Theme 4: Synergistic use of remote sensing data for high resolution predictions of hazardous weather, floods and water resources

1. Abstract

Storms, floods and droughts have a major impact on everyday life around the world. An improved ability to forecast, quantify and manage meteorological and hydrological risks and water resources is essential to protecting the public, property and infrastructure, and to maintaining a sustainable economy. Our approach is to use Earth observation to improve our understanding of high impact weather, floods, and water resources; to use these data to confront models, evaluate their results, and so improve the models and their predictive capability. We emphasize the development of novel data assimilation techniques, and consequent optimization of the amount of observational information propagated in a forecast. We also aim to provide underpinning science that will influence the choice of future Earth observation missions. Our work is timely: we plan to exploit newly available models together with newly available observations. At least eight space agencies are launching satellites relevant to this work. The research retains and develops key researchers who both have the skills to investigate fundamental questions and understand operational requirements. It provides a vital, long-term link to space and operational agencies. We are well integrated with international activities, and expect to provide a conduit for the UK scientific community both to take advantage of international investments and to contribute to the science. We have an agreement for a joint national programme with NCAS and the Met Office. We will work in partnership across NCEO, with research council centres and programmes, with UK operational agencies, with the private sector, with space agencies and with international collaborators, towards the ultimate goal of a realistic, end-to-end integrated forecasting capability.

2. Rationale

Background and the science challenge

During 2006 an estimated 130 million people worldwide were affected by storms, storm surges, floods and droughts. One consequence of climate change is that the frequency and intensity of hazardous events may increase in the future. Annual UK damage from flooding is predicted to rise from the present level of £1 billion to up to about £25 billion, and there will be increasing pressure on water resources. It follows that an improved ability to forecast, quantify and manage meteorological and hydrological risks and water resources is critical for the protection of the public, property and infrastructure, and to maintain a stable economy.

There are complex feedbacks between the hydro-meteorological processes that govern hazardous events. With new, high spatiotemporal frequency observation types along with new high resolution models, we are well placed to address the fundamental scientific questions that will lead to tangible improvements in forecasting and mitigation. Much of our focus is on mid-latitude events, due to the local availability of a wealth of accessible observations, particularly in the UK. Nevertheless, much of the scientific understanding and techniques developed here are more widely applicable (e.g. to tropical cyclones, hurricanes and typhoons) in that forecasts of these events all depend on the observation, high resolution assimilation and modelling of moist processes.

Operational weather centres are currently developing storm-scale numerical weather prediction (NWP) models that allow better hazardous weather forecasts through explicit, rather than parameterized convection, and high resolution orography. To capitalize on these improvements, it is vital to provide accurate initial conditions on appropriate scales. Traditional synoptic observations do not provide enough detail for this purpose and it is necessary to use these in synergy with remote sensing. This presents major challenges. While some satellite data are routinely assimilated into synoptic scale NWP models, much of the data are thrown away or used suboptimally, because of issues such as cloud contamination and correlated observation errors. Attempts to assimilate observations of precipitation have met with little success so far, due to inconsistencies between the a priori assumptions and the observations about the location and timing of features. Furthermore, at the storm-scale, the basic character of the dynamical system is changed, and many of the assumptions used in synoptic scale assimilation algorithms are violated, so there is a need to develop new methods that take better account of multiscale effects, nonlinearity and uncertainty. Coarser models provide lateral boundary conditions for regional modelling. Predictions of storm tracks with such models may be sensitive to new observations. Land-surface boundary conditions depend on observations of snow and soil moisture.

Quantitative precipitation forecasts represent a significant source of uncertainty to hydraulic flood and drought models. Even if these are improved, better observations of snow, soil moisture and topography are needed to improve the initial and boundary conditions for such models. To validate and improve flood predictions, measurements of flood extents are needed at high spatiotemporal resolutions, particularly in urban areas. Appropriate models and observations enable the evaluation of works carried out to protect areas vulnerable to flooding. Since available observations are often only provide partial coverage, it will be important to use these in synergy with other data and the model via data assimilation.

Our approach to these challenges is to use Earth observation to improve our understanding of high impact weather, floods, droughts and water resources; to use these data to confront models, evaluate their results, and so improve the models and their predictive capability. We emphasize the development of novel data assimilation techniques, and consequent optimization of the amount of observational information propagated in a forecast, as well as methods for quantifying improvements in prediction. Our work is timely: we plan to exploit new models together with new observations. At least eight space agencies are launching satellites relevant to this work. The research retains and develops key researchers who both have the skills to investigate fundamental questions and understand operational requirements. It provides a vital, long-term link to space and operational agencies. Hence it needs to be supported as a critical national capability. The research is at varying levels of maturity, but all is well integrated with international activities. We expect to provide a conduit for the UK scientific community both to take advantage of international investments and to contribute to the science. We have an agreement for a joint national programme with NCAS and the Met Office. NCAS-Weather will work on atmospheric modelling and process studies, and we will concentrate on data assimilation. The Met Office will concentrate on near-term operational requirements, and we will take the strategic view, addressing fundamental questions key to improved forecasting in the longer term. Additionally, we will work in partnership across NCEO, with research council centres and programmes such as POL, CEH, FREE and FRMRC; with UK operational agencies such as the EA; with the private sector; with space agencies and with international collaborators (see letters of support), towards the ultimate goal of a realistic, end-to-end integrated forecasting capability.

3 Objectives

Our objectives are

- To use Earth observations to improve our understanding of the physical and dynamic processes governing storms, storm-surges, floods, droughts and water resources; to use these data to confront models, evaluate their results, and so improve the models and their predictive capability.
- To maximize the value of observational information, by developing novel methods of assimilating observations of multiscale, highly nonlinear processes, including moist processes, and using NWP extensively in improved retrievals.
- To use a range of observation-types in synergy, to provide model initial conditions, to evaluate model parameters, and to assess hazard mitigation strategies
- To provide underpinning science that will influence the choice of future Earth observation missions, and optimize the use of both current and future observation types

- To work in partnership across NCEO, NERC centres and programmes, with operational agencies, private sector and international collaborators

The work is structured around a set of sub-themes that are organised around the delivery of better understanding and forecasts. Each sub-theme begins with process studies to understand and make use of diverse sets of novel observations, and will then be integrated into the operational systems. Some initial work will be carried out using idealized model test-beds. Such an approach allows for ideas to be tested and results fully understood, before dealing with the added complications of a complex, imperfect model (such as the Met Office Unified Model) and real observations with their associated uncertainties. Some of these models already exist, e.g., a one-dimensional shallow water model and simple SVAT models.

3.1 Exploitation of precipitation measurements *(Researchers Dance/Hogan, 1 PDRA)*

Summary

This sub-theme aims to exploit new observations of precipitation. Previous attempts to assimilate radar reflectivity factor (Z) have met with little success, due to inconsistencies between the prior forecast and the observations in the location and timing of small-scale features. We propose to assimilate novel observations of differential phase shift, ϕ_{dp}, from the new Met Office polarimetric radar at Thurnham. Unlike Z, ϕ_{dp} is virtually unaffected by attenuation and hail, so provides new information in situations of heavy rain that will be particularly valuable for flood forecasting. Furthermore, ϕ_{dp} provides information on a path-integrated rain-rate, hence if a convective system is incorrectly located in the prior forecast, there is great potential for the data assimilation algorithm to shift it along the ray-path. While polarimetric radar is ground-based, and generally only available over land in parts of the developed world, the planned Global Precipitation Mission (GPM, operational in 2013) will provide radar observations from space. Although the GPM radar is not polarimetric, the understanding gained here will contribute to a longer term goal of preparation for this mission, in increasing our understanding of the best treatment of all types of precipitation data and moist processes in assimilation and prediction. Much of this research will be carried out using the Met Office high resolution assimilation and forecasting system, ensuring seamless transfer of results to operational practice. While the Met Office's focus has to be on near-term operational issues, we are able to have a unique, strategic viewpoint in developing scientific ideas, and investigating the fundamental questions relating to assimilation of precipitation data. Thus this work adds to critical national capability.

