1 Introduction

The problem of forecasting convective precipitation is important because of the increasing amounts of damage being caused by flooding, and also the winds associated with the storms. A number of storms 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 is very low at present. Specifically, the forecast accuracy of a mesoscale model and object-oriented models is strongly dependent on the accuracy of the forecast of the initial development.

This proposal is concerned primarily with research aimed at understanding the mechanisms responsible for the initiation of precipitating convection. It is for the conduct and exploitation of a special observational programme involving a consortium of universities which will not only provide better understanding, but will also provide unique datasets for validation and development of the Met Office's mesoscale numerical weather forecast model. This bid is timely for several reasons: (a) as a result of a successful Joint Infrastructure (JIF) bid the various components of the Universities Facility for Atmospheric Measurements (UFAM), operated by several UK Universities, will be completely operational and ready to address the challenging problems for which they were designed; (b) The Met Office's mesoscale model is now non-hydrostatic, its resolution has been improved and it is now ready to be tested with a grid length of 1 km using detailed mesoscale data with a grid length of 1 km; (c) 4DVAR, a 4-dimensional data assimilation scheme, will be ready to be tested by the middle of 2003 - both (b) and (c) represent big advances in modelling capability; (d) as already noted, severe floods are becoming more of a major problem and forecasting the position and intensity of the convective systems is increasingly important; and (e) very little theoretical or observational research has been done on the *initiation* of precipitating convection in the UK.

This consortium bid is one of several linked steps that are being taken by NERC scientists to address the problem of flood forecasting. The first is a small project funded by the NERC Centres for Atmospheric Science on the development of improved data assimilation schemes in collaboration with the Met Office in the Joint Centre for Mesoscale Meteorology. The second is an EPSRC/EA/DEFRA/UKWIR programme aimed at flooding issues concerning the precipitation once it has reached the ground. It aims to develop operational procedures that may be used by the EA and others to forecast floods. Further developments will occur through a proposal to be submitted to NERC by Prof C. Collier for an end-to-end NERC thematic programme covering several aspects of NERC science called Flood Risk from Extreme Events (FREE) which aims to focus on the predictability of environmental parameters including rainfall, and upon the transfer functions relating these parameters to the quantities that particular users need. FREE will be a major programme linking the hydrological, atmospheric and other components within a total system. To improve the prospects of success in FREE it will be important first to address the weakest links in this system. This is being done for the hydrological side through the EPSRC/EA/DEFRA/UKWIR programme. A parallel activity is required for the atmosphere because, as stated recently by Prof R Krzysztofowicz, the representative of the World Meteorological Organization's Hydrology and Water Resources Programme, the quantitative forecasting of precipitation represents the last frontier in hydrology, with future precipitation being the predominant source of uncertainty in hydrological forecasts. The initiation of convection is the weakest link on the atmospheric side and so the present proposal is regarded as an essential pilot project to underpin FREE. There will also be a link between the present proposal and the NERC lowland catchment research (LOCAR) programme in the event that a convective storm develops during the project over the instrumented Frome/Piddle or Pang/Lambourne catchments. Furthermore, there will be a link between the current proposal and a proposal to be submitted simultaneously to NERC to study the development of ice and precipitation in convective clouds over the south of England.

A considerable body of research now exists in the literature regarding the structure of convective clouds, the important physical processes operating within them and the processes leading to their propagation. Mechanisms leading to the development of long-lived systems and, especially, their mesoscale organization are broadly understood. However, much of this work has concentrated on tropical systems or continental extra-tropical mesoscale convective systems rather than the smaller, but sometimes locally intense convective systems encountered in the UK. Moreover, the understanding has, to date, not been translated into an ability to forecast quantitatively the development and propagation of individual convective storms. In part this is because the computer power necessary to simulate such systems has made real-time forecasting impracticable. This limitation will vanish with the next generation of Met Office supercomputers to arrive in 2003. Once the practical computational constraint is overcome, there will remain the question of what observations are required to initialize the mesoscale models. And, equally importantly, some fundamental scientific problems also remain.

2. Overarching Scientific Questions and the Need for a Consortium Bid

The most poorly understood aspect of forecasting convection is the initiation of new convective cells. There are three key aspects to this problem.

(i) What are the localized perturbations in the boundary layer that trigger new convective cells? Candidate processes include horizontal convergence and locally enhanced uplift directly associated with orography, land/sea contrasts, and land-use heterogeneity, as well as variability in temperature and especially moisture, due to variations in surface characteristics and soil moisture, that lead to variability in boundary-layer convection and conditional instability.

(ii) What are the mesoscale forcing processes in the troposphere that create regions sensitive to triggering? These will include mesoscale vortices and dry intrusions leading to split frontal structures and regions of conditional instability.

(iii) How do local modifications of the atmosphere by previous convective cells influence or even dominate over the other perturbations? Convective clouds produce cold pools with associated lifting, as well as tropospheric moisture anomalies and transient static-stability variations due to convectively generated gravity waves.

In addition to the fundamental need to characterise the physical processes responsible for convective initiation, there is the important practical problem of how to represent these processes in models and data assimilation schemes that only represent a subset of the relevant scales. Data assimilation methods must be developed that retain as much fine-scale information as possible, while models must allow a physically reasonable and self-consistent interaction of resolved scales with sub-grid parameterisation schemes.

We propose a two-stage project that will address both the fundamental and practical problems. We will conduct a field campaign over southern England during the summer of 2004 in Phase 1 of this project. The results of the field campaign will be used in Phase 2 to develop understanding of the processes associated with initiation of precipitating convection, and evaluate and improve the performance of high-resolution models and data assimilation techniques. The field campaign will have some similarities to the International H_2O Project (IHOP; Dr. D. Parsons), which was a field experiment over the Southern Great Plains of the United States during May and June of 2002. However, different mechanisms of initiation occur in the more maritime convective environment of the UK. Some previous research has been carried out in the UK, mainly using satellite images, routine radar data, limited radiosonde ascents and post-event modelling with modest resolution. However, a dedicated field campaign to investigate the initiation of precipitating convection has never before been carried out in the UK. A key feature of the research proposed in this consortium bid is to bring together a large range of newly acquired observational equipment, along with the Met Office's new high-resolution model and new data assimilation techniques, to focus on the initiation of precipitating convection.

