Stratospheric variability and blocking in high-top and low-top coupled GCM simulations

James A. Anstey[1], Paolo Davini[2], Lesley J. Gray[1], Tim J. Woollings[3], Scott M. Osprey[1], Steven C.Hardiman[4], Neal Butchart[4], Bo Christiansen[5]

1. AOPP, Dept. of Physics, University of Oxford, Oxford, UK. 2. CMCC (Euro-Mediterranean Centre for Climate Change), Bologna, Italy. 3. Dept. of Meteorology, University of Reading, Reading, UK. 4. Met Office, Exeter, UK. 5. Danish Meteorological Institute, Copenhagen, Denmark.

1. Introduction

- Poor blocking representation, particularly over Europe, is a **longstanding problem in climate models** *(D'Andrea et al. 1998).*
- Increased horizontal resolution may help. But it may be that the background (climatological) state is most important, which could be good news for models with lower horizontal resolutions, such as are used in long climate integrations *(Scaife et al. 2010).*
- **Here we investigate the effect of changing model vertical resolution**, motivated by several factors including:
  - observed connections between stratospheric variability and blocking activity *(Martius et al. 2009; Woollings et al. 2010);*
  - correspondence between negative NAO episodes and high-latitude blocking events *(Woolings et al. 2008);*
  - tropospheric annular mode persistence associated with stratospheric vortex anomalies *(Baldwin & Dunkerton 2001).*

2. Data

The recently completed CMIP5 experiments provide a large ensemble of long integrations of coupled (*i.e.*, ocean-atmosphere) general circulation models (**GCMs**). Here we employ models for which high-top and low-top versions are available, **so as to test whether a well-resolved stratosphere affects the representation of atmospheric blocking in these models**. GCMs used are:

HadGEM2, high-top and low-top: control, historical & future runs
EC-EARTH, high-top and low-top: historical runs
- High-top and low-top runs differ only by vertical grid (resolution and lid height)
  → *clean comparisons to test effects of stratospheric resolution*
- Horizontally, HadGEM2 is a gridpoint model (N96) while EC-EARTH is spectral (T159). The two models also differ in many other respects.

HadGEM2-ES, low-top: control run
CMCC, high-top and low-top: historical runs
- Other aspects of model differ besides vertical grid (*e.g.* horizontal resolution is not the same for CMCC high-top & low-top runs).
  → *not clean comparisons, but can use to test robustness*

ERA-40, 1957-2001: used as observations.

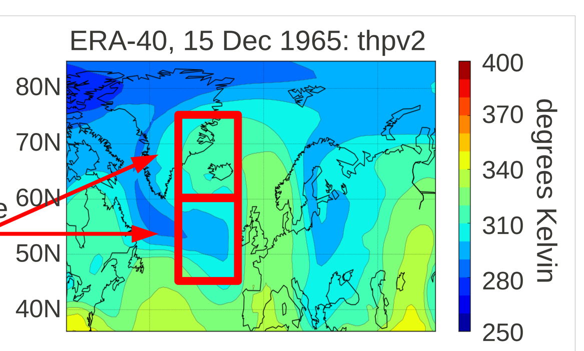
Climate forcing scenarios are standardized for CMIP5 experiments. We use:
- control: fixed preindustrial (1860) forcings
- historical: 1860-2005 historical forcings
- future: projected 2006-2099 forcings, RCP 4.5 & 8.5 scenarios

December-January-February (DJF) period is shown for all plots.
Control runs (HadGEM2) are 240 years long.