Work description and methodology

A large amount of new Doppler radar data (order 1-5km resolution, every 5 minutes) will soon be available over much of the UK landmass. The Met Office, working with the Universities of Salford (Rihan et al, 2005) and Reading (under the NERC FREE programme) is developing technology to assimilate radar Doppler winds (from precipitation and insect returns), reflectivities and refractivities. In 2013, the Global Precipitation Mission (GPM) radar will provide global coverage. Although precipitation is well observed by radar, attempts to assimilate reflectivity data have so far met with little success. By the time precipitation develops, the forecast may have created qualitatively correct small-scale features, such as thunderstorms, but with the wrong location or timing. Thus the model air motions are inconsistent with the position of the first radar echo and attempts to assimilate the data result in spurious rain events within the first few hours of the forecast (Dance, 2004).

The Met Office has a new 5cm polarimetric radar at Thurnham. In this sub-theme, assimilation of differential phase-shift ϕ_{dp} from this radar, will be implemented in the variational data assimilation system associated with the Met Office high resolution model. ϕ_{dp} is virtually unaffected by attenuation and hail, so provides new information in situations of heavy rain that will be valuable for flood forecasting. Furthermore, these observations provide information on a path integrated rain-rate, hence if a convective system is incorrectly located in the prior forecast, there is great potential for the data assimilation algorithm to shift it along the ray-path to a position more consistent with the observations.

The first step will be to build an observation operator (or forward model), based on Hogan (2007). The measurement is a path-integral, and in this sense it is similar to the problem of assimilating refractivity (from GPS satellites or radar). We are already working on radar refractivity, with the Met Office, and so we will be able to take advantage of existing expertise to solve many of the technical issues.

Our pragmatic approach will be to evaluate the benefit of assimilating ϕ_{dp} using OSSE-type experiments with pseudo-observations, before completing the complex and time-consuming task of setting up software for observation pre-processing. The OSSE set-up will also allow for preliminary evaluation of optimal observation densities, updating frequencies and the suitability of the forecast error covariances for spreading and filtering these types of observational information. This aspect of the work will require close cooperation with subtheme 3.2 and Theme 7. Assuming that these OSSE experiments are successful, close attention will have to be paid to quality control and observation error estimation with the real data, before case studies are carried out. The new scheme will be tested on data both from the new Met Office 5-cm polarimetric radar at Thurnham, and the 10-cm research radar at Chilbolton. The use of Chilbolton data will allow for verification with rich observational data-sets from the recent CSIP (Convective Storm Initiation Project) field campaign (Browning et al, 2007). The quality of the analyses and subsequent precipitation forecasts will be compared when assimilating ϕ_{dp} and Z both together and separately, using verification techniques developed by Roberts (2004), and also informed by 3.4.

As well as allowing us to study the differing assimilation properties of ϕ_{dp}, the experience gained in the OSSE studies assimilating Z will contribute to preparations for assimilation of GPM, when it becomes operational in 2013. In particular, we plan to investigate and anticipate any problems that may be caused by the infrequent overpass schedule. Our improved understanding of the treatment of precipitation data and moist processes, will help us to maximize the value of these observations in the forecast.

3.2 Observation influence and forecast uncertainty *(Researchers Dance/Bannister)*

Summary

The aim of this sub-theme is to improve the way that information from observations is taken up in the analysis and propagated in the forecast. Forecast error statistics are used in the assimilation to filter and spread observational information in a multivariate way to model fields. They contribute crucially to the successful use of the data. However, differences in dynamics mean that error covariance modelling techniques used for synoptic scales cannot simply be carried forward to storm-scales. By examining instantaneous statistics from high resolution ensemble forecasts, and developing ways to encapsulate their important dynamical features, new forecast error models suitable for the storm-scale will be developed. This new approach should have an impact on the way that observations of dynamic variables influence the moist thermodynamics, and vice versa, and will allow maximum information to be extracted from observations (e.g. satellite atmospheric motion vector winds; satellite radiances, including cloudy radiances; the UK radar network and the future GPM and MTG satellite missions). Without appropriate statistics, the observations may degrade the forecast, and they may not be used operationally. Much of this fundamental research will be carried out using the Met Office high resolution assimilation/forecasting system, but the results are expected to represent a significant departure from current practice. The work is strategic, key to the use of observations by operations in the longer term, and requires the concentrated work on fundamental questions and collaborative engagement provided only by NCEO. It is a critical contribution to national capability.

Work description and methodology

Forecast error covariances play a significant role in physically consistent spreading of observational information in data assimilation. For example, on large scales, winds can be inferred from pressure observations via the use of a dynamical balance relationship encoded in the forecast error covariance, which also helps to prevent the excitation of spurious acoustic and gravity waves in the forecast. At small scales, it will be key to encapsulate correlations between moist processes and dynamic variables in the assimilation. However, unlike balance on the large scale, it is not clear, a priori, that this can be achieved by extracting simplified relationships from the equations of motion. A better treatment will lead to improved uptake of information from some data types that currently cause problems. As noted in 3.1, previous attempts to assimilate radar reflectivity data have met with little success, thought to be due in part to poor representation of the correlations between moisture and potential vorticity. Also, the presence of cloud complicates the treatment of satellite data, leading to many infrared and visible data being thrown away (e.g. Chevallier et al. 2004). While ECMWF is developing a 1D+4D-Var approach that can account for cloudy radiances (Marécal and Mahfouf, 2003), the nature of the error statistics contributes crucially to the successful use of the data. For example, incorrect horizontal and vertical spreading of observed moisture can lead to cloud anomalously forming above the true cloud top.

We will build on previous studies (Bannister 2007, Katz 2007) investigating forecast error covariance modelling for synoptic flows. At small scales forecast errors are expected to change rapidly with the evolving flow and so a method needs to be used that captures the instantaneous forecast error statistics. This represents a significant advance over current methods, which require proxies of forecast error to be averaged over long periods of time. Other studies have looked at forecast errors on mesoscales (Berre 2000, Zhang 2005), but have limitations, either because the resolution of the model has not allowed small enough scales to be probed or the studies have used measures that result in time-averaged (rather than time-resolved) statistics. Our new approach will capture the characteristics of the instantaneous errors by generating ensembles (Fischer et al. 2005, Berre et al. 2006) of high-resolution forecasts from the Met Office system. In its use of ensemble forecasts, this work will share common ground with the proposed research in sub-theme 3.5 and Theme 7 on ensemble Kalman filters and uncertainty. Using these instantaneous forecast error statistics we will address the following questions: What are the magnitudes of forecast errors at small-scales? How significantly do the error statistics change from day-to-day? What is the spatial structure of the errors? How different are they from homogeneous and isotropic? What balances (if any) are appropriate for forecast errors at small scales? In particular, what are the multivariate relationships between variables associated with the hydrological cycle?

