Development of a Microscale Model as a Research Tool for the UWERN Community

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1. Summary

A new microscale atmospheric modelling system for scales from building scales (∼10m) to tens of kilometres will be developed for use by the UWERN research community. The project will begin by undertaking a thorough review of existing models and the extent to which they meet and/or fall short of the requirements of the UWERN science programme. The new modelling system will then be built, drawing on the best features of existing models and adding new features as required. Within the remaining 4.5 years of the UWERN programme, the new model will be used to address some of UWERN's research objectives in the areas of orographic flows and boundary-layer turbulence. By the end of the 4.5 years, a wide range of applications will be using the model.

2. Background

The Universities Weather Research Network (UWERN) is a group of UK university departments (led by Reading, Leeds, UMIST, Aberystwyth, Salford, Essex and Surrey) working in close collaboration with each other and with providers and users of regional and local weather services. UWERN aims to harness expertise from within UK Universities, and exploit facilities within Universities, Research Institutes and the Meteorological Office to advance the knowledge, understanding and prediction of atmospheric behaviour on regional and smaller scales. The UWERN research programme aims both to improve understanding of Weather phenomena and small-scale processes in their own right (because of their practical importance, for example in hazard mitigation, flooding prediction, urban pollution, etc.) and to improve understanding of their large-scale effects (because, for example, these processes need to be parametrized in numerical weather prediction and climate models).

UWERN has a broad research programme encompassing theoretical and numerical modelling underpinned by a comprehensive observational programme. The latter has recently been strongly enhanced by the creation within UWERN of the Universities Facilities for Atmospheric Measurements (UFAM) — a distributed observational facility including radar, lidar, sodar, radiosonde, aircraft and tethersonde facilities. UFAM has recently obtained funding of £5M from Joint Infrastructure Fund to create this distributed network.

UWERN is broadly organised into five sections, dealing with boundary-layer meteorology, convective clouds, cyclonic storms, orographic processes and regional atmospheric transport. Current research priorities within these areas include dispersion in urban environments, boundary-layer entrainment and troposphere/boundary-layer exchange, gravity-wave processes, cloud-resolving modelling, tropopause exchanges and quantitative precipitation modelling. Each of the five UWERN sections makes extensive use of numerical models. Some of these are widely used models such as the UK Meteorological Office Unified Model (UM) and the Meteorological Office LES model (LEM). Others, such as NH3D (used in Reading and Leeds for orographic research), BLASIUS (an orographic flow model written at the Meteorological Office and also used at Reading and Leeds), the Clark Mesoscale Model (used at UMIST) and 3DVOM (used for gravity-wave forecasting at Leeds) are more specialised. This proposal aims to enhance the UWERN cooperative modelling programme by bringing together the combined modelling expertise in the creation of a new modelling system aimed at scales ranging from a few metres up to tens of kilometres. The approach will be flexible; there is no *a priori* assumption that a new modelling system needs to be written from scratch. Instead, the project will bring together the best available knowledge and practice in a modular system aimed principally *at meeting UWERN's modelling requirements.* In addition to the creation of a state-of-the-art modelling system, a further considerable benefit for the research aims of UWERN will be the bringing together in a coordinated way the combined modelling expertise of the UWERN members.

3. Justification and Rationale

As explained above, UWERN has an extensive numerical modelling programme but lacks coordinated model support or development. The proposed project may be thought of as principally initiating this coordination, rather than simply aiming to create a new model. It will review extensively the UWERN research user requirements, the existing models (both within and outside UWERN) and the current best modelling practice. Out of this review will emerge a set of modelling system specifications which will be used to create the new modelling system. This will undoubtedly be a combination of the best features of existing models and new model developments.

