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Are current sensitivity products sufficiently informative in targeting campaigns? A DTS-MEDEX-2009 case study

L. Garcies* and V. Homar

Departament de Fisica, Universitat de les Illes Balears, Palma de Mallorca, Spain

*Correspondence to: L. Garcies. Departament de Fisica, Universitat de les Illes Balears, Carretera de Valldemossa, km. 7.5, 07122 Palma de Mallorca, Spain. E-mail: lorena.garcies@uib.es

The DTS-MEDEX-2009 campaign was a field experiment in which extra observations were adaptively deployed to improve the short-range forecast of Mediterranean high-impact weather (HIW) during autumn 2009. For the DTS-MEDEX-2009 cases, five different sensitivity analysis techniques were carried out to provide targeting guidance: singular vectors (SV) from the ECMWF; ensemble transform Kalman filter (ETKF) and Kalman filter sensitivity (KFS) from Météo France; and ensemble and adjoint sensitivities from the University of the Balearic Islands. However, the value of the targeting guidance provided by such a variety of sensitivity products has never been assessed for a Mediterranean HIW event. Since radiosonde and AMDAR profiles were the only observational means available during the DTS-MEDEX targeting campaign, this study tests the ability of each sensitivity product in identifying the region where a plausible sounding leads to a greater impact on the forecast of a potential high-impact cyclone over southern Italy on 5 December 2009. All targetable radio-sounding sites are also tested and a severe-weather meteorologist is used as a confronting reference. The verification testbed comprehends single sounding experiments and multiple sounding strategies by using the WRF Data Assimilation system. Single sounding tests reveal that sensitivity products fail to recognize the best location for a single observation since most of the soundings added over operational radio-sounding stations have a larger influence on intense cyclone forecast than the points highlighted by the objective sensitivity calculation methods. Additionally, it is shown that human-based decisions, after evaluating available sensitivity information, are not optimal, either in single or in multiple sounding strategies.

Key Words: sensitivity analysis; Mediterranean high-impact weather; targeting; MEDEX

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1. Introduction

The starting point for any numerical weather prediction is given by data assimilation procedures that estimate the state of the atmosphere by considering all available observations. Nevertheless, weather observations are neither large enough in number nor homogeneous in their distribution to unequivocally resolve all degrees of freedom of the system. Thompson (1957) had already stressed the need to increase the density of reporting stations over regions with incomplete data coverage. The routine observing network is riddled with data voids due to economic, technical and geographical concerns. Thus the question of improving atmospheric observation, not only in number but also in type and quality, is not easily solved and becomes an economic problem of national and international proportions.

The optimization of the Global Observing System (GOS) has now developed into a mature activity for providing new observing systems as well as guidance to policymakers on plans to design optimal observing strategies. Supplementary observations to the current GOS can be collected regarding the specific requirements of the flow of the day in order to improve atmospheric analyses for a particular weather event, and thereby reduce forecast uncertainty. Since resources are limited and targeting campaigns notably expensive, forecast cases and extra targeted observations need to be carefully selected. Forecasts of events with a potentially large societal impact and with significant uncertainty in the forecast are prime candidates for selection because returns from the observational investment are potentially larger. Thus targeted observations are expected to minimize the ratio between the cost of the observation deployment and the benefit derived from it.

The first experiment that regularly deployed adaptive observations was conducted by NOAA's Hurricane Research Division in the North Atlantic basin during 1982–1996 (Burpee *et al.*, 1996). Since then, many field experiments have followed, including, for example: in 1997 the Fronts and Atlantic Storm-Track Experiments (FASTEX; Joly *et al.*, 1999); in 1998 the North-Pacific Experiment (NORPEX; Langland *et al.*, 1999); from 1999 to the present the NOAA's Winter Storm Reconnaissance programme (WSR; Szunyogh *et al.*, 2000); and several campaigns as part of THe Observing system Research and Predictability EXperiment (THORPEX; http://www.wmo.int/thorpex/) such as the Atlantic-THORPEX Regional Campaign in 2003 (A-TReC; Fourrié *et al.*, 2006; Rabier *et al.*, 2008) and the THORPEX Pacific Asian Regional Campaign in 2008 and 2009 (T-PARC; Elsberry and Harr, 2008). Also under the THORPEX umbrella, international programmes such as the Mediterranean experiment on cyclones that produce high impact weather in the Mediterranean (MEDEX; http://medex.aemet.uib.es) and the HYdrological cycle in the Mediterranean EXperiment (HyMeX; http://www.hymex.org) have developed field experiments devoted to improving the accuracy of monitoring and forecasting Mediterranean HIW events. It is well known that the Mediterranean basin is frequently affected by heavy rainfall, producing flash floods, strong winds, damaging hail and tornadic thunderstorms that hit Mediterranean densely populated areas, causing severe damage to property, disruption of activity and human losses (Romero *et al.*, 1998; Llasat *et al.*, 2010).

Within the second phase of MEDEX, a field experiment was carried out during the autumn of 2009 in which the adaptive observation concept was applied to the operational radio-sounding network and to commercial aircraft data (AMDAR) (Jansà *et al.*, 2011). This targeting campaign (hereafter, DTS-MEDEX-2009) was focused on improving the forecast skill of HIW events linked to Mediterranean cyclones and used the Data Targeting System (DTS; Prates *et al.*, 2009) from the European Centre for Medium-Range Weather Forecasts (ECMWF) to manage the main issues in the targeting observation process such as case identification, sensitive area prediction, extra-observation proposals and observation monitoring. However, the most crucial concern in any targeting campaign is to guide the decision about where additional observations would most benefit the quality of the forecast of each potential adverse event. To this end, five different sensitivity analysis techniques were carried out to provide targeting guidance to the lead user who, after evaluating all the proposed target regions, proposed a specific targeted observation strategy. Despite not all sensitivity computations being available to the forecasters/scientific teams in real time, all these sensitivity computations were devised to identify the best location for additional observations. Therefore one immediate question arises: which sensitivity method best advises decision makers on where to deploy an extra observation? To shed light on this question and other such targeting concerns, we contribute to the discussion on the use of sensitivity information in the operations offices of targeting campaigns by evaluating the skill of the sensitivity products available for the MEDEX-DTS 2009 campaign. We focus our attention on the particularly relevant event of the intense cyclone that matured over southern Italy on 5 December 2009 and conduct verification experiments on the sensitivity fields made available to the lead user for that particular event.

This paper is organized as follows. Section 2 gives an overview of sensitivity methods for targeting guidance and, specifically, for the DTS-MEDEX-2009 campaign. Section 3 presents the particular case under study. The methodological details for testing target regions are described in section 4. Results for single-sounding targeting strategies are shown in section 5.1, whereas multiple simultaneous soundings tests are discussed in section 5.2. Conclusions and final remarks are given in section 6.

2. Targeting guidance

The essential issue in adaptive observations is to predict the optimal locations and times for targeting prior to deployment. To this end, as stressed by many authors (e.g. Langland, 2005; Majumdar *et al.*, 2011), effective adaptive observation strategies should ideally account for (i) forecast uncertainty, (ii) analysis error, (iii) the data assimilation scheme and (iv) the effect of targeted observations on forecast error reduction. However, it is hard to satisfy all these requirements and simplified approaches have been used over time for targeting guidance.

The earliest targeting methods were founded on adjoint-based sensitivity analyses. Since the mid 1990s, the adjoint of a linearized numerical weather prediction model arose as a powerful diagnostic tool for determining the linear sensitivity of a given forecast aspect to initial conditions (Errico, 1997). The adjoint model results from the transposition of a linear operator which is tangent to the phase space trajectory, followed by the nonlinear simulation (LeDimet and Talagrand, 1986). Thus adjoint models allow the computation of the gradient of a forecast aspect, which is commonly referred to as *response function*, with respect to initial and boundary conditions. This gradient, restricted to linear approximations, is the so-called *adjoint sensitivity*. Within the adjoint theoretical framework, it is worth stressing the singular vector (SV) method (Buizza *et al.*, 1993; Gelaro *et al.*, 1998), which identifies error structures in the analysis field that mostly grow over a finite time interval. This procedure uses the tangent linear model and its adjoint together with an appropriate measure of perturbation growth (usually an energy norm) to define a matrix problem, whose largest singular values are associated with the most rapidly amplifying singular vectors of the forecast error (Baker and Daley, 2000). Thus both adjoint and singular vector techniques identify regions or structures where the forecast is sensitive to analysis errors. However, the above-mentioned methods are purely dynamical and do not bear any information concerning the statistics of the observing system. Newer extensions of adjoint-based techniques account for certain properties of the observations and data assimilation procedures, such as: the Hessian singular vectors (HSVs), which use the Hessian (or second derivative) of the cost function, providing an estimate of the inverse of the analysis error covariance matrix that is consistent with the statistical assumptions made in the assimilation scheme and the observing network (Barkmeijer *et al.*, 1998; Fisher and Courtier, 1995); the Hessian Reduced Rank Estimate (HRRE), introduced by Leutbecher (2003), which predicts forecast error variance in the direction of a subspace of leading HSV in order to reduce the rank of the problem; and the Kalman Filter Sensitivity (KFS), proposed by Bergot and Doerenbecher (2002), which uses analysis error covariances consistent with the error estimates of an operational variational data assimilation scheme.

