Numerical sensitivities of the ECMWF semi-Lagrangian model in the stratosphere

(Improving Sudden Stratospheric Warming Forecasts in IFS)

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ECMWF

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(thanks to: Filip Vana, Sean Healy, Niels Borman)

Outline

- Very brief overview of the ECMWF model
- How departure points are computed
- A modification of the operational departure point scheme to improve forecasts of Sudden Stratospheric Warming (SSW) events
- Validation on SSW cases

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ECMWF IFS (Integrated Forecast System)

Operational IFS model:

- Hydrostatic shallow atmosphere model (NH option available)
- Pressure-based hybrid vertical coordinate
- Spectral transform method (spherical harmonics) in horizontal + FEM vertical discretization
- Two-time-level (2TL) semi-Lagrangian (SL) transport scheme (3D) on linear reduced Gaussian grid + semi-implicit timestepping + constant coefficient Helmholtz solver

Forecasting system:

- Deterministic: 10-day forecast at T1279 horizontal resolution (16km) and 137 vertical levels (up to 0.01 hPa height)
- Probabilistic: 50 member ensemble prediction system at T639 and 91 levels

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Basic steps in semi-Lagrangian transport

There are two important computational tasks in a SL advection scheme when marching from time t to $t + \Delta t$:

1. SL trajectory: for every model grid-point compute a departure point solving

$$\frac{D\mathbf{r}}{Dt} = \mathbf{V}(\mathbf{r}, t), \qquad \mathbf{V} = (u, v, \dot{\eta})$$

2. Interpolation: the advected field is interpolated at the departure point

An accurate scheme for calculating the departure point (d.p.) and an accurate interpolation scheme are two important elements of every SL model. In IFS:

- Departure point: SETTLS (Hortal 2002, QJRMS)
  - this replaced midpoint scheme which was noisy
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SETTLS: stable extrapolation for computing d.p.

$$\mathbf{r}(t+\Delta t) = \mathbf{r_d}(t) + \Delta t \left(\frac{D\mathbf{r}}{Dt}\right)_d + \frac{\Delta t^2}{2}\left(\frac{D^2\mathbf{r}}{Dt^2}\right)_{AV}, \quad \left(\frac{D^2\mathbf{r}}{Dt^2}\right)_{AV} \approx \frac{\mathbf{V}(t) - \mathbf{V_d}(t-\Delta t)}{\Delta t}$$

$$\boxed{\mathbf{r}(t+\Delta t) = \mathbf{r}_d(t) + \frac{\Delta t}{2}\{\mathbf{V}(t) + [2\mathbf{V}(t) - \mathbf{V}(t-\Delta t)]_d\}}$$

1. Store: $\mathbf{V}^{ext} = 2\mathbf{V}^t - \mathbf{V}^{t-\Delta t}$
2. Initialise: ${\mathbf{r_d}}^{(1)} = \mathbf{r} - \Delta t \mathbf{V}^t(\mathbf{r})$
3. For $\ell = 2, \ldots, L$:
   1. Interpolate $\mathbf{V}^{ext}$ to latest computed d.p. ${\mathbf{r_d}}^{(\ell-1)}$: $\mathbf{V}^{ext}\left({\mathbf{r_d}}^{(\ell-1)}\right)$
   2. Update: $\mathbf{r}_d^{(\ell)} = \mathbf{r} - 0.5\Delta t\left[\mathbf{V}^t + \mathbf{V}^{ext}\left({\mathbf{r_d}}^{(\ell-1)}\right)\right]$

But there was still noise in upper stratosphere ...

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Cases of numerical noise in upper stratosphere

- SETTLS reduced noise except for the cases where the stratospheric night polar jet is disrupted and moved away from the poles
  - This circulation is associated with Sudden Stratospheric Warming events (SSW)
- There are side-effects of this instability
  - Large background forecast - sat observations departures (differences) resulting to data rejections in 4DVAR assimilation
  - Model unable to predict stratospheric warming
- The solution originally coded was "smoothing the vertical velocities"
  - it was switched off by accident at Cy38r1 (2012) and ...
  - stratospheric forecasts improved for most days (except SSW ones)
  - so, it was decided to keep it switched off ...
  - but it was necessary to find an alternative solution that removes noise without negative impact on overall skill

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A cost free alternative: modified SETTLS scheme

Testing, previous experience but also theory (see Cordero et al QJRMS 2005) suggest that the source of this noise is often the extrapolation of the vertical wind component. In IFS this is $\dot{\eta}$.

