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The Relevance of Numerical Weather Prediction for Forecasting Natural Hazards and for Monitoring the Global Environment

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To appear in: A Half Century of Progress in Meteorology:
A Tribute to Richard J. Reed. Ed. R.H Johnson and R A Houze Jr (2002).
pub American Meteorological Society

March 2002

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ABSTRACT

Recent years have seen considerable improvement in the quality and scope of numerical weather predictions. Over the last decade, the accuracy of global numerical weather predictions of mean-sea-level pressure and 500hPa height has improved by one-day in the northern hemisphere. In the southern hemisphere a corresponding gain in accuracy has been achieved in the last three years. There have been corresponding substantial improvements in forecasts of extensive heavy rains. Increasingly, ensemble weather predictions are the prime medium-range forecasting tool in many countries. As an example, we review a set of medium-range deterministic forecasts and ensemble forecasts for the precipitation in the Po valley on 14-15 October 2000.

Many natural hazards arise from severe weather events such as intense mid-latitude storms and tropical cyclones. Society is making increased demands for reliable forecasts of natural hazards and their consequences for the safety of life and property. New systems for forecasting severe weather are under development, based on the ensemble forecasts and on characterisation of the climatology of extremes of the model used for the ensemble forecasts. Efforts are underway to provide improved environmental forecasts of natural hazards, by coupling specialised environmental models (e.g. hydrological models, coastal zone models, air-quality models…) to weather prediction models. We suggest that the ensemble approach developed for NWP should be extended to a range of environmental forecast problems, on medium-range and seasonal timescales.

Advanced four-dimensional variational assimilation systems enable numerical weather prediction centres to use observations in unexpected ways: Time series of observations of a nearly –conserved tracer quantity such as lower-stratospheric ozone provide information on the winds advecting the tracer. For this reasons a number of NWP centres are using lower stratospheric ozone measurements to infer wind information. Many space missions addressing climate issues can only achieve their goals if they can have accurate information on many aspects of the evolving meteorological context in which the measurements are made. For example, pilot studies of advanced sounders such as AIRS and IASI suggest that if the assimilation system does a good job on extracting meteorological information from the sounders, then one should also be able to infer the seasonal fluctuations of total column CO2. Considerations of this kind are the basis for the developing collaboration between the NWP community and those interested in monitoring key aspects of atmospheric composition from space. We indicate how these collaborations can be developed into a rather comprehensive capability for global monitoring from space of the atmosphere, ocean and land.

1. INTRODUCTION

Many natural hazards arise from weather events such as tropical cyclones or intense mid-latitude storms, with associated floods, land-slides, wind damage, heavy seas and coastal damage. Because of the growing vulnerability of densely populated areas to natural hazards, society makes increased demands for reliable forecasts of natural hazards, and reliable forecasts of the consequences for the safety of life and property. As discussed in section 2, recent years have seen remarkable improvement in the quality and scope of numerical weather predictions. The accuracy of global numerical weather predictions of mean-sea-level pressure and 500hPa height has improved by one-day over the last decade in the northern hemisphere, and by one day over the last three years in the southern hemisphere. Increasingly, ensemble weather predictions are used as the prime medium-range forecasting tool in many countries. The skill of deterministic forecasts and ensemble forecasts have benefited in equal measure from developments in data availability, data assimilation methods, and model physics, numerics and resolution. New systems for forecasting severe weather are under development, based on the ensemble forecasts and on characterisation of the climatology of extremes of the model used for the ensemble forecasts. NWP will benefit further from forthcoming advanced satellite-sounding capabilities, effective assimilation of information on moist processes, more efficient numerics, and more accurate physical parametrizations.

Earth-system scientists use a spectrum or hierarchy of Earth-system models to synthesise, or assimilate, the wide range of satellite and in-situ observations of the earth system. The same models are used to make forecasts on a range of time scales: medium-range forecasts, seasonal-to-interannual forecasts (i.e. short-term climate forecasts) and decadal-time-scale forecasts; section 2 describes recent progress and current status in medium range forecasting. All of these forecasts can be used by the civil protection authorities to make advance preparations for coping with and mitigating the consequences of natural hazards. At one end of the spectrum of models are global General Circulation Models (GCMs) with coupled atmosphere-ocean models and with more or less simplified models for the land-surface biosphere and hydrology, for ice and for atmospheric chemistry. The GCMs models are used for global data assimilation and to provide the global forecasts and simulations. At the other end of the spectrum of Earth-system models is a variety of specialised Earth-system models such as chemical transport models, crop-yield models, forest / biosphere models, coastal zone models, regional atmospheric models and hydrological models. Increasingly, the output of the GCMs is used to drive the specialised Earth-system so as to provide the best possible interpretation of the GCM results in terms of quantities that are of direct interest to end-users.

Efforts are underway in several countries to provide improved environmental forecasts of natural hazards, by coupling specialised environmental models (e.g. hydrological models, coastal zone models, air-quality models…) to weather prediction models. In such a context it is natural to explore the value of the ensemble weather forecasts in environmental forecasting. Trans-national floods have caused much loss of life and property in Europe in recent years. The European Flood Forecast System project (EFFS) is an EU-funded project to assess the value of using deterministic and ensemble precipitation forecasts from both global and regional meteorological models to drive distributed hydrological models for flood-forecasting purposes for lead-times of 3-10 days. The EFFS project will investigate if the existing level of meteorological forecast skill for precipitation can be translated into useful hydrological forecasts, whose skill should be easier to measure. As an introduction to such a study, we examine in section 3 a set of medium-range deterministic forecasts and ensemble forecasts for the precipitation in the Po valley on 14-15 October 2000. From the meteorological view-point the precipitation forecasts look encouraging. Ongoing work will assess the value of the precipitation forecasts for flood forecasting.

Similar approaches to environmental forecasting are being assessed in the seasonal forecast arena. Short-term climate fluctuations such as ENSO are frequently implicated in extended periods of tropical and sub-tropical drought or flood, with devastating consequences for human safety and for essential economic activities including agriculture and food and fibre production. Given the need to assess the uncertainties in all such forecasts, increasing use is made of ensembles of GCM forecasts which sample uncertainties arising from initial conditions and from the range of possible choices in GCM model formulation. Such GCM ensembles can then be used to drive ensembles of specialised models, thus providing estimates of the uncertainties in the forecasts for the end-users. On-going studies will assess the value of ensemble seasonal forecasts for forecasting crop production and disease incidence.

Future developments in NWP are discussed in section 4. Forecast skill will benefit from advanced satellite-sounding capabilities, effective assimilation of information on moist processes, more efficient numerics, and more accurate physical parametrizations. Section discusses how the meteorological data assimilation systems can be extended to use a wide variety of satellite data to establish an effective global environmental monitoring atmosphere ocean and land.

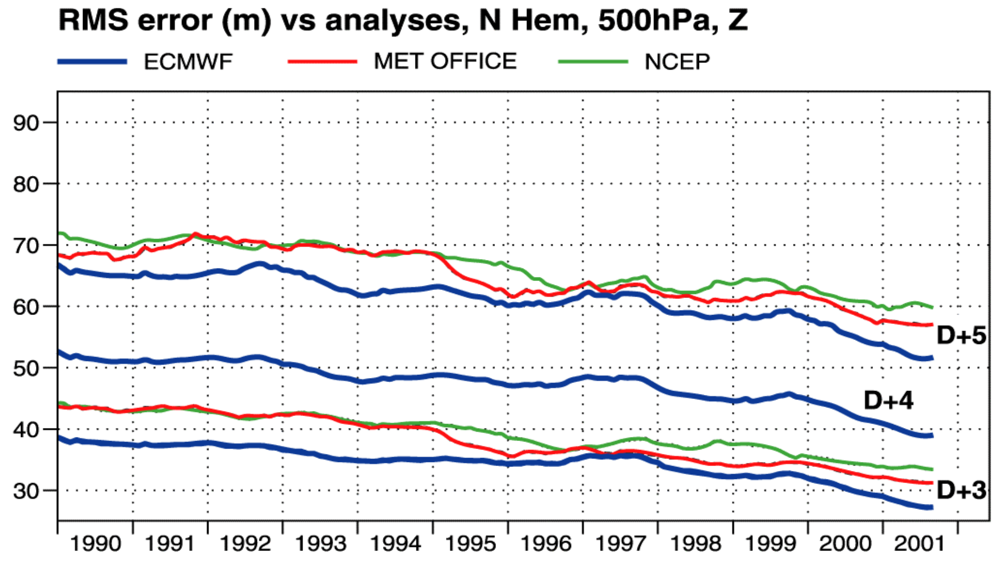
2. RECENT IMPROVEMENTS IN OPERATIONAL FORECASTS

Fig. 1 [from Simmons and Hollingsworth (2002), hereafter referred to as S&H] presents root-mean-square (r.m.s.) errors of forecasts of 500hPa for the extratropical northern and southern hemispheres. Time series from 1990 onwards are shown for three-day and five-day forecasts from three global prediction systems, that of ECMWF and those of the Met Office and NCEP, the two national centres closest to ECMWF's performance on these measures of forecast accuracy. ECMWF results are also presented for the four-day range. The plots show annual running means derived from the verification statistics that forecasting centres exchange monthly under the auspices of the World Meteorological Organization. Each centre's forecasts are verified by comparison with its own analyses. Results are presented for initial forecast times of 12UTC for ECMWF and the Met Office, and 00UTC for NCEP. The ECMWF forecasts are routinely produced with a cut-off time for data reception that is several hours later than used by the other centres. Evidence from ECMWF forecasts produced with earlier cut-off times indicates that differences in the forecasting systems rather than in data reception are the primary cause of the differences in forecast accuracy illustrated here.

