

## Meeting Report

# Understanding and representing atmospheric convection across scales: recommendations from the meeting held at Dartington Hall, Devon, UK, 28–30 January 2013

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## Abstract

As weather and climate models move towards higher resolution, there is growing excitement about potential future improvements in the understanding and prediction of atmospheric convection and its interaction with larger-scale phenomena. A meeting in January 2013 in Dartington, Devon was convened to address the best way to maximise these improvements, specifically in a UK context but with international relevance. Specific recommendations included increased convective-scale observations, high-resolution virtual laboratories, and a system of parameterization test beds with a range of complexities. The main recommendation was to facilitate the development of physically based convective parameterizations that are scale-aware, non-local, non-equilibrium, and stochastic.

**Keywords:** convective parameterization; UK weather and climate modelling; parameterization development; next-generation climate models; next-generation NWP

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## Introduction

Atmospheric convection is arguably the biggest current obstacle to the improvement of global weather and climate prediction (e.g. Sherwood *et al.*, 2014). Convection interacts with the larger-scale dynamics in ways that remain poorly represented in global models. Errors in convection contribute to errors in many parts of the climate system, including cloud radiative properties, diurnal-to-interannual variability, and the global water cycle (Stevens and Bony, 2013). Short-term forecasts of global convection remain poor, with biases that have not been removed by increasing resolution in current operational forecast models (Lin *et al.*, 2012). Convection is crucial for forecasts of severe windstorms, flooding, and drought, which in turn have fundamental impacts on human safety, agriculture, and the biosphere.

Recently, the community has reached a critical point in convection research in that we have broken two barriers to successful modelling: we can 'permit' the representation of deep convection (order 1 km grid

spacing) in model domains of global scale, and we can resolve large eddies (order 10 m grid spacing) in model domains containing small numbers of individual clouds. These advances mean that we have an opportunity now to make rapid progress in convection research.

In this light of increasing resolution and complexity of models, and increasing scientific and policy expectations for these models, a meeting was held at Dartington Hall in Devon to lay the groundwork for a new strategy on convection studies and modelling in the UK (and a subset of participants have had several follow-up meetings throughout 2013). Although the meeting had a UK context, several international experts also attended, and it is believed that many of the findings of the meeting are relevant to the wider atmospheric convection community. The organizers posed two main questions to the workshop participants:

1. What do we need, and what can we realistically expect models to deliver, in the next 5–10 years?

2. How do we improve our knowledge and representation of convection and its coupling to other processes across scales to help achieve this?

Several common themes emerged from the various breakout groups, talks, and discussions (see the agenda at <http://www.jwcrp.org.uk/events/meeting-jan13.asp> for further details). With the expected increase in computing power it is assumed that in the next 10 years global operational modelling systems for weather and climate will be using atmospheric grid lengths ranging from a few kilometres to around a hundred kilometres. On the other hand, for some problems requiring very long integration times (e.g. paleoclimate modelling), large forecast ensembles, or significant additional complexity (e.g. atmospheric chemistry and/or ocean biogeochemistry), a 100 km grid length may still be too expensive. Regional modelling will continue to face the same tradeoffs between domain size, grid length, ensemble size, and complexity that it currently faces. Decisions about grid resolution, data assimilation resolution, ensemble size, and convective parameterization will depend on the regime or phenomena of interest, and some flexibility may arise from using adaptive mesh model grids or temporally-fixed but spatially-varying grids. While the need for convective parameterization will stay with us in the coming years, with increased computing power will come exciting research opportunities to investigate scale interactions involving convective processes and larger-scale phenomena. There will also be a greater ability to investigate fundamental processes using very high-resolution large eddy simulation models (LESs) and cloud-system resolving models (CRMs) covering an increasing range of scales. Increasingly high-resolution weather forecasts and hindcasts will be confronted with observations across a wide range of scales, leading to further insight into important physical processes and giving more hope of being able to answer questions such as ‘what will the weather be when climate changes?’