Another approach to objective-targeting techniques has been developed with the proliferation of ensemble prediction systems. Without taking into account the computational cost of the ensemble itself, the ensemble-based sensitivity techniques are less computationally expensive than the adjoint-based methods. In line with the adjoint sensitivity, the ensemble sensitivity method (hereafter, ENSB; Hakim and Torn, 2008) estimates the gradient of a response function with respect to the initial conditions. To this end, this technique linearly correlates independent samples of the initial and final state to statistically estimate how changes to the initial conditions affect the forecast metric (Ancell and Hakim, 2007). It is worth stressing that adjoint and ensemble sensitivities are equivalent at the limit of uncorrelated initial state variables. A further extension of the ensemble sensitivity technique can be used to determine the targeting location that leads to a greater reduction of the response function variance in the ensemble forecast. This later approximation is in agreement with the ensemble transform Kalman filter (ETKF) (Bishop *et al.*, 2001), which is a further development of the initial ensemble transform (ET) technique (Bishop and Toth, 1999). Both the ET and the ETKF methods are aimed at predicting the forecast variance associated with a particular deployment of observations at a prior time. After testing over multiple possible deployments of observations, the most favourable for forecast variance reduction is selected. Note that the ETKF is often used to generate summary maps of the signal variance, which are then used to identify target regions and not specific observation locations.

Most of the aforementioned sensitivity techniques have been used in several targeting field experiments in order to identify promising targets for the deployment of additional observations. However, the effectiveness of targeted observations on forecast error reduction has been mixed to date. While observations sampled in sensitivity regions are shown to be, on average, more valuable than observations located in random areas, their benefit is not guaranteed for individual cases and the average return of investments in targeting field experiments is questionable (Buizza *et al.*, 2007; Majumdar *et al.*, 2011). This fact is not surprising because the impact of any group of targeted observations depends on the flow regime, the coverage of the targeted region by routine observations, the observations available for targeting, the forecast model and data assimilation system, and the verification method. Furthermore, sensitivity methods for targeting guidance are conditioned by the forecast system and the metric used to derive them.

The research described in this article attempts to bridge the gap between the evaluation of the reliability of sensitivity fields and the assessment of the impact of targeted observations on a forecast in a full assimilation-forecast system. To this end, we quantify the skill of sensitivity products through Observing System Simulation Experiments (OSSE) by comparing the forecast impact of synthetic soundings in sensitivity-based areas and in fixed sites which may be coincidentally located within a sensitive region. Although this paper is focused on a single case of the DTS-MEDEX-2009 campaign, and thereby conclusions cannot be generalized to other targeting situations, a wealth of experiments are carried out to extensively test the guidance provided by a wide catalogue of sensitivity computations for a particularly relevant example of Mediterranean HIW. Specifically, we put under evaluation five different sensitivity products: total energy moist-TL95 SV based on the ECMWF Integrated Forecast System (Buizza and Montani, 1999); ETKF (Bishop *et al.*, 2001) and KFS (Bergot and Doerenbecher, 2002) from Météo France, both using the ARPEGE model; MM5 adjoint sensitivities computed using ECMWF analysis (Zou *et al.*, 1997) and ensemble sensitivities based on the ECMWF ensemble prediction system (Hakim and Torn, 2008) from the University of the Balearic Islands (hereafter UIB). Several intercomparisons have been performed between guidance provided by different sensitivity methods such as the ETKF and SV (Majumdar *et al.*, 2002) or adjoint and ensemble sensitivities (Ancell and Hakim, 2007), different models (e.g. Wu *et al.*, 2009) or metrics used to define the optimization problem (e.g. Reynolds *et al.*, 2007) but results are mixed and flow-dependent. Nevertheless, the research described here is the first attempt at confronting five different sensitivity methods for a Mediterranean HIW event.

3. Case study

The DTS-MEDEX-2009 field experiment took place from 30 September to 20 December. Eventually, 132 cases were selected as targeting episodes. On-demand operational radio soundings at non-standard times and AMDAR profiles were the observational means available for this campaign, although some radio-sounding stations were made available for targeting operations after the beginning of the campaign. In addition, due to the demanding time constraints during operations and the width of some temporal windows (time between analysis time (AT) and verifying time (VT)) for which linear assumptions are not valid for sensitivity analysis, not all five of the aforementioned sensitivity fields are available for all cases defined in the campaign. For the sake of generality in the findings of this study, we based the decision regarding the case to analyse on the intensity of the actual meteorological episode but also on the availability of all radio-sounding stations and sensitivity fields in the DTS-MEDEX database.

The selected case study was evaluated on 2 December 2009 (AT). At this time, after recommendations from the scientific/forecaster team, the lead user of the campaign selected a potential high-impact cyclone forecast 72 h later as a targeting case. This cyclone was forecast over southern Italy, and heavy rain over the Balkan area and strong winds

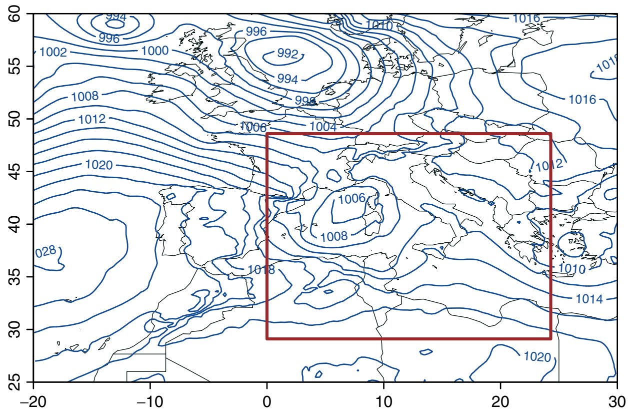

Figure 1. Mean sea-level pressure field (hPa, solid lines) on 5 December 2009 0000 UTC (VT) (from 6 h ECMWF forecast started on 2 December 2009 0000 UTC (AT)). The dark box centred near Sicily delineates the verifying area (VA) valid at VT. This figure is available in colour online at wileyonlinelibrary.com/journal/qj

in the western Mediterranean and Tyrrhenian seas were expected. The time of maximum potential impact was established at 0000 UTC on 5 December (VT) and the region of special interest (verifying area, VA) was centred near Sicily, encompassing the central and western Mediterranean, except for the Alboran Sea (Figure 1). The computation of the response function is performed over the VA for all sensitivity methods applied to the campaign. Sensitivities are computed with respect to the precursor conditions at the targeting time (TT), which was set at 1800 UTC on 3 December 2009. Thus, for this case, the lead time is 42 h (time span between AT and TT) and the optimization time is 30 h (period between TT and VT) (Figure 2).

Regarding the sensitivity information available for this case study, sensitivity fields are different in scale and magnitude due to a different theoretical basis (Figure 3). It is shown that guidance provided by different methods tends to possess similar characteristics to each other showing common targets, but they substantially differ in some cases (Majumdar *et al.*, 2011). For this case study, adjoint sensitivities reveal mesoscale structures, whereas ETKF emphasize synoptic-scale features which are associated with significant large-scale weather features at the initial time. However, except for the adjoint sensitivity field, which seems to have a non-direct dynamical interpretation, sensitivity analyses highlight the region upstream of the VA associated with the Atlantic ridge and the strong thermal front. These sensitivity structures are likely pointing towards the relevant effect of the evolution of the Atlantic high-pressure system on the deepening of the European trough and, thereby, on the intense cyclonic system over Italy 30 h later.