Fig. 1 shows a general trend towards lower 500mb forecast errors in both hemispheres; S&H show similar results for mean sea-level pressure. The improvement between 1990 and 2001 in ECMWF forecasts for the northern hemisphere amounts to around a one-day extension of the forecast range at which a given level of error is reached. In other words, today's four- and five-day forecasts are respectively about as accurate on average as the three- and four-day forecasts of ten years ago. The rate of improvement has recently been especially rapid in forecasts for the southern hemisphere, amounting to a one-day gain in predictability in just three years.

The starting point for the rapid recent improvement in ECMWF forecasts shown in Fig. 1 was the operational introduction of four-dimensional variational (4D-Var) data assimilation (Mahfouf and Rabier 2000, and refs.) in late November 1997. Subsequent data assimilation changes include improved utilization of surface (Järvinen *et al*. 1999) and radiosonde data, assimilation of raw microwave radiances from the TOVS and new ATOVS satellite-borne instruments (McNally *et al*. 1999), assimilation of retrievals of humidity (Gérard and Saunders 1999) and surface wind-speed from the SSM/I satellite-borne instrument, and general refinements and extensions of the 4D-Var analysis and use of raw radiances. The atmospheric forecast model has been coupled with an ocean-wave model (Janssen *et al*. 2000) and improved in a number of other ways, including increased vertical resolution in the stratosphere (Untch and Simmons 1999) and planetary boundary layer (Teixeira 1999), revisions to the representations of clouds and convection (Jakob and Klein 2000; Gregory *et al*., 2000) and new schemes for long-wave radiation (Morcrette *et al*. 2001) and for the land surface and sea-ice (van den Hurk *et al*. 2000). Significant increases in the horizontal resolutions of the model and 4D-Var analysis were introduced in November 2000. Also noteworthy in Fig. 1 are the substantial recent improvements in the forecasts for the southern hemisphere produced by the Met Office and NCEP. Both of these centres have reported benefits from use of three-dimensional variational analysis and direct assimilation of TOVS and ATOVS radiances (Parrish and Derber 1992; English *et al*. 2000; Lorenc *et al*. 2000; McNally *et al*. 2000).

Recent improvements in short-range ECMWF forecasts can be linked very directly to the forecasting- system changes summarised above. As detailed in S&H, the ECMWF system undergoes constant development, with several major upgrades each year. Before implementation, the gain expected from each upgrade is assessed in pre-operational trials, which may cover over 100 days in several seasons. Fig. 2 shows the actual annual-



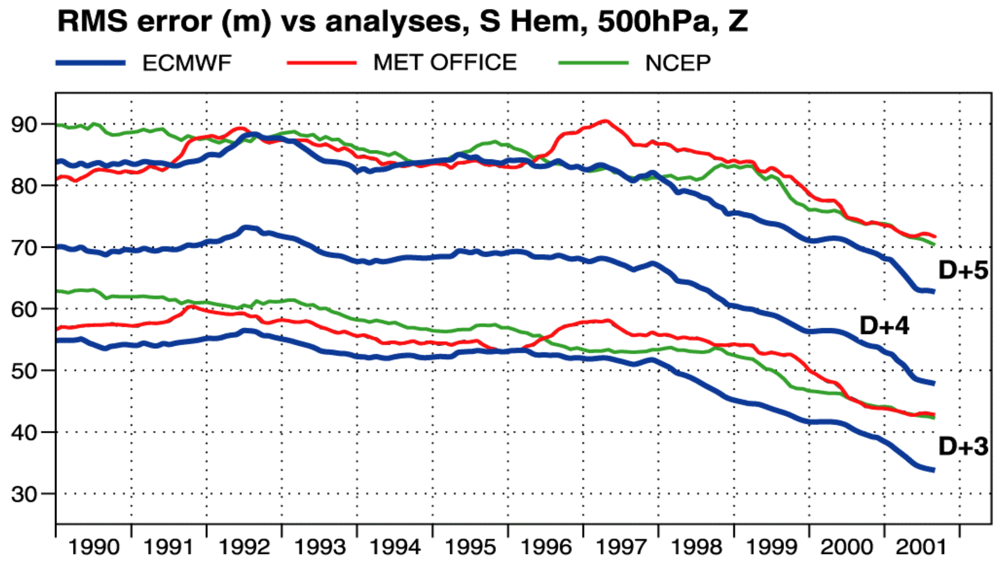
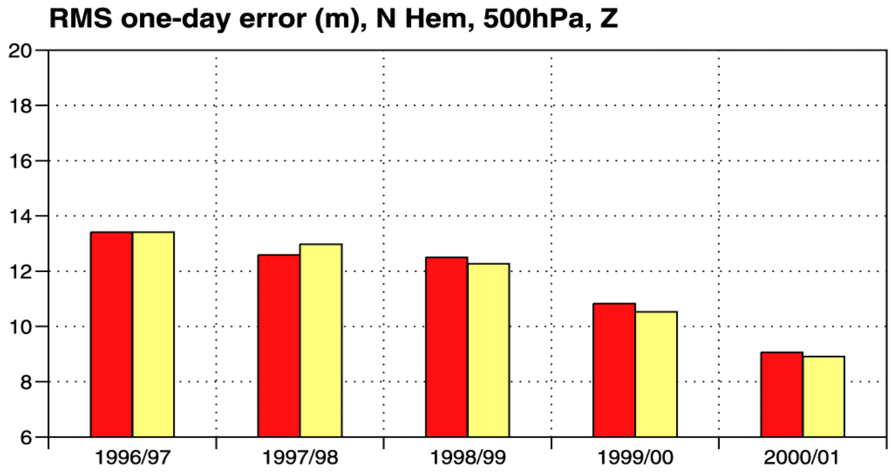


Fig 1 Root-mean-square errors of 3- and 5-day forecasts of 500hPa height (m) for the extra-tropical northern (top) and southern (bottom) hemispheres. Results from ECMWF, the Met Office and NCEP are plotted in the form of annual running means of all monthly data exchanged by the centres from January 1989 to August 2001. ECMWF 4-day forecast errors are also shown. Values plotted for a particular month are averages over that month and the eleven preceding months, so that the effect of a forecasting-system change introduced in that month is seen from then onwards.

mean r.m.s. errors of one-day 500hPa height forecasts for the past five years, together with the errors that would have occurred had the changes introduced between November 1997 and November 2000 given exactly the same average forecast improvements in operational use as were measured in the pre-operational trials. The agreement is remarkable, and indicates that the overall recent improvement in short-range forecasts is indeed due overwhelmingly to changes to the forecasting system rather than to circulation regimes that were unusually easy to predict in the last year or two.



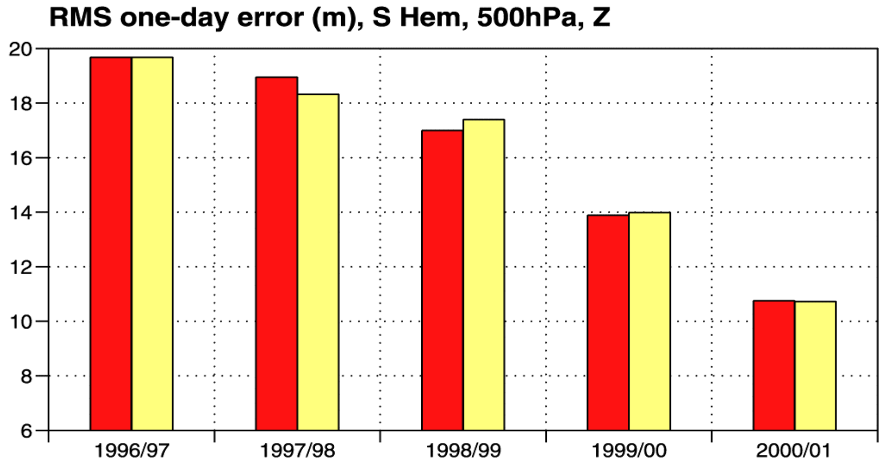


Fig 2. Root-mean-square errors of ECMWF's one-day forecasts of 500hPa height (m) for the extratropical northern (top) and southern (bottom) hemispheres. Twelve-month averages from September to August are plotted for the five years up to August 2001. The red bars denote the actual annual-mean errors, and the yellow bars denote the errors that would have occurred had these operational forecasts been improved by exactly the average amounts as measured in the pre-operational trials of the forecasting- system changes introduced between November 1997 and November 2000.

The extent of the reduction in one-day forecast errors shown in Fig. 2 is also noteworthy. The error has been reduced by almost a third from 13.4 to 9.1m over four years for the northern hemisphere, and almost halved from 19.7 to 10.7m over the same period for the southern hemisphere. As discussed in S&H, the northern hemisphere results shown here are consistent with radiosonde verifications. Verification of forecasts by comparison with radiosonde observations provides a more independent validation than verification by comparison with a centre's own analysis. The observations are however mostly located over land, and where sparsely distributed can give rise to difficulties in interpretation of verification statistics due to variations over time in the number of stations reporting. This inhibits the straightforward comparison of ECMWF and NCEP verifications against radiosondes over the southern hemisphere in particular, since the internationally-exchanged verification statistics are for different forecast starting times, and the verification is quite sensitive to differences in radiosonde coverage between 00 and 12UTC. For example, the five-day southern hemisphere errors for the year to August 2001 are 72m for both 00 and 12UTC Met Office forecasts when verified against analyses, but are 53m and 57m respectively for the 00 and 12UTC forecasts when verified against radiosondes. Verification against radiosondes gives generally lower values than against analyses for this hemisphere because the observations are predominantly located away from the main band of variance over the Southern Ocean.