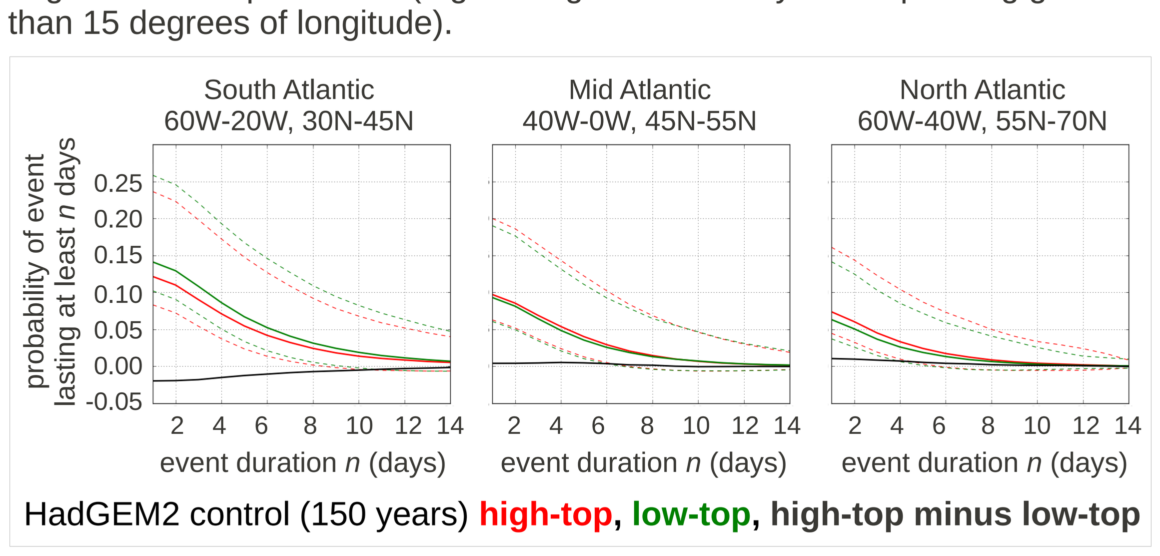
3. Blocking, or wave-breaking, indices

- Potential temperature on PV=2 (**thpv2**, the dynamical tropopause) is used to define an index that identifies the synoptic characteristics typical of blocking *(Pelly and Hoskins 2003; Berrisford et al. 2007).*
- 500 hPa geopotential height (**Z500**, in the mid-troposphere) is also used to define a blocking index *(Tibaldi and Molteni 1990; Scherrer et al. 2006).*

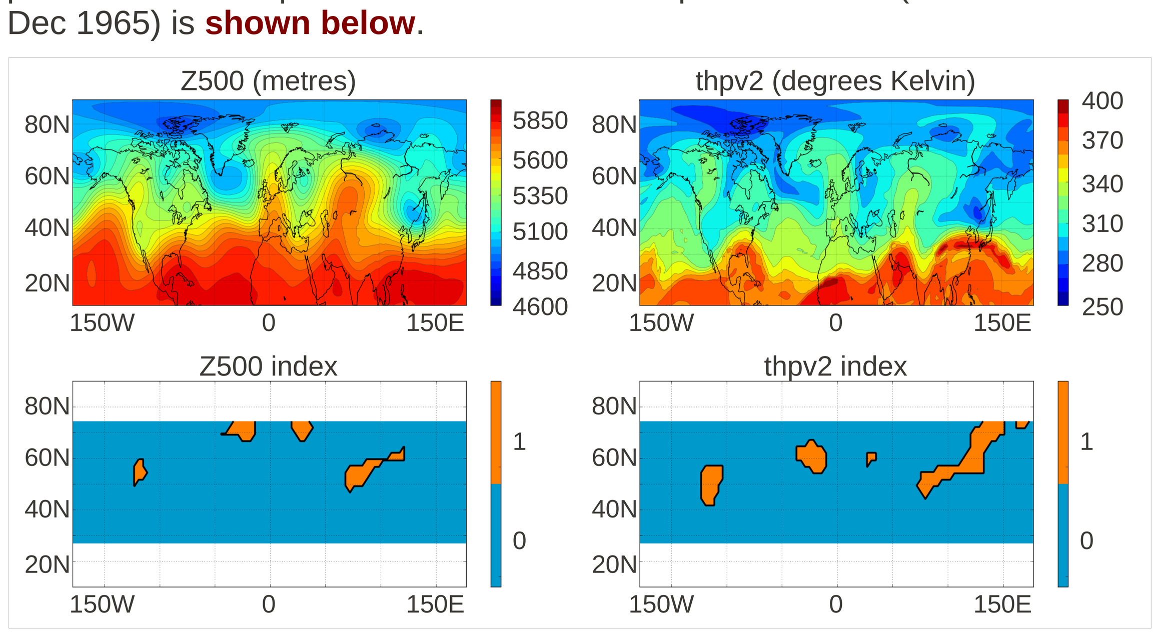
Schematic of **thpv2** index definition:
(following Pelly & Hoskins 2003)
- Reversal of meridional gradient from its climatological value defines an event.
- Index = 1 where this occurs, 0 otherwise.
- Gradient reversal is quantified by difference of northern and southern box means.
- **Z500** index defined in a somewhat similar manner *(following Tibaldi & Molteni 1990).*



- More generally this is a **"wave breaking" index**. The term "blocking" is usually reserved for events identified by this wave breaking index that are both large-scale and persistent (e.g. lasting at least 5 days and spanning greater than 15 degrees of longitude).

