Sensitivity of North American Numerical Weather Prediction to Initial State Uncertainty in Selected Upstream Subdomains

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ABSTRACT

In this study the impact of initial uncertainty in localized regions on midrange forecast sensitivity over North America is studied. The local regions considered are the North American domain and two areas upstream, one covering the northeast Pacific and another extending farther west to include most of the North Pacific. The University of Utah Global Model and an estimate of initial uncertainty given by the differences between ECMWF and NCEP reanalyses are used. Control runs are performed with NCEP initial data globally. The effect of initial uncertainty on the control forecasts is simulated by a change of initial data from NCEP to ECMWF reanalysis first globally, and then only inside or only outside the selected domains. The impact of local initial uncertainty is quantified in comparison to the impact of initial uncertainty over the whole globe. Results from 17 cases show that regional state differences are less important than global state differences, unless the considered region covers most of the North Pacific.

1. Introduction

One effective manner of increasing forecast skill of numerical models is through a better specification of the initial state. The analysis of the initial state of the atmosphere is obtained by assimilating observational data into a model, and the result of the assimilation process is presumably in more error over areas with sparse data, where observations are mainly replaced by the model first guess.

It is still very costly to observe the whole globe with high resolution. The present observational network is relatively dense over land areas of the Northern Hemisphere, but is clearly deficient over the oceans and the Southern Hemisphere in general. Recent effort has been focused on what is most important to observe in the initial state, to produce the most benefit in model predictions.

To improve the skill of forecasts over a certain area, one strategy that has received particular emphasis is the targeting of regions of pronounced dynamical instability (or perturbation amplification) that affect the considered domain, enhancing local observations of the initial state there. Several studies suggest the feasibility of the methods without actually making added observations. Lorenz and Emanuel (1998) use a simple low-order model analog of the atmosphere and show that single targeted observations do lead to improved “forecasts” provided the targeted site is adequately chosen.

Calculations using singular vectors, adjoint methods, and other techniques identify areas where forecasts are most sensitive to perturbations in the initial conditions. When measuring forecast sensitivity in terms of total energy, small-scale structures indicate the places where initial uncertainty has a large impact. Palmer et al. (1998) provide comprehensive overviews of singular vector analyses and discuss the reasons that total energy is often used to describe forecast sensitivity. These results provide a method of selecting sites for the deployment of dense observational coverage. The sites would depend on the synoptic situation, and the technique is known as adaptive targeting (e.g., Bergot et al. 1999; Bishop and Toth 1999; Montani et al. 1999; Szunyogh et al. 2000). Adaptive or targeted observations focus on movable observing platforms such as aircraft, which can be deployed to those specific sites where the atmosphere might require additional observations.

Other studies emphasize the role of initial errors in the long waves of the initial fields. Miguez-Macho and Paegle (2000) contrast the impact of initial uncertainty in the large scales versus the effect of errors in the small scales. According to their results, uncertainty in the long waves causes misplacement of the embedded short waves, with a relatively rapid loss of predictive skill and this is more important on average than the triggering of barotropic or baroclinic instability by local errors in the initial conditions. The reduction of large-scale errors would require a very different approach than would
adaptive targeting since locally enhanced observational coverage would no longer be effective.

In this paper we focus on predictions over North America and investigate the effect of initial uncertainty in regions that include the North American domain itself, the northeastern Pacific and the complete North Pacific. The selected areas are fixed, and this represents a fundamental difference with other work relating the influence of local errors on regional forecasts. The size of the studied regions varies from the relatively reduced dimensions of the northeast Pacific domain to the large area containing most of the North Pacific. The estimate of initial uncertainty is given by the differences between European Centre for Medium-Range Weather Forecasts (ECMWF) and National Centers for Environmental Prediction (NCEP) reanalysis.

Seventeen cases are utilized for this study, corresponding to the winter season of 1993. Results are illustrated for the case of the 12–14 March superstorm and then extended for the full 17-case set. Section 2 of this paper briefly describes the University of Utah Global Model (referred to hereafter as the Utah Model) used in the experiments, the datasets, and the experimental setup. Section 3 presents results for experiments that test the impact of initial uncertainty over North America, whereas sections 4 and 5 depict effects of initial uncertainty over the northeast Pacific and more extensive North Pacific domains, respectively. Results from the present experiments relative to those from adaptive targeting experiments are discussed in section 6, and conclusions are summarized in section 7.