The levels of skill of northern and southern hemisphere forecasts cannot be compared simply in terms of r.m.s. errors because of inter-hemispheric differences in the levels of variance of the fields. Comparison can, however, be made directly in terms of anomaly correlation coefficients, which are closely related to mean-square errors normalized by corresponding variances (see e.g. Simmons *et al*. 1995). Fig. 3 presents anomaly correlations of 500hPa height based on ECMWF's operational three-, five- and seven-day forecasts from January 1980 to August 2001. Running annual means of the monthly-mean skill scores archived routinely over the years are plotted for the two hemispheres. Fig. 3 shows a higher overall rate of improvement in the forecasts for the southern hemisphere. In the early 1980s, the skill levels of the three- and five-day forecasts for this hemisphere were only a little better than those of the five- and seven-day northern hemisphere forecasts. At the time this was not surprising in view of the sparsity of conventional ground-based and aircraft observations in the southern hemisphere (Bengtsson and Simmons 1983). Today, however, the skill at a particular forecast range in the southern hemisphere is only a little lower than that at the same range in the northern hemisphere.

Evolution of forecast skill for northern and southern hemispheres

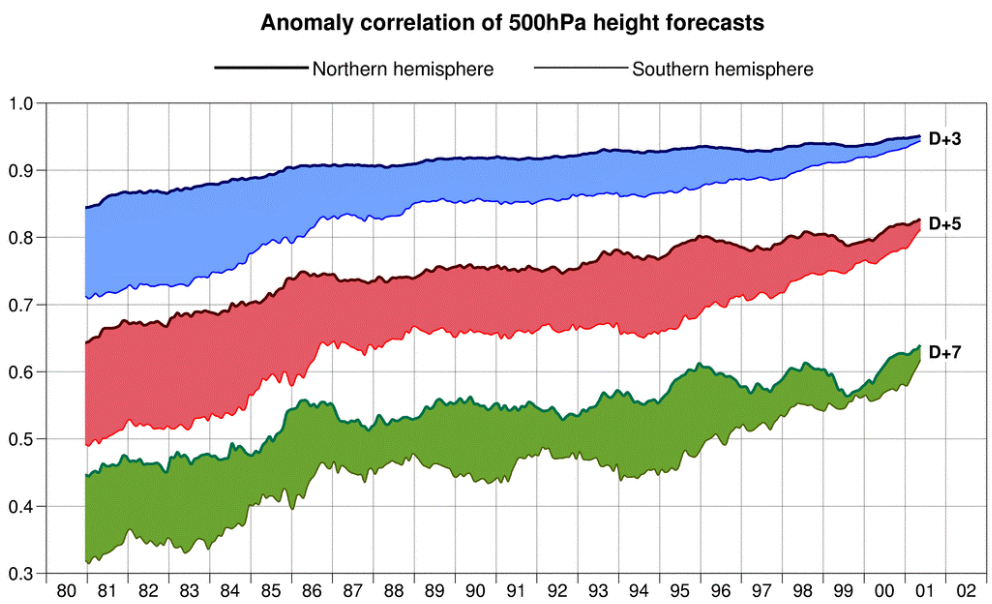


Fig 3. Anomaly correlation coefficients of 3-, 5- and 7-day ECMWF 500hPa height forecasts for the extratropical northern and southern hemispheres, plotted in the form of annual running means of archived monthly-mean scores for the period from January 1980 to August 2001. Values plotted for a particular month are averages over that month and the 11 preceding months. The shading shows the differences in scores between the two hemispheres at the forecast ranges indicated.

There is little doubt that improvements in the availability, accuracy and assimilation of satellite data have been major factors contributing to the relative improvement in forecast skill. In addition to the changes referred to earlier, information on marine winds has come also from scatterometers on the ERS satellites (Tomassini *et al*. 1998) while ERS altimeter data are used in the analysis of ocean wave heights (Janssen 1999). There have been evolutionary improvements in the wind estimates derived by tracking features in successive images from geostationary satellites (Tomassini *et al*. 1999; Rohn *et al*. 2001). Moreover, the newly-assimilated raw ATOVS radiances are used more comprehensively over the oceans (where surface radiative properties are easier to characterize) than over land. All these developments would be expected to improve forecasts more in the southern than in the northern hemisphere, both because satellite data provide a more important component of the observing system in the southern hemisphere and because of the greater extent of the oceans in that hemisphere.

Interannual variations in skill are also evident in Fig. 3, especially for the northern hemisphere at the five- and seven-day time ranges. In particular, there is a pronounced minimum in the northern hemisphere scores arising from relatively poor performance over the year to August 1999. A corresponding maximum can be seen in the time series of r.m.s. errors shown in the left panels of Fig. 1. This is evident for the Met Office forecasts as well as for those of ECMWF.

3. ENSEMBLE FORECASTS OF HIGH-IMPACT WEATHER

Weather forecasters categorise forecasts as short-range (0-3 days ahead), medium-range (3-10days ahead), extended-range (10-90 days ahead) and seasonal to interannual. A prime task of a medium-range forecast centre is to provide early and quantitative warnings of high impact weather. As shown above, there is a consensus view among meteorologists that there is skill to about 7 days in deterministic winter forecasts of the Northern Hemisphere pressure and wind fields; skill in forecasting these fields has improved by 1.5 to 2.0 days over the last twenty years. There can be marked fluctuations in forecast skill, depending on the weather situation: some situations are easier to forecast than others.

Because of the many difficulties of precipitation verification (sampling difficulties in measuring a field that is finely structured in space and time, orographic effects, instrumental difficulties.... see Cherubini *et al*, 2002) there is less consensus among meteorologists on the range for which precipitation forecasts are likely to be useful. There is agreement that precipitation forecasts are better in winter than in summer because of the more dominant role of synoptic-scale dynamical processes in winter than in summer, and there is agreement that forecasts of area averaged rainfall accumulations verify better than forecasts of point accumulations (e.g. Lanziger 1996). However there is little material in the literature on which to formulate a statement of the form: "Based on generally agreed verification standards, mid-latitude winter rainfall forecasts have improved by NN days over the last MM years". Here we illustrate an example where mid-latitude precipitiation forecasts were useful to eight days or more.

Predictability studies have shown that high-impact weather is often associated with very energetic phenomena, which may have limited predictability, so that forecasts are best couched in probabilistic terms. Traditionally, numerical weather predictions have been issued in a deterministic form, using the highest affordable resolution in the forecast model. Such forecasts could be converted into probabilistic forecasts using the climatology of forecast error statistics. Starting in 1992, weather forecast institutes have begun to issue real-time forecasts in the form of ensembles forecasts (at lower resolution than the deterministic forecasts) to sample the uncertainties in the initial conditions and in model formulation (Molteni *et al*. (1996), Palmer (1996), Toth and Kalnay (1997), Buizza and Hollingsworth (2002)). There is substantial evidence that in the later medium-range (5-10 days ahead), and for many important weather quantities, probabilistic forecasts derived from the ensemble forecasts are more skilful than probabilistic forecasts derived from the deterministic forecasts (Richardson, 2000).

3.1 The October 2000 flood in the Po Valley

As noted by Lawrimore *et al* (2001): "*Torrential mid-October rainfall led to floods and mudflows and contributed to numerous deaths in the Southern Alps in an area stretching from the Rhone valley in France to the Po valley in northern Italy. The town of Locarno, located in Switzerland near the Italian border received more than 285mm of rainfall from 11 to 16 October. This led to the overflow of Lago Maggiore and flooding throughout much of the surrounding area. A mudslide, brought down by heavy rainfall, also swept away much of the tiny town of Gondo, Switzerland. Nine-day precipitation totals were greater than 200mm along much of the border region between Italy and Switzerland (Fig 4). In the agriculturally rich Po valley heavy rainfall began on 14 October and continued for the next three days. More than 500mm was recorded near Milan in the 3-day period from 15-17 October. Two-day rainfall totals in Turin , Italy, exceeded 115mm. This extreme regional rainfall event brought the Po river to historic heights , causing it to break over its banks in some parts of Italy requiring the evacuation of thousands of people. Roads were closed, dozens of bridges were destroyed, and many rail services from Italy to France and Switzerland were suspended*."

