Predictability and Targeted Observations

Alan Thorpe

University of Reading

Abstract

The aim of this paper is to provide a summary of the development of the ideas behind, and experiments undertaking, so-called targeted observations of the atmosphere. The scientific issue is the assessment of the role of such targeted observations in improving the skill of numerical weather predictions for time periods up to 2 weeks ahead. Particular reference will be made to the problem of forecasting extratropical cyclones. Within the context of the emerging international programme THORpex, a vision of the NWP system of the future will be given involving a two-way interaction between the observing system and the NWP system.

1. Introduction

Severe windstorms and precipitation cause substantial societal and economic impact. An important question to be addressed is: can we accelerate improvements in predictive skill? Tremendous strides have been taken in numerically predicting the weather: “3 day forecasts of surface pressure are now as accurate as 1 day forecasts were 20 years ago”. This is one of the greatest scientific achievements of the 20th Century, with huge societal and economic benefits.

These advances came from the following developments in modelling and in making, and utilising, observations:

- ensemble prediction and probability estimation
- satellite observational capability
- variational data assimilation

However, problems remain and inaccurate initial conditions, and errors in model formulation, still cause:

- significant failures in forecasts of high- impact weather
- inability to extend the range of skillful predictions out to “week 2”
- poor description of tropical influences on extratropical forecasts
- inadequate skill in predicting mesoscale weather such as precipitation

Storms are the principal natural hazard in NW Europe – it has been estimated that one has a “higher chance of being killed in a UK windstorm than in a hurricane in Florida”. Examples of societal and economic impact of such windstorms include:

- Two storms December 1999: 100 fatalities; 400 million trees blown down; 3.5 million electricity users affected for up to 20 days; 3 million people without water; 12% of mobile phone transmitters inoperative
- Annual average insurance loss from European windstorms is around €1.2 → 1.7 billion
- Total insurance loss since 1985 is the same as that due to US hurricanes: about €24 billion

To improve predictive skill of such storms a range of scientific developments are taking place. Model improvements are being made using process studies from research field experiments. Observations from the new generation of satellite instruments will improve initial conditions. Nevertheless significant data-poor regions will remain, such as in: cloud layers in both the extratropics and the tropics.

The concept of dynamically-determined adaptive observing was first discussed during the meeting in October 1994 of the First Prospectus Development Team of the US Weather Research Program (Emanuel et al 1995). The idea was developed further during planning for the "Fronts and Atlantic Storm-Track Experiment" (Joly et al 1997), during the meeting in May 1995 of the Second Prospectus Development Team of the US Weather Research Program: (Dabberdt et al 1996) and at a workshop at NCAR in May 1995 (Snyder 1996).

In Emanuel et al 1995, it is noted that "Another intriguing technique that should be explored is to use ensemble forecasting methods to make a priori estimates of the distribution of sensitivity to observational error, so that programmable observation platforms, such as unmanned aerial vehicles or programmed deployment of dropsondes from commercial aircraft, can be directed to focus on sensitive regions. Adaptive observational strategies may serve to help optimize observations in aid of numerical weather prediction." That report concludes by saying that "Advanced applications of adjoint techniques to numerical weather prediction may reveal, in near real time, those parts of the atmosphere that are particularly susceptible to initial error, allowing us to target such regions for observational scrutiny and thereby greatly reduce numerical forecast errors."

Dabberdt et al 1996 used the term adaptive to mean the same as on-demand. To avoid any confusion here we shall use the term targeting in the following way. Targeting is the process of locating regions in which observations would maximally improve the skill of a weather forecast, using knowledge of the "flow-of-the day" or more generally dynamically-determined information obtained from the forecast model. Such observations will be called targeted observations. The regions that targeting locates are usually referred to as sensitive regions.

Sensitive regions are the localised zones of the atmosphere from which analysis errors grow significantly and thereby degrade forecast skill. The sensitive locations depend strongly on many factors including the forecast time-range and the verification region. Sensitive regions may exist:

- in geographical zones – e.g. maritime continent: flare-up of tropical convection leads to downstream wave-train propagation
- associated with weather types – e.g. extratropical storm-track and tropical cyclone genesis regions
- in flow-dependent zones – from which analysis errors grow rapidly.

The use of adjoint products to predict the location of sensitive regions was first suggested in 1995. It is now possible, in principle, to:

- make such predictions operationally - "targeting" – and thereby also
- decide how optimally to make observations there, and
- design perturbations for regionally targeted ensembles.

2. Theory of Predicting the Location of Sensitive Regions

Since the idea of adaptive observing using dynamical means was first raised in 1995, a number of distinct, but related, mathematical methods to identify the location of sensitive regions have been proposed and tested. This class of methods builds upon the use of the perturbations to initial conditions that are used in operational ensemble prediction systems. This class uses a full nonlinear forecast trajectory, which here we call the preliminary forecast, and estimates of the (linear) growth of small perturbations to the trajectory.

