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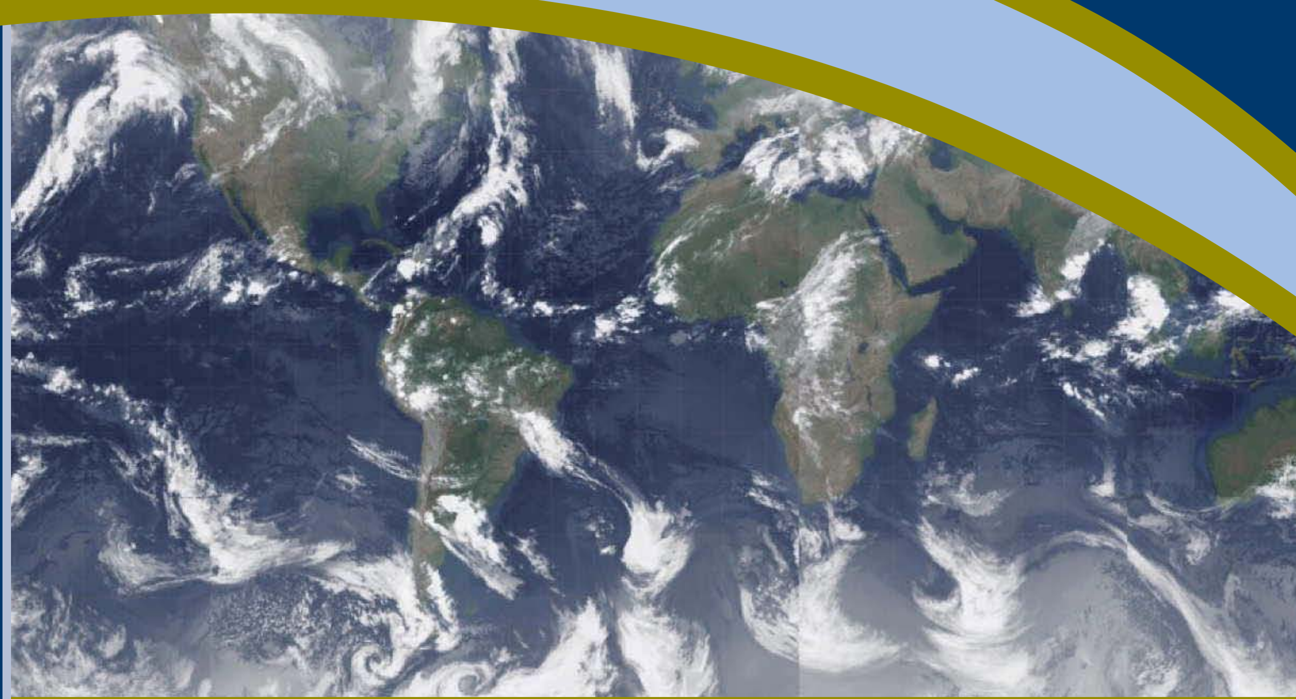
TARGETED OBSERVATIONS FOR IMPROVING NUMERICAL WEATHER PREDICTION: AN OVERVIEW



World Weather Research Programme

WORLD METEOROLOGICAL ORGANIZATION

WORLD WEATHER RESEARCH PROGRAMME

COMMISSION FOR ATMOSPHERIC SCIENCES

TARGETED OBSERVATIONS FOR IMPROVING NUMERICAL WEATHER PREDICTION: AN OVERVIEW

Prepared by

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WWRP/THORPEX No. 15

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Abstract

"Targeted observations" refers to the augmentation of the regular observing network with additional, specially chosen observations to be assimilated into operational numerical weather prediction models. Observation locations are chosen in order to improve forecasts of high-impact weather events of importance to society. Examples include dropwindsondes launched from aircraft or balloons, additional rawinsonde ascents, remotely sensed observations, and the inclusion of enhanced regular satellite observations (such as radiances or winds) that may normally be excluded from data assimilation due to routine thinning or quality control procedures. As a consequence of many field campaigns worldwide during the past decade, advancements have been made in the development of objective strategies for targeting observations, and in quantitative evaluations of the impact of assimilating these extra observations on numerical weather predictions. The successes and shortcomings of these efforts are reviewed here and recommendations are made to the community for the use of targeted observations in the future to maximize the impact on forecasts.

1. INTRODUCTION

Although there have been steady advances in observational coverage and numerical weather prediction models, and techniques employed to assimilate the data, forecasts of high-impact weather are sometimes still prone to large errors. For example, there was very high uncertainty in the 2-day forecast of the 26-27 December 2010 snowstorm that brought over two feet of snow to heavily populated areas of the northeastern United States. In 2008, the track of Typhoon Fengshen, which left over a thousand people dead in the Philippines, had also been forecast poorly. In many failed forecasts, particularly those of synoptic-scale systems with lead times up to ~5 days, forecast errors are often attributed in large part to inaccuracies in the initial conditions. These initial condition errors may have been initially small but grew rapidly, or they may have been large due to a paucity of observations or previous errors in the forecasts supplying the first guess. Initial condition errors can be attributed partially to deficiencies in the routine observational network. For example, the global rawinsonde network is nearly non-existent over the ocean, and is of limited density over land compared with the current resolution of operational global forecast models (mostly < 50 km as of 2011). And while satellite data and the methods to assimilate them continue to advance, satellite radiances are typically screened to preclude observations in cloudy areas and at lower levels over land. To augment the routine observational network, which cannot easily be varied at will, it had been suggested for several decades that adaptively deployable resources ought to be *targeted* to fill important data voids, reducing initial condition error and thereby the subsequent propagation and/or amplification of these errors in forecasts. This has only recently become practicable on an operational basis.

Due in large part to several international field campaigns, and the establishment of the THORPEX[1] programme in 2003, the field of *targeted observations* has advanced rapidly. One objective of several of the THORPEX-sponsored field experiments to date has been to determine the potential utility of targeted observations to improve forecasts of high-impact weather. A key issue is whether the benefits of establishing observational networks on a more adaptive basis, such as the commissioning of more upper air data in specific meteorological situations, are sufficiently important to society to justify the potential increases in cost and complexity. Accordingly, one role of the THORPEX Data Assimilation and Observing Systems Working Group (DAOS WG) to date has been "to assess the impact of observations and various targeting methods to provide guidance for observation campaigns and for the configuration of the Global Observing System" (*Rabier et al. 2008*).

At the mid-point of the THORPEX decade, we present a review of progress from the perspective of the DAOS WG and collaborators, expanding on earlier articles by *Langland (2005)* and *Rabier et al. (2008).* In the next section, a brief history of relevant observation campaigns is given, followed by a review of the targeting procedure in Section 3. Results on the impact of assimilating targeted observations on numerical forecasts are reviewed in Section 4. Finally, conclusions and recommendations are presented in Section 5.

2. REVIEW OF FIELD CAMPAIGNS AND OBSERVATIONS

Although targeted observations need not be restricted to any space or time scale, the majority of applications to date have focused on the improvement of short-range (1-3 day) weather forecasts. The field campaigns that have involved a targeting component are summarized below, with their vital statistics and key references listed in Table A1 in the Annex.

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[1] The Observing Research and Predictability Experiment, under the auspices of the World Meteorological Organization (WMO), is 'A World Weather Research Programme accelerating improvements in the accuracy of one day to two week high-impact weather forecasts for the benefit of society, the economy and the environment' (Shapiro and Thorpe 2004).

a. Pre-THORPEX era

The first example of regularly deployed adaptive observations was the "Hurricane Synoptic Flow" experiments conducted by NOAA's Hurricane Research Division in the north Atlantic basin during 1982-96. Dropwindsondes were deployed from the WP-3D (P-3) aircraft, to test the hypothesis that measuring vertical wind and thermodynamic profiles in the tropical cyclone (TC) environment would improve analyses and thereby numerical forecasts of the TC track. In contrast to future field campaigns, there was only a subjective strategy to target the observations. These early experiments were a resounding success *(Burpee et al. 1996*), leading to NOAA's procurement of the Gulfstream IV (G-IV) jet aircraft to conduct "synoptic surveillance" missions around TCs prior to the issuing of watches and warnings. During the first decade of operation, 176 missions were conducted, normally with 25-30 Global Positioning System (GPS) dropwindsondes released in the upper troposphere at 150-200 km intervals in the TC environment during each mission (*Aberson 2010*). These data are now assimilated routinely into operational global models. In the western North Pacific basin, the annual Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSTAR) field programme has been implemented since 2003 (*Wu et al. 2005*). Both the Atlantic and western North Pacific surveillance missions now use model-based guidance to identify preferred target locations, although subjective judgment is still used in mission planning.

Field campaigns in the mid-latitudes began with the multi-national Fronts and Atlantic Storm Track Experiment (FASTEX) in 1997 (*Joly et al. 1999*). In addition to testing scientific hypotheses on cyclone development and to document their three-dimensional structure, a primary goal of FASTEX was to improve 1-3 day forecasts of frontal cyclones over the Atlantic Ocean. In order to offer guidance on optimal locations for targeting dropwindsondes, several objective mathematical techniques were tested for the first time. Approximately one-third of all publications from FASTEX were on targeting, with many papers appearing in a special issue of *Quart. J. Royal. Meteor. Soc*. Following the success of FASTEX, the North Pacific Experiment (NORPEX) was run in 1998, with the focus on releasing dropwindsondes in areas selected by the objective targeting techniques, in order to improve forecasts of winter storms over the western United States *(Langland et al. 1999).* Smaller programmes such as CALJET and PACJET made use of targeting on a limited basis. In 1999, NOAA established and conducted the annual Winter Storm Reconnaissance (WSR) programme, with the objective being to deploy targeted dropwindsondes over the northern Pacific Ocean in order to improve short-range forecasts anywhere over the United States (*Szunyogh et al. 2000, 2002*). The WSR programme became operational in 2001 and has continued every winter to the present day.

b. The THORPEX era

The first major field campaign under the THORPEX umbrella was the Atlantic-THORPEX Regional Campaign (A-TReC) during the Northern Hemisphere autumn of 2003. The primary objective was to "test the feasibility of quasi-operational targeting of observations over the north Atlantic Ocean" and was sponsored by EUCOS[2] (*Fourrié et al. 2006*). A large quantity of *in situ* and remotely sensed observational data was collected to supplement the routine observational network (see Table A1), targeted at 1-3 day forecasts of potential high-impact weather events over Europe.

Since 2003, several experiments with a smaller targeting component have been conducted. During the African Monsoon Multidisciplinary Analysis (AMMA) campaign, a THORPEX component was aimed at improving short-range forecasts of western African rainfall and easterly waves that may lead to tropical cyclogenesis. In addition to additional rawinsonde balloons launched over Africa, the driftsonde system, comprising a large super-pressure balloon and a gondola carrying up to 40 dropwindsondes drifting westward at ~50 hPa was introduced. Several campaigns over Europe, aimed partially at improving short-range forecasts of specific high-impact weather events

[2] *EUMETNET (European meteorological network) Composite Observing System*

such as winter flow distortion past Greenland, summer rainfall in Central Europe or autumn heavy precipitation events in the Mediterranean region have taken place between 2007-9 (COPS, E-TReC, GFDex, MEDEX, see Table A1).

In Europe, an increased flexibility in the land-based rawinsonde network has been established with the EUCOS system together with in-situ components such as ASAP (rawinsondes from merchant ships) and AMDAR. Owing to the development of automated rawinsonde launch systems, it grew easier to manage adapted configurations of routine observing resources with a near automated targeting system. To coordinate requests for multiple types of adaptive observations during field operations, the EURORISK PREVIEW Data Targeting System (DTS) was established through the support of EUCOS, ECMWF, UK Met Office and Météo-France. The PREVIEW DTS was first implemented in 2008 in conjunction with MEDEX. The web-based facility allows registered users to identify potential high-impact weather events, request sensitive area calculations for chosen cases, identify those additional observations to issue requests, and monitor the requested observations.

