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SENSITIVITIES OF AN INTENSE CYCLONE OVER THE WESTERN MEDITERRANEAN

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1. INTRODUCTION

The Mediterranean region is a very active cyclogenetic area. Although most Mediterranean cyclones are not significant in the sense of producing hazardous weather, Jansà et al. (2001) show that in more than 94% of the heavy precipitation events in the Western Mediterranean, a cyclonic center is present within 600 km. A particularly damaging type of cyclone is the north African baroclinic low. They originate over north Africa under a deep tropopause fold and low levels Atlantic cold advection. The surface low then moves northward to the Mediterranean sea, where evaporation enhances the diabatic heating from condensation. As a result, strong winds and floods produce catastrophic damage across the Western Mediterranean basin.

The identification of the upstream features that most affect the numerical forecast of these events is extremely useful in numerical prediction and especially in this area where the numerical forecasts are typically hampered by the lack of observations over the Atlantic Ocean, north Africa and the Mediterranean Sea. The adjoint model of the tangent linearization to the full non-linear model provides an excellent tool to determine the sensitivities of a particular feature of interest (*response function J*). Given a particular response function, the adjoint model traces back its sensitivity, computing the gradients of the response function to the initial and boundary conditions.

However, the application of the adjoint model has limitations that must be considered carefully. The adjoint states are tangent linear and no information can be deduced about the sensitivities of the nonlinear evolution of perturbations. Thus, a measure of the accuracy of the tangent linear model for each sensitivity study should be addressed to confirm the validity of the linear results in the actual nonlinear evolution. This is particularly important when moist physics and convection strongly influence the response function chosen (Errico and Raeder, 1999).

The aim of this study is to determine the areas and fields to which the simulation of a destructive north-African Western Mediterranean cyclone shows the highest sensitivities. As a test of the suitability of the linear models in reproducing the main aspects of the event, comparison between linear and nonlinear perturbation forecasts are compared. Once the range of validity for the sensitivities is set, interpretation of the sensitivities, showing the highlighted aspects of the IC is done.

2. NUMERICAL CONFIGURATION

The Penn State-NCAR nonhydrostatic mesoscale modeling system version 5 is used to perform all the simulations presented in this study. A limited number of physical parameterization scheme options are available in the adjoint and tangent codes compared to the full nonlinear model. The domain configuration is 71x71 points at 60km-resolution, covering all the Western Mediterranean, north Africa, northwest Atlantic Ocean and Europe. In the vertical, 23 σ levels are used. Although a 180s timestep is used in the nonlinear model, the linear models require the use of shorter 120s timestep to avoid numerical instabilities. In order to analyze how the sensitivity fields change with integration time, four time spans are used during the study: 12, 24, 36, 48 hours.

The most relevant parameterizations used for this study are the microphysics and convective schemes. The Grell et al. (1995) convective parameterization and the microphysics scheme of Dudhia (1989) are used in both nonlinear and adjoint runs. However, the tangent linear code currently available includes a more limited set of options and a modified version of the Kuo (1974) scheme and a simple removal of the large-scale saturation have to be used. These limitations are critical to the validation of the adjoint results, since no identical configuration can be used in the tangent linear model, used to validate the accuracy of the linear forecast, and in the adjoint. Thus, an additional validation of the adjoint results, especially for the moisture field, is conducted by perturbing the nonlinear runs using perturbations derived from the sensitivity fields.