2. Model, datasets, and experiment design

a. Model

The model used for this study is a multilevel, baroclinic version of the global model described by Paegle (1989). The present integrations retain nodal spacing 2.22° latitude and 42 waves in longitude on 20 vertical levels.

The Utah model was originally designed to address predictability questions. It has been used to study the impact of wind data voids on objective analyses (Paegle and Horel 1991), for predictability studies (Vukicevic and Paegle 1989; Paegle et al. 1997), for idealized global simulations of tropical–extratropical interactions (Buchmann et al. 1995), to study topographically forced regional circulations (Nogués-Paegle et al. 1998), and to describe model accuracy for rainfall simulation (Wang et al. 1999). Error statistics for the Utah model are presented in Miguez-Macho and Paegle (2000), and individual forecast errors for the extreme case of the March 1993 North American “superstorm” are compared to NCEP model predictions by Miguez-Macho and Paegle (1999) and shown to possess similar characteristics.

b. Datasets

The initial state for the experiments is obtained from reanalysis datasets of NCEP (Kalnay et al. 1996) and ECMWF (Gibson et al. 1997). NCEP and ECMWF have performed gridded retrospective analyses, based upon assimilation of all available observations by a frozen state-of-the-art global data assimilation system. Our estimates of initial state uncertainty are obtained from the difference of these two equally credible analyses.

Seventeen cases were selected from January, February, and March of 1993, at 5-day intervals starting on 1 January. The period includes the case of the superstorm (12–14 Mar), a remarkable event that set several low pressure records from the Carolinas to the Canadian Maritimes (Dickinson et al. 1997). Simulations for this case are initialized on 10 March at 1200 UTC (rather than on 12 Mar), 84 h before the maximum storm amplitude displayed in Fig. 1 from Caplan (1995).

c. Experiment design

The purpose of the experiments is to study the impact of initial uncertainty in selected domains on forecast skill over a North American region. The selected domains are the North American region itself and two Pacific regions upstream of the North American validation domain: one covering a relatively small area west of the United States, and a second one extending farther west to include most of the North Pacific. Maps of the selected areas and further details are given in sections 3, 4, and 5. The duration of the simulations is 120 h.

For each case, a control integration is performed with initial data from NCEP reanalysis over the whole globe. A change of initial data from NCEP to ECMWF reanalysis simulates the effect of the estimated initial uncertainty on the control forecast. First, ECMWF initial conditions are used globally, and in further experiments, ECMWF initial data are employed only inside or outside the selected regions, with NCEP reanalysis data over the rest of the globe. The transitions between ECMWF and NCEP initial data are linearly interpolated over a zone that depends on the size of the considered domain.

The impact of global uncertainty in the initial conditions is estimated by the difference between the integration initialized with ECMWF data globally, and the control run, which has initial conditions from NCEP reanalysis over the whole globe. The impact of the local initial uncertainty on the forecast differences is estimated by comparing to the impact of initial uncertainty over the whole globe. The superstorm system illustrates the experimental results, and statistics are presented for the 17-case set.

3. Impact of initial uncertainty over North America

These experiments are intended to isolate the effect of initial uncertainty over North America for forecasts
validating over the same North American area. For this purpose, we perturb the initial conditions of the control experiment, which are from NCEP reanalysis, by changing them to ECMWF reanalysis data over a zone that extends from 140°W (eastern Pacific) to 62°W (western Atlantic) and 32°N (U.S.–Mexico border) to 61°N (northern Canada). The change between the two zones is done smoothly, with five grid points of linear transition. The considered domain, as well as the transition zone, are shown in Fig. 1.

We also perform complementary experiments, where the data change is done over the rest of the globe, leaving NCEP reanalysis initial data only inside the North American area. There are five points of linear transition zone as before. The validation region is slightly larger than the selected region and includes part of the transition zone. It is marked by a thicker line in Fig. 1.

**a. Superstorm case**

As discussed earlier, for this case the initial time for the simulations is 1200 UTC on 10 March. Figure 2a shows the initial differences in the meridional component of the wind at \( \sigma = 0.53 \) for the experiments initialized with ECMWF and NCEP reanalysis globally. Figure 3b reflects the forecast differences at 84 h, the time of maximum intensity of the superstorm. Initial differences only peak above 5 or below \(-5\) m s\(^{-1}\) in localized ocean sites, but produce 84-h differences up to 18 m s\(^{-1}\) close to the center of the superstorm. We emphasize the meridional wind component because forecast differences in this field reflect forecast differences of Rossby wave phase and amplitude.