The scientific motivation for this initiative is extensive and diverse, but includes:

1. The UK currently has no community mesoscale or boundary-layer model but makes extensive use of the UM and LEM. These are not supported or maintained by the UWERN community and are not, by necessity, aimed principally at meeting UWERN's research objectives.
2. The UM has no LES capability, is primarily designed for mesoscale and larger scales and current plans will not extend it down to the scale of tens of metres where many of the physical processes of interest to UWERN act (e.g. cloud microphysical processes).
3. The LEM has no orographic capability.
4. Large Eddy Modelling will not be possible on regional scales (upwards of several kilometres) for the foreseeable future. Thus there is a need to extend current capability to allow LES models to assimilate data from larger scale models, or alternatively, to allow some form of variable mesh spacing or nesting. This will facilitate simultaneous turbulence resolution and unsteady large-scale forcing, and therefore allow resolution of clouds and turbulence at small scales and regional weather systems at larger scales.
5. The science objectives of UWERN will best be met by close coordination between these objectives and ongoing model development. Thus, whilst there is a very considerable overhead in maintaining a community research model, we believe that there will be profound medium and long term advantages for the research which would not be realised by continuing to use models which are primarily designed for other purposes.
6. By focusing a considerable proportion of UWERN's numerical modelling effort on one community model, interaction within the community will be considerably enhanced, with benefits not only for numerical model development but also for the research more generally.
7. UWERN benefits from strong collaborations with the UK Meteorological Office, greatly enhancing its access to numerical modelling expertise and thereby improving the viability of a coordinated numerical modelling strategy.
8. It is also envisaged that as a UWERN member and collaborator on this project, the Met Office will have access, as required, to any developments and improvements which may benefit their models, specifically the Met Office LEM and BLASIUS. In particular the testing of any appropriate pressure solvers within BLASIUS would be of interest.

4. Objectives of the Project During Current UWERN Programme

The objectives of this numerical modelling initiative during the remaining 4.5 years of the current UWERN research programme are, in broad terms:

1. To carry out a thorough review of the numerical model requirements of the UWERN research programme, focusing in particular on identifying the best available numerical modelling practices (irrespective of whether they are currently available within models used by UWERN) for the specific UWERN research projects. Particular issues of great importance are conservation (particularly for the emerging problems in chemical transport), variable resolution or nesting, representation of steep and complex orography and turbulence resolution/closure. *This review is a crucial feature of the current proposal. Although we do have* a priori *preferences for the model design, we believe that many long-term benefits from the model will follow from careful planning at the design stage, involving the whole UWERN research community.*
2. To build, either from existing published knowledge or by adapting a currently available model, a core dry dynamics/thermodynamics code which can be used immediately to address some of the research objectives of UWERN in the areas of orographic flow and boundary-layer turbulence. Whilst this code will in the early stages be restrictive in its range of applications, it will be modular and flexible in design, maximising the potential for development both within the currently proposed project period and beyond.
3. To draw on physical and chemical modelling expertise within and outside the UWERN community to develop the core model outlined above to create a comprehensive microscale modelling system for scales from building scale ($\sim$ 10 m) to regional scales ($\sim$ 10s of km). Early priorities will be the incorporation of moist processes (water vapour, clouds, precipitation), tracer transport and surface exchange processes, the ordering of which will be governed by the science priorities.
4. To develop the modelling system, through comprehensive documentation and a research-orientated design, in a manner which allows extensive and straightforward user control. It should be possible for UWERN researchers to adapt the models for their particular needs and in particular, know exactly what is included in a particular model set-up and what is not included.
5. To coordinate an ongoing exchange of ideas concerning numerical modelling within the UWERN community, both as a means of maximising the utility and quality of the new modelling system and also assist in the individual numerical modelling activities. A key part of this coordination will be twice-yearly workshops bringing together interested parties from within and outside the UWERN community.

5. Methodology and Approach

This proposal does not aim to be prescriptive about the eventual design of the modelling system. Two key features are:

a. Flexibility. The modelling system will aim to have maximum user control in order to meet diverse research requirements.
b. A thorough review of both the needs of the researchers and the best available current practice.

