Report on the 3rd SPARC DynVar Workshop on Modelling the Dynamics and Variability of the Stratosphere-Troposphere System

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The third Workshop of SPARC's (Stratosphere-troposphere Processes and their Role in Climate) DynVar activity took place in Reading from 22-24 April 2013, jointly with the first SPARC SNAP Activity workshop, held from 24-26 April 2013. Both workshops were kindly hosted by the Department of Meteorology, University of Reading. We would like to acknowledge the great hospitality of the University of Reading and the excellent organization by the local committee. Synergy between the DynVar and SNAP themes provided a vibrant environment for the whole week. A total of ~100 participants from 16 countries attended both workshops.

The DynVar workshop was structured around the DynVar Research Topics (**http://www.sparcdynvar.org/research-topics-groups-folder/**), with invited oral and contributed poster presentations spread over the week (see report this issue) and two keynote presentations by **Ted Shepherd** (22 April) and **Joan Alexander** (23 April). Results from many CMIP5 analyses were discussed in the nine invited oral and 24 contributed poster presentations of the first two days. This outcome is a recognition of the unique opportunity that the CMIP5 archive presented to assess the stratosphere and its impacts on the climate system, which DynVar decided it would focus on during its second workshop held in 2010 (Gerber *et al.,* 2012; Manzini *et al.*, 2010, 2011; Charlton-Perez *et al.*, 2013). Discussions in Reading demonstrated that the stratosphere-troposphere dynamical coupling community was highly interested in being informed and participating in the broader activities of the World Climate Research Programme (WCRP), specifically in the development of the next phase of the Coupled Model Intercomparison Project Phase 6 (CMIP6).

In his keynote presentation, **Ted Shepherd** focused on the challenges of understanding and modelling the mechanisms of stratosphere-troposphere coupling on various timescales. On long time scales, the causes, extent and magnitude of a strengthened Brewer-Dobson Circulation (BDC) in response to climate change are current topics of investigation: Which dynamical processes (wave breaking, critical layer filtering, dissipation) and which spatial and temporal scales are dominant? Proposed mechanisms need to be examined systematically. Ted also pointed out that while there is strong consensus among climate models on the energetics of climate change, there is less consensus on the dynamical aspects of climate change, and that simulations suggest considerable multi-decadal variability in the stratosphere, whose origin still needs to be identified. Improving climate models by incorporating realistic stratosphere-troposphere coupling, might reduce uncertainty related to atmospheric circulation variability and change, with implications for regional climate change. Ted also called for a systematic assessment of model sensitivity and biases arising from gravity wave parameterizations, the topic of the keynote presentation by **Joan Alexander**. In her presentation, Joan emphasized the importance of the indirect role that gravity waves play in shaping the mean stratospheric flow, and consequently in affecting the behaviour of planetary and synoptic waves, both crucial elements of stratosphere-troposphere coupling. She questioned the current use of gravity wave parameterizations and their limitations in correcting model biases. Future directions in gravity wave parameterization development, such as climate sensitive gravity wave sources and lateral propagation, are underway and may provide the needed realism and coupling between the lower and upper atmosphere, although their benefits still need to be demonstrated.

A common theme of the DynVar presentations was the need for a renewed appreciation of the definition of a “well-resolved” stratosphere. There is a clear tendency to raise the lid of climate models - almost all CMIP5 models have tops at pressures <10hPa, and a substantial fraction of the CMIP5 models have tops at pressures <1hPa. However, drawing from our expertise in constructing and analysing models, it is clear that raising a model’s lid to include the stratosphere in a climate model domain is a necessary but not a sufficient condition for a fully satisfactory representation of stratospheric dynamical processes, such as the Quasi-Biennial Oscillation (QBO), stratospheric sudden warming events, extreme wave events, variations in the wave forcing of the BDC, tropopause variability, water vapour variability, and vortex variability and change.

Nevertheless, the high-/low-top subdivision (top pressure <1hPa for high-top models) grouping of the CMIP5 model set has proven to be useful in demonstrating that stratospheric variability at all scales is better represented in the high-top models (**Andrew Charlton-Perez**). Further insights of high-/low-top differences emerged in presentations reporting inter-comparisons of: (1) tropopause characteristics: the CCMVal2 models with anomalously cold tropopause cold points tend to be anomalously cold throughout the stratosphere, but this behaviour is not exactly true for all CMIP5 models, due to high-/low-top differences in mean temperature (**Thomas Birner**); (2) ENSO teleconnections: Eastern Pacific ENSO events in high-top CMIP5 models generate anomalous signals in the polar stratosphere in the Northern Hemisphere, while low-top models do not show such a coherent signal. A negative Arctic Oscillation-like pattern in sea level pressure and surface temperature is stronger in the high-top than low-top models (**Natalie Calvo, Margaret Hurwitz**); (3) upper troposphere-lower stratosphere water vapour: clear differences between high- and low-top models arise only in the representation of the water vapour tape recorder (**Chiara Cagnazzo**); and (4) planetary wave coupling: most low-top models underestimate negative and extreme positive heat flux events. The bias in the negative events has implications for the downward dynamical coupling during strong vortex events, manifested by low pressure and eastward near-surface winds in the North Atlantic basin, impacts consistent with the positive phase of the North Atlantic Oscillation (**Tiffany Shaw**).

