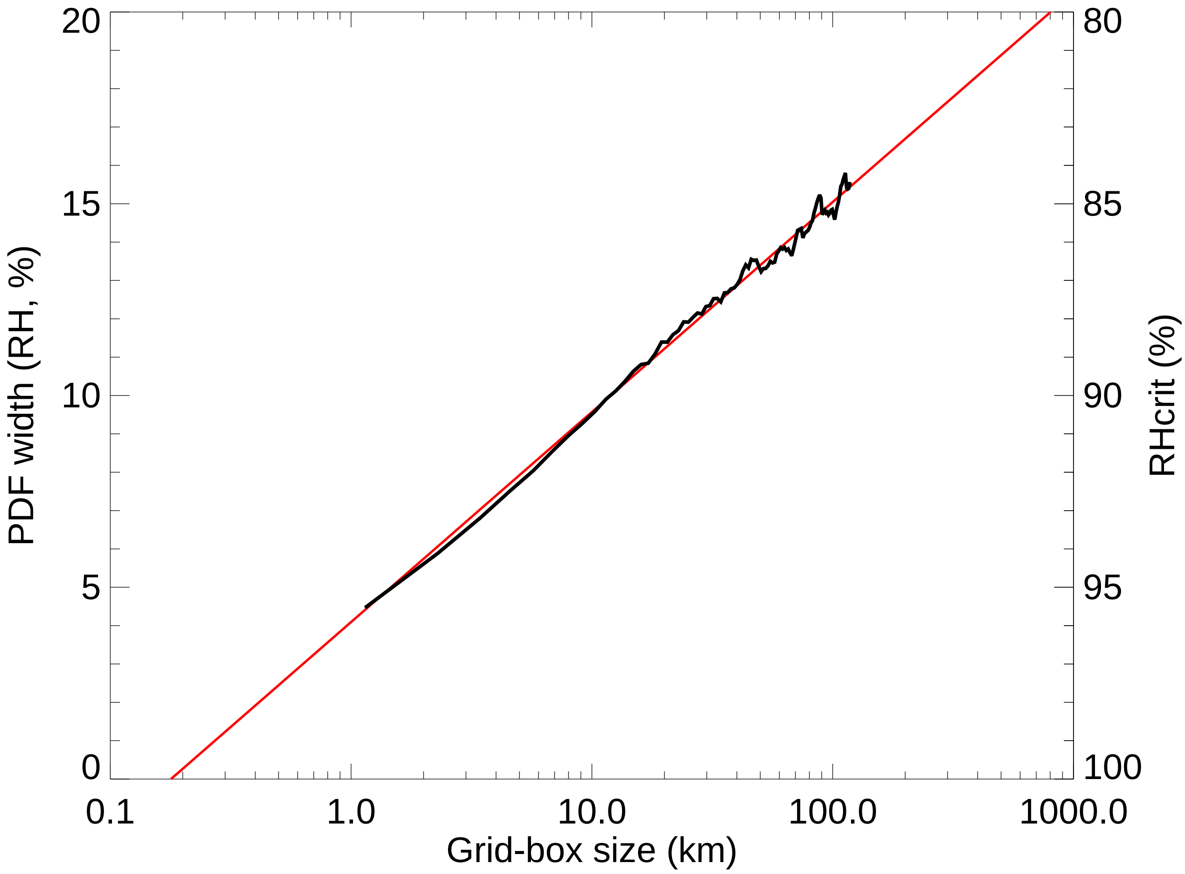

Figure 3: Analysis of aircraft data used to infer the variation of the width of the moisture PDF as a function of averaging over different length periods and hence over different distances (Figure provided by Ian Boutle of the Met Office).