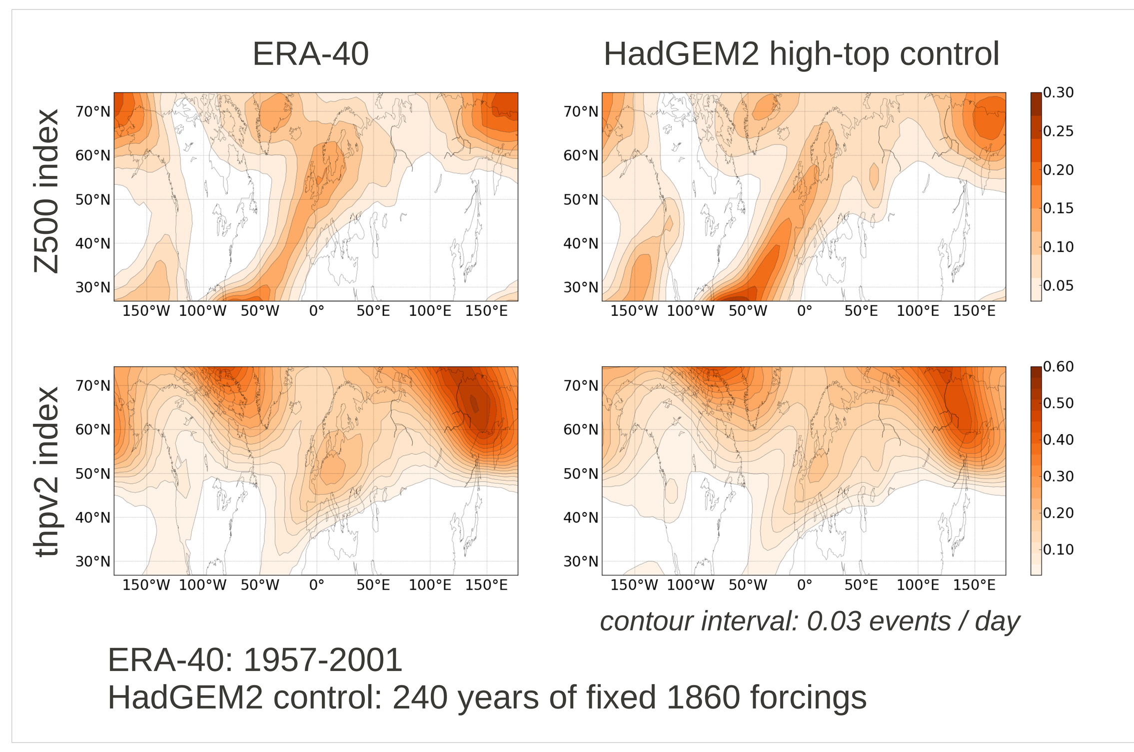


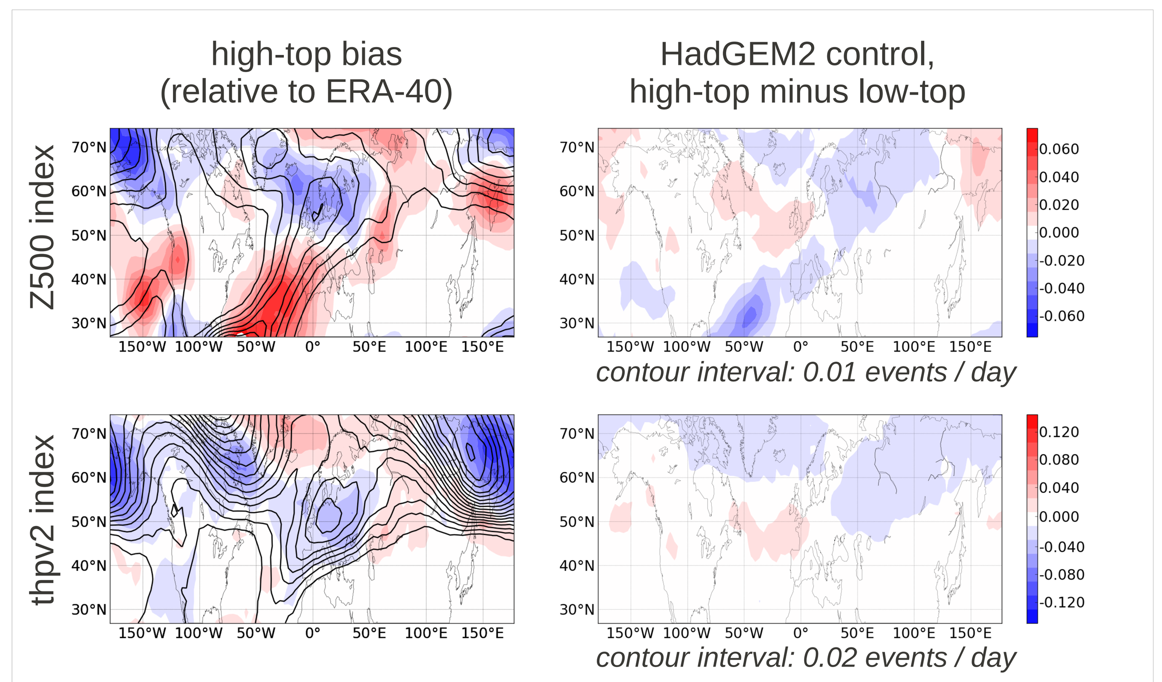
- **Above**: high vs. low-top differences are not very sensitive to event duration.
- The instantaneous "wave breaking" index, *i.e.* without filtering for duration or spatial scale, is used hereafter (for both **Z500** and **thpv2** indices).
- The **Z500** and **thpv2** indices generally differ. We use both indices where possible. An example of the two indices for a particular time (ERA-40 on 15 Dec 1965) is **shown below**.



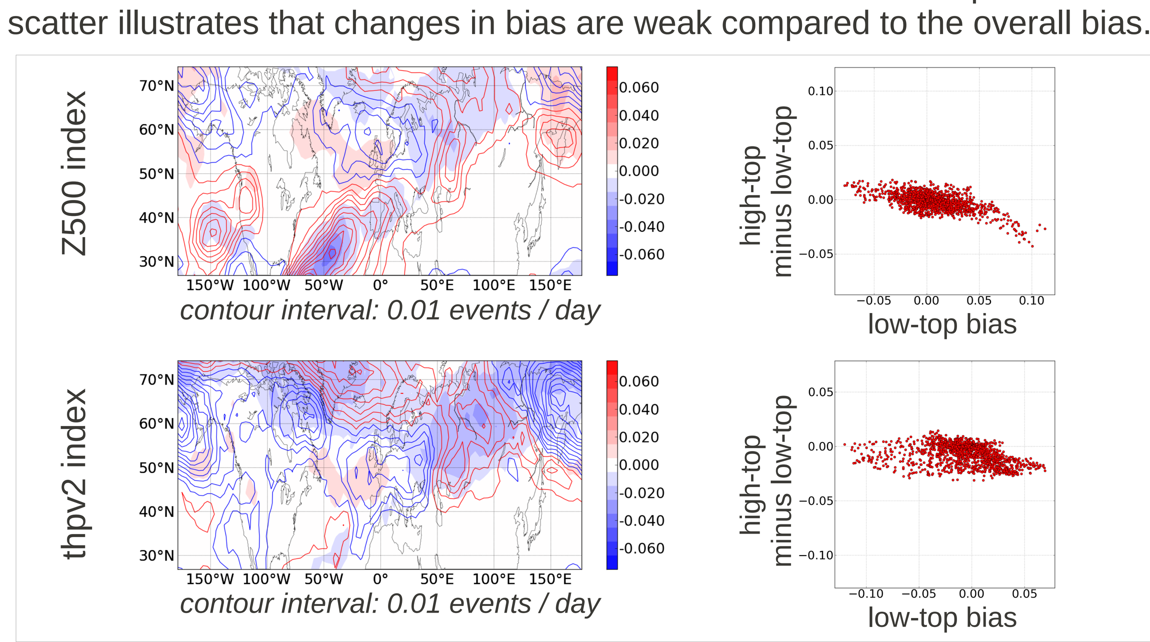
4. High top GCMs vs. low-top GCMs

- **Shown below** are DJF climatologies of **Z500** and **thpv2** indices for ERA-40 (1957-2001) and HadGEM2 high-top control (240 years). The HadGEM2 climatology has a fairly realistic structure, but some discrepancies with ERA-40 – most obviously in the European sector – are apparent.
- Using the HadGEM2 ensemble of historical runs for the ERA-40 period obtains a very similar climatology to that of the control run (not shown). We focus here on results from the control run, since its length (240 years) suggests it should yield the most stable statistics.

