PARAMETERIZATION OF CLOUD FROM NWP TO CLIMATE MODEL RESOLUTION

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1. INTRODUCTION

General Circulation Model (GCM) simulations are performed across a range of resolutions depending on their application, from hundreds of kilometres for decadal climate down to a couple of tens of kilometres for current global operational Numerical Weather Prediction (NWP). Even with the trend in increasing high performance computing power enabling the use of higher and higher resolution, there will still be a need for models with a wide range of grid resolutions for the foreseeable future. The parametrization of cloud is a vital component of models for both climate prediction and NWP, and an effective parametrization is able to represent the effects of sub-grid cloud processes across the scales used in these models. Although GCMs are able to represent a large proportion of the dominant atmospheric motions that lead to cloud generation and dissipation, they may not always be adequately capturing the impacts of smaller scale motions that can significantly affect cloud and precipitation development and evolution. This paper discusses some of the issues for cloud parametrization at different spatial scales and provides an indication of the behaviour of the cloud scheme in the ECMWF model at resolutions appropriate for short-range and long-term prediction of the atmosphere.

2. ISSUES FOR CLOUD PARAMETRIZATION AT DIFFERENT SPATIAL SCALES

A GCM solves the partial differential equations governing the evolution of the atmospheric state variable after discretizing in time and space with a resolution that is usually determined by the application and available computing resources. The definition of "resolution" here will cover both spatial (horizontal and vertical) and temporal (timestep) discretization. At any resolution there is a part of the flow along with other physical properties of the atmosphere at scales below the resolution of the model, and it is necessary to find parameters that describe the statistical behaviour of these unresolved processes at the resolved scale of the model. The aim of a parametrization is to represents these average statistical properties as a function of resolved variables of the GCM represented on the model grid. Most GCMs represent cloud with a "bulk" formulation, predicting the evolution of quantities such as mean grid-box cloud condensate with additional information on sub-grid variability within the grid cell. For the purpose of the discussion here, it is convenient to consider three aspects of the cloud parametrization: (a) choice of variables and formulation of microphysical processes, (b) representation of sub-grid inhomogeneities and their overlap in the vertical, (c) numerical techniques for efficient implementation. These three aspects are discussed briefly below, with reference to the ECMWF model.

(a) Choice and formulation of microphysical processes

As the resolution of the model is increased, the range of spatial and temporal scales of the atmospheric motion that are represented increases. Since it is these atmospheric motions that provide a significant source for cloud formation and dissipation, the microphysical processes in the model need to be representative of the scales of the dynamical forcing. For example, a model with a higher grid resolution will resolve locally higher vertical velocities. The response of the microphysical scheme to the changing forcing will depend on the non-linearity of the processes involved (and many microphysical processes are very non-linear).

Parametrization schemes are based on an assumed break in space and time scales, so that the impact of scales not resolved by the model can be represented diagnostically from the (prognosed) variables at the resolved scale. The diagnostic assumption is equivalent to an assumption of equilibrium within a timestep based on the fact that the timescales of these sub-grid processes are small compared to the timescale associated with typical resolved motions at the grid scale. An example in many GCMs is the diagnostic representation of rain. Diagnosing the profile of rain from the prognosed liquid and ice water contents within a grid

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column is an appropriate assumption as long as the sedimentation timescale is short compared to
the advection timescale across the grid box. As
the resolution of the model increases, this assump-
tion becomes increasingly invalid and a prognostic
representation of rain would be required for a more
accurate solution at the smaller time and space
scales of the model.

As GCM resolution continues to increase, some
of the choices of prognostic vs. diagnostic vari-
ables and formulation of non-linear microphysical
processes need to be reviewed, and at ECMWF
a change from a diagnostic to a prognostic repre-
sentation of precipitation with corresponding micro-
physical processes is being investigated.

(b) Representation of sub-grid inhomogeneities

Models that predict only the mean value of
cloud properties in each grid cell can be subject
to large biases in many process rates (Pincus and
Klein, 2000). Therefore the representation of sub-
grid inhomogeneities is an important component
of the cloud parametrization, as for an area of a
typical grid box there is considerable variability in
the quantities represented in the model (vertical
velocity, humidity, temperature, liquid and ice wa-
ter content,...) and only part of the grid box may
contain cloud. A common approach is to formu-
late the prognostic equations for the grid box mean
liquid/ice water content and corresponding cloud
fraction (Tiedtke, 1993; Gregory et al. 2002; Lar-
sen 2004) based on assumed probability density
functions of total water. An alternative approach is
to prognose moments of the underlying probability
density function of total water or a related variable
(e.g. Tompkins, 2002) and then diagnose the cloud
fraction. The latter has the conceptually attract-
ive property of attempting to describe variations in
the underlying inhomogeneities in the atmosphere
at the sub-grid scale which could be used consist-
tently between different parametrizations within the
model. However, both approaches rely on the ac-
curate specification of sinks and sources due to a
variety of dynamical and physical processes which
are often difficult to represent and in some cases
are unknown. The debate is still open as to which
of these approaches or indeed whether alterna-
tives are the most appropriate.

