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3A.6 HURRICANES IVAN, JEANNE, KARL (2004) AND MID-LATITUDE TROUGH INTERACTIONS

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1. INTRODUCTION

The Atlantic hurricane season of 2004 featured several powerful, landfalling storms that caused considerable damage and loss of life in many countries. During September, three hurricanes, Ivan, Jeanne, and Karl, were linked together involving a midlatitude trough. This study shows how one mid-latitude trough can impact three storms as revealed by forecast model dynamics using singular vector (SV) sensitivity. The SV analysis identifies the influence of remote synoptic features on tropical cyclone evolution by finding the fastest-growing initial perturbations localized about the tropical cyclone at the end of the optimization period.

SV diagnostics have been applied mostly to midlatitude phenomena (Palmer et al. 1998). Only recently have singular vectors been applied to understanding tropical ensemble forecasting and analysis problems (e.g. Barkmeijer et al. 2001, Peng and Reynolds 2005a, b). Peng and Reynolds (2005a, b) examined the dynamics of tropical cyclone motion for the 2003 North Hemisphere tropical cyclones and found a distinct relationship between the SV sensitivity and the local potential vorticity gradient surrounding the storm. The SV sensitivity also indicated that environmental influences well away from the cyclone can have a direct impact upon the track and intensity of the storm.

2. CONSTRUCTION OF SINGULAR VECTORS

As optimally growing perturbations to a forecast trajectory (Palmer et al. 1998), singular vectors can be used to identify sensitive regions of dynamic significance to the evolution of that forecast. The SVs employed in this research optimize the perturbation growth centered upon the final-storm position (red box in SV sensitivity plots) of a tropical cyclone over a 2-day optimization period using a local projection operator. The SVs are calculated from the tangent linear and adjoint models of NOGAPS using a total energy metric (Rosmond 1997). The linearization of the SVs is calculated about the full physics, high-resolution (T259L30) operational NOGAPS forecasts as the trajectory.

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The initial-time SV sensitivity (largest shaded values in figures) indicates regions where perturbations to the initial state would have the largest impact on the 2-day forecast (regions where the forecast is most sensitive to changes in the initial analysis). The final SVs portray the amplitude and distribution of the energy associated with the fastest growing perturbations at the end of the forecast (here 48 hours). The sensitivity shown is the vertically integrated total energy of the SV perturbations summed over the first 3 leading SVs and weighted by the singular vector amplification factors.

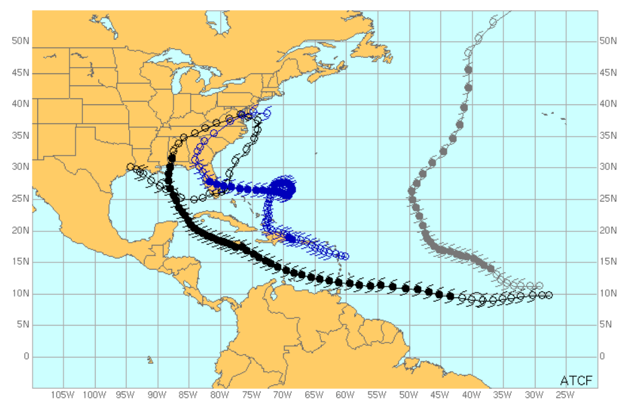


FIGURE 1. Best tracks for Ivan (left), Jeanne (middle) and Karl (right) in 2004.

