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Improving ECMWF forecasts of sudden stratospheric warmings

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Improving ECMWF forecasts of sudden stratospheric warmings

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During winter a strong circumpolar cyclonic flow of cold air develops in the stratosphere which is known as the 'stratospheric polar vortex'. Observation records dating back to the 1950s show that on a number of occasions each winter this apparently stable circulation pattern can be suddenly disrupted. A warming of up to 50 K occurs in the space of just a few days (at altitudes around 30 km and above), weakening the westerly zonal-mean flow or even reversing it to be easterly in the most extreme cases. This phenomenon is called a sudden stratospheric warming (SSW) and primarily occurs in the northern hemisphere.

Figure 1 shows a time series of the mean brightness temperature at around 5 hPa in the vicinity of the north and south poles as observed by the NOAA-15 spacecraft from 1999 to the present day. This shows that in the northern polar region the seasonal variation in temperature is frequently disrupted by SSWs, but SSWs are rare in southern polar region.

It is important that our forecast model is capable of accurately predicting these dramatic events for two reasons. Firstly, despite being a stratospheric phenomenon, there is strong evidence to suggest that SSWs influence the large-scale tropospheric circulation below and therefore the winter weather that we experience. Secondly, a failure to represent the large thermal changes associated with SSWs can lead to a significant discrepancy between the model and observations (primarily from satellites). Under these conditions the data assimilation system may incorrectly interpret the mismatch as a problem with the measurements and wrongly reject perfectly good observations. Failing to use these observations (that may have helped correct the model) means that both our forecasts and analyses of these important events can be very poor.

In SSW regimes the numerical scheme currently employed by the Integrated Forecasting System (IFS) for finding the departure point of the semi-Lagrangian trajectory (SETTLS) becomes very 'noisy'. This can result in a significant under- prediction of the warming events. To address this problem a simple modification to the SETTLS will be included in the next operational cycle. The scheme identifies gridpoints that are prone to instabilities and for these a more stable scheme is applied. For the remaining points the standard SETTLS procedure is applied, which is in general more accurate when time evolution is relatively smooth.

During SSW events the new scheme shows large improvements in the accuracy of stratospheric forecasts and a significant reduction in the number of satellite observations wrongly rejected by the data assimilation system.

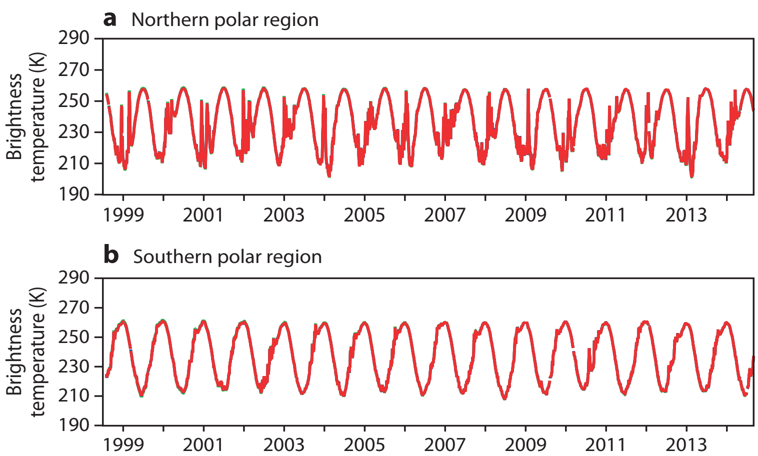

Figure 1 Time series of the mean brightness temperature observed in channel 13 of the AMSU-A instrument on board the NOAA-15 satellite. Channel 13 is sensitive to temperatures around 5 hPa. Panel (a) shows the seasonal variations in the northern polar region being disrupted by SSW events. For reference, panel (b) shows that SSWs are rare in the southern polar region.

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Different types of sudden stratospheric warming and their origin and influence

Labitzke & van Loon (1999) classify SSWs into four categories according to their strength.

- ***Major Midwinter Warmings*** occur mostly in January–February and are accompanied by a migration of the cold polar vortex south of 65°N or even a split into two separate vortices. The westerly circulation around 10 hPa is reversed to easterly and high pressure forms in the stratospheric polar region.
- ***Minor Warmings*** are strong enough to reverse the temperature gradients between the poles and mid-latitudes, but not severe enough to reverse the circulation.
- ***Canadian Warmings*** occur in early winter and may briefly change the wind direction, but they are not strong enough to cause a complete breakdown of the polar vortex.
- ***Final Warmings*** appear at the end of the winter, signalling the transition from winter to summer as the cold cyclonic stratospheric vortex is replaced by a warm high-pressure system.