Figure 3a shows the initial meridional flow differences at \( \sigma = 0.53 \) between the regional uncertainty experiment and the control, which uses NCEP reanalysis globally for the initial state. Initial uncertainty, given by the differences between ECMWF and NCEP reanalysis is now only apparent over the North American domain and gradually diminishes over the transition zone to become zero outside the considered region. Values peak at 6 and \(-7\) m s\(^{-1}\) over ocean sites of the border zone, and are smaller inside the North American area. Figure 3b shows differences at 84 h reaching \(-8\) and 8 m s\(^{-1}\) on the southeast corner of the considered region, about the position of the superstorm system. They also extend to the outside domain, mainly downstream of North America, but values do not increase significantly from initial differences.

The relatively small contribution of regional initial state modifications relative to global initial state modifications through 96 h suggests that the latter may be driven through the initial state differences outside the presently considered region. The next experiment tests this interpretation. This experiment uses NCEP reanalyses within the formerly considered region, and ECMWF reanalyses outside this zone for the initial state, with a linear transition border of five grid points.

Figure 4 shows initial (Fig. 4a) and 84-h (Fig. 4b) differences in the meridional flow at \( \sigma = 0.53 \), between the experiment and the control. Initial differences are zero inside the considered North American region, yet
Fig. 2. Meridional flow differences at $\sigma = 0.53$ between the experiment with initial data from ECMWF reanalysis over the whole globe and the control, initialized with NCEP reanalysis globally. (a) Initial time and (b) $t = 84$ h. Units are m s$^{-1}$ and the contour interval is 2 m s$^{-1}$. Negative contours are dashed. The North American validation domain is also outlined.
Fig. 3. Meridional flow differences at $\sigma = 0.53$ between the experiment with initial uncertainty over North America and the control, initialized with NCEP reanalysis globally. (a) Initial time and (b) $t = 84$ h. Units are m s$^{-1}$ and the contour interval is 2 m s$^{-1}$. Negative contours are dashed. The considered region and the transition zone, as well as the validation domain are also outlined.
Fig. 4. Meridional flow differences at $\sigma = 0.53$ between the experiment with initial uncertainty outside North America and the control, initialized with NCEP reanalysis globally. (a) Initial time and (b) $t = 84$ h. Units are m s$^{-1}$ and the contour interval is 2 m s$^{-1}$. Negative contours are dashed. The considered region and the transition zone, as well as the validation domain are also outlined.
FIG. 5. Variances of $v$ at $\sigma = 0.53$ computed over the North American domain. The solid curve shows variances for the experiment initialized globally from ECMWF reanalysis. Dotted curves are for the experiment with initial uncertainty over North America (closed circles) and the complementary case, perturbing the rest of the globe (open circles). Units are $m^2 \, s^{-2}$.

at 84 h the pattern looks very similar to that of Fig. 2b, which shows the forecast differences when the initial uncertainty is added globally. This suggests that the forecast differences in the validation domain are mainly driven by uncertainty outside that region.

To quantify the forecast difference of the experiments with respect to the control we use variances computed over the North American validation domain:

$$\text{variance} = \frac{\int_{\text{NAm}} (v_{\exp} - v_{\cont})^2 \, dA}{\int_{\text{NAm}} dA},$$

where $v_{\exp}$ is the meridional component of the wind for the considered experiment and $v_{\cont}$ for the control, which has initial data from NCEP reanalysis globally. This measure tends to be biased toward large-area perturbation domains.

Figure 5 shows these variances at $\sigma = 0.53$. The solid curve is for the experiment where the initial data change from NCEP to ECMWF was done over the whole globe. It has an upward trend until 96 h, reflecting the solution divergence between the experiment and the control, and it decreases sharply thereafter, when the superstorm exits the validation domain.

The dotted curve with closed circles in Fig. 5 corresponds to the experiment where the initial uncertainty is added only in the North American domain. At initial time the value is very close to the one for the solid curve, which reflects the effect of global initial data change. The validation domain is slightly larger than the targeted domain, since it includes part of the transition zone. The curve for the local uncertainty experiment barely grows from its initial value during the forecasts.