Before summarizing the different variants within this class of methods, it is useful to note that another class of more empirical methods of targeting have also been proposed. An example of this second class is the so-called water vapour-potential vorticity method described by Demirtas and Thorpe 1999. Localised mismatches between an analysis and a timely water vapour satellite image can be interpreted as a tropopause-level potential vorticity analysis error. Inversion of the potential vorticity error allows (balanced) targeted wind and temperature "observations" to be available to the forecast model. Other examples include the practice of bogusing hypothetical observations creating a tropical cyclone vortex in analyses to enable such cyclones to be more effectively initiated. Also human forecasters can apply their experience to suggest subjectively key, or sensitive, regions where synoptic development may be most strongly affected by analysis errors. Browning et al 2000 provide a perspective on the forecasting of ex-hurricane Lili and compare the empirical class with the class based on linear growth of perturbations. The conclusion is that the sensitive regions highlighted by the two classes are in similar locations at least for that case.

We now return to the linear perturbation class of methods. One might wish that the targeting method was in some senses statistically optimal in that over a number of cases the predicted locations of the sensitive regions would lead, if targeted observations were obtained therein, to a significant reduction in forecast error, Berliner et al 1999. The required estimates of the change in the forecast error covariance due to the addition of targeted observations could be found using an extended Kalman filter. However this is not currently feasible due to the large dimension of the state space of the NWP model.

In principle the problem of finding sensitive regions is one of estimating where analysis errors may be large and of estimating the rate at which such errors will grow during the forecast. Targeting is, in simplified terms, aimed at finding regions with potentially large analysis errors that will also grow rapidly. Lorenz and Emanuel 1998 and Hamill and Snyder 2002 focus on locations where initial condition uncertainty is large or where targeted observations would reduce the analysis error the most. On the other hand Buizza and Montani 1999 and Montani et al 1999 focus on estimating the growth rate of singular vectors during the forecast. The leading singular vectors (SV) are the structures that grow the most rapidly, in a linear sense, over a fixed forecast period. As well as the SV method, adjoint sensitivities (Langland and Rohaly 1996) and quasi-inverse linear integrations (Pu et al 1997) use the adjoint or tangent-linear of the full forecast model trajectory.

It is important to also take into account the characteristics of the data assimilation system and various methods for targeting have been proposed that aim to do so. Baker and Daley 2000 and Doerenbecher and Bergot 2001 examine sensitivity with respect to the observations. On the other hand Bishop and Toth 1999 and Bishop et al 2001 use the already computed ensemble members. These are manipulated by linear combination to evaluate the likely forecast error reduction resulting from a localized analysis error reduction presumed to have arisen from targeted observations located there. These are referred to as the ensemble transform (Kalman filter) methods. One approximation in this method is due to the finite, and usually small, number of ensemble members on which to project such errors and like the other methods in this class a linear assumption has to be made.

Another way to predict the likely forecast error reduction resulting from deployment of targeted observations is by a reduced-rank state estimation using the leading order Hessian singular vectors, Leutbecher 2003. In this way the dependence of the likely forecast error reduction on the particular deployment of observations within the sensitive region can be evaluated.

For further details of these various methods, and other related ones, the reader is referred to the published papers quoted herein. To provide one example of what is possible we now present some results from Leutbecher et al 2002 on the Lothar Storm that caused significant damage and loss of life in France and neighbouring countries on 26 December 1999. Observing system simulation experiments, over a 48 hour forecast period, were carried out using the ECMWF forecast model and its 4D VAR assimilation system. Both total energy and Hessian singular vectors are computed for comparison purposes. A truth trajectory (using the Météo-France analysis and ECMWF model) and a poor forecast (using the ECMWF analysis and model) were selected from an ensemble of forecasts. It was then possible to locate sensitive regions with the poor forecast trajectory and transplant soundings taken from the analysis leading to the truth trajectory as the theoretical targeted observations.

The sensitive region was formed from a weighted average of the first 5 singular vectors and are shown in figure 1 for both total energy (TESV) and Hessian (HSV) singular vectors. There is significant overlap between the two predictions of the sensitive region.

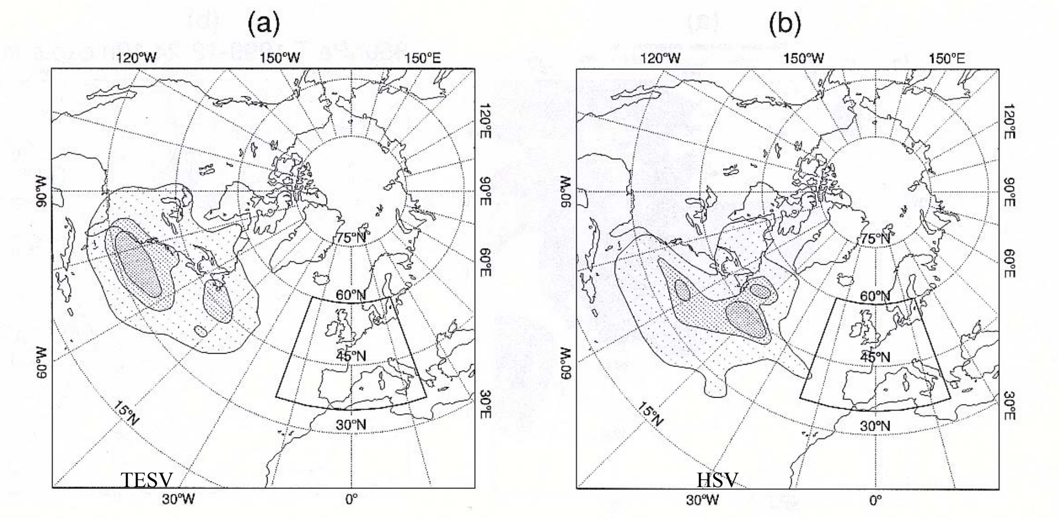


Figure 1: Sensitive regions for Lothar predicted using (a) total energy and (b) Hessian singular vectors, from Leutbecher et al 2002

