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ADJOINT-BASED TARGETING OF OBSERVATIONS
FOR FASTEX CYCLONES

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1. INTRODUCTION

Recent development of adjoint versions of numerical weather prediction models makes possible a number of new diagnostic and interpretive techniques that can be applied to atmospheric forecasting. For example, adjoint models can be used to evaluate conceptual ideas of atmospheric processes, including considerations of potential vorticity and the Charney and Eady problems that relate to extratropical cyclone development (Langland et al. 1995)

In addition, the sensitivity of forecasts to initial condition error can be studied with adjoint methods, providing insight into atmospheric predictability. A related problem is the idea of using an adjoint model to "target" specific upstream locations where additional observations are likely to have maximum impact on forecast skill. The work described here is performed with the goal of assisting the Fronts and Atlantic Storm Track Experiment (FASTEX), which has a field phase in January and February 1997.

Patterns of initial condition sensitivity in four North Atlantic frontal cyclones are examined using adjoint and tangent linear versions of the Navy Operational Global Atmospheric Prediction System (NOGAPS, Hogan and Rosmond 1991), and the Mesoscale Adjoint Modeling System Version 1 (MAMS1, Errico et al. 1994). In MAMS1, moist processes, including convective and nonconvective precipitation are included. NOGAPS is run at T79L18 resolution, MAMS1 with 60km grid spacing and 14 sigma levels.

2. DEFINITION OF ADJOINT SENSITIVITY

An adjoint variable represents a gradient of a scalar forecast aspect J with respect to the model initial conditions. For example $\partial J / \partial T$ (t=0 h) can represent the sensitivity of J (at t=48 h) to perturbations of temperature (at t=0 h), and is obtained by a 48 h integration of the adjoint model backwards in time. The adjoint model is the transpose of a tangent linear model (TLM), and is not a direct inverse method or an integration of the nonlinear forward model or TLM backward in time.

In these experiments, we define J as average vorticity in a vertical column in the lower troposphere

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(below 650 hPa) in a localized region at the position of the cyclone at the end of a 48 h model forecast. In real-time targeting, J is a surrogate for the forecast error at the cyclone location, since the actual forecast error will be unknown.

A first-order estimate of the nonlinear change in J is obtained by a dot product of an initial condition perturbation with the adjoint sensitivity gradient:

$$J'_{48} = x'_0 \cdot \frac{\partial J}{\partial x_0} \quad ,$$

where subscripts $(_0)$ and $(_{48})$ indicate 0 h and 48 h, respectively. The perturbation vector x_0' can represent small magnitude perturbations of the model initial variables at any number of grid points.

3. A TARGETED OBSERVING STRATEGY

We have examined sensitivity patterns in four FASTEX type-cyclones.

1: 00UTC 20 Jan - 00UTC 22 Jan 1995 *
2: 12UTC 01 Feb - 12UTC 03 Feb 1994
3: 12UTC 11 Jan - 12UTC 13 Jan 1993
4: 00UTC 14 Oct - 00UTC 16 Oct 1987

Each of these cyclones begins as a small-scale frontal wave in a baroclinic zone in the mid or western North Atlantic and intensifies towards the end of the North Atlantic storm track. Here, we present adjoint sensitivity for the 20-22 Jan 1995 cyclone. Sensitivity for the remaining storms is similar in many respects to that described here.

The 48 h nonlinear (MAMS1) forecast ending at 00UTC 22 Jan 1995 places a cyclone in the North Sea between England and Norway (Fig. 1) with associated vorticity of about 24 x 10^{-5} s^{-1} near 850 hPa.

As determined by the (moist) MAMS1 adjoint, the location of strongest initial condition (-48 h) sensitivity is located between 500-800 hPa in a region roughly bounded by 50°-55° N and 45°-60° W ("target area" in Fig. 2a). Sensitivity from a dry version of the MAMS1 adjoint (not shown) is very similar in terms of sensitivity location, but has roughly half the magnitude, since perturbation growth is smaller in the absence of moist processes.