In order to answer the scientific questions posed by convection initiation, contributions are required in the areas of atmospheric measurements, mesoscale modelling and data assimilation. So multifaceted are these contributions that it has been necessary to put together a consortium of seven University groups, alongside groups of collaborators from the Met Office. These may be grouped

UFAM, is already a consortium in its own right; five of the seven UFAM university groups are involved in this proposal (see later). Since the proposed research hinges on the field campaign, the Manager of UFAM, Dr. Alan Blyth, is leading the overall effort in collaboration with the Director of UFAM, Prof. Keith Browning. The second group is based at the Joint Centre for Mesoscale Meteorology (JCMM), University of Reading where the Met Office's high-resolution mesoscale model is being developed. This group is led by Mr. Peter Clark and Prof. Paul Mason. The data assimilation group is jointly led by Prof. Stephen Mobbs, University of Leeds, Prof. Mike Cullen, Dept. of Mathematics, University of Reading and Dr. Ian Roulstone from the JCMM. All of these groups will be involved in both phases of the project.

3 Science Background

The initiation of precipitating convection in the UK is most frequently caused by lifting of high-θ_w boundary-layer air which is capped by a high-θ lid causing convective inhibition (CIN), and which has been overrun by low-θ_w air. The necessary lifting can occur due to, for example, topography, coastal and land-surface induced circulations and upper-level potential-vorticity anomalies. The specific location of the new convective outbreaks may be due to mesoscale variability at low levels and/or high levels and we shall consider these in turn.

(i) Localised low-level forcing of the initiation of first-generation convective cells

Harrold and Browning (1971) observed aggregates of "inverted-cup" echoes from the upper edges of individual thermals and clouds in the boundary-layer and above using a 3 GHz (S-band) radar. They found that precipitating clouds formed only within areas of deeper convection (ADC) which had persisted for some hours, and the tendency for showers to break out in clusters appeared to be a result of the pre-existing organization of dry convection. Indeed, they suggested that "by using a high-power radar to identify ADCs it may be possible to forecast the location of outbreaks of showers and thunderstorms more precisely than is possible at present." The instruments and the modelling capability now exist to test this prediction as will be explained below.

The ADCs that Harrold and Browning (1971) observed were closely related to the high ground of the Cotswold Hills in southern England suggesting that topography can play a significant role in their formation. Tian et al. (2003) recently examined cellular convection over the Chilterns, also in southern England, using the Chilbolton Advanced Meteorological Radar (CAMRa) and the BLASIUS (Boundary Layer Above Stationary Inhomogeneous Uneven Surfaces) numerical model. The model results discussed by Tian et al. (2003) and Tian and Parker (2002) showed that topographically-enhanced vertical motion persisted all day in some areas, albeit transiently at times, and acted to modulate the convective structures later in the day.

In addition to mechanical forcing, the hills or mountains heated by the sun can act as an elevated heat-island, with the air over the summits having a higher potential temperature than over the lowlands. Raymond and Wilkening (1980), for example, found that air flow over a mountain range in New Mexico had the general character of a toroidal circulation superimposed on the ambient wind. The upward mesoscale flow above the mountain was characterised by a series of updrafts and downdrafts with a weak net upward flow. Harrold and Browning suggested that this was probably the effect responsible for the deeper convection forming preferentially over the Cotswolds. Variations in the concentration of water vapour in the pre-convective environment on the convective scale, such as observed by Weckworth et al. (1999), have been linked to the initiation of severe convection in the US. It is clear from previous studies of precipitating convection in the UK, that it is also important to characterise water vapour in the lower troposphere over the UK.

(ii) Localised upper-level forcing of the initiation of first-generation convective cells

Particularly favourable conditions for precipitating convection exist in the vicinity of the UK when low-θ_w air from behind an upper-level trough overruns high-θ_w boundary-layer air (Browning and Roberts 1994) generating potential instability, where deep convection can be triggered if there is sufficient lifting. Sometimes (e.g. Hill and Browning 1987; Browning and Roberts 1994), the overrunning and the lifting are associated with a small upper-level vortex in the vicinity of a trailing

(1982) where the leading edge of the dry intrusion (the upper cold front) runs ahead of the surface cold front formed by the boundary of the high-θ_w surface air. Browning and Roberts (1994) point out that it is not uncommon for thunderstorm outbreaks to be associated with dry intrusions, which can be detected in the water vapour channel on the Meteosat and other satellites.

The high-θ_w air in the boundary layer is usually trapped beneath a capping inversion of warm air. This lid ensures that the convective available potential energy (CAPE) is not immediately released by smaller convection, but is allowed to build up until substantial amounts of CAPE are available for deeper precipitating convection if there is a suitable triggering. Browning and Roberts (1995) examined details of the cold-frontal thunderstorms observed by Browning and Roberts (1994). Lines of rope clouds were found with smooth tops which became higher with time and distance north. Some of the clouds eventually erupted into thunderstorms at the northern end. Their analysis suggested that the rope clouds were caused by lines of convergence in the lower troposphere. The cloudy high-θ_w boundary-layer air was initially capped by a stable layer which weakened with time owing to lifting and was eventually breached. The deepening of this convective boundary layer occurred as a result of the lifting induced by an upper-level vortex (PV anomaly) as explained by Hoskins et al. (1985). However, the large-scale ascent was modulated by the mesoscale convergence responsible for the rope clouds. As in the rolls observed and modelled by Tien et al. (2003), such differential lifting provides a means for initiating precipitating convection locally, while restraining it elsewhere.

Extremes of the conditions described above occur in the so-called “Spanish plume” a kind of situation studied by Carlson and Ludlam (1968). High-θ_w air in the boundary layer from France is trapped beneath a high-θ lid in air coming from Spanish plateau, causing convective inhibition (CIN). Particularly severe thunderstorms can be initiated and can develop into mesoscale convective systems (MCS). Browning and Hill (1984) gives an example of such a case.