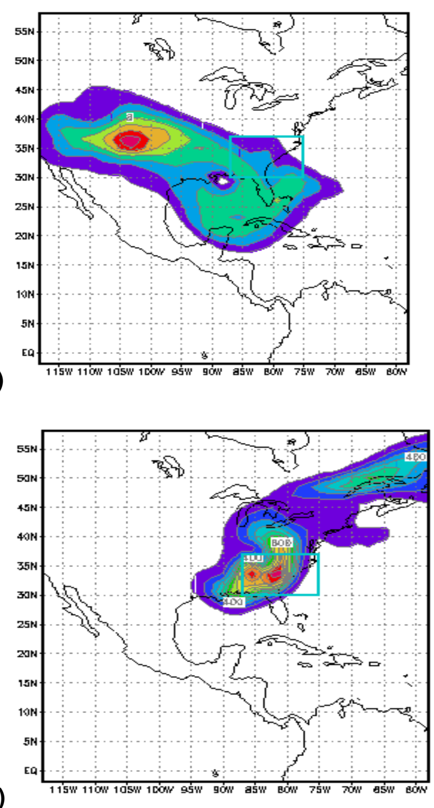
3. EPISODES OF THREE HURRICANES

Hurricanes Ivan, Jeanne, and Karl (2004) occurred in a sequence (Fig. 1), often coexisting in time. The cases we studies include one forecast for Ivan from September 16 to the 18th, three forecasts for Jeanne starting from the 18th, 20th, and 22nd, and one case for Karl starting on the 22nd and ending on the 24th of September.

3.1 Hurricane Ivan

Ivan was a powerful, long-lived category-5 storm that weakened slightly before landfall just west of Gulf Shores AL on 16 September. As a classical Cape Verde Islands hurricane, it traversed the Caribbean beneath the periphery of a strong subtropical high and geared northward as it entered the Gulf of Mexico. Ivan then moved northeast over central Alabama where it weakened to a tropical depression less than 24 hours after landfall. Transition to an extratropical low was completed on 18 September 18UTC after passage over the Appalachians.

The initial and final time singular vectors are plotted in Figure 2 for Ivan for the 48-hour optimization period from 16/00z to 18/00z. While there is a ring of sensitivity surrounding the cyclone in the initial SV, it is apparent that the maximum sensitivity is well upstream from the storm center, stretching from the Texas panhandle northward to Montana. Winds at the 500 mb level on the 16th (Fig 3), decomposed into the radial and tangential components with respect to the storm center, show that the flow behind a weak trough and to the east of an anticyclone that moves toward Ivan, has the largest impact on the future of the storm. At the final time (Fig. 2b), the maximum perturbation includes Ivan itself and a crescent shaped disturbance that is the downstream part of the trough, evolved from the upstream maximum in the initial SV. Synoptic diagrams indicate that Ivan becomes part of the trough at this stage and the trough itself has intensified. The development of the trough/ex-Ivan modulated the synoptic flow over the North Atlantic for the next 6 days.



(a)

(b)

FIGURE 2. Total energy SV demonstration optimized on Ivan and midlatitude trough 48-hour location position at (a) initial time 00UTC 16 September and (b) final time 00UTC 18 September.

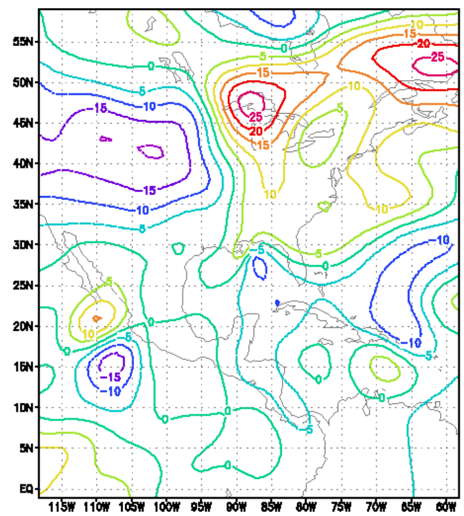


FIGURE 3. The radial component wind at 500 mb on 16/00z centered on Ivan. Colored lines with labeled values indicate flow into the storm center.

3.2 Hurricane Jeanne

During the 48-hour period extending from 18 September to 20 September, Jeanne moved northward (Fig. 1) into a weakness in the subtropical ridge due to the approaching midlatitude trough associated with the extratropical transition of Ivan. The initial SV is concentrated in the rear quadrant of Jeanne and extends along an upper-level trough axis over Florida associated with a weak cold-front/deformation zone associated with TD Ivan now centered over western Virginia. As seen in Peng and Reynolds (2005b), considerable initial time sensitivity occurs along the upstream part of the trough where sharp PV gradients associated with jet streaks commonly are found (Fig. 4a). At the final time (Figure 4b), three separate maxima of perturbation energy exist outside the optimization region surrounding the 48-hour forecast position of Jeanne (red box). Each of these regions has dynamical significance: the weaker band over the Southeast corresponds to the mid- and low-level vorticity remnants of Ivan (which later redeveloped after crossing Florida), and the two separate areas over New England and Nova Scotia are associated with the surface and upper-level reflections of the developing extratropical trough (attributed to remnants of Ivan). Consequently, changing the forecast of those midlatitude features would directly impact the forecast of Jeanne, evidencing the need for accurate observations / model analysis well away from tropical cyclones.