The NOGAPS adjoint results (Fig. 2b) indicate an observational target area quite similar to MAMS1. Here, the adjoint does not include moist processes, but is linearized with respect to a full physics T79
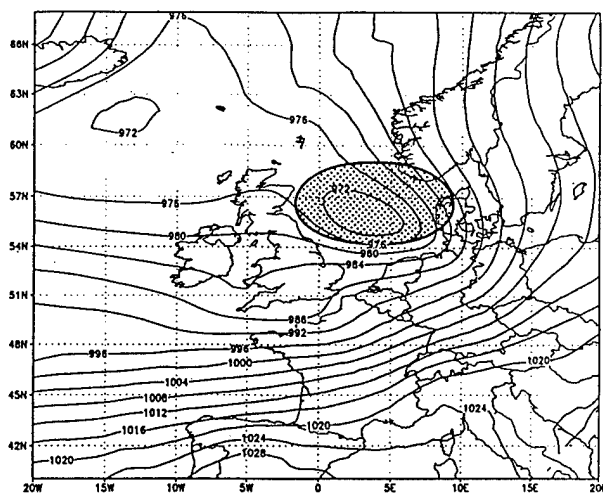
Fig. 1: Sea level pressure (hPa), 48 h MAMS1 fcst valid at 00UTC 22 Jan 1995. Forecast aspect J is vorticity between 650 hPa and surface in shaded region.

Fig. 3: Maximum adjoint sensitivity magnitude in MAMS1 domain valid at 00UTC 20 Jan 1995 (-48 h). $\partial J/\partial T$ (heavy dash, s^{-1} deg^{-1}), $\partial J/\partial u$ (thin dash, m^{-1}), $\partial J/\partial v$ (thin solid, m^{-1}). All values multiplied by 10^8. Symbols indicate model levels.

nonlinear basic state. This comparison demonstrates that the dry adjoint of a global model at T79 resolution can be used to identify the primary sensitivity for FASTEX-type cyclones.

The box outlined in Fig. 2 corresponds to the area where small magnitude changes to initial conditions (temperature, wind, mixing ratio) in the middle and lower troposphere have greatest impact on the cyclone forecast. If we assume that analysis error does exist in the upstream target region, then additional observations can improve the initial conditions and thereby reduce forecast error.

In general (for the four FASTEX cases examined), sensitivity to temperature is greater than to zonal or meridional wind components (for unit perturbations, °C, m s^{-1}), especially in the region of maximum sensitivity between 500 and 800 hPa (Fig. 3). This implies that for these types of baroclinic developments *errors in initial thermal structure in the middle and*
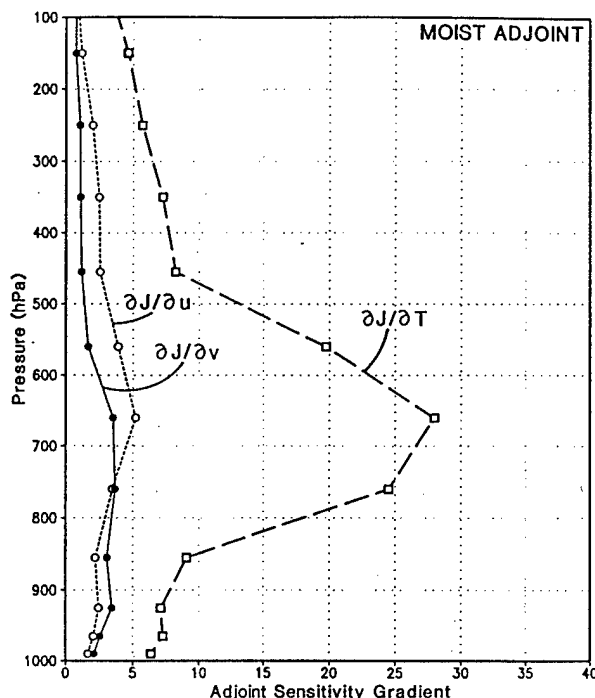
lower troposphere are potentially more significant than wind errors, and can be more significant than errors above 500 hPa, unless the analysis error is much larger (5-10 times) in the upper troposphere.