(iii) Localised forcing of the triggering of second-generation convective cells

Evaporation of the precipitation generated by cumulonimbus cells leads to chilling of the low-level air beneath the storm, and a ‘cold pool’ of air develops at the surface. The cold pool spreads outwards due to its negative buoyancy and intrudes beneath the warmer ambient air. It has been known for some years that secondary convection is often triggered at the convergence lines (gust fronts) at the head of the cold pool, through lifting of the warm environmental air. A cold pool will tend to spread outwards in all directions from the parent storm, but second-generation (i.e. daughter) cells generally appear at preferred locations relative to the parent, and persistent triggering on one flank of a system can lead to multi-cellular storms which may last far longer than the lifetimes of individual cells within the system. In some cases, such as the flood-producing Hampstead storm (Thorpe and Miller 1978), it is thought that the interaction of the convergence line with the ambient flow can lead to a stationary system, in which new cells are repeatedly generated in the same location, leading to extreme rainfall over a relatively long time. Considerable observational and theoretical work (e.g. Thorpe et al. 1980; Rotunno et al. 1988; Parker 1996; 1998) has been devoted to determining the conditions favourable to storm triggering at the gust front. But despite our broad-brush understanding of this process of secondary triggering, application of these ideas in quantitative prediction is not yet successful and the present Met Office mesoscale forecast model appears incapable of representing this process (Done et al. 2002). Problems in applying the simple models to real cases include difficulties in specifying the source conditions for the cold pool (e.g. Parker, 1998), effects of the ambient shear and stratification, and the possible role of surface fluxes in modifying the flow.

4 Scientific Goals

The primary goals of this research are *to understand how precipitating convection is initiated in the maritime environment of the UK* and *to use this understanding to improve the initiation of convection in high-resolution mesoscale models.* There are two integrated phases to the research which address these goals. A field campaign is proposed in Phase 1 and a further analysis and modelling project to provide understanding of the initiation processed and to exploit the resulting data in improving high-resolution models is proposed in Phase 2. Phase 2 will begin during the field campaign in that mesoscale model output will be used to provide testable predictions of events.

Phase 1 – Field Campaign

We aim to observe, and statistically characterise, the variations in convergence, wind shear, virtual temperature, water vapour, stratification, etc in the lower troposphere. Observations will be made on the mesoscale (length scale $l > 5$ km) and the small scale ($l < 5$ km) in order to determine the mechanisms responsible for the initiation of precipitating convection.

Phase 2 – Data Exploitation

We will use the field campaign results

- to improve understanding of the initiation of convection, particularly how much can be explained by a combination of topography and land-use heterogeneity with balanced dynamics, and how much is stochastic in nature;
- to evaluate and improve the performance of high-resolution models by improving parameterisations in a convective environment and using ensembles for validation and prediction;
- to incorporate all the mesoscale observations effectively in the data assimilation, including quality control issues
- to identify the key structures that must be successfully represented to make the larger-scale environment consistent with observations of convection

We are concerned with both *primary* initiation (Sec 3(i) and (ii)) and *secondary* initiation (Sec 3(iii)). The two forms of initiation depend on different scientific processes and both will be studied observationally. Where the development of modelling and assimilation techniques are concerned, the technical developments required for the two kinds of initiation are likely to be very different. Priority will be given to the problem of primary initiation, assuming we are successful in obtaining good IOPs of such events (primary initiation occurs less frequently over southern England than secondary initiation).

5 Work Plan

We propose to conduct a field campaign centred on the radar at Chilbolton in the south of England during June, July and August, 2004. Figure 1 illustrates the location of Chilbolton and the location of the ground-based instruments that will be used in the project. A key feature of the campaign is the new 1275 MHz radar which, on convective summer days, will be capable of observing to a range of 60 km, small-scale boundary-layer features, such as thermals, as well as the horizontal variations in wind speed and direction associated with coastal and land-surface induced circulations on the mesoscale. Measurements of the detailed 3-D distribution of precipitation intensity and type, and associated velocity distributions, will be obtained out to a range of 100 km from the 3 GHz Chilbolton polarisation Doppler radar. Polarisation and Doppler data will also be obtained from the new Kent radar. The dynamics of the boundary layer and free troposphere will also be intensively sampled within the 100 km radius range of the 3 GHz Chilbolton radar using the UFAM and Met Office wind profilers, the UFAM mobile sodars and Doppler lidar, and the radars, lidar and radiometers at Chilbolton, plus a network of Met Office and UFAM radiosondes and a proposed mesonet system. In addition, the UFAM/UMIST Cessna aircraft will make high-resolution measurements in the boundary layer and above of temperature, humidity and 3-D wind.

To make progress it is important to understand the mechanisms that lead to convective triggering both in the real world and in a model system. This requires a model capable of simulating real-world cases as well as more idealised scenarios. The Met Office's Unified Model (UM, Cullen et al. 1997) forms a very suitable tool; it now has a non-hydrostatic deep-atmosphere dynamical core which has been shown capable of simulating convection. In its operational form it provides routine analyses and forecasts over NW Europe at approximately 12 km resolution - these are insufficient for studying the details of triggering but have been shown to provide a realistic mesoscale environment for convection (Done et al. 2002). Furthermore, the model is being adapted to simulate convection directly, including more comprehensive microphysics appropriate for convective scales, and has already produced realistic looking results in case studies over the UK nested from 12 km through 4 km to 1 km resolution. In addition to its direct impact on model evolution, the availability of more comprehensive microphysics will enable the development of diagnostic tools to predict radar

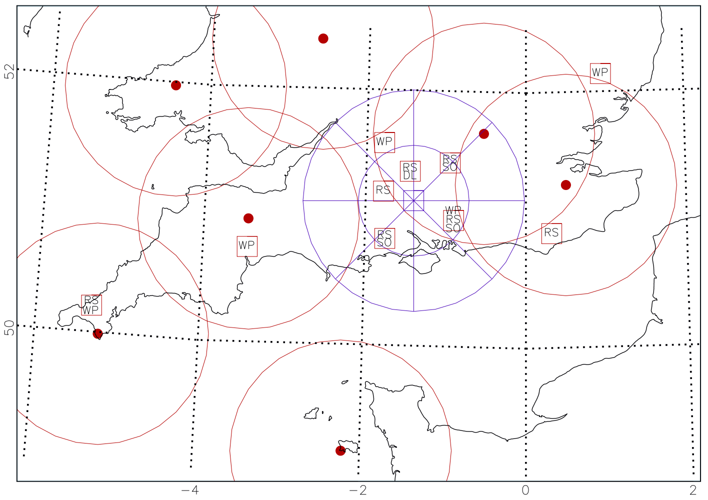

Figure 1: *Position of ground-based instruments in the field campaign. The key is as follows: Chilbolton radars – small square with range rings and large cross; Met Office radars – dot with range rings; WP – wind profilers; RS – radiosonde stations; SO – sodar; DL – Doppler lidar. The UFAM instruments are all within the range covered by the Chilbolton radars.*

reflectivity and associated variables which may be directly validated against the Chilbolton radar. This will form the forward model which may form the basis of variational approaches to assimilation of radar reflectivity data in Phase 2.

