Convection over complex terrain (UK-COPS)

Summary

Flooding caused by heavy convective rain is a serious problem in the UK. Flash floods in hilly terrain can be particularly damaging. The Convective Orographically-induced Precipitation Study (COPS) is an international project designed to address this problem and to improve predictions of heavy convective precipitation. This proposal is the UK component of COPS which adds specific objectives complementary to those of other COPS partners. It will produce an understanding of the processes that control the formation and development of convective precipitation over hilly terrain which will be used by scientists within the Mesoscale Modelling group of the Met Office in reducing uncertainty in predictability of convection over complex terrain with the Unified Model (UM). This will be achieved by synthesising COPS data alongside modelling activities focussed on interpreting the data. The problem involves five integrated parts that need to be tackled together. (1) The thermally driven flows in complex terrain depends critically on the surface exchanges of heat and water. (2) The composition and size distribution of the aerosol particles have a crucial influence on the microphysics and dynamics of the convective clouds and particularly the amount of precipitation. (3) The thermals and other features in the boundary layer transport heat, moisture and aerosols to the convective clouds. (4) The development of precipitation depends critically on the detailed microphysics and dynamics of the convective clouds. (5) Finally, reducing uncertainty in predictability of the location and timing of convective storms in hilly terrain with the UM, depends on the knowledge gained from these In particular the relative contributions of different sources of uncertainty in predictability of convective storms in hilly terrain will be quantified, thus providing the basis for an ensemble forecast system.

1. Introduction

The forecasting of convective precipitation in hilly terrain is important because of the devastating flooding that can be caused by the intense precipitation. A number of storms over the hills and low mountains have recently caused substantial flooding and other damage in the UK and other parts of Europe. The Hadley Centre regional model HadRM2 shows that one of the impacts of climate change is likely to be significant reductions in the return periods of extreme precipitation (Senior et al. 2002). Convection plays an important part in many flood situations, especially flash floods. Unfortunately the forecasting skill for heavy convective showers and thunderstorms over orography is low at present, mainly because there is poor understanding of thermally-driven orographic flow of moisture and aerosols feeding the storms and the details of the aerosols, microphysics and dynamics of the convective clouds, all of which control the production of precipitation in orographic convection.

This proposal addresses deficiencies in the understanding of these processes. A consortium of UK universities is carrying out an observational programme within the Convective and Orographically-induced Precipitation Study (COPS). This analysis will provide a greatly improved understanding of both the dynamical and microphysical processes controlling convective precipitation and so provide the basis for improving quantitative forecasts of convective precipitation within NWP. The UK part of the field measurements is being carried out by the Instrument Scientists in the National Centre for Atmospheric Science (NCAS) University Facility for Atmospheric Measurement (UFAM). This proposal is concerned with converting data gathered in the field campaign into understanding of the physical processed leading to real improvements in predictability of convective storms. [Stephen M - please add.]

COPS is a German-led international field campaign to be held in the summer of 2007 in the Black Forest and Swabian Jura of south-west Germany and Vosges Mountains of eastern France. These mountains are typical of the larger ranges of mountains in the UK. The region has been chosen by the COPS community because of the severe thunderstorm activity, but low skill of numerical weather forecasts in the region. This is typical of such regions of complex and varied terrain. COPS offers a unique opportunity to address scientific questions that could not be addressed without the large number of German, other European and US ground-based instruments and aircraft facilities. This proposal lies at the core of COPS objectives: understanding the precipitation produced in orographic convection. The outcomes will be not only to provide better understanding of the processes, but also unique datasets for validation and development of the Met

Office's mesoscale numerical weather forecast model. In this regard, this proposed research is related to the highly successful Convective Storm Initiation Project (CSIP).

Poor forcasts of convective precipitation are also a world-wide problem. A memo of understanding exists between the US, Germany and UK to exchange ideas, scientists and students for the projects IHOP_2002 (the US led project on convective initiation in the flat plains of the US), CSIP (led by Professors Blyth and Browning, UK, held in the low-hill region influenced by coasts in southern England) and COPS (led by scientists in Germany, held in the hilly terrain of the Black Forest). In addition, importantly, the physics of many of the fundamental processes, such as surface fluxes, are common to all projects, but each project has focussed on different aspects (due to funding limitations) and since the projects have taken place in different climates. Therefore, the combined series of projects provides an opportunity to improve the understanding of severe convective storms and thus forecasting ability of heavy precipitation in the UK (for example) that would not be possible without world-wide collaboration. In particular, the role of aerosols and cloud microphysics in precipitation development and convective predictability cannot be addressed using data from CSIP or IHOP. COPS provides a unqiue opporunity to understand the relative contributions of uncertatinties in fluxes, synpotic features and cloud microphysics to uncertainties in forecasts of convective precipitation.

The COPS *Scientific Overview Document* (SOD) is available from the COPS web site: http://www.uni-hohenheim.de/spp-iop/. The objectives of the current proposal are included in the SOD. Material from the SOD is included in this proposal. The PI, Prof Blyth and co-PI, Prof Mobbs are members of the COPS international steering committee.

The timing of this proposal being submitted before the field campaign is crucial in order to guarantee that the UK consortium be part of the international COPS experiment, to allow them access to the data, and to allow full committed participation in COPS science workshops. Unpublished results (Weckwerth and Wilson) showed that precipitation is observed in the Black Forest region on more than 50% of all days every summer.

2. Overarching Scientific Questions and Need for a Consortium Approach

The ultimate goal is to understand the formation and development of convection over complex, hilly terrain and thus to improve forecasts of heavy, orographically-induced precipitation. The project addresses the two most poorly understood aspects.

1. The prediction of deep convection over hilly terrain is extremely challenging because it depends critically on the mass, heat and water vapour fluxes associated with thermally driven flows which themselves depend critically on the highly detailed surface exchanges of heat and water. *Question: what are the pathways for heat, mass, water vapour and aerosols to enter terrain-locked convective cells?*
2. The development of precipitating clouds is further complicated because it depends on the transport of aerosols by these thermal flows and on the highly nonlinear interaction between the cloud microphysics and the dynamics. *Question: How is the development of deep convection and precipitation over complex terrain influenced by the cloud/aerosol interaction?*

The important link between the two fundamental questions is the aerosol particles that are transported in the orographic flow and ingested into the convective clouds. This project directly addresses both the mass, heat, water vapour flux problem and the cloud, aerosol, dynamics interaction problem. The goal is to produce a substantial improvement of the predictive capability for orographic precipitation through understanding of these processes. A key component of this research therefore will be using the knowledge gained to enhance the predictability of the Met Office Unified Model (UM).

This problem has five strongly-linked parts: (1) flow in complex terrain; (2) composition and size distribution of the aerosol particles; (3) characteristics of thermals in the boundary layer; (4) microphysics and dynamics of the convective clouds and the precipitation produced; and (5) understanding sources of uncertainty in predictability of the UM in forecasting heavy convective precipition. We have therefore assembled a consortium of experts from: the University of Leeds (orographic flow, cloud microphysics and dynamics and aerosol/cloud interactions); University of Manchester (characterisation of aerosols, cloud microphysics and transport of aerosols from boundary layer); University of Salford (turbulence structure of the BL and thermals in the BL); JCMM (with scientists in the Dept of Meteorology and the Met Office) based in the University of Reading (evaluating predictability of convective storms with the UM) the University of Hoheneheim (leader of COPS and convective initiation) and University of Karlsruhe (aircraft measurements, surface fluxes and boundary layer process) in Germany. It would not be possible to tackle such a large multi-part problem without a consortium.