To verify the sensitivity, a nonlinear run of MAMS1 is made, in which the initial temperature is *perturbed by 1°C* on one model level (760 hPa) in a square of nine grid points near 53°N 48°W (shaded area in Fig. 4). In this same location of maximum temperature sensitivity, there is strong sensitivity to perturbations of meridional wind and mixing ratio (not shown). Also,
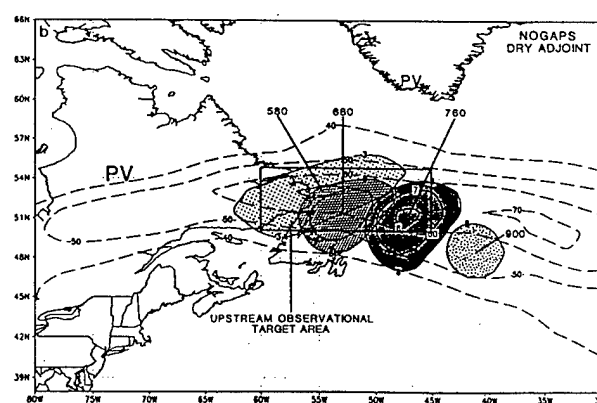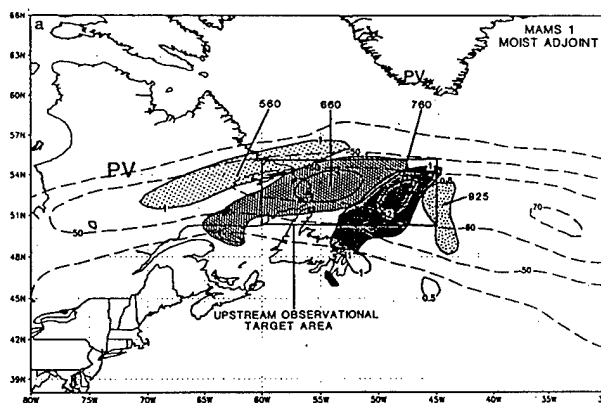

Fig. 2: Sensitivity to initial temperature ($\partial J/\partial T$) valid at 00UTC 20 Jan 1995 (-48 h) at indicated pressure levels, shown by shaded areas and solid contours: (a) MAMS1 moist adjoint, units are 10^{-7} s^{-1} deg^{-1}; (b) NOGAPS dry adjoint, units are 10^{-9} s^{-1} deg^{-1}. Dashed lines are initial 250 hPa wind speed (only values greater than 40 m s^{-1} are shown). PV indicates location of maximum potential vorticity at 250 hPa level.
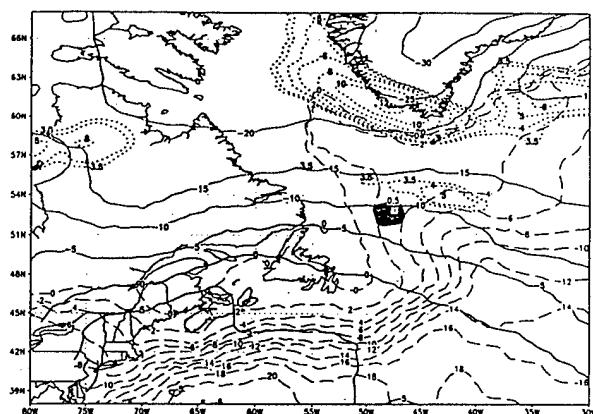
Fig. 4: Initial 760 hPa temperature (heavy solid contours, °C), and sea surface temperature (long dashed contours, °C). **Shaded region near 53°N, 48°W indicates area of 1° C initial condition temperature perturbation used in forecast for Fig. 5.** Dotted contours correspond to initial vorticity (10^{-5} s^{-1}) at 760 hPa. Valid at 00UTC 20 Jan 1995.

in this area, a region of enhanced vorticity in the lower troposphere exists above a warm sea surface temperature anomaly (Fig. 4).