The issues to be addressed during the course of the review will include:

1. The equation set. A version of the anelastic equations seems most likely, but will be thoroughly reviewed, bearing in mind in particular the fundamental conservation properties of the equations. The issue of which thermodynamic variables to carry will need to take account of the possible range of microphysical processes to be incorporated in the future.
2. Coordinates. It is likely that spatial variables (x, y, z) will be used as coordinates. This however is closely linked to the question of the lower boundary conditions and the representation of orography (see (5) below).

3. Initialisation and/or data assimilation. A requirement will be the facility to assimilate data (either initial data or boundary data) from existing larger scale models (Meteorological Office and ECMWF models in particular). The model design will aim to make this straightforward.
4. Variable horizontal resolution. A range of science objectives, including cloud-resolving modelling, orographic flows and urban modelling will require resolution down to fine scales (e.g. tens of metres) in an "inner" region whilst simultaneously modelling a much larger domain. It is likely that an interactive, two-way nesting strategy will be adopted (e.g. Clark & Hall 1991) but coordinate stretching will also be considered.
5. Vertical coordinate and representation of orography. Vertical stretching for boundary-layer resolution will inevitably be required. A challenging question for the representation of orography concerns the choice between a traditional boundary fitting (of which there are many variations, see e.g. Mesinger 1997) and a non-transformed vertical mesh arrangement which intersects the orography (e.g. Bonaventura 2000). The former has well-known advantages concerning resolution of near-surface turbulence whereas the latter is a newly emerging idea which could have considerable advantages for conservation properties, LES modelling (avoiding grid dependence of the sub-grid model) and efficient solution of pressure equations. We will investigate the practicality of including both options within the modelling system.
6. Discretisation of equations. Finite difference and finite volume schemes will be reviewed, bearing in mind flexibility and implementation of conservative schemes.
7. Numerical schemes, particularly for advection and time-stepping. Careful consideration will be given to conservation and stability properties. It would seem to be advantageous to adopt a sufficiently modular design to allow flexible interchange of schemes and elliptic equation solvers.
8. Turbulence models and LES schemes, allowing sufficient flexibility for higher-order (up to second) turbulence closure and a range of LES facilities (perhaps only on inner domains if a nesting approach is adopted) including stochastic backscatter.
9. The scope of physical parametrizations. Within the 4.5 years of the project currently proposed, this should include:
   i. passive tracer transport
   ii. clouds (water & ice)
   iii. precipitation (water & ice)
   iv. surface (and later) cloud radiation
   v. transport and reaction of chemical species.
10. Code design, allowing for efficient parallelisation from the start (rather than having to modify the code structure to allow parallelisation at a later stage). Also, should be easy to run in 1-D and 2-D modes.
11. Programming language (probably FORTRAN 90), programming standards (ensuring maximum portability), code management (e.g. Makefile, RCS).
12. Tests and test cases. During the development of the dry dynamics code, a standard set of tests will need to be developed (accuracy, conservation, symmetry, etc) and applied to all future changes. Some of these already exist for use with the UM modelling system and others are being developed by the UWERN community (for convection in particular).
13. Diagnostics and graphics. These should be separate from the core code. Standard data output formats (e.g. NetCDF) will be essential, to allow interfacing to a range of widely-used graphics and data analysis packages. The UWERN community already makes extensive use of diagnostics and graphics (e.g. JPLOT) from the Meteorological Office Unified Model system and the microscale model output will be designed to be compatible with and make maximum use of the UM facilities.

The review will consider not only models already being used within UWERN (the UM, LEM, BLASIUS, NH3D) but also other widely used systems such as the French Meso-NH model (Lafore *et al.* 1998), RAMS (Pielke *et al.* 1992) and MM5 (e.g. Davis *et al.* 1999).

The development of the modelling system will be carried out principally in Leeds, coordinated by the PI and the PDRA for whom funding is requested here. Computational resources for the development will be provided by the School of the Environment at the University of Leeds (using local workstations and the School of the Environment's share in the University of Leeds SGI Origin 2000 computational server). As the project progresses towards scientific application of the modelling system (from year 3 onwards), further computational resources will be required. This matter is currently being addressed separately under a UWERN review of its computational requirements.