4. Verification methodology

Given the heterogeneity of the sensitivity information, it is imperative for future targeting guidance to provide a quantitative test of the suitability of the target regions indicated by each technique. Since radiosonde and AMDAR profiles were the observational means available during the DTS-MEDEX targeting campaign, we design the verifying tests based on analysing where the forecast is most sensitive to the assimilation of a pseudo-observed vertical profile in the initial conditions at TT. It is worth keeping in mind that all sensitivity information in the campaign was treated (post-processed) to be fed into the DTS – independently of their theoretical foundation – in order to be used in the operations centre when choosing the location of the extra soundings. Since the main aim of this study was to discern which sensitivity methods provided valuable guidance in deploying extra observations (beyond the limitations in observational means that specific campaigns can allocate), evaluating the impact of the sites actually selected by the lead user during operations could be misleading for our purpose. The fact that maximum sensitivity signals can spread across areas with no eligible sites during DTS-MEDEX-2009 (areas with no operational radio-sounding stations or AMDAR airports) adds a level of complexity when trying to assess the guidance provided by the sensitivity fields to decision makers at the campaign operations centre. Therefore, we quantify the skill of the considered sensitivity fields by means of observing-system simulation experiments (OSSE) by assimilating synthetic soundings at the location of the maximum value of each available sensitivity field. Additionally, the ability of a human meteorologist to process the available information and identify an optimal targeting location is also analysed. This research does not reproduce the set-up of the DTS-MEDEX-2009 campaign but aims at evaluating the guidance provided by five different sensitivity fields to final decision makers. For the sake of completeness, the impact of synthetic soundings over

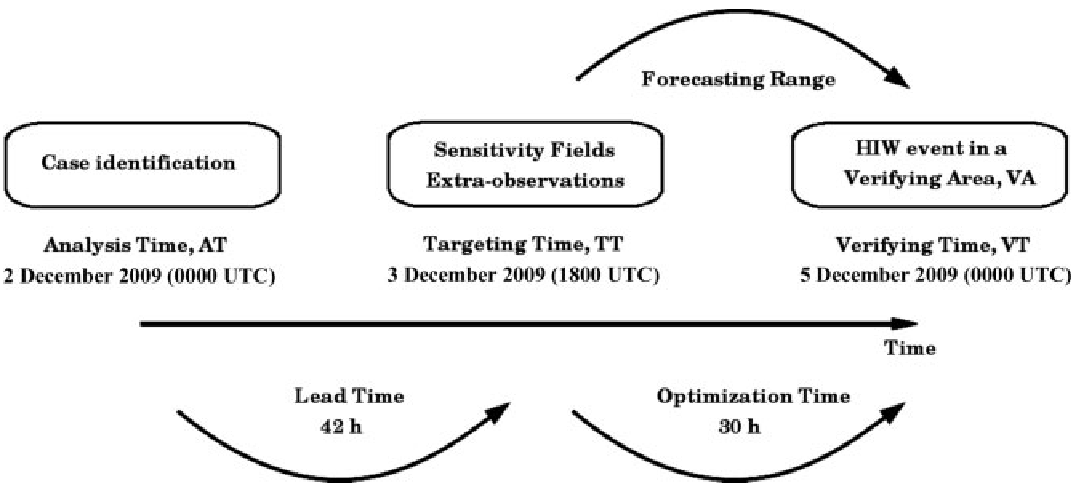

Figure 2. Schematic of the timing for each targeting case during the DTS-MEDEX-2009 campaign with the particular data of the case study.

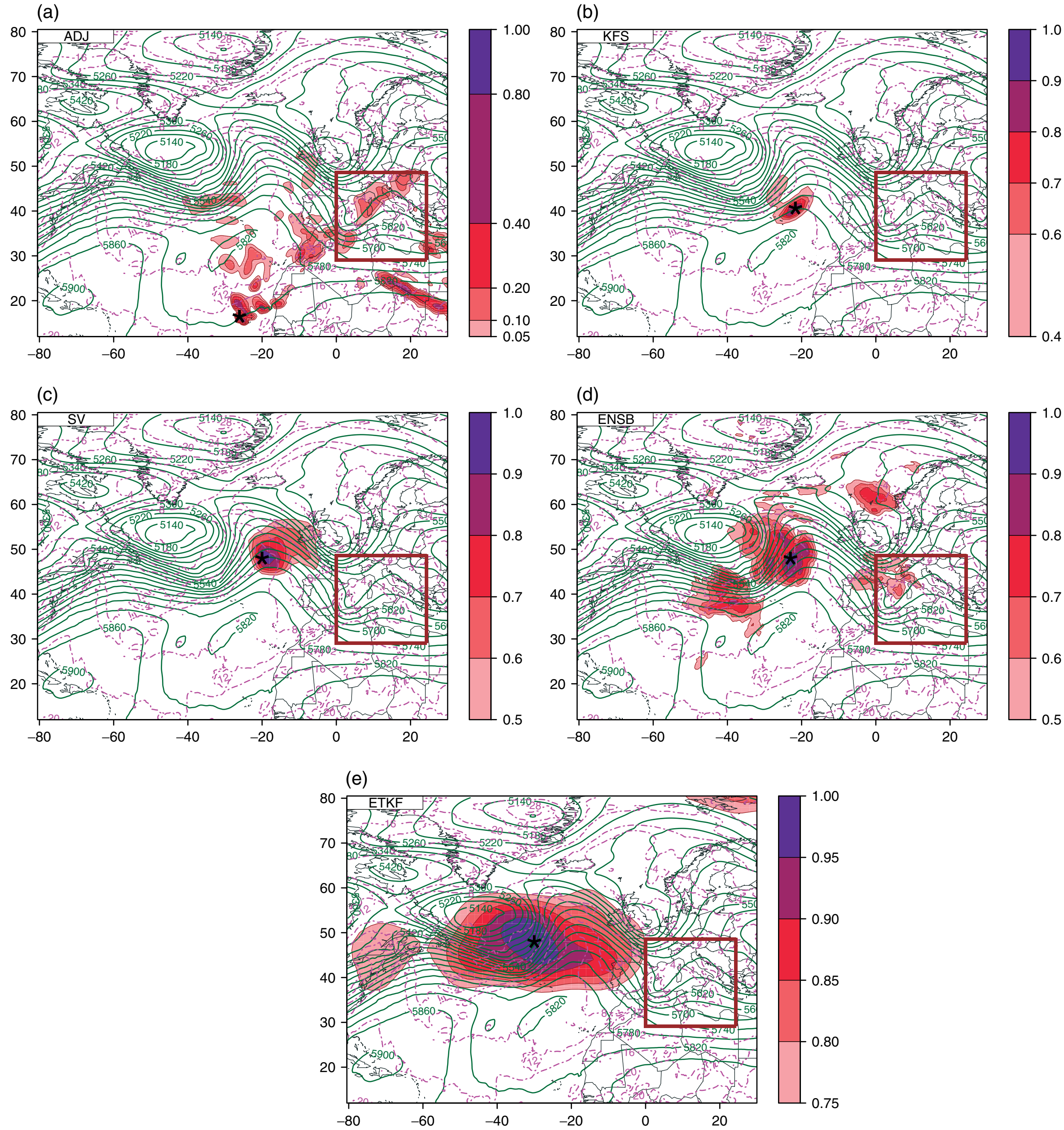

Figure 3. (a) Adjoint-based, (b) KFS-based, (c) SV-based, (d) ensemble-based and (e) ETKF-based sensitivity products normalized to their respective maximums (shaded; note the scale change between figures); geopotential height field at 500 hPa (gpm, solid lines) and temperature field at 850 hPa (°C, dashed lines) from 6 h ECMWF forecast. Valid at targeting time (TT) on 3 December 2009 at 1800 UTC. The maximum value of each sensitivity field is labelled with an asterisk. The dark box centred near Sicily delineates the verifying area (VA) valid at the verifying time (VT). This figure is available in colour online at wileyonlinelibrary.com/journal/qj

the locations of the operational radio-sounding stations are also tested. Specifically, 47 radio-sounding locations available for this case study are considered. Moreover, since it is widely recognized that the impact of targeted observations depends on the number of extra observations deployed (among many other characteristics such as type and accuracy), the verification testbed comprehends single and multiple sampling experiments, both based on OSSE.

