Data assimilation and targeting

Observability and positioning of the structure functions

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Singular vectors (SV) of the **tangent linear model** (TLM) are promising candidates to define **targeting subspaces** and **flow-dependent structure functions** for **data assimilation** (DA). It is suggested that **SVs could be shifted** due to nonlinear interaction between synoptic or planetary waves and the **Jet Stream**. Better understanding of the triggered Rossby wavetrain effect on SVs position is needed. Observing System Simulated Experiments (OSSE) are proposed to identify key elements of these interactions on the SVs position.

Problematic

- Recent observing system experiments (OSE) suggest that the forecast error reduction due to targeted observations assimilation is generally positive but small (~10-15%)[6][3].
- Targeting observations in the context of particular meteorological events (extratropical transitions) results in more important error reduction[2].
- DA should integrate a flow-dependent structure function[6].
- Recent studies reveal that SVs realisation in the atmosphere have a very small amplitude, often below the level of observation error, making them difficult to be detected[4].
- It has been shown that the potential vorticity (PV) gradient in the vincinity of the Jet Stream can act as waveguide for Rossby waves[1][7].

Variational Data Assimilation

DA combines information from the Global Observing System and a background forecast to produce **initial conditions** (IC) for the models. The variational formulation solve the statistical estimation problem by **minimizing a scalar function**, the **cost function** J, a sum of *distances* from a model solution to the background forecast and to the observations.

$$J(\mathbf{x}) = \frac{1}{2}\|\mathbf{x}-\mathbf{x}_b\|^2_{\mathbf{B}^{-1}} + \frac{1}{2}\|H(\mathbf{x})-\mathbf{y}\|^2_{\mathbf{R}^{-1}} \quad (1)$$

In 4D-Var, the cost function is expressed in term of the IC and each observation is compared with the model state at the corresponding time through the action of the nonlinear observation operator H.

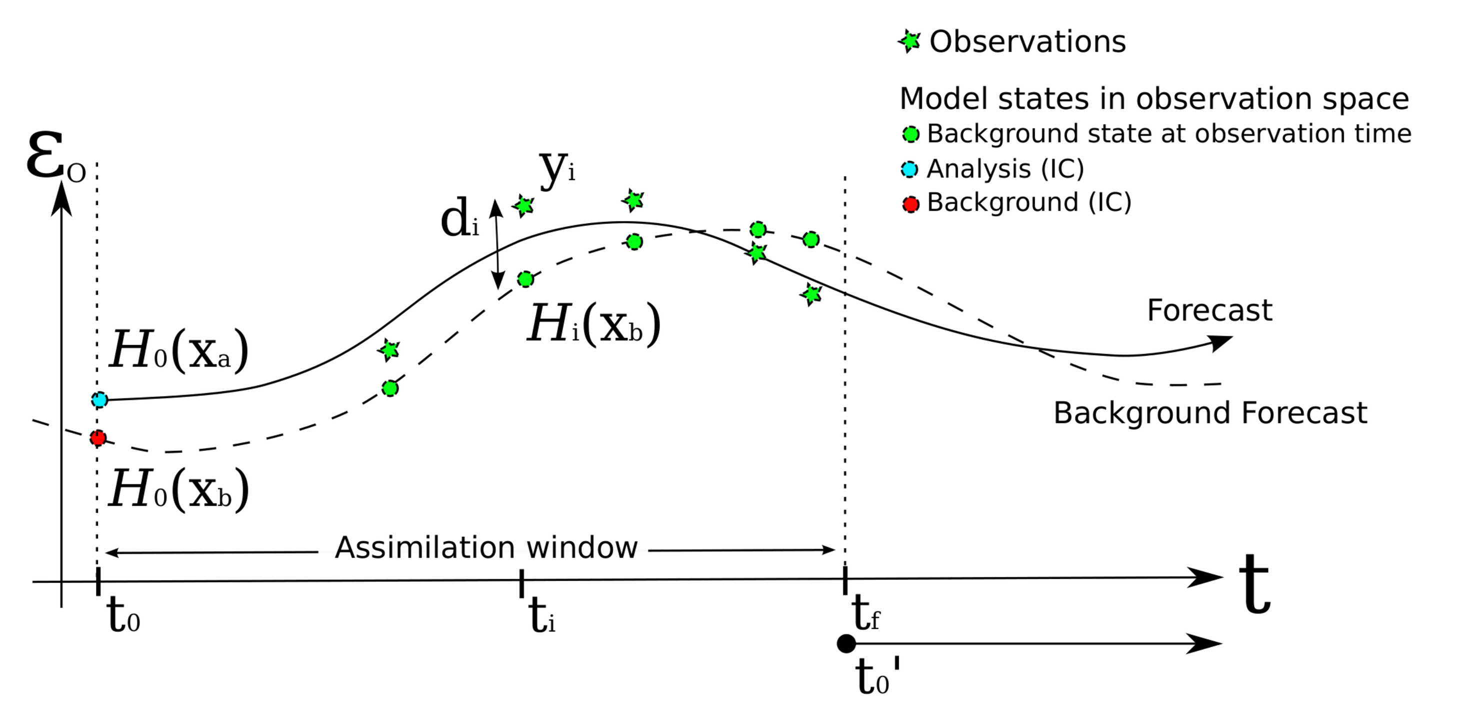

Figure 1: 4D-Var represented on observation space, $\mathcal{E}_O$. Assimilation cycle over $[t_0, t_f]$.