To address this problem a modification to SETTLS has been developed:

1. *grid-points which have "high risk" to develop instability are identified at each timestep*
2. *the 2nd order SETTLS is switched off at these grid-points and a non-extrapolatory 1st order but more stable scheme is applied*

This strategy achieves to improve stability while preserving 2nd order accuracy in regions where 2nd order scheme produces smooth solutions. Neutral (in accuracy) results for usual weather regimes BUT noticeable improvement in the stratosphere during SSW episodes.

- In practice 1st order scheme is used only in a small percentage of points in the forecast model (depends on timestep length)

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Modified SETTLS formula

Iterative SETTLS for computing η_d:

$$\eta_d^{(\ell)} = \eta - \frac{\Delta t}{2}\left[\dot{\eta}^t + \left(2\dot{\eta}^t - \dot{\eta}^{t-\Delta t}\right)_{d^{(\ell-1)}}\right]$$

is modified to

$$\eta_d^{(\ell)} = \begin{cases} \eta - \frac{\Delta t}{2}\left[\dot{\eta}^t + \left(2\dot{\eta}^t - \dot{\eta}^{t-\Delta t}\right)_{d^{(\ell-1)}}\right], & \left|\dot{\eta}^t - \dot{\eta}^{t-\Delta t}\right| \leq \beta \frac{\left|\dot{\eta}^t\right| + \left|\dot{\eta}^{t-\Delta t}\right|}{2} \\ \eta - \frac{\Delta t}{2}\left[\dot{\eta}^t + \dot{\eta}^t_{d^{(\ell-1)}}\right], & \left|\dot{\eta}^t - \dot{\eta}^{t-\Delta t}\right| > \beta \frac{\left|\dot{\eta}^t\right| + \left|\dot{\eta}^{t-\Delta t}\right|}{2} \end{cases}$$

d	*departure point*
$\dot{\eta}$	*vertical velocity*
$\left\lvert\dot{\eta}^t - \dot{\eta}^{t-\Delta t}\right\rvert$	*jump in vertical velocity across two time steps*
β	*tuning parameter which determines how often to apply 1st order scheme* $0 \leq \beta \leq 2$

Asymptotic error analysis

Taylor expansion of d.p. (arrival point: $\eta \equiv \eta^{n+1}$):

$$\eta_d = \eta^{n+1} - \Delta t \left(\frac{d\eta}{dt}\right)^{n+1} + \frac{\Delta t^2}{2}\left(\frac{d^2\eta}{dt^2}\right)^{n+1} + O(\Delta t^3)$$

2-iteration SETTLS ($\ell = 2$) applied on vertical d.p.:

$$\eta_d^{(1)} = \eta^{n+1} - \Delta t\, \dot{\eta}(\eta^{n+1}, t^n) \tag{1}$$

$$\eta_d^{(2)} = \eta^{n+1} - \frac{\Delta t}{2}\left[\dot{\eta}\left(\eta_d^{(1)}, t^n\right) + 2\dot{\eta}\left(\eta_d^{(1)}, t^n\right) - \dot{\eta}\left(\eta_d^{(1)}, t^{n-1}\right)\right] \tag{2}$$

Substitute (1) to (2) and expand to obtain:

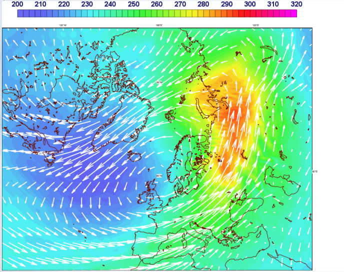
$$\eta_d^{(2)} = \eta^{n+1} - \Delta t \left(\frac{d\eta}{dt}\right)^{n+1} + \frac{\Delta t^2}{2}\left(\frac{d^2\eta}{dt^2}\right)^{n+1} + O(\Delta t^3)$$

Non-extrapolated scheme in modified SETTLS:

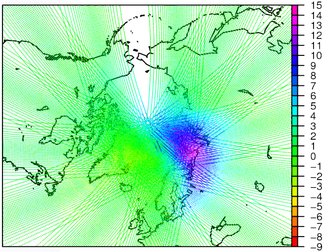
$$\eta_d^{*(2)} = \eta^{n+1} - \Delta t \left(\frac{d\eta}{dt}\right)^{n+1} + \frac{\Delta t^2}{2}\left(\frac{d^2\eta}{dt^2}\right)^{n+1} + \frac{\Delta t^2}{2}\left(\frac{\partial\dot{\eta}}{\partial t}\right)^{n+1} + O(\Delta t^3)$$

Principal term difference: $\eta_d^{*(2)} - \eta_d^{(2)} = \frac{\Delta t^2}{2}\left(\frac{\partial\dot{\eta}}{\partial t}\right)^{n+1}$