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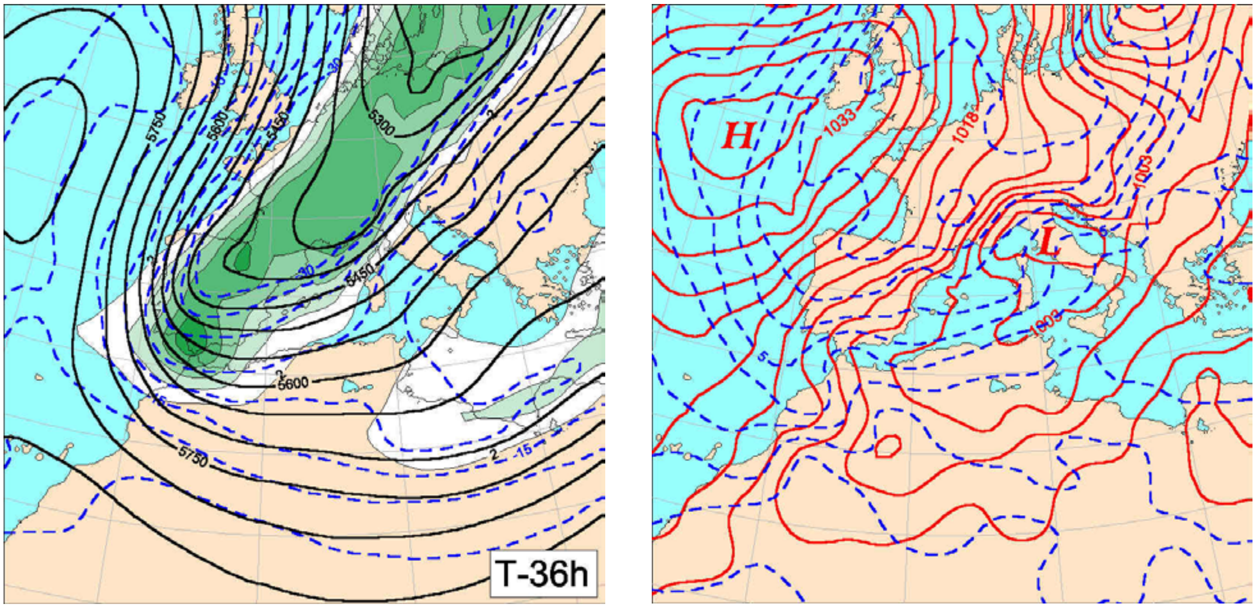

Figure 1. NCEP analyses at 1200 UTC 9 November. Left panel show geopotential height (m, black) and temperature (^{o}C, blue) at 500 hPa, and PV (PVU=10^{-6}Km^{2}s^{-1}, green shaded) at 250 hPa. Right panel show sea-level pressure (hPa, solid) and temperature (^{o}C, blue) at 850 hPa.

3. SYNOPTIC OVERVIEW

During 9 and 10 November 2001 more than 700 people were killed, thousands injured and about 23,000 homes destroyed from damaging winds and severe flash floods in Algeria. Strong winds and persistent rainfall also affected the Balearic Islands on November 11, producing 4 casualties, the uprooting of about 220,000 pines and the removal of 60% of beach sand. Insurance companies estimated a total of more than 100 M€ in private property damage.

The synoptic situation on 1200 UTC 9 November 2001 shows a large positively-tilted upper-level cold trough covering Europe and extending southward over north Africa (Fig. 1a). At surface, a weak low-pressure area over the Western Mediterranean is associated with a secondary upper-level wave identifiable east of the basin (Fig. 1b). Cold advection is identifiable throughout Spain, Morocco and north Algeria,