Targeting the Unstable Subspace

Targeting techniques aim at reducing IC error impact on the forecast quality by identifying **unstable modes** of the TLM, $\mathbf{L}$, and assimilating extra observations on their structure.

$$\|\delta\mathbf{x}(t)\|^2_{\mathbf{g}} \equiv \langle \mathbf{L}\delta\mathbf{x}_0, \mathbf{L}\delta\mathbf{x}_0\rangle_{\mathbf{g}} = \langle \mathbf{L}^*_{\mathbf{g}}\mathbf{L}\delta\mathbf{x}_0, \delta\mathbf{x}_0\rangle_{\mathbf{g}} \quad (2)$$

The ordered eigenvectors of $\mathbf{L}^*_{\mathbf{g}}\mathbf{L}$ are SVs of the TLM. The first k SVs spawn the **unstable subspace** of order k on which we define the **target subspace**, Σ_0.

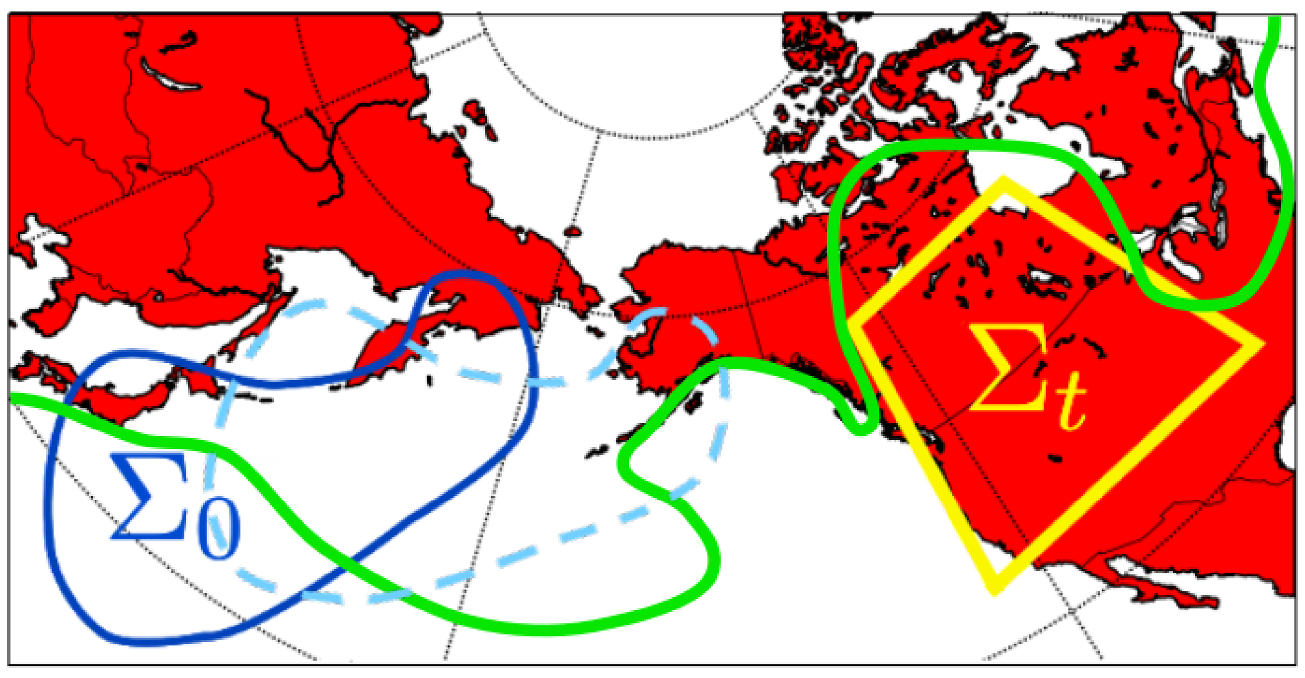

Figure 2: Targeting observations: target subspace at $t = 0$ (Σ_0) and verification area (defined by the choice of metric, $\mathbf{g}$) at $t = \Delta t > 0$ (Σ_t). Also shown, the Jet Stream (in green) and a shifted unstable region (in light blue dotted line).