In order to assess whether these (linear) estimates of the most sensitive region are accurate, a set of 14 test sensitive regions were defined. The impact of adding 40 targeted soundings into each of these was found by integration of the full non-linear forecast model. In this way the optimal zone for observations (OZO) could be found and compared with the sensitive regions highlighted in Figure 1. The OZO was well estimated by the HSV providing evidence for the accuracy of this targeting method. In figure 2 the evolution of the forecast error for Lothar is shown using targeted observations in a variety of locations. It can be seen that putting these observations in the HSV region is almost as good as in the OZO showing the potential power of targeting in reducing forecast error.

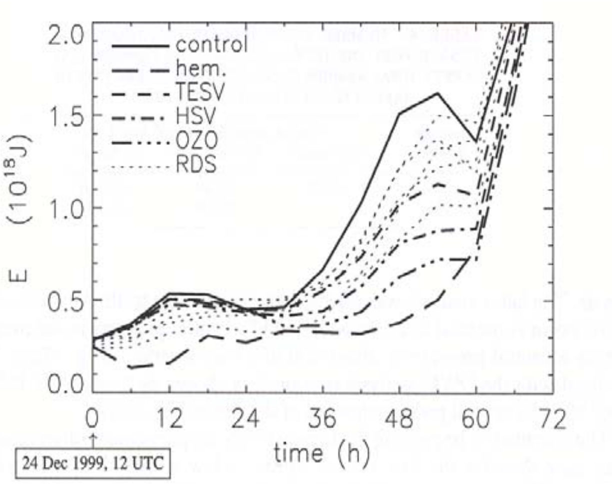
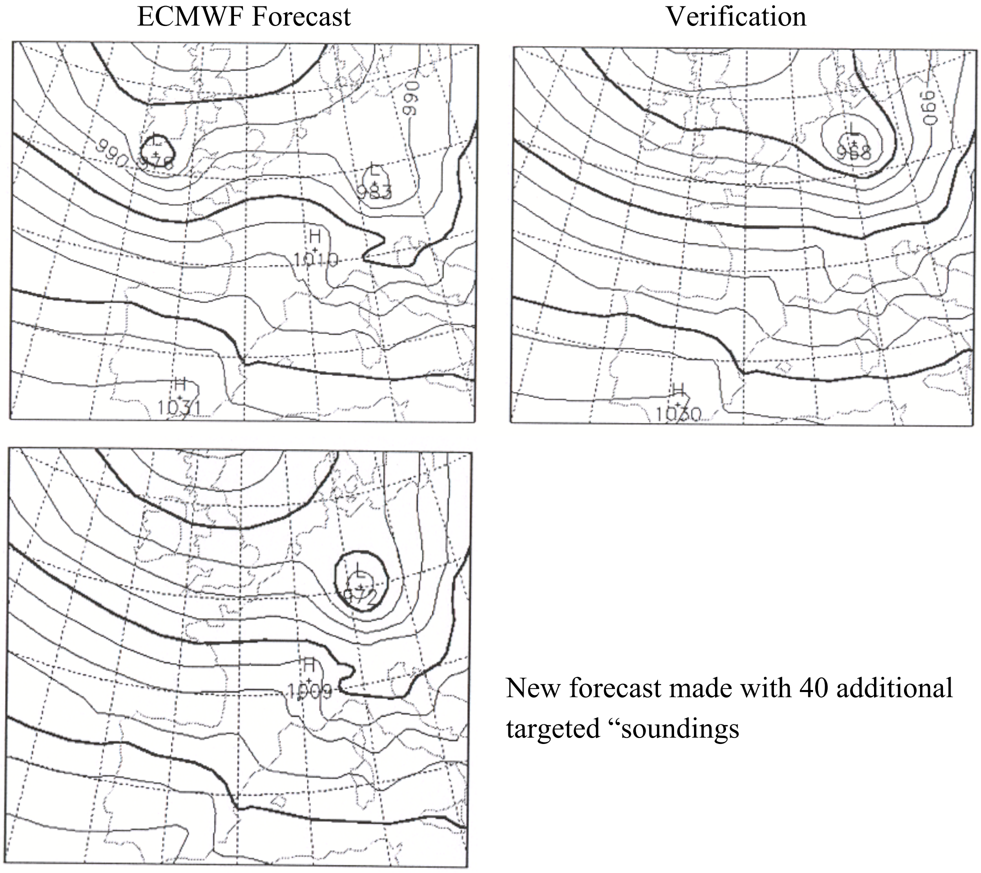


Figure 2: Evolution of the Forecast Error for Lothar including 40 targeted profiles in various locations, from Leutbecher et al 2002

In figure 3 the implications of the forecast error reduction in total energy for the sea-level pressure field is shown. The verification is the truth forecast and it is clear that the ECMWF forecast exhibited a significant error, in this case, at 48-hour range. The final frame shows the excellent improvement possible by including 40 targeted soundings in the sensitive region.