The model will be used in several stages. During field campaigns, forecast data from the operational model will be used in real time to predict general regions where convective instability may occur. A variety of diagnostic tools will be used beyond the model's own predicted convection, including examination of predicted Convectively Available Potential Energy (CAPE) and Convective Inhibition (CIN). This will be used as guidance for the deployment of radar observing systems and, in particular, the aircraft measurements to choose regions where triggering is thought most likely to occur. Subsequent operational analyses will be used to verify this guidance along with the collected observations.

The proposed research is subdivided in Tables 1 and 2 into separate inter-related work packages for Phases 1 and 2 respectively. The tables describe the tasks which will be performed, the investigators and UFAM Instrument Scientists (IS) involved, the personnel support requested, and the deliverables for each package. A detailed description of each package now follows.

5.1 The Field Campaign

5.1.1 WP1A: Field campaign coordination

See later under Section 6.3.

5.1.2 WP1B: Radars

The 25 m dish at Chilbolton will be used to provide: (i) maps of low-level refractivity fields, using the technique of Fabrey et al. (1997) to reveal low-level inhomogeneities of moisture, from the absolute phase change of stationary ground clutter at 3 GHz obtained from a series of low-elevation PPI scans; (ii) the evolution of the depth and dynamic properties of the individual elements in the developing boundary layer using the techniques of Harrold and Browning (1971) to reveal the clear-air echoes obtained at 1275 MHz with a series of round-the-clock RHI scans; and (iii) maps of the 3D structure of cumulonimbus clouds and the precipitation type during the evolution of the cells.

(i) The refractivity measurements will be derived from the S-Band radar exploiting the phase change of 7.2°/km which occurs for a one part per million change in air refractive index. A map of refractivity can be built up by recording the phase changes of ground targets at various distances and azimuths. For temperatures above 20°C, changes in refractive index are dominated by the humidity, with a 1 ppm change equivalent to about 1% change in relative humidity. The data system at Chilbolton now records the absolute phase of the returns together with the rms variation in phase for a standard quarter second (64 H polarisation pulses and 64 V pulses). Observations have shown that good stationary ground targets with low phase noise can be identified from a phase return with a standard deviation of less than 2°.

(ii) The 1275 MHz transmitter on the Chilbolton dish will detect and measure the Doppler shift from clear-air Bragg-scatter returns resulting from humidity and temperature gradients on the scale of half the radar wavelengths. These gradients diminish fairly abruptly above the boundary layer thereby enabling the depth of the boundary layer to be mapped as well as the location of individual thermals. In summer-time convective situations returns in the boundary layer should be attained out to a range of 60 km.

(iii) The S-Band radar at Chilbolton provides both Doppler and polarization information. Such data obtained during volume scans will be analysed to describe the distribution of precipitation type and intensity, as well as aspects of the associated airflow. These analyses will be related to measurements from the other instruments with a view to determining how the interactions between existing convective cells and their environment influence the development of secondary convective cells.

The overall scanning procedure will be as follows. (i) A complete low-elevation PPI scan will be made taking six minutes at a scanning rate of 1 deg/second, to measure the phase of the ground clutter and hence the near ground-level refractivity field and thus the moisture field. (ii) The PPI will be interspersed with a series of round-the-clock RHIs up to 5 degrees at 15-deg azimuth intervals

Work package	TASK	Scientists	Personnel Support	Deliverables
WP1A	Field campaign co-ordination including pre-planning	Blyth Browning Clark		Forecasting & scheduling activities based at Reading control centre
WP1B	Operation & analysis of 1275 MHz & 3 GHz, 35 GHz and 94 GHz radars at Chilbolton and MO radars, including new Kent radar	Illingworth, Kitchen, Pavelin (IS[†])	$\frac{1}{2}$PDRA with WP2A[‡] (Reading)	(a) Maps of BL depth & structure (b) Maps of horizontal variability of humidity (c) Maps of 3D structure and precipitation type during evolution of cells (d) Structure and statistical properties of thermals and small cumulus clouds
WP1C	Deployment and operation of wind and thermodynamic sounding systems, analysis & interpretation of data	Parker, Vaughan, Kilburn, Norton (IS), Brooks (IS), Clark	$\frac{1}{2}$PDRA with WP2D (Leeds), $\frac{1}{2}$ Student with WP2E (Leeds), $\frac{1}{2}$PDRA with WP2F (Wales)	Time-height records from wind profilers, and radiosondes and combined analysis of data from deliverables WP1B(b), WP1C, WP1D(b), WP1E & WP1G
WP1D	Deployment and operation of surface mesonet & sodars, analysis & interpretation of data	Mobbs, Brooks (IS)	$\frac{1}{2}$PDRA with WP2C (Leeds), 4 months Tech	(a) Maps of surface variables (b) Time-height records from sodars
WP1E	Operation of Cessna aircraft, analysis & interpretation of data	Gallagher, Flynn (IS)	$\frac{1}{2}$PDRA with WP2E (UMIST)	Maps of temperature & humidity & winds in the BL
WP1F	Operation of Doppler Lidar, analysis & interpretation of data	Collier, Bozier (IS)	$\frac{1}{2}$PDRA with WP2G (Salford)	High time-resolution time-height records of thermal structure and associated vertical air velocity associated with BL convection
WP1G	Operation of GPS sounders & analysis of data	Watson, Clark	3-month Tech	Time records of total-column WV

[†] Instrument Scientists (IS) have been funded separately through the UFAM JIF award. Only travel and subsistence for the field campaign is requested in this proposal.

[‡] All PDRA's are assumed to be for 36 months. The same PDRA would perform the tasks in the shared work packages.