3. Science Background

Precipitating convection over hilly regions is notoriously difficult to forecast principally because of the problem in describing the thermally-driven flows. For example, results from German NWP models run for the COPS region (COPS SOD) produce an overestimation and underestimation of precipitation on the windward and lee side of the mountains, respectively and a phase error in the diurnal cycle of precipitation leading to the predicted onset of precipitation several hours too early. Also lack of knowledge of the aerosols ingested into the convective clouds, which is crudely parameterized in most of the current NWP models (including the UM), can lead to significant errors in precipitation intensity and distribution in upland and lowland areas. Knowledge of the aerosols and their ice nucleating ability are particularly important when tops are relatively warm. For example, it is believed that the tops of the convective clouds that caused the Boscastle flood were only between -15 and -20°C (Golding et al. 2005) and yet the precipitation was intense. The influence of aerosols on the microphysics and dynamics of mixed-phase convective clouds is only beginning to be explored (e.g. Khain et al. 2005).

(i) Thermally-driven Flow Over Complex Orography and Transport of Aerosols into the Free Troposphere and Convective Clouds

Recent field campaigns studying thermally-driven flows in complex terrain have included VTMX in the USA, the German VERTIKATOR experiment and the MAP Riviera experiment. The supporting and follow-up modelling studies for these projects, whilst varied in their aims, have shared a common conclusion: that adequate modelling of the thermally driven flows in complex terrain requires an accurate and detailed sub-model of the surface exchanges of heat and moisture, including good radiation modelling which accounts for slope and shading effects. The importance of accurate modelling of soil moisture and associated surface moisture fluxes was demonstrated by Berg & Zhong (2005) using VTMX data and the MM5 model. Very similar conclusions were reached by Chow et al. (2004) for the Riviera project using the RAMS model. Weigel et al. (2004) also demonstrated the importance of along-valley advection and subsidence associated with the diurnal valley flow on scales larger than the valley itself in determining the thermal and moisture structure of the valley atmosphere. Weigel & Rotach (2004) used MAP-Riviera data to demonstrate the importance of secondary circulations (probably due to curvature of the valley) which led to strong asymmetry in the observed flow and significant *vertical* transport. They also identified the importance of slope dependent radiative heating of the surface. Similar conclusions concerning the surface radiative balance were reached by Matzinger et al. (2003). Similarly, the detailed modelling study of de Wekker et al. (2005) for the Riviera project using the RAMS model highlighted both the slope/shadowing radiative effect and the need for an accurate soil moisture model.

On a scale larger than individual valleys, the interaction of valley/mountain thermal flows with the flow in the convective boundary layer (CBL) has been found to be extremely complex. An earlier study in the Black Forest region by Kossmann et al. (1998) demonstrated the importance of upslope winds in reducing the heating rate over the slopes. The mountain range scale flow suppressed the CBL growth at the mountain ridge by forcing the capping inversion upwards. In addition, mountain scale secondary flows affected the heat budget and therefore the growth of the convective boundary layer over the mountain slopes. The overall effect was that empirical rules for convective boundary layer growth, derived for simple terrain, were shown to fail badly over the mountains.

Kossmann et al. (1999) later showed that convective cells occurred over the same location above a particular valley on different days, an observation consistent with the experience of glider pilots. Kossmann et al. suggested that the cells are caused by thermally induced upslope winds over the steep sidewalls of the valley. In a study in more mountainous terrain, Henne et al. (2004) found a similar result: the valleys acted as an efficient air pump that transported pollutants upward. So the thermally-driven flows in some valleys appear to be important for transporting aerosols out of the valley into the convective clouds and free troposphere.

A relatively simple but highly illuminating observational study by Reuten et al. (2005) also found a highly complex interaction between upslope flows and the CBL. Such was the complexity of these flows that the simple assumption that upslope flows would vent pollutants out of a valley was shown in some cases to be incorrect; instead, recirculating flows kept constituents trapped within the valley.

The structure of well-developed thermals is quite well understood, particularly in cumulus clouds (Blyth et al. 2005). However, it is possible that the "chimney" flow caused by the valley sides produces a plume that feeds the clouds which has different dynamics to a thermal. If thermals are important, it is not clear how they will be modified in complex terrain. There is likely to be more turbulence produced in hilly regions due to sharp gradients in the surface and differential heating of slopes. Hasel et al. (2005) found evidence of this from the modification of the dominant length scales.

We stress at this point the reason why we need to study thermally driven valley/mountain flows: these are the flows which create the convergence zones leading to preferred locations of convective cells over orography. All of the above studies therefore point to the need for accurate and reliable modelling of all the components of the surface exchanges of heat and moisture if the orographic convection is to be explained and predicted. We also stress the importance of these flows to the properties (size, concentration and composition) of the aerosols that are transported towards cloud base.

(ii) Aerosols, Microphysics and Dynamics of Orographic Convective Precipitation

The aerosol population (size distribution and composition) has a major influence on the dynamics and microphysics of orographic convection. The cloud condensation nuclei (CCN) population entering cloud base determines the extent and onset of warm rain produced by collision coalescence. These, along with the presence of heterogeneous ice nuclei affect the onset of the glaciation process and the efficiency of secondary ice processes such as the Hallett-Mossop (H-M) process of ice splintering. These in turn determine the release of latent heat of fusion in the cloud, which has a major influence on the vigour and structure of the cloud dynamics. The initiation and development of the ice phase is crucial to the precipitation formation and its location within the cloud. These in turn will modify the cloud dynamics through latent heat release and through precipitation induced downdraughts.

Similarly, CCN and ice nuclei (IN) entrained into the cloud as it ascends may have a significant influence on the microphysics and hence dynamics. Yin et al. (2005), for example, found using a detailed cloud physics and chemistry model that the development of graupel was very sensitive to the re-entrained processed aerosol. Sensitivity studies showed that ignoring this re-entrained CCN caused a 37% increase in precipitation. They pointed out that the effects would be even more complicated if the entrained aerosols were IN.

The microphysics and dynamics of the convective clouds that form over the Magdalena Mountains in central New Mexico have been examined extensively. Clouds do not form at all if there is insufficient moisture, although a convective core still develops over the mountain (Raymond and Wilkening 1980). In fact Raymond and Wilkening (1982) found that the convergent low-level flow was only slightly larger in cloudy than in dry conditions.

The amount of moisture in air feeding the convective clouds can play an important role in the microphysical and hence the dynamical development of the cloud. For example, Blyth & Latham (1993) found no evidence for the H-M mechanism in one cloud with a high base probably because the cloud drops in the critical temperature region $(-8 \leq T \leq -3)$ were too small. According to the modelling study of Raymond & Blyth (1992), the release of latent heat due to secondary ice production is sufficient to cause the New Mexico cumulus congestus clouds to develop quite suddenly into cumulonimbus clouds, as observed by Raymond and Blyth (1989). The higher cloud-base cloud observed by Blyth and Latham did not develop into a major thunderstorm and produced very little precipitation, possibly because the H-M process did not operate. This sensitivity to cloud base height may have a similar magnitude to that found due to changes in aerosol concentrations (e.g. Phillips et al. 2002). The properties of aerosols have never been studied for the New Mexico orographic clouds.