Due to the large matrices involved (order 10^{12} elements or more), forecast error covariances cannot be used directly in the assimilation problem. Hence, a realistic, but compact representation of forecast errors will be devised. This may follow the current methodology (Fisher 2003), but adapted in order to preserve the important features found in the earlier stages of this work. High-resolution systems of useful domain size will not exclude synoptic scale flows, and so the storm-scale errors will coexist with synoptic-scale errors. This poses a further complication of the problem, but some methods (e.g. wavelets, Bannister 2007) allow naturally for a multiscale solution. The development and evaluation of the multiscale aspect of the statistics will be carried out in collaboration with sub-theme 3.3. Single observation tests and assimilation-forecast case studies will look especially at the dynamical effects of the new error models on the assimilation of radar and satellite radiance observations. Verification techniques developed by Roberts (2004) will be used in conjunction with independent observations, such as from the recent CSIP field campaign, (Browning et al. 2007), or planned summer 2007 COPS (Wulfmeyer et al, 2005) field campaign over Germany, to evaluate the impact of the new error models in analyses and subsequent precipitation forecasts. Verification will also be informed by the work in 3.4

3.3 Synergistic use of heterogeneous data: the multi-scale problem *(Researchers Dance/Lawless/Nichols)*

Summary

Assimilation for storm-scale numerical weather prediction requires the synergistic use of data from diverse sources, in order to provide detail on relevant space and time-scales. Each type of measurement has a different spatio-temporal resolution, different uncertainties, and is representative of different scales of motion. Furthermore, there are strong dynamical feedbacks between storm- and synoptic-scales.

Hence assimilation at the storm-scale is a multi-scale problem, which must try to preserve information coming from sources not well-represented by the storm-scale model, while using observations to correct those scales which can be captured. Our approach will be to investigate how information from different scales is projected into the analysis and propagated in the forecast, the inclusion of scale-dependent constraints in the assimilation problem, the treatment of unresolved scales as stochastic processes, and multi-scale optimization methods that are especially suited to these types of problems. These methods will be developed through theoretical studies supported by idealized modelling and will require input from Theme 7. The work is strategic, key to the use of observations by operations in the longer term, and requires the concentrated work on fundamental questions and collaborative engagement provided only by NCEO.

Work description and methodology

The Met Office high resolution trial assimilation system uses a diverse range of data including surface temperature, humidity, pressure, winds and visibility; radiosonde, pilot and dropsonde data; satellite atmospheric motion winds, ATOVS radiances, wind profiler data and cloud fraction and humidity from the Moisture Observation Pre-processing System (MOPS) cloud analysis (Lean et al, 2005). Systems currently under development, or planned in the future include those for radar Doppler winds, reflectivity, refractivity, and polarimetric radar (sub-theme 3.1). Other possibilities include GPS, ground-based radiometers, currently and newly available satellite data that is not yet fully exploited e.g., MetOp, MSG, and future satellite missions such as GPM and MTG. For low resolution forecasts, dense observations are thinned or 'super-robbed' to avoid issues with error correlations, and to ensure that the scales represented are compatible with the model grid. While this allows a reduction in computations, significant information is lost. For storm-scale NWP, it will be key to use dense sets of observations on scales comparable with the grid. Approximation techniques to deal with error correlations are already being developed by the operational centres (Fisher 2005), and we are working in partnership with the Met Office to evaluate and improve upon these techniques (Stewart et al, 2007).

As well as dealing with heterogeneous data, the assimilation algorithm must also cope with multiscale dynamics. The Met Office high-resolution model is a limited area model (order 1.5km horizontal resolution) embedded in a larger scale model. The fine scale model receives information about larger scale flows through lateral boundary conditions (LBCs); the effects of new observations on the larger-scale flows to provide those boundary conditions is investigated in 3.4. To make running a fine-scale model operationally feasible, the domain size is minimized, so there are both upper and lower limits to the scales that can be represented. This means that processes that have smaller scales or faster motion than can be represented by the model must be parametrized as sub-grid-scale effects, possibly using stochastic techniques (e.g. turbulence). In the assimilation, observed sub-grid-scale effects must be accounted for as an error of representativity. For phenomena with length-scales larger or comparable to the domain size the LBCs must play a significant role in the modelling (e.g. long Rossby-wave motion). This can cause inconsistencies when the large-scale analysis used to generate the LBCs for the storm-scale model uses observations that lie just outside the domain used for the storm-scale analysis.

Initially this project will consider simplified high resolution systems embedded in larger scale systems, in order to understand how observed information from different scales is projected onto the analysis and propagated into the forecast, building on initial studies (Baxter et al, 2007), and in collaboration with Theme 7. Here we will carry out a systematic study of the incorporation of various scale-dependent constraints in idealized assimilation-forecast models, which has the potential to preserve large-scale information from a large-scale analysis, made using synoptic observations over a large domain, while filling in details on the storm-scale in the limited-area using independent, high-resolution observations. We will consider several approaches such as forecast error modelling using wavelets, (Bannister, 2007), the use of additional cost function penalties, (Guidard and Fischer, *pers. comm.*), and a graphical tree approach (Zhou et al., 2007). At the same time, it makes sense to explore more efficient optimization techniques that have been designed to deal with multiscale problems, such as multi-grid. To deal with sub-grid-effects we would anticipate carrying out some OSSE studies using stochastic models and examining errors of representativity.

More generally, when using forecast models with stochastic parametrizations, it may be necessary to treat the underlying model differential equations in some averaged or homogenized sense in the assimilation. Novel techniques for the optimization of stochastically-forced systems will need to be invented. This will be a significant challenge, requiring collaboration with Theme 7, however the ability to solve the optimization problem accurately under such constraints is considered essential if we are to make full use of high resolution observations in convective-scale assimilation.

3.4 Observational impacts on storm-track predictions *(Researchers Bengtsson/Hodges)*

Summary

As noted in 3.3 global and large regional models provide important boundary conditions for high resolution NWP. Predictions of storm tracks in such large-scale models are recognised as a very high priority for flood prediction, for instance in the NERC FREE Science Plan. It is important to understand how data from new instruments will impact on the representation of storm-tracks in analyses and forecasts and to explore the importance of data from current and historical EO platforms to inform the choice of future missions (Bengtsson et al., 2004a, 2005). Operational centres will conduct much of the work in developing global data assimilation systems for satellite data and produce re-analyses, but NCEO is in a unique position in being able, through access to ECMWF, Met Office and other data assimilation systems, to conduct sensitivity studies not routinely performed by the operational centres to assess the impact of new observations. For example, ADM-Aeolus will provide new measurements of winds through the depth of the atmosphere, MetOp will provide a variety of better quality sounding data and EarthCARE will provide new measurements of clouds, aerosols and top of the atmosphere radiances. We can also prepare for the next generation of satellites, such as MTG, by participating in analyses of OSSEs in NWP centres to improve the observation systems. Measures of improvements can be supplied by the objective identification and tracking of storms, together with methods of validating and verifying the storm properties. We have already developed sophisticated methods to do this for a wide range of storm phenomena and have performed studies exploring the sensitivity and predictability of model storm representations to different observations (Bengtsson et al., 2004b) in both deterministic and ensemble prediction systems (Froude et al., 2007a, b). We propose to extend this work to analyse carefully the effect on representation of storm tracks of the many new observations now becoming available, and to allow our techniques to be used for high resolution verification. These techniques will also be used in Theme 1. The work is strategic, key to the use of observations by operations in the longer term, and requires the concentrated work on fundamental questions and collaborative engagement provided only by NCEO. It is a critical contribution to national capability.