The 48 h forecast difference in 925 hPa vorticity (perturbed nonlinear minus control nonlinear) is shown in Fig. 5. The magnitude and localization of the forecast perturbation over the region of the 48 h cyclone is remarkable (compare to Fig. 1), given the small amplitude and extent of the initial temperature perturbation. Sea level pressure decreases by 0.4 hPa (not shown), and zonal wind above the cyclone at 350 hPa is modified by -0.6 to 0.4 m s^{-1} (Fig. 5).
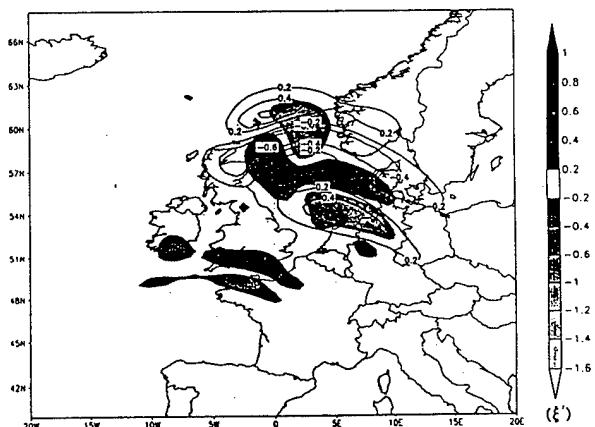

Fig. 5: Difference between 48 h nonlinear forecasts perturbed as in Fig.4 and nonperturbed forecast: 925 hPa vorticity (shaded, 10^{-5} s^{-1}); 350 hPa zonal wind (contour = 0.2 m s^{-1}). Valid at 00UTC 22 Jan 1995.

The temperature perturbation shown in Fig. 4 projects strongly onto a growing instability that forms the cyclone observed in the North Sea 48 h later. Initial condition perturbations of similar magnitude only a small distance away (outside the localized region of strong sensitivity) have much less impact on

the cyclone forecast.

During the FASTEX field phase, it will be possible to provide this type of adjoint-based sensitivity information in real-time, allowing aircraft or other observational platforms to be directed to upstream locations of strong initial condition sensitivity along the cyclone trajectory.

It is also noted that the NOGAPS sensitivity results obtained here using J = vorticity provide similar guidance as singular vector patterns which maximize perturbation energy at 48 h over the cyclone position. Thus, for this type of observational targeting application, the additional computational expense of singular vector calculations may not be necessary.

4. DISCUSSION

Adjoint methods allow initial condition sensitivity to be identified in a systematic and computationally efficient manner, and *provide insight into the cyclone life cycle that would be difficult or impossible to obtain from observational or diagnostic studies alone.* Adjoint sensitivity pertains to perturbations that *will grow* (in this case over 48 h), which do not necessarily correspond to features such as jet streak or potential vorticity anomalies, which are *already developed at initial time.*

The sensitivity results described here imply that the Eady model representation of cyclogenesis in terms of tropopause and "surface" anomalies alone may not be appropriate for targeting observations over periods as long as 48 h, because forecast error growth can be dominated by small initial errors in the middle and lower troposphere, especially in the early phase of the cyclone life cycle. The cyclone life cycle may be viewed in terms of an initially small-scale instability that propagates upward from a baroclinic zone in the lower troposphere, leading to intensification of larger-scale anomalies in both the upper and lower troposphere at the end of the storm track.

5. REFERENCES

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