Model studies and some observations have shown that the intensity and depth of convective clouds can change dramatically when aerosol concentrations are varied. It is well known that clouds with fewer cloud droplets can produce warm rain much faster than clouds with a greater number of drops (Squires 1952). The "suppression of rain" due to increases in CCN, mostly in biomass burning plumes, has received considerable attention recently. However, the process is not straightforward and there are many more effects on the cloud, particularly when IN are considered as well. Khain & Pedlovsky (2004) suggested that the cloud response to increased CCN may be ambiguous and non-linear and depend on the atmospheric stability, initial aerosol distribution and humidity. Cotton et al. (1995) investigated the affect of changes in CCN and IN for clouds forming over Florida and showed that they had a competing effect on the total rainfall. Several satellite-based investigations indicate a possible link between input aerosol particles, microphysical evolution of convective clouds and resulting precipitation (e.g. Ramanathan et al. 2001).

Observations have shown that convection can significantly perturb aerosol concentrations aloft (Kleinman & Daum 1991). A modelling study by Yin et al. (2001) showed that vertical transport by a cumuliform cloud enhanced aerosol number concentrations in the free troposphere by a factor of 1–3. Other observations have revealed the presence of distinct laminae of aerosol and precursor species in the free troposphere (e.g. Curtius et al. 2001). Important questions to address are how cumulus clouds affect the vertical and horizontal variability of aerosol particles, and especially the inter-relationship of these properties above and below cloud base.

The warm rain process and the production of graupel and hail via riming very efficiently scavenge aerosol from the cloud and deposit it to the surface. Whereas the production of snow scavenges the aerosol much less efficiently. If cloud water evaporates rather than precipitates then the aerosol remains in the free troposphere and is available to influence subsequent cloud formation.

None of the above processes can be considered in isolation as all have feedbacks on the others. For example, Koren et al. (2005) found that sub-cloud aerosol concentrations can modify the vertical extent of convection. Observations are required to test model results of the aerosol-cloud interactions so that the non-linear interactions between the processes in the orographic convective clouds can be understood.

4. Project Background: The Convective Orographically-induced Precipitation Study (COPS)

Data gathered during COPS will be analysed and synthesized in this project. The convective clouds that are anchored to the mountains of the Black Forest are a natural laboratory for studying the formation and development of the precipitation and the variation in the intensity of precipitation in response to variations in properties of aerosols. As a consequence, radars can be well positioned so the spatial and temporal resolution of the observations is high and aircraft can easily follow the development of the clouds from their incipient stages to the cumulonimbus stage. The maximum in daily thunderstorm cycle occurs at 16:00 local time.

The COPS field campaign is being held in the summer of 2007 in the Black Forest and Swabian Jura of SW Germany and Vosges Mountains of E. France. The objectives outlined above and in the work packages will be addressed by combining the ground-based and remote sensing instrumentation of UFAM and the FAAM BAe 146 aircraft with the extensive set of instruments and aircraft from Germany, France, US, Austria and Italy. The ground-based instruments of COPS will be concentrated in five supersites (Fig. 1) that form an east-west transect of the COPS area. Table 1 lists the instruments at each of the sites.

Supersite H will be located on the top of Hornisgrinde, the highest peak (1163 m) in the northern Black Forest where convection is likely to develop. The typical height of the mountains in the central and northern part of the Black Forest (near Freudenstadt) is between 500 and 800 m. The UFAM/Manchester ground-based aerosol instruments will be deployed at this site. providing information on the size-resolved composition of the aerosols. Further details are given in Section 5.2 describing Work Package 2.

Site	Group and Instrument	Measurement
S	German Wind Temperature Radar	Vertical profiles of wind and temperature
	German Micro Rain Radar	Vertical profile of Precip particles, velocity, size distr.
	Austrian Radiosondes	Profile of tempr and humidty, winds
	Austrian Tethersonde	Continuous Tempr, humidity, winds at x altitudes
	Italian MW radiometer	Tempr and humidity profiles
M	US Arm Mobile Facility	Various (see text)
	German HATPRO radiometer	Vertical profiles of tempr and humidity
	German 90-150 GHz radiometer	Vertical profile of water vapour
	German Multi-λ Raman lidar	Vertical profile of water vapour, temperature, EC & BC at 355 and 532 nm, B at 400, 710, 800, 1064 nm
	German vertical Doppler lidar	Vertical winds, B at 2000 nm
	German Micro Rain Radar	Vertical profile of Precip particles, velocity, size distr.
	UK 1290 MHz Wind profiler	3D winds, position of lids, structure in BL
H	German WV DIAL (scanning)	RHIs of water vapour, B at 820 nm
	German rotnl Raman Lidar (scan)	RHIs of temperature, BC and EC at 355 nm
	German (scanning) Doppler lidar	RHIs of wind, B at 2000 nm
	German Cloud Radar (scanning)	Cloud particles, velocity
	German X-Band (vertical) radar	Vertical profile of precip particles
	UK Radiosondes	Vertical profiles of Tempr, humidity and wind velocity
	UK aerosol in-situ analysis	See text
R	Italian Raman lidar	Vertical profile of water vapour, tempr, EC and BC at 355 nm
	UK Doppler lidar (scanning)	RHIs of wind and aerosols, B at 2000 nm
	UK radiometer	Vertical profile of tempr and humidity
	German cloud radar	Cloud particles, velocity
	Netherlands TARA (radar)	Precip particles, velocity
	UK Radiosondes	Vertical profiles of Tempr, humidity and wind velocity
	UK sodar	Vertical profiles of wind velocity
V	French WV Raman lidar	Vertical profiles of water vapour
	French Aerosol Raman Lidar	Vertical profiles of aerosol properties, BC and EC at 355 nm
	French IR radiometer	Vertical profile of water vapour
	French Sun photometer	Aerosol optical depth
	French X and K-B radars	RHIs of Precip particles, velocity
	French Radiosondes	Vertical profiles of Tempr, humidity and wind velocity
	French Surf. Flux Stations (3)	Fluxes of sensible and latent heat
	French soil moisture (1-3)	Soil moisture
	French UHF sodar	Vertical profile of wind velocity

Table 1: *Table showing instruments at the 5 supersites in the COPS field field campaign.*

The properties and fluxes of aerosols, characteristics of BL processes (thermals, enrtainment/detrainment) and the turbulence structure of the boundary layer will all be made in the Murg Valley at Supersite M (marked as ‘M’ in Fig. 1). The US ARM Mobile Facility (AMF) will be deployed at this site. The facility will include a cloud radar, radiometers, sun photometer, standard meteorological instruments and instruments to measure the properties of aerosols. The UFAM wind profiler will also be positioned within the valley to provide measurements of the 3D wind field and the properties of lids.

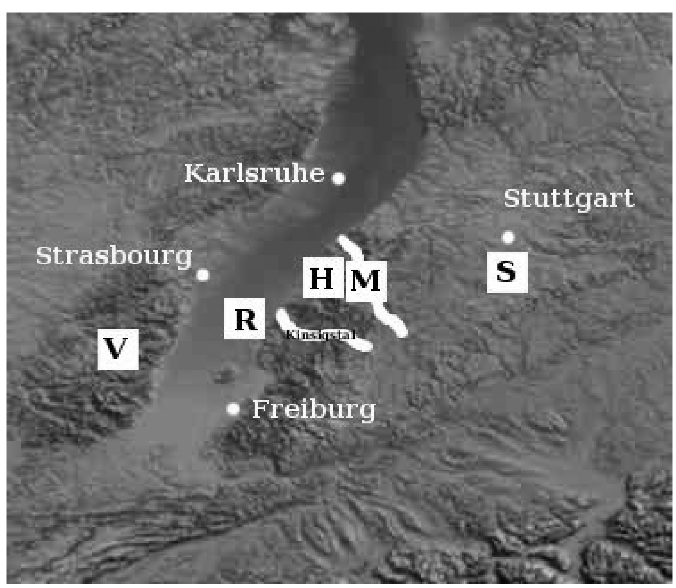

Fig. 1. Overview of the COPS region showing the locations of the supersites and the Kinzig and Murg Valleys.