4.1. Model system

Different numerical weather prediction models are involved in the computation of the sensitivity fields catalogue: the ECMWF Integrated Forecasting System (IFS) for SV sensitivities and, in turn, for the ensemble sensitivities through the ECMWF ensemble prediction system; the ARPEGE and its derived ensemble prediction system at Météo France for ETKF and KFS; and the MM5 adjoint model at the UIB to compute adjoint sensitivities. Therefore, in search of an equal opportunity test, we do not use any of the aforementioned forecasting models. We perform the verification experiments with the Advanced Research WRF (Weather Research and Forecasting) limited-area model (hereafter, WRF ARW). It is a fully compressible, non-hydrostatic model widely used in research and operations (Skamarock *et al.*, 2008). Our simulations use 28 vertical σ levels and 300×240 grid points, with 30 km grid spacing. The domain is centred over the Iberian peninsula and stretches across northern Africa, Europe and parts of the east North Atlantic (e.g. Figure 7). Initial and boundary conditions are provided by the 6 h ECMWF forecast fields. Regarding the physical parametrizations, the WRF single-moment 6-class scheme (Hong *et al.*, 2004), including ice sedimentation and other ice-phase parametrizations, is used for subgrid microphysics calculations. Moist convection is parametrized using an improved version of the Kain and Fritsch (1990, 1993) schemes, based on testing within the Eta model (Kain, 2004). A modified MRF PBL (medium-range forecast model planetary boundary layer; Hong and Pan, 1996), Yonsei University scheme, accounts for planetary boundary layer processes, whereas the rapid radiative transfer model (Mlawer *et al.*, 1997) is used to parametrize radiation effects. All simulations use the same numerical set-up and are run from the TT on 3 December 2009 at 1800 UTC until the VT on 5 December at 0000 UTC, i.e. a 30 h forecast.

4.2. Experimental design

The synthetic soundings are extracted from the ECMWF analysis valid at TT and at the specific location under test. In this set-up, the ECMWF analysis is considered as a pseudo-truth from which we obtain realistic sounding values. Thus vertical profiles of geopotential, wind, temperature and humidity are added to the 6 h ECMWF forecast, the background field, valid at TT which indeed does not contain any extra observation. Therefore, each experiment allows evaluation of the impact of each synthetic sounding configuration. To this end, synthetic soundings are fed into the WRF data assimilation (WRFDA) system, which uses a three-dimensional variational (3D-Var) scheme (Barker *et al.*, 2004) with a background error covariance in physical space, and the resulting initial conditions (IC) are evolved until the VT using WRF ARW. Additionally, a control run starting from the 6 h ECMWF forecast without any assimilated observation is carried out, which is considered the reference forecast state. It is worth mentioning that this verification testbed does not mimic operational targeting studies since routine observations are not considered at the TT, because we do not attempt to directly assess whether the observation has improved or degraded the forecast, but we aim at identifying the most sensitive location for a plausible sounding, i.e. the location that produces the largest impact over the VA at the VT. It is also noteworthy that in real operations, and in a strict sense, observation impact strongly depends on the initial state of the forecast, which in turn depends on the set of observations assimilated and the characteristics of the data assimilation system (Kelly *et al.*, 2007). This is a fundamental moving-target-like problem that hampers all attempts to rigorously design targeting campaigns and, thus, sensitivity verification experiments.

5. Results

5.1. Single sounding experiments

This section attempts to assess where the forecast of the intense cyclone on 5 December at 0000 UTC is most sensitive to a single sounding at the TT. To this end, 53 different locations are evaluated: the location of the maximum value of each of the five sensitivity fields, the 47 radio-sounding station points available for this case study and one human-based sensitivity location (Figure 4). For

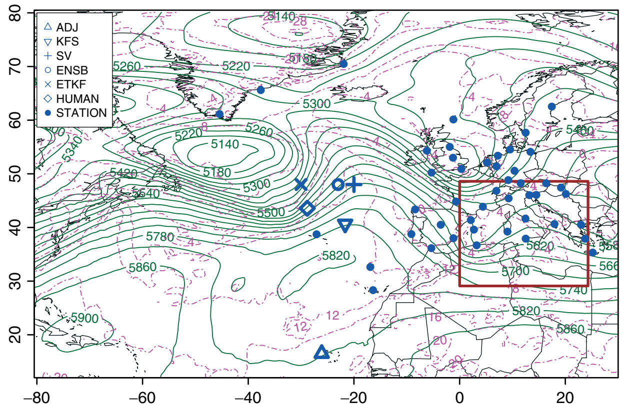

Figure 4. Geopotential height field at 500 hPa (gpm, solid lines) and temperature field at 850 hPa (°C, dashed lines) from 6 h ECMWF forecast valid at Targeting Time (TT) on 3 December 2009 at 1800 UTC. The dark box centred near Sicily delineates the verifying area (VA) valid at the verifying time (VT). All 53 tested points (47 targetable stations, five sensitivity-based and one human-based) are symbolized. This figure is available in colour online at wileyonlinelibrary.com/journal/qj

the subjective decision of the (hindcast mode) lead user, an experienced meteorologist is asked to highlight the most valuable sounding location after evaluating the available sensitivity fields. This choice was influenced by the fact that all ensemble-based methods pointed to the difluent area upstream of the North Atlantic 500 hPa ridge. The west side of the European trough could also arguably be linked to the 30 h forecast over the VA area if advective reasoning was used. However, since ensemble-based methods highlighted areas further upstream, the pseudo-lead user finally pointed out this region as the most sensitive for an extra sounding.

For each of the 53 experiments, a synthetic sounding is independently fed into the WRFDA system. Although each single sounding provided to the WRF data assimilation cycle is equivalently obtained from ECMWF analysis for all 53 tested points, the derived IC increments are quite different. Bear in mind that the specified background error and observation error statistics in the data assimilation process determine how the observation affects the initial conditions. Nevertheless, it is not necessary for the observation to produce a large change to the initial conditions to cause a large forecast impact (Langland and Baker, 2004). Among the 53 assimilations, some increments show a dipole around the target region, whereas in other cases the assimilation of the observation results in a Gaussian-like or circular-like perturbation of the IC (e.g. Figure 5) but the initial energy perturbation as a result of the assimilation of a single sounding does not show systematic differences over the Atlantic Ocean and over continental Europe, as shown in the following subsections.

Once the synthetic soundings are assimilated independently, 53 perturbed experiments, in addition to the control run, are rendered. With the aim of evaluating how sensitive each location is to an additional sounding, the impact of each observation on the prediction of the intense cyclone is evaluated over the VA. Although sensitivity fields strongly depend on the forecast metric, which is commonly based on total energy (Palmer *et al.*, 1998; Rabier *et al.*, 1996; Langland *et al.*, 2002), we focus our test on the actual interests of an HIW-oriented targeting campaign. Specifically, the DTS-MEDEX-2009 objectives are heavy rain, strong winds and/or a cyclonic signature (Jansà *et al.*, 2011), precisely the