Table 1: Table describing work packages in Phase 1

Work Package	TASK	Scientists	Personnel Support	Deliverables
WP2A	Case study synthesis of observational datasets and verification of high-resolution model	Browning, Clark, Blyth	$\frac{1}{2}$PDRA with WP1B (Reading)	Detailed description of the convective events and their mesoscale environment and of the ability of the model to reproduce them
WP2B	Development of high-resolution model	Mason, Clark	PDRA (Reading)†	Improved version of high resolution modelling system
WP2C	Development of mesoscale data assimilation and initialisation techniques	Mobbs, Dance, Roulstone, Bebbington, Cullen	$\frac{1}{2}$PDRA with WP1D (Leeds), Student (Essex)	
WP2D	Case study synthesis of information on thermals and small cumulus clouds	Blyth, Parker, Craig, Collier, Kilburn	$\frac{1}{2}$PDRA with WP1C (Leeds)	Understanding role of sub-km scale convective elements and input into design of stochastic model
WP2E	Case study synthesis of information on the effects of topography, orography and land-use heterogeneity	Parker, Blyth, Gallagher	$\frac{1}{2}$student with WP1C (Leeds), $\frac{1}{2}$PDRA with WP1E (UMIST),	Understanding of the influence of topography, orography and land-use heterogeneity on the initiation of convection and input into improving its representation in models
WP2F	Case study synthesis of dry intrusions	Vaughan	$\frac{1}{2}$PDRA with WP1C (Wales)	Understanding of the properties of dry intrusions and their influence on convective initiation
WP2G	Evaluation and development of conceptual models that may be useful for forecasting applications	Collier, Hand	$\frac{1}{2}$PDRA with WP1F (Salford)	Improvement of conceptual models relating to the initiation of secondary convective cells

† Supervision of the PDRA will be the responsibility of Prof. Anthony Illingworth until Dr. Paul Mason joins the University of Reading on 1 March 2003.

Table 2: Table describing work packages in Phase 2.

taking an extra 4 minutes. The total scan sequence would be repeated with a ten-minute cycle time. Alternatively, extra sensitivity for the boundary-layer scanning can be achieved by slowing the RHI scans to 0.5 deg/sec which would increase the scan sequence time from 10 to 14 mins.

The cloud radars (35 GHz and 94 GHz) will be used to observe the time sequence of the detailed dynamical structure of the small cumulus clouds which form over Chilbolton and the development of the depth of the clouds.

The operational weather radar network in England and Wales currently consists of eight radars. Projects are in progress to add a further three over the next two years. Data at 2 km / 5 minute resolution is available over most of the land area and at 1 km / 5 minute resolution within 50 km of each radar. The radars currently scan at four different elevation angles but this will be increased to eight during 2003 at some sites. The new radar scheduled for installation in Kent during 2003 will, like the Chilbolton radar, have a dual-polarisation capability.

5.1.3 WP1C: Wind Profilers and Radiosondes

The UFAM mobile wind profiler operated by the University of Wales (Aberystwyth) is a “clear-air” three panel 1290 MHz UHF Doppler radar system designed by Degreane Horizon to measure both wind speed and direction 24 hours a day under all weather conditions. Like the Chilbolton radar it detects irregularities in backscattered signals due to refractive index inhomogenieties caused by turbulence. The wind profiler consists of three panels to emit and receive three separate beams one vertical from the central panel and the other two at an elevation of 73°to enable full wind vectors to be calculated. Each panel is an array of eight aerials every one being an assembly of eight collinear dipoles.

The Met Office operates three wind profilers, at Camborne, Dunkeswell and Wattisham (see Fig. 1) as part of the COST Wind Initiative for a Network Demonstration in Europe (CWINDE). The profiler at Camborne is a Lower Atmospheric Profiler (LAP). The LAP’s operating frequency is centered at 915 MHz and it is able to provide wind measurements in the clear air from about 100 m up to at least 3 km above the surface (higher during precipitation). The operating frequency of the Dunkeswell and Wattisham profilers is 1290 MHz. The low mode provides high-resolution wind information up to 2 km above the surface, while the high mode, with 210 m resolution can see up to 8 km under appropriate conditions. In addition a 915 MHz Met Office system may be available to deploy during the field campaign. Data are received on a real-time basis from the profilers and plots are generated and updated every 30 minutes. In addition, there are profilers in northern France, in the Netherlands and elsewhere in Europe.

The UK Met Office operate two manned and four Vaisala Autosonde radiosonde Stations routinely. Sondes are released daily at 00 and 12 hrs GMT. The two of most relevance to this project are at Camborne in Cornwall and Herstmonceux in East Sussex (see Fig. 1). Additional ascents will be sought from these stations as well as from the Met Office site at Larkhill (near Chilbolton). Two UFAM and one Met Office mobile radiosonde systems will also be deployed within the 100 km range of the Chilbolton 3 GHz radar, as illustrated in Fig. 1. The first sondes will be released at 06:00 GMT on “good-forecast” days. Two-hourly sondes will be released during periods of interest. There is also a no-wind radiosonde system at the University of Reading. There are seven operational upper-air stations which release sondes at 00:00 and 12:00 GMT in France, one station in each of Belgium and the Netherlands and six in Spain. All data are available in real-time on the University of Wyoming web site.

5.1.4 WP1D: Surface mesonet and sodars

Surface-based observations from automatic weather stations can provide data in a form that is directly usable in data assimilation systems to improve forecasts. A network of 36 automatic weather stations (the *mesonet*) will be constructed with typical separation of about 20 km for use close to Chilbolton. Asynchronous communications with a base station will be achieved using cellphone technology, providing regular and event-driven data. Each station will measure temperature, humidity, pressure, wind, and radiation. These will be most useful in providing information on the small scale within range of the Chilbolton radar, on the absolute values and the variations in surface temperature, humidity, pressure and winds. The mesonet is important for determining the effects of heterogeneity in surface characteristics and soil moisture, and for observing local convergence lines. It will also be used for testing new techniques to combine gridded surface measurements with radar data for assimilation. The feasibility of real-time data assimilation will be tested.

Three UFAM Scintec sodars operated by the School of Environment, University of Leeds will be used to provide a time-height record of the 3D wind in the boundary layer. They have a maximum range of between 500 and 1000 m depending on atmospheric conditions. A typical averaging time required to produce meaningful profiles is about 10 min. The lowest measurement height is 20 m, the maximum number of layers is 100 and the thickness of the measurement layers varies between 10 to 250 m. The sodars are designed to be operated continuously and will supplement the profiles obtained in WP1C.

