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Strategy for further improvements to boundary layer cloud and temperature forecasts

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1. Introduction

Boundary layer cloud and fog are very important forecast products, both because of their direct importance, and also because of their very large impact on near-surface and surface temperatures which are crucial for many customers. However, whilst the motivation to continue to improve forecasts of these boundary layer quantities is clear, the problem is very challenging scientifically. The paper will present our strategy for moving forwards, with a particular focus on the cloud problem.

2. Key areas of work

Five key areas of work have been identified. These are:

- Vertical resolution
- Model physics and evaluation
- Ensembles and post-processing
- Data assimilation
- Observations (including satellite derived cloud products)

Separate sections follow, detailing and explaining our motivation and priorities for work in each of these areas.

All of the detailed deliverables and milestones are available in the research plan. As much of the work is spread across a number of different research themes, the introduction to the plan now contains a short section (consistent with previous MOSAC advice) identifying the work relevant to boundary layer cloud. This is done under the same headings as used here.

2.1 Vertical resolution

We will prioritize work to assess the benefits of increasing the vertical resolution of our models, in view of the potential to improve the representation of boundary layer structure

The UK4 model was upgraded from 38 to 70 levels in Dec 2007. The project to achieve this went very smoothly, and cloud and temperature results were improved both objectively and subjectively (as reported to MOSAC last year). The temperature improvements were believed to result from a combination of better cloud, and better resolution of temperature structure of the stable boundary layer. Subjective routine monitoring has also strongly suggested that the upgraded UK4 has been outperforming the NAE in terms of its ability to predict the locations of patchy stratocumulus in anticyclonic conditions.

Recent work has looked at effects of upgrading the global and NAE models to 70 levels (although it should be noted that, due to the higher model top in these models, this still does not give as high boundary layer resolution as is used in UK4 and UKV). Although the NAE results are broadly neutral overall as measured by the NWP index, there have been some encouraging results with respect to cloud performance in blocked conditions. Examples are given in Figures 1 and 2.
All of the above indicates that, even without major changes to data assimilation or physics, substantial benefits in the representation of the boundary layer cloud (and boundary layer structure more generally) have been achieved through increasing the vertical resolution of our models. However, the grid spacing is still not particularly fine (~160m at 1000m in the global and NAE models; ~110m at the same height in the UK models), and it seems entirely plausible that further improvements in stratocumulus performance could be gained through further increases in resolution. Although an upgrade to O(100) vertical levels is unlikely to be affordable operationally until at least the mid-life upgrade of the supercomputer, we will prioritize work now to assess the benefits of such an increase (for the UKV) in order to inform decisions as to what is the most cost-effective use of the increased computer power (e.g. resolution / data assimilation upgrades (e.g. 4D-Var) / number of ensemble members).

Our physics plans also contain a new commitment to start longer term investigations of the potential benefits of significantly higher vertical resolution still. It is possible that in order to realize any benefits, some significant development may be needed (e.g. improved numerics and removal of jump assumptions). Initial testing is likely to be in the context of comparisons with case studies from Cardington and the COLPEX experiments (see 2.2). Additionally we will start to routinely test new physics schemes in the single column model at a variety of different vertical resolutions. Separately from any potential move to use much higher resolution, this will in any event be a good discipline to avoid any explicit resolution dependencies being introduced.

2.2 Model physics and evaluation

We will continue to take advantage of the seamless framework of the Unified Model, noting, for example, that climate and global NWP tests can both provide valuable insights into the performance of cloud modelling that are relevant for UK forecasting. However, we will continue to focus additional effort on understanding and alleviating problems directly of relevance for UK forecasting.

One of the original motivations for the development of our boundary layer scheme, including non-local turbulent mixing and an explicit entrainment parametrization, was to improve our ability to simulate stratocumulus. International comparisons (e.g. of single column models against large-eddy simulation (LES) data as organized by GCSS, or of climate models under AMIP) have suggested that we had significant success in that respect, and many other modelling centres have been moving to schemes similar to ours. This encourages us in our belief that the scheme is fundamentally sound, both for global and convective scale NWP and our basic strategy is to remain with it (although we will in 2010 report on an investigation of the potential benefits, particularly for the high resolution models, of using a TKE-based scheme).