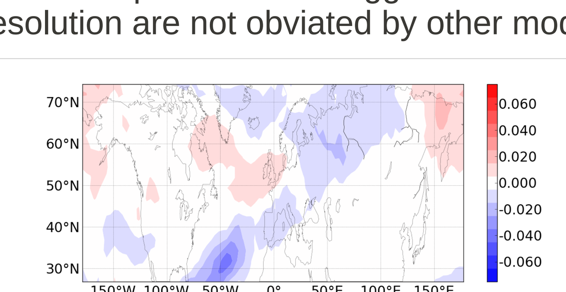




- **Above left**, the bias of the high-top climatology (filled contours) is shown superimposed on the ERA-40 climatology (line contours). Negative bias is co-located with the European climatological maximum. It is common for GCMs to underestimate blocking in the European region *(Scaife et al. 2010)*.
- **Above right**, the difference of high-top and low-top control runs is shown. The general high-top minus low-top difference patterns shown here are found in all HadGEM2 runs (control, historical & future).
- **Below left**, the co-location of low-top bias (line contours) with the high-top minus low-top difference (filled contours) is shown. Regions where superimposed colours are opposite are regions where the higher model lid – *i.e.* the better-resolved stratosphere – reduces the bias.
- **Below right**, the scatter over all horizontal gridpoints of the two fields is shown. For both indices, the greatest number of points are found in the opposite-signed quadrants, indicating that the better-resolved stratosphere is associated with an overall reduction in bias. But the flattened shape of the scatter illustrates that changes in bias are weak compared to the overall bias.

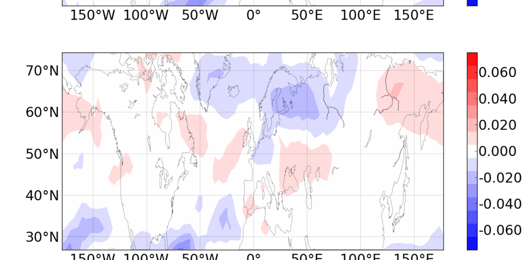


- **Below** are shown high-top minus low-top differences for the **Z500 index** from three different GCMs. It is notable that **the same general pattern prevails for all three models**, suggesting robustness.
- For HadGEM2, substituting the "standard" CMIP5 low-top model (HadGEM2-ES) for the "clean comparison" low-top produces an essentially identical difference pattern. This suggests that the effects of improved stratospheric resolution are not obviated by other model changes.

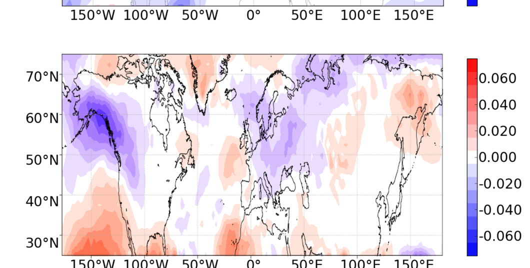


HadGEM2 (control, 240 years)
clean comparison (only vertical resolution and lid height differ)

Using HadGEM2-ES low-top gives very similar signal (*not shown*)