Studies show that SSWs are triggered by upward propagating Rossby waves entering the stratosphere and interacting with the westerly zonal-mean flow. These vertically-propagating waves decelerate the stratospheric westerlies and their effect increases with height as the wave amplitude increases due to reduced air density. Flow disturbances grow to the point that westerlies may completely shut down and reverse to become easterlies. As this happens, air near the polar cap region descends adiabatically and intense warming occurs. For a detailed analysis the reader may consult the paper by *Matsuno* (1971).

SSWs are primarily a winter northern hemisphere phenomenon where substantial Rossby wave activity can be found. Summer conditions are not favourable for such phenomena as during the warm season strong easterlies prevail in the stratosphere and the coupling of the troposphere-stratosphere system is weak. Stratospheric warmings have a variable frequency. Almost every year will have some warming event, with a major SSW typically occurring every second year.

Are SSWs important for the weather we experience on the ground? A number of studies, for example *Baldwin & Dunkerton* (1999), have found that upper-stratospheric geopotential anomalies observed in major SSWs frequently descend into the troposphere. The process is slow and results in the typical winter westerlies being replaced in some regions by easterlies or northerlies depending on the positioning of the developing surface high-pressure system. For many parts of Europe this change is associated with cold weather. As it usually takes up to three weeks for this anomalous circulation to fully develop near the surface, giving an accurate medium-range prediction of a major SSW event can extend the forecast horizon of a high impact cold weather event to a timescale exceeding one month.

Semi-Lagrangian trajectories and ‘numerical noise’ in ECMWF model

A fundamental assumption in the semi-Lagrangian (SL) framework is that at each model instant t an air parcel starts its trajectory at a location called the ‘departure point’ and arrives at t+Dt at a model gridpoint called the ‘arrival point’. For each given arrival point there is a unique departure point which needs to be found. This is done by solving the so-called ‘semi-Lagrangian trajectory’ equation at each timestep. The solution method has been revised a few times since the introduction of the SL scheme in the IFS and the one currently used is based on scheme called SETTLS (Stable Extrapolating Two Time Level Scheme) which was developed by *Hortal* (2002). Box A describes how SETTLS has been implemented in the IFS.

SETTLS gave improved predictions compared with schemes that had been used previously. However, from an early stage it was found that noisy fields occasionally occur in forecasts in the upper part of the stratosphere, mostly when the stratospheric vortex is displaced away from the pole. As noise contaminates the vertical velocity field, large errors are introduced in the vertical transport scheme which is a key ingredient in capturing the warming accurately.

Other formulations based on extrapolation do exist. However, as demonstrated by *Hortal* (2002), SETTLS is preferable as it has better stability than the other schemes. SETTLS plays a central role in the IFS as it is also used to extrapolate nonlinear terms in the semi-implicit time integration scheme. However, in this article we will confine our discussion to the application of SETTLS in the SL trajectory equation. This particular scheme is often called SETTLST, while the corresponding scheme applied to semi-implicit computations is called SETTLS.

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Implementation of SETTLS

A

Semi-Lagrangian (SL) schemes are used to solve numerically the transport equations of NWP. Such schemes are unconditionally stable and have good phase speed properties with little numerical dispersion. Also SL schemes have the benefit of being relatively simple – the computation of the non-linear advection term becomes part of an interpolation process in which transported fields are remapped from the fixed Eulerian model grid on the Lagrangian time-dependent 'departure point grid'.

The 'SL trajectory' equation is:

$$\frac{\mathrm{D}\mathbf{r}}{\mathrm{D}t} = \mathbf{V}(\mathbf{r}, t), \quad \frac{\mathrm{D}}{\mathrm{D}t} = \frac{\partial}{\partial t} + \mathbf{V}\cdot\nabla \qquad \text{(A1)}$$

where $\mathrm{D}\mathbf{r}/\mathrm{D}t$ denotes the Lagrangian derivative of the coordinates r of an air parcel which moves with velocity $\mathbf{V} = (u, v, \dot{\eta})$. The vertical wind component $\dot{\eta}$ is expressed as the time-derivative of the terrain following vertical coordinate used in the IFS. Solving the trajectory equation (A1) is an important step in every SL model as it has a big impact on forecast accuracy.

Equation (A1) is solved by discretizing its time integral in $[t, t+\Delta t]$. One discretization method often used is the second order accurate mid-point rule:

$$\mathbf{r_A} - \mathbf{r_D} = \Delta t\, \mathbf{V}_{\mathrm{M}}^{t+\frac{\Delta t}{2}}, \quad \mathbf{V}_{\mathrm{M}}^{t+\frac{\Delta t}{2}} \approx \mathbf{V}\left(\frac{\mathbf{r_A}+\mathbf{r_D}}{2}, t + \frac{\Delta t}{2}\right) \qquad \text{(A2)}$$

where M is the trajectory mid-point, D is the departure point and $\mathrm{r_D}$ its coordinates (at time t) which are unknown and must be found. The coordinates of the arrival point $\mathrm{r_A}$ (defined at time $t+\Delta t$) are given and, by definition of the SL method, must be a gridpoint.