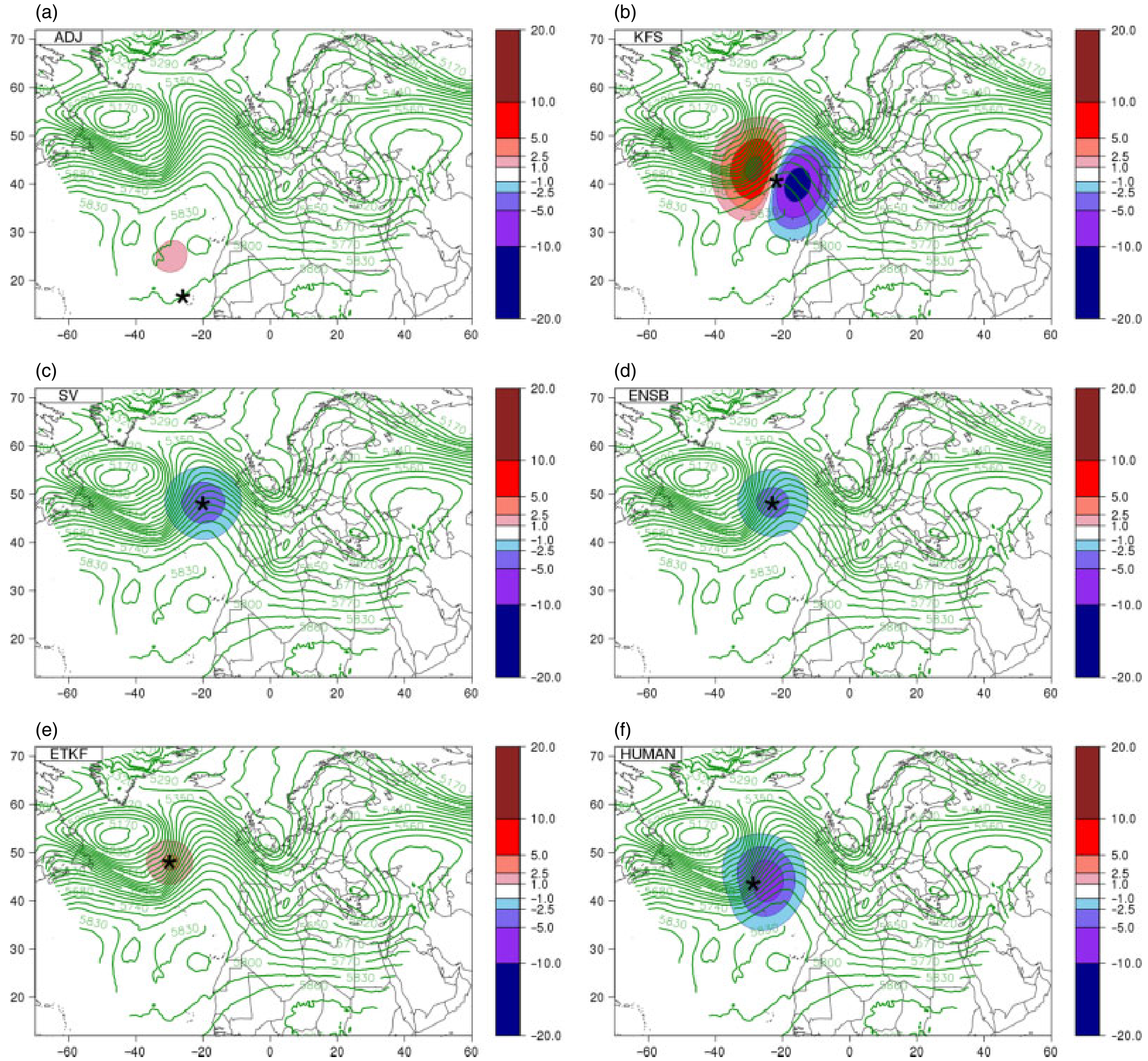

Figure 5. (a) Adjoint-based, (b) KFS-based, (c) SV-based, (d) ensemble-based, (e) ETKF-based, and (f) human-based perturbations (gpm, shaded) over geopotential height field at 500 hPa (gpm, solid lines) from 6 h ECMWF forecast valid at targeting time (TT) on 3 December 2009 at 1800 UTC as a result from the assimilation of a single sounding over each corresponding location represented in Figure 4. This figure is available in colour online at wileyonlinelibrary.com/journal/qj

features that characterize the selected case study. Therefore, we compute statistical diagnostics between each perturbed simulation and the control one over the VA at the VT for mean sea-level pressure (MSLP), accumulated rain and wind speed fields.

5.1.1. Mean sea-level pressure

The root mean square difference (RMSD) of the MSLP field reveals a significant result. The impact obtained by adding a sounding over the regions highlighted by the available sensitivity fields is much lower than expected, which is reflected in poor values of the RMSD (Figure 6). In fact, most of the experiments in which synthetic soundings were assimilated over operational radio-sounding stations have a larger influence on the predicted MSLP than the sites indicated by the objective sensitivity methods independently of the initial energy perturbation produced by the assimilation of each single sounding (Figure 6). This indicates that the addition of a sounding over these locations at the TT has a relevant role in the cyclone deepening. Specifically, the synthetic sounding assimilated over the maximum KFS sensitivity value is the most effective sensitivity location but it ranks a poor 30th among all considered locations. That is, the MSLP field is more sensitive to the information assimilated from 29 fixed stations than any of the sensitivity-based points. SV-, human-, ensemble-, ETKF- and adjoint-based sensitivity locations produce, in that order, even poorer RMSD values. A detailed analysis of the impact sensitivity-based soundings have on the MSLP at VT over the VA (Figure 7) confirms this poor repercussion on the mature cyclone depth. In fact, most of the initial sensitivity perturbations are trapped in the Atlantic depression instead of perturbing the Italian low. As mentioned earlier, the KFS experiment produces the highest variation in the Mediterranean cyclone MSLP field.

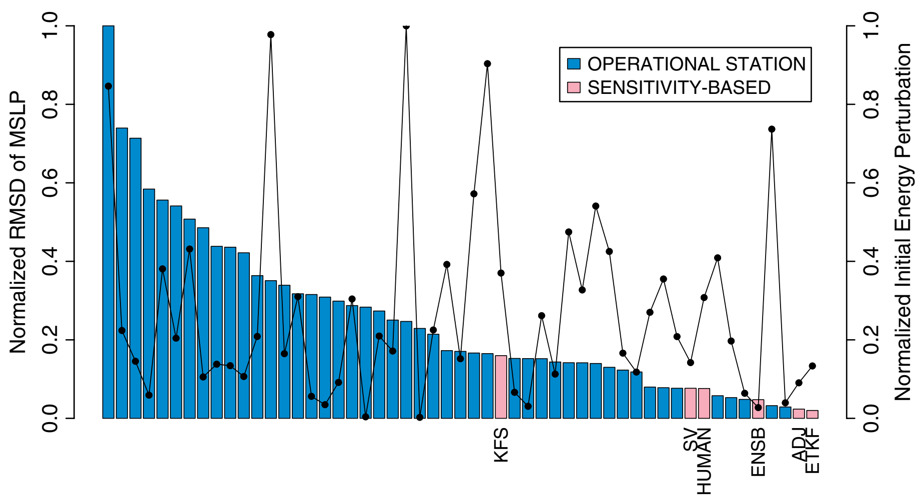

Figure 6. Root mean square difference (RMSD, bars) between perturbed and control simulations for the mean sea-level pressure (MSLP) field over the verifying area (VA) at the verifying time (VT). Initial energy perturbation (lines) as a result of the assimilation of each synthetic sounding. This figure is available in colour online at wileyonlinelibrary.com/journal/qj

The derived perturbation consists of an extensive dipole around the cyclone centre which indicates a northwestward shift of the cyclonic structure in the perturbed simulation. However, when compared with the impact obtained with the sounding added over *A Coruña* station in the northwestern Iberian peninsula, which produces the highest RMSD, the difference is notable. Although the sounding influences the entire domain, it is mainly centred on the Mediterranean circulation.

5.1.2. Wind field

The observation impact on the forecast wind field is assessed by two different statistical measures. On the one hand, the RMSD for the wind speed field at 925 hPa between the perturbed experiments and the control one (Figure 8) is in agreement with the previous results for the MSLP. Wind speed RMSD indicates that the best location for a single sounding is not any of the regions pointed out by the sensitivity methods, not even by the human meteorologist. Again, most of the station points are more influential for the circulation of the Italian cyclone. On the other hand, the difference of the third quantile of the wind speed profile between perturbed and control experiments over the VA at the VT confirms this behavioural pattern. Thus the distribution of the strongest winds is indeed most affected by soundings added over station points.

5.1.3. Accumulated rain

The RMSD of the accumulated rain over the VA during the simulation period (30 h) reflects how poorly sensitive the total rain amount is to the added soundings guided by sensitivity methods (Figure 9). Once again, the sensitivity-based locations are the least sensitive points for the forecast over the VA at the VT. For this field, 37 soundings assimilated over station locations produce the highest impact on the predicted rain, followed by the KFS-, SV-, human-, ensemble-, adjoint- and ETKF-based sensitivity locations. Also, the initial error perturbation does not show reciprocity with the sounding impact on the forecast. Since the RMSD score strongly penalizes outliers, the mean absolute error (MAE) has also been computed as it is more representative of the forecast as a whole. Nevertheless, the MAE results present the same ranking for the observation impact, evidencing the consistency of the results.