Supersite S will be located to the east of SH in a region of lower hills. The focus at this site will be on measuring the surface energy balance. Continuous information on the vertical wind and temperature structure will be derived from a wind-temperature-radar (FZK WTR) from both inside and outside of clouds and from a Sodar/RASS for the boundary layer.

Instruments that will be deployed at Supersites R and V in the lowlands of the Rhine valley and in the Vosges Mountains, respectively include lidars, radars, flux stations and radiosonde stations. In addition, sodars will be placed at the valley entrances to the Black Forest (Murg, Rench and Nagold valleys). Mobile radiosonde stations will be deployed between H and M.

Five aircraft and one Zeppelin will participate in COPS: the German Aerospace Center (DLR) Falcon aircraft; the University of Braunschweig DO-128, the French Safire F20; the Max-Planck-Institute for Chemistry Learjet; and the UK FAAM BAe 146. In addition to traditional *in-situ* meteorological instruments, the Falcon will carry the water vapour DIAL and Doppler lidar for measuring horizontal and vertical wind. Dropsondes will be deployed from the aircraft. The Falcon will make measurements at the boundary of the COPS region with transects over the supersites. The DO-128 aircraft will also perform observations with transects of the supersites. The DO-128 will be equipped with basic met, dropsondes and chemistry instruments.

5. Work Packages

The objectives address specific aspects of the two over-arching questions: quantifying the pathways for heat, mass, water vapour, trace chemical species and aerosols to enter orographically-locked convective cells; identifying the physical processes by which aerosols and orographic flows determine the development of deep convection and precipitation over orography. Understanding convective precipitation over complex terrain requires a consortium of modelling groups.

Four process models are needed in this research: the Boundary Layer Above Stationary Inhomogeneous Uneven Surfaces (BLASIUS) model to orographic flow and processes in the boundary layer; the Aerosol Diameter Dependent Equilibrium Model (ADDEM) to examine the thermodynamics of cloud activation; the Met Office Cloud Resolving Model (CRM) used at 250 m resolution to examine the dynamics of the thunderstorms; the 1D Explicit Microphysics Model (EMM) that is driven by the CRM dynamics to examine the details of the microphysical processes; and the new 3D Microphysics Cloud Resolving Model (MCRM) (developed at Leeds by a core position of APPRAISE) that will be used to examine the influence of aerosols on the microphysics and dynamics. These will inform the Met Office Unified Model (UM) and similarly, information learned in runs of the UM output from the UM will be used to intialise and force the process models. Figure 2 is a diagram showing the science area to be addressed with each of these models, the PDRAs that will lead the research and the interrelationship between the different models. Each model will be run independently (except for EMM) at the beginning of the grant, but results from BLASIUS on aerosol transport and dynamics will be fed into the CRM, EMM and MCRM in year 2. Similarly knowledge gained from the process studies will be used to uncertainty in the predictability of the UM. The details of each model will be described in the following sections.

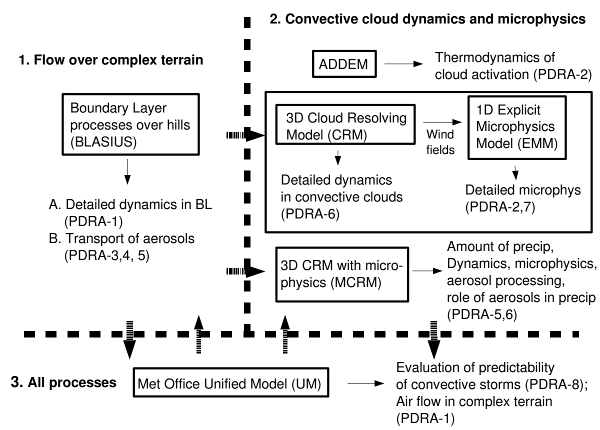

Fig. 2: Models to be used in the research, purpose and PDRAs responsible.

Table 2 shows the PDRAs and scientists associated with the five Work Packages described in Sections 5.1–5.5.

5.1 Work Package 1: Orographic flow leading to development of convective cells

Our ability to model thermally driven flows in complex hill/valley systems is poor because of the lack of

WP	PDRA	Tasks	Scientists	Location
1	PDRA-1	BLASIUS; Interpretation of orographic flow data	**Stephen Mobbs**, Alan Gadian, Andrew Ross, Doug Parker	Leeds
2	PDRA-2	Interpretation of aerosol measurements; closure with CCN; results into EMM; Analysis and interp of aircraft obs of ice crstals using CPI and aerosol size resolved composition using AMS	**Hugh Coe**, Tom Choularton, Martin Gallagher, Gordon McFiggans, Paul Williams	Manchester
	PDRA-6	Results into MCRM	Ken Carslaw	Leeds
3	PDRA-3 PDRA-5	Interpretation of Wind Profiler data; Characterise lids, propagating waves along lids; Characterisation of thermals and development of cumulus clouds; Transport out of BL	**Geraint Vaughan**, Emily Norton, Alan Blyth, Doug Parker,	Manchester, Leeds
	PDRA-4	Interpretation of Doppler lidar data; Role of sfce conditions on BL turbulence and representation in UM	Chris Collier, Karen Bozier, Fay Davies	Salford
4	PDRA-5	Interpretation of detailed microphysics data from BAe 146, and radars; Comparison of observations with model reslts	**Alan Blyth**, Phil Brown, Alan Gadian, Doug Parker	Leeds
	PDRA-6	MCRM; influence of aerosols on precipitation from convective clouds	Ken Carslaw, Alan Blyth	Leeds
	PDRA-7	Modelling of microphysics and dynamics using CRM+EMM based on size-resolved aerosol composition measured at sfce and on aircraft; Comparison of model results with obs	Tom Choularton, Martin Gallagher, Hugh Coe	Manchester
5	PDRA-8	Evaluate predictability of convective storms with UM; sensitivity to results from WPs 1-4	**Stephen Belcher**, Peter Clark	Reading
	PDRA-9 (25%)	Evaluate the predictability of convective storms over a nine month period	Anthony Illingworth	

Table 2: PDRAs and scientists associated with the five Work Packages. The first scientist (in bold) listed in a work package will lead that package.

good observations of *all* the significant components of the surface heat and moisture balances and the frequent inadequacy of the understanding and representation of these processes in larger scale models. Significant processes to consider include full representation of the surface energy balance (including slope/shading effects), good representation of the boundary-layer turbulence, the influence of the overlying atmospheric wind and thermodynamic structure.

OBJ 1.1 To quantify the flow patterns over and around orography

OBJ 1.2 To determine pathways for heat and moisture to reach convective activity over a range of tropospheric conditions (stability, wind structure) and through the life-cycles of the cells.