Equation (A2) defines a recurrence relation and can be solved for $\mathrm{r_D}$ using standard fixed-point iteration. At each new iteration the wind field at the trajectory midpoint is needed and is obtained using spatial interpolation. However, the wind field that needs to be interpolated is specified at future time $t+\mathrm{D}t/2$ but it has been computed only up to t. To tackle this problem in a computationally efficient manner, time extrapolation is utilised.

The IFS scheme SETTLS (Stable Two Time Level Extrapolation) is based on the formula

$$\mathbf{r_A} - \mathbf{r_D} = \frac{\Delta t}{2}\{\mathbf{V}_\mathbf{A}^t + [2\mathbf{V}^t - \mathbf{V}^{t-\Delta t}]_\mathrm{D}\} \qquad \text{(A3)}$$

where the term in curly brackets on the right-hand side of equation (A3) provides an approximation for the velocity at the mid-point of the trajectory and the subscript D implies interpolation of the wind field at the departure point. Once again, from equation (A3) we can define the recurrence relation

$$\mathbf{r}_\mathrm{D} = \mathbf{r_A} - \frac{\Delta t}{2}\{\mathbf{V}_\mathbf{A}^t + [2\mathbf{V}^t - \mathbf{V}^{t-\Delta t}]_\mathrm{D}\} \qquad \text{(A4)}$$

which can be solved iteratively starting with $\mathbf{r_D} = \mathbf{r_A} - \Delta t \mathbf{V}_\mathbf{A}^t$ and cycling two further times. The final value of $\mathrm{r_D}$ becomes the departure point. In practice, the mathematical details are more complex as spherical geometry has to be taken into account.

Despite the improvements that SETTLS and SETTLST introduced into the IFS, testing showed that very noisy fields at model levels lying in the upper half of the stratosphere sometimes occur when the night polar stratospheric jet is shifted away from the poles, a situation typical in SSWs. Experiments identified that the term which corresponds to the vertical part of vector equation used in the SETTLST (equation (A3) in Box A) is the 'numerical component' of the SL scheme that mostly contributes to noise generation.

The numerical issue does not threaten the overall stability and robustness of the model; in other words the associated instability is weak. Nevertheless, it has a negative impact on forecast error in the stratosphere. Very noisy vertical velocities result in large errors in vertical transport; this in turn affects the temperature field. Initially, the approach used for dealing with this problem was to smooth the vertical component of the wind (see *Hortal*, 2004) when the departure points were computed. However, at current resolutions smoothing has a negative impact on accuracy in the stratosphere which became apparent when it was switched off (accidentally) in IFS cycle 38r1. Because of this improvement in forecasting scores, it was decided not to re-activate the smoothing and to explore alternatives for dealing with the numerical noise problem.

Alternative techniques for smoothing have been tried and they all showed improvements in dealing with under-prediction of SSWs and noise amplification. For example, we have tested off-centring the semi-implicit scheme (a standard method to control numerical noise) and using the Iterative Centred Implicit (ICI) version of SL dynamics. However, each of these methods had its problems. Off-centring increases the damping of the numerical solver and as a result reduces the model accuracy. Gravity waves can be wiped-out if a large amount of off-centring is used. The other alternative, ICI, does not have this drawback; it is a second order accurate fully-centred scheme which in addition offers enhanced stability

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and for this reason it is used in the non-hydrostatic version of IFS. Improved stability comes from the fact that ICI is essentially a predictor-corrector scheme. Thus the need to extrapolate is eliminated. Unfortunately the extra benefits come at the expense of the computational cost increasing by about 30% to 40%.

As well as considering the off-centring and ICI approaches, the option of replacing the term in the vertical part of SETTLST causing the noise was investigated. The approach taken was to apply a low order non-extrapolatory scheme as described in Box B. Since this approach required only a minor change in the SL scheme and all other parts of it remained unchanged, the hope was that there would be small impact on overall model accuracy. Tests showed that this modification is successful in controlling numerical noise in the stratosphere and giving improved SSW forecasts. However, it was found that there is a clear negative impact by enforcing such change everywhere and this will be demonstrated later.

Improving the SL trajectory algorithm

It was clear that to address the problems encountered with the SETTLST there was a need for a new approach. Inspired by the findings of these experiments in which it became clear that the vertical transport and the time extrapolation in SETTLST are two crucial factors responsible for under-prediction of SSWs, a modified scheme was proposed for the vertical coordinate of the departure point. The main idea behind this modification was to identify gridpoints which have the potential to develop noise and apply the non-extrapolatory scheme described in Box B at those points while applying the standard SETTLST method elsewhere. In effect this is what we often call ‘limiter’ or ‘filter’ in NWP. The new scheme is outlined in Box C.