For the cloud scheme, the climate model has already moved to use the PC2 scheme (which removes an overly strong link between cloud water and cloud area). We aim to move to this scheme for the global and NAE NWP models within the next year and by 2011 to review its suitability for the UKV.

Within the broad framework described above, there is however no doubt that the devil lies in the detail, and that developments to or tunings of various aspects of
these schemes (and others such as microphysics and land surface) have the potential to significantly impact on the quality of our cloud and temperature forecasts.

A key strand of our strategy is therefore continual evaluation of where we are now in terms of quality of forecasts and evidence for areas of the physics that could be improved. The first part of this involves routine monitoring of the operational models – particularly necessary at the moment with the advent of a new model, in the UKV, and the potential for the NAE to have different characteristics following the resolution upgrade. Feedback from the NWP problems group is valuable here. Additionally boundary layer research staff have for the last few years maintained a log (e.g. Figure 3) of notable successes and failures of the various models with respect to cloud performance (particularly in anticyclonic conditions). This has proved valuable and will be continued. Secondly, we require detailed research quality measurements (or other aids such as theory or high resolution large-eddy simulations) to help us understand in more detail the cause of errors and ways to alleviate them. Very often this work entails a collaborative approach with the UK academic or international research communities.

Current foci include exploitation of results from the international VOCALS field campaign (with a particular interest in the sensitivity of stratocumulus to microphysical parameters) and comparisons between the single column version of the UM, LES and fog measurements from Cardington. The COLPEX campaign (joint with NCAS), which has extensively instrumented a region of complex terrain in Shropshire, is now providing data – both routine, which will provide a long climatology, and with extra Intensive Observing Periods. This will be used to improve our downscaling techniques, noting that dramatic variations in temperature (and visibility) can occur due to surface variations that are unresolved even in the UKV model. We are also extremely pleased that the experimental work will be complemented by high resolution (100m) UM simulations which will be performed collaboratively with NCAS on the joint supercomputer. These will both aid the interpretation of the data, and provide a focus for model evaluation and improvement.

Looking slightly further ahead, we are beginning to plan a further experiment on the evolution of stratocumulus over the UK for 2011. This is likely to involve ground-based instrumentation (at Cardington and hopefully elsewhere) supplemented by a number of flights of the BAE146, and detailed UM studies.

Other physics work relevant in the context of improving cloud forecasts includes ongoing evaluation of the model surface energy balance and offline assessment of the JULES land surface scheme, developments in stochastic physics (paper 14.5 and discussed in this report in section 2.3 in the context of optimizing cloud spread in the ensemble system), and developments in our representation of aerosols (paper 14.11).

2.3 Ensemble prediction and post-processing

We will provide improved guidance and products through an increased focus on the performance of ensemble prediction systems with respect to boundary layer cloud and temperature. Our post-processing systems will be designed to allow us to make best use of the available data and maximize its value to the customer.
Ensemble systems have a key role in our future strategy for improving the quality of cloud and temperature-related products. In many cases the end state which we should work towards will be truly probabilistic products. However in the medium term at least there is likely to continue to be a demand for a ‘most likely’ scenario, and the forecasting review envisages using selection of an alternative model solution (e.g. from one of the ensemble members) as an effective way of intervening when the deterministic model is judged to be seriously in error. Either of these approaches (and also the possible use of the ensemble system to provide errors of the day for data assimilation) require the ensemble system to perform well for cloud (e.g. showing an appropriate level of spread between members, rather than, for example, all tending to show the same errors). We therefore plan to increase the focus on evaluation of ensemble performance with respect to cloud and temperature, particularly in the difficult but important blocked situations.

Even without full quantitative verification of the current performance, there are indications that the model is under-spread for cloud in anticyclonic conditions. In many ways this would be unsurprising as the parameters targeted in the stochastic physics are not those that would be expected to impact most directly on boundary layer cloud. Accordingly, within our overall strategy for stochastic physics development, we will also in the short-term give specific consideration to modifications to the current random parameters scheme to optimize spread in boundary-layer cloud and near surface temperature. Developments will be tested in MOGREPS with a view to implementation in winter 2010/11.