The THORPEX Pacific Asian Regional Campaign (T-PARC) possessed a broader scope than those experiments introduced above, focusing on the large northern Pacific basin with a large array of instrumentation at hand. The "summer" phase in 2008 was aimed at investigating a wide variety of issues related to the science and predictability of the life cycle of TCs in the western North Pacific basin, from formation through to recurvature and extratropical transition, including the impact on the flow far downstream in the mid-latitude storm track (*Elsberry and Harr 2008*). In the "winter" phase that followed, the primary purpose was to investigate the potential for targeted aircraft and rawinsonde observations to improve forecasts of weather systems over North America beyond the 1-3 day range commonly used in WSR. During both phases, the PREVIEW DTS was employed, facilitating comparison of different targeting guidance products and improving the efficiency of the decision making process for multiple observation types.

Several campaigns that involve a targeting component are ongoing and planned. As part of the THORPEX International Polar Year (IPY), a campaign aimed at targeting to improve forecasts over Scandinavia took place in 2010 (*Irvine et al. 2011*). Concordiasi is another international collaboration that is a part of THORPEX-IPY, in which the primary effort is to improve the use of data (primarily advanced sounders such as IASI) from polar-orbiting satellites over the Antarctic (*Rabier et al. 2010*). The longer-term goal is to establish a sustainable observing system to understand climate processes and ozone depletion over Antarctica, exploiting the potential of advanced sounders. As a successor to MEDEX, the multinational Hydrological Cycle in the Mediterranean Experiment (HyMeX, planned for 2012-14) is aimed at a better understanding and prediction of high impact natural hazards, ranging from droughts and heat-waves at the seasonal scale through to heavy precipitation events inducing flash-floods on the mesoscale. Finally, future field programmes including HALO-THORPEX and the THORPEX-North Atlantic Waveguide and Downstream impact Experiment (T-NAWDEX) are proposed. The scope of targeting in these future campaigns remains to be determined.

This section has mainly provided a review of field campaigns and supplemental observational resources such as dropwindsondes and supplementary rawinsondes that were specially made available for those campaigns. Observational resources that are routinely available and potentially adaptable may also be targeted for specific weather events. The increased spatial and temporal density of satellite-based atmospheric motion vectors via the activation of rapid-scan mode is one such possibility. Reducing the thinning of satellite radiances is another. Thinning of data reduces the data volume and helps to avoid spatially correlated observation errors that may not be accounted for in the data assimilation scheme.

Following a review of the general procedure for targeting observations in Section 3, results from evaluation studies will be presented. Following the conclusions and recommendations, an extensive reference list is provided (including all cited references).

3. THE TARGETED OBSERVING PROCEDURE

The procedure for selecting targeted observations is complex and imperfect. An illustration of the components used in several field campaigns is shown in Figure 1, and the main issues involved are described in this section.

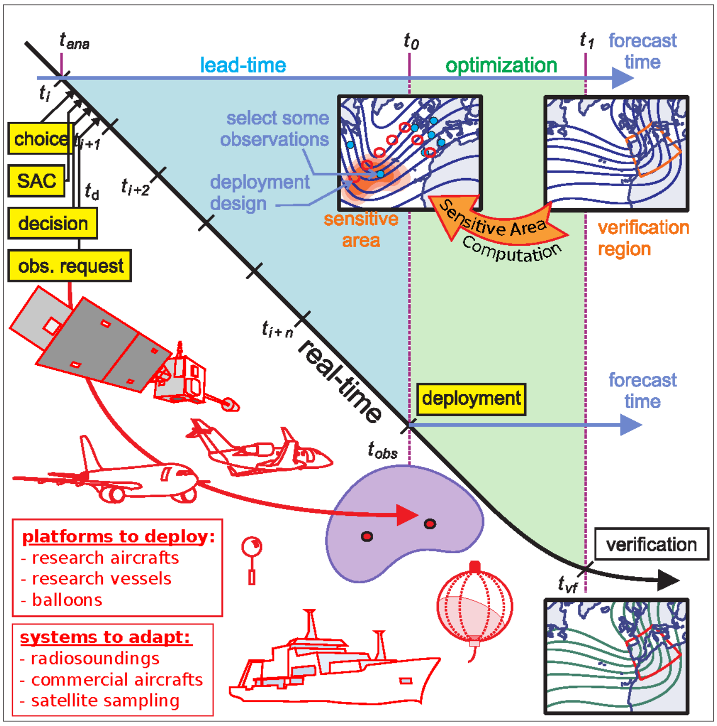

Figure 1 - Illustration of the typical procedure for the deployment of targeted observations

a. Case Selection

During field campaigns, the selection of forecast cases for deployment of adaptive observations has been conducted subjectively by forecasters or lead investigators. In the mid-latitude campaigns, forecasters first provide coordinates and "verification times" for weather events of interest. These cases are selected both for their potential to impact society (such as a precipitation event), and for forecast uncertainty using, for example, ensemble-based estimates of fields such as precipitation and 500 hPa geopotential height. Each case may be accordingly assigned a priority. An important part of the case selection is the geographical "verification region", upon which the guidance products for targeting are based, and within which retrospective evaluations are made. There is ongoing debate over the relative merits of selecting mobile versus fixed verification regions. In campaigns such as WSR, a small verification region centred on the selected coordinate of the expected event at the verification time is chosen to capture the potential spread of forecast storm locations. Alternatively, the use of larger fixed verification regions makes it easier to increase the level of automation in the procedure, and increase the breadth of observations (such as rawinsondes) available for forecast verification. A drawback is that verification statistics over large areas may be diluted by regions that are not directly associated with the weather event and may be relatively predictable.

For tropical cyclone surveillance, aircraft equipped with dropwindsondes are normally deployed 2-3 days prior to a potential landfall or impact, in order for numerical forecasts to derive benefit from the data prior to the issuance of watches and warnings. To date, these missions have been planned with the direct goal being to improve the track forecast. Although the objective of reducing forecast uncertainty is important, the decision on whether to deploy a surveillance mission is predominantly based on the potential impact to society.

It is still unclear whether predictive measures such as ensemble spread are able to accurately indicate uncertainty in high-impact events, and whether the low predictability is identified appropriately. On occasions, cases that were initially identified as having low predictability were found to be much more predictable by the targeting time, due to the intervening assimilation of routine observations.

b. Techniques to identify observing locations ("targets")

In order to predict the optimal locations and times for targeting prior to deployment, several mathematical techniques have been developed since the mid-1990s. Only a basic review is presented here. Given the process of an operational assimilation-forecast cycle, a strategy for adaptive sampling would ideally account for the following: (i) the probability that a forecast of a high-impact event is in error; (ii) the influence of all other observations to be assimilated routinely up to and including the targeted analysis time; (iii) the characteristics of the data assimilation scheme; (iv) the characteristics (type, accuracy) of the deployable observation types; and (v) the projected influence of assimilating a group of targeted observations on a future forecast of a given metric. Most of these cannot easily be determined. Due to the prohibitively high computational power that is required to account for all of these facets, it has been necessary to make crude assumptions. The earliest strategies developed for use in FASTEX were based on *analysis sensitivity*; in other words, how a modification to the analysis may affect forecast errors. Examples include adjoint sensitivity that predicts the response of a scalar forecast aspect to perturbations of any variable at the earlier analysis (targeting) time (*Bergot 1999*); singular vectors (SVs, *Palmer et al. 1998*) that use an adjoint to compute optimally growing perturbations (in a tangent linear sense) over the forecast interval; and the ensemble transform technique in which analysis ensemble perturbations are transformed to produce an estimate of forecast error variance (*Bishop and Toth 1999*). Over the following few years, the *observations* and *data assimilation scheme* were incorporated into existing or new methodologies, including Hessian SVs (HSVs, *Barkmeijer 1998*), analysis error covariance SVs (*Gelaro et al. 2002, Hamill et al. 2003*), Kalman Filter Sensitivity (*Bergot and Doerenbecher 2002*) and the ensemble transform Kalman filter (ETKF, *Bishop et al. 2001*) which has been used exclusively during annual WSR programmes over the past decade (*Majumdar et al. 2002a*). The ETKF aims to make quantitative predictions of the influence of assimilating any given set of targeted observations on forecast error variance. And while used sparingly to date, the ETKF also offers the capability of *serial* adaptive sampling, in which secondary groups of targeted observations can be identified based on the assumption that a specific primary group has been chosen and will be assimilated. Newer techniques such as ensemble sensitivity (*Torn and Hakim 2008*) and the adjoint-derived sensitivity steering vector for tropical cyclones (ADSSV, *Wu et al. 2007*) have been developed and implemented during field programmes. Adjoint sensitivity was applied to mesoscale models of tropical cyclones for the first time during the summer phase of T-PARC (*Reynolds et al. 2010*).

The meteorological characteristics of the guidance produced by these strategies have been investigated. An intercomparison between guidance provided by the ETKF and SVs for 1-2 day forecasts of eastern Pacific winter storms illustrated some common targets (such as baroclinic zones) but also several differences (*Majumdar et al. 2002b*). Extending the guidance into the medium-range, where the assumptions of linear perturbation dynamics are further compromised, the ETKF targets were found to be continuously traceable upstream in the storm track, from a verification region over North America at short leads (up to 1 day) to the vicinity of Japan at longer leads (4-7 days) (*Majumdar et al. 2010*). In contrast to the short-range, multiple and broad target regions were diagnosed. Coherent targets were more clearly discernible in non-blocked flows, and in the presence of an upper-tropospheric wave packet.

For 2-day forecasts of tropical cyclones, singular vectors identify sensitivity to the initial state in an annulus around the TC center, and upstream locations in the mid-latitude trough for recurving TCs (*Peng and Reynolds 2006*). Guidance provided by SVs from different models tended to possess similar characteristics to each other, albeit with different optimal regions in some cases, while they differed substantially from guidance issued by the ETKF or ADSSV (*Majumdar et al. 2006, Wu et al. 2009*). The SV targets show considerable sensitivity to the metric used to define the optimization problem (*Reynolds et al. 2007*). The ADSSV identifies sensitivities to the steering flow such as the mid-level subtropical high pressure system adjacent to the TC and the trough interacting with the typhoon (*Wu et al. 2009*). The ETKF identifies features such as adjacent ridges and troughs and, in contrast to SVs or ADSSV, regions downstream in the mid-latitude storm track (*Majumdar et al. 2011*). An example of sensitive areas selected by different techniques during the summer phase of T-PARC is given in Figure 2. A large body of literature now exists on the science behind the various sensitivity techniques for tropical cyclones.

