Hirlam CAPE singular vectors

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1 Background

To account for the uncertainty in NWP analyses an ensemble of forecasts is typically produced by running the model several times from slightly different initial conditions (sometimes combined with physics perturbations). One method to determine these perturbations is the use of singular vectors (SVs), fast growing perturbations in terms of a certain norm over a certain time interval. At ECMWF, for example, the members of the EPS are linear combinations of these SVs calculated using a dry total energy norm at initial and final time [Leutbecher 07].

The main application for the HIRLAM system is the production of general weather forecasts, with particular emphasis on detection and forecasting of severe weather (hirlam.org, Memorandum of Understanding). In this presentation we will show results of SVs specifically designed to trigger one type of high impact weather namely, deep convective systems. This is achieved by looking for perturbations that maximize convective available potential energy (CAPE) instead of total energy. The results will be applied to a thunderstorm case which the operational FMI model failed to forecast. The case study shows that the CAPE-SVs are located near the active region. Therefore the failed forecasts could be a result of analysis errors instead of model errors.

2 Theory

The time evolution of small perturbations $\epsilon(0)$ of the initial condition $x(0)$ over a certain time T is given by

$$\epsilon(T) = \mathbf{M}(0,T)\epsilon(0) \tag{1}$$

Here M is the tangent linear propagator. The leading singular vector is the vector $\epsilon(0)$ that maximizes the ratio

$$\frac{||\mathbf{P}\epsilon(T)||^2_{\mathbf{C}_1}}{||\epsilon(0)||^2_{\mathbf{C}_0}} \tag{2}$$

for given projection $\mathbf{P}$ and norms $||\cdot||_{\mathbf{C_1}}$ and $||\cdot||_{\mathbf{C_0}}$.

Let $\mathcal{C}(T,q)$ be a function that computes CAPE for given profiles of temperature T and specific humidity q. Taylor expansion of $\mathcal{C}(T,q)$ around a reference profile x^* gives

$$\mathcal{C}(x) - \mathcal{C}(x^*) = \left.\frac{\partial\mathcal{C}}{\partial x}\right|_{x^*}\epsilon \tag{3}$$

Where ϵ is a small perturbation. The matrix $\left.\frac{\partial\mathcal{C}}{\partial x}\right|_{x^*}$ will be denoted by $\mathbf{C}$ without explicit reference to the reference profile x^*.

The SV problem becomes

$$\frac{||\mathbf{C}\epsilon(T)||^2}{||\epsilon(0)||^2_{\mathbf{C_0}}} \tag{4}$$

Or written explicitly as an eigenvalue problem

$$\mathbf{S}\mathbf{C_0}^{-1/2}\mathbf{M}^*\mathbf{C}^*\mathbf{C}\mathbf{M}\mathbf{C_0}^{-1/2}x = \lambda x \tag{5}$$

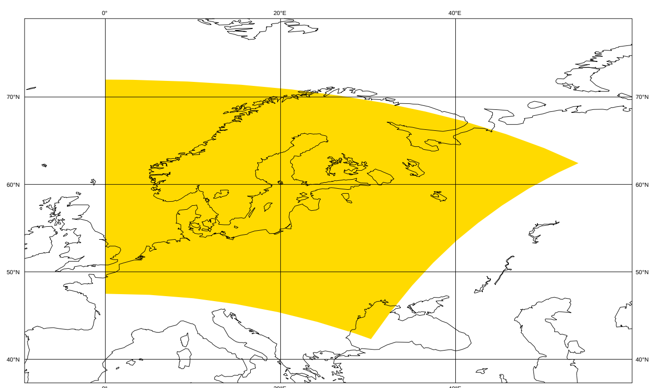
The operator $\mathbf{S}$ appears here because the Hirlam adjoint of the spectral tangent linear model is defined w.r.t a different inner product than the one used in the eigenproblem solver. The SVs corresponding to solutions of this eigenvalue problem are given by $\mathbf{C_0}^{-1/2}x$. The $\mathbf{C}$ and $\mathbf{C}^*$ are derived from an approximate CAPE-calculation as used in the operational ECMWF-model [ECMWF CY31r1 06] with the help of an automatic code generation tool [Giering 99].

3 The “Finnish” case

In the morning of August 22nd 2007 a thunderstorm hit Finland which the operational FMI-model failed to predict in any of the cycles verifying at the same time. The predictability is investigated using CAPE-SVs

3.1 Experiment settings

To following domain and settings were used in Hirlam



- Resolution: $0.5° \times 0.5°$
- Start 21 Aug 2007 18 UTC
- Optimization time: 12 h
- (Dry) total energy norm at initial time
- Cape/TE-norm at final time

The TL-model with only vertical diffusion switched on will be referred to as dry TL-model. The TL-model with vertical diffusion, large scale condensation and convection will be called moist TL-model.