We are also working to improve (and start to bring together) the post-processing of our ensemble and deterministic systems. The first version of a new KFMOS post-processing scheme which includes a weather-dependency has been completed, and work will continue to take full advantage of the potential benefits (e.g. by introducing more parameters). Note however, that while this can be expected to improve overall scores for temperature, it is unlikely to be able to deal effectively (at least in a deterministic sense) with temperature errors caused by misplaced patches of stratocumulus where the errors are essentially random and vary from day to day.

2.4 Data assimilation

Promising avenues for improving the ability of the data assimilation system to deal with the sharp vertical structures at the top of the stratocumulus clouds will be pursued. A particular focus will be on covariance model developments (which are relevant for both 3D-Var and 4D-Var).

Dealing with the sharp structures at the top of the stratocumulus-topped boundary layer is challenging for a data assimilation system, and a common complaint of the forecasters concerns mismatches between the model cloud and reality at T+0. Certainly these discrepancies are not all down to failures of the data assimilation system. For example Section 2.1 showed how simply improving the vertical resolution gives benefits, and the top panel of Figure 4 shows an example of the T+0 profiles with 70 levels showing a strong inversion in good agreement with the observations at Lerwick. However, the Castor Bay (Northern Ireland) comparison from the same case is much less impressive, and any developments which enabled the assimilation system to better cope with stratocumulus would clearly be highly desirable.

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Encouragingly there are a number of well-advanced developments which offer the prospect of progress, and a primary focus of research work activity is to provide a package of improvements focussed on stratocumulus (March 2011 deliverable). These improvements will be implementable within a 3D-Var framework (as used for UKV) but are believed to still be highly relevant for 4D-Var. Likely candidates include the use of the new humidity control variable (which has better behaviour near saturation), and covariance developments e.g. use of adaptive vertical mesh (see Figure 5), and use of new boundary layer control variable. Outputs from this activity will be fed to operational implementation projects.

Another avenue of some promise is the inclusion of outer loops in 4D-Var, which may be expected to help cloud due to improved handling of non-linearity. Indeed early tests in the NAE showed promising results. However, the cost of implementation would be substantial (even in the global and NAE models which already have 4D-Var), and going forward will require careful cost-benefit analysis and very probably further code optimizations.

Further ahead, the focus moves to 4D-Var for the UKV, and developments under the coupled variational / ensemble data assimilation activity. Here there are thought to be potential benefits of using errors of the day to get different vertical structures (e.g. sharper in the presence of stratocumulus). The relationship between this work and earlier work on adaptive vertical grids will need to be thought through carefully (as to some extent they may be different ways of achieving the same thing). It is believed that the other developments described above would remain relevant in any future hybrid system.

2.5 Observations

Increased effort will be put to improving satellite-derived cloud products and their use in NWP. We will also continue to engage with the FUND (Future Upper-air Network Design) project regarding the potential use of new observations.

We have increased effort on the use of satellite derived cloud information, in all of our models. Our strategy is to take a twin-track approach, keeping open the possibilities both of assimilating SEVIRI radiances directly, and continuing to go via intermediate retrieved cloud products. Further thought is being given as to how to combine new implementations of satellite-derived cloud information with existing ground-based observations.

In terms of new observations, we are closely engaged with the FUND project, with work in the short-range integrated analysis and forecasting theme linking a trial SE England 4D-Var configuration with the FUND demonstration network (see paper 14.6). However, expansion of this network to provide national coverage would appear to be many years away at best. Accordingly some work is currently ongoing in the Observations programme assessing the extent to which more information can be extracted from the existing network of laser ceilometers located at AWS sites. Another welcome development has been the agreement of Easyjet to equip their entire Airbus fleet (over 100 aircraft) to provide AMDARS. This will provide profiles from an extra 12 regional airports from which we currently do not get any AMDAR profiles. Through the EUMETNET programme we are also looking at the potential to obtain humidity measurements from aircraft.
Figure 1: Low cloud analysis for 00Z 25/12/08. Left: NAE 38 levels; middle: NAE 70 levels; right: difference (70 levels minus 38 levels). In reality most of England was covered by low cloud. This is significantly lacking in the 38 level run, and forecaster comments from this date noted 'Fields modified again to increase cloud cover in a major way'. The L70 solution is a significant improvement.
Figure 2: Timeseries of mean (top) and root mean square (bottom) error in cloud cover over the UK from the 38 level NAE (red) and the 70 level trial (blue). The timeseries run from 0Z on 23/12/2008 to 12Z on 30/12/2008. Note the particularly significant improvements in the blocked period from around 23rd to the 26th. A corresponding improvement in temperature scores for this period was also seen (not shown).
Monitoring of BL performance for Winter 09-10