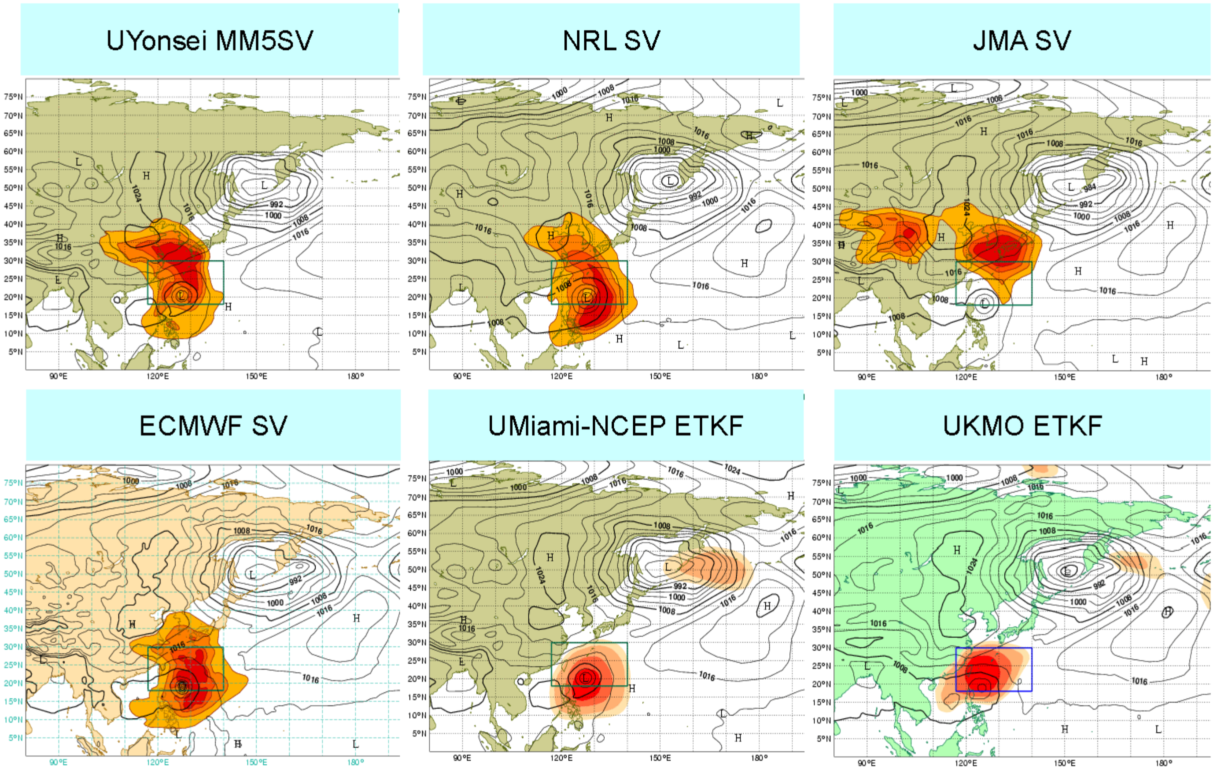

Figure 2 - Intercomparison of sensitivity guidance for a 2-day forecast of Typhoon Sinlaku during the summer phase of T-PARC, for a targeted analysis time of 0000 UTC 10 September 2008. Shading: maxima of guidance values. Contours: mean sea level pressure from the respective deterministic model. The rectangular box is the forecast verification region. All guidance was plotted on the PREVIEW Data Targeting System

Importantly, very few of the targeting techniques applied during field campaigns have explicitly accounted for the data assimilation scheme that is used at operational centers: HSVs (E-TreC 2003) and KFS (DTS-MEDEX 2009) do account for 4D-Var aspects but these techniques have not been used extensively. Nevertheless, recent adjoint-based techniques (*Daescu and Todling 2010*) and Hessian singular vectors associated with a 4d-Var scheme show promise in this area. Additionally, given the consideration by some operational centers to incorporate ensemble Kalman filtering (e.g. *Whitaker et al. 2008*) the assumptions inherent to the ETKF would become more consistent with those of the data assimilation scheme.

In addition to the aforementioned incompatibility with the data assimilation scheme, these targeting methodologies are limited by other gross assumptions such as linear perturbation dynamics. The results of investigations that have been conducted into their effectiveness will be reported in Section 4. The general consensus among the community is that these objective strategies employed in field programmes are superior to subjective decisions on deployment, particularly for mid-latitude systems.

4. EVALUATING THE INFLUENCE OF TARGETED OBSERVATIONS ON NUMERICAL PREDICTIONS

a. Evaluation Methods

Targeted observations, after assimilation, should result in a reduction in forecast error. There are several methods for quantifying their influence on forecasts.

(i) Observing System Experiments (OSEs)

Observing System Experiments, or OSEs, directly measure the influence on a forecast from the presence or absence of a particular observation type. Typically, a "control" assimilation-forecast cycle is first run through the period of interest with all operationally assimilated observations. Second, a parallel cycle, which is identical to the control except that the dataset in question is either added or withheld from the assimilation, is also run. The difference between the two forecasts integrated from analyses valid at the same time in the two cycles provides a measure of the "data impact". The improvement in the forecast is defined as the difference between the errors of the two parallel forecasts, evaluated against either observations or a verifying analysis. This method is standard in pre-operational testing of new data types, and has been used in all major adaptive observing programmes.

OSE methods have limitations. First, it is computationally expensive to perform the parallel integrations, particularly if one wishes to test different components of the targeted data sets independently. Second, tiny differences between the two parallel cycles' initial analyses may appear far from the observations and amplify, particularly in convective areas, and grow upscale to influence the synoptic flow (*Hodyss and Majumdar 2007*). Such differences can accumulate in a continuously cycled data assimilation system to affect forecasts of high-impact weather events such as hurricanes (*Aberson 2010*).

(ii) Adjoint-based observation impact

Given that an integration of the full assimilation-forecast cycle is needed for each observation type under investigation in OSEs, only a limited range of numerical experiments may be possible. An alternative method has recently emerged, based on formulations proposed by *Baker and Daley (2000*) and *Langland and Baker (2004).* It uses the adjoint of a data assimilation system to compute the contribution of *any* selected subset of observations to the overall reduction in short-range forecast error. This new technique is more computationally efficient than the OSE, and offers the capability to compute the quantitative impact on the forecast for *any* specific data type, location or channel at once (*Gelaro et al. 2010*). It should be emphasized that if this method deemed that some amount α of mean square error reduction was due to observation type 'A', that would *not* mean that the mean square error would increase by α if observation type 'A' was removed from the system. Hence, it does not quantitatively predict the results of OSEs, although it has been demonstrated to yield qualitatively similar results to an OSE *(Cardinali 2009, Gelaro and Zhu 2009)*. Several operational centers now use this method to monitor the global observing system and the impact on their global models, and a comparison between several centers, facilitated by the THORPEX DAOS Working Group is ongoing.

The adjoint-based observation impact produces a variety of insightful diagnostics and can act as a benchmark for assessment of the global observing system in which targeting is conducted. It is limited by the tangent linear assumption and so is suited to short range forecasts. It measures observation impact on a single selected cost function, although different cost functions can be evaluated. The adjoint-based observation impact and OSE methods are a useful complement to each other, with each method providing unique and helpful information about the impact of observations.

(iii) Observing System Simulation Experiments (OSSEs)

In contrast to OSEs which evaluate the impact of actual observations on analyses and forecasts, Observation System Simulation Experiments (OSSEs) evaluate the potential impact of *synthetic* configurations of observations, including those that are yet to be deployed or even manufactured. The primary use of OSSEs has historically been to evaluate the potential for future satellite observing systems to improve NWP (*Atlas 1997*). OSSEs need to be constructed carefully, and this can be an onerous task. First, a continuous numerical model integration that gives a realistic simulation of nature (or "truth") is required. All evaluations are performed with respect to this nature run, which should be constructed using a different model than that used in the assimilation-forecast cycle so as to simulate the effects of model error. The nature run must produce a realistic climatology and physical characteristics of common weather systems. Further, the OSSE needs to be calibrated, such that the impact of assimilating a group of synthetic observations (such as synthetic rawinsonde or radiance data) is quantitatively similar to that of assimilating the real data in the same NWP system. Over the past decade, a collaborative effort on OSSEs using a nature run from ECMWF has been ongoing (*Masutani et al. 2010*). The potential for high-density observations with uncorrelated errors in sensitive areas has been demonstrated in an OSSE by *Liu and Rabier (2003*). Observing systems under investigation in OSSEs include space-based Doppler lidar winds (*Atlas and Emmitt 2008*) and unmanned aircraft systems. In addition to evaluating the impact of future observations, OSSEs can be used to evaluate targeting techniques, data assimilation methods and verification metrics (*Bishop et al. 2006; Errico 2011*). While the OSSE offers versatility, it does suffer from practical constraints. The computation of a (typically high resolution) nature run is computationally expensive; careful analysis is required to calibrate the OSSE; and it is laborious to maintain an OSSE with an ever-changing model and observational network.

b. Results from evaluations

Several results from the most significant studies with a large number of cases are summarized in Table A2 in the Annex, with more detailed descriptions and explanations herein.

(i) Field programmes focused on winter weather

A large number of data impact studies were performed for FASTEX cases, with several reported in the Special Issue of *Quart. J. Royal. Meteor. Soc.* in 1999. The general impact from the targeted aircraft observations was positive, using a range of global forecast models. A study by *Bergot (2001*) was the first to emphasize the influence of the data assimilation scheme on the results, with the FASTEX observations producing a greater impact on the forecast when 4d-Var was used instead of 3d-Var. In NORPEX, the dropwindsonde data improved 2-day NOGAPS forecasts by 10% on average (*Langland et al. 1999*). However, the same impact was not found by ECMWF, due to a different evaluation procedure, and sometimes the mismatch between the locations in which the targeted observations were released and the region targeted by the singular vectors (*Cardinali and Buizza 2003*). *Gelaro et al. (2000*) used cloud-track atmospheric motion vectors from geostationary satellites (*Velden et al. 1997*) to determine that analysis corrections in the lower and middle troposphere were particularly important for improving 2-day forecasts in NORPEX, and that only a small number of fast growing SVs were required to explain a large fraction of the error growth in NOGAPS forecasts.

For the evaluations of the NOAA Winter Storm Reconnaissance (WSR) campaigns, OSEs with low-resolution (T62 followed by T126) versions of the NCEP GFS were performed prior to 2008, with the operational-resolution (T382) version used thereafter in conjunction with the 3-d variational Gridpoint Statistical Interpolation (GSI) data assimilation scheme. Initial evaluations of the WSR programme were reported by *Szunyogh et al. (2000, 2002*), who concluded that the forecasts of surface pressure, tropospheric wind and temperature were improved in approximately 70% of all cases during the 2000 WSR programme. Similar evaluations were repeated at NCEP (though not published) in subsequent years, with a conclusion that approximately 70% of 128 forecasts between 2004-7 were again improved due to the assimilation of the WSR observations.

For the FASTEX, WSR and A-TReC experiments, the sensitive areas in which targeted observations were collected were associated with important synoptic features, such as upper-tropospheric waves, potential vorticity anomalies and mature cyclones (*Gelaro et al. 1999, Reynolds et al. 2001, Szunyogh et al. 2002, Petersen et al. 2007*). Such areas are often cloudy, limiting the influence of satellite data on the data assimilation. *Szunyogh et al. (2002*) also determined that the biggest impacts on the WSR forecasts occurred when landfalling systems were targeted, with downstream baroclinic development playing a major role in propagating the influence of the targeted data. Generally, the assimilation of observations sampled within target regions selected by the ETKF produced a larger improvement to the forecasts than those outside target regions (*Majumdar et al. 2001, 2002a*).

In comparing results from WSR versus other field campaigns, it is important to bear in mind key differences between their respective targeting procedures. First, the verification region in WSR is a flow-dependent cylinder of radius 1000 km over any point in the contiguous United States and/or Alaska where at the proposed verification time there is a high degree of ensemble spread *and* the possibility of weather with a high societal impact. These regions are often downstream of the largest storm track over the ocean in the Northern Hemisphere, where the largest analysis errors exist (*Langland et al. 2008*). The OSSEs of *Bishop et al. (2006)* indicated that judicious selection of verification regions based on ensemble spread greatly increased the beneficial impact of targeted observations because it allows the adaptive observations to be focused on verification regions where the forecast is likely to be unusually poor. In contrast, other campaigns have used much larger verification regions that are not always selected based on the specific event. Consequently, these campaigns have often found that the forecasts without adaptive observations often possess low average error and that there is little marginal benefit to adding targeted observations.