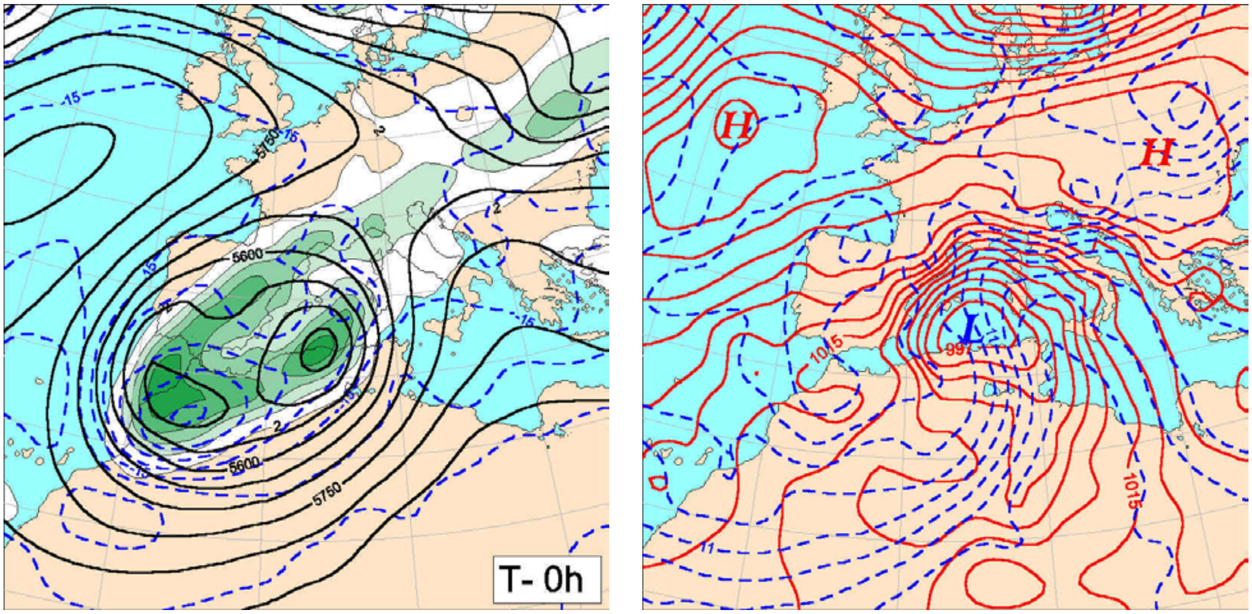

Figure 2 As Fig. 1 but at 0000 UTC 11 November.

tightening the temperature gradient over north Africa. Under the dynamic forcing of the eastern upper-level PV center, within a baroclinically unstable region, an intense low-level cyclogenesis occurs over Algeria on November 10. Steered by the upper-level flow, the cyclone follows a northern trajectory evolving over the western Mediterranean Sea, where latent heat from condensation plays an important role in sustaining the cyclone intensity (Arreola et al. 2003). The maximum intensity of the analysis is observed at 0000 UTC 11 November an this is selected as the *sensitivity time* along this study.

This analysis of the evolution suggests that the upper-level trough over Europe and the low-level cold invasion over north Africa are key features in the development of the intense cyclone and so high sensitivity is expected from the adjoint results over these regions.

4. VALIDATION

The skill of the adjoint (ADJ) and tangent linear (TGL) models is tested by analyzing the accuracy of the TGL in reproducing the nonlinear evolution of perturbations. In order to focus upon the cyclone, an adjoint run with all variables initialized to 1 over the Western Mediterranean at the sensitivity time is perfomed. We build the perturbations by using the shape of the sensitivity fields reescaled to sensible values:

$$\vec{x}_i = \alpha s_i \frac{\vec{\nabla}_i J(t_0)}{\left|\vec{\nabla}_i J(t_0)\right|_{\max}} \qquad \text{Eq. 1}$$

where *i* refers to each model variable, s_i is the variable-dependent reference scale (i.e. 1 ms^{-1}, 1 K, 1 hPa and 1 gkg^{-1}) and α is an amplification factor which controls the perturbation size.