Work description and methodology

ECMWF operational systems will be used predominantly because of the close relationship of ECMWF to ESA, which means that the ECMWF are early adopters of new observations. There is already considerable knowledge exchange based on this methodology between ESA, ECMWF, Reading and the other European met agencies, and this sub-theme will strengthen this exchange further. There are several areas where the existing methodology will be improved. The first is a more refined and objective method for specifying the tracking constraints based on high temporally sampled data, particularly important with the range of more sophisticated geostationary observations now coming available. The usefulness and best implementation of the steering level flow will also be explored using these data. Second, more diagnostics will be developed to provide more detailed diagnostics of the impacts of new types of EO data, such as from ADM-Aeolus, on storms. Third, improvements to the diagnostics produced for Ensemble Prediction Systems will be explored such as probabilistic skill scores for storms, and how this can be related to flood models. Finally, the use of Monte Carlo techniques for determining confidence intervals and significance tests for storms relates to the Theme 1 and will continue development.

The tracking methodology is currently being used to study the impact of model and observation resolution on tropical and extra-tropical cyclones. This will continue, but there are also several new areas where the method will be applied, in the context of the evaluation of new and historical EO data. Firstly, we will examine the sensitivity of new observations on the vertical structure of storms, which has a particular importance for intense storms. Second, we will examine the representation and predictability of cyclones in Ensemble Predictions Systems (EPS) using THORPEX Interactive Grand Global Ensemble (TIGGE) data, including an inter-comparison between different EPS systems, to provide input into sub-theme 3.7 and the FREE programme by providing likely candidates for running flood risk models. The same analysis system developed for Earth observation will be used to examine the representation of extra-tropical and tropical cyclones in climate models with a focus on severe weather under climate change, to improve statistical representations of flood risk. Data will be used from the Max Planck Institute for Meterology, the Hadley Centre and HIGEM and so will enhance knowledge exchange with the climate modelling community. We also plan to apply the methodology to very high resolution data from non-hydrostatic models currently being developed by the Met Office, for example, to forecast mesoscale events which can lead to heavy precipitation, thereby allowing verification of such events. The verification techniques developed will be used alongside other measures in 3.1, 3.2 and 3.5.

3.5 Probabilistic forecasting *(Researchers Dance/Migliorini)*

Summary

As resolution of NWP models increases, the effects of nonlinearity begin to dominate the assimilation cycle: observations at these scales typically have nonlinear relationships with the model variables (e.g. satellite radiances, radar and lidar). The model dynamics are also nonlinear; timescales of predictability for a developing storm (order 10 mins) are much shorter than current operational assimilation windows (6-12 hours). Beyond this predictability limit, useful information can be obtained, but it becomes important to determine the uncertainties in the analysis and forecast. Here we will investigate and develop ensemble assimilation techniques. Unlike variational methods, these maintain a flow dependent estimate of analysis uncertainty that could provide the basis of a seamless probabilistic assimilation-prediction system. Applying them for successful convective scale predictions presents considerable challenges, and will require collaboration with sub-themes 3.2, 3.3 and Theme 7. The ultimate goal is to build and evaluate an ensemble assimilation scheme for the Met Office NWP system and compare its performance at the storm-scale with variational methods. The work is strategic, key to the use of earth observations in the longer term, and requires the concentrated work on fundamental questions and collaborative engagement provided only by NCEO. It is a critical contribution to national capability.

Work description and methodology

Initial conditions are not the only cause of inaccuracies in storm-scale NWP. Boundary condition and modelling errors also contribute. Even if these errors were reduced, the nonlinear nature of the convective dynamics ensures that there is a predictability limit, beyond which the value of deterministic forecasts becomes questionable. Beyond that point, useful information can still be obtained. However, since it becomes important to determine the uncertainties in the forecast precipitation, an ensemble approach is required. Since the size of the ensemble is computationally limited, the appropriate construction of the forecast ensemble must be both statistically representative of analysis errors, and dynamically diverse, in order to capture the full range of possible outcomes.

A recently developed class of algorithms, known as ensemble Kalman filters and smoothers, has potential for storm scale forecasting, and other areas of earth observation (e.g., Themes 2 and 7). These methods present a compromise: they are able to use a fully nonlinear forecast ensemble as a statistical sample to keep track of the forecast statistics, but apply a Gaussian assumption to observation updates.

While preliminary work comparing variational and ensemble methods has been carried out (Lorenc, 2003; Caya et al, 2005) the results have been inconclusive. Further research, both generic and specific to storm-scale applications, is required to determine the best scheme, for example:

- How well do the schemes deal with nonlinear observation operators such as those for satellite radiances, radar and lidar? (Lorenc, 2003; Anderson, 2003; sub-theme 3.1)
- At what frequency should data be ingested? Does this vary diurnally? (If we are able to reduce the uncertainty in the morning, ahead of an afternoon storm, this may be of more benefit in the forecast than assimilating large quantities of data during the storm itself.) (sub-theme 3.3)
- Is increased diversity (reduced skewness etc.) in the ensemble more important than reducing the noise in analyses? (Lawson and Hansen, 2004) Are there ways to do both e.g. by rotating the ensemble perturbations (Leeuwenburgh et al, 2005) without biasing the analyses (Livings et al, 2006)? Can we choose perturbations that are both consistent with analysis error and known to be capable of triggering convective activity or significantly influencing its evolution? (cf. FREE).
- What is the best way to implement a limited area ensemble at the storm-scale? (Torn et al. 2006)
- Are there better methods than localization for avoiding problems with noisy covariances? Do they preserve real correlations between variables, on multiple scales? Is it necessary to use multiscale ensemble methods for storm-scale problems e.g., Zhou et al, 2007? (sub-themes 3.2 and 3.3)
- What is the best way to include model error?

The first phase will involve the use of simplified models and simulated observations to investigate various strategies for practical implementation. The conclusions will be taken forward to implement an appropriate scheme for the Met Office high resolution version of the Unified Model. The observation operators used will be taken from those available at the time as part of the Met Office operational variational assimilation system (these observation types are detailed in 3.3). The performance of the new ensemble system will be evaluated in assimilation-forecast case studies, and results compared to control experiments using the Met Office variational assimilation system. In common with sub-theme 3.1 and 3.2 some of these studies will use CSIP data for independent verification. An evaluation of the quantitative accuracy of probabilistic analyses and forecasts produced by the ensemble system, would require an extended trial. Because of the supercomputer time required for such a trial, it would only be carried out if the results of the case studies have significant positive impacts.

3.6 Snow and soil moisture retrievals *(Researchers Gurney/Davenport/Sandells)*

Summary

Snow mass and near-surface soil moisture are strongly coupled to the atmospheric circulation, and affect both droughts and floods, as well as being key for the carbon cycle and a boundary condition for climate change predictions. Both are poorly represented in both NWP and climate models, and are hard to observe using surface-based techniques over large areas. Global estimates of soil moisture will become available in 2008 with the launch of the SMOS satellite. It will be essential for the retrievals to be carried out in a NWP context because the retrievals are sensitive to the accuracy and availability of meteorological data. Although snow mass estimates have been available for some years (Chang et al, 1982) these retrievals have been limited because of the assumptions, for instance, of a fixed grain size. Again it is clear that more satisfactory retrievals will be made in a NWP context, but working in close collaboration with the space agencies to allow for data reprocessing. The spatial resolutions of the initial retrievals will be of the order of tens of kilometres, which is too coarse for many flood models but useful in NWP and climate models. However, the advent of constellations of SARs, with Terrasar-X, Radarsat 2, and COSMO-SkyMed, will allow a finer spatial and temporal resolution to be used for establishing snow melt, while SAOCOM, with its quad-pole L-band capability, will allow relative soil moisture to be studied within the coarser footprint of the SMOS retrievals from 2010. Specific objectives are to understand and exploit existing and new passive microwave observations to retrieve snow mass and near-surface soil moisture; to evaluate how to use new SAR data to study the spatial variability of snow mass and soil moisture; to examine the impact of spatial and temporal resolution on retrieval accuracy; to perform process studies to understand how to assimilate these data and to evaluate and improve the representation of snow mass and soil moisture in global and regional models. Developments in JULES will feed back into better climate prediction (Theme 1) as well as NWP. Snow and soil moisture are also critical for modelling the land surface carbon budget (Theme 2). The work is strategic, key to the use of observations by operations in the longer term, and requires the concentrated work on fundamental issues and collaborative engagement provided only by NCEO. It is a critical contribution to national capability.