The modified scheme was initially tested having it active on all model levels. However, as it was found that the modified scheme improves the flow only in the stratosphere, it was finally applied only at model levels lying at or above 60 hPa. The scheme is gradually relaxed to standard SETTLS in the vertical by introducing a height dependency to the parameter b which controls the extent to which the non-extrapolatory scheme is applied; b increases gradually to 2.0 in the layer between 30 hPa and 60 hPa.

We shall call the modified scheme SETTLSTF. The letter ‘F’ implies that a filter is applied on the standard SETTLST; this means that the condition given in Box C is used to select those gridpoints where the non-extrapolatory scheme will be activated.

Non-extrapolatory scheme in the vertical **B**

SETTLST computes the vertical component of the departure point using the formula based on equation (A4):

$$\eta_{\mathrm{D}} = \eta_{\mathrm{A}} - \frac{\Delta t}{2}\{\dot{\eta}_{\mathrm{A}}^{t} + [2\dot{\eta}^{t} - \dot{\eta}^{t-\Delta t}]_{\mathrm{D}}\}$$

Experiments indicate that it is the following extrapolation term that is causing the noise problems:

$$[2\dot{\eta}^{t} - \dot{\eta}^{t-\Delta t}]_{\mathrm{D}}$$

This term can be replaced by $\dot{\eta}_{\mathrm{D}}^{t}$ giving the non-extrapolatory scheme:

$$\eta_{\mathrm{D}} = \eta_{\mathrm{A}} - \frac{\Delta t}{2}(\dot{\eta}_{\mathrm{A}}^{t} + \dot{\eta}_{\mathrm{D}}^{t}).$$

Meteorological impact

SETTLSTF has been tested on various atmospheric flow regimes. For those having SSW events, results suggest that SETTLSTF can provide accurate predictions of stratospheric temperatures both in short and medium ranges. Noise that is usually observed in velocity and temperature fields in the stratosphere is reduced or eliminated. A consequence of these improvements is a noticeable increase in the number of satellite observations assimilated and the forecast skill in the stratosphere improves. The impact on the troposphere and on situations when no SSWs occur is neutral.

Reduction in noise with SETTLSTF

In Figures 2b & 2d the divergence field at 5 hPa is plotted for 24-hour forecasts using SETTLST and SETTLSTF. Both forecasts start from the same analysis which corresponds to the noisy divergence field shown in Figure 2a. Unlike the standard scheme, SETTLSTF produces a smooth solution. It is interesting that the gridpoints where the non-extrapolatory scheme used in SETTLSTF is triggered remain close to the noisy region as demonstrated in Figure 2c.

More importantly, the practical outcome of eliminating this noise is that SETTLSTF correctly forecasts much warmer conditions with differences exceeding 20 K even in the analysis field. This is shown clearly in Figure 3 where the 24-hour forecasts using SETTLST and SETTLSTF are compared with the corresponding analyses.

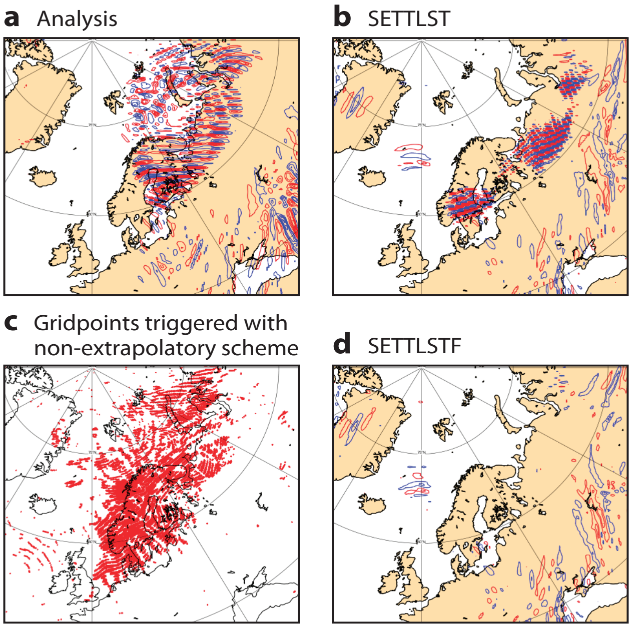

Figure 2 Divergence field at 5 hPa for (a) the analysis at 12 UTC on 15 January 2012 and 24-hour forecasts using (b) SETTLST and (d) SETTLSTF starting from the analysis given in (a). (c) Shows the gridpoints where the non-extrapolatory scheme described in Box B is triggered at 24 hours with SETTLSTF.