FIG. 6. Normalized variances of $v$ at $\sigma = 0.53$ computed over the North American domain. Curves are for the experiment with initial uncertainty over North America (closed circles) and the complementary case, perturbing the rest of the globe (open circles).

The variance of the meridional flow predicted by the experiment with initial differences outside the North American region, relative to that predicted by the control, is depicted by the dotted curve with open circles in Fig. 5. It starts very close to zero at initial time, but equals the effect of regional initial uncertainty (dotted curve with closed circles) at 1 day, and after that it evolves similarly to the curve for the experiment with initial uncertainty over the whole globe (solid curve), and shows growth until 96 h with a sharp decrease thereafter. The variance values are smaller than for the case of global initial uncertainty.

b. Statistics for the 17 cases

The same experiments were repeated for the 17 cases previously described. Variances of the meridional component of the wind are computed over the North American domain, and results are now normalized by dividing by the variance of the forecast meridional flow difference produced by initial state changes over the whole globe:

$$\text{normalized variance} = \frac{\int_{\text{NAm}} (v_{\exp} - v_{\cont})^2 \, dA}{\int_{\text{NAm}} (v_{\EC} - v_{\cont})^2 \, dA},$$

where $v_{\exp}$ is again the meridional component of the wind for the considered experiment, $v_{\cont}$ for the control, and $v_{\EC}$ for the experiment with initial data from ECMWF globally, or equivalently, with initial uncertainty over the whole globe.

Figure 6 shows the normalized variance evolution at $\sigma = 0.53$ averaged for the 17 cases. The curve with closed circles corresponds to experiments with initial uncertainty only inside the North American region. At
initial time the value is about 0.9, since the targeted region is slightly smaller than the validation domain. This curve has a continuous downward trend, and at 5 days the value reduces to 0.1. The initial uncertainty over North America apparently explains on average only about 10% of the forecast differences at 120 h caused by uncertainty over the whole globe.

The curve with open circles shows the effect of initial state uncertainty outside the North American domain. It starts from almost zero and at about 30 h equals the value for the experiments with uncertainty inside the selected region. It grows steadily throughout the period and reaches a value of 0.84 at 120 h. Initial state uncertainties outside the considered domain are clearly more important than uncertainties over that same region after about 36 h. The results in Fig. 6 are for the average, but they are also systematically true for each case considered.

4. Impact of initial uncertainty over the northeast Pacific

Similar experiments were repeated by considering regions focused mainly on the North Pacific data void. First we focus on the area of the northeast Pacific, extending from 160°W (Hawaii Islands) to 135°W (Alexander Archipelago in Alaska) and from 34°N (southern California) to 57°N (Alaska peninsula). This region includes the Gulf of Alaska, and it extends farther south to cover all the Pacific area west of the U.S. coast. There is a three-gridpoint-wide transition zone along the border, where the data go from being purely ECMWF inside the domain to purely NCEP outside (or vice versa) by linear interpolation. The perturbed area is therefore somewhat larger than the selected area. The considered region, as well as the transition zone, is shown in Fig. 7. The validation domain is the North American region, similar to experiments in section 3 (bordered by a thick line in Fig. 1 and Fig. 7).

The experiments are intended to determine effects of initial uncertainty over the region immediately upstream of North America. We also choose this area because there have been several experiments such as the North Pacific Experiment (NORPEX; Langland et al. 1999) and the Winter Storm Reconnaissance Program (WSRP; Szunyogh et al. 2000) to assess the effect on forecast skill over the United States of extra observations taken in this region. Further discussion of their results in comparison with results of the present study is given in section 6.

a. Superstorm case

Figure 8a shows meridional wind perturbation at $\sigma = 0.53$, given by the differences between ECMWF and NCEP reanalyses. The values of the differences peak at 4 and $-4 \text{ m s}^{-1}$ and cover only the targeted region and border zone. The forecast differences at 84 h between the experiment and the control are depicted in Fig. 8b. Differences extend downstream of the northeast Pacific region to cover the North American domain, but are...
Fig. 8. Meridional flow differences at $\sigma = 0.53$ between the experiment with initial uncertainty over the northeast Pacific region and the control, initialized with NCEP reanalysis globally. (a) Initial time and (b) $t = 84$ h. Units are m s$^{-1}$ and the contour interval is 2 m s$^{-1}$. Negative contours are dashed. The considered region and the transition zone, as well as the validation domain are also outlined.
significantly smaller than those caused by global initial uncertainty (Fig. 2b).