In a similar manner to the Tiedtke (1993) scheme, PC2 is process based. It considers each of the physical processes represented in the model and then calculates how that processes changes the cloud cover and condensate amounts. During the development of PC2 is has been found useful to look at the cloud cover and condensate tendency terms to see how the scheme is behaving (Morcrette and Petch, 2010). Analysis of these budget tendency terms has highlighted issues with the formulation of one of the PC2 process rates, which was then improved upon by developing a new method for calculating the cloud erosion rate (Morcrette, 2012a). Inspection of cloud scheme tendency terms can also help identify inconsistencies in the formulation of various terms. Looking at the increment terms from the cloud scheme can be very informative in showing how the cloud scheme is producing its cloud, whether this be by looking at zonally-averaged increments or by looking at cloud scheme increments within a mid-latitude cyclone and looking at a cross-section through the warm-front, warm sector and cold-front (Morcrette, 2012b).

6 The cloud parametrization and convection parametrization grey zones

If one runs GCMs using grid-boxes whose dimension are of the order of hundreds of kilometres, then it is accepted that some form of cloud parametrization is required. When we run large-eddy simulations with grid-boxes of the order of tens of metres, we generally assume that we can get away without a cloud scheme and instead assume an all-or-nothing approach. For models whose grid-length is in between there is a "cloud-scheme grey zone" where some models are run with cloud fraction schemes and some are not. Numerical models that run with grid-lengths between those of global NWP models and LES without including a cloud fraction parametrization scheme include some regional NWP models and CRMs, including CRMs that are used to form the basis of super-parametrizations. For those intermediate-resolution NWP models that do run with a cloud scheme, there is usually a parameter, such as RH_{crit}, which should perhaps be varied as the grid-size is reduced. However, without clear information about how this parameter should vary with the horizontal and vertical resolution, model developers are often left to vary it based on pragmatic considerations rather than sound theoretical arguments or detailed observations.

From the point of view of convection, when running GCMs with grid-length of the order of hundreds of kilometres, we make use of convective parametrization schemes. When running simulations using grid-lengths of the order of a hundred metres however, the convective motions are generally sufficiently well-resolved that a satisfactory simulation can be achived without the need for a convection scheme. In between these two horizontal scales there is a "convection-scheme grey zone" where it is not clear whether one should or should not use a convection scheme, or whether one should use a convection scheme which a modified closure. There is no simple answer. The method which gives the best performance depends on the size of the typical convective motions and on the aspect of the atmosphere's response to convection that one is hoping to accurately capture.

The convective parametrization used in the Met Office global model is the dominant source of cloud in the model Morcrette and Petch (2010). So as one increases resolution and stops representing convection explicitly, it is sensible to ask whether a scheme such as PC2 can continue to produce credible simulations. This is an area of active research at the Met Office.

7 Evaluation of cloud forecasts

In order to improve cloud parametrization schemes, one must have an idea of the schemes' current performance, and their weaknesses. One must also be able to compare the performance of a potential new scheme to the old one it is trying to replace. This involves evaluating both schemes and deciding which is best. Obviously the best scheme is the one with the smallest errors. However there are different ways that a cloud forecast can be in error. Morcrette et al. (2012) recently discussed this in the context of evaluating two different cloud schemes in the Met Office global NWP model. A cloud forecast can be in errors due to an error in the frequency of occurrence (FOO) of cloud (Fig. 4). Alternatively, the cloud forecast can have the FOO correct but can be wrong in terms of the Amount When Present (AWP). Finally, a cloud forecast can have the right FOO and AWP in a statistical sense but have an error in timing. When evaluating a cloud forecasts, each of these types of forecast errors co-exist and when comparing two different cloud schemes the extent to which some errors cancel others will be different.

8 The cloud evaluation grey zone

From the point of view of developing packages of physical parametrizations for use in higher resolution models, an extra level of complexity comes from the fact that since different grid-length models are used for different purposes, they are assessed in different ways too.