The high-/low-top distinction was not found to be a predictor for the climate change signal in the stratosphere in CMIP5 models (**Alexey Karperchko**), a sign that other model features other than stratospheric variability, such as parameterized gravity wave processes, or tropospheric and ocean responses to climate change, play a more dominant role in shaping the simulated response of the stratospheric circulation to climate change. A similar difficulty is found in identifying a signature of the high-/low-top model distinction in simulating the connection between the stratosphere and the North Atlantic Ocean, in spite of a stronger air-sea coupling in the high-top model set (**Thomas Reichler**).

The regular program of the workshop was followed by discussion sections focused on three main topics: (1) QBO, (2) circulation and climate change, and (3) mechanisms of stratosphere-troposphere coupling. This discussion time was the first step toward the construction of a new DynVar implementation plan. A second discussion session is planned as a side event at the SPARC General Assembly, to be held from 12-17 January 2014 in Queenstown, New Zealand. In Reading, the goal of the discussions focused on how DynVar can best participate and take advantage of the next phase of climate model inter-comparisons (CMIP6), expected to start in 2015. One important common outcome of the three discussion sessions was the need to provide justification for diagnostics focused on stratospheric dynamics, such as Transformed Eulerian Mean (TEM) variables, gravity wave parameterization tendencies, as well as all physical tendencies to assess the momentum and heat budgets.

Quasi-biennial oscillation

Simulation of the QBO in climate models remains challenging, with only a small minority of CMIP5 models reporting successful simulation of the QBO (**Thomas Krismer** and **Scott Osprey**). New developments based on stochastic and/or convection-driven gravity wave sources (**François Lott**) have the potential to increase the number of climate models with a QBO in the next phase of CMIP. However, given the competition of resources in climate modelling centres, it is expected that there will be the need to justify the application of atmospheric model components with proper resolution and parameterizations to be able to simulate the QBO. We assessed several robust reasons why the QBO is important: the QBO is a dominant mode of stratospheric inter-annual variability; the QBO and solar cycle variability interact in their modulation of the propagation of planetary waves in the stratosphere; the residual circulation driven by the QBO affects the BDC; and the QBO affects tropopause temperature in the tropics, and hence water vapour in the stratosphere. Tropospheric QBO impacts such as the effects on the Monsoon, Madden Julian Oscillation, NAO and ENSO are much less robust and are just starting to be investigated. In addition, the impact of the QBO on the mid-latitude stratosphere, through the Holton and Tan effect, needs to be re-assessed since this effect does not appear much in the CMIP5 models (**Bo Christiansen**), with consequences on the representation of the QBO-NAO relationship. An open question is whether improvements in the simulation of precipitation variability may facilitate the simulation of the QBO, given that convection generates the tropical waves (at planetary and gravity scales) that drive the QBO. Specific issues to be addressed are:

- What makes equatorial waves dissipate so fast in the lower stratosphere?
- Lower level penetration of the QBO is underestimated in current models, why? This affects water vapour entry and stratosphere-troposphere coupling.
- Radiative ozone feedback.

Recommendations for further analysis of the CMIP5 runs include:

- Equatorial waves and QBO structure (Lott *et al.*, in preparation)
- Relations with tropical tropospheric variability
- The QBO-NAO relationship (Hardiman *et al.*, in planning; Christiansen, in preparation).

To progress further, more data will be need to be output in CMIP6, including tendencies from the physics at all levels. The extraction of more diagnostics may possibly be restricted to dedicated experiments, such as AMIP-type runs. Note, however, that ocean coupling may degenerate the QBO performance. We agreed that the QBO initiative presented by Osprey *et al.*, aimed at designing a set of experiments to address the limitation of current models in simulating the QBO, could possibly be initiated by involving a core group of modelling centres and by reporting what progress has been made in modelling the QBO so far.

Circulation and climate change

To reduce the uncertainty in climate projections of atmospheric circulation and its implications for surface and regional climate, the assessment of tropospheric and stratospheric dynamical processes in climate models is crucial. Fundamental questions that need to be addressed are:

- What are the causes of tropospheric and stratospheric circulation changes?
- What are the impacts of tropospheric changes on the stratosphere, and *vice versa*? For which changes do we understand the mechanisms?
- Which atmospheric circulation changes are robust across models?
- What are the dominant sources of uncertainty in projections of atmospheric circulation changes?