Even if we assume that the sub-grid inho-

togeneities are represented appropriately in each
grid box, there is then also the question of how
inhomogeneities are distributed relative to one an-
other in the vertical. This is particularly important
for cloud-radiation interactions and precipitation
sedimentation (which are both dominated by the
vertical component). Atmospheric models which
have a sub-grid representation of cloud fraction
parametrize how clouds within a grid column over-
lap in the vertical. The particular choice of assump-
tions can have a significant impact on the radia-
tion scheme and performance of the model. Tradi-
tionally GCMs have used the maximum-random as-
sumption for fractional cloud cover overlap (Geleyn
and Hollingsworth, 1979), but more recently, ob-
servations (Hogan and Illingworth 2000; Mace and
Benson-Troth 2002; Naud et al. 2008) and cloud
modelling results (Oreopoulos and Khairoutdinov,
2003) have suggested a more realistic assumption
based on increasing randomness in the overlap as
the separation between two layers within a cloud in-
creases (referred to here as “generalised overlap”) with
the degree of randomness dependent on wind shear
or synoptic regime. A form of the generalised
overlap has been applied to both cloud cover and
inhomogeneities in cloud condensate in GCM radi-
ation schemes (Räisänen et al. 2004; Morcrette
et al. 2007) resulting in a reduced dependence on
vertical resolution. Another process in which the
vertical overlap assumption can be important is
that of precipitation enhancement and evapora-
tion. Jakob and Klein (1999,2000) showed a signif-
icient impact of assuming cloud/precipitation overlap
on the evaporation of precipitation, but there are
other areas of the parametrization such as mixed
phase clouds where overlap of ice and liquid inho-
mogeneities can be crucial and can lead to resolu-
tion sensitivity.

(c) Numerical techniques for efficient implementa-
tion

A particular problem for GCMs is the combina-
tion of high vertical resolution and long timesteps
for computational efficiency, where the chosen
timestep is based primarily on horizontal advect-
tion velocities and the horizontal grid resolution.
For example, the ECWMF IFS GCM with semi-
lagrangian dynamics may use a timestep of 1 hour
for a horizontal grid spacing of 125 km. In con-
trast the vertical resolution in parts of the tropo-
sphere may be of the order of 100m. There are
thus implications for the sedimentation scheme
with hydrometeors falling through many model lay-
ers within a timestep. A previous CFL limited ex-
licit sedimentation scheme in the ECMWF model
lead to a significant sensitivity to vertical resolu-
tion and timestep. A forward-in-time upstream im-
plicit solver is now used for the cloud variables, us-
ing a mass flux form for the advection term to en-
sure conservation, and the sensitivity to resolution
is much reduced (Tompkins, pers. comm.).
3. SENSITIVITY OF THE ECMWF CLOUD SCHEME TO MODEL RESOLUTION

A number of sources of resolution sensitivity to cloud parametrization in GCMs have been outlined in the previous section. Here we investigate the sensitivity of aspects of the cloud and precipitation in the ECMWF model (www.ecmwf.int/research) to spatial resolution.

At ECMWF, the IFS (Integrated Forecast System) is used at its highest resolution for global NWP (currently with a spectral truncation of T799 equivalent to a grid spacing of 25 km, 91 levels and a timestep of 12 minutes). A 50 member global ensemble is also run operationally at a lower resolution (T399L62, 50 km grid, 30 minute timestep). Also, the ECMWF seasonal forecasting system currently includes the atmospheric model at T159L62 resolution (125 km grid, 1 hour timestep). All configurations use the same physical parametrizations without tunable resolution dependent parameters, so that the same parametrizations can be used across the range of resolutions.

To assess the extent to which the ECMWF model is successful at different resolutions, the sensitivity of various aspects of the cloud and precipitation to resolution will be evaluated. Clearly, the aim is also to get the model as close to observations as possible for the appropriate scales represented by the model, and one example for global precipitation is highlighted in this section.