Crucially, all the evaluations of WSR have to date only been performed with one operational system (NCEP GFS), and the results may vary between operational centers depending on their data assimilation scheme and their respective treatments of dropwindsonde and satellite observations.

During A-TReC, the ability to collect a variety of targeted observations on a large scale, and to control the types of observations to be targeted, was deemed a technical success. However, the forecasts over Europe were comparably accurate even without the targeted observations and the assimilation of the targeted observations made little difference to the quality of the forecasts (*Petersen and Thorpe 2007, Rabier et al. 2008*). On the positive side, the airborne DWL showed promise, producing a 3% reduction in 2-4 day forecast errors of geopotential height averaged over a 2-week period and a large verification area over Europe (*Weissmann and Cardinali 2007*). Additionally, *Langland (2005*) used the adjoint-based method to conclude that the data from the A-TReC dropwindsondes possessed about 3 times the impact per observation than data from routine rawinsondes, suggesting that the dropwindsondes were deployed in an area of relatively high sensitivity to observations. However, since the total number of dropwindsondes was (and is always) small, the cumulative benefit to the forecasts was small compared with routine observing systems. The influence of dropwindsonde data may have decreased between FASTEX (1997) and A-TReC (2003) due to improvements in the routine observational network, data assimilation and numerical models in the intervening period. The improvement in the ability to extract information from satellite radiances may have been a factor, rendering the marginal benefit of targeted observations insignificant. Additionally, it was suggested by *Fourrié et al. (2006*) that the small number of observations plus their proximity to well-observed land areas, the sub-optimality of sensitive area calculations, and the lack of high-impact weather cases that were difficult to predict, all potentially played a role in the mostly neutral results for A-TReC.

The winter phase of T-PARC in 2009 produced positive impacts in the operational NCEP system. An example of an improved forecast is illustrated in Figures 3a-c, for a large winter storm that produced snowfall totals of over 8 inches (200 mm) over much of the eastern United States, and considerable rainfall over the western United States in early March 2009. The assimilation of the dropwindsonde data from a G-IV mission served to produce a more accurate 5-day NCEP GFS forecast of the precipitation distribution over the eastern United States, and correctly reduced the quantity of precipitation for the same forecast on the west coast. Overall, 70% of the 52 cases were improved, using similar verification metrics as for WSR (an example for surface pressure is shown in Figure 3d). For Winter T-PARC and WSR 2010, the cases with the highest improvement occurred when an upper-tropospheric Rossby wave packet was discernible over the northern Pacific Ocean, consistent with the findings of Szunyogh et al. (2002). The most difficult cases to evaluate were those in which a weak secondary development occurred downstream of the initial primary signal from the targeted data, and this secondary development triggered a local signal that could amplify. In such cases, improvement was often not discernible.

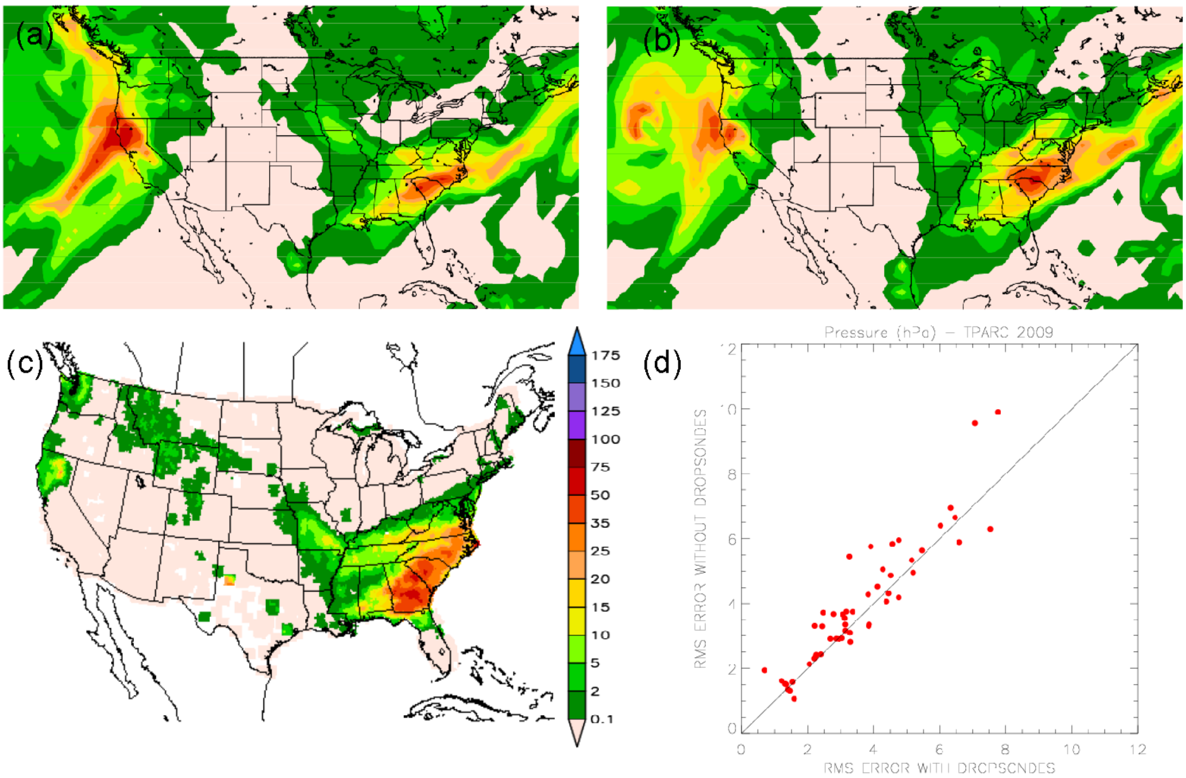

Figure 3 - (a) 5-day NCEP Global Forecast System (GFS) forecast of 24-hourly accumulated precipitation (mm), initialized at 12 UTC February 24 2009 (and valid at 12 UTC March 1 2009) with dropwindsonde data collected during the winter phase of T-PARC excluded from the assimilation cycle.
(b) As in (a), but with the dropwindsonde data assimilated.
(c) Corresponding NOAA Climate Prediction Center analysis of accumulated precipitation for the 24-h period ending on 12 UTC March 1 2009.
(d) RMS forecast error of surface pressure in NCEP GFS with and without targeted dropwindsonde data, for all cases during the winter T-PARC period. The verification metric is the fit to rawinsonde observations within mobile verification regions of 1000 km radius selected during the field experiment.
Of the 52 cases, 37 were improved and 15 were degraded.
(*From Yucheng Song*)

In a separate study, it was found that the targeted dropwindsonde observations collected during the winter phase of T-PARC often resided in areas of high sensitivity of the 1-day NOGAPS forecast error to initial conditions (Figure 4a) and that the adjoint-based observation impact of these dropwindsondes on 1-day NOGAPS forecasts was usually positive when a norm of moist total energy error was used (Figure 4b). Similar results were found for eastern Asian AMDAR, and special rawinsondes launched over Russia.

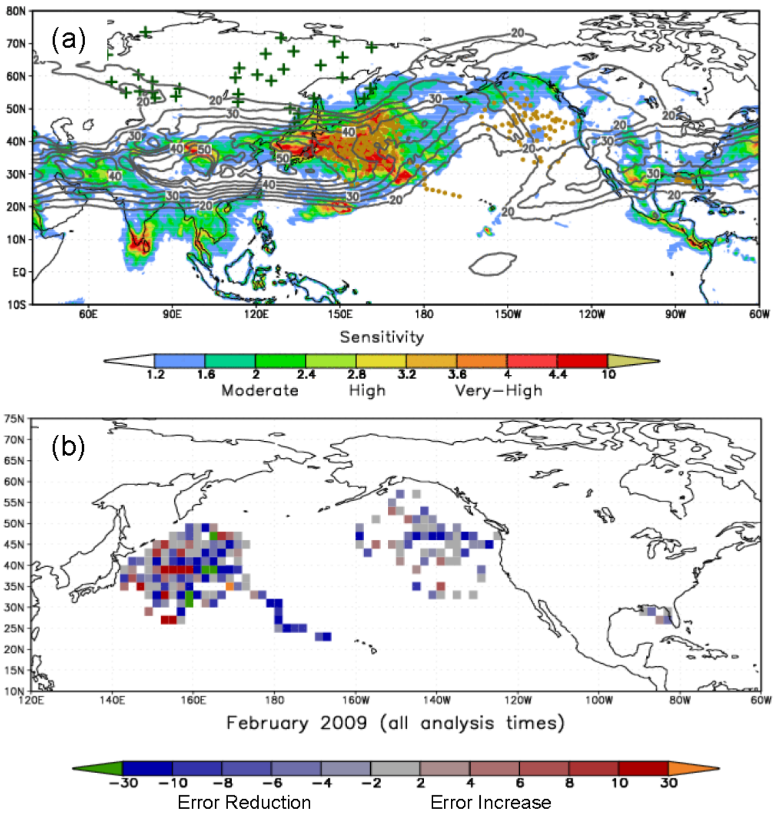

Figure 4 - (a) Composite of adjoint sensitivity of 24-h NOGAPS forecast error to initial conditions, between 1-28 February 2009. (b) Targeted dropwindsonde impact on 24-h forecast error in NOGAPS/NAVDAS for the same period. A norm of moist total energy error in the global domain is used, with units of 1×10^{-3} J kg^{-1}. A total of 355 dropwindsonde profiles were used. (From Rolf Langland)

In the other THORPEX field campaigns that focused more heavily on process studies, the very small sample of cases in the evaluations led to results that were interesting on a case-by-case basis, but ultimately without decisive statistical conclusions.

In addition to the evaluation of the impact of targeted data in the field experiments, the techniques used to identify sensitive areas require evaluation. As described earlier, all techniques possess limitations, which are expected to become more severe as non-linearity and model error begin to dominate forecast error growth. The ETKF was found to be effective in quantitatively predicting signal variance for short-range forecasts, an example of which is illustrated in Figure 5. The signal variance that is predicted over a day prior to collecting the targeted data (Figure 5a) often resembles the actual influence of the targeted data on the operational forecast (known as the “signal”, Figure 5b), and a quantitative relationship over full season between the predicted ETKF signal variance and the variance of NCEP GFS signal realizations has been found (*Majumdar et al. 2001, 2002a*). It is important to note, however, that a substantial signal in a verification region of interest (e.g. Figure 5b) may not necessarily correspond to a large overall improvement in the forecast (Figure 5c). The ETKF was also found to be capable of predicting signal variance for forecasts out to 6 days, in a limited number of cases in which the flow was not blocked. Interestingly, the cases in which the ETKF performed best quantitatively were also those in which the signal was highest (*Sellwood et al. 2008*), and in which the ETKF targets were traceable far upstream, from the United States back to Japan (*Majumdar et al. 2010*). These results suggest that, in certain flow regimes, some current methods can be effective in selecting areas to target for medium-range forecasts in the mid-latitude storm track, and that the deployment of the NOAA G-IV aircraft to Japan during the winter phase of T-PARC and the subsequent 2010 and 2011 WSR programmes was a sensible strategy.