Comparison of nonlinear and TGL results show that as $|\alpha|$ decreases, the correlation increase, achieving values larger than .93 for all time spans (Fig. 3a). However, a consistent degradation of the TGL skill is obtained for very small perturbations ($\alpha<10^{-2}$). This effect occurs through excitation of highly nonlinear or discontinuous processes, such as those depending on moist convective stability (Errico and Vukićević, 1992). Likewise, no consistent trend in the TGL skill with simulation time can be deduced. A second set of tests without the convective scheme is performed (Fig. 3b). For this configuration lower correlations are found though no loss in skill is observed fo the smallest α, suggesting that the effect observed in Fig. 3a is due to the Kuo convective scheme, which can produce relatively large differences in response to small perturbations. Finally, a set of dry experiments confirms the high number of nonlinear modes related to the moist physics in the experiments shown in Figs. 3a and 3b. The dry experiments show a smooth reduction in the correlations as the perturbation size and integration time increase.

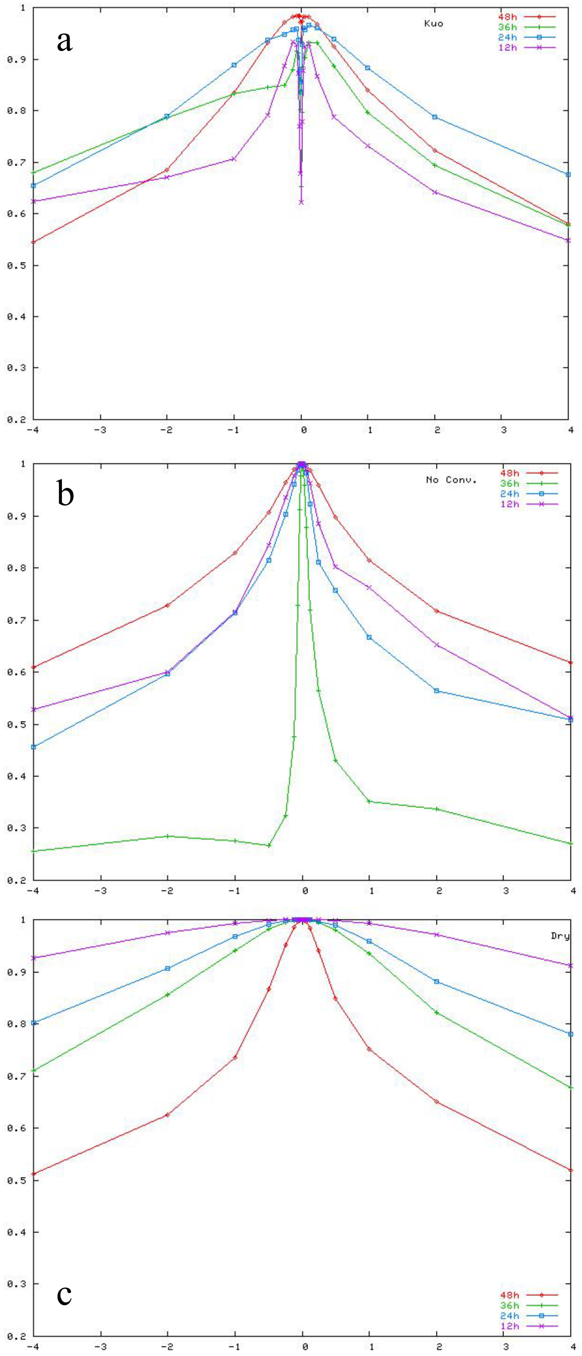

Figure 3 Correlation between TGL and nonlinear forecast perturbations for a) Kuo and simple microphysics, b) no Kuo and c) dry runs. Horizontal axis represents α and vertical axis is correlation.

Therefore, besides the effects of the moist processes and the convective scheme, Fig 3a reveals that for this African cyclone simulation, the linear models reproduce the evolution of perturbations in the nonlinear model with acceptable accuracy for perturbation sizes up to α=1.