OBJ 1.3 To determine importance of surface properties (e.g. moisture, vegetation) on flow structure within complex terrain.

OBJ 1.4 To determine the factors controlling whether anabatic up-valley and up-mountain-range flows are trapped or penetrate the free troposphere.

OBJ 1.5 To determine the role of small-scale effects in more complex terrain with steep slopes.

The central theme of this work package is to identify the key surface and boundary layer features which control the development of anabatic flows and the initiation of convection, and to validate the surface flux schemes used to model these processes over complex terrain. Variability in surface heat fluxes may be connected to the orography through variations in slope, aspect and shadowing. The orography will also be closely linked with variations in land use and vegetation, surface temperature and soil moisture, all of which will affect the surface fluxes. These heterogeneous small scale variations in surface fluxes will play an important role in determining the local thermally-driven circulations in complex terrain. Together the anabatic flow and the surface fluxes will be important in controlling where convection occurs and whether it will penetrate the free troposphere. Similarly they will determine the locations of the convergence.

Measurements of turbulent fluxes and energy balance are being made with the German systems positioned in the Kinzig and Murg Valleys (see Fig. 1). Surface fluxes will be measured from at least three 15-m masts instrumented at 2 levels with sonic anemometers and high-rate temperature and humidity sensors. Up and down-welling long and shortwave radiation fluxes, soil temperature, and soil heat flux are also being measured at the supersites, enabling the full surface energy balance to be calculated. Reference measurements of mean air temperature, pressure, humidity, wind speed and direction will accompany the flux measurements at each site. In complex terrain, individual flux measurements may not be representative of the wider area. Multiple sites are therefore being equipped in order to estimate spatial variability, and in particular coherent spatial differences between the valley and mountain slopes. In addition, importantly, radiosondes will be launched from the ARM site in the Murg Valley, along the Kinzig Valley, and ...? [Stephen over to you + AWSs.] Energy balance stations will be arranged to cover different typical types of land-use. A network of low-cost innovative soil moisture sensors will be installed to study the role of moisture storage from previous rainfall and of transpiration on the sensible and latent heat fluxes.

The relative importance of these processes and the complex interactions between the surface fluxes, the orography and the thermally-driven flow will be addressed through the synthesis of the experimental data in conjunction with numerical simulations using two complementary models — BLASIUS and the UM.

- BLASIUS is a non-hydrostatic model designed for idealised studies of boundary layer processes over hills. The original model, from the UK Met Office, has recently been developed at Leeds to include the addition of a bulk microphysical scheme, and a more sophisticated surface energy balance scheme. In addition, a new pressure solver has been developed at the Met Office to be able to deal with steep slopes. The model will be used for high resolution process studies using idealised orography and a range of atmospheric profiles.
- The UM (Unified Model) is the UK Met Office operational forecast model. As such, it is more suitable for performing real case studies using real orography and operational UM analyses. As of version 6.1 this includes improved microphysics and prognostic rain.

A series of BLASIUS runs will be conducted over an idealised mountain/valley orography for a range of idealised atmospheric profiles to determine flow patterns over and around the orography and will quantify the fluxes of moisture and heat from the valleys into the sub-cloud layer. In particular the runs will investigate what boundary layer parameters determine whether the anabatic flow penetrates the free troposphere and where the convergence lines / zones occurs. These will indicate likely spots for convective initiation.

Simulations of the diurnal cycle over the same idealised orography will be used to investigate the importance of soil moisture, vegetation, surface radiation (modified by slope, aspect and shading) and initial atmospheric structure on the flow within the mountain / valley system. Flow patterns will be qualitatively compared with observations of temperature, humidity and winds made using aircraft and remote sensing instruments. Such simulations will demonstrate which factors are important to include in an operational surface flux scheme and where the greatest sensitivity to initial conditions may be.

UM runs with real orography, but using idealised initial profiles will be used to investigate how the small scale details of a more complex orography will affect the local flow. Real case studies will also be run using the UM. These will be at a high resolution of 250 m (compared to a current operational resolution of 4 km over the UK). The Met Office Model currently does a reasonable job of forecasting the position and timing of orographic convection in the UK, but there are problems associated with the intensity of precipitation (Pete Clark, personal communication). Using the extensive observations available in this case we will be able to quantify any forecast errors and investigate whether they are related to the dynamics / thermodynamics (e.g. errors in the latent and sensible heat fluxes) or the microphysics (e.g. incorrect aerosol distribution, inadequate microphysical parameterisations). We will also be able to test whether modifications made to the surface flux schemes in light of the more idealised experiments improve model performance and examine how well the new microphysics scheme, applied at these high resolutuons compares with observations.

In addition to using the model runs to evaluate and improve current surface flux schemes, simulations will also investigate the transport processes within the boundary layer. In particular they will be used to investigate the pathways for heat and moisture and aerosols to reach regions of convective activity.

5.2 Work Package 2. Interpretation of Ground-based aerosol measurements at Hornisgrinde

The aerosol effects on cloud properties remain poorly understood and a lack of predictive capability exists. The influence of the organic fraction has been postulated to be important via the suppression of surface tension and the change in the Raoult effect but field assessment of this is, at present, very limited. A range of new instruments has led to a vast improvement in our ability to probe the physical and chemical properties of the aerosol (e.g. Allan et al., 2003) and investigate properties such as their ability to act as cloud condensation nuclei (CCN) (Cubison et al., 2004; Nenes and Roberts 2004). Furthermore, new models are being developed that can predict the water content and activation properties of particles from size and composition information based on fundamental thermodynamics (Topping et al., 2004a,b; McFiggans et al., 2005). Such models are important if we are to understand the influence aerosol particles have on cloud properties and behaviour. The thermodynamical models cited above form the basis of a Cloud Resolving Model for mixed phased clouds that treats aerosol-cloud interactions that is being developed within the NERC APPRAISE Core Cloud Activity. The model needs to be tested against field measurements of cloud as is being done in WP4, but the thermodynamics code cannot be tested in such a way. This WP aims to use the ground based COPS measurements to perform these tests in a continentally polluted environment.

Whilst the aircraft payload is comprehensive it cannot characterize the aerosol completely. In particular the cloud activation properties, the Aitken mode population and the coarse mode composition, necessary for relating to the ice nucleus population, cannot be probed in detail. These will be measured during COPS. The focus of this work package is to use the results of these measurements to make a detailed characterisation of the aerosol that can be linked to the aircraft measurements, and used as input in the cloud modelling studies (WP4). This characterisation will include an assessment of giant and ultra-giant aerosols that may be crucial in the initiation of warm rain.

Specific objectives of WP2 are:

OBJ 2.1 To characterize, the physical, chemical, hygroscopic, cloud droplet and ice nucleating properties of the aerosol interacting with the clouds in the region.

OBJ 2.2 To assess the extent to which the sub and super-saturated behaviour of the aerosol can be predicted by models of varying complexity.

OBJ 2.3 To incorporate results into models (EMM and MCRM).