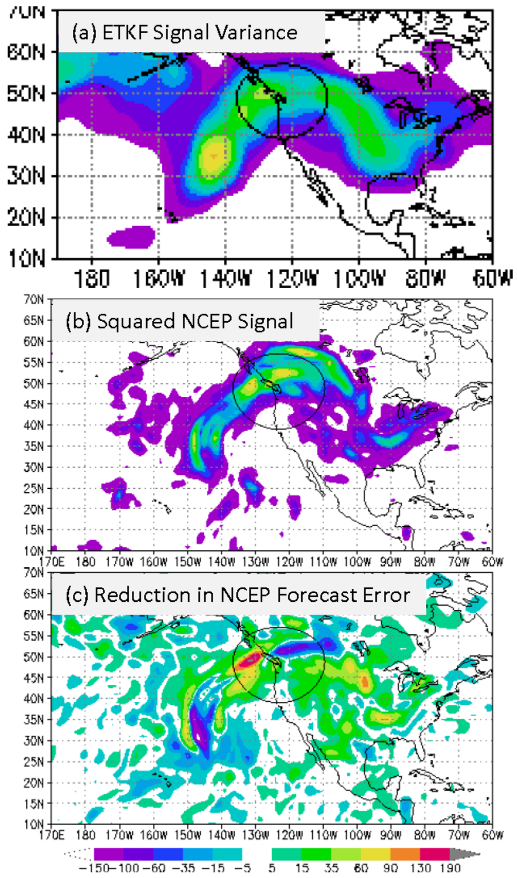

Figure 5 - (a) ETKF prediction of 48-h forecast signal variance, assuming a WSR mission from Hawaii. A total energy norm comprising tropospheric horizontal winds and temperature (units m^2/s^2) is used, based on perturbations from a 50-member ECMWF ensemble initialized 36 h prior to the targeted observing time. The black circle in each panel indicates the verification regions of radius 1000 km. (b) Corresponding 48-h forecast 'difference total energy' signal in the NCEP GFS system, due to targeted dropwindsondes launched from the same flight. The signal is computed as the mean square difference between two NCEP GFS cycles, which respectively include and exclude the dropwindsonde data. (c) The reduction in error of the 48-h NCEP GFS forecast due to the assimilation of the dropwindsonde data. Errors are computed with respect to the verifying NCEP GFS analysis. Warm colours represent an improvement to the forecast; cold colours represent degradation. (*From Sharanya Majumdar*)

(ii) Field Programmes focused on tropical weather

NOAA's Hurricane Synoptic Flow experiments between 1982-1996 were highly successful, even with a purely subjective strategy to target the dropwindsonde data in the synoptic environment of the TC. The mean track errors in 12-60 h forecasts were reduced by 16-30% due to the assimilation of these data (*Burpee et al. 1996*). These track improvements were as large as the official forecast improvements obtained by the National Hurricane Center during the previous 25 years. The operational Synoptic Surveillance programme that followed from 1997 onwards have also yielded positive results over the following decade. The assimilation of dropwindsonde data provided an average of 10-15% improvement in NCEP GFS track forecasts through to 60 h during the critical watch and warning period before the anticipated landfall (*Aberson 2010*). The differences between the average track errors were negligible beyond 72 h, suggesting that the track forecasts beyond 3 days may be more sensitive to remote features that are not reachable by the surveillance aircraft, or that the targeting methodology was ineffective for forecasts beyond this range. Over the past decade, a targeting strategy aimed at sampling maxima of the ensemble variance of mean wind in the 850-200 hPa layer in the TC environment has been used. In contrast to the GFS results, the average improvements to the GFDL track forecasts were found to be not as large. Part of the reason may be that the fields in and near the TC that are influenced by the surveillance data are removed via the GFDL vortex initialization procedure. Some large improvements to the GFS and GFDL track forecasts were found in individual cases, such as that of Katrina prior to its entrance in the Gulf of Mexico (*Aberson 2010*). On the other hand, large degradations were also found in earlier versions of the GFS, suggesting the need for carefully understanding the data quality control and assimilation procedures in or near the TC *(Aberson 2008).*

A more recent example demonstrating the improvement to the operational NCEP GFS track forecast of Hurricane Irene (2011) is illustrated in Figure 6. Due to the assimilation of dropwindsonde data from 3 flights which acted to slightly amplify the ridge to the north of the hurricane in the analysis (Figure 6a), an improvement was found in the track forecast of the storm as it travelled almost parallel to the heavily populated coastline of the eastern United States (Figure 6b). However, the intensity forecasts for Irene were challenging, possibly due to the misrepresentation of its interaction with surrounding dry air. If this was the case, the improved assimilation of moisture profiles such as from AIRS or IASI may have improved the forecast.

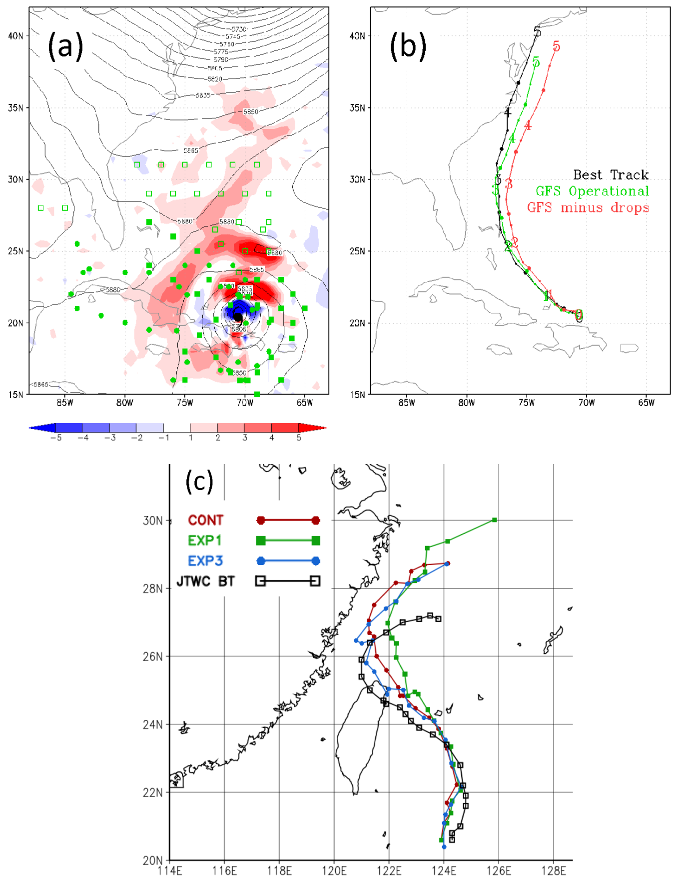

Figure 6 - The beneficial impact to tropical cyclone track forecasts due to the assimilation of (a, b) dropwindsondes and (c) satellite AMVs.

(a) Dropwindsondes deployed from the NOAA C-130 aircraft on 0000 UTC 23 August 2011 (green open squares), the NOAA G-IV aircraft on 0000 UTC (green solid squares) and 1200 UTC (green solid circles) 23 August 2011, around Hurricane Irene (black symbol). The influence of assimilating the dropwindsonde data on the operational NCEP GFS analysis of 500 hPa geopotential height at 1200 UTC 23 August 2011 is given by the shading: Red shading indicates an increase in the height, and blue shading indicates a decrease. The operational NCEP GFS 500 hPa geopotential height contours are illustrated for reference.

(b) 5-day NCEP GFS track forecasts of Hurricane Irene, initialized on 0000 UTC 23 August 2011, with dropwindsondes from the three flights removed (red track) and included (green track). The NHC best track is shown for reference. (*from Sharanya Majumdar*)

(c) (Adapted from *Berger et al. 2011*): Composite track forecasts of Typhoon Sinlaku for 3 NOGAPS experiments: CONT: All operational observations including hourly AMVs. EXP1: Same as CONT but excludes all AMVs processed by CIMSS. EXP3: Same as CONT but with rapid-scan winds added between 1200 UTC 10 September 2008 and 0600 UTC 13 September 2008. For each numerical experiment, an average position of all forecasts initialized at 12-hourly intervals beginning 1200 UTC 10 September 2008 is plotted. Each solid circle or square corresponds to the average of all analyses and forecasts from the particular experiment, valid at a particular time. Note that these points vary in the number of forecasts and the forecast lengths that are provided in the composite; the points early in Sinlaku's life cycle only include short-range forecasts, whereas the points late in Sinlaku's life cycle represent a composite of 0-5 day forecasts. (*from Rolf Langland)*

Results from the DOTSTAR programme in the western north Pacific have been similarly encouraging. For the GFS, NOGAPS and JMA models, the assimilation of the targeted dropwindsonde data caused the average track errors for forecasts up to 3 days to be reduced by at least 14% *(Wu et al. 2007).* DOTSTAR also played a vital role as a complement to the summer phase of T-PARC. Several evaluations have recently been completed, with varied but generally positive results. First, an intercomparison of four OSEs was performed by *Weissmann et al. (2011a)* during the intensive observing periods covering two long-lived typhoons. The DOTSTAR and T-PARC data were found to improve the track forecasts by 20-40% in two of the modelling systems (NCEP GFS, Korean Meteorological Agency WRF), but only modest improvements to forecasts up to 3 days were found in two other systems (ECMWF, Japan Meteorological Agency) (Figure 7). It is also worth noting from Figure 7 that the JMA and ECMWF forecast skill scores without the targeted data were similar to those of NCEP with the targeted data, for this sample. *Weissmann et al. (2011a)* attributed the lower track errors without dropwindsondes in the latter two models, to a more extensive use of satellite data, and to both these centers using 4d-Var instead of 3d-Var. Another evaluation by *Chou et al. (2010)* showed that the mean 1–5 day track forecast error is reduced by 10–20% for DOTSTAR and T-PARC cases. A major conclusion of their study, consistent with *Weissmann et al.* (*2011a)*, is that the benefit of the targeted observations to the track forecast depends highly on the type of model and data assimilation system.

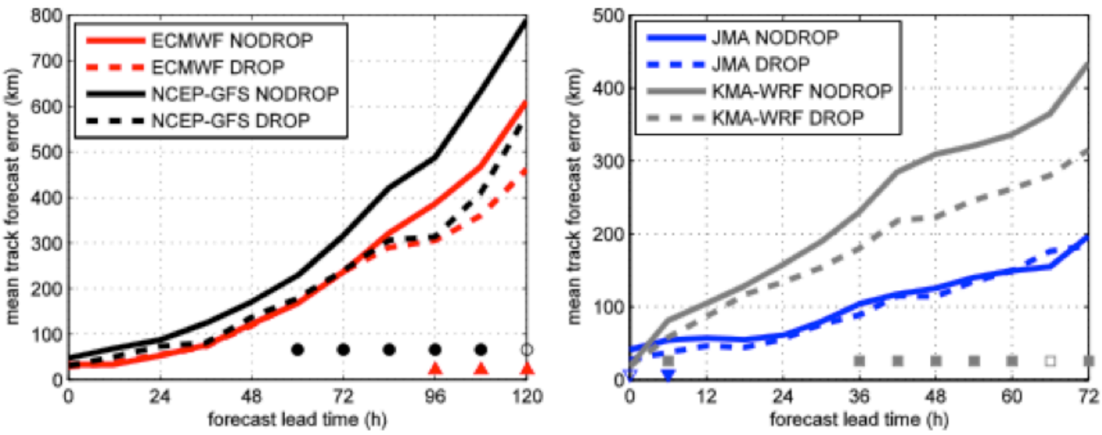

Figure 7 - Tropical cyclone track forecast errors during the Summer T-PARC period for four assimilation-forecast systems. The solid (dashed) lines represent parallel analysis-forecast cycles excluding (including) T-PARC dropwindsonde data. Empty (filled) markers indicate times where the mean differences are significant at a 90% (95%) confidence level using a Student's t-test. Note that the sample size is different for the panels. (Adapted from Figures 5 and 6 in *Weissmann et al. 2011)*

T-PARC also offered the opportunity to sample approximately 2500 high-quality Doppler Wind Lidar (DWL) profiles from the DLR Falcon aircraft targeted in sensitive areas (*Weissmann et al. 2011b*). Using OSEs, *Weissmann et al. (2011b)* found that the ECMWF 1-5 day track forecasts of Typhoon Sinlaku were improved by up to 50 km on average, comparable to the data impact from dropwindsondes, but less impact was found in NOGAPS which uses a bogus vortex. Adjoint-based observation impact in ECMWF and NOGAPS confirmed the positive influence of DWL observations.