3.2 Results

CAPE singular vectors where calculated for the period 2007-08-15 00UTC until 2007-08-30 12 UTC at 6 hour intervals with an optimization time of 12 hours using a dry and a moist tangent linear model. In figure 1 the leading singular values are given as function of the start of the SV-calculation with the total energy and CAPE norm using both a moist and dry TL-model.

We can clearly see that while the dry-TL model produces realistic singular values over the two week period the moist TL-model gives unrealistic singular values at certain times (e.g. at August 25 00 UTC the TE-norm run gives error growth of 5000 in 12 hours). The corresponding leading SVs have their maximum perturbation

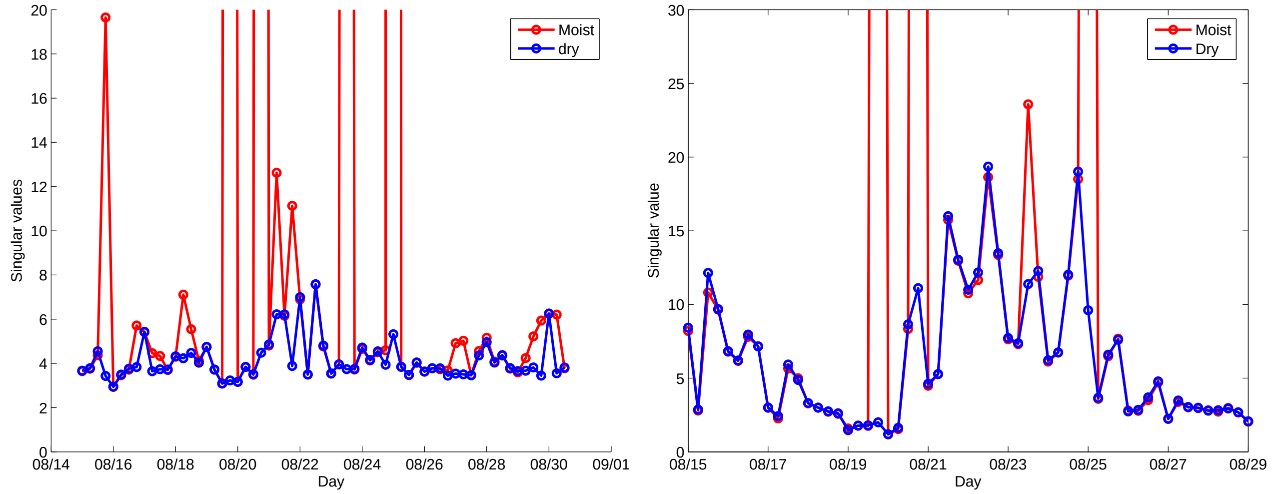


Figure 1: Leading singular value as function of start of SV-calculation with TE-norm (left) and CAPE-norm (right) using the moist and dry TL-model

in energy units at the lowest model level (compare to figure 3 upper right). Because of these problems with the moist TL-model we will only show the results using the dry TL-model from now on.

Figure 2 contains the same information as figure 1 but the lines are colored based on the start of the calculation. There is a daily pattern in the singular values with the CAPE-norm with higher values during the windows 12–00 UTC and 18–06UTC. Both runs show higher values around August 22nd indicating that the atmosphere was sensitive to small analysis perturbations in the period when the FMI-model failed. In figure 3the vertical energy distribution of the leading 10 TE-SVs and 10 CAPE-SVs at initial and final time are given for August 21 at 18 UTC. Both cases used a dry total energy norm at initial time (no specific humidity perturbations). For comparison the temperature, wind and moisture fields are converted to units of energy using the total energy norm. For the TE-SVs most perturbation energy is initially in the temperature field which is converted to kinetic energy at final time. Because the TE-SVs are located high in the troposphere while CAPE is determined by the stability in the lower troposphere we do not expect that these TE-SV have a large impact on CAPE. The CAPE-SVs are located below 500 hPa at initial and final time and they mainly influence the moisture distribution in the lower troposhere at final time.

Figure 4and 5 show the geographical location of the leading TE-SV and CAPE-SV at initial and final time. The evolved TE-SV is located exactly in the active region where the thunderstorm occured. The evolved CAPE-SV is located south west of the active region.

At evolved time the RMS of CAPE for the TE-SV and CAPE-SVs are 9.7 and 289.4 respectively showing that the CAPE-SVs are almost 30 times more effective in triggering CAPE.

4 Conclusions

The SV experiments with the Finnish case have shown that the final time norm may have a large impact on the structure of the SVs. The CAPE norm has been presented and it was shown that the calculated structures are considerably more effective in perturbing CAPE than TE-SVs. Both TE-SVs and CAPE-SVs suggest that the failed FMI forecast might be a result of errors in the analysis.