5.1.5 WP1E: Cessna aircraft

The Cessna aircraft will also be used to map out the temperature and humidity structure of the boundary layer and to study the vertical structure of individual ADC's (Areas of Deeper Convection). It is equipped with standard instruments to measure position, *in-situ* temperature and dew point. It has a cruise speed of 55 m s^{-1}, a range of 1400 km, an endurance of about 4 - 5 hrs and a ceiling of about 4 km. The Cessna will fly flexibly in a manner to cover the area covered by the Chilbolton radar to measure the horizontal structure in the boundary layer. Flights at different altitudes can be made through particular regions of interest, sometimes beyond the range of the Chilbolton radar if necessary. The aircraft will make flights from its home base (Woodford) to ease the logistical problems and to cut down on cost. However, it can easily be refuelled at one of many small airports in the vicinity of Chilbolton.

5.1.6 WP1F: Doppler Lidar

The Salford Doppler lidar system will be used at a fixed location within range of the Chilbolton radar to observe the detailed wind and turbulence structure of boundary-layer features, such as convergence lines, thermals and small cumulus clouds. It uses a CO_2 laser with a wavelength of 10.6 μm. It has a pulse energy of 70 mJ and a pulse repetition rate of 9 Hz. The minimum and maximum range are 800 m and 9 km respectively, and the range resolution is 112 m. Further details are discussed in Pearson and Collier (1999). The lidar system is housed within a mobile unit which is equipped with a scanner capable of performing scans at rates of up to 6 deg per second. The scanner is capable of scanning from 0 - 42 deg in elevation and 0 - 295 deg in azimuth. A third mirror enables the lidar beam to be pointed vertically and this will be used to obtain time-height records of vertical air velocity.

5.1.7 WP1G: GPS sounders

A technique to measure the integrated water vapour (IWV) relies on the delay of radio signals received from Global Positioning System (GPS) satellites. The IWV represents the total water vapour content of atmosphere along the path between the GPS satellite and the receiver; most of this is contained within the lowest few kilometres of the atmosphere. As a GPS signal passes through the troposphere the velocity of the signal will be reduced due to water vapour and oxygen in the troposphere. The delays to the individual satellites are combined into a zenith delay measurement using a mapping function. The delay due to oxygen can be adequately modelled if the atmospheric pressure at ground level is known. The remaining delay due to water vapour is then converted into a measure of water vapour content. The mapping function relies upon the assumption of a horizontally stratified atmosphere, which is often not entirely valid. The University of Bath run two GPS systems at Chilbolton and Sparsholt and the Met Office operate seven systems throughout the UK under the European Co-operation in the Field of Scientific and Technical Research (COST) framework.

5.1.8 Other instruments

The UK Met Office and other European networks of weather radars, wind profilers and radiosondes will provide information over neighbouring geographical areas. This is useful for the study of convective systems which form outside the operations area, but continue to propagate new storm cells as they travel across southern England. Meteosat Second Generation satellite data will be used to follow the individual convective cells at 15-min intervals and the Met Office network of lightning detection instruments will provide lightning flash rates and the position of the most intense regions of some convection.

There are a number of microwave radiometers based at Chilbolton which will be used to determine the total liquid water path and total precipitable water vapour. They measure the zenith sky brightness temperature at 22.2, 28.8 and 37 GHz. Measurements are also made of temperature, pressure, and wind speed and direction. There is also a raingauge, distrometer, cloud camera, and a visible and IR broadband radiometer. A UV lidar will be used to determine water vapour profiles; temperature profiling is also under development. In addition, the ozone lidar operated by the University of Wales (Aberystwyth) will be used to detect dry intrusions of stratospheric air.

Dr. Jim Wilson at NCAR has expressed a strong interest in bringing the National Center for Atmospheric Research (NCAR) S-Pol Doppler dual-polarization radar to the project. This would bring the total number of high-quality dual-polarisation radars up to three.

5.2 Exploitation of the Observational Datasets

5.2.1 WP2A: Synthesis of Observational Datasets and Verification of High-Resolution Model

At the heart of this proposal is the synthesis of the datasets from the many different kinds of instruments being operated simultaneously during the IOPs. Operators of each instrument or network of similar instruments will first analysis their own datasets, but the real insight into the complex interacting processes that characterize convective initiation will be obtained by then going on to synthesise the different kinds of data to provide a conceptual (physical) description of what is going on. This is a labour-intensive and time-consuming activity that can be undertaken thoroughly for only 1 or 2 IOPs.

The resulting detailed case studies will in themselves provide some understanding of the factors affecting convective initiation. However, to deepen that understanding it will be necessary to try to reproduce the observed structures within the high-resolution model. After field data have been collected for an event, operational mesoscale model analyses will be used as initial data for convective resolution (about 1 km) configurations of the model. The intention will be to identify those structures in the model which lead to convective cloud triggering and to understand their origin through a series of model sensitivity experiments modifying aspects such as the initial model humidity distribution, large-scale PV distribution, orography, land use and soil moisture. It is not anticipated, at this stage, that the model will necessarily be able to predict the detailed location of convection observed in reality. Instead, validation will concentrate on the statistical properties of the atmosphere, especially the boundary layer, on a range of scales.

5.2.2 WP2B: Development of the High-resolution Mesoscale Model

The comparisons between the observational data sets and the model will be exploited in an attempt to identify ways of improving the design and performance of the high-resolution model. In particular the model output will be investigated to determine whether it reproduces the spatial and temporal variability of the fields seen in the measurements. To judge this, measurements will need to be analysed to ensure a match to model scales. It is anticipated that, due to the ensemble-mean nature of model parameterisation, the observed smaller-scale variability may be absent. Large-eddy simulations of small-scale convection will be used to inform the design of methods to incorporate the stochastic forcing from smaller scales.

A further stage will use ensemble techniques to assess the sensitivity of the model triggering to random variations arising from initial conditions and from the stochastic nature of the unresolved flow. This will address the predictability of both first and subsequent generations of convection. The methods used to generate perturbations will be a particular subject of study: Done et al. (2002), has already shown that, used carefully, random perturbations can lead to useful insight, but the applicability of more sophisticated techniques, such as error breeding (Toth and Kalnay 1997), to the convection problem requires investigation.

5.2.3 WP2C: Development of Data Assimilation Initialization Techniques

High-resolution simulations of severe weather events present us with new challenges because the physical assumptions and mathematical approximations employed in global models, and even in current mesoscale models, are likely to be invalid at finer resolutions. Data assimilation systems provide the link between observations and numerical simulations using mathematics and statistics.