Figure 9 is similar to Fig. 8 but for the complementary experiment, perturbing the areas outside the northeast Pacific. Initially (Fig. 9a), differences are zero only inside the selected region. At 84 h (Fig. 9b) forecast differences are apparent everywhere and greatly resemble those in Fig. 2b, induced by initial uncertainty over the whole globe.

Forecast differences for the regional initial uncertainty experiment (Fig. 8b) and its complement (Fig. 9b) approximately additive to the total forecast difference represented in Fig. 2b, suggesting linearity in the growth of perturbations until 84 h.

We again quantify the forecast divergence over North America between the experiments and the control by computing the variance of the meridional wind. The values at $\sigma = 0.53$ are shown in Fig. 10. At initial time, the variances for the regional uncertainty experiment are close to zero, since the validation region only includes part of the targeted region and the contiguous transition zone. The curve grows steadily and at 84 h (time of maximum intensity of the superstorm) reaches a value of about 40% of that for the experiment with initial uncertainty over the whole globe.

The curve for the complementary experiment, where the initial uncertainty covers the whole globe except for the considered region, starts with a value close to the value of the experiment with initial uncertainty globally, and it follows a trend similar to that curve throughout the 5-day period, with smaller values. At 84 h, the initial uncertainty outside the considered region causes a forecast divergence that is 70% of the experiment with global initial uncertainty. The linearity is clearly lost after 84 h, and the curves for the regional initial uncertainty experiment and the complementary experiment no longer add up to the curve for the experiment with uncertainty covering the whole globe.

In this case, the targeted northeastern Pacific region appears to have an effect on the forecast over North America. While the regional uncertainty experiment and its complementary case evolve quasi-linearly, the uncertainty over the northeastern Pacific region explains up to 40% of the total forecast divergence, including time of maximum intensification of the superstorm (84 h).

b. Statistics for the 17 cases

Similar experiments were performed for the 17 case sample. Figure 11 shows the averaged variances of the meridional component of the wind at $\sigma = 0.53$ computed over North American domain. The results are again normalized by dividing by the variance of the forecast meridional flow difference produced by initial state changes over the whole globe.

The curve with closed circles corresponds to experiments with initial uncertainty only inside the northeastern Pacific targeted region. At initial time the variances for these experiments are only about 19% of the one for the total, because the validation domain only composes part of the targeted region and border zone. The curve barely grows throughout the 120-h period of the simulations, and at 5 days its value is about 23% of the one for the experiments with uncertainty over the whole globe.

The curve with open circles is for experiments with initial uncertainty outside the considered region. The initial values are around 0.73 and after a slight decrease in the first 60 h to a minimum of 0.59, they rise to a value of 0.8 at 5 days.

Both curves add up to approximately 1 throughout the 5-day period, consistent with linearity in the growth of errors. This was not true for the later period of the simulations for the superstorm, but appears to characterize the average. We can consequently interpret the values of the curves as fractions of the total forecast differences due to the uncertainty over the targeted region or outside of it. The initial uncertainty over the northeastern Pacific explains at 5 days about 23% of the forecast sensitivity caused by uncertainty in the initial conditions over the whole globe. This value is smaller than for the case of the superstorm. The initial uncertainty over the rest of the globe explains about 80% of the sensitivity to global data change. The relative effect of northeast Pacific perturbations reaches its maximum of almost 30% at 84 h, when the complementary region accounts for 68% of the global impact.

The results for the individual cases reflect more spread with respect to the average than when considering the North American region. In 10 out of 17 cases the effect of initial uncertainty over the northeast Pacific is very small, and variances barely grow from their initial value. For the other seven cases the impact is larger but in each case smaller than the impact of initial uncertainty over the rest of the globe. The superstorm case produced the largest impact.

The fact that there is more spread in the results for the northeast Pacific perturbations than for the North American perturbations is not surprising, since, in most cases, forecasts over North America are more sensitive to perturbations upstream (as these and other results confirm). It might also be argued that the larger spread reflected by the increased impact in 7 out of 17 cases is consistent with the possibility that the primary regions of sensitivity may be small scale, though they are not always located within this northeast Pacific domain.