Work Description and Methodology

Passive microwave emissions from the soil surface have been shown (Schmugge, 1978) to be related to the near-surface soil moisture. The emission is scattered by vegetation, and the vegetation also emits microwave radiation. This limits the use of the technique at most wavelengths to bare ground or areas of very short vegetation. At longer wavelengths, retrievals are possible over taller vegetation because it still remains optically thin. The deployment of radiometers at longer wavelengths is challenging, because of the size of antenna required, and so it is only in 2008 that the first L-band (21cm wavelength) radiometer with a useful spatial resolution (~40km) will be launched by ESA. Although higher frequency radiometers have been used to make retrievals of soil moisture in arid and semi-arid areas (e.g. van de Griend and Owe 1994), this is the first time that retrievals will be possible over large areas of the world. Considerable work has already been done by several groups to understand how to retrieve soil moisture from L-band radiometry, using a variety of airborne and field experiments. All have shown that retrievals are possible, even in heterogeneous areas. In recent work connected with SMOS, Davenport et al (2005) have shown that good (+/- 2K) estimates of surface temperature are required for consistent retrievals for SMOS, and areas of open water need to be known well (to 0.5% total area), although this can be relaxed if time series of observations are used to identify flooding. This points strongly to the use in retrievals of ancillary information most easily available in numerical weather prediction.

We will work closely with the international community who will be carrying out field experiments to validate SMOS, including in France, the US and in Australia. The results will be used to design and test a retrieval system for soil moisture from SMOS, using a 1-D version of the Met Office Unified Model, with the JULES SVAT model (see Theme 1) coupled to a passive microwave emission model (Wilheit, 1978). This will be run as a forward model to estimate top of atmosphere microwave brightness temperature estimates that will be compared with observations of microwave emission and tested using the field validation data. Once a satisfactory approach is agreed, the model will be implemented in the Unified Model. There will be close liaison with Theme 1, which is also developing JULES. Close contact will be maintained with groups such as ECMWF (who are already assimilating ASCAT and will be assimilating SMOS observations) in order to share best practice, and learn from the operational experience, and with the CNES-funded Level 3 processor for SMOS to be developed by CESBIO.

A variety of other estimates related to soil moisture will be made over the next few years, and comparisons will be made with the SMOS retrievals, including validated retrievals from AMSR, in semi-arid areas. In addition, information related to the spatial variability of soil moisture will be available at much higher spatial resolution from SAR observations, such as the quad-pole L-band SAOCOM. These data will also be analysed to understand the effect of spatial variability on soil moisture retrievals and to provide better boundary conditions for flood models

A similar approach will be adopted with retrievals of snow mass. This is badly represented in NWP models but provides the source for severe flooding in many areas. SSM/I and other microwave radiometers such as AMSR provide estimates of snow mass, but these have large errors because they do not make use of other weather information available in NWP models. This information can be used to model the change in grain size and melt state of the snow, and therefore microwave scattering and emission. It is proposed to use a forward model in an NWP context to estimate top of the atmosphere microwave brightness temperatures, for comparison with SSM/I observed brightness temperatures. Current comparisons are between a modelled snow mass and a snow mass retrieved from observations, but differences could be due to errors in the retrieval algorithm or errors in the land surface model. A more direct approach allows unequivocal comparisons with the microwave observations. Errors in the model will be examined through comparisons with field measurements. Surface observations will be used from experiments such as CLPX and from experimental sites such as Reynolds Creek. Initially, 1-D versions of the Unified Model will be coupled to a microwave emission model, to improve both models and comparisons with observations, and the new methods will then be applied globally.

3.7 Improving river flood modelling using remote sensing *(Researcher Mason)*

Summary

Hydraulic models of river flood flow employ tuneable parameters such as floodplain and channel friction coefficients. The model performance measures usually used to calibrate these parameters rely on comparing modelled and measured flood extents from a satellite SAR image. The weakness of this approach is that these measures are not very sensitive to these parameters. For example, it has been found that for a particular event many different sets of model friction parameters may give flood extents that match the observed extent to a greater or lesser degree. Furthermore, while SAR images have been appropriate sources of data for rural floods, because of their all-weather day-night capability, up until now the spatial and temporal resolution of these SARs has been too poor to make them useful for observing urban flood extent. However, this situation is likely to change over the next two years, since a number of SAR instruments are due to be launched with higher spatial resolutions and temporal frequencies (TerraSAR, RADARSAT-2 and the COSMO-SkyMed constellation). The synergy of the new SAR data with lidar observations could allow for water-surface elevations to become part of performance measures, and should alleviate some of the difficulties with waterline retrievals. Our approach is to use these data to and produce validation data sets and reduce the uncertainty of modelled flood extents. Ideas from control theory will enable us to evaluate if these two sources of data are sufficient to give good estimates of the model friction parameters using data assimilation, and help us design observing strategies that allow objective estimates of these parameters. This is also contributing to the goals of FRMRC. The work is strategic, key to the use of observations by operations in the longer term, and requires the concentrated work on fundamental questions and collaborative engagement provided only by NCEO.

Work description and methodology

The objectives of this work are to reduce uncertainty in modelled flood extents, obtain validation data of urban flood extent, and use assimilation to estimate flood model parameters. Methods have already been developed in ESSC of using remotely sensed data to validate and parameterise 2D flood models. The models are finite element or finite difference models solving the shallow water equations at each node of the model mesh as a function of time, given an input hydrograph. Previous work has involved extracting flood extent from SAR data in order to validate model flood extents (Horritt et al 2001), and using lidar data to parameterise 2D flood models (Mason et al 2003, Cobby et al 2003), in particular providing a DTM for model bathymetry, and vegetation heights to estimate floodplain friction coefficients.

Observations of flood extents in urban areas are needed for validation of the extents predicted by urban flood models. These model surface water flow including channel-floodplain interactions as in rural floods, but must also model surface flows interacting with the built environment and sub-surface flows in storm drainage systems. Currently many studies are being performed inter-comparing different urban flood models (e.g. Hunter et al, submitted), but there are few validation data to back up their findings. Satellite SARs are often used to provide validation data for rural floods because of their all-weather day-night capability, but up until now the spatial and temporal resolution of these SARs has been too poor to make them useful for observing urban flood extent. This situation is likely to change over the next few years. The TerraSAR X-band SAR should be launched in 2007, giving 1m resolution and a temporal repeat interval of a few days. In 2007 RADARSAT-2, capable of 3m resolution, is due for launch. This should be followed later in 2007/8 by the 4-satellite COSMO-SkyMed SAR constellation, giving 1m resolution and a repeat interval of several hours. In 2010, the SAOCOM satellites, capable of 2m resolution, will be launched. The automatic discrimination of the land-water boundary (waterline) in SAR images of urban areas is difficult due to many corner reflectors, radar layover and shadowing (Balz et al 2003). However, by combining the SAR data with lidar data, it should be possible to identify sections of waterline in areas not influenced by nearby buildings, which were not misclassified roads. This will require a SAR simulator working in conjunction with a lidar DTM containing buildings. Even disjoint sections of waterline will provide areal extent information which is more useful for 2D model validation than point measures (e.g. of water depth). Some of the SARs have advanced specification that will allow greater discrimination of flood edge without recourse to other data.

