Final Report

FARADAY FAST TRACK PROPOSAL: Direct and Inverse Modelling in End–to–End Environmental Estimation (DIME)

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1 Overview

The objective of DIME was to assess the potential economic benefits of numerical weather forecasts and in particular ensemble forecasts. To use weather predictions effectively, industries require mathematical tools to tailor–make probabilistic forecasts for their specific needs. Significant progress was made towards the goals of the project as stated in the grant proposal. We will first give a general overview of the project achievements as well as the context of the research. Subsequent sections will give a more detailed report and specific results on each of the objectives as present in the grant proposal. Research impact as well as dissemination activities and further research are each given a separate section.
The major successes of the DIME project include:

- A £25,000 (+VAT) extension of the project funded by EDF to allow LSE to develop and deploy a real-time in-house EDF version of the results; this version is now operational.
- Successful NERC knowledge transfer project "Nonlinear Analysis and Prediction of Statistics from Timeseries and Ensemble-forecast Realizations" (NAPSTER) over two years at £152,480.
- Reviewed journal articles and trade journal papers, conference presentations and online discussion with researchers and end-users.
- Online inter-comparison of forecast products and interpretation techniques (see `dime.lse.ac.uk`), and the emtool (see `cats.lse.ac.uk/forums`).
- Followup application to DTI (pending) with NGT, Scottish Southern, the UK MetOffice, and the Department of Trade and Industry for short range wind forecasting (budget 500,000 over three years).

At the heart of DIME's direct approach lie methods for the statistical post-processing of ensemble weather forecasts. Raw ensemble output is provided by numerical weather prediction models of global weather forecasting centres such as NCEP (National Centre for Environmental Prediction, USA) and ECMWF (European Centre for Medium Range Weather Forecasting). This raw ensemble output is then post-processed to make forecasts. DIME strives to both enhance the quality of these ensemble forecasts through various post processing techniques and subsequently to evaluate the quality of these forecasts using various measures of quality. This requires methods different from what would be applied to classical point forecasts, for point forecasts do not contain uncertainty information, yet it is exactly this uncertainty information that is of interest. Delays in acquiring the full archive of ECMWF forecasts (the final 50GB of data reached CATS only in January 2006 and are only just now re-archived and on-line), have meant that a number of papers are still awaiting the full analysis for submission. Comparisons for 5 weather stations are already on-line.
DIME aims at considering both direct and indirect methods for down-scaling ensemble weather forecasts. Inverse methods for down-scaling ensemble weather forecast were considered, but competitive performance with direct methods was obtained only for lead times on the order of seasons [2].
In summary, the project has lead to insight into statistical post-processing and quality assessment of probabilistic forecasts in general along with combining forecasts meaningfully for added value. This insight was documented in various publications (both peer–reviewed and industrial trade journals) and disseminated via our web site as well as during two well–attended industrial weather risk workshops. Furthermore, software toolboxes were developed and made available to interested researchers.

2 Key Advances and Methodology

The objectives of the DIME project at the LSE are to investigate and enhance the value of ensemble weather forecasts delivered by institutions like NCEP (USA) or ECMWF (Europe) and to provide knowledge and tools for further utilisation of the forecasts by end users. Considering the pure ensemble forecasts as a raw product, DIME strives to

1. refine the information content,
2. disseminate both refined forecast information along with long time performance evaluation,
3. process forecasts for decision support.