The Jet Stream Waveguide

An idealized representation of a zonal Jet Stream can be described by two domains of constant PV, $q(y) = \mathrm{sign}(y)\Delta q/2$, on a β-plane. It has been shown that the discontinuity act as a waveguide for perturbations, ψ' [7].

$$\mathbf{u}(y) = \mathbf{i}\left(u_0 - \frac{\Delta q}{2}|y| + \frac{1}{2}\beta y^2\right) \quad (3)$$

$$\psi' \propto \mathrm{e}^{-k|y|}\mathrm{e}^{\imath(kx-\omega t)}, \quad \omega = u_0 - \frac{\Delta q}{2} \quad (4)$$

- Nearby PV anomalies (topographic or atmospheric) can interact with the Jet and **trigger downstream wavetrains** which propagate westward at the Jet speed, u_0. These wavetrains can lead to the formation of cut-off lows responsible for unstability and severe convective events[2][5].
- We hypothesize that **SVs are greatly influenced by these wavetrains** and incidently their upstream trigger mecanism.
- In the simple discontinuous β-plane model, a PV anomaly of wavenumber $k \in \mathbb{N}$ advecting with a velocity of u^* will **trigger a resonant response** with the wavetrain if $k = k^*$:

$$k^* = \frac{\Delta q}{2(u_0 - u^*)} \quad (5)$$

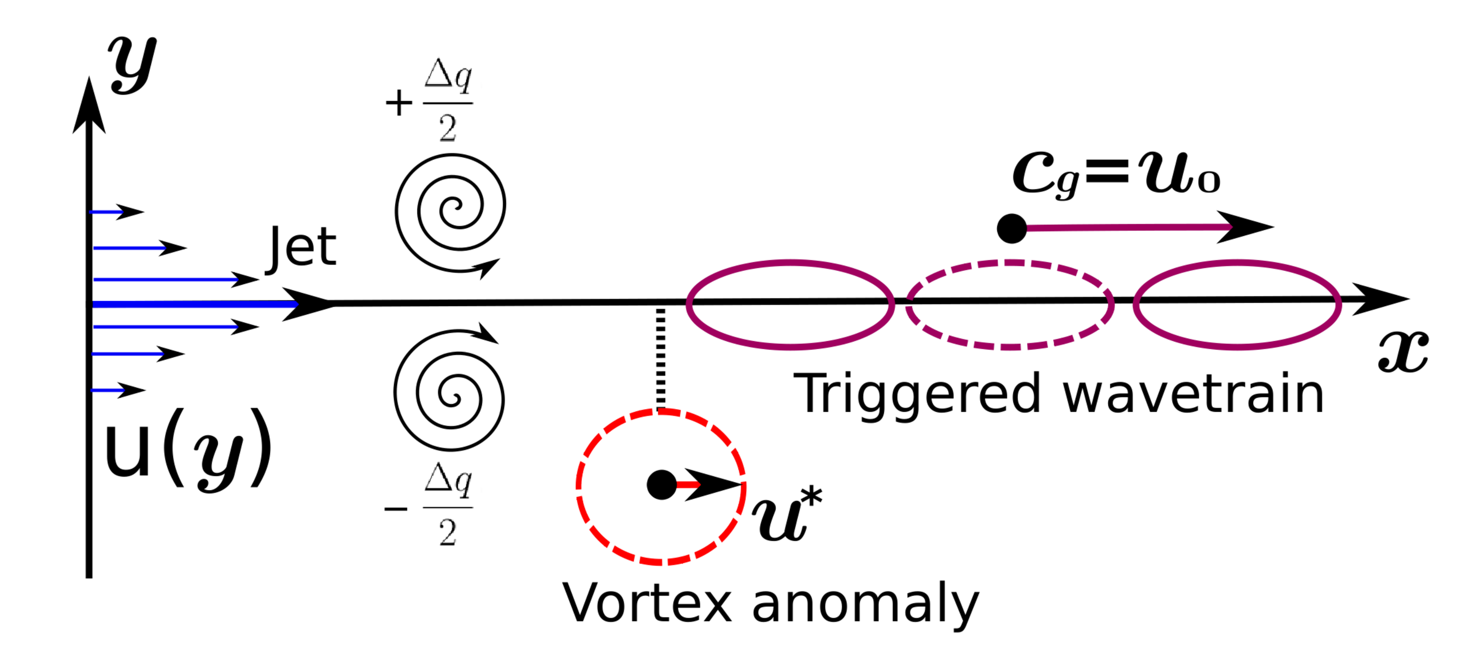

Figure 3: Rossby wavetrain (purple), trapped on PV discontinuity ($y = 0$), triggered by an upstream perturbation (red) advected parallel to the zonal Jet[7].

Research proposal

Objectives

1. Characterize the influence on SVs evolution of planetary and synoptic waves interaction with the Jet Stream ;
2. Define an appropriate metric for the characterization of SVs ;
3. Investigate SVs observability as they evolve in time ;
4. Investigate the relevance to the deployment of adaptive observations and the inclusions of flow-dependent structure functions (in the $\mathbf{B}$ matrix).

Methodology

Conduct OSSEs with focus on nonlinear wave interaction and downstream propagation of error and instability patterns.

1. Investigation on a weakly nonlinear wave interaction model
   - Unstable subspace and spatial correlation with flow structure ;
   - Evolution of SVs and correspondence with features of the reference trajectory ;
   - Energy fluxes and scale transfer ;
   - DA simulation on degraded reference trajectories.
2. OSSE on a Numerical Weather Prediction model
   - Realistic nature run (reference trajectory) ;
   - Detailed observing system simulation (including satellite observations).

References

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