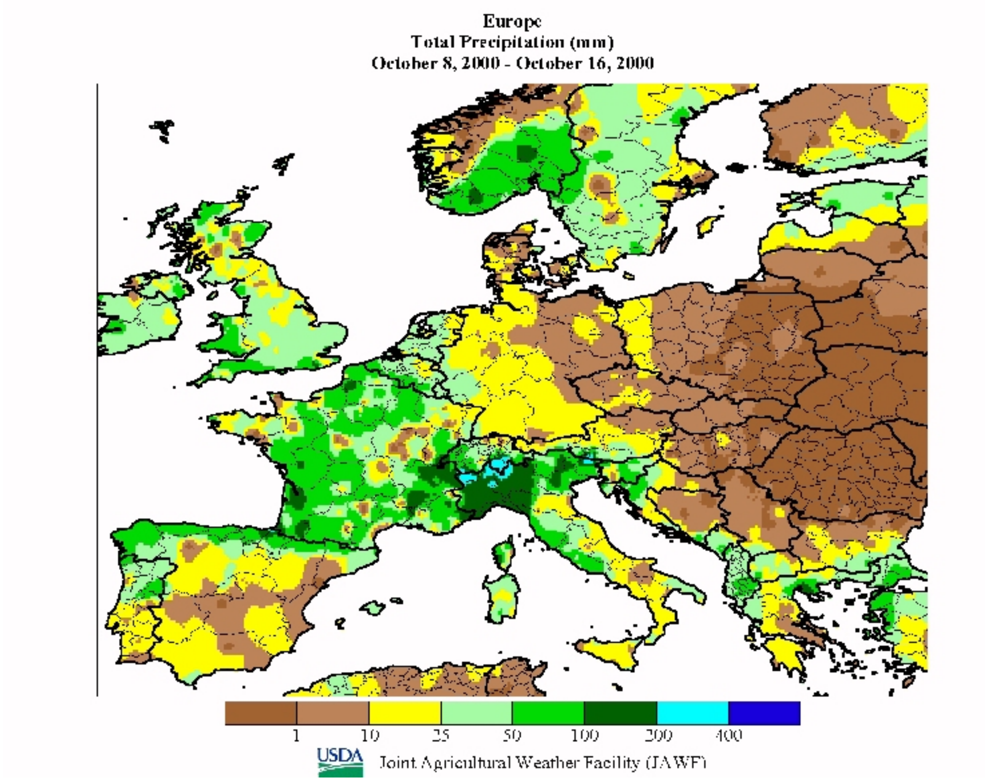
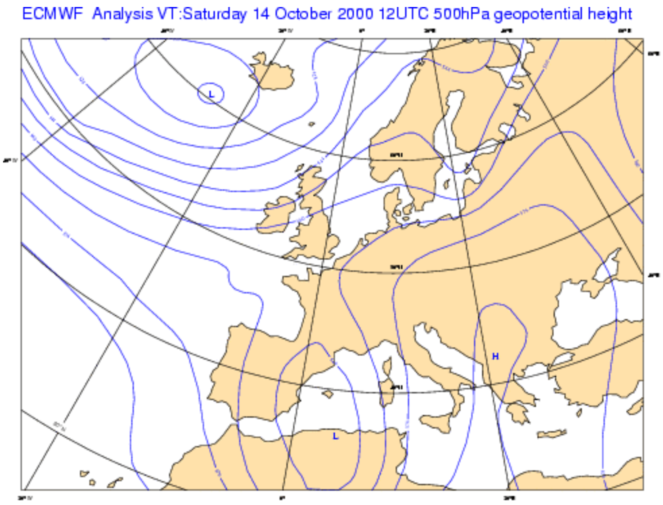


Fig 4 Accumulated precipitation (mm) for the period 8-16 October 2000 (Courtesy of the US Department of Agriculture) from Lawrimore et al 2001.

The heaviest precipitation started around Thursday 12 October; it produced large accumulations in the 48 hours from 1200UTC on Saturday 14 October to 1200 UTC on Monday 16 October; there was little significant accumulation thereafter. Fig 5 illustrates the synoptic situation at 1200UTC on Saturday 14 October. The top frame shows a deep trough at 500mb in the Western Mediterranean, with strong southerly flow across the central Mediterranean. The bottom frame shows the winds at 925mb at the same time, together with the wet-bulb equivalent potential temperature for values above 316K. The latter plot shows that the strong southerly flow across the central Mediterranean is extremely moist, and is likely to play a key role in contributing to the heavy rain over the mountains to the north. In the upper troposphere there is a deep intrusion of high potential vorticity air into the western Mediterranean, in association with the 500mb trough. Such marked “PV banners” are regularly associated with heavy rain in the southern Alps (Ferretti *et al*.. (2001), Rotunno and Ferretti (2001)), and are a prime focus of study of the recent Mesoscale Alpine Experiment (Bougeault, Richard, and Roux, 2001; Bougeault *et al*., 2001).



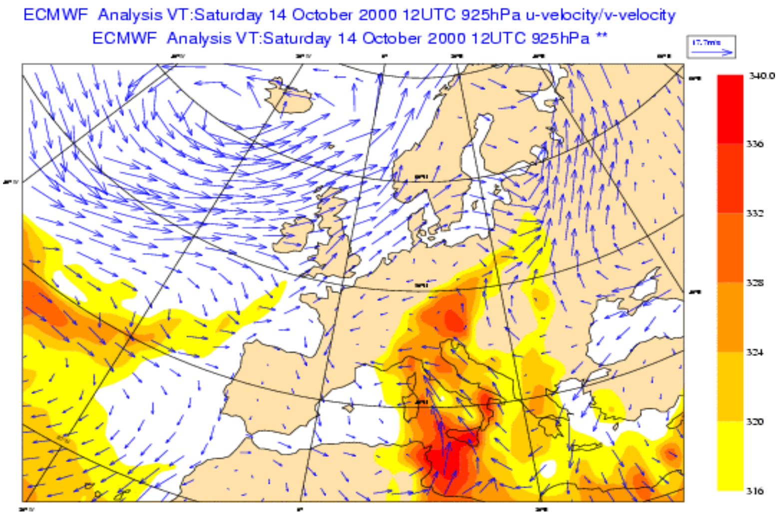


Fig 5 Top:- 500 mb analysis at 1200UTC on Friday 14 October 2000, contour interval 4dam. Bottom:- winds and wet bulb equivalent potential temperature at 925 mb at 1200UTC on Friday 14 October 2000. The wet-bulb equivalent potential temperature is plotted only for values above 316K

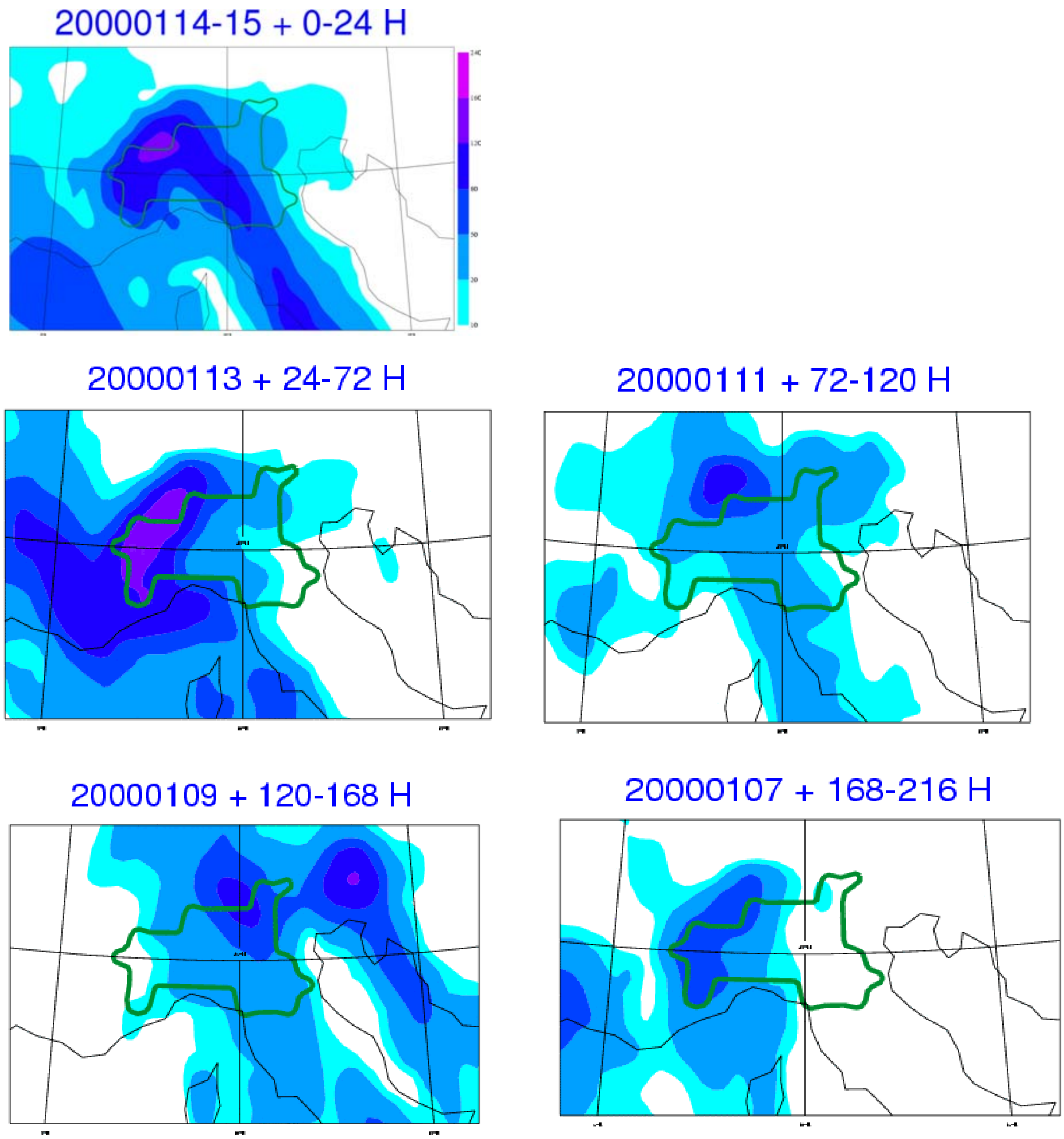


Fig 6 Top left: the accumulated precipitation in the two successive 24hour forecasts with the 40km model from 1200UTC on Saturday 14 October and Sunday 15 October (the 'proxy truth', see text). The lower four frames show the rain accumulations for the same 48-hour period in the forecasts from (i) 1200 UTC on Friday 13 October (centre left); from (ii) 1200 UTC on Wednesday 11 October (centre right); from (iii) 1200 UTC on Monday 9 October (bottom left); and from (iv)1200 UTC on Saturday 12 October (bottom right). These forecasts may be thought of as 2-day, 4-day, 6-day and 8-day forecasts respectively.