The new scheme – SETTLSTF

C

The algorithm for the vertical component of the departure point η_D is written as:

$$\eta_D = \begin{cases} \eta_A - \frac{\Delta t}{2}(\dot{\eta}_A^t + [2\dot{\eta}^t - \dot{\eta}^{t-\Delta t}]_D) \text{ if A} \\ \eta_A - \frac{\Delta t}{2}(\dot{\eta}_A^t + \dot{\eta}_D^t) \text{ if B} \end{cases}$$

$$\text{A: } |\dot{\eta}_A^t - \dot{\eta}_A^{t-\Delta t}| \leq \frac{\beta}{2}\left(|\dot{\eta}_A^t| + |\dot{\eta}_A^{t-\Delta t}|\right)$$

$$\text{B: } |\dot{\eta}_A^t - \dot{\eta}_A^{t-\Delta t}| > \frac{\beta}{2}\left(|\dot{\eta}_A^t| + |\dot{\eta}_A^{t-\Delta t}|\right)$$

where $0 \leq \beta/2 \leq 1$.

It is a hybrid between SETTLST and the non-extrapolatory scheme given in Box B. It is applied in the vertical only, while in the horizontal the standard SETTLS is used.

The right-hand side condition in used in SETTLSTF is a simple criterion to detect gridpoints which can become noisy. This heuristic rule compares the magnitude of the vertical velocity jump during two consecutive timesteps with a two-timestep average of the vertical velocity magnitude.

Big jumps are warnings that the extrapolation may produce noisy results and therefore when this occurs the non-extrapolatory scheme is activated.

The parameter β controls the extent to which the non-extrapolatory scheme is applied: for $\beta = 2$ the standard SETTLST will be applied on all gridpoints while for $\beta = 0$ the non-extrapolatory scheme will be activated everywhere. Values smaller than 2 but near to it penalise points that jump from negative to positive values as well as those that maintain the same sign but exhibit very big jumps.

Testing showed that β values near 2 are sufficient to yield satisfactory results (i.e. control noise growth and provide accurate prediction of SSW events without reducing overall accuracy of forecasts). For example, for β=1.9 about 5%–10% of the points per level switch to the non-extrapolatory scheme in forecasts at T1279L137 resolution (approximately 16 km spacing on the reduced Gaussian linear grid and 137 levels in the vertical). As expected, this percentage depends strongly on timestep which determines how much the SETTLST formula extrapolates. So for larger timesteps the non-extrapolatory scheme becomes more active.

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Comparing SETTLSTF with other methods

During the period from late December 2012 to mid-January 2013 two SSW events occurred. The first event took place over Siberia while the second one, a major event, was over Canada. The short-range forecast, which largely under-predicted the temperature, resulted in a frequent and large number of rejections of satellite observations. To assess the impact of the different methods for controlling the noise discussed earlier in this article, forecast experiments were run at T1279L137 resolution using the following:

- SETTLST as the control.
- SETTLST with a short timestep (D*t*=2 min).
- Off-centring the semi-implicit scheme.
- Smoothing the vertical velocity.
- Iterative Centred Implicit (ICI) scheme.
- SETTLSTF.

They all start at 00 UTC on 10 January 2013 from the same analysis.

The plots in Figure 4 show that the short timestep forecast (Dt=2 min) using SETTLST predicts a major warming at 5 hPa level while the standard timestep (Dt=10 min) forecast has only a very weak signal. ICI and SETTLSTF give the best results that are very close to the short timestep solution. However, SETTLSTF achieves this without increasing the computing cost. Off-centring the semi-implicit scheme improves the temperature prediction but the improvement is very moderate compared with the one obtained by ICI or SETTLSTF. The same is true for the forecast with smoothing.

Comparison against GPS radio occultation observations (not included here) confirms that the largest errors occur with SETTLST, while ICI gives the most accurate prediction closely followed by SETTLSTF. They both outperform smoothing. Furthermore, as shown in Figures 5 and 6, the new scheme can predict the warming at least one week ahead, while below model level 15 (1.2 hPa approximately) there is a very weak signal in the standard SETTLST scheme even in the one-day forecast.

