Inspecting the trajectory instabilities of a convection-resolving model

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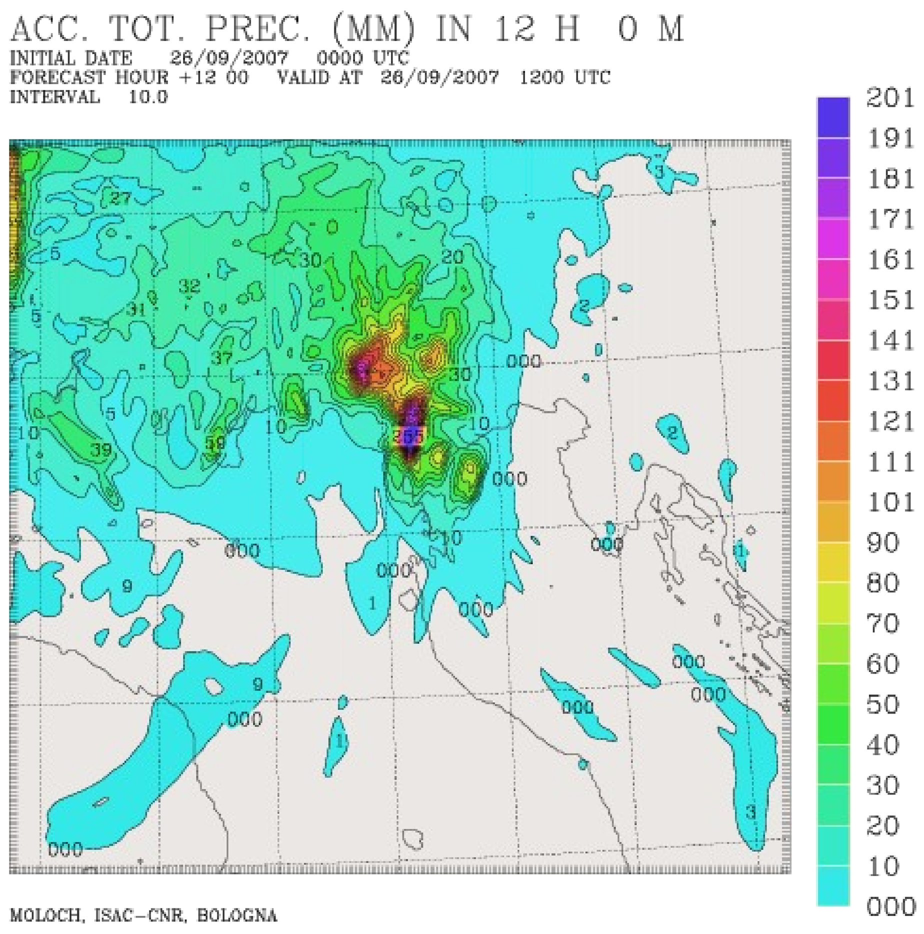
The predictability of convective systems is limited by the rapidly evolving non-hydrostatic dynamics and by the strong non-linearities present in moist thermodynamics, associated to convection processes.
The perspective of the study is to assess the applicability of advanced data assimilation methods like AUS (*Assimilation in the Unstable Subspace, Trevisan and Uboldi, 2006*), but also 4D-Var or EnKF, which were successfully applied to larger scales.

The model is **MOLOCH**, developed at the atmosphere dynamics group of ISAC-CNR, Bologna, Italy.
MOLOCH is a convection-resolving, non-hydrostatic atmospheric model, running at about 2.3 km resolution over northern Italy, including an Alpine area and portions of both the Liguran Sea and the Adriatic Sea.
The control trajectory is a simulation of the real case 26 September 2006, with initial and boundary conditions from GFS.
The circulation at 500 hPa is characterized by a deep trough West of the Alps. Near the surface, a pressure low is located in the Genoa gulf, and strong winds from SE over the Adriatic Sea. The Venice area was invested by intense convective precipitation, mostly during the morning.
The figure shows the integration area and the total precipitation, cumulated from 00 to 12 UTC in the control run.

MOLOCH:
Malguzzi et al., JGR-Atmospheres, 2006
Davolio et al., MAP, 2007; 2009
http://www.isac.cnr.it/dinamica/projects/forecasts/



A perturbation breeding technique is used to estimate the local unstable structures that characterize the dynamic growth of small perturbations and errors.