5. SENSITIVITIES

The response function J is defined as an aspect of the forecast field in which we are interested at the sensitivity time t_f. The derivatives of J with respect to the forward model state are indeed the adjoint variables, which are initialized at t_f by $\vec{\nabla} J$. In this study, we define the vertical component of the relative vorticity near the surface as the response function characterizing the cyclone's intensity. Then, we run the adjoint for the 12, 24, 36 and 48h time spans. The sensitivities are summarized in Fig. 4 by a vertical average of the adjoint variables. The sensitivity field intensifies and spreads out with increasing simulation time. The 12h field is weak but highlights the surface cold front and vorticity maximum associated with the trough aloft (Fig. 4a). The 24h sensitivities are located along the cold and warm surface fronts, intensified over north Africa by the upper-level trough (Fig. 4b). The next (previous, in forward usual time) 12 hours the sensitivity spreads northward, focusing upon the downstream side of the upper-level

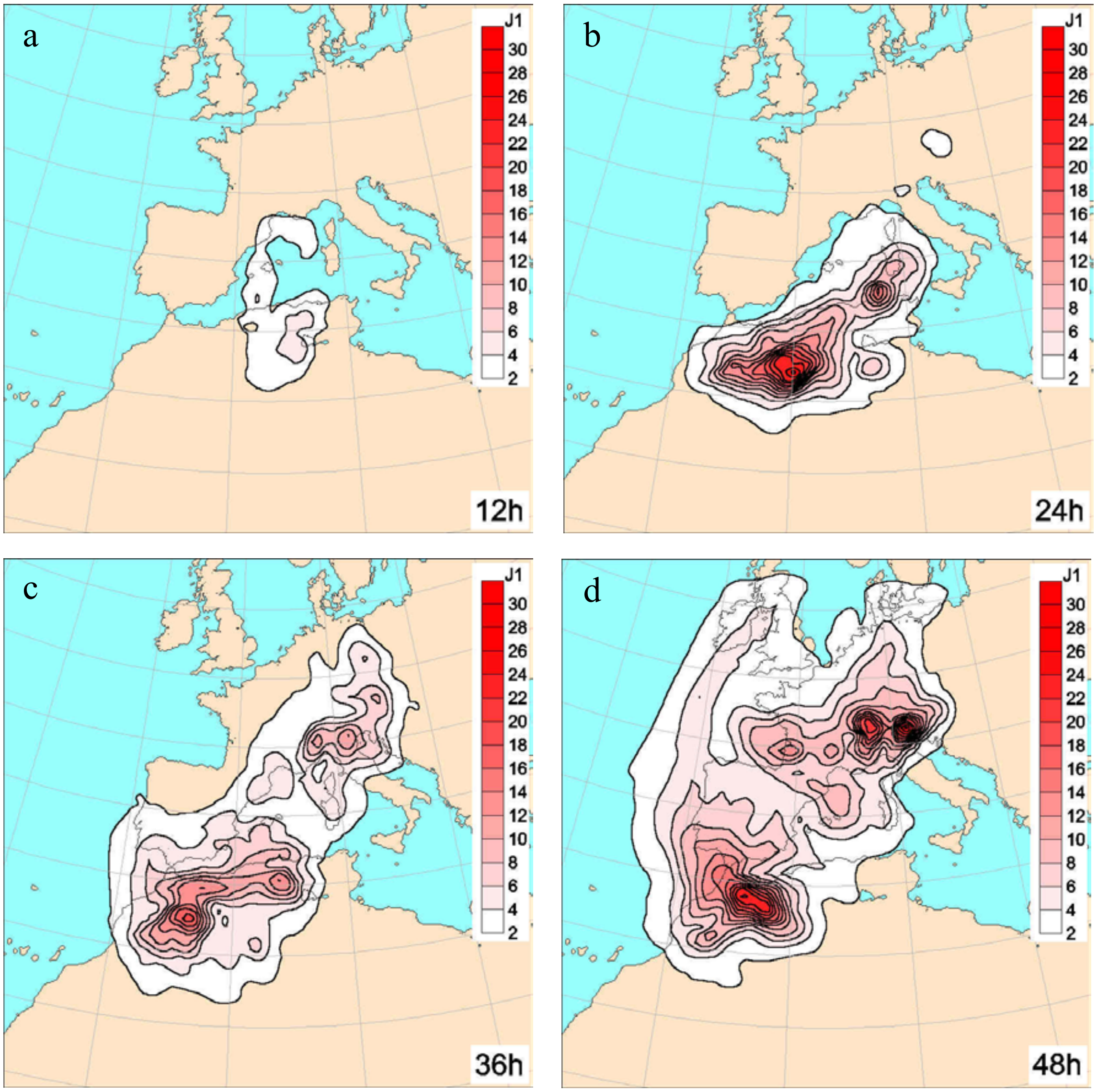

Figure 4 Vertical average of the absolute value of the sensitivities to J for the 4 time spans. Units are non-physical (s^{-1}/[Model Input]).

trough and the general area of low-level cold advection ahead of the cold front across the Mediterranean basin and northern Spain. The 48h field highlights the same features as the 36h run but with a temporal shift to the northwest (Fig. 4d). Thus, the important areas for the simulation of the cyclone in the analyzed time spans are the Moroccan and Algerian coastlands, together with southwestern Europe. Note that no important sensitivity is found to areas as inland north Africa, central Mediterranean and Atlantic Ocean.

In order to assess the vertical distribution of the sensitivities and the relative impact of each of the prognostic variables, the adjoint results are partitioned by level and adjoint variable in Fig. 5. A common feature among the simulations is the 4-6 times larger sensitivity shown to the temperature and specific humidity fields than for the wind and pressure fields. The 12h run shows the highest sensitivities at low levels, indicating that the