This page is to collate examples of model successes and failures in forecasting near surface temperatures, low cloud and fog over the UK in Autumn/Winter 2009/10. This page follows on from the logs for Winter 07-08 and Winter 08-09.

More detailed discussion of loggy cases can be found here.

Summary of Issues arising so far

- L70 NAE in PS22 giving much better low cloud forecasts than operational L38, as expected.

Shortcuts to cases

- **17th August**: Interesting stratocumulus structure in the UKY
- **30th September**: Much improved stratocumulus in the NAE with PS22 (L70)
- **1st October**: Excessive cumulus cloud cover in UK
- **4th October**: Better cloud cover in PS22 NAE

Cases

- **17th August**
  - All this time the UKY was running in forecast only mode from NAE interpolated start dumps. This series of **UKY cloud evolution** figures shows the Initially homogenous cloud sheet over the SW approaches and Channel develop realistic looking mesoscale (10s of km) structures that appear to be triggered by regions of locally heavier precip. Although the magnitude of the precip appears too strong, similar precip structure can also be seen in the model.
  - **30th September**: There has been a period of prolonged anticyclonic weather with extensive low cloud and some fog from mid-September which is coincident with the running of PS22 – L70 in the NAE and global models.
  - On this day, forecaster guidance says: "The model cloud enveolopes looks a good fit at front hand but there is still a marked deficiency south of it in central and SE England."
  - This can be seen in the operational NAE cloud cover (LHS) at 002 at T12 and to a lesser extent at T42. The L70 PS22 forecasts (RHS) are much better, as expected from the enhanced vertical resolution.
  - The 00 forecast from interpolated NAE and parallel Tier DA suite **UKY** forecasts are similar to each other but with slightly more cloud in the parallel (DA) suite.
  - **Topography** from the operational NAE and UK4 for Camborne (LHS) show both the model's inceptions are very low, and that the analysis raises it towards the observed. The UK4 may be influenced by its L30s from the NAE. At Hereford (RHS) the inversion height is better, especially in the UK4, while the NAE analysis makes significant improvements. Profiles from NAE PS22 are not easily available but would be interesting to see if its improved cloud cover was associated with an improved inversion height.
  - The above subjective impression that L70 NAE is giving improved cloud forecasts is backed up by the **objective verification** too.
- **1st October**
  - Both operational (ie forecast only) and PS22 (ie DA cycling) GFS UKY forecasts generated excessive **cloud cover** over the southern UK today in what should have been more scattered cumulus.
- **4th October**
  - PS22 (ie L70) NAE forecast of **cloud cover** significantly better than operational (L38), especially over the SW England.

Figure 3: Log of cloud issues maintained by boundary layer research staff. The links (not available in this report) provide more detailed information on each case.
Figure 4: T+0 tephigrams at 00Z on 25/12/2008 for Lerwick (top) and Castor Bay (bottom). Red: 38 level NAE; green: 70 level trial. At Lerwick there is evidence of the 70 level inversion being both higher and sharper, such that the profiles are in good agreement with the sonde. However, at Castor Bay, while the 70 level inversion is again rather sharper, the analysis has still clearly failed to match the sonde profile.
Figure 5: Illustration (courtesy of Chiara Piccolo) in a single observation test of the impact of using an adaptive mesh. In this test, a single observation was placed just above a model inversion. In the control (top), the background covariance matrix spreads the information from that observation in all directions. In the adaptive mesh case, a monitor function based on local potential temperature gradient is used to control the transform from the analysis grid to the physical grid. The net result is that the spreading of information down below the inversion is much reduced.