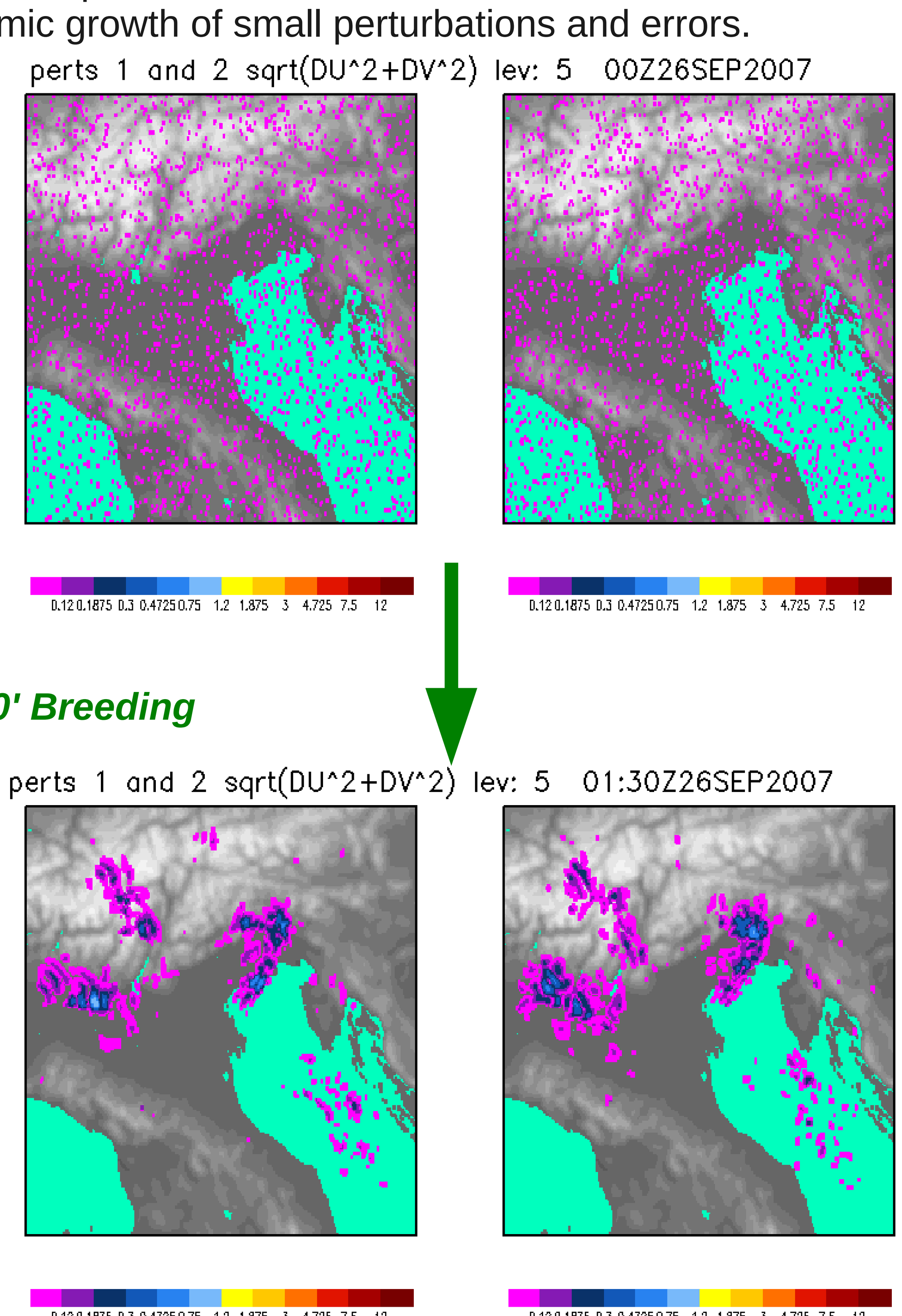
Two initial small (*), random, independent perturbations.
Each variable is scaled with its variability.