The clouds in global climate models tend to be evaluated by looking at the seasonal mean of the clouds in terms of their cloud-top height and optical properties, or by looking at their short-wave and long-wave cloud radiative effect. The key thing being that one wishes to have a model that is in radiative balance. Sometimes however, this is at the expense of not quite accutaely predicting the timing of the clouds as a function of the diurnal cycle of convection or of not having the correct balance of short-wave to long-

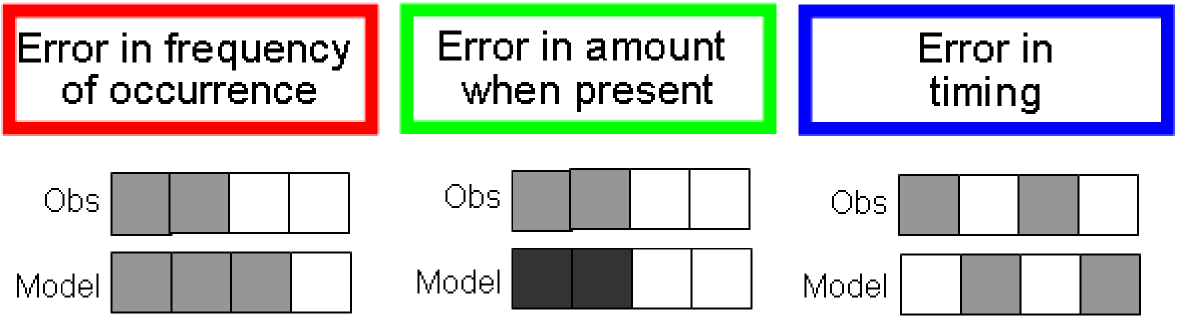

Figure 4: Schematic showing observed and modelled value of cloud cover predicted at a certain site as a function of time. The shading represents fractional cloudiness. The cloud forecast can be in error due to an error in the frequency of occurrence, the amount when present or the timing.

wave cloud forcing, cloud amount to condensate content or frequency of occurrence to amount when present.

When doing global NWP it is much more important to have an accurate representation of the cloud and of their frequency of occurrence, amount when present and timing rather than the correct radiative balance. This is because NWP models are re-initialised a couple of times a day and run over a period of several days, not years. As a result a model that is not in perfect radiative balance does not have time to drift, in the same way that it might if it were run over many decades as part of a climate simulation.

The manner in which NWP models are evaluated also varies depending on the scale they are run at. The NWP-index for our global model comprises of quantitative measure of its skill at predicting things related to the large-scale flow, such as mean-sea-level pressure, 500 hPa geopotential height and upper and low-level winds. This makes sense as the global NWP is there to predict the synoptic-scale flow and to provide boundary conditions for the higher resolution models. Our global NWP index does not currently include a component that explicitly quantifies the skill of the cloud forecast.

The NWP models we run at higher resolution over limited domains are evaluated in a different way. Their NWP index quantifies the models' skill at predicting near-surface weather variables such as temperature, wind speed, rainfall and visibility. The NWP index for the limited area models also includes components measuring the skill at predicting cloud cover and cloud-base.

This difference in how we evaluate the models make sense, since it reflects the different uses of the model's output. However, it does complicate the process of model development. This is because the best package of physical parametrization, as measured by metrics appropriate for one model and its applications, is not necessarily the best package of parametrizations for another model, when assessed using the different metrics appropriate to the applications of that model run with a different resolution.

It makes sense that when evaluating a global NWP system running with grid-length of the order of 50 km, the model should be assessed based on its skill at predicting large-scale flow patterns and variables such as MSLP, 500 hPa height and aircraft cruising-level wind speed. Similarly, when running an NWP model with grid-lengths of a couple of kilometres over a country-sized region, it makes sense to evaluate it in terms of how well the model predicts things like rainfall accumulation, surface temperature and the occurrence of low cloud which affects aircrafts landing.