As suggested previously, a number of developments of the ECMWF IFS model cloud parametrization over recent years have contributed to an improved simulation of cloud and precipitation and increased consistency across a range of resolutions. These include a modified implicit numerical formulation to give increased robustness for longer timesteps, particularly affecting the sedimentation scheme for ice, and modified vertical overlap of cloud fraction and sub-grid condensate inhomogeneities with a dependence on vertical distance rather than model level.

Although a number of aspects of the cloud and precipitation representation in the ECMWF model will be evaluated, only the impact on global precipitation (convective + large scale) is described here. Figure 1 shows a comparison of global precipitation averaged over a 1 year period from Sep 2000 to Aug 2001 between the ECMWF T159L91 IFS model at version CY32R3 and the precipitation estimate from the Global Precipitation Climatology Project (GPCP, Adler et al., 2003). Although there are identifiable regional differences in the model precipitation compared to the observed estimate and there is still scope for improvement (particularly in the tropics), overall the model is able to capture the global patterns and magnitudes reasonably well at this resolution.

Global average precipitation is calculated from three simulations to look at the sensitivity to horizontal resolution. These simulations have resolutions of T159 (125 km), T399 (50 km) and T799 (25 km), but the same vertical resolution (91 levels). The respective values of average precipitation for the three models are 2.93 mm/day, 3.03 mm/day and 3.09 mm/day with differences coming primarily from the large-scale cloud scheme rather than the convection parametrization. This is a difference of 0.16 mm/day (5% of the total) between the T159 and T799 resolutions for which the grid spacing differs by a factor of 5 and the grid box area differs by a factor of 25. The estimated mean error of the T159 model compared to the GPCP observations is 0.29 mm/day, so the variation between models is significantly less than the bias compared to GPCP. The large scale spatial pattern of differences is also very similar between models (not shown). This relative insensitivity to resolution is encouraging, but of course there are still possibilities for further improvement, particularly regarding the regional differences from observations. Also, this is just one measure of the robustness of the cloud and precipitation in the model and other characteristics include ice and liquid water content, cloud cover, and humidity, not just averages but other moments of the distributions and sensitivity to timestep and vertical resolution.

4. CONCLUSIONS

Global climate and Numerical Weather Prediction models are currently used across a wide range of scales and require parametrizations that ideally give the correct statistical representation of the sub-grid impacts on the prognostic variables of the model and that are ideally valid across a wide range of model spatial and temporal resolutions. This applies to all parametrizations, but the focus here is on the cloud parametrization scheme.

There are a number of aspects of cloud parametrization formulation that can lead to strong sensitivities to resolution but cloud parametrizations are continuously being improved and are increasingly robust to horizontal, vertical and temporal resolution. One particular example of global precipitation in the ECMWF model is highlighted, but there are still further improvements to be made.
One future direction is towards a formulation using physical assumptions that can be applied consistently across the different parametrization schemes in a GCM (e.g. cloud, convection and radiation); for example, microphysical particle characteristics or sub-grid PDFs of condensate, humidity or even vertical velocity. This also ties in with improving the representation of interactions between the microphysics at the particle scale and the small scale dynamics unresolved by the model, which in some situations can be the primary driver of cloud and precipitation processes; for example, the role of in-cloud circulations on sub-grid variability, generating higher super-saturations, activating aerosols and enabling ice particle nucleation, or maintaining layers of supercooled liquid water.

To improve the cloud and precipitation parametrizations for GCMs, we therefore need information about sub-grid inhomogeneities and interactions with cloud-scale dynamics with input from observations, detailed microphysical models and cloud resolving models (CRMs). With active modelling studies (e.g. GCSS, http://www.gewex.org/gcss.html), different approaches to the global parametrization problem (Khairoutdinov et al., 2005), the beginnings of large domain/global near convective-scale resolution models (Tomita et al., 2005) and new global observational data sets such as the A-Train with active profiling radar and lidar sensors (Stephens et al., 2002) to name a few of the recent advances, there is certainly potential to improve cloud parametrization across the wide range of model resolutions required for climate and numerical weather prediction now and into the future.

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5. BIBLIOGRAPHY


Figure 1: Comparison of global precipitation (mm/day) averaged over a 1-year period from Sep 2000 to Aug 2001 between (top panel) the ECMWF T159L92 IFS model at version CY32R3 and (middle panel) the precipitation estimate from the Global Precipitation Climatology Project (GPCP), with the "model minus obs" differences highlighted in the bottom panel. The right hand panels show zonal and meridional means for the model and GPCP precipitation data.