(*) Initial perturbation amplitude is 0.05 m s^{-1} for horizontal velocity at model level 5.
(about 925 hPa over sea)

1H30' Breeding

The organized bred vectors show similar spatial structures, localized in dynamically active areas (intense winds and convective precipitation)

Maps show the perturbation horizontal velocity module $\sqrt{\delta u^2 + \delta v^2}$ at model level 5



NON-linear evolution of states perturbed by organized bred vectors

The growth of perturbations is characterized by estimating the **growth exponent** λ and the **doubling time** T_D : $e^{\lambda T_D} = 2$

The logarithm of the **amplification factor** after *n* time steps is approximately linear in time during a period of linear growth regime.

$$\ln \frac{\|\boldsymbol{\pi}_n\|}{\|\boldsymbol{\pi}_0\|} = \overline{\lambda_n} \cdot n \Delta t$$

Free non-linear evolution of two "opposed" perturbations (same direction, different sign) after a breeding period (1h30'):

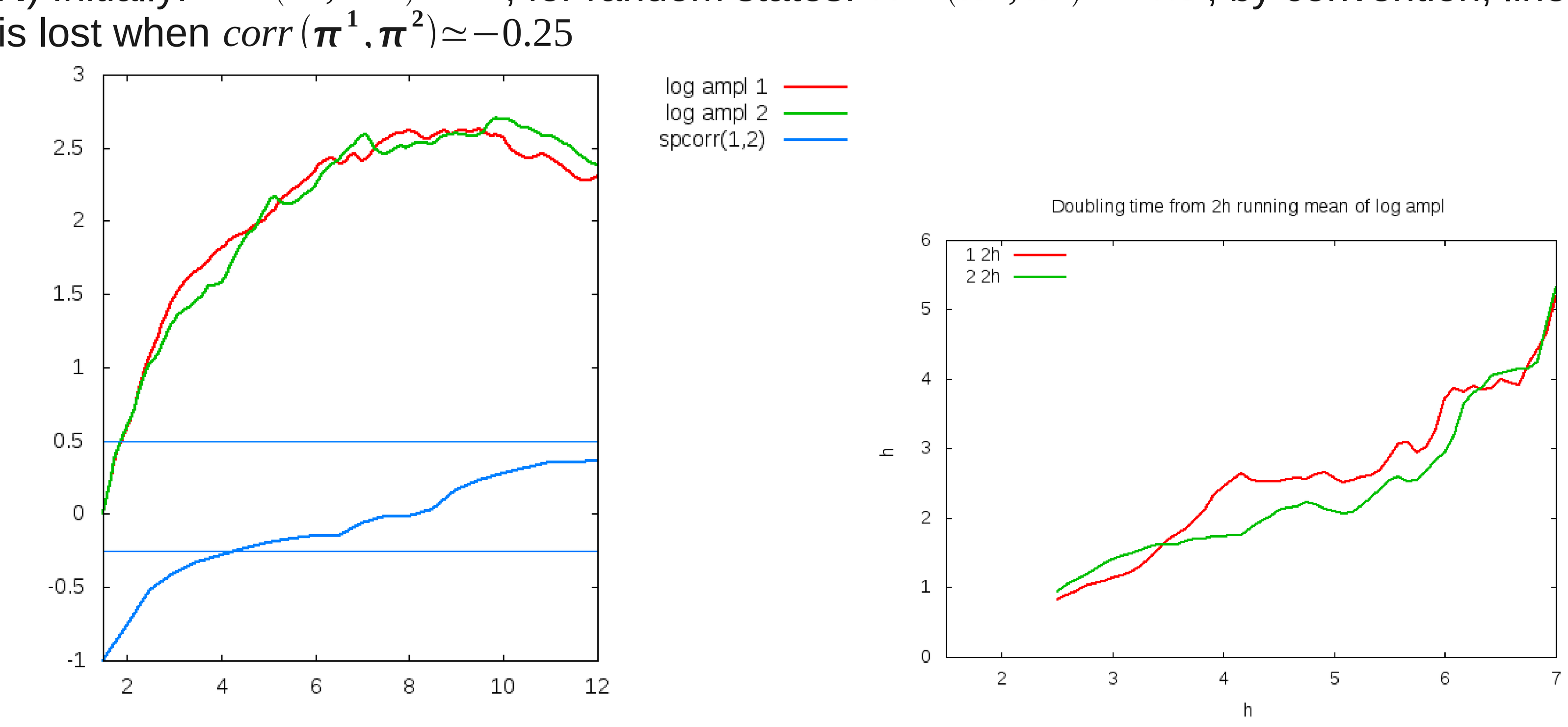
Initial time: $\mathbf{x}^{p1} = \mathbf{x}^c + \boldsymbol{\pi}$ $\quad \mathbf{x}^{p2} = \mathbf{x}^c - \boldsymbol{\pi}$ $\qquad$ Later times: $\boldsymbol{\pi}^1 = \mathbf{x}^{p1} - \mathbf{x}^c$ $\quad \boldsymbol{\pi}^2 = \mathbf{x}^{p2} - \mathbf{x}^c$