With the increased use of shorter grid lengths for regional modelling of weather and climate, some of the emphasis for physics parameterization development will shift from traditional convection schemes to other sub-grid parameterizations including those for micro-physics and turbulence. To support this, observations will need to target higher moments of the distributions of physical quantities as well as smaller-scale aspects of convection such as in-cloud vertical velocities, mass flux, entrainment, detrainment, and heating rates. However, as discussed, most global weather and climate forecasts will continue to use grid lengths of tens to hundreds of kilometres, and therefore a step change is still needed in our ability to understand and parameterize convection across these scales.

## Main findings

Discussions during the workshop identified several key challenges for the future:

- What is the best way to represent convection in the ‘deep convection grey zone’, i.e. at grid scales that are around the same order of magnitude as a typical deep convective cell? This challenge arises because conventional quasi-equilibrium ideas break down at these scales (and have significant deficiencies even at coarse grid scales).
- How do we significantly advance our ability to model phenomena that rely on interactions across a large range of scales, such as the Madden–Julian Oscillation (MJO), monsoons, extratropical and tropical cyclones, and extreme events, both in the current climate and in future climates?
- To what extent will realistic convective organization and scale interactions emerge simply by moving to models with higher resolution (and explicit convection), and to what extent do we need to parameterize aspects of organization?
- How do we reconcile potential tension between improving variability and improving the mean state (as discussed with regards to the MJO in Mapes and Neale, 2011 and Kim *et al.*, 2011)?

To address these challenges, we envisage the need to develop *physically based* convective parameterizations that are:

- scale-aware: adapting automatically to changes in grid length and in updraught area fraction;
- non-local: simulating realistic spatial and temporal structure, with representations of memory and interactions between grid points based on the intrinsic physical space and time scales of convective organization;
- non-equilibrium: with closures that take account of triggering mechanisms, particularly sub-cloud environment variability at both resolved and sub-grid scales (which will need to be better understood in observations and high-resolution process models); and
- stochastic: with the aim of the parameterization at one time step and grid point being to represent a single realization of convection taken from a probability density function (PDF) given the larger-scale conditions and history, rather than the mean of this PDF, such that the result should vary systematically with spatial and temporal resolution.

Progress on these goals will build on current innovative efforts in the larger convection community. Work has already begun on scale-aware parameterizations that allow explicit convection to do more of the work when the estimated fractional gridpoint area covered by updraughts is large (Arakawa and Wu, 2013). The Plant–Craig scheme (Plant and Craig, 2008) is also formulated in a scale-independent (and stochastic) manner. A convection scheme with a prognostic variable representing convective organization, and thus allowing for memory and spatial interactions, has been tested (Mapes and Neale, 2011), and non-local parameterizations were explored by Brown and Grant (1997) for boundary layers. A non-equilibrium convection scheme

using boundary layer energetics, based on downdraught properties, for both triggering and closure is being developed (e.g. Rio *et al.*, 2013). A global model using superparameterized convection, in which a 2-D CRM is embedded in each large-scale grid cell, has shown promising results (e.g. Khairoutdinov and Randall, 2001; Randall, 2013). Global CRMs are also beginning to increase our understanding of large-scale convectively coupled phenomena (e.g. Satoh *et al.*, 2012). Work on the effects of nondeterministic statistics of convection is helping to show the benefits of stochastic parameterizations, especially at higher resolution (e.g. Berner *et al.*, 2012; Peters *et al.*, 2013). Several of the parameterization features proposed above, including scale awareness and stochasticity, are recommended (or at least discussed as possible ways forward) in a chapter of a recent World Climate Research Programme volume on research, modelling, and prediction priorities (Sherwood *et al.*, 2013), highlighting agreement within the larger scientific community regarding these goals.

The meeting consensus was that mass-flux based convection parameterizations will continue to be useful in the foreseeable future over a range of model grid lengths, although the merits of other types of schemes, such as superparameterization, were also discussed. If the convection community does continue using mass-flux schemes, we will most probably need to separate total mass flux into updraught fraction and updraught velocity (required for aerosol-cloud interactions), and we should allow parameterizations to do proportionately less of the work as the updraught fraction becomes large. We note that this depends on the convective regime being parameterized, not just on the model grid size (see Arakawa and Wu, 2013).