5. Impact of initial uncertainty over a more extensive North Pacific region

Initial uncertainty in the Pacific area immediately contiguous to the North American validation domain appears to explain a reduced fraction of the total forecast divergence. In this section we extend the considered region much farther upstream, to cover the North Pacific
FIG. 9. Meridional flow differences at $\sigma = 0.53$ between the experiment with initial uncertainty outside the northeast Pacific region and the control, initialized with NCEP reanalysis globally. (a) Initial time and (b) $t = 84$ h. Units are m s$^{-1}$ and the contour interval is 2 m s$^{-1}$. Negative contours are dashed. The considered region and the transition zone, as well as the validation domain are also outlined.
from 154°E (Kuril Islands) to 129°W (British Columbia coast), and from 25°N (north of Hawaii) to 54°N (north of the Aleutians). The transition zone between the selected area and the outside domain is five grid points wide. The considered region with the border zone, as well as the validation domain, are presented in Fig. 12.

a. Superstorm case

Figure 13a shows the initial uncertainty over the selected region, in terms of the meridional component of the wind at $\sigma = 0.53$. The differences between the two reanalyses are larger over areas with sparse observational coverage such as the North Pacific, and peak at 8 and $-8$ m s$^{-1}$. These initial differences propagate downstream and amplify to a value of $-14$ m s$^{-1}$ over the southern United States at 84 h (Fig. 13b).

Similar diagrams for the complementary experiment, with uncertainty over the rest of the globe are shown in Fig. 14a ($t = 0$ h) and Fig. 14b ($t = 84$ h). At initial time, differences are only absent inside the North Pacific region. At 84 h, over the validation domain the pattern
FIG. 13. Meridional flow differences at $\mathcal{O} = 0.53$ between the experiment with initial uncertainty over the North Pacific region and the control, initialized with NCEP reanalysis globally. (a) Initial time and (b) $t = 84$ h. Units are m s$^{-1}$ and the contour interval is 2 m s$^{-1}$. Negative contours are dashed. The considered region and the transition zone, as well as the validation domain, are also outlined.
Fig. 14. Meridional flow differences at $\sigma = 0.53$ between the experiment with initial uncertainty outside the North Pacific region and the control, initialized with NCEP reanalysis globally. (a) Initial time and (b) $t = 84$ h. Units are m s$^{-1}$ and the contour interval is 2 m s$^{-1}$. Negative contours are dashed. The considered region and the transition zone, as well as the validation domain, are also outlined.
is similar to that of Fig. 2b, caused by initial differences over the whole globe, with smaller values.

Time evolution of variances of $\nu$ with respect to the control experiment at $\sigma = 0.53$ is shown in Fig. 15. The control experiment is again initialized with NCEP reanalysis data over the whole globe and the validation domain is the North American area (thick line in Fig. 12). The solid curve is for the experiment with initial data from ECMWF globally, or equivalently, with initial uncertainty over the whole globe. This curve is the same as in Figs. 4 and 10.

The curve with closed circles corresponds to the experiment with initial uncertainty in the North Pacific region. It starts at about 2 m$^2$ s$^{-2}$, about half of the value for the solid curve. The reason for this relatively high value is that the east portion of the considered region overlaps the validation domain. This common area is not very extensive, but it has larger values of uncertainty than the area over land. The curve follows an upward trend until 96 h and then decreases, similarly to the curve for the experiment with initial global uncertainty, but the values are smaller. At 84 h (time of maximum intensity of the superstorm) the variance for the regional uncertainty experiment is slightly larger than 50% of the experiment with initial uncertainty over the whole globe.

The curve with open circles shows the impact of initial uncertainty outside the North Pacific region. It departs from a value only slightly larger than that of the experiment with initial uncertainty inside the considered region. Again, the reason is that the outside region covers mainly continental areas of the validation domain (Fig. 12), where ECMWF and NCEP reanalysis are in better agreement and uncertainty is reduced. The curve follows the same trend as the one for the regional uncertainty experiment, but with smaller values. At 84 h its value is very similar, about 50% of the case for the experiment with initial uncertainty globally.

The curves for the regional uncertainty experiment and its complementary case approximately add up to that for the experiment with initial uncertainty over the whole globe, especially before 96 h. This indicates linearity in the growth of solution divergence, and allows interpretation of the impacts of experiments as fractions of total forecast difference explained. The uncertainty over the North Pacific explains most of the forecast divergence, but the fraction explained by the outside uncertainty is not negligible and of the order of 50% at 84 h.