Linearity indicators (*Hohenegger et al., BAMS 2006)* are used to estimate the time period T_{lin} of validity of the tangent linear approximation along the non-linear evolution.

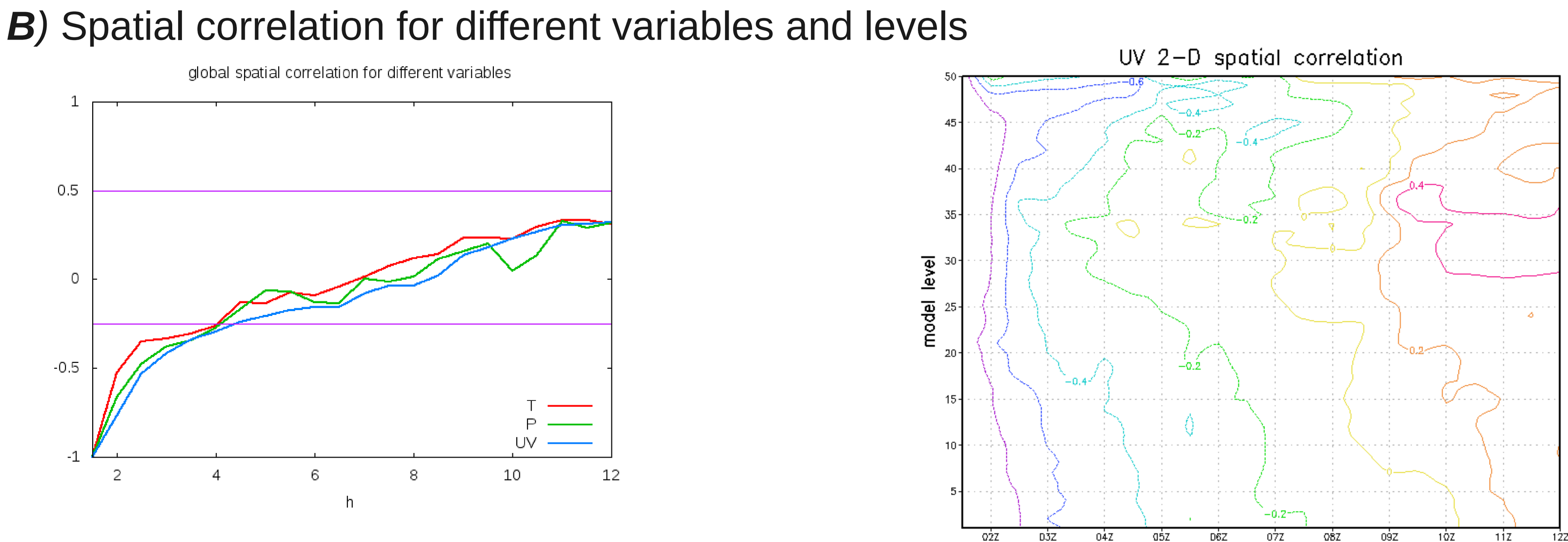
Spatial correlation: $corr(\boldsymbol{\pi}^1, \boldsymbol{\pi}^2) = \frac{\langle \boldsymbol{\pi}^1 | \boldsymbol{\pi}^2 \rangle}{\|\boldsymbol{\pi}^1\| \, \|\boldsymbol{\pi}^2\|}$ where: $\|\boldsymbol{\pi}\| = \sqrt{\langle \boldsymbol{\pi} | \boldsymbol{\pi} \rangle}$ $\quad \langle \boldsymbol{\pi}^1 | \boldsymbol{\pi}^2 \rangle = \sum_i \pi_i^1 \pi_i^2$

Linearity indicators are calculated for each variable separately. The scalar product is extended: ***A***) to the whole domain to obtain **global** indicators; ***B***) separately to each model **level**; ***C***) **locally**, in the neighbourhood (10 km) of each gridpoint.