ECMWF Forecast

Verification

New forecast made with 40 additional targeted “soundings

Figure 3: Observation system simulation experiments for Lothar, adapted from Leutbecher et al 2002

3. Experimental testing of Targeting in FASTEX

The first opportunity to test the real-time targeting of observations came in the Fronts and Atlantic Storm-Track Experiment, FASTEX, which took place during January and February 1997. FASTEX involved research aircraft, ship and enhanced routine radiosondes being utilized to provide an enhanced observational description of the evolution of extratropical cyclones across the north Atlantic storm-track. Real-time targeting calculations were made by a variety of centres: ECMWF, Météo France, NCEP and NRL. These allowed the location of sensitive zones to be predicted and various research aircraft to be directed into these regions to release dropsondes. The resulting profiles thereby produced targeted observations for later inclusion in the operational forecast suites. A number of sample hindcasts with and without the targeted observations were then carried out by the various participating groups. Results of these various studies were published in the Quarterly Journal of the Royal Meteorological Society Special Issue on FASTEX (October C 1999). The overall conclusion was that there were cases of significantly improved skill when using the targeted observations but also there were a significant number of small and even negative impact cases. One important point to bear in mind was that many of the cyclones in FASTEX were relatively well forecast using the routine observing network and so the potential for improvements by including additional targeted observations was somewhat limited.

The study that used the ECMWF forecast system gave some of the more encouraging results, which may reflect the relative sophistication of the data assimilation system and the quality of the model in terms of both resolution and parametrisations. In Figure 4 we show results from Montani et al 1999. This study used the ECMWF total energy norm singular vectors to provide the estimates of the locations of the sensitive regions in the western Atlantic sector. Dropsonde data obtained in the predicted sensitive area were used as the targeted observations. Figure 4 shows a scatter plot of the forecast error (root-mean-square) of 500mb and 1000mb height fields averaged over a verification region in north-west Europe encompassing the UK. Forecast periods, every 6 hours, between 30 and 48 hours are included and the error is plotted for forecast re-runs with the targeted observations included against those where they were not included. Very few points are below the dashed line (representing zero error reduction) indicating that in most cases the targeted observations reduced the forecast error. The error reduction is particularly large when the control forecast, without the targeted observations, exhibited large prediction errors. On average the gain in forecast accuracy is about 15% with the largest error reduction being about 37%.

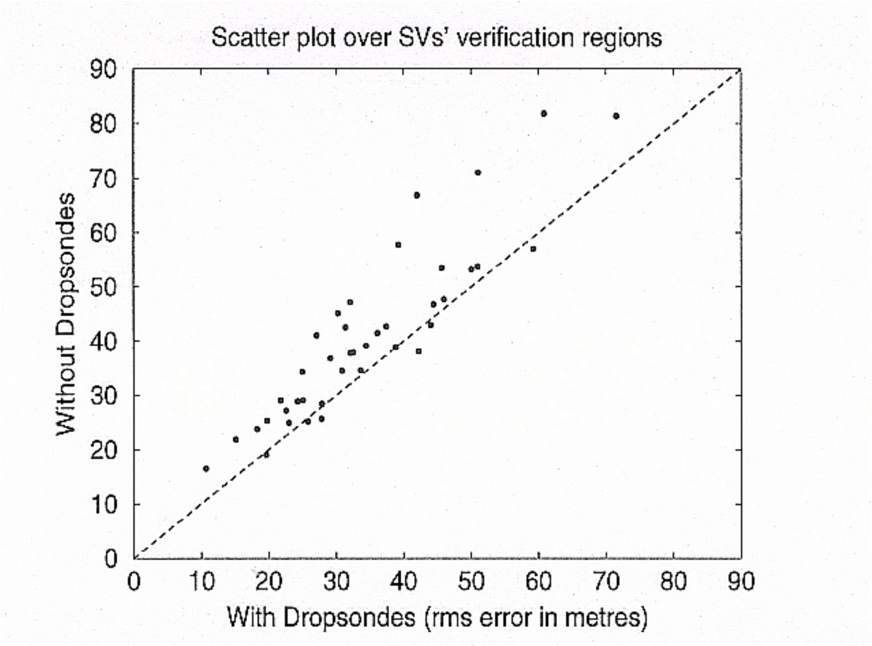


Figure 4: Scatter plot over SVs' verification regions, from Montani et al 1999, for FASTEX cases where forecast errors with the FASTEX dropsonde included are plotted against those without the targeted supplementary data.

