The Utility of Upper Boundary Nesting in NWP

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Global Model Description

• The increase in “lid” height of the global model takes the top model level from the mid-stratosphere (dashed yellow) into the mid-mesosphere (solid yellow)

• Stratospheric circulations and processes now included in the model domain (e.g.)
  • Stratospheric polar vortex
  • Meridional overturning
  • Ozone absorption
  • Methane oxidation

Schematic of the atmospheric temperature profile from Lyndon State College course notes.
Global Model Description

• The forecast improvements of the new model configuration (0.1 hPa) are not uniform over time, but occur episodically.

Time series of Northern Hemisphere of geopotential height RMSE in the 120h forecast over a two-month period between December 2006 and February 2007. The low-topped (10 hPa) Meso-Global model is identified as Global LOW, and the high-topped (0.1 hPa) Strato model is identified as Global HIGH. The standard deviation of RMSE over the period is grey-shaded so that separate indicates 95% significant differences (Data source: M. Roch)

Upper Troposphere / Lower Stratosphere

UTLS Interactions

Potential temperature (K, as indicated on the colour bar) on the dynamic tropopause (DT, 2 PVU surface) at 0000 UTC 25 December 2006. Layer-mean 925-850 hPa relative vorticity is shown in black contours at intervals of 0.5 x 10^-4 s^-1. The regions used to compute the Pelly and Hoskins (2003) blocking index are shown with red and blue boxes in the first panel.

Planetary-scale blocking in the European sector leads to an increase UTLS interaction as E-P fluxes converge into the polar cap.

Time series of Eliassen-Palm (E-P) flux vectors, which consist of an eddy heat flux vertical component (Fp) and an eddy momentum flux horizontal component (Fy) at 60°N (bottom).
Lower Stratospheric Evolution

What to look for:

A region of low PV originating over the subtropical Atlantic (W) impacts the stratospheric vortex and breaks anticyclonically over Siberia, creating a strong wave-1 asymmetry that appears as a tilted 850 K surface. Parcels within the polar vortex ascend and descend adiabatically along the sloped isentropic surface.
Lower Stratospheric Evolution

0000 UTC 29 December 2006

0000 UTC 29 December 2006

Lower Stratospheric Evolution

0000 UTC 02 January 2007

0000 UTC 02 January 2007
Understanding the Forecast Error

- Stratospheric wave amplification and breaking appears to be responsible for model error increase
- Error in the old operational model (10 hPa) is reproduced on a hemispheric domain: LOW-LAM
- The equivalent high-topped model (0.1 hPa) serves as a control: HIGH-LAM
- A comparison of the results of these two 5-day integrations shows that the failure mode is entirely related to the imposition of the upper boundary in the mid-stratosphere during the vortex perturbation event
- All forecasts initialized at 0000 UTC 29 December immediately prior to the stratospheric wave break

Stratospheric Temperature Error

- LOW-LAM fails to maintain thermal dipole through vertical motions, and instead predicts filamentation of the anomaly

Forecasts of 10 hPa potential temperature (K, as indicated on the colour bar), winds and pressure-coordinate vertical motion (black contours at 0.4 x 10^{-2} Pa s^{-1} with dashed values for upwards motion) after 120 h of integration in the LOW-LAM (left) and HIGH-LAM (right).

Analyzed pressure, pressure-coordinate vertical motion and winds on the 850 K surface at 0000 UTC 2 January 2007 as plotted previously.
The Upper Model Boundary

- Both model advection and the pressure solver impose 0 vertical motion as an upper boundary condition for the model.
- Horizontal advection is the only adiabatic term at the upper boundary.

\[
\frac{\partial T}{\partial t} = - \vec{V} \cdot \nabla_p T^+ + \omega \left( \frac{\partial \alpha}{\partial c_p} - \frac{\partial T}{\partial p} \right)
\]

interior:

\[
\frac{\partial T}{\partial t} = - \vec{V} \cdot \nabla_p T^+ + \omega \left( \frac{\partial \alpha}{\partial c_p} - \frac{\partial T}{\partial p} \right) \quad >> 0
\]