However, as computer power increases and we become more ambitious, we find ourselves able to run global NWP models using grid-lengths that were previously only used in regional models. There is a grey zone, in the sense that it is not clear how these models should be evaluated. Should the models be assessed: using the large-scale criteria traditionally used by coarser resolution global models, or using

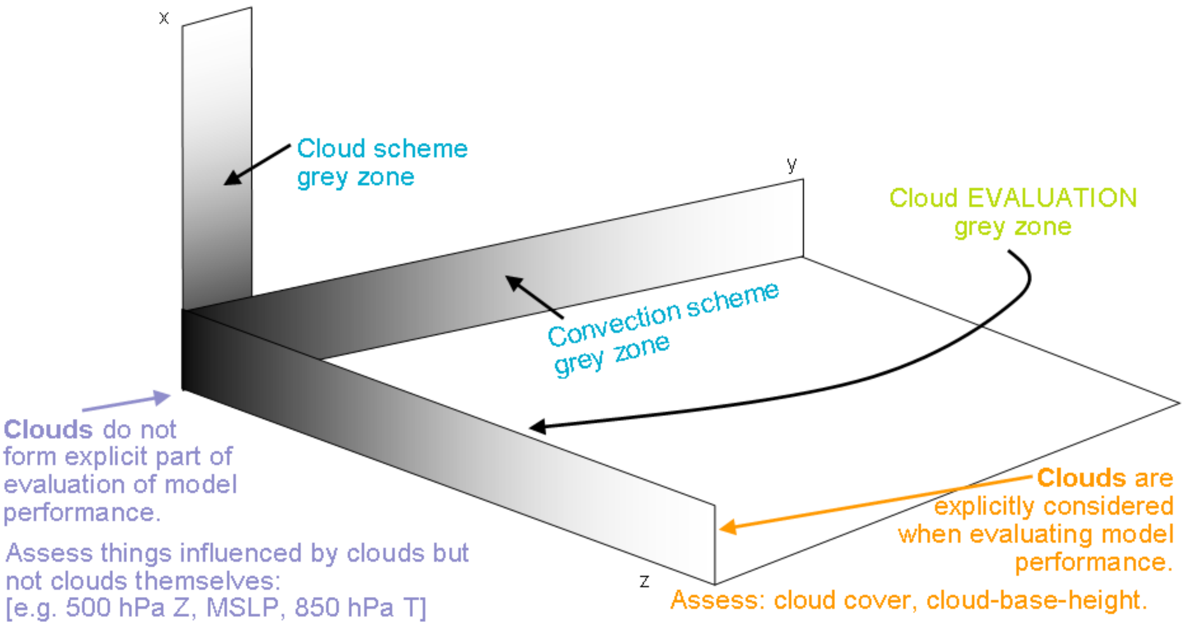

Figure 5: Schematic showing the cloud scheme (x-axis), convection scheme (y-axis) and cloud evaluation grey-zones (z-axis). Each axis, represents the horizontal dimension of the grid-box going from very large (hundreds of km in black) to very small (metres in white). At the very large grid-size (black) end of the x axis one generally makes uses of cloud cover parametrization to determine the fractional cloud cover. At the small grid-box (white) end one can assume that a grid-box is either cloudy or clear (i.e. all-or-nothing cloud scheme). There is probably a grid-box size dependence to the critical relative humidity used for the cloud schemes in the intermediate grid-lengths, but the form of this dependence is not well known. At the very large grid-size (black) end of the y axis one makes use of convection parametrization schemes. At the small grid-box (white) end there is no need to include a convection scheme as all convective motions are explicitly represented on the grid-scale. At the very large grid-size (black) end of the z axis clouds are not explicitly evaluated when calculative a quantitative measure of a model's performance. At the small grid-box (white) clouds form an integral part of the metrics used for NWP verifications. Each GCM or NWP system will find itself somewhere within the 3-dimensional parameter space illustrated above. As one tries to increase the resolution in can be helpful to try to think of the change as needing to occur with a component along all three axes and not just along two.

the criteria used by the same resolution regional models from a decade ago. As we continue to increase the resolution of our models while also trying to improve their physical parametrizations, the grey-zone issue in terms of how we evaluate the models could be just as important as the grey-zone issue in terms of how we parameterize.