### b. Statistics for the 17 cases

Figure 16 shows the average normalized variance of $\nu$ at $\sigma = 0.53$ for the 17-case set. The curve for the experiment with initial uncertainty over the North Pacific (closed circles) has the largest values after initial time. They grow from 0.5 in the earlier times to about 0.75 at later times. The effect of initial uncertainty over the rest of the globe is depicted by the curve with open circles. Values decrease from 0.6 at initial time to 0.25 at 48 h, and then slowly rise again to 0.47 at 120 h. Linearity is kept in the sense described before, since both curves approximately add up to one until late in the 5-day period. The errors in the North Pacific appear to be important for the forecast skill over North America, as they explain on average about 75% of the forecast divergence after 48 h.

### 6. Discussion of results relative to adaptive targeting

Results from present experiments can be related to those from studies of adaptive targeting of the initial state. This is particularly so for the experiments to in-
vestigate the effect of initial uncertainty over the northeast Pacific. The northeast Pacific area perturbed in the present study is fixed, but it includes approximately the coverage of extra observations from several adaptive targeting experiments [NORPEX, Langland et al. (1999); WSRP, Szunyogh et al. (2000)] carried out in that region. The magnitude of the perturbations used in this study, given by the differences between ECMWF and NCEP reanalyses, and the perturbations introduced in the analysis by the targeted observations, are also comparable (analyses including WSRP experimental data were kindly provided by Dr. K. Mo and these were used to determine the impact of extra observations on analyses).

The key idea underlying adaptive targeting techniques is that uncertainty in localized areas might be responsible for most of the forecast error. The locations where forecasts are more sensitive to errors in the initial conditions are identified with several methods, sometimes using the adjoint of a model.

Once a measure of the forecast error has been defined, using the adjoint of the linear propagator of a model, one can calculate the field of sensitivities of that measure with respect to small perturbations of the variables of the model at initial time. Knowing where the model forecast is more sensitive to perturbations in the initial conditions suggests the idea of adding observations there to reduce forecast error, provided that the regions of high sensitivity are localized.

Sensitivity analyses with the adjoint and the measure of forecast error employed are closely related to singular vector calculations and the metric used in those, and have also been used to determine sites for extra observations (Bergot 1999; Pu and Kalnay 1999). As in the case of singular vectors, different measures of error give different sensitivity fields. Because the most common variables to validate forecasts are temperatures and winds, the commonly used measure is total energy. For this norm, the regions of high sensitivity sometimes appear as localized structures, which indicate the sites for the additional data coverage.

The sites of high sensitivity for a selected norm do not necessarily correspond to those where the analysis error is largest. The adjoint calculations are based on linearizations that are more accurate for smaller perturbations and shorter-range predictions. In areas of strong sensitivity, even small analysis errors produce a large impact.

Rabier et al. (1996) use adjoint methods to determine sites that cause the greatest error in the 2-day forecasts of the ECMWF model. The adjoints determine corrections of the initial state required to minimize 2-day forecast error. Those corrections commonly appear as localized small-scale structures, that, when implemented to initialize new model forecasts correct, on average, about 10% of the day 2 forecast error and somewhat more than this at later times.

Pu et al. (1998) used data from U.S. Air Force drop-windsonde experiments carried out over the northeast Pacific off the coast of Oregon. Their diagram 2 shows that the forecast errors were reduced as much as 20% in two out of nine cases and less than that in other cases. However in four out of the nine cases the extra data had no impact, and in one case there was a degradation of the forecast over the United States.

Further experiments, like Fronts and Atlantic Storm Tracks Experiment (FASTEX) or NORPEX specifically designed to test the adaptive targeted observations techniques, show mixed results. During FASTEX in January–February 1997, adaptive sampling strategies proposed by various groups were tested (Emanuel and Langland 1998). The Naval Research Laboratories calculated areas of high sensitivity using their model adjoints and obtained improvement in some forecasts but degradation in others (Emanuel and Langland 1998). Météo-France also used an adjoint technique, obtaining a large spread in results, with a mixture of improvements and degradations of the forecasts at different geographical locations. The impact of the extra observations on the forecast was similar to the error of the analysis used for verification (Bergot 1999). The ECMWF strategy, based on their model adjoint, produced for five cases an average improvement of 15%. When the verification region was increased to include either Europe or North America, the positive impact of extra data was less marked (Montani et al. 1999). NCEP used a different technique, founded on the ensemble transform method, but also achieved little systematic improvement of the forecasts (Emanuel and Langland 1998), with a maximum forecast-error reduction on the order of 10% (Szunyogh et al. 1999b). Some results for NORPEX, a similar experiment carried out over the northeastern Pacific in January–February 1998, show that the NCEP ensemble transform method produces an average positive impact of about 5% in the forecast in 10 cases. One case had a maximum improvement of about 20%, and two cases showed a negative impact of about 10% and one no impact at all (Szunyogh et al. 1999a, Fig. 2).