Robust changes include a poleward shift of the subtropical jets, BDC strengthening, tropopause rise, and Antarctic vortex change (this latter also driven by ozone depletion). Less robust are shifts of the Arctic polar vortex and northern mid-latitude tropospheric jet, and the QBO response. The Arctic vortex and QBO response to climate change may be critical because both involve indirect responses of the tropospheric circulation and depend on the response of gravity wave parameterizations, sources of large uncertainty in stratospheric modelling.

For CMIP6, questions were posed about the availability of raw data versus more derived quantities (*e.g.*, EP flux divergence), the possibility of having more levels near the tropopause, all physical tendencies from parameterisations to close momentum and thermodynamical budgets, more flexibility in getting the model outputs, and observation datasets prepared for straightforward comparison with models. Concerning the availability of derived quantities, the question of developing a DynVar data archive was posed. Regarding the CMIP6 experiments, we felt that for characterizing the relative role of interannual versus inter-model variance, fewer scenarios and more ensemble members would be a valuable option, and that we might wish to focus on more idealized experiments (*e.g.*, AMIP4K) or reduced complexity models, including experiments with dynamical cores. However, concrete plans still need to be made, calling for a dedicated small workshop, as concluded during discussions about the following topics.

Mechanisms of stratosphere-troposphere coupling

A number of mechanisms have been proposed: downward control; hydrostatic and geostrophic (fast and slow) adjustments, as for instance inferred by PV inversion; eddy feedbacks (baroclinic, planetary, *etc.*); wave coupling; resonance; and linear versus non-linear (index of refraction). There are questions about how independent the mechanisms are? How can we create tests that can falsify some mechanisms? Whether different mechanisms matter on different time scales? Whether the mechanism can accurately capture the region where impacts are observed (*e.g.,* Pacific versus Atlantic)? What signal would we expect at the surface? And, under what conditions do events couple to the troposphere? Given the rapid growth of literature on stratosphere-troposphere coupling mechanisms, it would be timely to write a review paper, and two such efforts are currently underway (Kidston *et al.*, in preparation; Baldwin *et al.*, in planning). Note also that previous comprehensive reviews happened eight or more years ago (Haynes, 2005; Shepherd, 2002; Holton *et al.*, 1995).

Independently from these efforts, and based on our developing experience in analysing CMIP5 runs, a proposal was made to write a new position paper to help focus and clarify a set of diagnostic and possibly idealized experiments for CMIP6 (timeframe: one year from now). A major question emerged regarding which model experiments should be designed to test stratosphere-troposphere coupling mechanisms: Are there differences in how stratosphere-troposphere dynamical coupling operates if the coupling originates in the stratosphere from radiative perturbations (water vapour, ozone, solar, GHG) or via a dynamical source in the troposphere (*e.g.*, acting as a stratospheric pathway in tropospheric teleconnections)? Further questions are: What are the implications of distinguishing types of coupling? Could DynVar propose an idealized experiment to be carried out in models of varying complexities? These questions would need careful thought about goals and suitable approaches, and could be addressed in a dedicated small workshop.

Summary and future plans

The DynVar workshop was a successful event thanks to the dedicated participation of all attendees, to whom we would like to express our gratitude. The current focus of the DynVar Activity is on exploiting the unique opportunity offered by the CMIP5 and SHFP (Stratosphere-resolving Historical Forecast Project) archives. In terms of its future scientific direction, the emerging vision is to embrace the "one-atmosphere" concept, and address tropospheric dynamical issues as well. This is a natural evolution of DynVar since stratosphere-troposphere dynamical coupling is an essential process in extra-tropical climate variability and change, and is consistent across timescales. A further important emerging item of discussion is what research opportunities the WCRP Grand Challenges (GC) (**http://www.wcrp-climate.org/index.php/grand-challenges**) may open to DynVar, and how we can best contribute to them. DynVar appears to be well positioned to contribute to GC1 on Regional Climate information (given that the atmospheric circulation is a major source of uncertainty in regional climate) and GC5 on Cloud, Circulation and Climate Sensitivity (through the "changing patterns" initiative lead by Sobel and Shepherd). The ideas regarding the future scientific direction of the activity, its contribution to the GCs, and participation in CMIP6 will be the subject of discussion at a DynVar side event planned during the SPARC General Assembly. Revision of the DynVar Research Topics and Groups will follow, as well as the activity implementation plan requested by SPARC. DynVar will also maintain links with the seasonal forecasting community, the SHFP project (Butler and Scaife, leads), and the Polar Climate Predictability Initiative (Bitz and Shepherd, leads).

Given the common scientific interest of stratosphere-troposphere coupling (although different time scales are addressed) and that a joint DynVar and SNAP workshop has proven very successful, we are evaluating the possibility of reconvening with a second joint DynVar-SNAP workshop to be held in early 2015.

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