5.1.4. Spatial distribution of single-sounding impacts

Regarding the spatial distribution of the RMSD scores (Figure 10), the *A Coruña* (Spain) and the *Practica di Mare* (Italy), soundings are identified as the most sensitive locations since they produce the largest impact on the forecast at the VT over the VA. Generally, soundings located over the British Isles, linked to the strong westerly jet, and over the Alpine region in the vicinity of the mature cyclone, have a strong influence on the forecast of the Italian cyclone. Conversely, the VA is marginally affected by sensitivity-based experiments due to the fact that assimilated soundings produce changes only on the remote environment of the intense cyclone. As a result, the perturbations derived from sensitivity-based locations, which are further upstream than the fixed radio-sounding sites, are mainly linked to the Atlantic depression rather than the Italian low.

5.2. Multiple sounding strategies

In the light of the single-sounding impact results, the localized sensitivity maxima provide no reliable guidance on where a single sounding would produce the greatest impact on forecast features of societal, economic and environmental interests such as MSLP, total rain and wind speed. In addition, a human expert, guided by the available sensitivity fields, fails to recognize the most profitable sounding location. On the other hand, most of the operational radio-sounding locations are identified as more valuable sounding points. Admittedly, the verification procedure considers only the location of the available radio-sounding stations and many untested locations could lead to an even larger response in the forecast. Nevertheless, during the DTS-MEDEX-2009 field experiment only the 47 tested station points were targetable radio-sounding options. Thus, from a pragmatic point of view, the considered experiments provide a complete representation of feasible sounding locations.

Once the guidance provided by the sensitivity fields in single-sounding targeting strategy is evaluated, we can focus

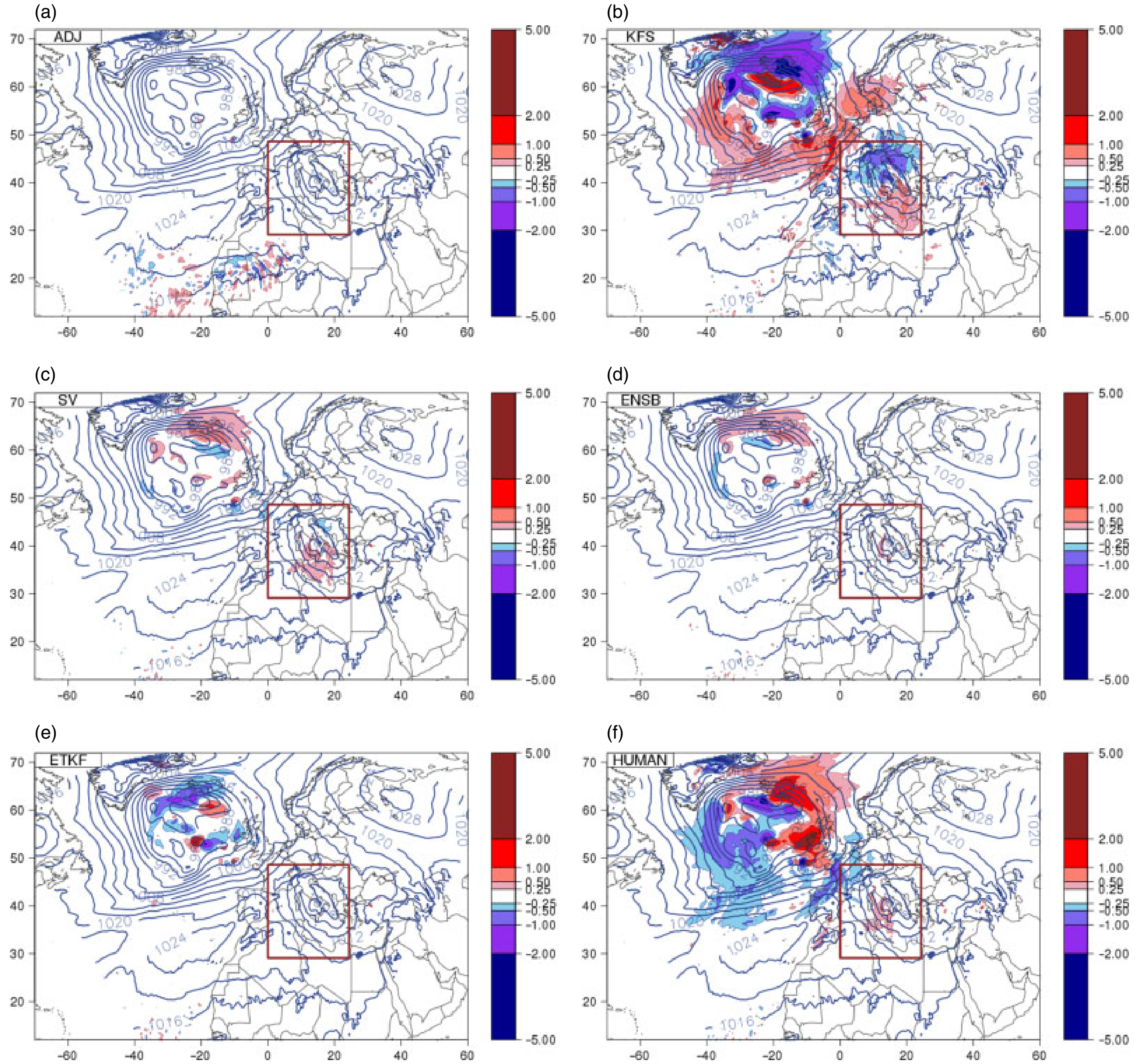

Figure 7. Difference between mean sea-level pressure (MSLP) field of the control simulation (hPa, solid lines) and the (a) adjoint-based, (b) KFS-based, (c) SV-based, (d) ensemble-based, (e) ETKF-based and (f) human-based perturbed simulations (hPa, shaded) at verifying time (VT) on 5 December 2009 at 0000 UTC. The dark box centred near Sicily delineates the verifying area (VA) valid at the VT. This figure is available in colour online at wileyonlinelibrary.com/journal/qj

on a more realistic set-up by assessing the value of sensitivity information when multiple simultaneous soundings are deployed. For the particular case we analyse in this study, the lead user selected a targeting area (TA) that spanned western Europe, north Africa and parts of the eastern Atlantic, covering most sensitivity regions highlighted by the objective methods (Figure 11). Within the TA, seven soundings were finally requested at the following stations: Murcia (Spain), Tenerife (Canarias, Spain), Gibraltar (UK), Lajes (Azores, Portugal), Dar-el-Beida (Algeria), Castor Bay (UK) and Bordeaux (France). The decision on how many and where the extra soundings should be deployed was ultimately made by the lead user without any directly related information derived from the sensitivity fields. The lead user did not have any quantitative means to make an informed decision on the basis of the minimization of the cost/benefit ratio of deploying a certain number of extra soundings. In fact, the decision was actually only guided by the available sensitivity fields, which mainly highlight the difluent area upstream of the North Atlantic 500 hPa ridge, and where indeed there were no targetable sites.

Given that the objective sensitivity calculation methods highlighted sensitive areas which were not targetable with the means available during the campaign, the targeting decisions made by the lead user are not relevant in assessing the value of the different objective sensitivity fields. However, the definition of the TA and the final selection of the seven stations seem to be influenced by the sensitivity fields as it extends westwards towards the Atlantic. Whether the lead user could have done better without any objective sensitivity guidance is an open question. However, we can explore the impact of various deployments that could have been adopted in order to assess the efficiency of the one actually used. Any exhaustive search for the optimal observational strategy, in line with the previously presented verification experiments, and given the 47 targetable stations, is unaffordable due