Current flood performance measures usually involve comparing binary areal modelled flood extents with the areal flood extent from a SAR image obtained during the flood (Aronica et al 2002). In a typical model run, the parameters that will require calibration using the performance measure are the effective channel and floodplain friction coefficients. The areal performance measures have a number of limitations, in particular a lack of sensitivity to these parameters. Recent work at ESSC has improved flood extents observed in SAR imagery using a lidar DTM to ensure that flood heights along the waterline vary smoothly along the reach (Mason et al, accepted). This has opened up the possibility of augmenting binary pattern matching by comparing observed and predicted water surface elevations at points along the reach. The height difference measure should be more sensitive than the areal measures and it should be possible to assign a probability to it. This in turn should reduce uncertainty in predicted extents produced by ensemble analyses. Emphasis is now placed on associating uncertainties with model flood extents, by deriving flood extent probability maps showing the probability of each pixel being flooded given a flood event of the given magnitude. It has been found that for a particular event many different sets of model friction parameters may give flood extents that match the observed extent to a greater or lesser degree. Such equifinality has resulted in the development of the Generalised Likelihood Uncertainty Estimation (GLUE) technique (Beven and Binley 1992). A flood extent probability map is obtained by performing a weighted average of the binary-valued modelled flood extents, with each model flood extent being weighted according to its performance measure relative to an observed flood extent. An improved performance measure should thus reduce flood extent uncertainty.

The short repeat interval made possible by the new SAR instruments should allow a time sequence of images to be built up over the duration of a flood, even though floods in catchments in many parts of the world, such as the UK, may last only a few days. Currently it is usual that only a single SAR image of flood extent is obtained over the course of a flood, which is used for model validation (Horritt 2006). If a time sequence of images could be acquired, this might make assimilation of areal flood extent data into the model run possible. This might allow better estimation of model parameter values such as floodplain and channel friction coefficients and also the associated errors. A suitable initial example data set of flood extents from four airborne SAR images taken over a 10-day period of a lower Severn flood has already been acquired (Bates et al 2006). The concept of *observability* from control theory will enable us to evaluate if these data are sufficient to give good estimates of the model friction parameters using assimilation, and help us design observing strategies that allow objective estimates of these parameters.

3.8 Improving coastal area morphodynamic models using data assimilation

(Researcher Mason/Dance)

Summary
Coastal flood forecasting is limited near-shore by a lack of knowledge of the evolving bathymetry. Furthermore, to protect areas vulnerable to coastal flooding, operational agencies often carry out beach nourishment works. Since the beach evolves over time, as sediment is eroded, transported and deposited by water action, it can be hard to tell if the scheme is working. This builds on work that will improve

coastal area morphodynamic models using data assimilation of samples of partial bathymetry such as SAR waterlines (Scott and Mason, 2007) that is already being carried out under FREE. Additional related work will be carried out here in using EO in this type of problem, and to explore and exploit new sources of data such as X-band radar, and hyperspectral scanning and lidar. The work is strategic, key to the use of observations by operations in the longer term, and requires the concentrated work on fundamental questions and collaborative engagement provided only by NCEO.

Work description and methodology

The current state-of-the-art in operational coastal flood forecasting is limited near-shore by a lack of knowledge of evolving bathymetry. Accurate up-to-date bathymetry immediately prior to a storm event would allow improved flood forecasting using coastal inundation models (Stelling 2000). The FREE project is using variational data assimilation techniques with a morphodynamic model to develop techniques for improving estimates of bathymetric changes over timescales of months to years at several sites on the UK coast. The available observations of bathymetry at these sites include time series of remotely sensed waterlines (Mason et al 1999), beach transects, X-band radar (Bell et al 2005), airborne lidar and swathe bathymetry. The morphodynamic model consists of coupled tide, wave and sediment transport models, which model the erosion, transport and deposition of sediment by tides and waves, as well as the changes in water motion caused by changing bed levels. The project will involve construction of morphodynamic assimilation-forecast systems for the Dee estuary, Morecambe Bay and the East Lincolnshire coast, quantification of the predictability of the models, evaluation of the impact of storm events on the bathymetry, and the use of data assimilation to estimate model parameters.

Additional related work not funded under the FREE project will be carried out in this sub-theme to add to national capability in using EO in this type of problem. For instance, the Proudman Oceanographic Laboratory's shore-mounted X-band radar in the Dee estuary is able to estimate bathymetry not just by measuring wave periodicity and height and inverting the wave equation, but also by extracting waterlines from the images and heighting them using a nearby tide gauge. As these waterlines can be obtained on an hourly basis, they can be subsampled to mimic the effects of aliasing in the satellite SAR waterlines, and so studying the effects of this on the model bathymetry after waterline assimilation. Tidal channels in the Dee may shift by a wavelength every 3-4 months, comparable to the time interval between low-tide waterline acquisitions from a single satellite SAR sensor such as ERS-2.

In the longer term, work will be driven by the outcomes of the FREE project, and is necessarily somewhat speculative at this stage. Morphodynamic assimilation-forecast systems will be used to study the impacts of increased storminess and sea level rise due to climate change, which could involve a link with the work on storm tracks in sub-theme 3.4. Another possibility might be to improve the assimilation scheme by assimilating not just changes in bathymetry but also changes in sand constitution with time into the model run. The sand used for beach nourishment schemes and berm replacement works typically has a different grain size to the sand naturally occurring on a beach. This is the case for the Lincshore beach nourishment scheme between Skegness and Mablethorpe (one of the FREE project study sites) carried out to protect the coastal towns and hinterland of this low-lying area vulnerable to coastal flooding (Zwiers et al, 1996). The spectral signature of sand depends upon its grain size. Multi-temporal airborne remote sensing using hyperspectral scanning and lidar should make it possible to measure changes in both volume and type of sand at different points in the inter-tidal zone (Deronde et al, submitted). Assimilation of bathymetric and sand type changes into the model run might make it better able to predict the movements of the sand used in the nourishment process, in order to assess if the latter is working properly. Although aircraft would have to be used at present, making multi-temporal monitoring expensive, UAVs carrying hyperspectral scanners and active lidars should be available before 2010. In the longer term, hyperspectral spacecraft observations of the required spatial and temporal resolution will become available commercially, allowing the method to be applied anywhere.

4. Deliverables, Dependencies and Data Requirements

New scientific understanding is key for the theme, and will be delivered via scientific papers in the refereed literature and at conferences. Training in Earth observation techniques relevant to meteorology and hydrology will be delivered via short courses. Operational agencies are fully involved in the theme delivery, including with co-location of Met Office staff in the JCMM at Reading, which allows us to have secure computer access to their database of operational observations. A number of software components will be developed within the Met Office system, and their transfer to operational use will therefore be particularly straightforward. The Met Office Unified Model is already available to run on NERC's high performance computing facility. This work will additionally require the porting of the VAR assimilation software to this facility. This will be completed by DARC by the start of NCEO. By making the VAR software more widely available, data assimilation and earth observation research will become accessible to a much wider community. In general, continuing close relationships with the operational agencies are critical for the delivery of this research, and this dependency cannot be managed completely at this stage for such a long-term programme. Live Access Servers and other GRID-based delivery mechanisms offer needed flexibility. The NCEO informatics theme will be developing these information delivery mechanisms, and there is an important dependency of this theme on that theme in this area. Some of these delivery mechanisms will continue to be developed jointly with the EA and Met Office, and their detailed specification will depend on operational needs.