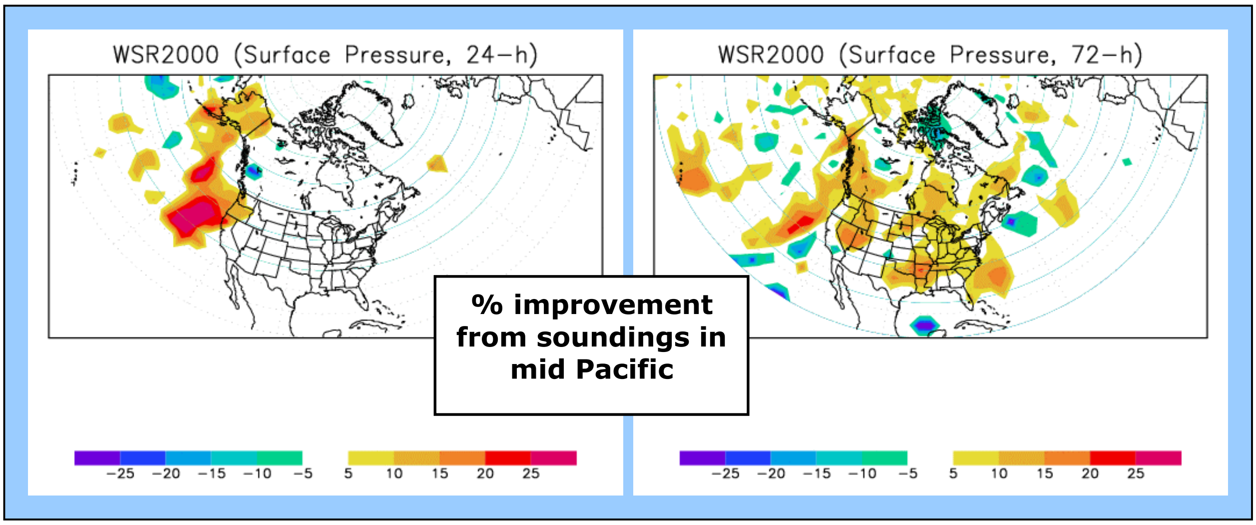
4. An operational system for the Pacific – WSR Programme

The FASTEX field campaign in the north Atlantic sector in early 1997 was followed by a targeting trial of a similar type in the north Pacific in early 1998 (NORPEX, Langland et al 1999). NOAA, via activities in NCEP, built on the success of these field campaigns by establishing the Winter Storm Reconnaissance (WSR) field programme in early 1999 (Toth et al 1999). Toth et al 2002 note that "The aim of the WSR program is to reduce forecast errors for significant winter weather events over the contiguous US and Alaska in the 24-96 hour lead time range through the use of adaptive observations over the data sparse northeast Pacific". NOAA and USAF manned aircraft flew from bases in Hawaii and Alaska to launch dropsondes into predicted sensitive regions.

The WSR 1999, and the follow-up WSR 2000, exercises were successes with the majority of the forecasts with targeted observations having significantly improved skill. The National Weather Service made the WSR programme operational in January 2001 with targeting occurring in January and February 2001 and also during these months in 2002.

The WSR 2001 programme was operational in the sense that the flights were triggered by forecasters. The process involved case selection followed by automated sensitivity calculations being triggered and choice of predesigned flight tracks in the light of the location of the sensitive regions being made. This chain of events was under the complete control of the forecasters, with no input from the research scientists. This scheme has been followed during WSR 2002.

During WSR 2001 there were a total of 27 flights/cases during a one-month period. Forecasts were improved in 60-70% of all WSR cases and the average rms error reduction in the 24-96 hour forecasts in the preselected verification regions was about 10%, with some cases in excess of 25%. This implies a lead-time gain for a 2-day forecast of about 12 hour. In figure 5, adapted from Szunyogh et al 2002, we see the propagation in WSR 2000 of the regions of positive forecast improvement from the location of targeted observations in the Pacific eastwards until at 72 hour the improvement covers many parts of the USA and Canada.



WSR2000 (Surface Pressure, 24–h)

WSR2000 (Surface Pressure, 72–h)

% improvement from soundings in mid Pacific

Figure 5: WSR Skill improvements, adapted from Szunyogh et al 2002

5. Cloudy Sensitive Regions

The WSR programme utilises the availability of manned meteorological research aircraft to make targeted observations. There is a wide potential for many other observing methods to be used for targeting. These methods, that could ultimately be made operational, include targeting of:

- satellite data
- ASAP ship soundings
- AMDAR aircraft reports
- supplementary mobile and fixed-location soundings
- other supplementary in-situ instruments

New satellite instruments will provide huge datasets, but targeting is essential for:

- selective dynamic utilisation of the huge data flows from satellites and
- determining locations for higher scan rates

But in cloud layers and below cloud-base the new satellite instruments will have poor resolution. Figure 6 shows the huge volume of GOES satellite derived winds in three layers (1000-700mb, 699-400mb and 399-100mb) at a single analysis time in mid Pacific. Given such huge data volumes there is a need to thin such datasets for real-time data assimilation.