Targeted observations may also benefit forecasts remote from the target regions. The ECMWF forecasts in the mid-latitudes downstream were improved due to the assimilation of T-PARC dropwindsonde data, and this was attributed more to the improved track forecasts than the data collected in sensitive areas with the verification region situated in the mid-latitudes (*Weissmann et al. 2011a*). *Aberson (2011)* demonstrated that GFS forecasts of tropical cyclone track were improved globally by the cumulative assimilation of Atlantic and western North Pacific dropwindsondes, even in basins in which no aircraft missions took place (such as the eastern

North Pacific). The results suggest that the global longwave pattern is modified by the targeted observations.

A concern raised by *Aberson (2008)* and *Weissmann et al. (2011a)* is that the assimilation of dropwindsonde data in the inner core of tropical cyclones can occasionally lead to degraded forecasts. While this is primarily a data assimilation issue in regions where the observation may be substantially different from the first guess and where the dropwindsonde drift may not be properly accounted for, it is relevant to targeting, particularly as sensitive areas often correspond to the TC inner-core (*Majumdar et al. 2006, Wu et al. 2009*) and that data are often collected in this region in order to improve predictions of structure and intensity change (*Rogers et al. 2006*).

A few investigations have been performed to investigate the potential efficacy of assimilating subsets of aircraft observations in specific target regions. *Yamaguchi et al. (2009)* demonstrated that the assimilation of a subset of DOTSTAR observations in a region deemed sensitive by singular vectors contributed to the majority of the forecast improvement in that case. *Aberson et al. (2010)* illustrated the potential for observations in sensitive areas to improve the track forecasts of Atlantic TCs, although they cautioned that the handling of the observations by the data assimilation method is central to any conclusions. Finally, *Harnisch and Weissmann (2010)* demonstrated that the assimilation of T-PARC observations in a circle of radius ~500 km from the storm improved the ECMWF track forecast more than the assimilation of observations exclusively in the TC inner-core or in areas remote from the TC (that were chosen based on a consensus of techniques while constrained by aircraft range limitations).

Outside the few papers reviewed here, a large body of literature exists on the sensitivity of tropical cyclone forecasts to initial conditions and observations. Many of these articles have been published in a Special Collection on Targeted Observations, Data Assimilation and Tropical Cyclone Predictability in *Mon. Wea. Rev.*, beginning in 2009[3].

Extending beyond the limited spatial and temporal density that is realizable with aircraft data, initial studies have also been conducted on the influence of assimilating extra satellite data on TC track forecasts. The positive influence of assimilating additional rapid-scan atmospheric motion vectors (AMVs) on NOGAPS forecasts of Hurricane Katrina (2005) was demonstrated by *Langland et al. (2009).* The inclusion of rapid-scan AMVs improved the forecasts of Katrina's landfall position by an average of 12%, compared against a control cycle that included G-IV dropwindsonde data. Following this initial result, AMV datasets at hourly intervals plus rapid-scan imagery at 15- and 4-minute intervals were specially processed during the summer phase of T-PARC. The mean reduction in 3-5 day NOGAPS track forecast errors due to the assimilation of the hourly AMVs was 6-10% over all tropical cyclone cases during the 2-month period, with a slight further improvement from the addition of rapid-scan AMVs (*Berger et al. 2011*, an example of which is given in Figure 6c for Typhoon Sinlaku).

Further numerical experiments on targeting for TC forecasts with satellite data have recently been completed at ECMWF. During the 2008 typhoon season, OSEs used to evaluate the use of extra satellite data in Singular Vector target regions (Figure 8a) suggested a consistent positive impact on the ECMWF track forecasts due to the homogeneous data coverage and diversity in data types. However, the dropwindsondes provided more extreme impacts – beneficial or detrimental – on the typhoon track forecasts. Evaluations using adjoint-based forecast sensitivity to observations suggest that most dropwindsondes provided a positive impact (Figure 8b).

[3] http://journals.ametsoc.org/page/Cyclone_Predictability

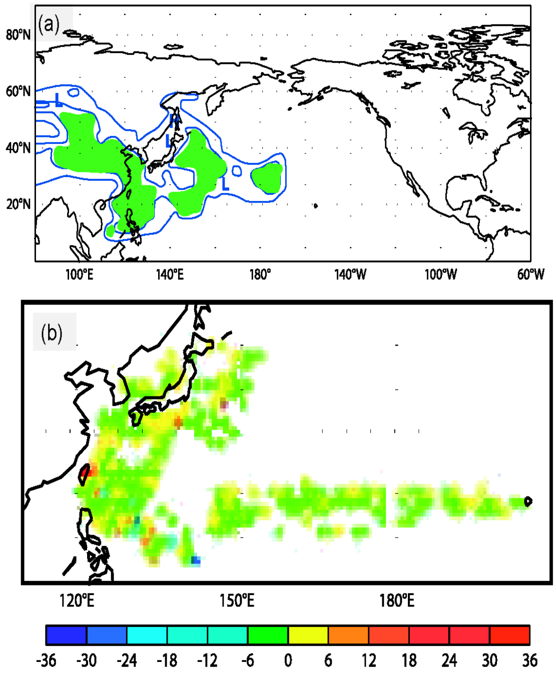

Figure 8 - (a) ECMWF Singular Vector sensitive areas for Typhoon Sinlaku, at 1200 UTC 10 September 2008. (b) Adjoint-based forecast sensitivity to each dropwindsonde observation collected during the summer phase of T-PARC in August-September 2008. Green represents a positive impact, red a negative impact. (From *Carla Cardinali*)

Currently, numerical experiments that involve mesoscale data assimilation in tropical cyclones are being conducted with the NCAR WRF-DART system (*Anderson et al. 2009*), with a focus on optimizing the combination of high-resolution satellite datasets to improve analyses and forecasts of tropical cyclone structure and intensity. It remains an open question whether objective tropical cyclone targeting principles based on global data assimilation and forecast systems will need to be adjusted for mesoscale systems.

Considering other aspects of tropical weather, the extra rawinsondes launched during AMMA yielded a significant impact on the ECMWF analysis of the low-level temperature over the Sahel, and on the structure of the African Easterly Jet, up to 24 h (*Agusti-Panareda et al. 2010*). In the French NWP system ARPEGE, the rawinsonde observations were also found to improve the representation of the African Easterly Jet and precipitation estimates, and forecast scores including 2-3 day forecasts over Europe (*Faccani et al. 2009*).

(iii) Adaptive selection of routinely available data

Several important evaluations of the potential impact of targeted observations have been conducted independently of field campaigns. In a 3-part series, the impact of removing routinely available observations over the Pacific and Atlantic oceans on the errors of 2-day ECMWF forecasts over North America and Europe respectively was investigated. First, *Kelly et al. (2007)* conducted OSEs in which all observations from the North Pacific or North Atlantic basins were systematically removed, for 183 cases over winter and summer periods. Their main conclusion was that the observational data improved 2-day ECMWF forecasts on average over downstream land areas, with the impact over North America from observations over the Pacific exceeding that over Europe from Atlantic observations. The impact of the Pacific observations on forecasts over Europe was small, but the results were found to be dependent on the data assimilation scheme. For the same group of cases, *Buizza et al. (2007)* explored the value of observations taken in Singular Vector (SV) target areas over the ocean on short-range forecasts downstream over land. They found that the observations taken in SV target areas were on average more valuable than those taken in randomly selected areas. They also concluded that the value of targeted observations was dependent on the region, the season, and the baseline observing system. For the winter sample, the 2-day forecast errors were on average reduced by 4% (2%) by adding SV-targeted observations over the Pacific (Atlantic). In the third paper of the series, *Cardinali et al. (2007)* investigated the influence of weather regimes in targeting observations over the North Atlantic. Their main conclusion was that the removal of observations in SV-sensitive regions (optimized on the 2-day forecast over Europe) degraded the skill of a forecast more so than observations selected randomly, particularly during periods of tropical cyclone activity including extratropical transition. The maximum averaged degradation of 500 hPa geopotential height downstream due to removing observations in SV-sensitive areas was ~13%. Results such as these motivated components of the summer T-PARC campaign.

A series of studies has also been performed using adjoint-based observation impact, focusing on specific observation types. In the initial study by *Langland and Baker (2004*), the largest error reductions for 1-day forecasts were generally found to be from rawinsondes, satellite wind data, commercial aircraft data and ATOVS temperature retrievals, with the impact of all observations below 500 hPa being larger (60%) than that above 500 hPa (40%). A significant positive correlation was also found to exist between observation impact and cloud cover at observation locations. An adjoint-based intercomparison study using a "baseline" set of observations in three forecast systems (Environment Canada, NOGAPS, NASA GEOS-5), conducted under the auspices of the THORPEX DAOS working group, was recently published by *Gelaro et al. (2010*). Even though the models and assimilation schemes were very different in the respective systems, the global impacts of the major observation types on 24 h forecast errors were found to be similar in each system, although regional details differed. The largest forecast error reductions were found to be due to the assimilation of satellite radiances, geostationary satellite winds, rawinsondes and commercial aircraft, consistent with the earlier findings of *Langland and Baker (2004)*. A key conclusion, consistent across the different forecasting systems, was that only a small majority (50-54%) of the total number of observations assimilated improved the forecast. Most of the improvement resulted from a large number of observations that had relatively small impacts per observation. This finding motivates the suggestion that additional effort is necessary to optimize the use of satellite data, and that regional targeting of flow regimes with lower predictability on a continuous basis for periods of days to weeks may be more effective than occasional, limited-area sampling if a global verification norm is used. In a comparison between the adjoint and OSE approaches, which possess fundamental differences, their respective estimates of the impact of observing systems in reducing 24 h forecast error was found to be consistent particularly over the globe and extratropics (*Gelaro and Zhu, 2009*)

The trade-off between impact and volume of satellite data, with denser data in SV-sensitive areas (occupying 15% of the hemisphere) and thinned data in non-sensitive areas has been evaluated *(Bauer et al. 2011).* OSEs were used to evaluate the impact. In comparison to a 'control' ECMWF analysis-forecast cycle that comprised global satellite observations at the operational setting of 1.25° resolution, the influence of adding further data at 0.625° resolution in sensitive areas selected by the ECMWF singular vectors was evaluated for two seasons in the southern hemisphere. The forecasts of 500 hPa height were best for the experiment in which the increased data were assimilated in SV areas computed for each analysis, as opposed to randomly distributed areas or climatological SV areas. The forecast impact was larger in the southern hemisphere summer than in the winter.

(iv) Mesoscale weather

To date, observations have mostly been targeted at synoptic-scale systems aimed at improving global model forecasts. Considerable scope exists for targeting on the mesoscale, to improve forecasts of high-impact systems such as squall lines, bands of snow, and convective thunderstorms, although this has not been performed yet. An OSE approach was employed by *Benjamin et al. (2010)* to consider the effects of assimilating observational data in a 1 h assimilation cycle for 3-12 h Rapid Update Cycle (RUC) forecasts. The observation systems explored include rawinsondes, aircraft, aviation routine weather report (METAR), mesonet, wind profilers, winds from ground-based Doppler radar, and satellite AMVs. The main conclusion was that aircraft data followed by rawinsondes produced the largest reductions in RUC forecast errors over the United States, with all other observation types playing a necessary role. To date, no targeting strategies have been used with this observational network.