A) Initially: $corr(\boldsymbol{\pi}, -\boldsymbol{\pi}) = -1$; for random states: $corr(\boldsymbol{\pi}^1, \boldsymbol{\pi}^2) = +0.5$; by convention, linearity is lost when $corr(\boldsymbol{\pi}^1, \boldsymbol{\pi}^2) \simeq -0.25$



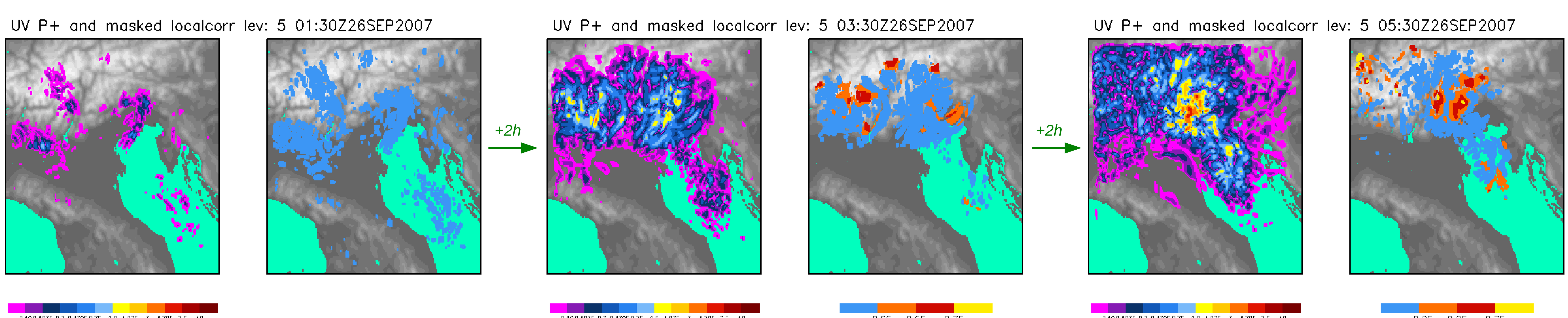
B) Spatial correlation for different variables and levels



Estimate in this case: $T_{lin} \simeq T_d \simeq 2.5\,h$
Order of magnitudes comparable with those obtained by *Hohenegger et al. (BAMS, 2006)*, but ratio is about 1, more optimistic than their result for convective scales $\left(T_{lin} \simeq 0.38\, T_d \simeq 1.5\,h\right)$
(If $T_{lin} << T_d$, small scale errors saturate when they are still small: a forecast improvement cannot be guaranteed by a reduction of the initial error).
A reasonable empirical estimate for a forecast lead time is 4.5 T_{lin}: here that would be 11 h.

- Estimates are dependent on the amplitude of the initial perturbation: a larger amplitude requires a larger domain to avoid / delay the stabilizing effect of boundary forcing.
- Possible dependence on the chosen case...
- Small dependence of the estimated T_{lin} on variable. However *corr* is systematically larger for temperature (and other variables) than for horizontal velocity.

C) The **local** spatial correlation is plotted (right), for horizontal velocity at level 5 (left, perturbation 1), during the nonlinear evolution of the perturbations, at 01h30 (initial time), at 03h30 (+2h), and at 05h30 (+4h). At 01h30 the local correlation is -1 everywhere. At later times, the local correlation field becomes orange and red where linearity is lost first. Both fields are masked for small values of the perturbation velocity module.



Preliminary results:

→ Bred vectors quickly get organized in spatially coherent structures. The growth of small errors in the linear regime is not immediately disrupted by strongly non-linear processes present in moist convection.

→ Strongly non-linear(*izable*) processes (moist thermodynamics, phase transitions during convection) seem to affect predictability when they succeed in determining non-linearity in the evolution of the horizontal velocity field. Other variables (temperature, pressure, vertical velocity, humidity and concentrations of condensed phases) are more directly affected. Wind seems then to be the best candidate as a control variable.

→ Estimated values of T_{lin} and T_d also lead to some optimism, at least for very short prediction range (nowcasting).

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ECODYC10 25-29 JAN 2010 DRESDEN

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