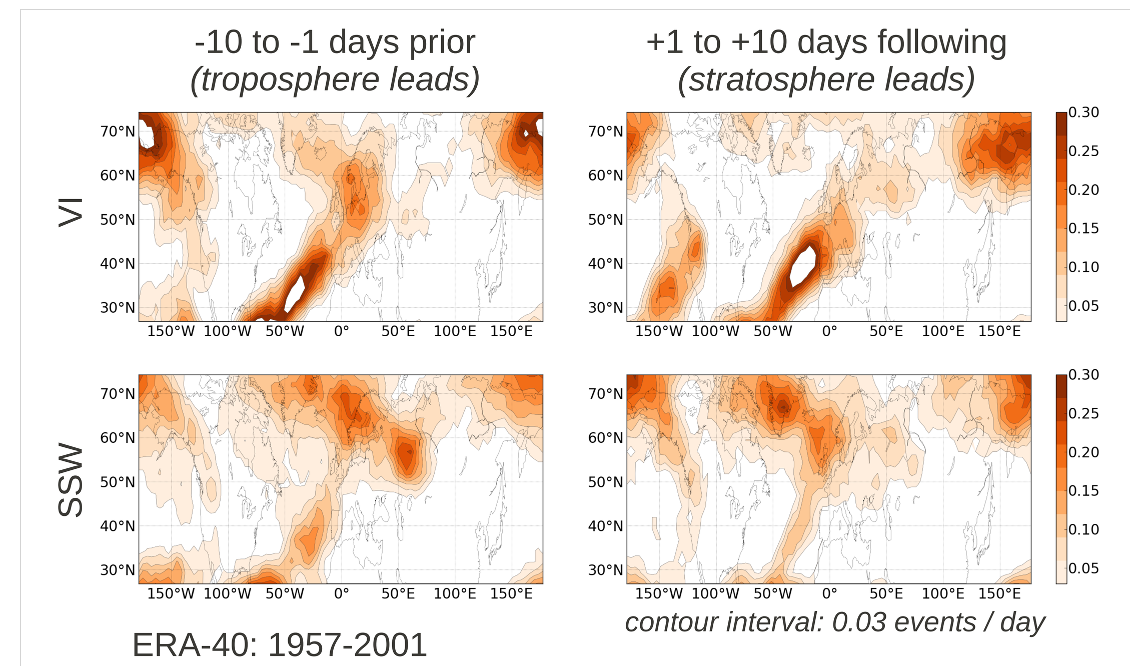
EC-EARTH (historical, 1900-2005)
clean comparison (only vertical resolution and lid height differ)



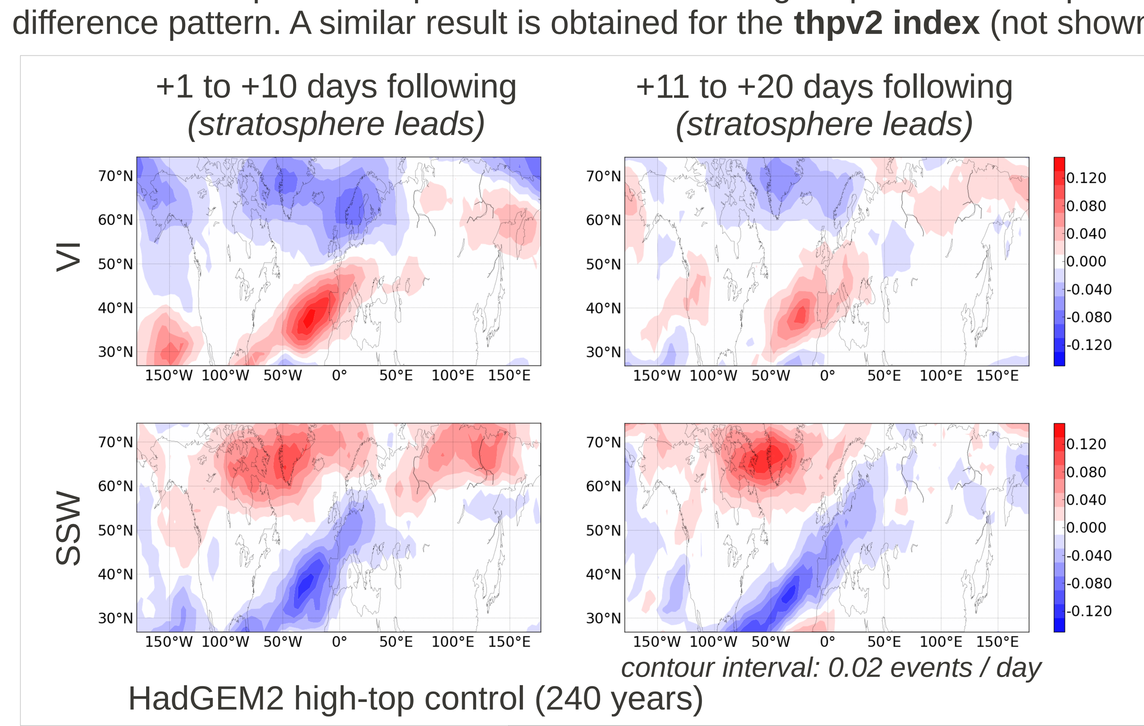
CMCC (historical, 1960-2001)
vertical resolution and lid height differ, but so does horizontal resolution:
high top: T63
low top: T159
(CMCC plot courtesy of Paolo Davini)