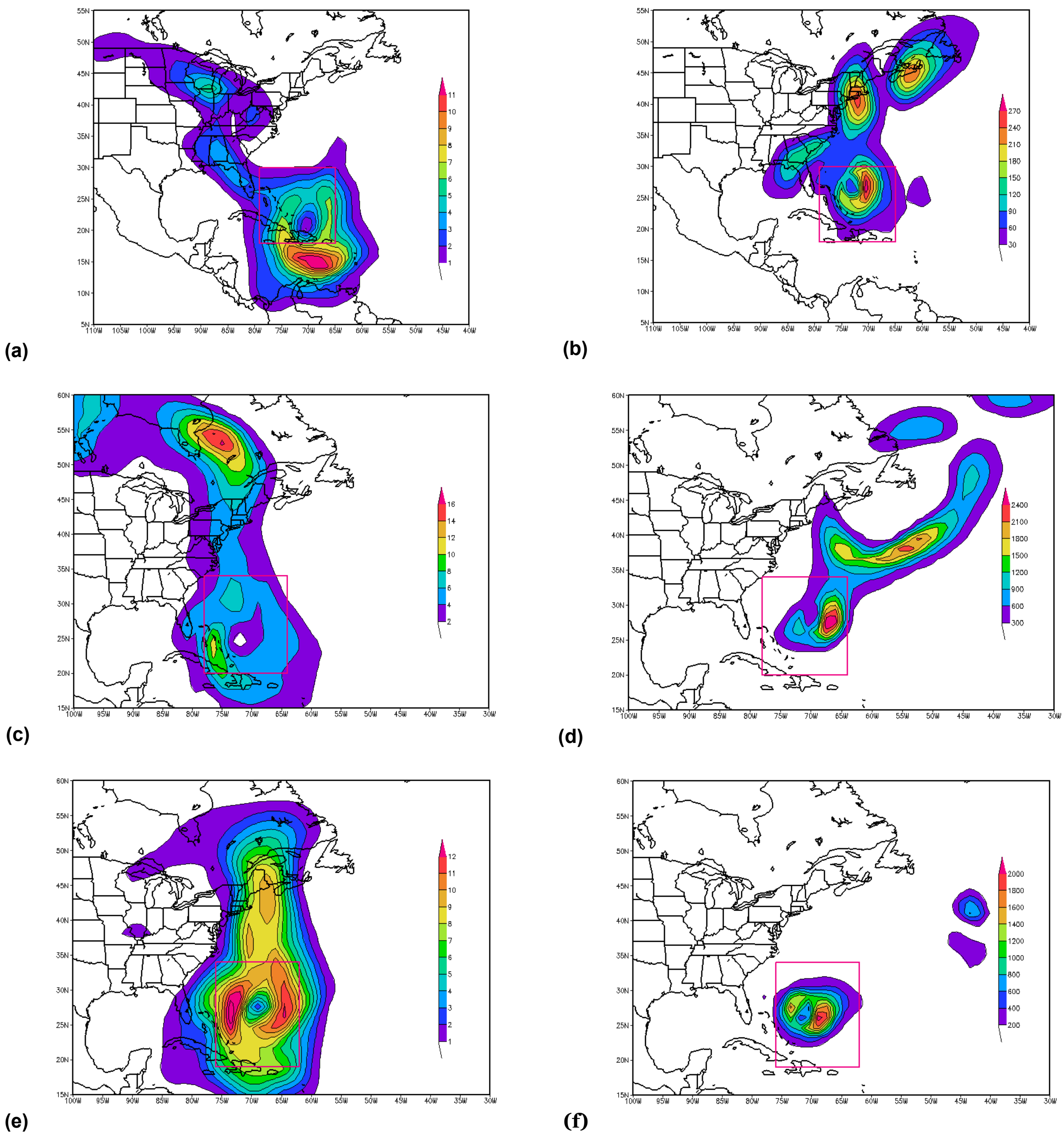


FIGURE 4. SV sensitivity of Hurricane Jeanne optimized on 48-hour forecast positions (red boxes) corresponding to the following times (a) initial 09/18 00z (b) final 09/20 00z (c) initial 09/20 00z (d) final 09/22 00z (e) initial 09/22 00z (f) final 09/24 00z.