In developing and evaluating new parameterizations, the convection community can make use of new simulations that represent macroscale convective dynamics (triggering, updraughts, downdraughts, and cold pools) in domains that capture large-scale circulations such as monsoons. Results from the *Cascade* project (e.g. Marsham *et al.*, 2013) have shown the power of these simulations in describing interactions between convection and dynamics that could not previously be observed or modelled. Global convection-permitting simulations are now becoming possible. In the coming years we will make increasing use of such simulations to connect process studies (observations and LES models) with global dynamics and the parameterization problem.

High-resolution models (with order 1 km grid length or smaller) remain a key tool for supporting parameterization development (e.g. Kendon *et al.*, 2012) and there is still a need for a comprehensive evaluation of the resolution dependence of simulations with these models for a range of environments and phenomena. This includes an evaluation of the appropriateness of current sub-grid parameterizations (such as turbulence and microphysics schemes) at different resolutions as well as the sensitivity of CRM and LES behaviour to changes in these parameterizations [e.g. recent work in the UK Dynamical and Microphysical Evolution of Convective

Storms (DYMECS) project, Hanley *et al.*, 2014]. For instance, work should further investigate whether or not increased microphysical complexity (e.g. aerosol-cloud interactions) is beneficial at high resolution for the convection problem.

Convective-scale observations will be needed to evaluate and develop LESs and CRMs. The new observations will require improved instrument capability and should include measurements of in-cloud quantities such as vertical velocity, mass flux, temperature, entrainment rate, detrainment rate, and heating rate. Higher moments (variability) of in-cloud and environmental properties will also need to be measured, along with surface properties over land (such as vegetation and soil moisture). More detailed measurements of rainfall (especially over orography) and cloud structures will be essential. Some new instruments that should be prioritized in the UK to achieve these aims include airborne and ground Doppler lidar, a second mobile radar (in addition to the current mobile Doppler radar maintained by the Facility for Ground-based Atmospheric Measurements), an aerosonde network, and a UK 'supersite' incorporating a suite of surface and atmospheric observations (see specific recommendations below for details).

### Specific recommendations and conclusions

To develop the new parameterization methods envisaged above, dedicated resourcing for the parameterization development work is essential (item 4 below). New data sources from observations (item 1) and LES (item 2), together with new methods for analyzing such data and assessing the emerging parameterization (item 3) provide the necessary underpinning. The specific recommendations below (summarized in Figure 1) are complementary and are not written in any priority order:

1. Develop a UK observational fixed-location supersite and/or a mobile supersite to place in regions important for furthering our understanding of convective processes, or places where we need to address model biases. A fixed supersite would provide long-term records of key environmental data related to convection, and during Intensive Observing Periods (IOPs) provide high-resolution observations of convective processes at the sub-cloud scale. A mobile supersite would be extremely useful in field campaigns, especially when combined with high-resolution modelling over the same region and time period. Supersites would include state-of-the-art scanning cloud and precipitation radar, lidar, radiometers, wind profilers, and aerosol observing systems, along with regular radiosondes and an array of instruments to measure surface conditions. The success of the US-funded Atmospheric Radiation Measurement (ARM) Programme provides evidence that both fixed and mobile supersites can greatly facilitate scientific progress (Long *et al.*, 2013).