Modern observational platforms, such as radars and satellites, provide an unrivalled data source at high temporal and spatial resolutions. However, much of this information is only used to a very limited extent in current operational forecasts for a number of logistical reasons, and because it is far from clear how best to use the data to modify the initial state of the model. There is a considerable challenge in using fine-resolution data, such as will be obtained in the proposed field programme, in a high-resolution forecast model in a way that the influence is not lost within an hour or two and so that short-range predictions are not dominated by spin-up effects caused by incompatibility between observed and modelled atmospheric structures. Research into assimilating Doppler wind data into a cloud-resolving model at NCAR, for example, has shown that retention of the information requires using the data to influence the large-scale environment of the storm as well as the storm dynamics itself (Crook and Sun 2001; Snyder 2001). While existing assimilation techniques will certainly allow Doppler wind data to influence the storm wind fields, the problem of getting the right information back onto the environmental fields is much harder. It is not clear, for instance, to what extent the use of the model dynamics within 4dVAR or ensemble Kalman filter techniques is able to constrain the large-scale evolution to be consistent with data in the storm itself, or whether additional dynamical information has to be used. In the project, the aim will be to identify the features of the large-scale environment that have to be analysed correctly in order to maintain the evolution of storms. It will then be possible to judge the effectiveness of various assimilation techniques.

The field campaign will provide the data required to help test and verify the assimilation systems under development during the period leading up to, and during, Phase 1. During Phase 2, the new data sources, such as Doppler winds and precipitation observations from the radar and data from the mesonet, will be incorporated into the assimilation schemes. Part of the development programme for the data assimilation system over the next 2 years will also be focussing on ways of incorporating boundary-layer depth, as mapped by the Chilbolton radar system. The error statistics of new types of data will have to be compiled and observations made during the field campaign will provide a basis for these statistics. Another prerequisite of the fine-resolution forecasting system is to understand the properties, and the relative importance, of the background error and the observational error covariances, and the balance relations, in fine-resolution, data-dense and data-sparse situations. This work will require validation against observations.

5.2.4 WP2D: Understanding the Roles of Thermals and Small Cumulus Clouds

Cumulonimbus occur as a result of boundary-layer air being lifted to release conditional instability, so one key to understanding their initiation lies in understanding the processes in the boundary layer which initiate the first cells. Some of these boundary layer processes are only recently being resolved by observations (e.g. Weckworth et al. 1999; Tian et al. 2003) and modelling (e.g. Tian et al. 2003), and the time is now right to attempt to quantify this mode of cumulonimbus triggering. In WP2D, case study analysis of convective events in conditions of low mesoscale forcing (so that local, surface triggers are dominant) will be performed. Coherent convective features in the boundary layer and shallow cumulus layer will be observed by the mesonet, Chilbolton radar, cloud radars and aircraft (WP1B, WP1D, WP1E). Tian et al. (2003) have shown that such modelling of boundary-layer convective structures is indeed possible: in WP2D we will extend Tian et al. (2003) in three fundamental ways: we will explicitly include the role of shallow cumulus in preconditioning the atmospheric profile through coherent convective structures; we will explicitly resolve the triggering mechanism right through the shallow cumulus phase to the release of CAPE; and we will perform thorough sensitivity tests to establish the repeatability of this triggering of cumulonimbus. Ultimately this work will resolve the transition from conditions of zero precipitation in a conditionally unstable atmosphere through to cumulonimbus initiation. By using the high-resolution model we will be able to explore the sensitivity of modelled features to initialisation and boundary conditions, and to explore the variability in triggering in sets of ensemble simulations. In conjunction with WP2B, we will compare these high-resolution results with UM results at resolutions of 1 km up to 12 km: this work will explore the behaviour of shallow cumulus in the UM in comparison with the observations and microscale model results, and assess the requirements of observing and modelling systems.

5.2.5 WP2E: Understanding the Effects of Topography, Orography and Land-Use Heterogeneity

In conjunction with the studies in WP2D, we wish to identify coherent boundary-layer features related to surface properties and conditions, and to relate these to observed convective initiation through the shallow cumulus phase. Such coherent features can be observed by the instrumented network, and Tian et al. (2003) have shown that convective structures in the boundary-layer can be reproduced successfully in a relatively simple model. In WP2E, a high-resolution model will be tested against local observational results, which will provide both the gross features of convective structures (e.g. orientation and spacing of convective rolls and cloud lines) and detailed quantitative data (such as propagation vectors for convective features). The model will be forced by UM boundary conditions and by observed time-dependent profiles. Having tested the model against observations, it will be used to explore the sensitivity of convective triggering to boundary conditions, surface properties and initialisation.

Idealised experiments will also be performed (as in Tian and Parker 2002) to quantify the relative significance of different surface features on different scales, such as hills and land-use changes. We wish to determine the importance of these surface controls and, by inference, the repeatability of the convective initiation events. We will also test the scale-sensitivity to surface features, with a view to informing the UM representations.

5.2.6 WP2F: Understanding the Role of Dry Intrusions

As explained in Section 3(ii), the overrunning of moist boundary-layer air by cold dry recently-descended upper-tropospheric air generates potential instability. When this air is part of a dry intrusion, the descending airstream occurs ahead of an upper-level trough. Convection can then be triggered either by low-level forced convergence or upper-level forcing by the advancing PV anomaly. In a recent case study, Reid and Vaughan (work in progress) examined convection initiated beneath a tropopause fold contained within a dry intrusion, with the result that the stratospheric air in the fold was mixed into the troposphere by the convection. The focus of that study was on the mixing processes; the physics triggering the convection was not previously considered, but will be the focus of the new study.

5.2.7 WP2G: Evaluation and Development of Conceptual Models

The system known as GANDOLF (Generating Automated Nowcasts for Deployment in Operational Land-Based Flood Forecasting) is a fully automated nowcasting system tailored to forecast only non-frontal, convective airmass events (Pierce et al. 2000). It employs an advection scheme instead of an extrapolation scheme, using representative wind vectors to forecast storm motion. GANDOLF also employs a conceptual model of the life cycle of an idealised convective cell, divided into five stages from birth to dissipation. The original work on the conceptual model was done by Hand and Conway (1995). GANDOLF identifies isolated convective cells, and applies the conceptual model to simulate their growth and decay thereby avoiding a detailed mathematical treatment of their thermodynamic properties. Its temporal and spatial resolutions are constrained only by the resolution of the radar data which are its principal input. By modelling the life cycle in such a way, and combining this with a linear extrapolation scheme it is hoped to produce forecasts of airmass events with improved skill. The proposed field campaign, by identifying the factors responsible for the initiation of new convective cells, will enable the development of improved conceptual models for use in GANDOLF. The performance of GANDOLF was discussed by Pierce et al. (2000). The forecasting of the initiation of new convective cells before radar echoes were observed was regarded as of particular importance. The Met Office are now working to incorporate the GANDOLF approach into the NIMROD short-period forecasting system within which the observational data can be blended with numerical forecast information.