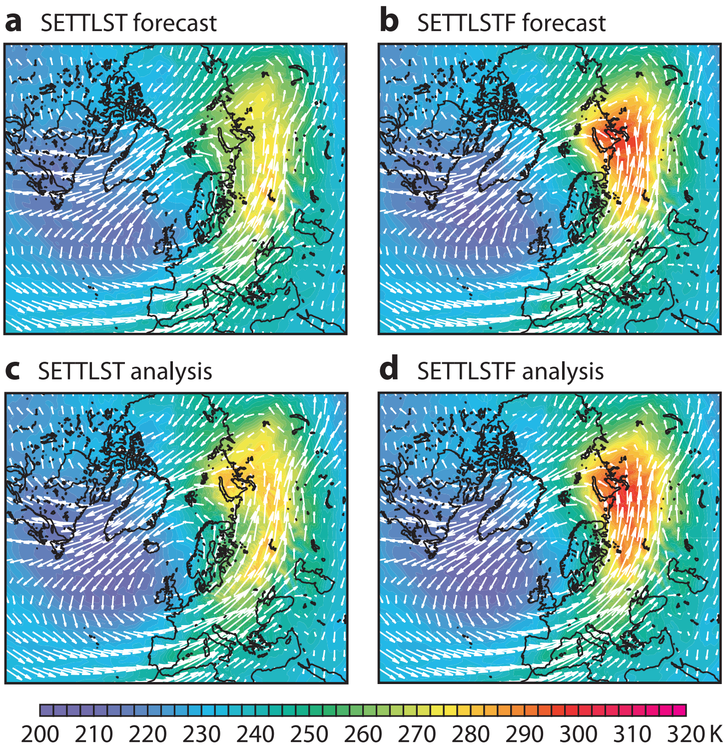

Figure 3 Temperature field at 5 hPa from two analysis (4DVAR) experiments: 24-hour forecasts from 12 UTC on 14 January 2012 using (a) SETTLST and (b) SETTLSTF. Also shown are the analyses at 12 UTC on 15 January with (c) SETTLST and (d) SETTLSTF.

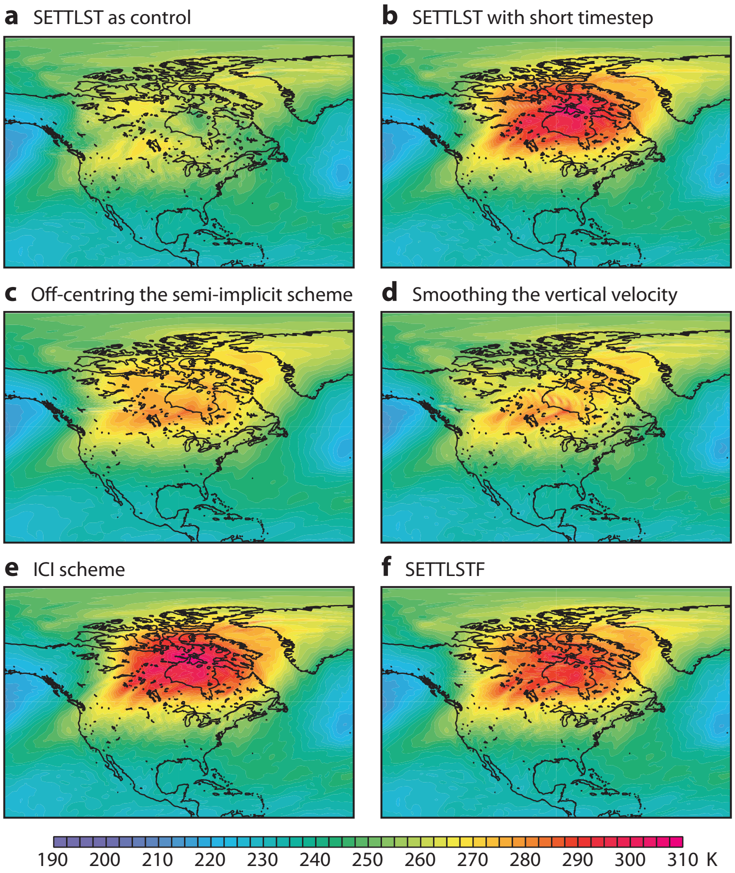

Figure 4 24-hour temperature at 5 hPa from forecasts using different SL options: (a) SETTLST as the control, (b) SETTLST with a short timestep (Δt=2 min), (c) off-centring the semi-implicit scheme, (d) smoothing the vertical velocity, (e) Iterative Centred Implicit (ICI) scheme and (f) SETTLSTF. All forecasts started at 00 UTC on 10 January 2013 from the same analysis.