Our verification data on rainfall accumulation is provided by the daily accumulation in successive ECMWF short-range 24 hour forecasts from 1200UTC on successive days. The forecasts were made with the 40km (T511, 60level) model that has been operational at ECMWF since 25 November 2000, and is described in the annex. The quality of such estimates have been discussed by Cherubini *et al* (2002) and by Rubel and Rudolf (2001). Fig 6 shows (top left) the sum of the precipitation in the two 24hour forecasts with the 40km model from 1200UTC on Saturday 14 October and Sunday 15 October. This sum is our proxy 'truth' or best estimate of the total accumulated rainfall in Southern Europe for the 48-hour period from 1200UTC on Saturday 14 October. The lower four frames of Fig 6 show the rain accumulations for the same period in the forecasts from (i) 1200 UTC on Friday 13 October (centre left); from (ii) 1200 UTC on Wednesday 11 October (centre right); from (iii) 1200 UTC on Monday 9 October (bottom left); and from (iv) 1200 UTC on Saturday 7 October (bottom right). These forecasts may be thought of as 2-day, 4-day, 6-day and 8-day forecasts respectively. Judged synoptically, these deterministic forecasts provide clear warnings of heavy precipitation over the Southern Alps during the 48-hour period from 1200 on Saturday 14 October.

3.2 Ensemble forecasts of integrated hyetographs for the Po Valley

In establishing a successful inter-disciplinary dialogue, it is helpful if one's presentations or displays communicate essential information in an effective manner. Displays based on integrated hyetographs have proven useful (K.Settler pers.comm., 2001) in discussing ensemble forecasts with the hydrological community. A hyetograph is a plot of the rain-rate at a given point. We define an integrated hyetograph as a plot showing the accumulation of rain (in mm) averaged over a particular area, and starting from zero at a particular time. For our purposes, the integrated hyetograph is set to zero at the beginning of each forecast, and the area average is taken over the Po catchment (incl. the Adige catchment). The catchment definition (resolution 30minutes of arc) is from the UNH/GRDC CD-ROM: Composite runoff fields V 1.0 (Fekete *et al*. (2000)). The catchment area is 102,183 square km, corresponding to about 64 grid boxes of the T511 (40km model), or 16 grid boxes of the T255 (80km) model. The catchment is outlined in each frame of Fig 5, and is defined following Fekete et. al. (2000)

Fig 7 shows deterministic and ensemble ECMWF forecasts of the integrated hyetographs for the Po catchment for forecasts starting at 1200UTC on 7, 9, 11, and 13 October 2000. Also shown in each frame is the proxy "truth" in green. This verification is produced by assuming that the successive T511 Day-0 to Day-1 forecast accumulations are truth (an assumption whose errors require quantification). The value of all integrated hyetographs is zero at time t = 0, i.e. at the start of each forecast. Hyetographs are shown in 24-hour steps for the 40 km resolution deterministic forecast (blue), the 80 km resolution ensemble forecasts (red), the 80 km resolution unperturbed forecast (black), and the verification (green). Also shown on the plots are the 25%, 50% (median) and 75% percentiles of the ensemble accumulations on each day of the forecast. In reviewing the forecasts, we focus on three issues (i) The quality of each deterministic forecast for the total precipitation in the Po basin from the start of the forecast (always at 1200UTC) until 1200UTC on Monday 16 October; (ii) The success of the ensemble forecasts in encompassing the observed accumulation in the Po basin from the start of each forecast until 1200UTC on Monday 16 October ; (iii) The success of the prediction of the cessation of the rain forecast after 1200 on Monday 16 October. All three issues are of direct interest to water managers and to civil protection authorities.

Forecasts from 1200UTC Saturday 7 October

Fig 7 (top left) shows the forecasts and verification from 1200UTC on Saturday 7 October. The profile of the observed rainfall shows a steady accumulation of about 60mm between 1200UTC on the 10^{th} and the 14^{th} i.e. (between D+3 and D+7), and an accumulation of about 75 mm in the two days from 1200UTC on 14^{th} to 16^{th} (i.e from D+7 to D+9). The observed 9-day accumulation to 1200UTC on 16 October is about 135mm. Both the 40km and 80km deterministic runs forecast a 9-day accumulation of about 80mm. The 40 km deterministic forecast did better on forecasting intensity than the 80km unperturbed forecast from the same initial data. Turning to the ensemble forecast, we note that the ensemble forecast seem to be bi-modal, with one cluster of forecasts showing a cessation of rain on Saturday 14 October and another cluster showing the rain continuing over the weekend. We also note that the observed hyetograph lies well within the spread of the ensemble. For each day out to 14th October (D+7), the ensemble forecast gives a 40-50% chance of exceeding the 40km forecast accumulation (and a 25% chance of exceeding the observed accumulation). The ensemble forecast also gives a 25% chance of a 9-day accumulation of more than 90mm. Finally we note that the 40km deterministic forecast shows a continuation of the rain over the weekend and a cessation of the rain on 16 October, as does one of the clusters of ensemble members mentioned above. Judged by the criteria set out above, we therefore conclude that the forecasts from 7 October were synoptically useful out to 9 or 10 days ahead.

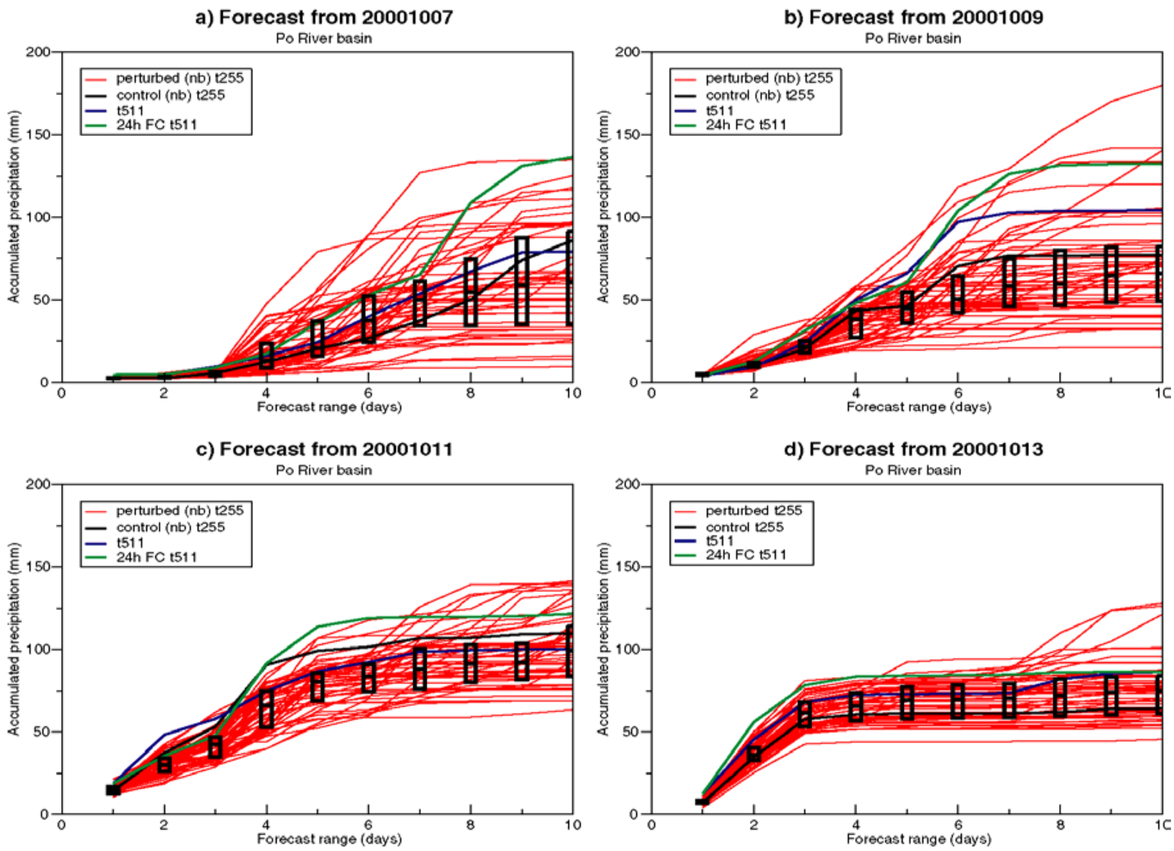


Fig 7 Integrated hyetographs from deterministic and ensemble ECMWF forecasts for the Po catchment, for the forecasts starting at 1200UTC on 7, 9, 11, and 13 October 2000. Also shown in each frame is the proxy "truth" in green (see text for details) The value of all integrated hyetographs is zero at time t = 0, i.e. at the start of each forecast. Hyetographs are shown in 24-hour steps for the 40 km resolution deterministic forecast (blue), the 80 km resolution ensemble forecasts (red), the 80 km resolution unperturbed forecast (black), and the verification (green). Also shown on the plots are the 25%, 50% (median) and 75% percentiles of the ensemble accumulations on each day of the forecast.

Forecasts from 1200UTC Monday 9 October

The top-right panel of Fig 7 shows the forecasts and verification from 1200UTC Monday 9 October. The deterministic 40km forecast gives a very good quantitative forecast for the accumulation out to D+6 (Sunday 15October) but stops the heavy rain a day too early. The control (unperturbed) 80km EPS from the same initial data shows a similar time evolution of the basin-wide accumulation, but with a smaller accumulation. The observed precipitation lies within the spread of the ensemble at all forecast ranges. The ensemble of forecast rain accumulations fall into two clusters, with a large cluster of ensemble members showing a cessation of rain at D+6 (Sunday 15 October), and a smaller cluster showing the rain continuing until Monday and beyond. Out to D+5, the ensemble shows a ~10% chance that the actual accumulation will exceed the deterministic forecast (and shows a ~10% chance of exceeding the observed accumulation). The ensemble also forecasts a 25% chance that the 7-day accumulation (to noon on Monday 16 October) will exceed 65-70mm. The judgement must be that these were synoptically useful forecasts.