In each case, this aim in interpreted according to the various demands of different end users. Note that operational centres tend to focus on their own products. By taking the users viewpoint, DIME was able to investigate the value of combining products from a variety of operational centres.
To meet the first task, various probabilistic forecast systems have been developed. These combine medium range ensemble forecasts from different institutions with historical analyses and observations to produce statistically enhanced forecasts. One of these forecast products, an ensemble of 100 equally likely scenarios, is operational. The re-sampling technique involves "dressing" each ensemble member with a distribution of appropriate historical forecast errors. Furthermore, forecasts of different variables of interest for various locations are calculated in the form of probability density functions ("kernel dressing"). These forecasts are not operational in real time but are compared in terms of their long term performance, using various measures of performance. The purpose of this study is to demonstrate that both the means of evaluation and the technique to produce these forecasts are user dependent. This includes the question as to what extent users may benefit from employing combined forecasts from different centres.
The importance of probabilistic forecasts, and the fundamental problems of using unequivocal forecasts, was appreciated by Ångström as far back as the 1920s. Yet unequivocal weather forecasts are still ubiquitous. A possible reason is the difficulty of presenting the forecasts to the non-expert user in a suitable manner. Multiple weather maps, or even geographical maps of ensemble spread, tend to be of more interest to meteorologists than to end users, the majority of whom are interested in the weather at a specific location or locations. This is fortunate, because removing the spatial dimension from the problem of presentation makes it easier to introduce uncertainty information.
The interactive nature of the web allows users to choose how probabilistic forecasts are presented. A Java based graphical user interface is provided to view the operational forecasts of the DIME project online. The user can select the appropriate level of complexity.
Another problem users are faced with is the lack of information on how the multitude of available products compare. Furthermore, various post-processing and dressing techniques exist for which the potential benefits are heavily dependent on particular end users applications. DIME addresses this by comparing and evaluating various different dressing techniques. The results of these studies are disseminated via the DIME web site. An interactive page allows the user to choose source, location, variable and post-processing technique to be evaluated. The result is a plot of the skill over lead time.
The investigated post processing techniques were documented in terms of the underlying principles as well as the implementation details. A software toolbox called *E*nsemble*M*odelling*Tool*box (emtool) was created, comprising the most advanced techniques used in DIME. This toolbox is currently intensively tested at CATS and ECMWF.
In the course of the DIME project, a considerable amount of time had to be spent in organising the data and transferring it to useful data formats. The archive started with NCEP data downloaded on a day–to–day basis, but by now comprises not only 3.5 years of global NCEP forecasts but also ECMWF and other forecast data with lead times in both the medium and the seasonal range. This archive will be continued and extended beyond the end of DIME and will be invaluable for further follow–up research.
Probabilistic weather forecasts can be used to generate probabilistic forecasts not only of weather variables but also of weather dependent variables of commercial interest. A future project might consider direct probabilistic forecasts of the weather dependent components of a user's utility, e.g. his or her gain or loss in money if a certain weather event occurs. The Internet provides an ideal medium for this "end

to end" approach. The forecasts may either be provided by DIME (if large numbers of users may demand the same utility) or locally by distributed tools accessing the forecasts via a standard web interface.
We will now explicitly address the five research objectives mentioned in the grant proposal

1. **Develop methods to extend and quantify the economic value of probabilistic weather forecasts.** The economical value of weather forecasts were investigated and the results brought to application, even down to the level of operational solutions. Statistical details and theoretical background has been or will be published in the academic literature. In terms of industrial applications, we have raised the profile of our applications by publishing in trade journals [3, 18, 17]

2. **Contrast and extend methods for estimating a variety of statistics of interest when pricing weather derivatives. In particular, contrast the performance of operational models with state–of–the–art statistical inverse models.** Statistical inverse methods were investigated, mostly in the range of seasonal lead times. Application to data from the seasonal re-forecasting project DEMETER was investigated [20]. Furthermore, the technique of ensemble random analog prediction (eRAP) was developed. The main illustration of the inverse methods explored under DIME was presented as a poster [1]. It will be the basis for several chapters in the PhD thesis of A. Adrianova [2], expected this summer 2006.

3. **Construct inverse models for end–to–end down-scaling of ensemble prediction systems (ensembles of models, initial conditions and lead–times) obtaining quantitative results. In particular, a quantitative comparison with existing direct (simulation) modelling approaches.** Methods for end–to–end down-scaling of probabilistic weather forecasts were developed and implemented as a software toolbox (available online on request on `cats.lse.ac.uk/forum`), currently beta–tested. Comparisons for 5 weather stations are already online. Publications are in preparation [7, 8], but are still awaiting full analysis using substantially more comprehensive data that just recently arrived.

4. **Develop and apply methods to rank the relative value of addressing: model inadequacy (model error), finite ensemble size (sampling error), and data assimilation uncertainty (initial condition error) in both direct (forward simulation) and inverse (databased statistical) modelling.** The relative importance of model inadequacy, initialisation error and finite ensemble sizes in forward simulation was investigated. First results were presented at the NOLTA conference [4]. Furthermore, DIME contributed to the problem of ensemble formation [15].