Ground-based field measurements of the physical and chemical properties of aerosol particles will be made throughout the intensive period at the Hornisgrinde site (Fig. 1) by NCAS. This hill top location is an ideal site to represent the inflow to the convection developing in the region. NCAS will have made measurements of: the aerosol number concentration above 3 nm and 10 nm diameter; the aerosol number size distribution using a Different Mobility Particle Sizer (dry mobility size D_p from 3 nm to 700 nm), an Aerosol Particle Sizer (dry aerodynamic size (D_a from 500 nm to 20 m), and a GRIMM 1.109 optical particle counter (scattering size D_{scat} from 250 nm to 32 m); the hygroscopic properties of the aerosol using a Hygroscopicity Tandem Differential Mobility Analyser (H-TDMA) (subsaturated hygroscopic behaviour for $D_p < 350$ nm); the CCN properties (DMT Counter); the size resolved mass of non-refractory components (Time of Flight Aerosol Mass Spectrometer, ToF-AMS); the fluorescence of particles as a function of their size (for biological content, WIBS on loan from University of Hertfordshire), ice nuclei (Ice Nucleus Counter) and black carbon mass and mixing state (Multi Angle Absorption Photometer and DMT Single Particle Soot Photometer respectively). A Differential Mobility Analyser will have been intermittently used to size select the aerosol entering the CCN counter and ToF-AMS instruments to obtain detailed activity spectra and density information. NCAS is planning to collect samples using size resolving impactors for subsequent ion chromatographic analyses. We propose further analyses on these samples focused on the coarse mode particulate. The UMAN group has access to a Scanning Electron Microscope with humidity control over the sample stage (Philips XL30 ESEM-FG). The SEM is fitted with autoscanning and imaging software that is able to conduct X-ray mapping for automated elemental analyses (GENESIS XM 4 System 60). This will make it possible to obtain histograms of the size resolved composition of coarse mode aerosol particles on a daily basis and to have the capability of probing the ice activation properties on a limited number of samples.

The ToF-AMS, WIBS and SP2 instruments all measure single particle properties. The UFAM container has a range of inlet systems that can deliver ensemble or size selected aerosol to the above instruments. Furthermore, by sampling monosized aerosol using the CCN or INC, the activated/nucleated fraction grows to much larger sizes. We propose to interface these instruments to the WIBS, ToF-AMS, and SP2 using an inline Counterflow Virtual Impactor (CVI), based on the NOAA design. This will allow us to probe the composition of the droplet and ice nucleated fractions of the aerosol for organic and inorganic semivolatiles, black carbon and biologically active particles.

The data collected will be synthesised in this work package and a detailed hygroscopic and cloud droplet activation closure study will be performed using the above data with a range of models of varying complexity. Recent studies indicate that in sub-saturated environments the water content of particulate is dictated almost entirely by the inorganic fraction and the organic fraction plays only a minor role (e.g. McFiggans et al., 2005). However, studies with sufficient measurement accuracy are rare and a further study of the type proposed would further validate the hypothesis that under sub-saturated conditions more simplistic models that do not consider solute interaction provide adequate assessments of behaviour. This will be tested against more complex models treating solute interaction in considerably more detail (ADDEM, Topping et al., 2004a; 2005b).

To date, there are no adequate closure studies of CCN activity from basic physical and chemical measurements of the aerosol that have been conducted under supersaturations that are representative of real clouds. Most recently, Dusek et al. (2006) have used similar instrumentation to that proposed above and shown that particle number dominates activation and composition is not important. However, the supersaturations used were very high and unrepresentative. Under such conditions it is no surprise that particle number is the most important parameter. The proposed WP2 activity aims to probe real aerosol particles and real clouds under real conditions and hence, aims to probe the extent to which a mixed organic-inorganic aerosol departs from ideal behaviour and to assess our ability to predict such a departure. ADDEM includes organic interactions and their influence on surface tension and hence provides a sensitive tool for assessing such effects.

Heterogeneous ice processes will be important in the cumulus clouds being studied in COPS. It is therefore important that the population of ice nuclei is studied in some detail. The approach will be to characterize the IN in the atmosphere and use this information to firstly determine if there is a link between different cloud behaviour and the aerosol composition (WP4) and secondly as input to the cloud resolving models (CRMs). Soot, organic and biological material will be observed at high time resolution during COPS and the offline samples will be analysed for a range of particle types, including dust. The CRMs developed in APPRAISE, and used and tested extensively in WP4, will include new parameterizations of ice nucleation based on recent laboratory studies conducted in the AIDA chamber on dust activation (e.g. Connolly et al. 2006). The results of the analyses will be used input into the Explicit Microphysics Model and the Microphysics CRM described in Work Package 4.

5.3 Work Package 3: Convective transport of aerosols out of BL

It is possible that anabatic flows will reach directly into the free troposphere and/or that orographically modified and enhanced boundary-layer turbulence (including gravity-wave induced turbulence) will provide mixing between the boundary layer and free tropospheric air. Objectives of this work package are:

OBJ 3.1 To determine the role of boundary-layer convective elements (thermals, detrainment mechanisms, clouds) in mixing aerosols into the free troposphere.

OBJ 3.2 To characterise lids, propagating waves along lids, and interaction of convection with the lids.

OBJ 3.3 To determine the role of surface conditions on BL turbulence and representation in UM.

OBJ 3.4 To determine the factors affecting the ability of the Met Office UM to reproduce the observed transport of aerosols into orographically-locked convection.

The development of thermals into small cumulus and cumulus congestus clouds and thus the vertical transport of aerosols, depends on the properties of the air that feeds the clouds. There is evidence from recent analysis of data gathered in the Convective Storm Initiation Project that thermal updrafts are typically narrow, warm and moist. In fact it is likely that air from near the surface survives in the core of thermals. However, regions of enhanced moisture are broader than that of the enhanced updraft speed which is probably a result of detrainment. This picture agrees with the LEM simulations made by Couvreux et al. (2005). The cores of boundary-layer thermal should therefore also contain enhanced concentrations of aerosols. We will examine the characteristics of thermals and other boundary-layer phenomena in this work package and particularly the transport of aerosols by thermals. Measurements of aerosol size distributions and number from aircraft flights made in the BL will be used to see if there are enhanced concentrations of aerosols within the cores of thermals.

The transport does not stop when clouds form. Convection is usually initially inhibited by one or more layers of stable dry air (lids). The clouds have to penetrate past the lids in order to develop from small cumulus into cumulus congestus. It is possible that this occurs as a result of increased surface heating during the morning. It is also possible that the interaction of the cloud with the lid causes the lid to weaken. Detrainment of moisture and hence (processed) aerosols occur at the location of lids (Raymond and Blyth 1986). So it is important to characterise the lids to understand the development of convection (and so forming the link between WP1 with WPs 4 and 5) and the resulting detrained aerosols.

We will focus on the following questions in this Work Package: How far do convective turrets need to penetrate to induce irreversible mixing of boundary layer aerosols into the free troposphere? Is most of the transport due to a few large events or do smaller, but more frequent (and shallower) events contribute? How does orography influence this transport? Do breaking gravity waves make a contribution at all? What influence does the synoptic scale exert?

Synthesis of data gathered from the ground-based radiosonde stations, Salford Doppler lidar and German lidars, UFAM wind profiler, the BAe 146 and from the Meteosat Second Generation (MSG) satellite will be combined with the results of data synthesis and the detailed modelling performed in WP1. Properties of aerosols are being measured at the ground-based stations as detailed in WP2. The BAe 146 will make measurements of aerosol composition and size, CCN and IN, and wind velocity, temperature and humidity during long legs below cloud base. Penetrations will also be made through cloud at all levels beginning just above cloud base. The link will be provided by the German DO-128 (Project Partner, Dr. Ulrich Corsemeier) which will fly in the middle of the boundary layer and just below the top of the boundary layer. The UK Doppler lidar and German lidars and the BAe 146 and German DO-128 will provide information on the properties of the thermals (scale length, frequency, depth and maximum altitude) and the aerosols contained within them. The lidars will enable us to examine better the spatial seperation and development of thermals and their relationship to the surface heteorogeneity.