The delivery of the theme will require collaboration across NCEO (see Annex). FREE and FRMRC have wide-ranging links to users and the wider community in weather and flood related research. Although this theme is based at Reading because of the ability this gives for very close links to operational agencies, there is already strong involvement with FREE, FRMRC and other programmes nationally and internationally, and this will be strengthened using KT programmes (see below) to make the programme truly national. Part of acting as a focus for national activities will be by organising meetings to allow users to interact effectively with Space Agencies and others and short courses for graduate students and others to learn the skills necessary to exploit the many missions being worked on in this theme; this is particularly critical here because of the diversity of users. Public engagement with the research will be facilitated by involvement in National Science Week activities, open days and schools outreach.

Most of the non-satellite data needed will be provided by operational agencies, particularly the Met Office, ECMWF and EA, and agreements are already in place for the initial work. The Informatics theme will be important for facilitating access to EO data, both for this theme and for the wider UK community to have access to the data subsequently. The existence of excellent operational data and a close working relationship with the operational agencies is a strong argument for basing the work of this theme in the UK as it reduces risks and aids knowledge exchange. Data from UK, Australian, US and other field experiments will be negotiated bilaterally, building on existing relationships.

5 Resource requirements, justification and management

Staff: The work requires experienced staff with strong quantitative backgrounds in both EO and environmental science. Funding for national capability is requested here; additional funding for mission specific and knowledge exchange will be sought from the EO research opportunity fund, KT funds and other research council and related funds, as indicated in the annex. We will participate in the NCEO graduate training programme.

Travel: Interactions across NCEO and with the wider community are key to the ability of NCEO to function coherently to promote the wider adoption of Earth Observation, and to interact with space agencies and other international partners. Attendance at conferences and workshops is vital in order to keep abreast of recent advances and to present the results of the work.

Computing: The Met Office will provide access to their supercomputer for some computations that are not able to be done on the NERC high performance facility (see top level document), or on the ESSC cluster. Desktop machines to access these separate networks will be needed, along with appropriate data storage servers.

Management and Reporting: Gurney and Dance are co-theme-leaders. A research co-ordinator will be appointed (as detailed in the top-level document). There will be close interaction with collocated Met Office staff in Reading, as well as from other institutions elsewhere. There will be weekly business meetings of all staff in the theme, when progress against targets will be monitored. There will be monthly scientific meetings of all staff, together with many informal meetings, and a formal weekly seminar programme of theme and external speakers. Prince2 methodology will be used as appropriate to manage the tasks and risks in the theme.

Strategic development: The sub-themes are at different levels of maturity in terms of the way they use EO data in models. We are requesting the majority of funding for the first three years of the programme to give flexibility, and will seek other funds to maintain and build capacity as the research and partnerships with the Met Office, NCAS, and national and international partners develop.

6 Knowledge Exchange

All sub-themes have strong user and data supplier engagement. There is a close engagement with operational agencies such as EA, Met Office and ECMWF, and co-location of staff. The FREE and FRMRC programmes already have strong user engagement and user funding (e.g., HR Wallingford, Halcrow etc.), and it would be confusing to have a separate programme to engage users. NERC knowledge transfer funding will be sought to broaden the user engagement of these programmes, and discussions have already started with both on sharing KT PDRAs, etc. Continued involvement by some of the Co-Is in NCAS activities will facilitate joint activities there. Reading is an ESL for SMOS, and involved with the other space agency teams who are providing data to this theme. The CEOI will be used to engage the UK space industry, and so close the circle on proposing new missions in this area. Funding will also be sought under the TSB sensors theme to assist with this KT activity. Interactions with relevant KTNs will be used to expand the range of relevant industrial interests, but although discussions have started these are best accomplished after the theme starts.

7 Risk assessment

There are a very large number of new satellites to be launched related to this theme. All themes also use existing data, so this is the initial mitigation if any launch fails. Close agreements exist or will be put in place with all relevant space agencies (NASA, ESA, CONAE, CNES, ASI, JAXA) to allow full access to science teams, and to allow NCEO investigators to profit from experience elsewhere working in conjunction with the NCEO Informatics theme. Most collaborations build on successful existing partnerships. Prince2 methodology will be used appropriately to minimise remaining risks.

8 References

Anderson JL (2003) A Local Least Squares Framework for Ensemble Filtering. *Mon. Wea. Rev*. **131**, 634–642

Aronica G., Bates P.D. and Horritt M.S. (2002). Assessing the uncertainty in distributed model predictions using observed binary pattern information within GLUE. *Hydrological Processes*, **16**, 2001-2016.

Bannister R.N. (2007) Can wavelets improve the representation of forecast error covariances in variational data assimilation? *Mon. Wea. Rev.* **135,** 387-408

Balz T., Haala N. and Soergel U. (2003) Combining LiDAR, InSAR, SAR and SAR simulation for change detection applications in cloud-prone urban areas. *First Int. Symp. on cloud-prone and rainy areas remote sensing*. Hong Kong, 2003, 68-79.

Bates P.D., Wilson M., Horritt M.S., Mason D.C., Holden N. and Currie A (2006). Reach scale floodplain inundation dynamics observed using airborne SAR imagery. *J. Hydrology,* **328**(1-2), 306-318.

Baxter, G.M., Ballard, S. P, Dance S.L., Lawless, A.S., and Nichols N.K.(2007) Multiscale data assimilation for high resolution nested models In *Proc of the ICFD Conference on Numerical Methods for Fluid Dynamics*, Reading UK (in press).

Bell, P.S., Williams, J.J., Clark, S., Morris, B.D. and Vila-Concejo, A. (2005). Nested radar systems for remote coastal observations. ,*J. Coastal Research*, SI **39** (Proceedings of the ICS 2004): in press.