UBN Implementation

- The assumptions related to null vertical motion at the model top need to be relaxed.
- Several steps are required to implement UBN:
  1. Create nesting (outside domain) and blending (within domain) zones that contain data from the high-topped driving model.
  2. Modify the advection scheme to allow back-trajectories to extend beyond the upper model level so that parcels can both enter and exit the domain.
  3. Modify the pressure solver to relax the 0 vertical motion upper boundary condition used to close the equation set.
3) Solver Boundary Conditions

- The nested vertical motion could be used directly to formulate a new upper boundary condition, but coordinate incompatibility and the fine-scale structure of the field make it a poor nesting candidate.
- Instead, a recombined form of the thermodynamic equation can be employed again so that prescribed temperature is all that is needed to close the equation set:

\[
\frac{\partial T}{\partial t} - \frac{1}{\alpha} \frac{\partial L}{\partial z} = \frac{1}{R_t} \left( \frac{\partial P}{\partial z} \right) \quad \text{(UBN Technique)}
\]

A prescribed value of \( T' \), the perturbation temperature \( (T = T_0 + T') \) makes this equation applicable as an "open" upper boundary condition for the solver.

Additional UBN term

UBN Performance

- Errors in LOW-LAM occur immediately at upper levels, where the AC score reaches "useless" levels by day-3.
- Noticeable errors persist through the mid-troposphere by day-5 in LOW-LAM.
- The results of UBN-LAM are indistinguishable from the HIGH-LAM control.

Anomaly correlation (left column) and RMSE scores from the high-topped (0.1 hPa, solid line) HIGH-LAM, low-topped (10 hPa, dash-dot line) LOW-LAM and UBN-nested UBN-LAM (10 hPa, dashed line) over the 5-day forecast initialized at 0000 UTC 29 December 2006. All scores are computed against ERA-Interim analysis grids on the full Northern Hemisphere domain.
Rapid Tropospheric Response

- Most studies of UTLS interactions have suggested that the timescale of stratospheric influence on the troposphere is >10 days (Baldwin and Dunkerton 2001)
- This timescale is too long for the 5-day forecasts investigated here
- Recent studies (Hartley et al. 1998; Colluci 2010) suggest that PV induction\(^1\) can have a direct effect on the lower troposphere
  - Height perturbations on the dynamic tropopause
  - Direct influence on the development of synoptic scale systems

\(^1\) As noted by Hartley et al. (1998), the word "induction" here is used in the context of the electrostatic analogy of PV inversion and is not intended to imply causality.

Structure Difference

- Typical stratospheric influence timescale is 10 days, but shorter ranges are affected here
- Recent studies [Hartley et al. (1998); Colluci (2010)] suggest that lower-stratospheric PV can directly influence the flow
- Similarity of difference (left) and inverted error (right) structure and magnitude suggests that PV induction is UTLS communication method in this case

Tropospheric height differences as plotted previously for UBN-LAM – LOW-LAM (left column). Height anomalies induced by stratospheric PV errors (UBN-LAM – LOW-LAM differences) are shown with the same plotting technique in the right-hand column.
Discussion

- A wave-1 tropospheric block leads to an upwards-directed wave activity flux across the tropopause
- The resulting stratospheric vortex displacement event is poorly represented in a low-topped (10 mb) model that imposes null vertical motions at a level that cuts across a strongly tilted isentropic surface
- The influence of errors in the PV structure of the lower stratosphere are noticeable within 2-3 days throughout the troposphere

Upper Boundary Nesting (UBN) allows low-topped models to benefit from enhanced predictability associated with the correct representation of the stratospheric flow in a high-topped driving model

References (1 of 2)

- ECMWF, 1999: Increased stratospheric resolution in the ECMWF forecast system. *ECMWF Newsletter*, 82, 2-8, ECMWF.
References (2 of 2)