6. Development Plan and Project Management

The project will be managed from the School of the Environment at the University of Leeds but will be highly interactive and collaborative. A key feature of the project will be twice-yearly 2-day workshops which will be open to all UWERN personnel involved in the project and will from time to time involve other researchers whose expertise will be valuable to the project. These workshops will review progress, provide input to ensure good match to user requirements and will also serve as more general scientific meetings during which recent developments in numerical modelling will be discussed.

6.1 Timetable of Model development

The following outline timetable is proposed:

1. 12 months. Review of requirements and current practice. Initial tests of likely schemes.

1a. Issue of model design proposal for consideration by the UWERN Steering Committee.

2. 24 months. Working dry dynamics model, with orography and limited variable resolution.
3. 30 months. Tracer transport. Multiple levels of nesting.
4. 36 months. Inclusion of arbitrary orography (special facilities for steep slopes).

4a. 36 months. Availability of version 1.0 as community UWERN model.

5. 42 months. Moist physics (including warm clouds) & surface energy balance.
6. 48 months. LES capability. Ice microphysics.
7. 54 months. Higher order turbulence closure. Simple chemistry.
8. Open ended, beyond current UWERN programme. Maintenance, user support and continued development.

Note that this project is by necessity limited in the first instance to the current period of the UWERN programme. However, it is proposed that the new modelling system should have a useful lifetime of not less than 15 years, during which time it would undergo continuous development and improvement.

6.2 Project Management

1. Key development decisions will be made by a group consisting of the PI and co-PIs, mainly at the six-monthly workshops but also by email discussion. Decision-making will be coordinated by the PDRA.
2. The UWERN Management Committee will be asked to review the model design proposal which will be issued after 12 months (see §6.1.1a).

7. Link to Existing UWERN Mesoscale Research Strategy

UWERN has a mesoscale modelling strategy, approved by the Management Committee in April 2000, which details work planned and underway using the Met Office Unified Model (UM) in its current (hydrostatic) and new (nonhydrostatic) versions. This includes testing at resolutions down to 1 km, moving nested grids and data assimilation. The work proposed here complements this strategy by identifying and implementing a modelling solution appropriate for smaller scales. As noted earlier, an extension of the nonhydrostatic UM is one potential candidate for this role.

Whether the UM or a new model is developed for microscale research, it will be possible to take advantage of the substantial mesoscale modelling infrastructure within UWERN. The UM and its data analysis package can be used to produce initial and boundary conditions. Test cases for a variety of small scale weather phenomena have been produced with the UM and existing microscale models, and will be available to validate the proposed model. Finally, a comprehensive package of analysis and graphics tools (including mdiag and jplot) have been developed by UWERN support staff and can easily be adapted for use with a microscale model.

8. Justification for Resources Requested

The resources requested are modest and bear in mind the resources already available to UWERN. The project will need to be coordinated by a highly experienced PDRA who has the depth of knowledge and experience to bring together input from across the UWERN community. This key role will require a researcher with a strong numerical atmospheric modelling or computational fluid dynamics background and excellent communication skills. This level of expertise will only be acquired after a considerable number of years' research experience, and so funding is required at the RA II level. The PDRA will have principal responsibility for carrying out the proposed review and for building the new modelling system, with extensive input from the PI, co-PIs, collaborators, recognised researcher and at least 4 of the UWERN PDRAs (those with responsibility for orographic models, mesoscale models, cloud resolving models and boundary-layer dispersion).

An essential feature of this project is the twice-yearly workshops which will bring together all the personnel mentioned in the previous paragraph, along with other researchers who from time-to-time may assist the project, to discuss and plan progress. These will be 2 day meetings. Funding is requested for 90 trips within the UK for UWERN personnel attending the workshops. Funding for two international conferences for the PDRA is also requested.