Forecasts from 1200UTC Wednesday 11 October

Fig 7 (lower left) shows the deterministic and ensemble forecasts from 1200 Wednesday 11 October. The 40km deterministic forecast is very consistent with the forecasts from the previous days, both in its good points (timing) and its bad points (20% underestimate of intensity from D+4 onwards). At D+5 (1200 on 16 October) the 40km model accumulation is about 100mm instead of the 'observed' 125-130mm. The observed rain accumulation lies on the upper fringe of the ensemble forecasts of rain accumulation. Compared to the earlier ensembles just discussed, this ensemble shows much more consistency, and smaller spread, in the forecasts of rain accumulation for the weekend. This result perhaps suggests that one may have more confidence in this forecast than in earlier forecasts. Most of the ensemble forecasts do well on the timing of the event, but underestimate the intensity of the event (the median accumulation forecast for 1200 on 16 October (D+5) is about 75mm). After D+4, the ensemble forecasts a 25% chance of exceeding the accumulation in the unperturbed 80km model. The similarity of the 40km and the unperturbed 80km forecasts adds to the confidence in the forecast that was engendered by the fact that the ensemble spread in the forecast for the weekend event is the lowest we have seen so far in the series. We also note that some of the ensemble members resumed substantial rain accumulations for a day or two after October 16 – indicating a finite probability of such an eventuality.

Forecasts from 1200UTC Friday 13 October

The observed accumulation from 1200 Friday 13, (Fig 7 Bottom left) is very low in the first 24 hours, and then shows a heavy accumulation of 75mm between noon on Saturday (D+1) and noon on Monday (D+3). There is remarkable consistency between the 40km deterministic forecast, the unperturbed 80km EPS forecast and the ensemble members on the timing of the heavy weekend precipitation, and on the cessation of the rain after D+3 (from noon on Monday), The 40km model underestimates the accumulation by about 20%and the 80km model underestimates it by about 35%. The verification again lies on the fringe of the ensemble. The ensemble forecasts show a 25% chance that the actual accumulation will exceed the forecast from the 40km model. These forecasts have to be judged as successful forecasts.

3.3 Discussion

The 'verifications' just shown of forecasts for basin averaged rainfall accumulations indicate that the forecasts are quite consistent and show encouraging levels of skill even at 7 to 9 days ahead. It remains to be seen if the meteorological forecast skill can be translated into useful hydrological forecast skill on this case and on other cases. We understand (C.Schaer, pers. comm.) that certain dam operators in the Southern Alps had to make an important water-management decision on Wednesday 11 October. If the rain continued at high intensity beyond Monday 16 October, they faced the risk that their dams would be over-topped, with potentially severe consequences. Avoidance of such an eventuality would require the release of 30% of the active water in the reservoirs in the 36 hours before the onset of the heaviest rain, as release of the water in an extended period of intense rain would exacerbate an already dangerous situation. Between Saturday 7 October and Wednesday 11 October, the consistency of the ECMWF forecasts for the cessation of the event on Monday 16 October was therefore an important input to the water managers' decision not to make a precautionary release of the valuable stored water. Their decision was justified by subsequent events, and carried with it a considerable financial saving. We also understand (J.Ambuehl, pers.comm.) that the ECMWF medium-range forecasts were very useful for planning civil protection in the Southern Alps, where correct decisions were made to evacuate vulnerable communities to higher ground.

The rainfall forecasts show a number of systematic problems, such as erroneous distributions of heavy rain in mountainous areas, a marked sensitivity of forecast precipitation to the resolution of the forecast model, and a growing unreliability of the forecasts beyond day seven. The spatial and temporal integrations involved in calculating and verifying integrated hyetographs for a basin mitigate these problems. Some of these issues will be difficult to resolve solely by developments of the meteorological forecast systems. For hydrological forecasting, a pragmatic approach may be worth investigating: e.g. downscaling of forecast rainfall accumulations to compensate for systematic model underestimates.

ECMWF is a partner in an EU-funded hydro-meteorological research project EFFS (European Flood Forecasting System) which is assessing the possibility of producing useful hydrological forecasts in the 3-10 day period using meteorological forecasts (both deterministic and ensemble) as forcing for distributed hydrological models. The project is studying major winter and summer flood events in Europe in recent years. Here we have commented on the ECMWF forecasts of accumulated rainfall for one of the EFFS case-studies, namely the floods in the Po valley in mid-October 2000. The event is a good test of medium-range forecast skill.

4. IMPROVED USE OF NWP FOR FORECASTING NATURAL HAZARDS

Reliable forecasts of natural hazards which threaten life and property, are increasingly demanded by society because of the growing vulnerability of densely populated areas to natural hazards, and because of improved scientific and technical capability to provide better information. Indeed, European policymakers (Commission of the European Communities, 2001) require the development by 2008 of a capability for operational forecasting of hazards such as floods, forecast fires and the consequences of oil-spills at sea. Many natural hazards arise from weather events such as tropical cyclones or intense mid-latitude storms, with their associated floods, land-slides, wind damage, heavy seas and coastal damage. Ensemble weather predictions are increasingly the prime medium-range forecasting tool in many countries. The skill of deterministic forecasts and ensemble forecasts have benefitted in equal measure from developments in data availability, data assimilation methods, and model physics, numerics and resolution

4.1 Environmental Prediction Models

For both operational and scientific purposes, the output from global Earth-System data assimilations and forecasts are used to drive a variety of specialised Earth-system models or environmental prediction models including:

Category	**Examples of Existing Applications**
Atmosphere	Regional Weather Models Chemical & Aerosol Transport Models Trajectory Models Inverse models for carbon source attribution
Land	Hydrological Models Fire Models Crop Models Disease Models
Ocean	Regional Ocean Models Coastal Zone Models Oil-spill Models Storm Surge Models

It is likely that the ensemble forecast methodology will prove as useful in environmental forecasts as it has proved in weather forecasting. Collaboration between the environmental and weather communities on optimisation of the interfaces between the global Earth-system models and the specialised environmental models will essential in translating assessments of severe weather risk into assessments of severe environmental risk. Ensemble methods for environmental forecasting are being explored also on the seasonal time scale. Short-term climate fluctuations such as ENSO are frequently implicated in extended periods of tropical and sub-tropical drought or flood, with their devastating consequences for human safety and for essential economic activities including agriculture and food and fibre production. The ECMWF coupled atmosphere-ocean system has been used for real-time seasonal forecasting since 1996. ECMWF's tropical seasonal forecast products are published monthly on the web, including forecasts for anomalies in rain, temperature, pressure and sea-surface temperature. The system gave good forecasts of the initiation, development and decay of the 1997-98 ENSO event (Stockdale *et al*., 1998). Derived products such as forecasts of tropical cyclone frequency have also been successful. The seasonal forecast system runs at an atmospheric resolution of 200km (shortest resolved half wave-length), while the meridional ocean resolution varies between 0.3 and 1.25 degrees. A major effort is underway in an EU-funded project (DEMETER) to assess and document the capabilities of several European coupled systems in seasonal forecasting over the last 30-40 years. An important element of the exercise will be the interfacing of the seasonal forecasts with a crop forecast model to assess the skill and utility of the ensuing crop forecasts.

4.2 High-resolution multi-model decadal scenarios

Climate change may affect the habitability of the continent by altering the frequency or severity of summer droughts and winter floods. Decision makers in the area of water management need credible assessments of the threats in the next 30 years arising from changes in the habitability of the continent, due to climate change. Ensembles of simulations at 500km (T42) resolution are useful in assessing if there may be a threat, but not for assessing the regional variations of the threat. To meet the requirements of water managers, their political masters, and others concerned with contingency preparations for extreme weather arising from global change, one needs to provide 30-50 year look-aheads at a resolution of at least 30-50km. In order to sample uncertainty arising from model formulations and dynamical noise, the look-aheads should be multi-model ensemble simulations. Such simulations will require extremely efficient integration schemes, and extremely powerful computers. Operational weather services have implemented remarkably accurate and efficient semi-Lagrangian time-integration schemes for high resolution models. Over the last decade ECMWF and other forecast institutes have gained a factor of up to 50 in model efficiency from the following multiplicative factors:

Algorithmic Change	**Gain in Efficiency**	**Reference**
Linear grid	x 3.4 (=1.5**3)	Côté and Staniforth (1988)
Reduced Gaussian grid	x 1.3	Hortal and Simmons (1991)
3-time-level semi-Lagrangian scheme	x 6	Ritchie *et al*. (1995)
2-time-level semi-Lagrangian scheme	x 2	Temperton *et al*. (2001), Hortal (2002)

Then taking account of the fact that the time-step is not strictly limited by strong stratospheric polar-night winds, nor by the thin layers in the well-resolved planetary boundary layer, it follows that the true gain in forecast model efficiency is closer to 150. In terms of Moore's law (which suggests a gain of a factor of 2 in computer power every 18 months), models which use these advanced techniques have a 10-year advantage (about seven successive doublings) in computer productivity over models which do not use these techniques. These efficient schemes will no doubt be adopted for General Circulation Modelling in the near future, since remaining scientific issues such as exact mass conservation are being resolved.

To illustrate the status of current technology we note that ECMWF's Fujitsu VPP-5000 computer and the Japanese Earth Simulator computer both have Processing Elements (PEs) operating at almost 10 Gflops, with 100 PEs on the VPP-5000 and 5120 PEs on the Earth Simulator. The Earth Simulator thus has about 50 times the power of the VPP-5000. A version of ECMWF's model with 60km resolution (T319) and 60 levels in the vertical (T319/L60) can deliver about 10 years of integration in one day on the VPP-5000, so the Earth Simulator can deliver an ensemble of 50 such integrations (500 years of integration time) of the TL319/L60 model in one day of elapsed time. The provision of a 50-member ensemble of 50 year integrations of the TL319/L60 model would take **5 days** on the Earth Simulator. If one makes the reasonable assumption that a 60km ocean model costs no more than a 60km atmospheric model, then these estimates apply to a coupled atmosphere-ocean AOGCM with 30 levels in the atmosphere and 30 levels in the ocean.