On September 20th, numerical weather prediction models wrestled with the motion and intensity of Jeanne with respect to its modulation by and interaction with the strong trough now located off of the Canadian Maritimes (Fig. 5a). The SV diagnostics from 09/20 00z – 09/22 00z (Figs. 4c, d), provide insight into the mechanisms dynamically significant to Jeanne. The initial time sensitivity located over Quebec is associated with the PV gradient south of a jet streak related to a coherent tropopause disturbance (CTD, Hakim 2000). These vortex-like features (class of Rossby waves) propagate along PV gradients lying on tropopause-intersecting isentropic surfaces and are kinematically related to jet streaks. Mesoscale model airflow trajectories calculated from the initial time (09/20 00z) to final time (09/22 00z) (not shown) indicate that significant inflow terminating at Jeanne originates from this highly sensitive region in Northern Canada. This inflow toward the storm is the upstream part of the flow of the midlatitude trough. The final SVs (Fig. 4d) draw attention to the importance of this trough in the forecast of Jeanne with a crescent shaped band of energy located outside the optimization region along the trough base. Jeanne underwent a trough interaction, which in this case was positive since the upper-level anticyclone was enhanced downstream ahead of the trough. The ability of the trough to tow the system out to sea was compromised due to trough thinning (Rossby wave breaking, Thorncroft et al. 1993) and reduction in vertical shear, resulting in a collapse of the steering currents.

The initial SVs (Fig. 4e) in the 48-hour forecast period extending from 09/22 00z -09/24 00z show considerable sensitivity to the upstream part of the trough, which has become cutoff and anchored east of the Maritimes (Fig. 5b). Note that the axis of the trough is actually to the east of the storm center at this time. However, the western part of the flow associated with the trough is now directly north of Jeanne and has an impact on the storm (Peng and Reynolds 2005b). The final time energy (Fig. 4f) is concentrated on Jeanne indicating that fast growing perturbations are primarily associated with the tropical cyclone and not the midlatitude trough, which has moved further to the east of Jeanne (Fig. 5c). Note that small, dipole-like perturbation energy is located at 43W in Figure 4f. This will be discussed in the optimization for Hurricane Karl next.

3.3 Hurricane Karl

Hurricane Karl (2004), another classic Cape Verde storm, remained out over the central Atlantic during its lifetime and did not affect land. Karl moved around the southern periphery of the subtropical ridge and recurved in response to erosion of that ridge by the same midlatitude trough affecting Jeanne's motion.