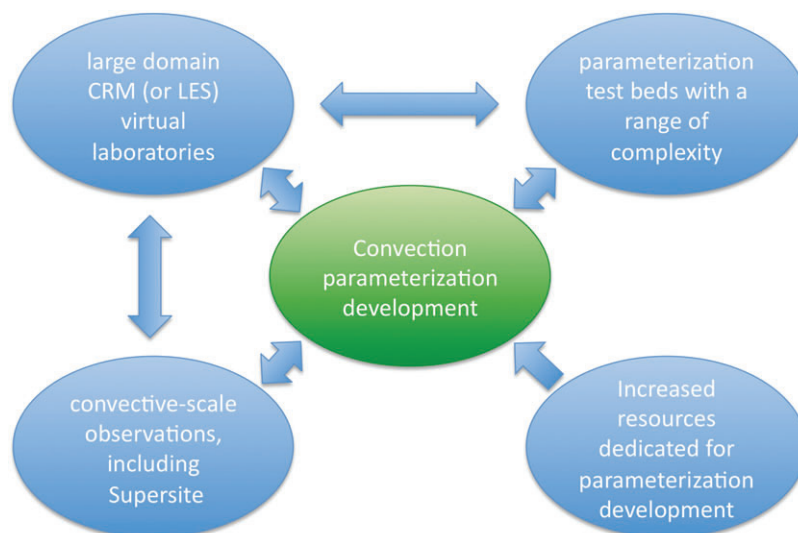
2. Invest significant high-performance computing in pursuing an LES ‘virtual laboratory’ approach with small horizontal grid lengths (order 10–100 m) combined with large domain sizes (order 100–1000 km), allowing important scale interactions. The LES virtual laboratory will provide sub-cloud process information (e.g. entrainment, detrainment, and in-cloud vertical velocities) and be evaluated by convective-scale observations described in (1) in order to make sure that the LESs can accurately simulate these processes. This is somewhat analogous to a much higher-resolution version of the UK *Cascade* project, which used limited-area simulations at CRM grid lengths (1.5–12 km) of tropical domains several thousand kilometres across to study convective interactions with larger-scale phenomena such as the West African Monsoon (Marsham *et al.*, 2013), the MJO (Holloway *et al.*, 2013), and the diurnal cycle of precipitation in the Maritime Continent (Love *et al.*, 2011). This virtual lab will allow us to observe and model cloud-scale dynamics over large domains and a large portion of convective regime parameter space. The simulations then provide a means of comparing coarser-resolution model simulations [CRMs and general circulation models (GCMs)], observations, higher-resolution process models, and theories of convective coupling. CRMs will need to be tested against this virtual lab, and different resolutions of LESs and CRMs should be rigorously tested for fidelity to observations and for convergence so that resolution dependence is better understood. The model output will require considerable planning and management to ensure that data is saved in the most condensed and accessible format as possible while providing the necessary richness of information (e.g. by making grid-scale, high-temporal-resolution calculations of important process terms on-line and saving them as coarser spatial and temporal averages).
3. Develop a new model ‘test bed’ for understanding the interaction of convective parameterizations with the larger-scale environment, allowing further focus on more process-based model evaluation. The test bed would consist of a hierarchy of model configurations for parameterization development by building on existing models with various degrees of complexity, from single column models and idealized 3-D simulations through to implementation in the full GCM. These should include large-domain simulations of idealized cases and realistic case studies using both explicit convection and convection parameterized at the desired operational resolution. The focus will be on systematic integration with GCM testing, and on understanding the relationships between parameterized processes and emergent phenomena (including non-local interactions), e.g. through weak-temperature-gradient or other new methodologies. For instance, a new

parameterization could be tested in a regional model hindcast mode, an aquaplanet mode, a single column model coupled via weak-temperature-gradient tendencies to a reference profile, etc. Although these types of model framework are not new, they should be integrated into the GCM parameterization testing process in a more systematic way.

4. Provide increased resources for model parameterization development. The meeting participants noted that it is often difficult to get funding for activities most closely related to model development and implementing new and changed parameterizations, and yet these activities are critical for major progress in weather and climate science as well as many aspects of Earth-system science (e.g. Stevens and Bony, 2013). The meeting attendees therefore concluded that there should be increased resources for improving and developing new convective parameterizations in order to maximise the positive impact of the new ideas developed from convective-scale observations, virtual laboratory experiments, the hierarchy of model frameworks, and process-based (and phenomena-based) model evaluation as described above in (1)–(3).