(v) Analysis uncertainty

Recently, areas in which the current global observing system has deficiencies have been identified, via quantitative assessments of analysis uncertainty in global models. For example, *Langland et al. (2008)* found regional patterns of uncertainty in upper-air temperature analyses, which were related to areas in which *in situ* data were relatively sparse, and in which instabilities are present. *Wei et al. (2010)* explored analyses from several operational centers. In agreement with *Langland et al. (2008*), the uncertainty was generally found to be largest over oceanic regions where conventional observations were sparse, such as the storm tracks over the Pacific Ocean and in the southern hemisphere. Different systematic errors and biases were also found in the respective models' analyses. It was suggested by *Wei et al. (2010)* that the removal of systematic errors is first necessary prior to providing an improved estimate of analysis error variance over all centers. These assessments of analysis error offer suggestions on where the deficiencies of the global observational network could be reduced via targeting. It should be cautioned, however, that the precursors to atmospheric instability, including key analysis errors and SV structures, may not be directly observable by operational observations (*Lupu and Gauthier 2010*). The quality of the observations may not be adequate for the small signal to be detected, and the estimation of the observational quality necessary is an active research topic.

5. CONCLUSIONS

Moving into the second half of the THORPEX decade, conclusions on the effectiveness of targeted observations have been mixed to date. This is perhaps not surprising, given the dependence of the results on the flow regime, observations available for targeting, the assimilation-forecast system, and the method of verification. The conclusions reported here are based on a synthesis by the THORPEX Data Assimilation and Observing Systems Working Group of peer-reviewed evaluation studies.

Observations have primarily been targeted in an attempt to improve short-range (1-3 day) forecasts of extratropical and tropical weather. In the *extratropics*, the value of targeted data has been found to be positive but small on average when evaluated over continental or hemispheric areas. For example, OSEs conducted over the A-TReC period found very little impact from targeted observations, which is not surprising given that the original forecasts without targeted data were generally accurate. In contrast, the ongoing WSR programme has found that targeting results in some improvement in 2-3 day forecasts over North America, although a full quantitative evaluation remains to be prepared. Results from smaller field campaigns have illustrated the promise of targeted observations in the mid-latitudes, for a limited number of cases.

For forecasts of the track of *tropical cyclones* (TCs), targeted observations have mostly proven to be beneficial statistically. The benefit to society is more straightforward to define than for mid-latitude weather, given the severity of the impact of a TC as it makes landfall over a populated coastline, and the ability to verify the track easily. However, in common with the extratropics, the quantitative benefit differs from model to model, and the range of aircraft is again a limiting constraint given that the sensitive areas are often of synoptic scale. Initial evaluations on the benefits of assimilating targeted (or enhanced) satellite data on TC forecasts are encouraging, although still in their infancy. It has recently been demonstrated that observations targeted for TCs can also improve the skill of forecasts in distant regions. The mechanisms behind how TC forecasts are improved, and can be improved further, by targeted observations are being widely investigated.

The impact of assimilating observations using *more general metrics* has been performed using OSEs and adjoint-based evaluation methods. These evaluations confirm the greater relative value of targeted observations compared with observations selected randomly or in areas guided by climatology. At the same time, adjoint-based evaluations show that only a relatively small majority (50-54%) of the observations (targeted or otherwise) specifically act to improve the forecast, and that large numbers of observations (such as satellite radiances and winds) with relatively small individual impact provide a larger cumulative benefit than small numbers of individual observations (such as dropwindsondes) with large individual impact. As for the event-driven cases, the impact of any group of observations on a particular forecast depends on (a) the errors that are present in the prior forecast, (b) the errors in the observations, and (c) the data assimilation and forecast methods.

Several mathematical *sensitivity methods* have been used to provide guidance for targeted observations. In the extratropics, the consensus is that observations sampled in dynamically sensitive areas have more value for targeting than observations deployed randomly. Advancing beyond sensitive area prediction, methods that account for the effects of a data assimilation scheme have also demonstrated the ability to quantitatively predict the reduction in forecast error variance prior to deployment, thereby providing the ability to discriminate between potentially good cases for targeting and null cases. For tropical cyclones, the average quantitative benefit to forecasts due to sampling in sensitive areas has yet to be determined. A sampling strategy as simple as observing uniformly around the TC has been shown to be effective, with most models exhibiting an improvement. In general, for both the extratropics and tropics, it is believed that while methods for defining sensitive (target) areas require advancement, they do not appear to be the first-order problem in maximizing the value of targeted observations. A more acute problem is that the deployable observations usually do not cover the entirety of the sensitive area, limiting the potential for a large systematic impact on the forecast. Finally, the characteristics of the guidance produced by different methods possess some similarities, but they can also differ significantly in some cases.

To place these results in perspective, it is worth emphasizing that the science behind synoptic-scale NWP is relatively mature. Forecast skill has been improving by roughly a day per decade due to improvements in resolution, treatment of observations, and model physics *(Simmons and Hollingsworth 2002).* This is a larger average improvement than seen in most of the experiments reviewed in this paper, albeit with different verification metrics. Associated with this general increase in skill, the average marginal impact of individual observing systems is decreasing; a single observation type such as AMSU-A radiances or the global rawinsonde network, now only improves skill by 6-12 hours (*WMO 2008*). Emphasis in these conclusions has therefore been given to recent published studies that use state-of-the-art data assimilation systems and models.

6. RECOMMENDATIONS

The conclusions suggest that the average impact of targeted data on synoptic-scale forecasts will normally be quite small, given the ongoing improvement to operational model analyses using the routine observational network. Field campaigns and studies aimed at improving the use of the global observational network should be designed with this in mind. The marginal cost of using more data from an existing component of the global observational network can be much lower than the total cost of that observing system or the cost of deploying new supplemental observations. At the same time, this marginal cost may not require such a rigorous justification, and therefore a limited number of important case studies demonstrating a clear benefit may suffice. Examples of existing operational resources that may be further optimized include aircraft equipped with dropwindsondes that can be used opportunistically; the EUCOS DTS which targets extra observations from existing systems such as AMDAR and radiosondes; and especially satellite data such as radiances or AMVs that can be adaptively targeted, thinned or processed. Given that the relative impact of satellite radiance data compared with all other routine observation types has increased dramatically over the past decade, even in the northern hemisphere, there is further scope for targeting of radiances, either via increasing the density in certain areas or by varying the selection of channels. It is also recommended that regional and systematic targeting on a continuous basis over days to weeks, especially during low predictability regimes and in areas with unusually high analysis uncertainty, is explored with satellite data. Unlike many situations in which aircraft are deployed, satellite data can be targeted over the full extent of sensitive areas selected using different techniques. In addition to increasing the number of satellite observations, it may be necessary to use higher quality observations in strategic areas. New observing platforms that may be used for targeting include a space-based lidar in which the observation frequency can be varied, and high-altitude, long-endurance unmanned aircraft that are able to sample broad areas (*MacDonald 2005*). The justification of significant expenditure requires statistically significant results on the expected value of these additional observations, via well-designed OSEs or OSSEs and, if possible, a rigorous cost-benefit analysis.

In this broad context, ten research priorities are recommended:

i. Assess the impact of targeted observations with more user-focused measures of the value of forecast improvements to society. The question of how to verify the value of targeted data in the mid-latitudes has not been adequately addressed. Results to date use physical fields such as winds, surface pressure, and geopotential height, but not precipitation or other user-focused metrics. Other verification aspects also require assessment: for example, should evaluations be conducted in large stationary regions over part of a continent, or varying with the weather, focused on a local area where the impact on society is highest? Given that the average impact of large observing systems on NWP is typically small, it is difficult to demonstrate average improvements due to relatively few targeted observations. There is a need to develop new measures that emphasize less common, high-impact events but remain statistically meaningful.

ii. Improve understanding and quantification of the socio-economic value of observations that may be targeted through a particular process. To achieve this, collaborations with the socio-economic impacts community are necessary. Are the benefits of establishing observational networks on a more adaptive basis sufficiently important to NWP and society to justify the added expense?

iii. Improve the theoretical basis for quantitatively predicting and evaluating the forecast error variance reduction due to any potential deployment of targeted observations. It is unsurprising that targeted observations add little value when the forecast is already accurate. Given the large number of cases in which this occurs, methods to identify *a priori* cases in which such low impacts are expected should result in the more effective use of observations. Related methods to select verification regions in which forecast errors are likely to be large, for example using ensemble forecasts, require improvement and testing. Studies to diagnose and understand the predictability, and characteristics of forecast error propagation and growth in the presence of evolving observing systems and data assimilation would also be helpful. Specifically, the low predictability regimes in which forecasts are most likely to ‘bust’, and therefore in targeted observations are expected to yield the highest benefit, require investigation.

iv. Given that we depend on the cumulative effect from many observations to have a positive average influence on the forecasts, explore the utility of broader-scale, regime-based sampling (e.g. adaptive use of satellite data) to ameliorate the sampling issue and increase the influence of targeted observations on both short- and extended-range forecasts.

v. Assess the role of the data assimilation schemes, including their treatment of routinely available observations versus targeted observations, and their use of fully flow-dependent spatial structure functions that control the spreading of the influence of the observations. Field campaigns and other exercises on targeted observations require consideration of the data assimilation scheme in their planning.

vi. The ongoing move away from deterministic forecasts toward probabilistic forecasts suggests that our ensemble forecast systems should accurately reflect reductions in initial condition uncertainty introduced through targeted observations, and the subsequent impact of these reductions on forecast uncertainty. This may be applied directly to iii above.

vii. Expand beyond the few studies that have so far investigated the use of targeted observations for medium- and long-range forecasts. Also continue to explore the utility of targeting in the ocean; for example, for adaptive sampling using autonomous underwater vehicles (AUVs).

viii. There is scope for targeting on the mesoscale with mobile observational assets, but this is still in its infancy and requires further development. Potential examples include targeting the mobile mesonet for forecasts of severe weather, and airborne Doppler radar and unmanned aircraft for forecasts of tropical cyclone structure and intensity. It remains unknown whether objective techniques designed for synoptic-scale targeting are applicable for mesoscale systems, or whether they require adjustment.

ix. Continue to evaluate regular field programmes in multiple NWP systems. These evaluations will help justify the benefit of the programmes such as WSR and TC surveillance, and also offer advice on how to derive further gain as observing systems, models and data assimilation all evolve.

x. For future field campaigns that are primarily oriented at investigating specific processes, continue to incorporate targeting strategies.

In closing, considerable progress has been made toward the goal of supplementing the routine global observing network with targeted observations, with enhanced international cooperation fostered through THORPEX. However, many open and fundamental questions remain, most notably the overall cost-effectiveness and benefits to society of creating a network on a more adaptive basis. The improved use of routine and new observations, the continued advancement of NWP and data assimilation, and algorithms that optimize the sampling of large volumes of satellite observations are expected to advance the field further. Observations may be targeted for a wider variety of situations than the synoptic-scale cases discussed in this article. The continued collaborative evaluation of existing and new strategies is necessary to provide the greatest benefit of the evolving observational network to society.