The distribution of lids will be measured primarily with the UFAM wind profiler, radiosondes and the aerosol lidars at a number of the COPS sites. The wind profiler will also measure the growth of the turbulent boundary layer during the day and record the passage of gravity waves. The lidars will also reveal whether there are elevated layers of aerosols within or between lids. Satellite IR and visible images (primarily from MSG) will be used to determine where convective cloud is breaking through the lids, allowing their position to be related to the model simulations in WP1. Synoptic-scale influences (e.g. from descending dry layers) will be included in this analysis from radiosonde profiles and forecast model analyses. Unravelling the effect of aerosol on cloud development from the effect of changes in atmospheric structure requires that the diurnal evolution of convection be followed for a range of lid morphologies as well as aerosol amounts.

The LEM will be used at about 50-m resolution to examine the properties of the boundary layer structures, small cumulus clouds and the interaction with lids. Sensitivity studies will be performed on the resolution.

5.4 Work Package 4: Microphysics and dynamics of convective clouds

In addition to the details of the orographic flows it is necessary to understand the properties and variability of aerosol particles being drawn into the convective clouds in order that the microphysics and dynamics can be understood, and to establish the influence of aerosols on the vigour and depth of the clouds and the intensity of the precipitation. The latent heat of freezing for example can be sufficient to allow clouds to grow much deeper. The objectives of this work package are:

OBJ 4.1 To quantify the aerosol distributions and composition in cloud inflow and in the cloud environment which are needed for cloud models.

OBJ 4.2 To determine the important microphysical and dynamical processes responsible for the development of precipitation in the orographic clouds.

OBJ 4.3 To determine how the quantity of convective precipitation depends on the details of the aerosols.

OBJ 4.4 To determine how the orographic cumulus congestus clouds process the aerosols, thereby influencing the aerosols ingested into the clouds.

OBJ 4.5 To evaluate the improved representation of the surface forcing in initiating clouds in the CRM and MCRM.

In this work package we aim to understand the microphysics and dynamics of the convective clouds through the growth stage. The mature cloud, which cannot be penetrated by the aircraft, will be studied by the German groups using the various radars. It is likely (although it has not been reported) that most of the precipitation in this region forms through the ice phase. Even so, the production of raindrops through collision and coalescence may be important. The raindrops can speed up the glaciation process by becoming instant rimers thus allowing the H-M process to commence earlier. Understanding the properties of aerosols is crucial for both the formation of cloud drops that play the crucial role in the growth of precipitation particles and the direct production of ice particle by primary nucleation. As such the detailed sub-objectives of this work package are: (a) How does the aerosol entering the cloud affect the development of the cloud and the precipitation? (b) Are raindrops produced by collision and coalescence and, if so, what role do they play in the production of precipitation via the ice phase and the glaciation of the cloud? (c) What is the relative roles of ice nuclei and secondary ice production processes?

These will be addressed through data synthesis in conjunction with model runs. The principal source of data will be from instruments on the FAAM BAe 146 which will be deployed for a period of about 6 weeks. It will be the only aircraft to make measurments of microphysics and dynamics of the developing convective clouds. It will be equipped with the aerosol mass spectrometer (AMS), CCN probe, VACC (volatility) and standard cloud microphysics instruments (PCASP, Cloudscope, Fast FSSP, 2DC, 2DP, Cloud Particle Imager and Small Ice Detector) in order to study the growth of cloud droplets, the formation and growth of ice particles and precipitation particles in the context of the detailed dynamics of the orographic convective clouds.

The DLR POLDIRAD radar will provide maps of the 3D structure of the precipitation within the cumulonimbus clouds. In addition, a series of German Micro Rain Radars will be positioned along a transect across from the Rhine Valley to the west side of the Black Forest mountains. The German and French network radars will supplement the research radars providing information on the larger-scale perspective development and movement of convection in the area. The Montancy French network radar also has dual-polarization capability.

Three different models are required as indicated in Fig. 2. The first two will be run together: The dynamics from the Met Office Cloud Resolving Model (CRM) are required as input for the Explicit Microphysics Model (EMM). The combination will be used to examine the detailed microphysics and dynamics of the convective clouds. The third is the new Microphysics Cloud Resolving Model developed at Leeds which will be used to specifically examine to the influence of aerosols on the intensity of precipitation and the dynamics of the clouds. The following is a description of the models:

- The Met Office CRM now incorporates a consistent three ice, two moment scheme (Lean et al. (2005) and will enable the detailed study of the large convective events which cause strong precipitation and provide 3D wind field for EMM.

- The 1D Explicit Microphysics Model (EMM) is a process model that will be used in a similar way as it has in the past for the mountain thunderstorms of New Mexico. EMM is a 1D detailed ice microphysics model. It was developed as described by Phillips et al. (2001) to investigate the production of splinters during the riming of graupel particles. In this way, EMM treats the microphysics explicitly in a much more detailed manner than in 3D models. It has been developed to include a detailed description of the droplet activation process on mixed organic and inorganic aerosol together with heterogeneous ice nucleation. The model, being developed as part of the APPRAISE programme using results from the AIDA chamber for ice nucleation and the detailed equilibrium description for multicomponent inorganic / organic mixtures developed under DIAC funding provided by the ADDEM model (Topping et al. 2005a; 2005b) will thus base the activation of the cloud droplets and the formation of ice crystals on the observed size resolved composition of the atmospheric aerosol. The model also includes the following microphysical processes:

  a. Activation of cloud droplets from the aerosol.
  b. Growth of raindrops by collision coalescence.
  c. Primary ice nucleation by treating the ice nucleating properties of the aerosol.
  d. Homogeneous nucleation of ice.
  e. Growth of ice particles by habit (by temperature and supersaturation); and aggregation and riming.
  f. Secondary ice production by riming splintering, raindrop freezing and ice crystal evaporation.
  g. Melting of precipitation below the freezing level and recirculation of hydrometeors between neighbouring updraughts and downdraughts.

  It is essential to run the CRM and EMM together as the explicit microphysics model contains a full description of the aerosol activation and ice nucleation processes while the CRM provides the dynamics that drives EMM.

- The 3D Explicit Microphysics Cloud Resolving Model uses the microphysics scheme developed in the MAC3 (Yin et al 2005) in the Met Office Cloud Resolving Model. The model has almost been completed as part of the core APPRAISE grant. It combines many of the attributes of EMM with the advanced 3D dynamics of the the CRM described above. It is essential to run the two schemes together...

  The new MCRM will be able to predict the microphysical properties of the cloud for direct comparison with the *in situ* measurements. MCRM contains a bin-resolved microphysics scheme for aerosols, drops, ice, graupel and aggregates. It considers the processes of drop nucleation, condensation, collision-coalescence, binary break-up, ice nucleation, multiplication, coagulation, accretion and riming. The model also describes the specific mass of aerosol in the air and in hydrometeors (impaction and nucleation scavenging) and the release of aerosol upon complete hydrometeor evaporation. It integrates dynamics and microphysics so the coupling can be studied for different aerosol properties.

The models will also be used to make testable predictions of the sensitivity of the cloud formation to the input aerosol and the effects of the clouds on the residual aerosol population in the free troposphere.