These recommendations are not meant to be exclusive or rigidly separate from each other. For instance, the UK fixed/mobile supersite is one approach towards convective-scale observations, but an aerosonde network, Doppler radar, and field campaigns are other approaches to increased observations that can complement the proposals above. The LES virtual laboratory approach will need to be tailored to the specific phenomena of interest, ideally showing very high simulation skill and convergence at the control resolution before testing at coarser resolutions and/or larger domains. LESs and CRMs will also be used for some of the idealized 3-D test beds in (3), and the parameterization development listed there includes all parameterizations (such as turbulence, radiation, and microphysics), not just convection parameterization. Finally, the increased resources for convective parameterization development that are recommended in (4) will provide the increased human skill and time (and computational support) needed to utilize all of the additional observations, simulations, and conceptual understanding and do the hard work of developing improved representations of convection.

In addition to insufficient allocated funding, there are also structural issues in the convection community that probably impede parameterization development. For instance, PhD students lack incentives to take on potentially risky model development work, modelling centres face short-term deadlines for useable new model versions and therefore tend to favour small incremental changes that do not require much tuning or modification of other model components, and academics in university departments are not always involved with model development work at modelling centres. While collaboration between modelling centres and the academic community is vital in order to bring together a wide



**Figure 1.** Recommendations for methods to improve understanding of convection and aid in development of better subgrid parameterizations.

range of expertise, academics in universities often rely on grants lasting only a few years, which is not enough time to see fundamentally new parameterizations developed from the underpinning science through to fully implemented schemes (see Jakob, 2010 for discussion of these points and possible solutions).

We acknowledge that there are significant resource implications from the range of suggestions above, and the workshop participants did not specifically address potential means of securing this coordinated funding. However, it is hoped that this report can be used by various weather and climate organizations as they plan for the future. Within the UK, programmes such as the Joint Weather and Climate Research Programme (JWCRP) and the Met Office Academic Partnership (MOAP) can provide a framework for developing and coordinating such planning as part of a strategic research partnership between universities and modelling centres.

The Dartington meeting in January 2013 brought together a range of atmospheric convection specialists with different perspectives on this critical problem, including observationalists, theoreticians, and modellers. In this meeting, and subsequent meetings throughout 2013, there was a positive engagement between these groups and strong optimism for rapid progress in the coming years, in part built on the fact that we now have modelling frameworks that can link across the scales separating convective processes and global dynamics. With these modelling tools, there is a tremendous opportunity to make significant improvements in convective parameterizations over the next 5–10 years, with associated improvements in global weather and climate predictions.

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### References

- Arakawa A, Wu C-M. 2013. A unified representation of deep moist convection in numerical modeling of the atmosphere. Part I. *Journal of the Atmospheric Sciences* **70**: 1977–1992, DOI: 10.1175/JAS-D-12-0330.1.
- Berner J, Jung T, Palmer TN. 2012. Systematic model error: the impact of increased horizontal resolution versus improved stochastic and deterministic parameterizations. *Journal of Climate* **25**: 4946–4962.
- Brown AR, Grant ALM. 1997. Non-local mixing of momentum in the convective boundary layer. *Boundary-Layer Meteorology* **84**: 1–22.
- Hanley KE, Plant RS, Stein THM, Hogan RJ, Nicol JC, Lean HW, Halliwell C, Clark PA. 2014. Mixing length controls on high resolution simulations of convective storms. *Quarterly Journal of the Royal Meteorological Society*, DOI: 10.1002/qj.2356.
- Holloway CE, Woolnough SJ, Lister GMS. 2013. The effects of explicit versus parameterized convection on the MJO in a large-domain high-resolution tropical case study. Part I: characterization of large-scale organization and propagation. *Journal of the Atmospheric Sciences* **70**: 1342–1369.
- Jakob C. 2010. Accelerating progress in global atmospheric model development through improved parametrizations – challenges, opportunities and strategies. *Bulletin of the American Meteorological Society* **91**: 869–875.
- Kendon EJ, Roberts NM, Senior CA, Roberts MJ. 2012. Realism of rainfall in a very high-resolution regional climate model. *Journal of Climate* **25**: 5791–5806.
- Khairoutdinov MF, Randall DA. 2001. A cloud resolving model as a cloud parameterization in the NCAR Community Climate System Model: preliminary results. *Geophysical Research Letters* **28**: 3617–3620.
- Kim D, Sobel AH, Maloney ED, Frierson DMW, Kang I-S. 2011. A systematic relationship between intraseasonal variability and mean state bias in AGCM simulations. *Journal of Climate* **24**: 5506–5520.