5. Link to stratospheric variability

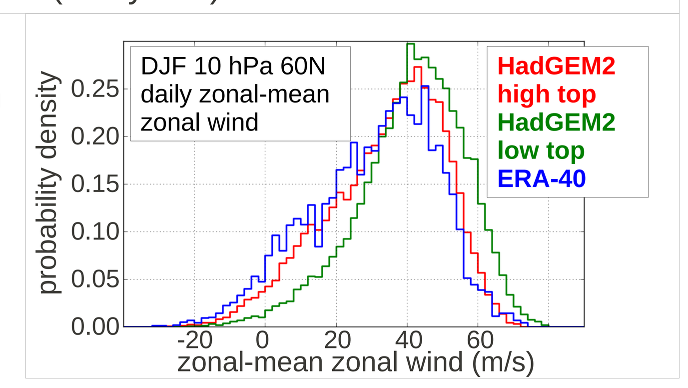
- For ERA-40, the **Z500 index** is composited at lags relative to stratospheric **vortex intensification** (**VI**) or **stratospheric sudden warming** (**SSW**) events. **Shown below** are the composites averaged over 10 days prior to and following the VI or SSW anomalies.
- The wave-breaking index (for either index) following the stratospheric anomaly splits into distinct states depending on whether the anomaly is SSW or VI. SSW favours high-latitude (Greenland) blocking, synonymous with negative NAO phase and an equatorward-shifted tropospheric jet *(Woollings et al. 2008)*. VI favours equatorward displacement of wave breaking activity and a poleward-shifted tropospheric jet.
- As the lags become more negative (*i.e.*, longer troposphere-leading lags) the VI and SSW composite patterns converge. As the lags become more positive (*i.e.*, longer stratosphere-leading lags) the VI and SSW composite patterns remain distinct in the manner indicated, out to a lag of 1-2 months. This timescale is consistent with the observed tendency for tropospheric annular mode anomalies to take the same sign as stratospheric annular mode anomalies *(Baldwin & Dunkerton 2001)*.



- Anomalous (*i.e.* climatology subtracted) VI and SSW composite patterns for the **Z500 index** in the HadGEM2 high-top control run are **shown below**. It is notable that the post-SSW patterns resemble the high-top minus low-top difference pattern. A similar result is obtained for the **thpv2 index** (not shown).



- In HadGEM2, SSW (VI) events are more (less) common in the high-top version, as **shown at right**.
- This suggests that the altered distribution of stratospheric vortex variability may underly the high top vs. low top blocking differences.



6. Summary and conclusions

- Blocking events are associated with prolonged occurrence of anomalous weather patterns. These may cause severe disruption to society, as in the Russian summer heat wave of 2010, or recent severe UK winters.
- Hence it is important for climate models to accurately represent blocking, so that possible future changes in extreme weather may be accurately assessed at the regional scale.

Our two main results are:

Apparently robust high-top vs. low-top differences are found in wave breaking (blocking) index climatologies for NH winter.
- Three models show similar high-top minus low-top difference patterns.
- Two of these models (HadGEM2 & EC-EARTH) are *clean comparisons* between high and low tops. These two models differ in many respects, and do not share a common ancestor model.
- High vs. low top comparisons that are *unclean* – where factors besides vertical resolution differ between the model versions – show difference patterns similar to the clean comparisons, further suggesting robustness.
- High-top reduces model bias in some locations, but increases it in others. In either case the effect is mostly not large compared to the overall bias, indicating (at least for these models) that other factors dominate the bias.

Wave breaking (blocking) index composites before and after extreme vortex events (VI or SSW) during NH winter suggest that the high-top vs. low-top differences are consistent with the tropospheric response to these stratospheric anomalies.
- Stratosphere-leading composites of the index show that its likely values branch into distinct states for VI and SSW events, reminiscent of "dripping paint" annular mode behaviour *(Baldwin & Dunkerton 2001).*
- The high-top minus low-top difference resembles the post-SSW composite for lead times of roughly 1-2 months, suggesting different SSW frequencies in HadGEM2 may explain the high-top minus low-top difference pattern.

Corresponding author: **anstey@atm.ox.ac.uk**