These results from the experimental tests of the theoretical identification of sites for extra observations do not contradict the ones from our study. They also show mixed impact of the extra observations in selected sites, with an improvement of the forecast skill over the considered region that on average is not very large. However, the comparison might not be so straightforward. Their validation regions have smaller sizes than the one used in this paper, even though some adaptive targeting studies report a positive impact of extra observations on domains as large as North America (Montani et al. 1999). Our results refer to predictions in the midrange, up to 5 days. Adaptive targeting studies usually apply to shorter-range predictions, of up to 2 days, with unclear results when extending in the midrange (Bergot 1999).

Our approach was also rather different, as described in this paper. We form an estimate of initial uncertainty,
given by the differences between the two equally credible analyses of ECMWF and NCEP. This estimated initial uncertainty is of the same order of magnitude as the corrections in the analysis introduced by extra observations. Then, we perform experiments to determine the influence of uncertainty over certain regions versus the impact of the uncertainty over the rest of the globe. Our results show that regional state differences are less important to North American forecasts than global differences, unless the considered region covers most of the North Pacific.

This, of course, does not prove that the important forecast errors are those possessing relatively large scale. It is possible that the important differences or structures that significantly affect the forecasts may be relatively small-scale ones that are simply embedded within this larger North Pacific domain. The present approach in which one analysis of the initial state is simply “transplanted” within another does not directly address these issues.

7. Summary and conclusions

In this paper we focused on forecast sensitivity over a North American domain and investigated the effect of initial uncertainty in different regions. The estimate of initial uncertainty is given by the differences between the ECMWF and NCEP reanalyses.

First we studied the impact of initial errors over the North American verification domain. Those errors appear to have a decreasing impact, and at 5 days they explain only 10% of the forecast sensitivity. The errors outside the North American region on the other hand have a growing effect, so that they become more important than the ones over North America by 36 h, and at 120 h they explain about 90% of the total forecast divergence.

This does not mean that observations over North America are not important for predictability over the same region. It simply indicates that the current observational coverage reduces the errors sufficiently, so that the loss in skill comes mainly from uncertainty in others parts of the globe after 24–36 h. Again, this conclusion relies on the validity of our estimate of initial errors, as well as on the adequacy of the model and the resolution used. Other models run at higher resolution may produce different results.

The impact of initial uncertainty over the northeast Pacific is larger, accounting for about 25% of the total forecast divergence throughout the 120-h period. However, the spread in the results for the different cases is greater than when considering the North American region. For most cases, the impact is minimal and the variances barely grow from the initial value. For some cases, like the superstorm, there is a larger impact, even though the effect of errors outside the selected local region is always largest.

For selected situations, the initial state uncertainty over the northeast Pacific can have larger impact on forecasts over North America, but this is generally smaller than the impact of errors over the rest of the globe. According to our results, better data coverage of the complete North Pacific would be necessary to significantly reduce forecast errors over North America. This can be deduced from the large fraction (up to 75% after 48 h) of the total forecast sensitivity explained by the experiments with initial uncertainty over a more extensive North Pacific region.

Our results raise other questions, which require further research. The forecast difference patterns of Figs. 3b, 8b, and 13b have remarkably similar phase, although they have different amplitudes and are excited by very different perturbations to the initial state. One explanation is that the same sensitive local perturbation is being excited to varying degrees in each experiment. Another explanation is that the superstorm developed from a rapidly growing, in situ instability whose properties may depend strongly on the character of the large-scale background flow. Each of the three zones targeted in the initial states of these experiments includes, or is near the upper-tropospheric potential vorticity maxima identified as the roots of the storm by Bosart et al. (1996), and the present experiments lend some credence to both possibilities, but further study is required for more definitive conclusions. Such studies should incorporate more detailed models, including higher resolution than used presently.

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