5.5 Work Package 5: Forecasting Convective Precipitation

The predictability of convection over complex terrain is a difficult (and important) question. It depends upon the complex interactions between: 1. Mesoscale uncertainty, probably dominated by uncertainty in upper level potential vorticity (PV) and lower level wet-bulb potential temperature (θ_w); 2. Mesoscale response to resolved surface forcing; 3. Model uncertainties resulting from uncertainty in unresolved processes (especially boundary-layer flows) and surface fluxes; and 4. Model uncertainties resulting from the lack of case-specific information such as CCN and IN spectra, as well as inadequacies in representation of the processes which would use this information. These may have a significant impact on first-generation cloud evolution (if not initiation) and hence initiation of subsequent generations via e.g. downdraft processes.

The objectives of this work package are:

OBJ 5.1 To quantify the predictability of severe convective storms encountered during COPS.

OBJ 5.2 To evaluate the role of different sources of uncertainty that reduce predictability, including (i) mesoscale dynamics setting the environmental conditions, (ii) the boundary layer response to resolved surface forcing, and (iii) the role of microphysics in generating downdrafts and subsequent convection.

OBJ 5.3 To evaluate how the data synthesized from WP1-4 enhance predictability of the UM, and hence to establish the degree to which initialization and boundary data control predictability.

OBJ 5.4 To evaluate the predictability of the Unified Model forecasts of convective storms over a nine month period.

Operational forecast models are reaching the stage where convective storms are explicitly represented. For example, Deutscher Wetterdienst (DWD) are running a forecast system at 2.8 km and the Met Office, UK, are running at 4 km and plan to move to 1.5 km in 2009. Such resolutions are designed to resolve well (most of) the processes leading to the mesoscale organisation of convection. However, the representation of individual convective cells and the flows associated with them is relatively crude. Furthermore, the processes leading to the initiation of individual cells cross the boundary between unresolved and resolved. Convection in such models is thus inherently unpredictable.

The work of Done et al. (2006) suggests a link between predictability and convective equilibrium. This is essentially connected to the scale over which convective inhibition is reduced to a negligible amount. If this scale is large compared with the cloud scale, the convective response, driven by small-scale variability, behaves more like a single realisation of a system close to convective equilibrium. A convection parametrization based on equilibrium assumptions provides a good estimate of the mean of an ensemble of simulations. In contrast, if the scale is small compared with the cloud scale, the response is highly non-equilibrium, and the equilibrium convection scheme fails. However, if a model has sufficiently high resolution to predict the region of destabilisation, the convection becomes highly predictable. This is more likely to be the case where variations in surface forcing modifies the strong Convective Inhibition (CIN) to generate locally strong destabilisation. It is therefore possible that convective storms may be more predictable in complex terrain in some situations [Pete OK??] than over flat, essentially uniform terrain. On the other hand, the inherent small-scale heterogeneity associated with complex terrain may counteract this increased predictability; i.e. the resolution of the model and/or input data may be insufficient to realise the high predictability. Furthermore, significant uncertainty remains in the meso-α scale which can interact with and be amplified by small-scale forcing (for example, if the larger scale flow has a Froude number close to a critical value (Vosper, 200?)). Small uncertainty at a larger scale could lead to a very wide range of behaviours at small scales.

This work package will focus on predictability within the Unified Model (UM) at O(1 km) resolution. An ensemble approach will be taken to the simulation of selected COPS events. It will be essential to quantify the magnitude of different sources of uncertainty. Mesoscale uncertainty will be derived using initial and boundary data from the Met Office Global and Regional Ensemble Prediction System (MOGREPS). Uncertainty in small-scale surface forcing will be simulated by varying the surface fluxes; the amplitude and scale of this variability will be informed by results from COPS field data and idealised results from Work Package 1. Uncertainty in microphysics will be informed by results from Work Package 4.

The US ARM mobile facility will be operating continuously at supersite M from 1 October to 31 December 2007 providing high resolution (1 minute/60m) profiles. US scientists have agreed to incorporate the 'CloudNET' analysis developed at Reading within ARM; variables such as cloud fraction liquid and ice water content are retrieved from the observed profiles and then compared with the values of these prognostic variables held within operational forecasting models (see www.cloud-net.org and Illingworth et al., 2007). Monthly skill scores for model performance will be derived for a range of forecast lead times so that the impact of any proposed changes to cloud parameterisation schemes in the UM can be rapidly and objectively quantified and the degree of predictability established.

This work package can be seen as an integration of results from the other work packages and forms the bedrock to the design of a practical ensemble based forecast system. It is anticipated that the results (and methodology) will be of direct value in determining the emphasis to be placed on different processes in a practical ensemble system.

6. Associated Collaborations and Co-Funding

6.1 Roles of the Project Partners

Professor Andreas Behrendt chairs the COPS international scientific steering committee and will provide access to the wide range of COPS observing platforms described throughout this proposal. Dr. Ulrich Corsemeier is chairing the group that coordinates aircraft measurements. He is responsible for the measurements with the German DO-128, which will provide measurements in the BL of temperature, water vapour, wind velocities and chemical species. Mr. Peter Clark is head of the Met Office section of the Joint Centre for Mesoscale Meteorology at the University of Reading and is responsible for the development of the Met Office Unified Model convection-resolving capability. Through his collaboration the project will gain access to a vast amount of experience and advice in using the UM and in return, Mr. Clark will be the user within the Met Office of the scientific outputs of the project. Mr. Phil Brown is Manager of Cloud Physics Research at the Met Office and will lead the Met Office collaboration with scientists at Leeds and Manchester on analysis of the cloud physics data gathered with the BAe 146 aircraft.

6.2 Integration into COPS Field Campaign

In addition to the collaborations made possible through the Project Partners Profs. Behrendt and Corsemeier, the PI Prof. Alan Blyth and co-PI, Prof Stephen Mobbs are members of the COPS international scientific steering committee. Through this, UK-COPS will become a full and active member of the COPS community.

7. Stewardship of Data and Dissemination of Results

Data management procedures are described in the separate management structures document, Data acquired from all sources for the IOPs will be converted to a format suitable for archiving at the British Atmospheric Data Centre (BADC). Where appropriate, non-operational data (e.g. radiosonde data) will also be transferred in rapid time into a form suitable for assimilation into the Met Office forecasting model.

Through the full integration of UK-COPS into COPS, the UK-COPS project members will gain access to the full COPS dataset (under COPS data policy rules). In return, COPS PIs and co-Is will gain access to the UK-COPS data and will be able to make use of it under NERC data policy rules.

The results of the research will be widely disseminated through participation in scientific conferences and publication in peer reviewed journals.

8. Beneficiaries of the Research

This is stated on a JeS form.

9. Knowledge Transfer

Two knowledge transfer activities are already planned and allowed for in the request for resources:

- (i) The COPS community will hold a summer school for students during the main observational phase. This will make use of the large and varied collection of observing platforms to introduce students to atmospheric measurement and also to fundamental aspects of meteorology such as convection, boundary-layer processes and orographic processes, We will take an active part in this summer school, both through cooperation using our instruments and through providing staff to teach. We are requesting funding for up to 10 NERC-funded students to attend the summer school.
- (ii) In order to ensure efficient take-up of the outcomes of the research by the Met Office and other weather services, we will hold a collaborative workshop at the end of the project specifically to discuss how best to use the results gained to improve forecasting models.

10. References