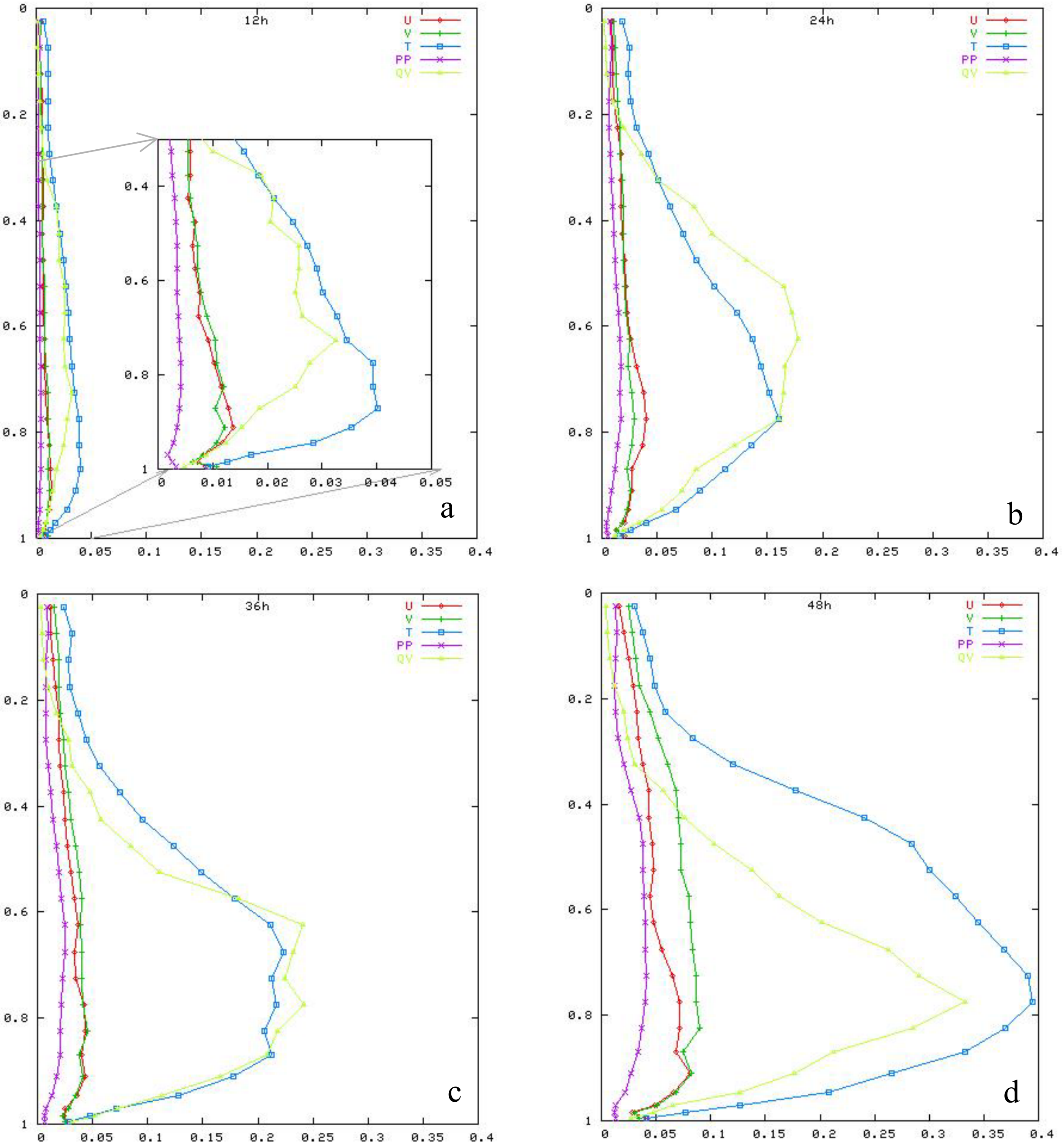

Figure 5 Horizontal average of the sensitivities to J vs σ. Horizontal axis units are s-1/[ms^{-1},K,hPa,gkg^{-1}].

representation of the frontal structures are relatively important for a good forecast for this time span (Fig. 5a). The sensitivity to mid levels becomes important for the longer runs though low-level features remain influential for all the simulation times. Despite the sensitivities to q are more likely to have large nonlinear components from the convective and microphysical schemes, its important role on the cyclone formation is suggested by the linear approximation for all time spans.

Nonlinear simulations perturbed using Eq. 1, reveal that the linear prediction of change in the response function is qualitatively correct and the cyclone is intensified for positive α and weakened for negative α (not shown). Quantitative evaluation of this accuracy presents some difficulties as the perturbed simulations may reproduce the feature of interest (the cyclone in this study) with a shift in space and/or time.

6. CONCLUSIONS

The adjoint of the tangent linear version of the MM5 is used to determine the areas of sensitivity for the simulation of a damaging cyclone occurred over the Western Mediterranean on 10-11 November 2001. Four time spans, 12, 24, 36 and 48h, are used in the study. Correlations between tangent linear and nonlinear forecasts reveal that, for the simulation of this intense cyclone, the linear model reproduces with acceptable accuracy the evolution of perturbations with amplitudes of the typical analysis error. However, the convective scheme is shown to introduce unexpected, yet relatively important, nonlinearities for very small perturbation sizes, and diabatic heating from simple stratiform condensation is also shown to hamper the linear model accuracy.

The relative vorticity is used as the response function to characterize the cyclone's intensity at 0000UTC 11 November. Sensitivity areas for the shorter 12h and 24h runs are mainly located over north Africa and the western Mediterranean sea, showing large signal in the lower to middle tropospheric levels. For the longer 36 and 48h runs, the sensitivities extend toward western Europe, with nuclei present over the Alpine region. Despite an increase in the response at mid-to-upper levels as integration time increases, the low levels have the largest sensitivities for all 4 time spans. Results show that the largest sensitivities occur for the temperature and specific humidity fields, especially in association with subsynoptic-scale features along the cold front associated with the trough at mid-to-low levels and over a tight gradient of specific humidity moving over north Africa during the simulations.

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