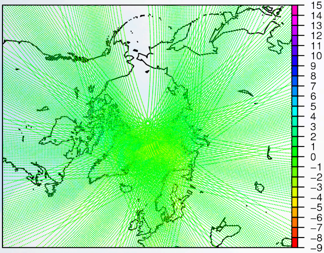
15/01/12: Model departures (T) from sat obs at 5hPa



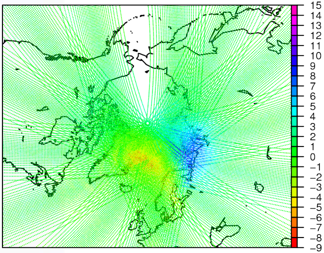
(a) T analysis



(b) Diff from CNTL

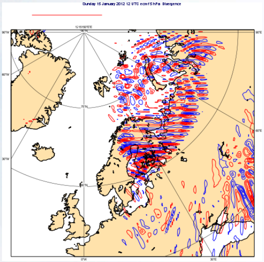


(c) Diff from new scheme

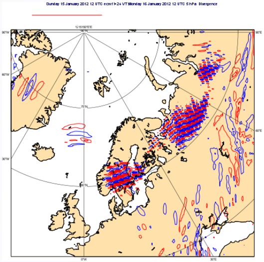


(d) Diff from smoothing $\dot{\eta}$

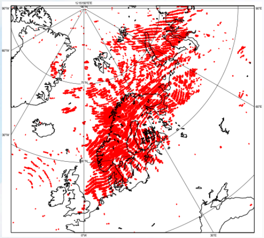
Numerical noise on divergence field (D)



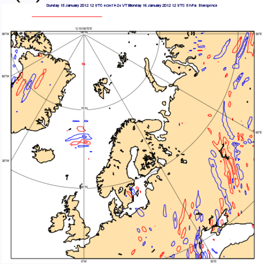
(a) D analysis time



(b) D t+24hrs SETTLS

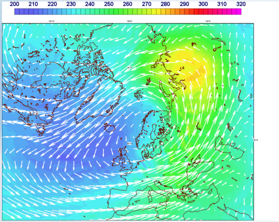


(c) non-extrapolated area

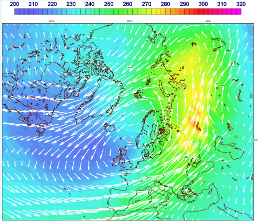


(d) D t+24hrs MODIFIED

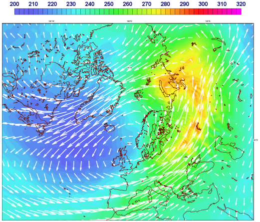
SSW case: SETTLS (row 1) vs MODIFIED (row 2)