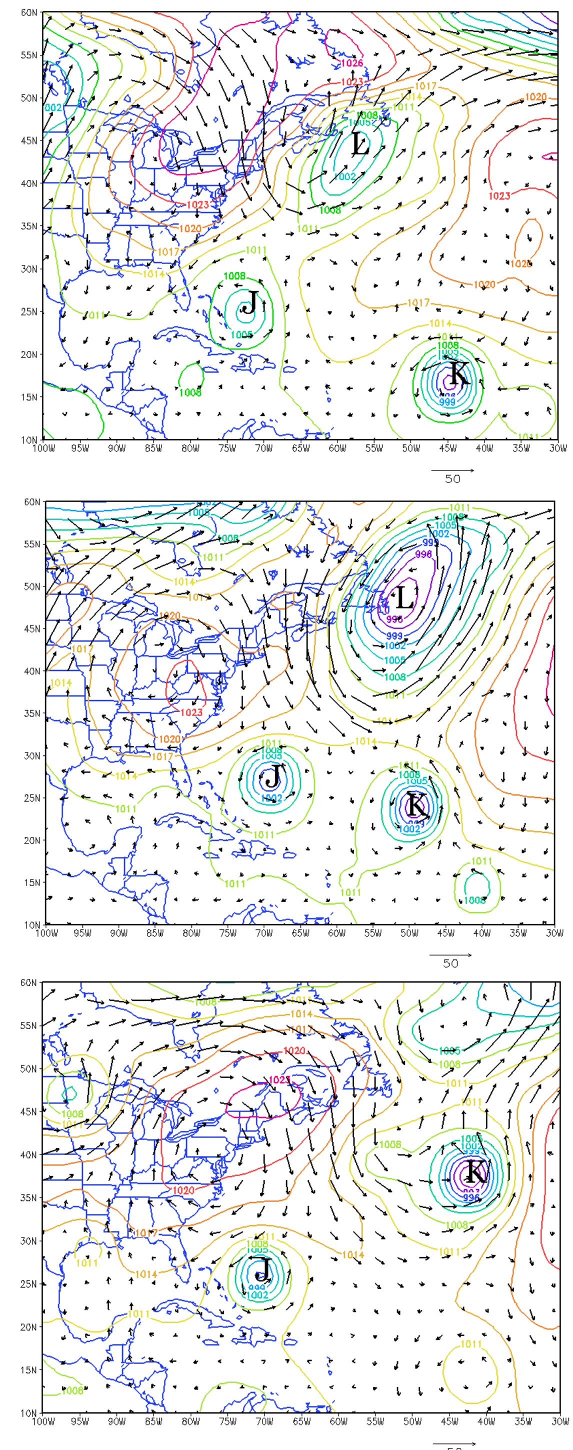
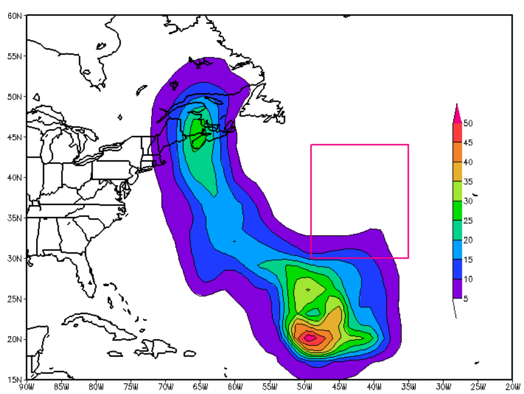
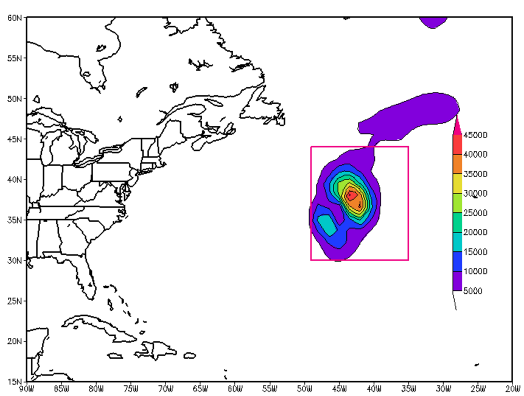


FIGURE 5. NOGAPS Analysis 500 mb wind and sea-level pressure on: (top) 20/00z, (middle) 22/00z, and (bottom) on 24/00z

The following is a discussion on Karl from 22/00z to 24/00z and its interaction with this trough and eventual extratropical transition. In this case, singular vectors are computed using the moist adjoint system of NOGAPS that contains large-scale precipitation instead of the dry adjoint used for the other cases. The addition of large-scale precipitation to the tangent linear model provides larger amplification of the SVs and smaller horizontal length scales when compared to dry SVs. While the moist and dry SVs occur in similar regions, the presence of latent heat release from large-scale precipitation processes is hypothesized to be important for TC intensity dynamics (Peng and Reynolds 2005b).



(a)



(b)

FIGURE 6. Moist SV sensitivity for Hurricane Karl and trough interaction optimized on 48-hour forecast position for (a) initial time 09/22 00z and (b) final time 09/24 00z.

Figure 6a shows the initial sensitivity extending to the northwest away from Karl along the backside of the trough, indicating regions of flow along isentropic trajectories towards the TC (Peng and Reynolds 2005b). The trough acts as a distant, positive influence, also enhancing upper-level outflow away from Karl causing a brief, but marked reintensification of the storm to major hurricane status after weakening slightly the day before. At final time (Figure 6b), the perturbation energy is concentrated inside the optimization region indicating that the fastest growing structures are mainly associated with Karl. The inclusion of moisture in the SV calculation is very useful for trough interaction since an upper level trough is essentially a catalyst for constructive or destructive diabatic mechanisms in the hurricane. In this “PV thinking” (Hoskins et al. 1985) approach to the problem, the scale matching of the respective PV anomalies is accomplished through the intimate interplay between vertical shear, diabatic heating, and vorticity advection. Future research with moist SVs should allow for more detailed understanding of the structures responsible for intensity fluctuations during trough interactions.