Given the strong dependence of computing cost on resolution, a 50-year look-ahead using a 30km AOGCM (30 levels each in the atmosphere and ocean) to generate a (multi-model) 50-member ensemble would take about 40 days on the Earth Simulator. There is a demand from policy-makers world-wide for answers to questions that can only be addressed if such simulation capabilities become available.

5. PROSPECTS FOR GLOBAL ENVIRONMENTAL MONITORING

European policymakers (EU 2001) require the development by 2008 of a capability for global monitoring of specific aspects of the atmosphere ocean and land, as follows:

GLOBAL ATMOSPHERE MONITORING delivering regular assessments of state of the atmosphere with particular attention to aerosols, ozone, UV radiation and specific pollutants.

GLOBAL OCEAN MONITORING in support to seasonal weather predictions, global change research, commercial oceanography and defence.

GLOBAL MONITORING to assess carbon fluxes and stocks in the biosphere.

Such capabilities will depend on Earth observation from space. Some of the relevant satellite missions to be launched in mid-decade (2003-2007) are listed in Table 3

Expected Launch	Mission	Objective
2003	EOS-Aura	Chemistry
2004	CLOUDSAT	Clouds
	CALIPSO	Aerosol
	CRYOSAT	Sea-ice freeboard
2005	METOP-1	Operational meteorology including advanced sounder and a scatterometer
	GIFTS	Advanced Sounder in GEO Orbit
	GOCE	Geoid to T360
2006	GPM	Global Precipitation Mission
2007	SMOS	Soil Moisture and Ocean Salinity Mission
	ADM-Aeolus	Doppler Wind Lidar

Table 3: Relevant Satellite Missions 2003-2007

Given the current scientific status of modelling and data assimilation in the NWP centres, and given the new satellite capabilities coming on-stream in the next five years, it is possible to plan the development of a global environmental monitoring system to meet policymakers' main requirements. Operational weather prediction centres such as ECMWF have strong R&D programmes for operational forecasting, which includes de-facto monitoring of the global hydrological and energy cycles. ECMWF, in partnership with the wider community, could extend its modelling and data assimilation framework to develop a global monitoring capability. In the initial phase, one envisages an experimental monitoring and assimilation system which could run daily, but perhaps with a delay of some weeks behind real time to facilitate a comprehensive data collection. The resolution is envisaged to be similar to that used for seasonal forecasting. The software would be built as an extension of the operational medium-range software, so that developments useful to medium-range work can be readily migrated into the operational environment. It is convenient to discuss the three global monitoring issues in sequence, beginning with the atmosphere, moving on to the ocean and then closing the loop with the land issues.

5.1 Global monitoring of greenhouse- gases, and aerosols

5.1.1 Estimation of total column amounts of greenhouse gases

Feasibility studies (Chedin *et al* 2002a, 2002b, 2002c) indicate the possibility of mapping seasonal fluctuations in total column CO_2 using the AIRS and AMSU instruments to be launched on NASA's AQUA mission in the first half of 2002, or the IASI and AMSU instruments to be launched on METOP-1 in 2005. Indeed pilot studies with operational TOVS data have already demonstrated impressive capabilities. A new EU-funded project (COCO) aims to develop an operational system to estimate total column CO_2, and to validate the results using inverse carbon modelling. Additional observations will be provided by the SCIAMACHY instrument to fly on ENVSAT in 2002. The COCO project will use the data assimilation system to exploit the synergy between the AIRS infra-red instrument (sensitive to both temperature and CO_2) and the AMSU microwave instrument (sensitive only to temperature) to back-out the CO_2 estimates. Because the assimilation system will provide consistent wind, temperature and CO_2 estimates, it should be possible to estimate the export or import of carbon from the land to the ocean. Initially COCO will focus on CO_2 estimates over ocean where the radiative properties are well understood in the infrared and in the microwave. It will also be possible to estimate the CO_2 exchange between atmosphere and ocean. The technology being developed for the estimation of total column CO_2 should be readily adaptable to provide total column estimates of other greenhouse gases such as CH_4, N_2O and CO.

5.1.2 Modelling and assimilation of the ocean carbon cycle

One could establish an independent verification of the ocean uptake of CO_2, if one introduced a carbon cycle into the atmospheric and ocean models, as a basis for assimilating ocean colour measurements, along with the ocean satellite data currently used directly or indirectly in the ocean data assimilation: scatterometer winds, SST, altimeter sea-level heights, as well as altimeter wave data. By the end of 2002 there will be 5 ocean colour instruments in orbit (SEAWIFS, MODIS-Terra, MODIS-Aqua, MERIS-ENVISAT, OCTS-ADEOS). No plans are in place in the meteorological world for real-time use of this huge data source. To tie down the ocean CO_2 budget by assimilating ocean colour, one needs to draw on the European science base for expertise in ocean-biology modelling, ocean-colour modelling and ocean assimilation, as well as for expertise in estimating primary production from ocean colour measurements. For the research phase one envisages a development system running at the resolution of the seasonal forecast model. Since an advanced assimilation system can infer information on upper ocean dynamics from ocean colour measurements, there would be a direct benefit for the ocean dynamical assimilation, and thus eventually for seasonal forecasts.

5.1.3 Modelling and assimilation of aerosol information

All the ocean colour instruments provide a capability to estimate aerosol optical depth. The largest errors in the atmospheric clear sky radiative calculations arise from uncertainties in aerosol. The introduction of an aerosol variable (say for desert aerosol) in the atmospheric model would enable one to assimilate a good deal of the aerosol information in the ocean colour measurements. This would certainly improve the ocean colour assimilation (by quantifying a part of the signal that would otherwise be treated as noise) as well as delivering a modest forecast benefit for the atmospheric model.

5.1.4 Modelling and assimilation of information on the land biosphere

Development of a capability to model the radiative properties of the land biosphere is a high priority for those concerned with estimating the stocks and fluxes of carbon related to the land reservoir. It is also a high priority for meteorologists because improved modelling of the land biosphere (i) will enable meteorologists to assimilate atmospheric sounding data over land and (ii) will lead to improved local weather forecasts. Until quite recently, our knowledge of the radiative properties of the land surface was so poor that almost all meteorological remote sounding data over land had to be discarded, because of our inability to model the radiative properties of the surface.

Satellite data on the land biosphere is available in the optical and near- infra-red (AVHRR, MODIS, MERIS, SEVIRI), in the thermal infra-red (HIRS, AIRS, IASI) and microwave (AMSU, SSMI, SSMI/S). The ESA instrument SMOS to estimate soil moisture is expected to fly in 2007. One needs to develop forward models which can simulate the satellite data, taking account of the dependence of the radiative properties of the land surface on the nature of the vegetation, on the nature of the soil and on recent meteorological events (rain, drought, snow). Effective interpretation of the satellite data thus requires an effective assimilation system. Several research initiatives are getting underway. ECMWF is a partner in the EU-funded initiative – ELDAS. ECMWF is also collaborating with EUMETSAT's Land-SAF, with ISLSCP, and with the US effort (GLDAS) on Land Data Assimilation.

Incorporation of a carbon cycle in the land, ocean and atmosphere modules of an Earth-system model, and assimilation of the range of satellite data that is or will be available, will provide global fields consistent with our understanding of the main processes in the Earth-system. A world-wide network (Fluxnet) of about 150 land observatories makes detailed boundary layer measurements of vertical fluxes of heat, moisture, momentum and carbon. This station network would provide detailed validation and verification data on the key boundary layer exchange processes of the carbon cycle as they do at present for the water and energy cycles of Earth-system assimilations and models. The intercomparisons would thus provide a sound scientific basis for identifying short-comings in the models, and a global basis for assessing proposed model improvements. This scientific approach has been successful in other research areas. For example, the global ocean wave assimilation uses satellite altimeter data only, while the sparse in-situ wave-buoy data provide independent and invaluable information for verification, diagnosis and development.

An important limitation of current or imminent observations is the inability to sense fluctuations of CO2 amounts in the planetary boundary layer. Proposals are under discussion to develop either active or passive satellite sensing capabilities to remedy the shortcoming. Experience with assimilation of AIRS, SCIAMACHY and IASI data for green-house gas monitoring may be helpful in refining the requirements for new instruments or missions. When such missions eventually fly, their data will be immediately exploitable in the Earth-system assimilations.

5.2 Global monitoring of reactive gases and aerosols

Atmospheric chemical data assimilation has traditionally used chemical transport models, driven by gridded winds and temperatures from an independent source such as a meteorological data assimilation system. Atmospheric chemical data contains information on the advecting winds. This was one motivation for developing an interactive dynamical-chemical assimilation system for ozone in the framework of ECMWF's 4D-Var variational assimilation system.

5.2.1 Dynamical-chemical assimilation system for ozone

With support from ESA and EU (Framework IV project SODA), ECMWF and Meteo-France have developed a capability to model the three-dimensional distribution of ozone, and to assimilate data on ozone from the following instruments presently in orbit or to be launched in the near future:

SBUV, TOMS, HIRS	on NOAA satellites
GOME	on ERS and METOP
SCIAMACHY	on ENVISAT
OMI	on EOS-AURA

This meteorological/ozone assimilation system will be used to support the calibration and validation of real-time data from the GOMOS, MIPAS and SCIAMACHY instruments on ENVISAT, and eventually for the assimilation of the products from these instruments. No plans are in place for use of data from NASA's chemistry mission AURA, due for launch in 2002-2003.

The ozone assimilation system is also being used in a simpler 3D_Var context to provide a 24-year assimilation (1979-2002) of all available satellite data on ozone as part of the EU-supported ERA-40 reanalysis project. Useful satellite data on ozone first became available in 1979. The ERA-40 project will assimilate both SBUV and TOMS data on ozone for the period of record. The full reanalysis will cover the period 1958-2002. Prior to 1979, the ozone field in the model will evolve freely, unconstrained by observations.