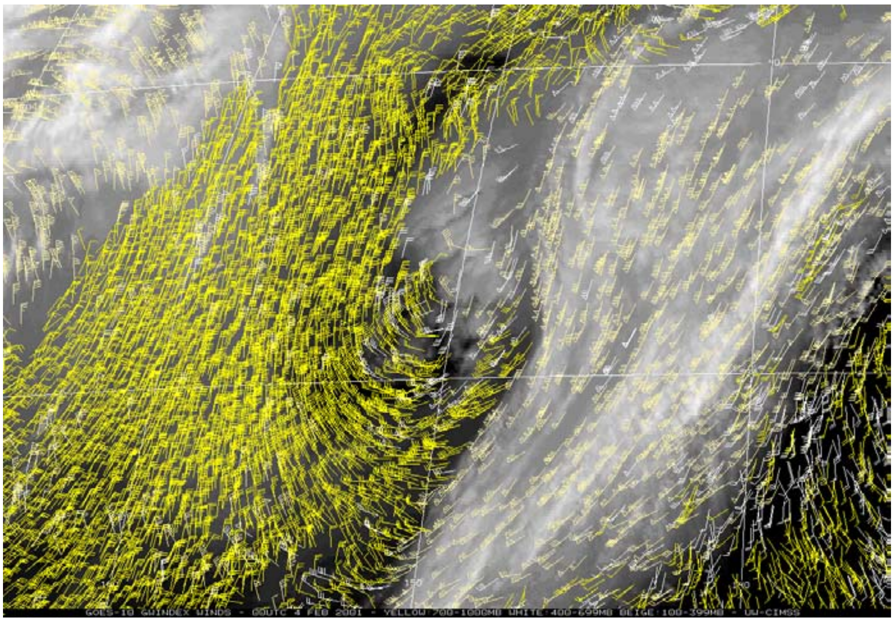


Figure 6: Satellite winds from GOES in three layers

One way to carry out such thinning is via dynamical targeting. If we retain only the data in the layer 400-700mb which is known from the singular vector calculations to be a key sensitive region then far fewer data are available, see Figure 7. This dramatic reduction in data availability in the sensitive region is because of the difficulty of sensing from satellites in significant cloud layers.

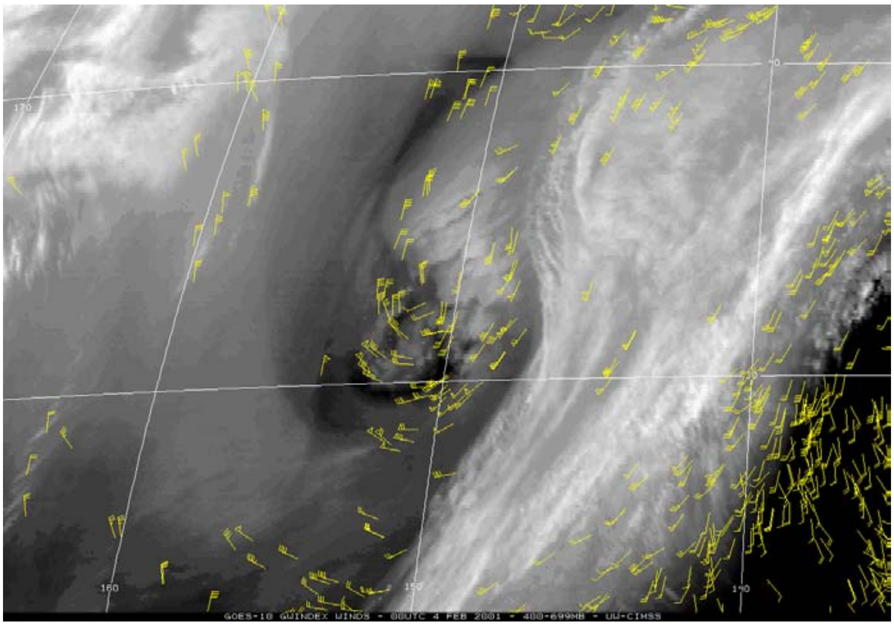


Figure 7: Satellite winds from GOES in sensitive layer: 400-700mb

Calculations made by Leutbecher et al 2002 of the location of the sensitive region for the Lothar storm are shown as striped and hatched regions in Figure 8. Also plotted are the model cloudy regions, given with continuous grey shading. It can be seen that there is a large overlap between cloud layers and sensitive regions. Given that the currently-planned generation of satellite instruments will have poor resolution in cloud layers, it is clear that other sources of targeted observations will have to be investigated.

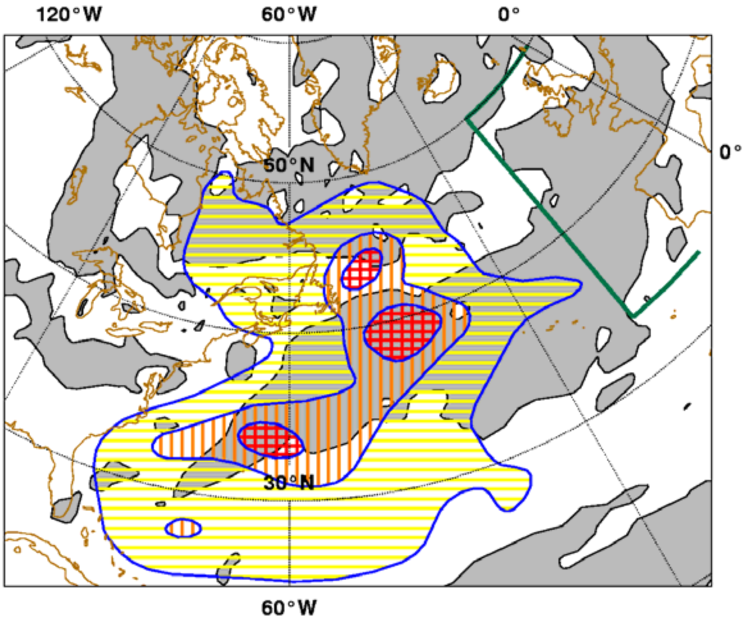


Figure 8: Sensitive regions (striped and hatched) occur within cloud layers (shaded), adapted from Leutbecher et al 2002

Fortunately there is substantial potential to enhance the observing system with new low-cost in-situ instruments. This opens up the exciting prospect of targeting additional mobile in-situ instruments into these zones.