The sensitivity of Jeanne from 09/22 00z to 09/24 00z is rerun with the large-scale precipitation (moist) adjoint. Comparison of the dry (Figs. 4e,f) and moist SVs (Figs. 7a,b) indicates that the initial SVs are very similar. The final-time integrated SV sensitivity shows a dipole pattern almost identical to the final SV for Karl shown in Figure 6b. [Note that similar information is shown in the dry SVs (Fig. 4f) with a smaller magnitude of the SV associated with Karl.] With the moist SVs, the presence of Karl at its 48-hour forecast position is prominently displayed in the final state SV optimized in a region enclosing Jeanne only. Since the optimization of Karl lacks any influence from Jeanne (Fig. 6a), the final disturbance representing Karl in Fig. 7b has to come from the flow associated with the trough in the optimization of Jeanne in Fig. 7a. This information shows how the mid-latitude trough influenced Karl as it transitioned to an extratropical cyclone. In another words, since the initial time SVs do not show the sensitivity of Karl with respect to Jeanne and vice versa, one must look to *the trough as the common dynamical linkage to both Jeanne and Karl*. The motion of each tropical cyclone is modulated by the large trough to the north through which Karl’s latent heat release manifests itself in the optimal growth structures associated with Jeanne. Much of this interaction occurred in the outflow layers of the hurricane.

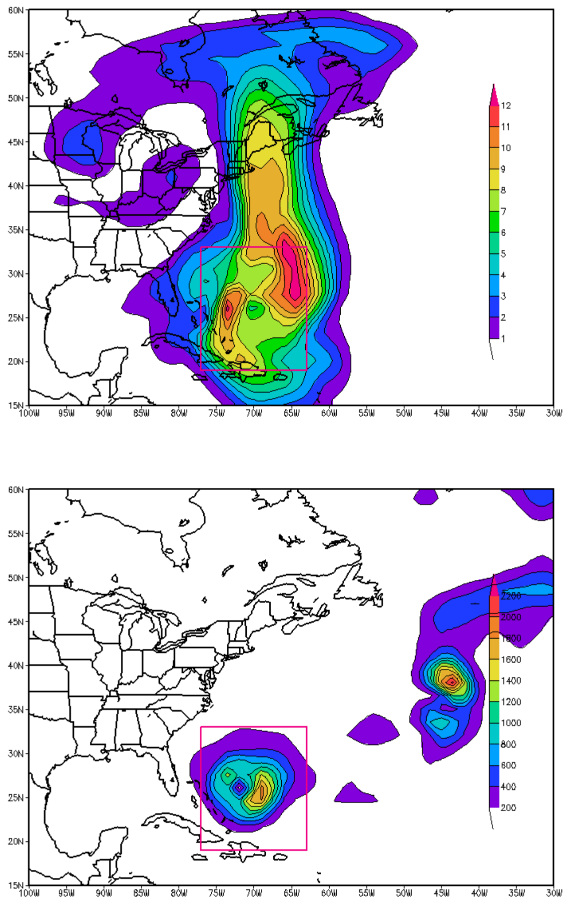


FIGURE 7. Moist SV demonstration of Hurricane Jeanne optimized at (a) initial time 09/22 00z and (b) final time 09/24 00z. Note the presence of Karl in the final energy in (b) by comparing it with Figure 6b.

4. SUMMARY

Singular vector sensitivity computed from the tangent linear and adjoint models of a global forecast system, NOGAPS, is applied to understand three hurricanes (Karl, Jeanne and Karl) in the Atlantic in 2004 that are affected by a mid-latitude trough. The first storm, Ivan, fed into the intensification of the trough and the trough subsequently affected Jeanne and finally merged with Karl as it transitioned into an extratropical cyclone. Our study indicates that the ability of forecasting hurricane landfall, trough interaction, and extratropical transition requires a detailed understanding of the initial conditions and the evolving dynamical structures.

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