6 Justification of resources, management structures and plans

6.1 PDRA and Student Support

Seven PDRA's are requested for the tasks specified in Tables 1 and 2. In summary: PDRA 1, Reading, WP1B and WP2A; PDRA 2, Reading, WP2B; PDRA 3, Leeds, WP1C and WP2D; PDRA 4, Leeds, WP1D and WP2C; PDRA 5, UMIST, WP1E and WP2E; PDRA 6, Aberystwyth, WP1C and WP2F; and PDRA 7, Salford, WP1F and WP2G. Two students are requested: student 1, Leeds, WP1C and WP2E; student 2: Essex, WP2C.

6.2 Schedule of Activities

Activity	S 03 - M 04	JJA 04	Year 2	Year 3	Year 4
Equipment preparation for field campaign	X				
Model preparation for field campaign	X				
Meetings to discuss objectives and plans	X				
Field campaign		X			
Mesoscale model runs to support field camp		X			
Data analysis, interpretation and synthesis		X	X	X	X
Mesoscale model runs on case studies		X	X	X	X
Improvements to mesoscale model			X	X	X
Data assimilation and initialisation			X	X	X
Science progress meetings			X	X	X
Publications			X	X	X

6.3 Operations Plan for Field Campaign

The Operations Centre will be in the Meteorology Department, University of Reading, where there will be access in real time to the Chilbolton radar data, all Met Office and other European radars, satellite imagery and radiosonde data. The Chilbolton radar can be controlled remotely from this location and all forecast-model products from the Met Office and ECMWF can be easily accessed.

The UFAM instruments, including the array of ground-based equipment and the Cessna, will be deployed for the 3 summer months of June, July and August, 2004, during which there will be several active periods (APs) (i.e. periods of several days or more when the large-scale situation is such that convective storms are possible and instrumentation must be in a state of readiness) and intensive observational periods (IOPs) (i.e. individual days when there is a high probability of convective storms occurring and all or most instrumentation needs to be operated intensively). Suitable weather conditions are expected to occur on between 10 and 30 days during that time. The wind profilers, Doppler lidar, cloud radars, sodars and mesonet will operate continuously during the APs as will the radiometers and the GPS water vapour system. The 3 GHz and 1275 MHz radars will also operate continuously for long periods during the IOPs, but will have to be continually monitored so that scanning patterns can be optimised. The aircraft will be on standby at Woodford and will fly only on IOP days and radiosondes will be launched only when required. Thus, a suitable warning will have to be given to set up the APs and short-range warnings will be needed for the IOPs. Forecasts from the ECMWF and Unified Model, plus NIMROD/GANDOLF nowcasts and additional guidance from the Met Office NWC such as streamline analyses, will be studied each day during the campaign to provide 5-day, 72-hour and 24-hour forecasts. The mesoscale model will be run every morning, hopefully at 4 km resolution.

There will be a meeting each day at 08:00 local time in the Operations Centre to discuss: the status of ground-based systems and aircraft; the results of the last IOP; operations for the current day; whether the next day is to be an IOP day; forecasts for 72 hours and outlook for the week ahead to identify likely APs; review of previous cases so as to assess the status of scientific objectives; and new ideas.

A number of operational plans will be prepared to cater for different situations. In order to illustrate the intended modus operandi we now consider one of the scenarios for convective initiation. Harrold and Browning (1971) suggested that it may be possible to forecast the location of outbreaks of showers and thunderstorms by using the clear-air radar to identify regions where populations of relatively deep thermals and/or small cumulus clouds exist. This suggestion will be tested in the following manner. When suitable conditions are forecast, the Chilbolton radar will make RHI's initially over 360°. A particular sector will be chosen for more detailed, higher time-resolution study if and when a more active region is identified. The Cessna aircraft will initially fly at an altitude of 500 m along radials centred on the radar to map the temperature, humidity and air flow in the boundary layer. The aircraft will divert to the region of interest if one is observed by the radars. The developing clouds will not be penetrated. The aircraft will also make passes in regions where there is weaker or no development to compare the humidity, temperature and winds in a variety of conditions. The other instruments mentioned above, such as the mesonet system, wind profilers and sodars, will not require special arrangements since they will operate continuously. The Doppler lidar, wind profiler and one of the sodars will be located on high ground (at 20 to 30 km range from Chilbolton radar; Fig. 1) to maximise the possibility of observing the development of thermals which lead to deeper convection. Data from the other sodars, the mesonet, the Met Office wind profilers and radiosondes will be used to provide a broader-perspective map of the temperature, humidity and wind structure. All radiosonde stations in the project area will release sondes serially at 1-2 hour intervals.

7 Associated Collaborations and Co-Funding

The Met Office regards the development of convective-scale forecast tools as an important part of its own Core Research programme. In addition to ongoing work enhancing its operational radar and radar-based nowcasting systems, the Met Office has dedicated staff at the JCMM (10 scientists, budget approx. £400k pa) to developing the capability to perform convective scale data assimilation and forecasting. This effort will be aligned to contribute directly to this consortium bid to provide the underlying UM modelling and data assimilation system. In addition, data from operational observing systems (including radars, wind profilers and radiosondes) and forecast systems will be provided in real time and for post-event analysis. The value of this data may be estimated as several hundred £k. Met Office involvement will be run through a managed project, with Peter Clark (JCMM) as project manager.

8 Stewardship of Data and Dissemination of Results

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 will also be transferred into a form suitable for assimilation into the Unified Model.

9 Wider Significance of the Results

The results from the study will greatly improve our understanding of the initiation of convection in a wide range of conditions and thus improve the accuracy of forecasts of the initial development of heavy convective showers. This in turn will lead to significant improvements in the ability to forecast flooding and severe winds associated with storms.

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