Other modest funding is for workstations for the PDRA (where day-to-day development of code will take place) and for related computer consumables.

9. Science Deliverables

9.1 Deliverables Within the Current UWERN Programme

It is envisaged that the following activities will use the microscale modelling system within the period of the current UWERN programme and will be able to report substantial results.

9.1.1 Stable Boundary-Layers

i. Dynamics of the stable nocturnal boundary layer, including temperature discontinuities and dislocation type events (BAS core activity linking with Antarctic field observations and modelling in Leeds).
ii. Urban flows on building scales (UWERN/Reading activity. Strong potential links to the NERC URGENT programme, new NERC polluted troposphere programme and proposed urban air pollution programme.).

9.1.2 Orographic Flows

i. Breaking gravity-waves and critical levels (UWERN/Leeds activity linking with non-NERC UWERN projects and NERC-supported aircraft observations).
ii. Katabatic flows and hydraulic jumps (BAS core activity)
iii. Strongly stratified flows past orography including vortex shedding and gravity wave breaking (Leeds/Surrey activity linking with EnFlo research). Low Froude number flow around orography and blocked flows (Leeds activity).
iv. Valley flows and blocked flows (UWERN/Leeds activity linking with MOD and NERC-funded projects).
v. Unsteady effects in gravity wave propagation due to temporal evolution of the synoptic-scale flow (Leeds activity).

9.1.3 Boundary-Layer-Free Troposphere Interaction

i. Gravity-wave/boundary-layer interaction, including launching and steering of gravity waves, severe turbulence events.

9.2 Activities Which Can Begin Within the Current UWERN Programme

It is envisaged that the following activities will be using the microscale modelling system before the end of the current programme but that the work will still be ongoing.

9.2.1 Stable Boundary-Layers

i. Boundary-layer flows over the marginal-ice-zone, with emphasis on surface exchanges (BAS core activity, Leeds activity).
ii Particulate (snow and sand) flows (Leeds activity linking to BAS core programme).

9.2.2 Boundary-Layer-Free Troposphere

i. Convective boundary-layer flows over hills (Leeds/UWERN activity linking with UFAM measurements and NERC-funded EnFlo research).
ii. Ventilation of the convective boundary-layer, particularly with application to the urban boundary-layer and chemistry/turbulence interactions (UWERN/Reading, UMIST, Salford activity. Links to new NERC polluted troposphere programme.)

9.2.3 Convective Clouds

i. Triggering of convection by orography and land surface features (UWERN/Reading activity).
ii. Case studies where observed clouds are simulated (UWERN/Reading activity linking to UFAM observations).

9.2.4 Mesoscale Fine Structure

i. Fine structures embedded within frontal zones, Kelvin-Helmholtz instability, cross-frontal exchanges, all requiring local fine-scale resolution (UWERN/Reading activity).
ii. Mesoscale cyclone simulations (BAS core activity).

9.2.5 Quantitative Precipitation Modelling

i. Development of precipitation models, driven and validated by assimilated radar data (Reading/Essex/UWERN activity).

10. Long Term Objectives

Although the project described here is for the remainder of the period of the current UWERN programme, the creation of a new microscale modelling system is undertaken with the intention that it should have long-term utility; a minimum period of 15 years is proposed at this stage. For this reason, care will be taken to ensure maximum flexibility in the design of the modelling system, to facilitate as yet unknown developments in science objectives or computational technology. Concepts which at this stage are too experimental to be included in a community model, but which may well become routine within a few years, include unsteady adaptive meshes and unstructured meshes. The review described in §6 will attempt to look forward to likely long-term developments.

11. Training Benefits

The workshops described in §6 will be open to all UWERN research students and research assistants. They will be able to take part in and benefit from the discussions and from time to time, where appropriate, become involved in aspects of the model development, testing and use. As the modelling system approaches maturity, the availability of a comprehensively documented facility will offer additional training opportunities.

12. References

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