Bengtsson, L., K. I. Hodges and S. Hagemann, (2004a). Sensitivity of Large-Scale Analyses to Humidity Observations and its Impact on the Global Water Cycle and Tropical and Extratropical Weather Systems in ERA40, *Tellus*, **V56A**, 202-217.
Bengtsson, L., K. I. Hodges and S. Hagemann, (2004b), Sensitivity of the ERA40 reanalysis to the observing system: determination of the global atmospheric circulation from reduced observations, *Tellus*, **V56A**, 456-471.
Bengtsson, L., K. I. Hodges and L. S. R. Froude, (2005), Global observations and forecast skill., Tellus, **V57A**, 515-527.
Berre L. (2000). Estimation of synoptic and mesoscale forecast error covariances in a limited area model, *Mon. Wea. Rev*., **128**, 644-667.
Berre L., Ştefănescu S.E. and Belo M. (2006). The representation of the analysis effect in three error simulation techniques, *Tellus*, **58A**, 196-209.
Beven K.J. and Binley A.M.(1992). The future of distributed models: model calibration and predictive uncertainty," *Hydrological Processes*, **6**, 279-298.
Browning K., Blyth A., Clark P. et al. (2007) The Convective Storm Initiation Project *Submitted to Bull. Amer. Meteor. Soc.*
Caya A, Sun J, Snyder C (2005) A Comparison between the 4DVAR and the Ensemble Kalman Filter Techniques for Radar Data Assimilation. *Mon. Wea. Rev.* **133**, 3081–3094
Chang, A.T.C., Foster J.L., Hall D.K, Rango A. and Hartline B. K. (1982**).** Snow water equivalent estimation by microwave radiometry. *Cold Reg. Sci. Technol.* **5**,259-267
Chevallier F., Lopez P., Tomkins A.M., Janisková M., Moreau E. (2004). The capability of 4D-Var systems to assimilate cloud-affected satellite infrared radiances, *Q.J.R. Meteorol. Soc*., **130**, 917-932.
Cobby, D.M., Mason, D.C., Horritt, M.S. and Bates, P.D. (2003). Two-dimensional hydraulic flood modelling using a finite element mesh decomposed according to vegetation and topographic features derived from airborne scanning laser altimetry. *Hydrological Processes* **17**, 1979-2000.
Cox et al., http://www.jchmr.org/jules/
Dance, S.L. (2004) Issues in high resolution limited area data assimilation for quantitative precipitation forecasting. *Physica D*, **196**(1-2), 1-27.
Davenport et al (2005). A sensitivity analysis of soil moisture retrieval from the tau-omega microwave emission model. *IEEE TGRS* **43** (6) 1304-1316
Deronde B., Houthuys R., Henriet J-P., Van Lanker V. (submitted). Monitoring the sediment dynamics along a sandy shoreline by means of airborne hyperspectral remote sensing and LiDAR, a case study in Belgium. *Earth Surface Processes and Landforms*.
Fischer C., Montmerle T., Berre L., Auger L. and Ştefănescu S.E., (2005) An overview of the variational assimilation in the ALADIN/France numerical weather-prediction system, *Q.J.R. Meteorol. Soc*., **131**, 3477-3492.
Fisher M. (2003). Background error covariance modelling, in ECMWF Seminar Proceedings, Recent developments in data assimilation for atmosphere and ocean, Sept. 2003, 45-64.
Fisher, M (2005) Accounting for Correlated Observation Error in the ECMWF Analysis, ECMWF Research Dept Memorandum, R48.3/MF/05106
Froude, L. S. R., L. Bengtsson and K. I. Hodges, (2007a), The Predictability of Extratropical Storm Tracks and the Sensitivity of their Prediction to the Observing system, *Mon. Weather Rev*., **V135**, 315-333.
Froude, L. S. R., L. Bengtsson and K. I. Hodges, (2007b), The Prediction of Extratropical Storm Tracks by the ECMWF and NCEP Ensemble Prediction Systems, *Mon. Weather Rev*., in press.
Hogan, R.J. (2007). A variational scheme for retrieving rainfall rate and hail reflectivity fraction from polarization radar. *J. Appl. Meteorol. Climatology,* in press.
Horritt, M.S., Mason, D.C. and Luckman, A.J. (2001). Flood boundary delineation from synthetic aperture radar imagery using a statistical active contour model. *Int. J. Remote Sensing*, **22**(13), 2489-2507.
Hunter N.M., Bates P.D., Neelz S., Pender G., Villanueva I., Wright N.G., Liang D., Falconer R.A., Lin B., Waller S., Crossley A.J. and Mason D.C. (submitted). Benchmarking 2D hydraulic models for urban flood simulations. *Proc ICE.*
Katz D. (2007). Balance constraints in variational data assimilation PhD thesis University of Reading.
Lawson W.G., Hansen J.A. (2004). Implications of stochastic and deterministic filters as ensemble-based data assimilation methods in varying regimes of error growth. *Mon Wea Rev* 132 (8): 1966-1981
Lean, H.W., Ballard, S.P., Clark, P.A., Dixon, M.A., Li, Z. and Roberts, N.M (2005) The Summer 2003 reruns with the High Resolution Trial Model. *Forecasting Research Technical Report* **457**. Met Office
Leeuwenburgh O., Evensen G., Bertino L. (2005) The impact of ensemble filter definition on the assimilation of temperature profiles in the tropical Pacific *Q. J. R. Meteorol. Soc.* **131 (613):** 3291-3300
Livings, D.M., Dance, S.L. and Nichols N.K. (2006) Unbiased ensemble square root filters. University of Reading Mathematics Dept Numerical Analysis Report 06/06
Lorenc, A.C. (2003) The potential of the ensemble Kalman filter for NWP - a comparison with 4D-Var, *Q.J.R. Meteorol .Soc* **129** 3183-3203
Marécal V. and Mahfouf J.-F. (2003). Experiments on 4D-Var assimilation of rainfall data using an incremental formulation, Q.J.R. Meteorol. Soc., **129**, 3137-3160.
Mason, D.C., Amin, M., Davenport, I.J., Flather, R.A., Robinson, G.J. and Smith, J.A. (1999). Measurement of recent intertidal sediment transport in Morecambe Bay using the waterline method. *Estuarine, Coastal and Shelf Science*, **49**, 427-456.
Mason, D.C., Cobby, D.M., Horritt, M.S. and Bates, P.D. (2003). Floodplain friction parameterization in two-dimensional river flood models using vegetation heights derived from airborne scanning laser altimetry. *Hydrological Processes* **17**, 1711-1732.
Mason, D.c., Horritt M.S., Dall'Amico, J.T., Scott, T.R., and Bates, P.D. (accepted) Improved river flood extent delineation from synthetic aperture radar using airborne laser altimetry. IEEE Trans. Geoscience Rem.Sens.
Rihan, F.A., Collier, C.G. and Roulstone, I.R. (2005) Four-dimensional variational data assimilation for Doppler radar wind data. *J. Comp. App. Math*., **176** (1), 15-34.
Roberts, N. (2004) A strategy for measuring the fit of rainfall analyses and forecasts to radar. *Forecasting Research Technical Report* **432.** Met Office
Scott T.R. and Mason D.C. (2007). Data assimilation for a coastal area morphodynamic model: Morecambe Bay. *Coastal Engineering,* **54**(2), 91-109.
Schmugge, T. (1978). Remote sensing of surface soil moisture. *J. App. Meteorol*. **17** (10) 1549-1557
Stelling, G.S. (2000). A numerical method for inundation simulations. *Proc. 4th Int. Conf. Hydro-Science and Engineering*, Seoul, Korea (ed. Y.N. Yoon, B.H. Jun, B.H. Seoh and G.W. Choi) (available on CD-ROM only).
Stewart, L. M., Dance, S.L. and Nichols, N.K. (2007). Information content and correlated observation errors. Submitted to *Int. J. Num. Meth. Fluid Mech*.
Torn R.D., Hakim G.J. and Snyder C. (2006). Boundary conditions for limited-area ensemble Kalman filters *Mon. Wea. Rev*.**134 (9)** 2490-2502
van de Griend and Owe (1994). Microwave vegetation optical depth and inverse modelling of soil emissivity using Nimbus / SMMR satellite observations. *Meteorology and Atmospheric Physics* **54** (1-4) 225-239.
Wilheit, T.T. (1978). Radiative transfer in a plane stratified dielectric. *IEEE Trans. Geosci. Electron*., **16**, 138–143.
Wulfmeyer , V., Behrendt, A., Kottmeier, C and Corsmeier, U. (2005) *Eds*. Convective and Orographically-induced Precipitation Study Science Overview Document. *Available from http://www.uni-hohenheim.de/spp-iop/index.htm*
Zhang F. (2005). Dynamics and structure of mesoscale error covariance of a winter cyclone estimated through short-range ensemble forecasts, *Mon. Wea. Rev*., **133**, 2876-2893.
Zhou Y., McLaughlin D. and Entekhabi D (2007). An ensemble multiscale filter for large nonlinear data assimilation problems Submitted to *Mon. Wea. Rev*.
Zwiers M., Dales D. and Hunt H. (1996). Mablethorpe to Skegness beach nourishment: is it working? In *Partnership in Coastal Zone Management* (J. Taussik and J. Mitchell (eds)), Samara Publishing, Cardigan, 631-637.