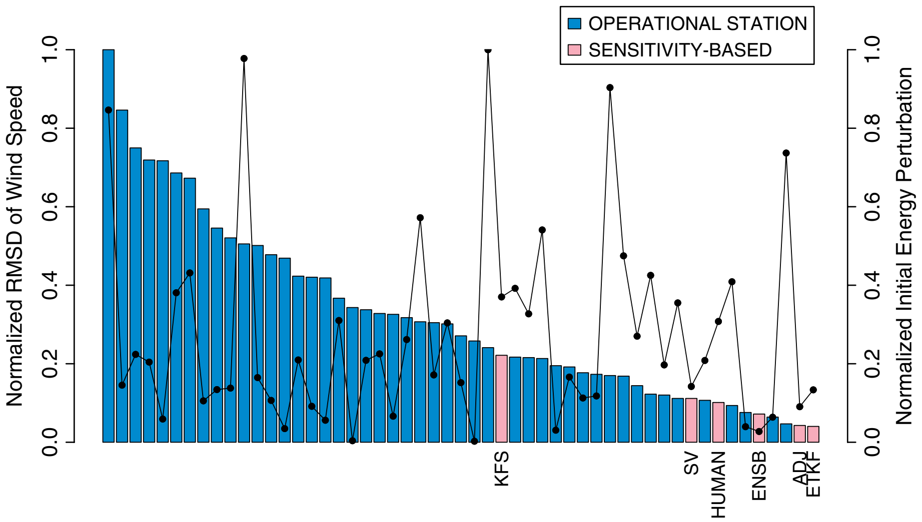

Figure 8. Root mean square difference (RMSD, bars) between perturbed and control simulations for the wind speed field over the verifying area (VA) at the verifying time (VT). Initial energy perturbation (lines) as a result of the assimilation of each synthetic sounding. This figure is available in colour online at wileyonlinelibrary.com/journal/qj

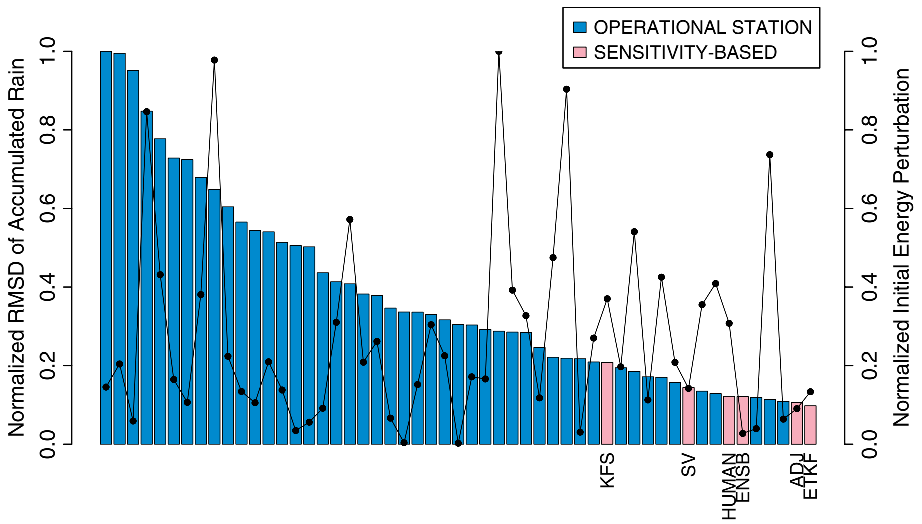

Figure 9. Root mean square difference (RMSD, bars) between perturbed and control simulations for the accumulated rain during all the simulation period (30 h) over the verifying area (VA) at the verifying time (VT). Initial energy perturbation (lines) as a result of the assimilation of each synthetic sounding. This figure is available in colour online at wileyonlinelibrary.com/journal/qj

to the host of possibilities to consider in terms of the sets of combinations of stations that can be conceived. However, interesting results emerge by comparing the impact of 12 different deployments of seven soundings each (the number of soundings actually deployed for this case study). Specifically, we consider 10 experiments in which seven station locations are chosen randomly, one pseudo-real experiment with the seven stations actually used and one RMSD-guided experiment with the seven best ranked stations according to the single-station results of the previous section for the MSLP field. Admittedly, the seven first RMSD-ranked soundings are not strictly informative about the impact of seven simultaneous probes, but it is easily conceivable as a plausible, straightforward decision which can easily be included in operational protocols in future campaign designs by evaluating a priori the impact of synthetic observations. Similarly to the experimental set-up explained in section 4, each experiment assimilates seven synthetic soundings at TT and the derived impact is evaluated over the VA at VT for the MSLP field. It is worth mentioning that the forecast impact of any set of observations may be compromised by initially small instabilities (Hodyss and Majumdar, 2007) and here only a single case is evaluated, but in all targeting campaigns the information added by a new observation is never known a priori, and thus both the perturbation created by the observation and the new sensitivity of the forecasting system are strictly unpredictable (moving-target problem).

Unexpectedly, the MSLP forecast over the VA is more sensitive to the information added through the A Coruña single sounding than both the seven soundings actually deployed and the seven sites with larger response in the single-sounding experiments (Figure 12). On the other hand, four of the 10 random experiments have a larger influence on the predicted MSLP than the actually deployed means which perform better than six experiments with random choices. Thus the actually deployed configuration leads to an impact slightly above average, but without being optimal, for this multiple sounding test. As a matter of fact, these results do not shed light on what is the optimal observational

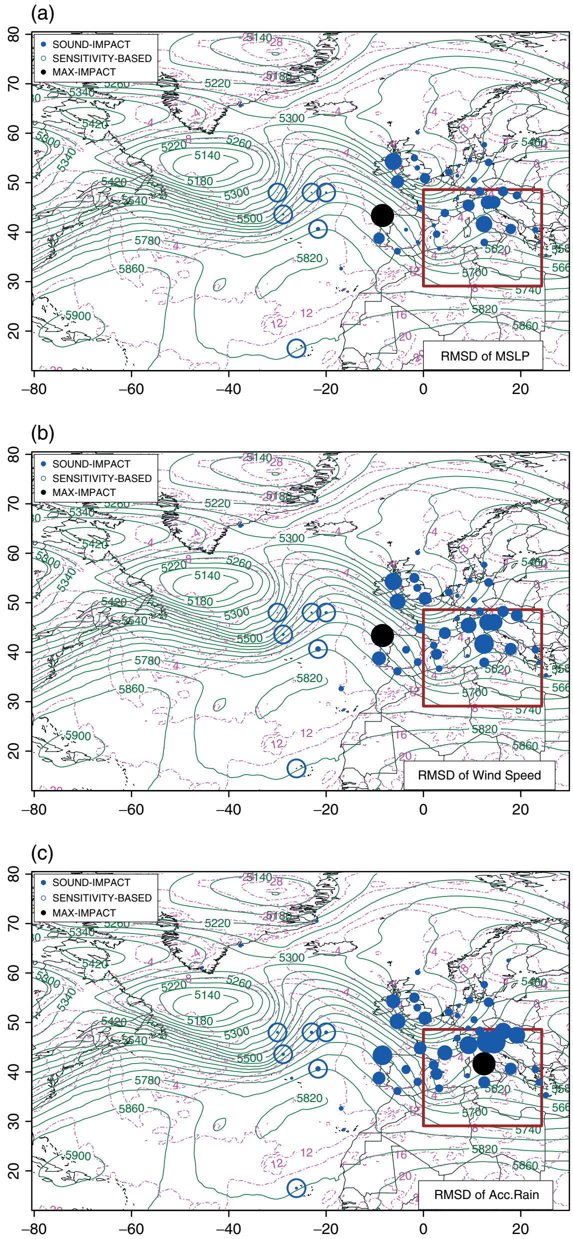

Figure 10. Geopotential height field at 500 hPa (gpm, solid lines) and temperature field at 850 hPa (°C, dashed lines) from 6 h ECMWF forecast valid at targeting time (TT) on 3 December 2009 at 1800 UTC. The dark box centred near Sicily delineates the verifying area (VA) valid at the verifying time (VT). All 53 tested points (47 targetable stations, five sensitivity-based and one human-based) are represented by a circle whose size is proportional to the corresponding RMSD value for (a) MSLP, (b) wind speed and (c) accumulated rain fields. This figure is available in colour online at wileyonlinelibrary.com/journal/qj