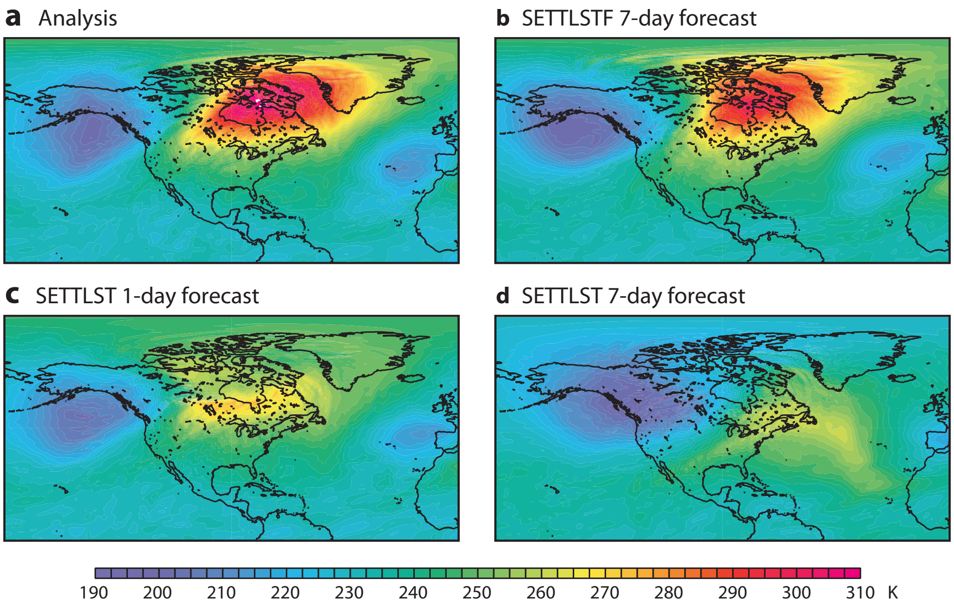

Figure 5 (a) Stratospheric temperature analysis (5 hPa) at 00 UTC on 10 January 2013 along with the corresponding 7-day forecasts using (b) SETTLSTF and (d) SETTLST. The one-day forecast using SETTLST is at (c). The plotted analysis field produced by the SETTLSTF experiment has much better agreement with observations than with SETTLST.

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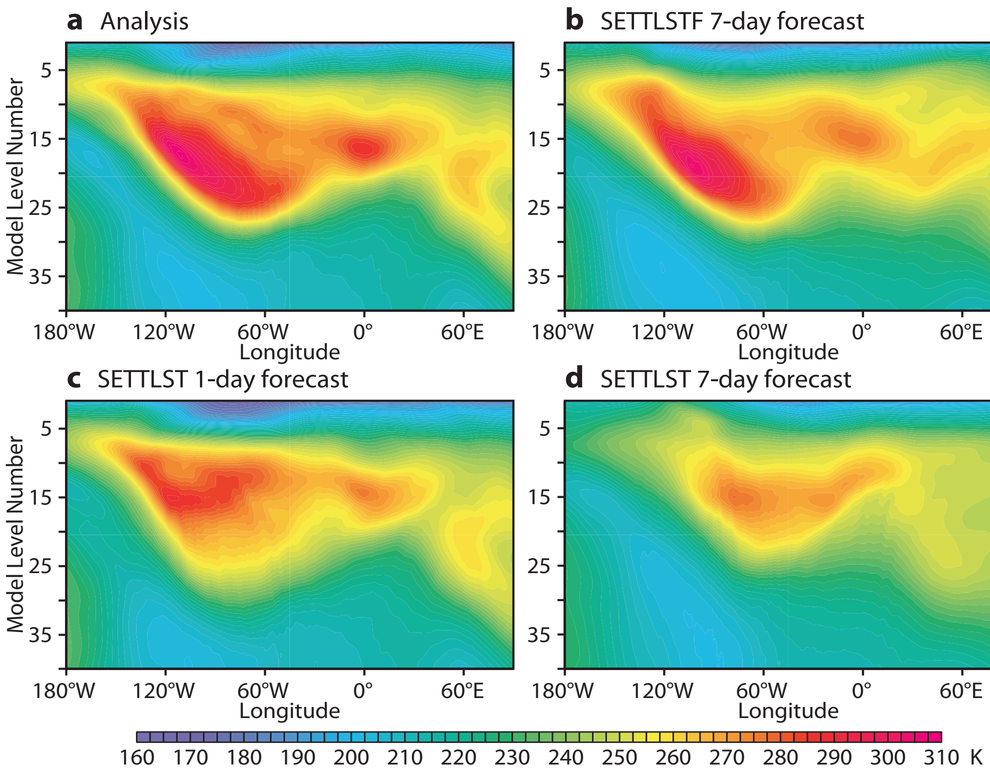

Figure 6 Vertical cross section of (a) analysed temperature at 00 UTC on 10 January 2013 along with the corresponding 7-day forecasts using (b) SETTLSTF and (d) SETTLST. The one-day forecast using SETTLST is at (c).Vertical slice corresponds to the zonal average between 50°N and 80°N.

Impact on the accuracy of forecasts

As mentioned earlier, using the non-extrapolatory scheme everywhere has a significant negative impact in actual forecast accuracy. This is clearly demonstrated in Figure 7a where timeseries of the Anomaly Correlation Coefficient (ACC) and Root-Mean-Square Error (RMSE) are plotted for the geopotential height field at 500 and 10 hPa for a 7-day forecast from three experiments.

- The standard SETTLST.
- The new SETTLSTF.
- The non-exploratory scheme used everywhere in the vertical.