References

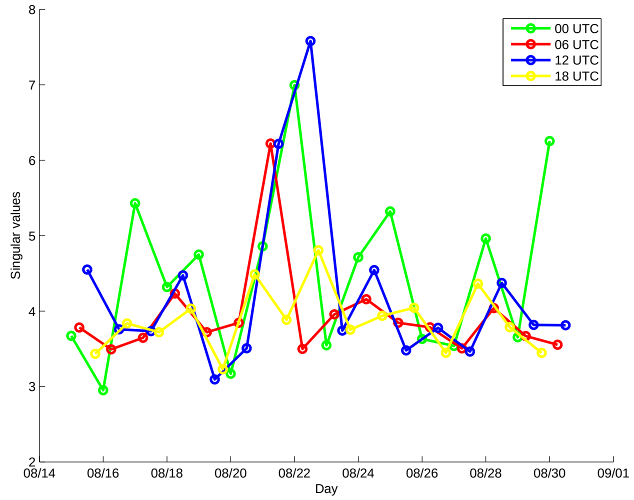


Figure 2: Leading singular value as function of start of SV-calculation with TE-norm (left) and CAPE-norm (right) using the dry TL-model

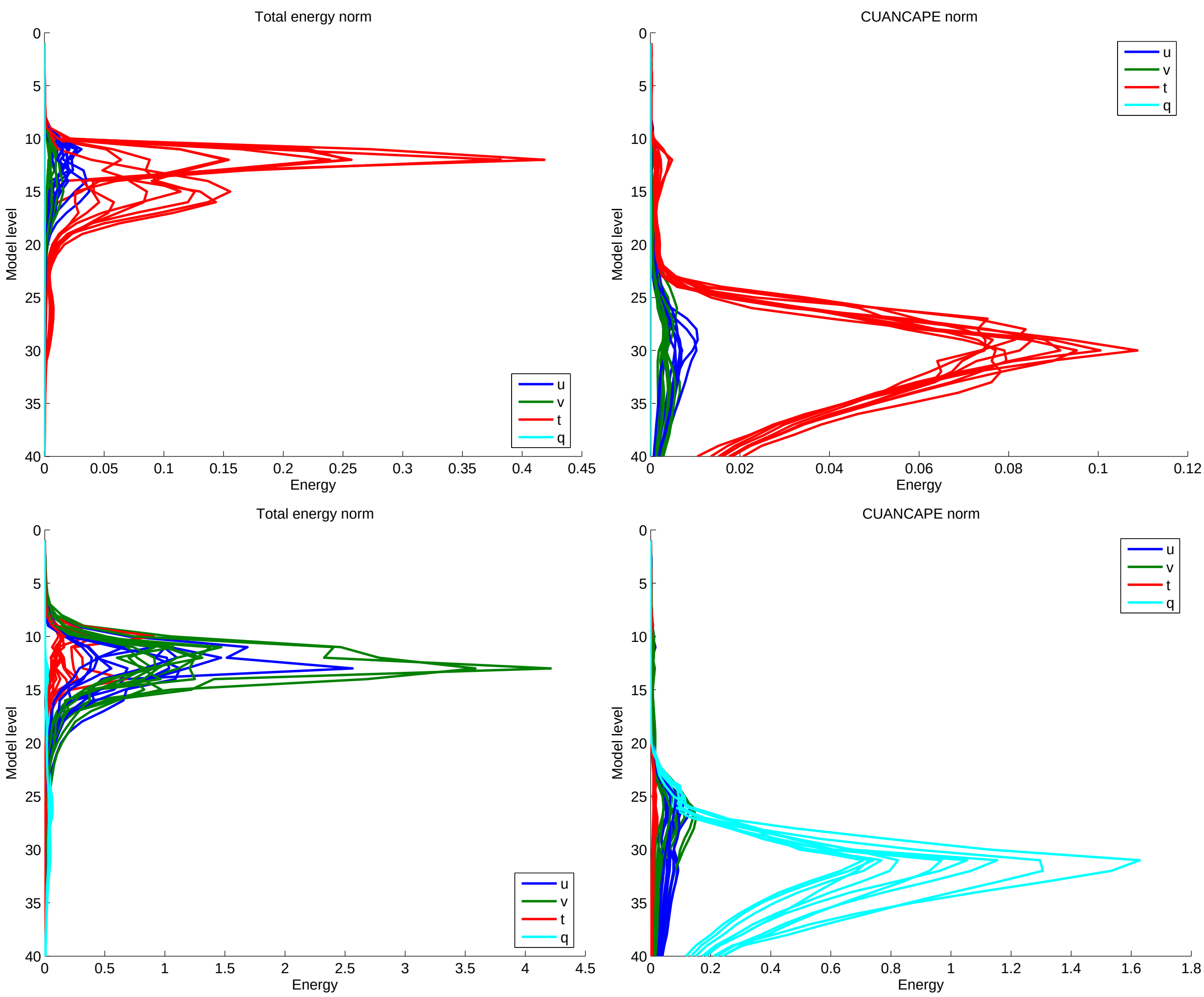


Figure 3: Vertical energy distribution of the leading 10 TE-SVs (left) versus CAPE-SVs (right) at initial time (top) and final time (bottom)