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ANNEX

Table A1 - Summary of field campaigns that included or may include a targeting component

Pre-THORPEX / Independent Field Campaigns					
Experiment	**Period and Sample**	**Cases of Interest**	**Techniques used**	**Targeted Observations**	**Main Reference**
NOAA Synoptic Flow	1982-1996. 21 experiments	Tropical cyclone track in Atlantic Basin	None	NOAA P-3 aircraft	Burpee et al. (1996)
NOAA Hurricane Synoptic Surveillance	1997 – pres. 214 cases up to and including 2010	12-60 h forecasts of tropical cyclone track, mostly in Atlantic Basin	Subjective; Ensemble variance of 850-200 hPa layer mean wind	NOAA G-IV and USAF C-130 aircraft over Atlantic Ocean or Gulf of Mexico. 20-30 drops per flight. Occasionally in eastern or central Pacific	Aberson (2010)
Fronts and Atlantic Storm Track Experiment (FASTEX)	Jan-Feb 1997. 19 intensive observing periods	Life cycle of mid-latitude cyclones. Targeting 1-3 day forecasts	Adjoint, Singular Vectors, Ensemble Transform	Aircraft based in Ireland and North America, ships, soundings, surface and satellite	Snyder (1996), Joly et al. (1999)
North Pacific Experiment (NORPEX-98)	Jan-Feb 1998. 27 days; 38 missions	1-3 day forecasts of Pacific winter storms over Canada, United States & Mexico	Ensemble Transform; Singular Vectors	~700 dropwindsondes. Winds from geostationary satellites	Langland et al. (1999)
California Land-Falling Jets Experiment (CALJET)	Jan-Mar 1998	0-12 h forecasts of winter storms	Ensemble Transform; Singular Vectors	NOAA P-3 aircraft	Ralph et al. (1999)
NOAA Winter Storm Reconnaissance (WSR)	Jan-Mar, 1999-pres. 20-30 cases per year	1-5 day forecasts of winter weather over North America	Ensemble Transform Kalman Filter (ETKF)	NOAA G-IV aircraft and USAF C-130s based on Alaska and Hawaii. Since 2009, G-IV stationed in Japan	Szunyogh et al. (2000; 2002)
Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSTAR)	Annual, 2003 – present. 51 cases up to 2010	1-4 day forecasts of tropical cyclone track in the western north Pacific basin	Subjective sampling & ensemble variance, ETKF, and ADSSV	ASTRA aircraft stationed in Taiwan. 13-20 dropwindsondes per mission	Wu et al. (2005)

Field Campaigns related to THORPEX					
Experiment	**Period and Sample**	**Cases of Interest**	**Techniques used**	**Targeted Observations**	**Main Reference**
Atlantic-THORPEX Regional Campaign (A-TReC)	Oct-Dec 2003. 32 events	1-3 day forecasts of high-impact weather over Europe	Total energy and Hessian Singular Vectors, Adjoint sensitivity, ETKF	Dropwindsondes from 4 aircraft; special rawinsondes (Europe, Greenland, Canada, ships), drifting buoys, commercial aircraft (AMDAR) activated over specific areas, airborne Doppler Wind Lidar (DWL), rapid-scan atmospheric motion vectors (AMVs) from geostationary satellites	Rabier et al. (2008)
AMMA (THORPEX component)	August 2006	1-3 day forecasts of African weather, including easterly waves	Adjoint sensitivity, ETKF	Rawinsondes over Africa. Dropwindsondes launched from driftsonde gondolas for validation	Agusti-Panareda et al. (2010)

Convective and Orographically Induced Precipitation Study (COPS) / European THORPEX Regional Campaign (E-TReC)	Jun – Aug 2007	24-36 h forecasts of warm season precipitation events over Europe	Adjoint sensitivity, Singular Vectors and ETKF	DWL, water vapor lidar, dropwindsondes from aircraft. EUCOS rawinsondes and enhanced AMDAR over central and southern Europe	Wulfmeyer et al. (2008)
GFDEx	Feb – Mar 2007. 4 cases	1-2 day forecasts over northwest Europe	Singular Vectors, ETKF	Additional rawinsondes, dropwindsondes from aircraft around southern Greenland and Iceland	Renfrew et al. (2008)
Eurorisk-PREVIEW	Feb – Dec 2008. 54 targeted events	1-3 day forecasts of high-impact weather over Europe	Singular Vectors, ETKF	1402 Land Stations. 226 E-ASAP. 224 E-AMDAR	Prates et al. (2009)
International Polar Year / THORPEX	Spring 2008	1-2 day forecasts over Scandinavia, particularly polar lows	Singular Vectors, ETKF	Dropwindsondes released from aircraft	Irvine et al. (2010)
T-PARC (Summer)	Aug-Sep 2008	1-4 day forecasts of tropical cyclones and their extratropical transition in the western North Pacific; a few non-tropical cyclone cases	Singular Vectors, adjoint, ETKF, ADSSV, ensemble variance, ensemble sensitivity	>1500 dropwindsondes from 4 aircraft. DWL and water vapor lidar. Rawinsondes, observations on research vessels, driftsondes, rapid-scan AMVs from geostationary satellite	Elsberry and Harr (2008)
T-PARC (Winter)	Jan-Mar 2009	1-5 day forecasts of winter storms over North America	ETKF	Dropwindsondes from NOAA G-IV and USAF C-130 aircraft; extra rawinsondes over Russia; AMDAR.	
DTS-MEDEX-2008 (coincided with Eurorisk-PREVIEW)	Sep – Dec 2008	High-impact weather over Mediterranean	Singular Vectors, ETKF	AMDAR, ~300 additional rawinsondes in Europe.	Prates et al. (2009)
DTS-MEDEX-2009	Oct – Dec 2009. 132 cases	High-impact weather over Mediterranean	Singular Vectors, ETKF, Kalman Filter Sensitivity	484 additional rawinsondes in Europe and Algeria; AMDAR	Jansa et al. (2011)
Concordiasi	2010	Validate use of satellite sounder data over Antarctic region	Singular Vectors	640 dropwindsondes launched from 13 driftsondes, only 25% being targeted. Single level data from 19 stratospheric balloons	Rabier et al. (2010)
DIAMET (DIAbatic influence on Mesoscale structures in ExTratropical storms)	2011-2	At the frontier with mesoscale adaptive deployment of observations but not truly targeting	Unknown as yet	British research aircrafts (BAE146 & B488)	http://www.cas.manchester.ac.uk/resprojects/diamet/
Halo-THORPEX and T-NAWDEX	To be confirmed	A variety of high-impact weather	Unknown as yet	Research aircraft HALO	http://www.pandowae.de/
Hydrological Cycle in the Mediterranean Experiment (HYMEX)	2012-4	Droughts and heatwaves on seasonal scale; heavy precipitation on mesoscale.	Both adjoint-based and ensemble-based techniques are planned	American and European research aircrafts, rawinsondes, AMDAR, drifting BL balloons	International Implementation Plan (http://www.hymex.org)

Table A2 - Summary of results from evaluations of field campaigns and other studies, in which a targeted observing strategy was used. Only those experiments possessing at least 10 independent cases are included

Experiment		Main References
NOAA Synoptic Flow	Mean errors in 12-60 h track forecasts in NOAA models reduced by 16-30%. Sample of 18 experiments in 11 Atlantic tropical cyclones	Burpee et al. (1996)
NOAA Hurricane Synoptic Surveillance	10-15% average improvement in NCEP GFS track forecasts through to 60 h. Negligible improvements beyond 72 h. Minimal impact on GFDL forecasts. Sample of 176 missions, 1997-2006	Aberson (2010)
DOTSTAR	>14% average improvement in NCEP GFS, NOGAPS and JMA 1-3 day forecast track errors (10 cases in 2004). 10-20% average improvement in NCEP GFS 1-5 day track forecasts, with 60% of all cases improved (42 cases in 2003-9). Minor improvements and degradations in ECMWF	Wu et al. (2007); Chou et al. (2011)
FASTEX	Positive impact over Atlantic and Western Europe in short range (2 days or less). Around 10-15% for most modeling and assimilation systems	Several papers, summarized by Langland (2005)
NORPEX-98	Improved 2-day NOGAPS forecasts by 10% on average. Relatively small improvement in ECMWF	Langland et al. (1999)
WSR	RMS surface pressure errors during 1999 and 2000 reduced by 10-25% in low-resolution NCEP GFS. Approximately 70% of cases have been improved on average through the past decade of WSR programmes	Szunyogh et al. (2000; 2002)
A-TReC	Small positive impact over large domains. Overall improvement in 32% of 38 forecasts using UKMO system. In ECMWF, forecasts of mean sea level pressure were improved (by at least 10%) in 24% of all cases. NOGAPS observation sensitivity showed the highest impact per observation to targeted dropwindsondes	Langland (2005), Fourrié et al. (2006), Petersen & Thorpe (2007), Rabier et al. (2008)
AMMA-THORPEX	Large impact on analysis fields over Africa, and improvement of the precipitation in the first day of the forecast over central Sahel (with local degradation where the model is biased and observations are not many). Positive downstream impact over Europe at the 2-3 day range	Faccani et al. (2009), Agusti-Panareda et al. (2010)
ECMWF studies	Removing SV-targeted observations over Pacific (Atlantic) reduces 2-day forecast errors of 500 hPa Z by 4.0% (2.0%). Increasing the radiance data density in SV-sensitive areas twice-daily improved forecasts at all levels, for forecasts up to 3-4 days in the southern hemisphere summer	Buizza et al. (2007), Bauer et al. (2011)
T-PARC (Summer)	20-40% improvement to NCEP GFS and Korean Meteorological Agency WRF track forecasts. Modest improvements to forecasts up to 3 days in ECMWF and JMA	Weissmann et al. (2011)
T-PARC (Winter)	75% of the 52 forecast cases of 1-5 days were improved. Magnitude of improvement to be determined	Song, personal communication
Concordiasi	Reduction of forecast error from dropsondes of the same order as that from Antarctica radiosondes	Rabier, personal communication

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1. International Core Steering Committee for THORPEX, Third Session, 16-17 December 2003, Montreal, Canada. Final Report. WMO/TD-No. 1217, WWRP/THORPEX No. 1.

2. M.A. Shapiro, A.J. Thorpe, 2004: THORPEX International Science Plan Version 3. WMO/TD-No.1246, WWRP/THORPEX No. 2.

3. International Core Steering Committee for THORPEX. Fourth Session 2-3 December 2004, Montreal, Canada. Final Report. WMO/TD-No. 1257, WWRP/THORPEX No. 3.

4. THORPEX International Research Implementation Plan Version 1. WMO/TD-No. 1258, WWRP/THORPEX No. 4.

5. First Workshop on the THORPEX Interactive Grand Global Ensemble (TIGGE), Reading, United Kingdom, 1-3 March 2005, WMO/TD-No. 1273, WWRP/THORPEX No.5.

6. Symposium Proceedings - The First THORPEX International Science Symposium, 6-10 December 2004, Montreal, Canada, WMO/TD-No. 1237 WWRP/THORPEX No. 6.

7. Symposium Proceedings – The Second THORPEX International Science Symposium, 4-8 December 2006, Landshut, Bavaria, Germany, WMO/TD-No. 1355, WWRP/THORPEX No. 7.

8. International Core Steering Committee for THORPEX. Sixth Session 25-27 April 2007, Geneva, Switzerland. Final Report. WMO/TD-No. 1389, WWRP/THORPEX No. 8.

9. The YOTC Science Plan – A Joint WCRP-WWRP/THORPEX International Initiative. WMO/TD-No. 1452, WCRP-130, WWRP/THORPEX No. 9.

10. African Science Plan – Version 1. WMO/TD-No. 1460, WWRP/THORPEX No. 10.

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12. International Core Steering Committee for THORPEX. Seventh Session 18-20 November 2008, Geneva, Switzerland. Final Report. WMO/TD-No. 1495, WWRP/THORPEX No. 12.

13. International Core Steering Committee for THORPEX. Eighth Session 2-4 November 2009, Offenbach, Germany. Final Report. WMO/TD-No. 1522, WWRP/THORPEX No. 13.

14. Weather Research in Europe – A THORPEX European Plan, Version 3.1. WMO/TD-No. 1531, WWRP/THORPEX No. 14.

15. Targeted Observations for Improving Numerical Weather Prediction: An Overview. WWRP/THORPEX No. 15.