While SETTLSTF is neutral in the troposphere, the non-extrapolatory scheme shows a consistent degradation of accuracy. In the stratosphere, as shown in Figure 7b, both SETTLSTF and the non-extrapolatory scheme perform similarly, resulting in a large reduction of RMSE (almost by a third) and an increase in ACC in the period when the SSW occurs. Further analysis of these results shows that the gains are statistically significant and justify use of this approach to satisfy the objective of improving SSW forecasting without reducing accuracy in the troposphere or in periods where such phenomena do not occur.

Additionally, there is also significant positive impact on the 4DVAR data assimilation system. Standard deviations and biases of forecast departures of brightness temperature from satellite observations in the stratosphere reduce significantly when SETTLSTF is used compared to SETTLST. These quantities are plotted in Figure 8 for various (height-dependent) channels of AMSU-A. Due to improved model predictions, satellite data rejections occurring in the assimilation cycle are also greatly reduced; for example approximately 10% more observations are assimilated at channels 11 to 14 for AMSU-A.

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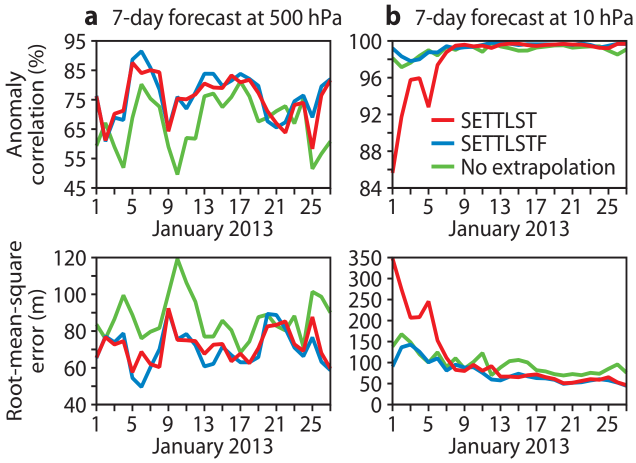

Figure 7 ACC (top) and RMSE (bottom) of the (a) 500 hPa and (b) 10 hPa geopotential for 7-day forecasts from three experiments: the standard SETTLST, new SETTLSTF and non-exploratory scheme everywhere in the vertical. Results are shown for the northern hemisphere extratropics (20°–90°N).

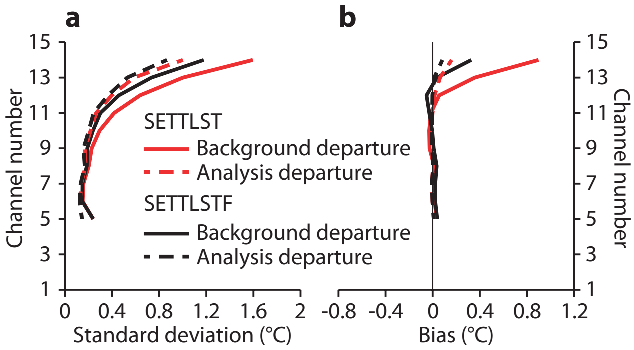

Figure 8 Standard deviation and bias of the background departure (observed minus background) and analysis departure (observed minus analysis) of brightness temperature for the northern hemisphere using SETTLSTF and SETTLST for various AMSU-A channels on board Metop-B.

Concluding remarks

A simple modification to the existing semi-Lagrangian trajectory scheme (SETTLST) is included in IFS cycle 40r3. The new scheme improves stability by identifying gridpoints which are prone to noise generation and applying there a non-extrapolating scheme that does not generate noise. It thus outperforms the standard SETTLST in numerically sensitive regions.

These modifications to the numerics improve the accuracy of forecasts, but also improve our analyses of SSWs by reducing inconsistencies between the model and satellite measurements. As a result the data assimilation system is able to exploit more observations to assist the detailed characterisation of these events.

Further reading

Baldwin, M.P. & **T.J. Dunkerton**, 1999: Propagation of the Arctic Oscillation from the stratosphere to the troposphere. *J. Geophys. Res.,* **104**, 30937–30946.

Hortal, M., 2002: The development and testing of a new two-time-level semi-Lagrangian scheme (SETTLS) in the ECMWF forecast model. *Q. J. R. Meteorol. Soc.,* **128**, 1671–1687.

Hortal, M., 2004: Overview of the numerics of the ECMWF atmospheric forecast model. *ECMWF Seminar on Recent Developments in Numerical Methods for Atmospheric and Ocean Modelling,* 6 to 10 September 2004, http://old.ecmwf.int/publications/library/do/references/list/1733.

Labitzke, K.G. & **H. van Loon**, 1999: *The Stratosphere: Phenomena, History, and Relevance.* Springer Verlag, Heidelberg, 179 pp.

Matsumo, T., 1971: A dynamical model of the stratospheric sudden warming. *J. Atmos. Sci.,* **28**, 1479–1494.

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