The ozone assimilation system will become operational at ECMWF in the spring of 2002, around the time of the expected ENVISAT launch. The assimilation will use the real-time ozone data from GOME on ERS-2, from SBUV on the NOAA satellites, and from ENVISAT on completion of the validation process. As such, the system will provide valuable products for operations (e.g. UV_B forecasting) and for research. Ground-based Dobson spectro-photometer ozone data could be included in the system (either by real-time delivery of the data, or by a delayed mode run of the assimilation). Inclusion of the Dobson spectro-photometer data would make the assimilation fields a useful adjunct in the monitoring of the Montreal convention. A further scientific development of considerable interest is the direct variational assimilation of limb-sounding radiances from instruments such as MIPAS. This would provide a better net result than the use of MIPAS retrieved profiles.

5.2.2 Coupled dynamical – chemical assimilation

Many chemical data assimilation activities use chemical transport models driven by specified winds. Unlike an interactive dynamical-chemical assimilation, they get no benefit from the wind information in the chemical data. The interactive dynamical-chemical assimilation approach could be extended from ozone alone to the entire NOx family of ozone precursors and perhaps also to the family of precursors of sulphate aerosol. This would offer substantial operational and scientific benefits by providing the most accurate possible wind and chemistry fields.

If a semi-Lagrangian model is used for the assimilation, then the marginal cost of the chemical advection computation is negligible. The additional costs are thus mainly memory and the costs of the chemical-interaction calculations.

5.2.3 Chemical-weather forecasting

There is a large demand across Europe for accurate forecasts of air quality at times of environmental stress. Such forecasts are normally a national responsibility, and are usually made with specialised regional models which require meteorological and chemical boundary conditions, analogous to the requirements of regional meteorological forecast models.

The availability of a global assimilation and forecast system providing consistent global analyses and forecasts of the meteorological, chemical and aerosol fields would offer substantial operational and scientific benefits.

5.3 Global monitoring and modelling of atmosphere, ocean and land

The proposals just outlined involve comprehensive global monitoring of the atmosphere, the ocean and the land at resolutions in the range 40-150 km corresponding to the range of models used for forecasting on medium-range, monthly, seasonal and decadal time-scales. Success in the enterprise will require the participation from wide spectrum of talent across the European science base. Success will also require improvement of the science of the atmospheric, ocean and land models to the point where they can realistically simulate the observations. This immediately guarantees the use of the scientific advances in improved models for forecasts and simulations. It also guarantees that periodic reanalyses of the available data (e.g. for studies of low-frequency variability or trends) will benefit from the new science developed in the monitoring programmes.

6. CONCLUSIONS

Over the last 50 years, Prof. Richard Reed has made numerous important contributions to the development of meteorological science, and to the development of the international collaborations that underpin that science. In particular he played an important role in the development of the plans for the 1974 GATE experiment and the 1979 First GARP Global Experiment [FGGE, later renamed as the Global Weather Experiment, Perry (2002)]. FGGE achieved Charney's vision of the deployment of a comprehensive global observing system, which has served us well for more than 20 years.

ECMWF played a leading role in creating the FGGE analyses in the early 1980s. The lessons learned in that research exercise were directly translated into operational practice. Prof. Reed's studies of the performance of the 1985 ECMWF assimilation/ forecast system (Reed *et al* 1988a, 1988b) validated the success of FGGE by demonstrating the capability of the operational system to make excellent tropical analyses and forecasts, when observations were available.

Since 1985 there have been many developments in the technology of numerical weather prediction. We are at the threshold of a new era in observational capability for weather forecasting and for environmental monitoring. The modelling and data assimilation tools needed to exploit those new observational capabilities have been made ready. This contribution is a progress report to Prof. Reed on those developments. We salute Prof. Reed's achievements and we thank him for his friendship, his collaboration and his sustained interest in our work.

Annex: ECMWF's 2002 operational assimilation and forecast system

ECMWF is an international organisation supported by twenty-two European governments, and its primary function is the delivery of operational medium-range weather forecasts of increasingly high quality, over the range from three to ten days and beyond; a complementary goal is to establish and deliver a reliable operational seasonal forecasting capability. As world leader in its field, ECMWF has pioneered numerous developments in the use of satellite data for determination of the state of the atmosphere's dynamics and composition, and of those aspects of the state of the land, ocean and cryo-sphere which are relevant for medium- and extended-range forecasting.

ECMWF's Earth-system model (Fig A1) comprises the following coupled modules:

Atmospheric Dynamics

- A global atmospheric 60-level general circulation model with a top at 65km, and a horizontal resolution of 40km

Ocean Circulation

- ·A global ocean general circulation model
- ·Ocean ice processes

Ocean Surface Waves

- A global third-generation ocean surface wave dynamics model, directly coupled to the atmospheric model

Land

- A land biosphere module
- A land surface, soil, hydrological and snow model

Atmospheric Composition

- A comprehensive model of the hydrological cycle, including all three phases of water
- Dynamic ozone with parametrized chemistry

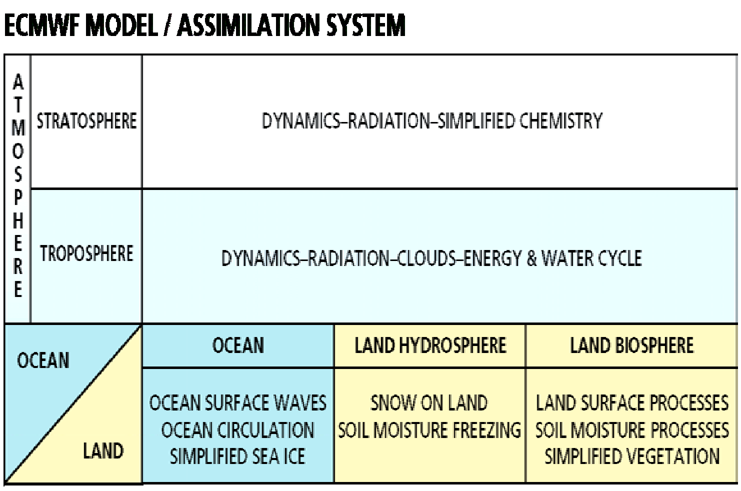


Fig A.1 Cartoon outlining the Structure of the ECMWF Earth-system model

In preparation for the new generation of operational and research satellites currently coming on-stream, ECMWF has developed a powerful four-dimensional variational assimilation system (4D-Var) as an effective method to use all observations. ECMWF has also developed scalable data ingest and processing techniques to enable the data-assimilation process to cope with the vast volumes of new data.

To support its assimilation and forecasting activities, ECMWF has high-performance computing facilities and data handling facilities which are amongst the best in the world. ECMWF routinely assimilates a wide variety of data from operational and research satellites (both polar and geo-stationary) from instruments as diverse as: infra-red and microwave sounders, visible and microwave imagers, scatterometers, radar altimeters and synthetic aperture radars. Table A1 lists the satellite data currently used in operations (or recently used, in the case of ERS).

ECMWF has made extensive preparations for the calibration and validation (CAL/VAL) and eventual assimilation of the data from the missions listed in Table 2, which are due for launch by the end of 2002. Use of the above data streams relies heavily on collaborations with mission teams at EUMETSAT, ESA, CNES, NESDIS, NASA, NASDA, and with the wider scientific community through such groups as ITOVS.

NOAA polar	Microwave and infrared radiances for temperature and humidity sounding
European, US and Japan Geostationary Satellites	Cloud winds, Water vapour radiances
DMSP series	SSM/I Water vapour, wind speed
ERS series	C-band scatterometer ocean winds Altimeter: Wave height, Sea-level height SAR Wave spectra
TRMM	Rain profiler and Microwave Imager data on rain-rate
QUICKSCAT	SeaWinds - Ku-band Scatterometer
SBUV/ GOME / TOMS	Ozone profiles and total column amount

Table A1: Satellite Data used for Operations and/or Research in 2002

EOS-AQUA	Advanced sounder (AIRS)
ENVISAT	Ozone (MIPAS, SCIAMACHY, GOMOS),Waves(RA-2) Spectra (ASAR)
ADEOS-II	SeaWinds- Ku-band scatterometer
SSMI/S	Microwave Sounder & Imager
JASON-1	Radar altimeter for Sea-Level, Waves
MSG	Winds, Ozone, Water vapour

Table A2: New Satellite Missions in 2002-2003 which will be used at ECMWF

ECMWF operational products are

3-hourly analyses
Daily deterministic forecasts to 10 days
Daily ensemble forecasts to 10 days
Daily deterministic and ensemble ocean surface wave forecasts to 10 days
Monthly ensemble seasonal forecasts to 6 months

The analyses and deterministic 10-day operational forecasts are global, at 40km resolution in the horizontal and cover the atmosphere to 65km. The ensemble 10-day forecasts are at a resolution of 80 km.

The ensemble prediction system samples uncertainties in the initial data through a set of specially formulated perturbations, and samples uncertainties in the model formulation through stochastic perturbations of the physical tendencies. A particular emphasis at ECMWF in the next few years will be the development of a medium-range severe weather forecast system, to complement existing forecast tools for quantitative forecasts of severe weather in the short range. The developments will comprise improvements to the existing forecast models, coupled with an extensive statistical processing of the ensemble forecasts to indicate the nature and severity of threatened natural hazards.

The seasonal forecast system issues forecasts monthly, and uses the ECMWF atmospheric model coupled to the HOPE ocean model (developed by the Max Planck Institute) through the OASIS coupler (developed at CERFACS). The ocean-assimilation system was developed by the Australian Bureau of Meteorology.

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