- Lin Y, Donner LJ, Petch J, Bechtold P, Boyle J, Klein SA, Komori T, Wapler K, Willett M, Xie X, Zhao M, Xie S, McFarlane SA, Schumacher C. 2012. TWP-ICE global atmospheric model intercomparison: convection responsiveness and resolution impact. *Journal of Geophysical Research* **117**: D09111, DOI: 10.1029/2011JD017018.
- Long CN, McFarlane SA, Del Genio A, Minnis P, Ackerman TP, Mather J, Comstock J, Mace GG, Jensen M, Jakob C. 2013. ARM research in the equatorial western Pacific: a decade and counting. *Bulletin of the American Meteorological Society* **94**: 695–708, DOI: 10.1175/BAMS-D-11-00137.1.
- Love BS, Matthews AJ, Lister GMS. 2011. The diurnal cycle of precipitation over the Maritime Continent in a high-resolution atmospheric model. *Quarterly Journal of the Royal Meteorological Society* **137**: 934–947.
- Mapes BE, Neale RB. 2011. Parameterizing convective organization to escape the entrainment dilemma. *Journal of Advances in Modeling Earth Systems* **3**: 20, DOI: 10.1029/2011MS000042.
- Marshall JH, Dixon N, Garcia-Carreras L, Lister GMS, Parker DJ, Knippertz P, Birch C. 2013. The role of moist convection in the West African monsoon system: insights from continental-scale convection-permitting simulations. *Geophysical Research Letters* **40**: 1843–1849, DOI: 10.1002/grl.50347.
- Peters K, Jakob C, Davies L, Khouider B, Majda AJ. 2013. Stochastic behavior of tropical convection in observations and a multicloud model. *Journal of the Atmospheric Sciences* **70**: 3556–3575.
- Plant RS, Craig GC. 2008. A stochastic parameterization for deep convection based on equilibrium statistics. *Journal of the Atmospheric Sciences* **65**: 87–105.
- Randall DA. 2013. Beyond deadlock. *Geophysical Research Letters* **40**: 5970–5976, DOI: 10.1002/2013GL057998.
- Rio C, Grandpeix J-Y, Hourdin F, Guichard F, Couvreux F, Lafore J-P, Fridlind A, Mrowiec A, Roehrig R, Rochetin N, Lefebvre M-P, Idelkadi A. 2013. Control of deep convection by sub-cloud lifting processes: the ALP closure in the LMDZ5B general circulation model. *Climate Dynamics* **40**: 2271–2292.
- Satoh M, Oouchi K, Nasuno T, Taniguchi H, Yamada Y, Tomita H, Kodama C, Kinter J, Achuthavarier D, Manganello J, Cash B, Jung T, Palmer T, Wedi N. 2012. The intra-seasonal oscillation and its control of tropical cyclones simulated by high-resolution global atmospheric models. *Climate Dynamics* **39**: 2185–2206.
- Sherwood SC, Alexander MJ, Brown AR, McFarlane NA, Gerber EP, Feingold G, Scaife AA, Grabowski WW. 2013. Climate processes: clouds, aerosols and dynamics. In *Climate Science for Serving Society: Research, Modelling and Prediction Priorities*, Asrar GR, Hurrell JW (eds). Springer: Dordrecht, Netherlands; Heidelberg, Germany; New York, NY and London; 73–103.
- Sherwood SC, Bony S, Dufresne J-L. 2014. Spread in model climate sensitivity traced to atmospheric convective mixing. *Nature* **505**: 37–42, DOI: 10.1038/nature12829.
- Stevens B, Bony S. 2013. Climate change. What are climate models missing? *Science* **340**(6136): 1053–1054, DOI: 10.1126/science.1237554.