References

Brown, A., S. Milton, M. Cullen, B. Golding, J. Mitchell, and A. Shelly (2012). Unified modeling and prediction of weather and climate: a 25 year journey. *B. Am. Meteorol. Soc. 93*, 1865–1877. doi: 10.1175/BAMS-D-12-00018.1.

Hewitt, H. T., D. Copsey, I. D. Culverwell, C. M. Harris, R. S. R. Hill, A. B. Keen, A. J. McLaren, and E. C. Hunke (2011). Design and implementation of the infrastructure of HadGEM3: the next-generation Met Office climate modelling system. *Geosci. Model Dev 4*, 223–253. DOI:10.5194/gmd-4-223-2011.

Lean, H. W., P. A. Clark, M. Dixon, N. M. Roberts, A. Fitch, R. Forbes, and C. Halliwell (2008). Characteristics of high-resolution versions of the met office unified model for forecasting convection over the united kingdom. *Mon. Weather Rev. 136*, 3408–3424. DOI:10.1175/2008MWR2332.1.

Morcrette, C. J. (2012a). Improvements to a prognostic cloud scheme through changes to its cloud erosion parametrization. *Atmos. Sci. Let. 13*, 95–102. DOI: 10.1002/asl.374.

Morcrette, C. J. (2012b). Prognostic-cloud-scheme increment diagnostics: a novel addition to the case-study tool kit. *Atmos. Sci. Let. 13*, 200207. DOI: 10.1002/asl.380.

Morcrette, C. J., E. J. O'Connor, and J. C. Petch (2012). Evaluation of two cloud parametrization schemes using ARM and Cloud-Net observations. *Q. J. Roy. Meteor. Soc. 138*, 964–979. DOI:10.1002/qj.969.

Morcrette, C. J. and J. C. Petch (2010). Analysis of prognostic cloud scheme increments in a climate model. *Q. J. Roy. Meteor. Soc. 136*, 2061–2073. DOI: 10.1002/qj.720.

Price, J. D., S. Vosper, A. Brown, A. Ross, P. Clark, F. Davies, V. Horlacher, B. Claxton, J. R. McGregor, J. S. Hoare, B. Jemmett-Smith, and P. Sheridan (2011). Colpex: Field and numerical studies over a region of small hills. *B. Am. Meteorol. Soc. 92*, 1636–1650. DOI:10.1175/2011BAMS3032.1.

Smith, R. N. B. (1990). A scheme for predicting layer cloud and their water content in a general circulation model. *Q. J. Roy. Meteor. Soc. 116*, 435–460.

Tiedtke, M. (1993). Representation of clouds in large-scale models. *Mon. Weather Rev. 121*, 3040–3061.

Walters, D. N., M. J. Best, A. C. Bushell, D. Copsey, J. M. Edwards, P. D. Falloon, C. M. Harris, A. P. Lock, J. C. Manners, C. J. Morcrette, M. J. Roberts, R. A. Stratton, S. Webster, J. M. Wilkinson, W. M. R., I. A. Boutle, P. D. Earnshaw, P. G. Hill, C. MacLachlan, G. M. Martin, W. Moufouma-Okia, M. D. Palmer, J. C. Petch, G. G. Rooney, A. A. Scaife, and K. D. Williams (2011). The Met Office Unified Model Global Atmosphere 3.0/3.1 and JULES Global Land 3.0/3.1 configurations. *Geosci. Model Dev. 4*, 919–941. DOI:10.5194/gmd-4-919-2011.

Wilson, D. R., A. C. Bushell, A. M. Kerr-Munslow, J. D. Price, and C. J. Morcrette (2008). PC2: A prognostic cloud fraction and condensation scheme. I: Scheme description. *Q. J. Roy. Meteor. Soc. 134*, 2093–2107.

Wilson, D. R., A. C. Bushell, A. M. Kerr-Munslow, J. D. Price, C. J. Morcrette, and A. Bodas-Salcedo (2008). PC2: A prognostic cloud fraction and condensation scheme. II: Climate model simulations. *Q. J. Roy. Meteor. Soc. 134*, 2109–2125.