6. A Global Programme on Targeting – THORpex

An internationally-coordinated programme of research and field experimentation is needed to determine the optimal utilisation of satellite and in-situ observing systems, leading to:

- an improved operational global observing system
- advances in data assimilation methodologies

The aim is to enable forecast skill to make a "leap forward" necessary to solve the problems described earlier.

The Global Atmospheric Research Programme, GARP, led to the Global Weather Experiment called the First GARP Global Experiment, FGGE, in 1979. This led to a significant acceleration in NWP skill improvements.

Recent advances (e.g. data assimilation, ensemble prediction & targeting) suggest that another leap forward is possible now.

In concept this is a "Second GARP Global Experiment": FGGE + 30 years. We call this THe Observing-system, Research and predictability experiment, THORpex; see for further information - http://www.mmm.ucar.edu/uswrp/programs/thorpex.html.

THORpex is a decade-long international research programme to accelerate the rate of improvements in weather forecasts of high-impact weather over the globe. This will be achieved by collaboration between the operational and research communities to improve NWP skill by using "dynamical control" of the observing system. THORpex aims to explore the new idea of a reactive two-way flow of information between the observational and NWP systems. Until now this flow has been one way from observations into the NWP system. We call this process "dynamical control" and this will allow us to:

- \- dynamically utilise satellite and other data
- \- determine the optimal mix of diverse observational types
- \- design ensembles so as to target supplementary observations

In order to achieve its goal THORpex needs to facilitate:

- advances in predictability theory, data assimilation and understanding of dynamical processes
- better methods of targeting to locate sensitive zones and to improve ensemble perturbations
- development of a diverse range of in-situ observing technologies to supplement satellite data in cloudy sensitive regions.
- design of the dynamically-controlled observing and NWP systems

THORpex is structured with four sub-programmes of research:

- Observing System Development and Evaluation
- Data Assimilation and Observing Strategies
- Predictability and Dynamical Processes
- Societal and Economic Impact Assessment

As mentioned in section 5 there are a range of new and innovative in-situ low cost instruments under current development capable in principle of obtaining targeted observations. THORpex will act as a spur to the development and testing of these instruments, which include:

- Driftsonde
- Robotic aircraft
- Aircraft-deployable ocean surface data buoys
- Rocketsonde
- Bi-directional radiosondes

In Figure 9 we show a schematic of the NCAR driftsonde system involving a zero-pressure balloon flying in the stratosphere with a gondola holding 24 dropsondes. The launch times of the driftsonde and the deployment time of the individual dropsondes will allow targeting to be implemented. The design specification of the driftsonde is that the total cost of each sounding of the atmosphere is similar to that of a routine radiosonde profile.

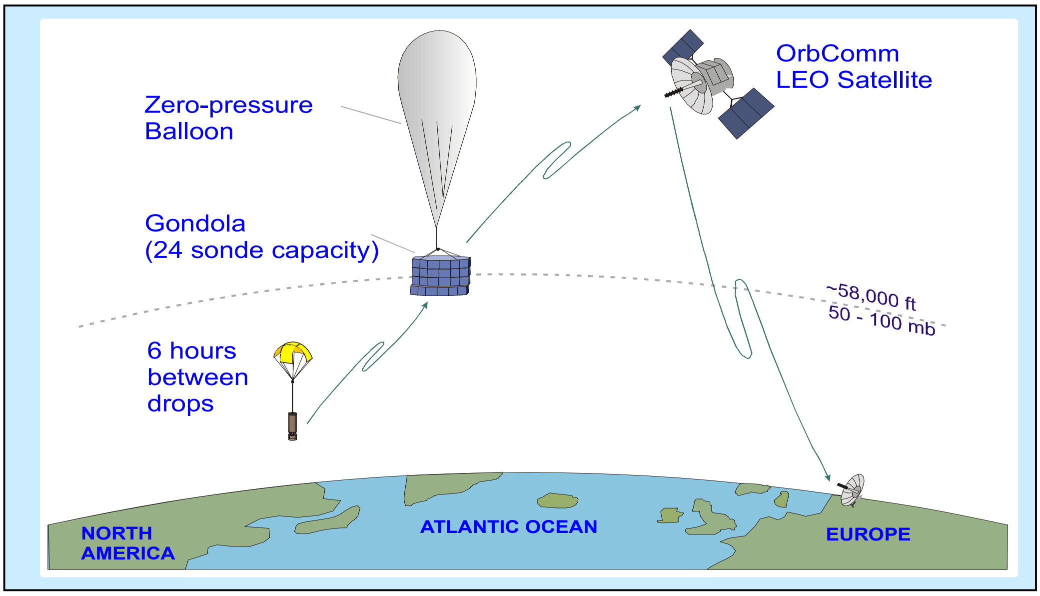


Figure 9: Driftsonde System

An example of the type of coverage possible over the north Pacific sector from 4 launch sites in Japan is given in Figure 10.