5. **Develop and illustrate skill scores which are useful in estimating the economic value of the forecast ti a given class of users; consider the utility of model output both as forecast and as an improved estimate of climatology.** Investigating the value of probabilistic weather forecasts was a core aspect of DIME. Skill scores that take into account the probabilistic nature of the forecasts were developed and illustrated [14, 20]. Furthermore, properties of the various skill scores already available were investigated, with the aim of aiding operational forecasters [9]. Other forecast evaluation techniques (especially reliability diagrams) were revisited in the same light [6, 10].

3 Research Impact, Benefits to Society and Dissemination Activity

The DIME project has had impact on other research as well as applications in industry. This plus the dissemination of DIME results both to other researches and the weather forecast end user, we consider as the main benefits to society. The following list mentions the most important points:

- Ongoing collaboration with ECMWF
- Continued interest by our industrial partner EDF and currently six other companies in that sector; new projects under consideration in the health sector.

- Dissemination both via "technology translators" at the Smith's Institute and both past and future Operational Weather Risk Workshops (see [11] and lists of attendees of held Workshops at the end of this section)
- Overarching publication in a larger volume on predictability [19].
- DIME insights have also contributed to testimony by Professor Smith to the UK Treasury's Stern Review and the US Academy of Sciences panel on the communication of uncertainty.
- Talks [16, 5, 12] were held at the first THORPEX International Science Symposium. THORPEX (`www.wmo.int/thorpex` is an international research programme to accelerate improvements in the accuracy of one day to two week high–impact weather forecasts. Smith was a co-author of the economic applications chapter of the original THORPEX science plan, and contributed to the Southern Hemispheric THORPEX meeting in February 2006, reporting DIME results in Cape Town.

Attendees of the Weather Risk Workshops

Workshop Atlanta
SAIC
The Weather Channel Inc.
Metra Information Limited
LSE
AER Inc.
Georgia Tech
The Weather Channel Inc.
NSSL/CIMMS
Georgia Power Company
Southern Company
Georgia Power Company
Meteorological Services of Canada
Pennsylvania State University

Workshop London
British Energy
ECMWF
EDF Energy
EDF Trading
Edison Mission Energy
Enfield Energy Centre Ltd
Entergy Koch Trading
Gaz de France EES
Scottish & Southern Energy Plc
Met Office
MetRisk Ltd
Morgan Stanley
Ofgem
Powergen
RHM Technology
Risk Management Solutions
RMS
RWE Npower
RWE Trading
SAIC
Scottish and Southern Energy
Total Gas & Power
VECTIS
Weather Exchange

4 Further Research and Conclusion

Research on the questions addressed during DIME remains fruitful and new topics came up during the project. To keep the results of DIME accessible to as wide an audience as possible, the DIME web site is kept updated, along with a discussion forum (see the cats website at `cats.lse.ac.uk`). The DIME weather data archive is maintained and updated and will be of great value to future projects. The aspect of DIME as a project for knowledge transfer will be pursued further in the follow–on project NAPSTER. Finally, the software developed under DIME is already used in other applications and will be maintained by CATS under follow-up projects. The discussion board is slowly becoming a focus for wider dissemination of research results and how to use the toolbox developed under DIME.
The analysis under DIME has shown that there is significant, unexploited valuable information in current operational weather forecasts. We know that several companies, including our industrial partners EDF

and others that attended one of our Operational Weather Risk meetings, have now become active users of the ECMWF ensemble forecasts. New objectives include knowledge transfer across the energy sector (so that all firms benefit from DIME research) and the extension of projects similar to DIME but targeting other sectors. We expect that health, transport, and distribution sectors to hold the most promise. In addition to industrial uptake, DIME has clarified a number of foundational problems in the theory of forecasting if not applied probability theory itself. There are significant opportunities not only for the interpretation of uncertainty from ensemble forecasts, but mathematical issues surrounding the design of the ensembles themselves, resource allocation between ensemble size and model complexity, and foundational questions of interpretation of a finite ensemble evolved under an imperfect model. These are issues of deep mathematical significance and immediate economic interest.

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