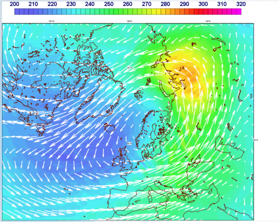
(a) anal 14 Jan 12



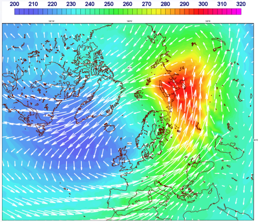
(b) t+24hrs fc AT 15 Jan



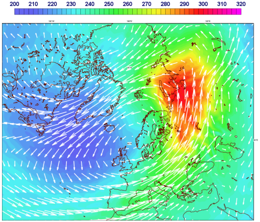
(c) anal 15 Jan



(d) anal 14 Jan 12



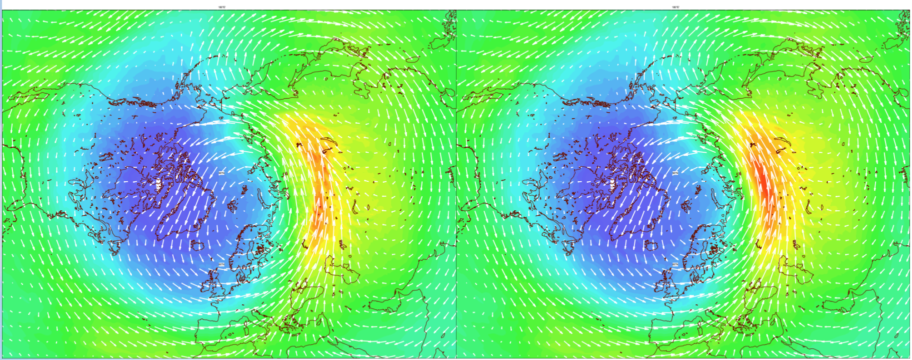
(e) t+24hrs fc AT 15 Jan

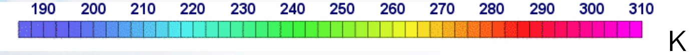


(f) anal 15 Jan

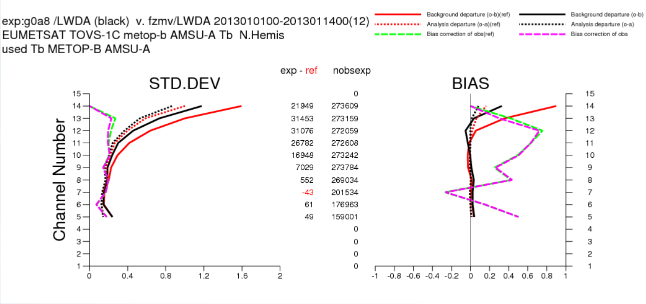
January 2013 SSW episodes

Analyses sequence (12hrs step) for T/winds from 01 to 14 Jan 2013:





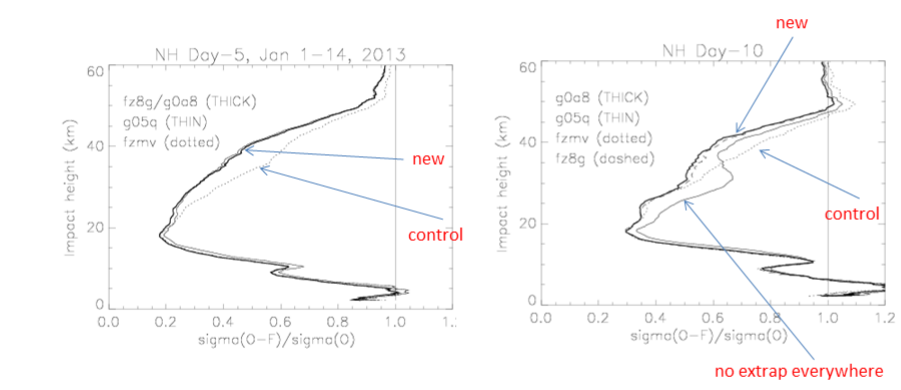
January 1-14 SSW case statistics



SETTLS MODIFIED

- Analysis: big reduction in bias and stdev of (bg fc) - (sat obs) in the stratosphere and increase in the number of sat obs assimilated ($\approx$ 10% more)
- Forecasts: while neutral in terms of skill scores at SH and NH troposphere, noticeable increase of ACC and reduction of RMSE in stratosphere

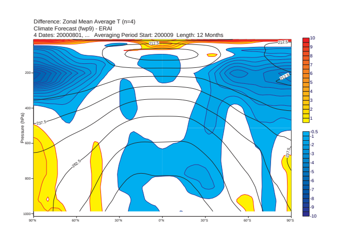
Verification against sat obs: bending angle diagnostics



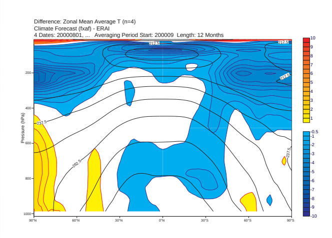
[Standard deviation of GPS-RO bending angle errors (tool developed by Sean Healy)]

- Noticeable improvement at medium-range (day 5, 10)
- Applying non-extrapolatory scheme EVERYWHERE decreases accuracy at medium range ⇒ combined approach the right one

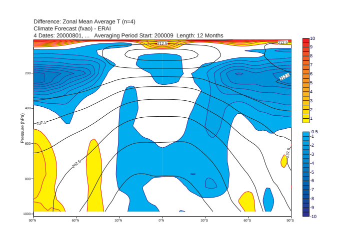
Long range fc cold bias sensitivity: T-errors wrt to ERAI



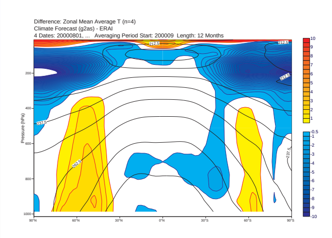
(a) SETTLS



(b) SETTLS + smoothing $\dot{\eta}$



(c) MODIFIED SETTLS



(d) sensitivity wrt humidity interp: linear in the vertical (cf. cubic)

Summary

- In SSW regimes the IFS SL scheme is quite sensitive to the trajectory (d.p.) algorithm used and may become very "noisy" resulting to incorrect flow and significant under prediction of the warming
- To address this problem a simple modification of SETTLS trajectory scheme in the vertical has been presented which identifies gridpoints that are prone to instabilities and applies there a low order non-extrapolatory scheme
- The practical result is:
  - reduction of noise + better prediction of SSWs
  - marked increase in mumber of satellite obs assimilated (in SSW weather regimes)
  - noticeable improvement in skill during SSWs while neutral results in other cases

Thank you for your attention!

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