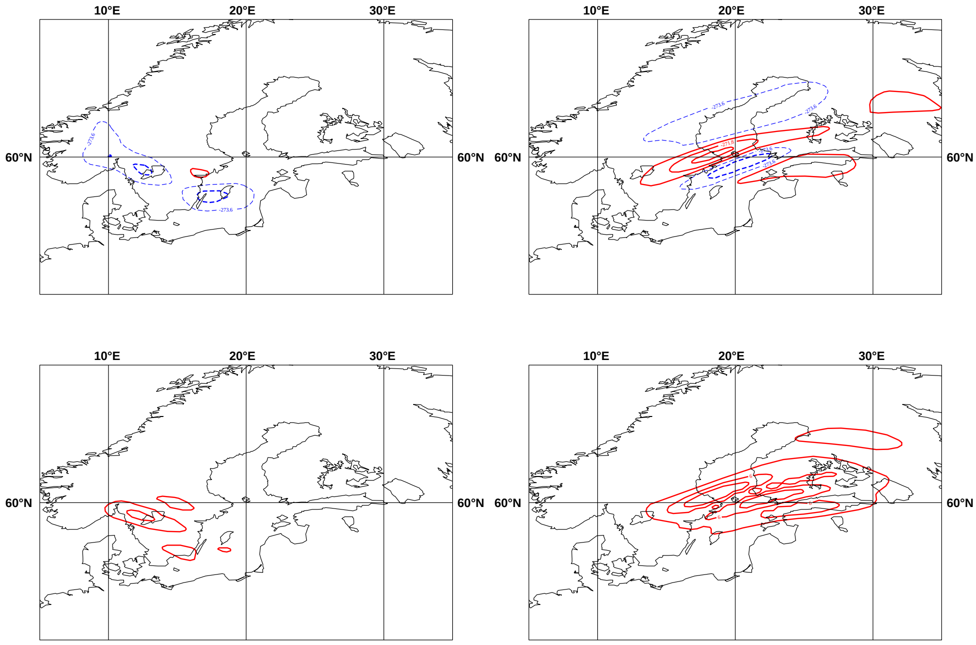


Figure 4: Temperature (top) and wind speed (bottom) of the leading TE-SV at initial time (left) and final time (right) at model level 14

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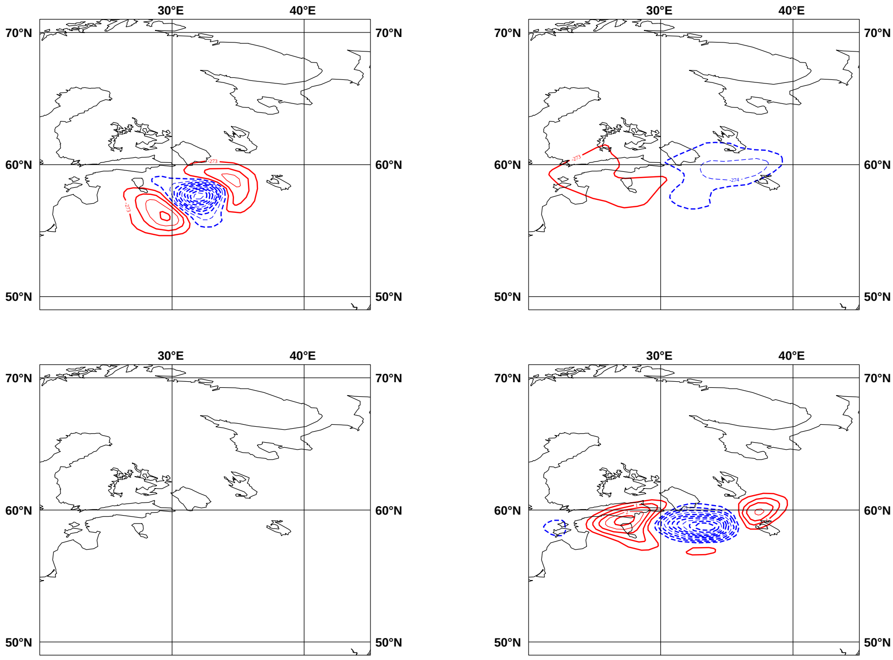

Figure 5: Temperature (top) and specific humidity (bottom) of the leading CAPE-SV at initial time (left) and final time (right) at model level 30