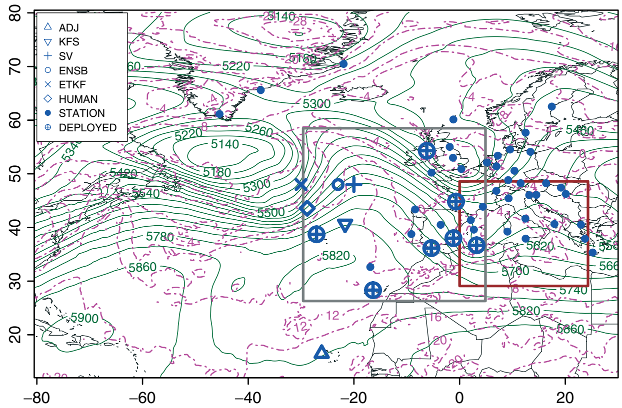

Figure 11. Geopotential height field at 500 hPa (gpm, solid lines) and temperature field at 850 hPa (°C, dashed lines) from 6 h ECMWF forecast valid at targeting time (TT) on 3 December 2009 at 1800 UTC. The eastern (dark) box centred near Sicily delineates the verifying area (VA) valid at the verifying time (VT), and the western (light) box represents the targeting area (TA) valid at TT. All 53 tested points (47 targetable stations, five sensitivity-based and one human-based) are symbolized, as well as the location of the actual deployments of radio soundings for the case study. This figure is available in colour online at wileyonlinelibrary.com/journal/qj

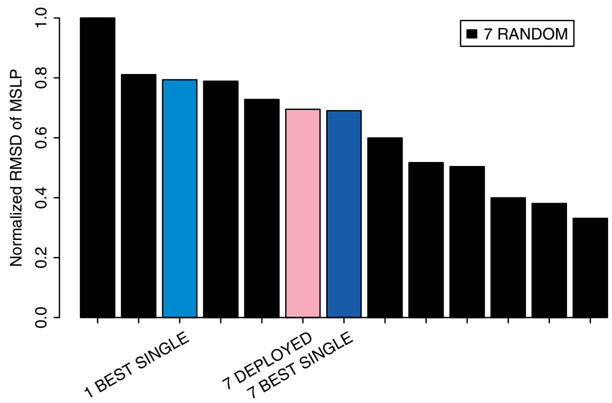

Figure 12. Root mean square difference (RMSD) between perturbed and control simulations for the mean sea-level pressure (MSLP) field over the verifying area (VA) at the verifying time (VT). This figure is available in colour online at wileyonlinelibrary.com/journal/qj

strategy that should have been adopted on that particular day, but they question the subjective decisions adopted in targeting campaigns without user-focused measures of the value of plausible extra observations aimed at predicting the reduction in forecast error variance prior to deployment.

6. Summary and discussion

The primary concern of targeting is to identify the region that can optimize the effect of targeted observations with respect to a selected forecast feature since time and type of observations are usually determined by practical considerations and technical limitations. With the aim of providing such information, several sensitivity analysis methods have been developed in recent years. However, the skill of the multiple sensitivity methods for targeting guidance is not extensively tested nor verified for Mediterranean HIW.

The DTS-MEDEX-2009 targeting campaign provides a unique framework to evaluate the performance of five sensitivity products (KFS-, SV-, ETKF-, ensemble- and adjoint-based) in identifying the most favourable region to an extra observation. Since radiosonde and AMDAR profiles were the observational means available during the DTS-MEDEX targeting campaign, this study is focused on analysing the most sensitive location to deploy a plausible sounding for a potential high-impact cyclone over southern Italy on 5 December 2009. To this end, OSSE are used to assimilate a synthetic sounding over each location under test. In addition to the location of the maximum value of the available sensitivity fields, all 47 targetable station sites have been tested. Additionally, we also take into account the region highlighted by an experienced severe weather meteorologist after evaluating all available sensitivity products as a proxy of decision making at a campaign operation centre. The impact of each assimilated single sounding on forecast aspects of interest (MSLP, wind speed and accumulated rain) is quantified to assess the suitability of all 53 tested points. This research does not reproduce an operational targeting situation in which routine observations are considered; consequently we do not attempt to determine whether the observation has improved or degraded the forecast. This testbed set-up is aimed at identifying the most sensitive location for plausible sounding deployments by assessing which configuration produces the highest forecast impact on the VA at the VT.

The verification results for this particular case study reveal that sensitivity products fail to recognize the best location for a single sounding, and most of the soundings added over operational radio-sounding stations have a larger influence on the intense cyclone forecast, although some may be coincidentally located within sensitive regions highlighted by sensitivity products. Furthermore, and perhaps most importantly, the sensitivity information leads to suboptimal decisions of the pseudo-lead user, who demonstrates poor skill in identifying a sensitive region. Admittedly, when only the localized sensitivity maximum is targeted, a consistent or large forecast improvement is not guaranteed owing to statistical assumptions involved in data assimilation. Therefore, in order to test the suitability of a multiple sampling, we compare the forecast impact of the seven targetable stations chosen by the lead user during the campaign and a plausible deployment consisting of the seven most sensitive sites from the single-sounding experiments against 10 configurations with seven random sounding sites. Again, it is shown that the human-based decision is not optimal (and neither the subjective selection of observations with the largest single-site impact) since random configurations and one single sounding produce larger impacts on the forecast; nevertheless, the impact derived from the human-based experiment is slightly above average.

Unlike initially small instabilities in dynamically unrelated locations that may be present in observation impact experiments, all in all these results reveal that simply choosing a target highlighted by a sensitivity product and deploying a sounding over it does not guarantee a significant impact on the forecast in this particular case study. Moreover, the benefits of a multiple sampling are not assured. Although a positive average impact of targeted observations is expected when a statistically significant sample is evaluated, these results suggest that methods for defining target-sensitive areas require advancement since successful targeting is not yet assured for individual cases. In fact, many studies show that objective sensitivity techniques, which identify regions where the forecast is sensitive to analysis errors, do not provide specific observational guidance. For instance, Ancell and Hakim (2007), when comparing adjoint and ensemble sensitivities, had already shown that the leading primary targeting site is located at neither the region of maximum ensemble nor adjoint sensitivity; and Harnisch and Weissmann (2010) did not obtain the largest improvement in typhoon tracks by sampling SV sensitivity regions. Likewise, for the case investigated in this study, the sensitivity products available for the DTS-MEDEX-2009 campaign are not informative about the best observational strategy, either in location or in the number of observations to be deployed, and they do not discriminate between potentially good cases for targeting and null cases accounting for the expected forecast error reduction. By no means do our conclusions intend to impeach the validity or accuracy of the contributed sensitivity calculation products, but rather the results question the use and interpretation made in decision-making frameworks such as the DTS-MEDEX-2009 targeting campaign, raising a concern to be considered in the design of future similar campaigns, perhaps within the HyMeX context.

How extra observations affect the analysis, and thereby the forecast, depends on the accuracy of the targeted observation, the number, type and configuration of other routine observations in the vicinity, and the specified background- and observation error statistics (Baker and Daley, 2000; Langland and Baker, 2004). Thus targeting exercises strongly depend on data assimilation issues (Kelly *et al.*, 2007) which suggest that targeted observation strategies require consideration of the data assimilation scheme in their planning (Majumdar *et al.*, 2011). It should be noted that the stochastic nature of data assimilation does not guarantee the benefits of targeting for individual cases, but targeted observations are expected to improve forecast skill in an average sense. Nevertheless, targeted observations are poorly effective when the forecast is already accurate and the baseline observation system is data-rich (e.g. Buizza *et al.*, 2007).

Overall, objective sensitivity products for targeting guidance should be informative about the forecast error reduction due to potential deployment of targeted observations. To address this problem, we suggest the use of well-designed OSSEs in combination with forecast sensitivity fields to observations. In this regard, Langland and Baker (2004) developed observation sensitivity methods with the adjoints of both a numerical model and a variational data assimilation system with a static background error covariance matrix, which allow assessment of the observational impact of assimilated observations. In an ensemble context, Ancell and Hakim (2007) demonstrated how this observation sensitivity field is consistent with ensemble sensitivity estimates of the impact of potential new observations as well as the equivalence, in the appropriate norm, to the ETKF (Bishop *et al.*, 2001).

In practice, targeting guidance involves significant approximations and restrictions. On the one hand, exhaustive sampling strategies are not affordable owing to technical and economic limitations. On the other hand, to predict the uncertainty in a future analysed model state using observations that are unknown ahead of time is an arduous task, as is determining the forecast error started from this unknown analysed model state (Langland, 2005). Furthermore, the ever-present linear assumptions in sensitivity analysis reduce successful targeting guidance to short time spans and large atmospheric features (Gilmour *et al.*, 2001; Reynolds and Rosmond, 2003).

Thus further research efforts must still be devoted to the refinement of objective methods to identify optimal locations and times for targeted observations to increase the average return of investments in targeting campaigns.

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