As a culmination of THORpex research it is envisaged that there will be a "THORpex Global Experiment" by analogy with FGGE. This will:

- last for a year, say in 2009 or 2010
- include all candidate in-situ systems and available remote sensing systems
- data will be available in real-time
- will consider all predictable spatial and temporal scales out to 14 days

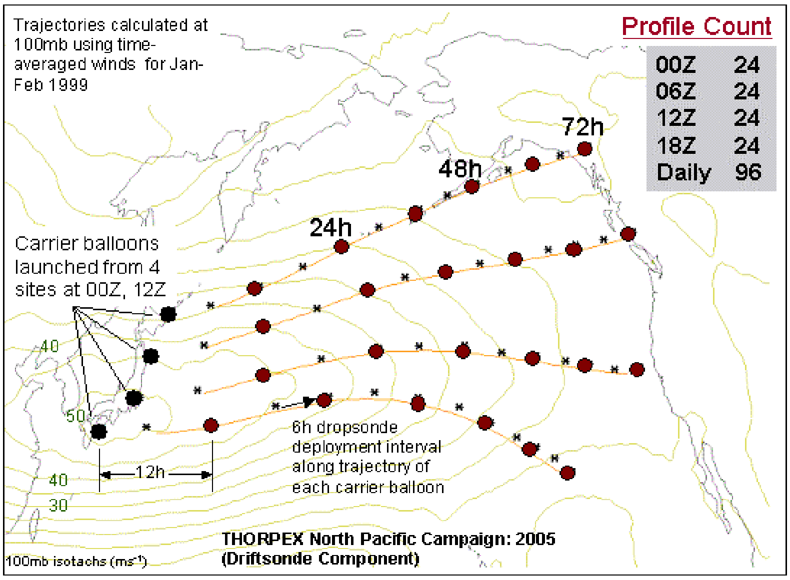


Figure 10: Example of possible Driftsonde deployment from Japan

THORpex aims to assist global coordination to develop the observing system for weather forecasting, e.g. it has strong links with the Commission for Basic Systems and the EUropean Composite Observing System.

It also needs to coordinate with the design of the Global Climate Observing System so that advances will also benefit climate. THORpex is a programme of the World Weather Research Programme and is supported by the Working Group on Numerical Experimentation.

7. Concluding Remarks

Building on the ideas of targeting observations we can propose a vision of the way numerical weather prediction could be done in the future. This vision involves a preliminary forecast being made using observations from the routine observing system and the NWP model. Ensembles of the future will involve an ensemble design that is optimized for particular customer needs. As computing resources become more readily available, suites of ensembles each separately designed for different customers can be contemplated. Part of the output from the ensemble design step is the identification of sensitive regions in which to make additional targeted observations to improve the skill of each particular ensemble. The additional targeted observations are then ingested into the data assimilation system and the production of the optimized ensemble occurs. This represents a two-way flow between observations and the model, with the data assimilation system acting as the flow-controller. It can be described as a four-step process:

Step 1 (Preliminary forecast) – observations from the routine observing system with the highest resolution model version used for that problem, generating, what we call here, the routine analysis and the preliminary numerical forecast. (Information flows from the observing system to the model.)

Step 2 (Perturbation computation) – computation of a set of initial condition perturbations, from a simpler (probably lower resolution and simpler physics) version of the model, using the preliminary numerical forecast trajectory and customer-targeted metrics such as maximum error growth over north-west Europe. There will be a suite of these sets of perturbations, depending on the metrics chosen, feeding, in principle, a suite of ensembles.

Step 3 (Targeted observations) – definition of sensitive regions for additional targeted observations to be obtained for that particular member of the ensemble suite, serving particular customer's needs. Either additional targeted observations can be made, or otherwise discarded observations utilized, in the sensitive regions, if resources permit (information flows from the model back to the observing system). These targeted observations are used along with the routine observations to generate an improved analysis.

Step 4 (Ensemble computation) – addition of the perturbations, from step 2, to the improved analysis to initialize the individual ensemble members within that particular member of the suite of ensembles. The ensemble forecast is produced and disseminated to the relevant customers.

This structure of the NWP sytem is shown schematically in Figure 11.

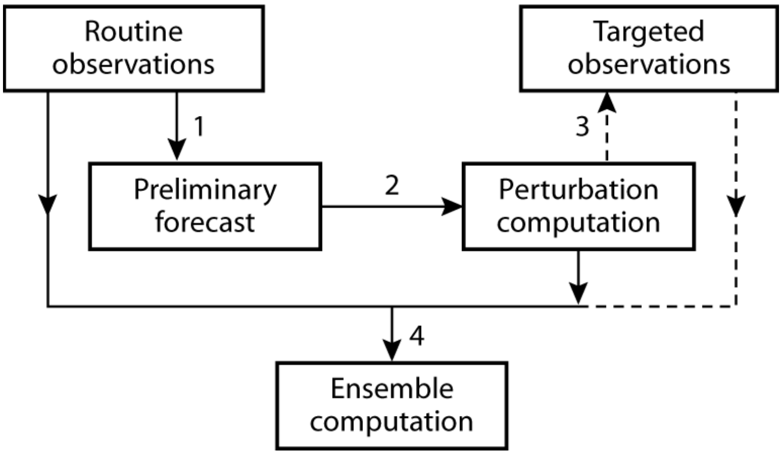


Figure 11: NWP System with the new step 3 to include targeted observations

The advent of dynamical targeting allows the new step 3 to be introduced into the NWP system. It consequently allows, in principle, information to flow to and fro between the observing system and the NWP system in an interactive way to optimize forecast skill. The international programme THORpex will carry out global testing and refinement of these ideas to assess the potential impact on operational forecast skill.

Acknowledgements

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