# The SPARC DynVar Project: A SPARC Project on the Dynamics and Variability of the Coupled Stratosphere-Troposphere System

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## Introduction

In light of the growing need to understand the global climate system and its future evolution, stratospheric science requires a renewed and sustained research focus. Although we have known for some time that the tropospheric circulation influences the stratosphere, we have more recently learned that the stratosphere can in turn influence the tropospheric circulation all the way to the surface. This two-way stratosphere-troposphere coupling implies that the stratosphere can significantly influence the global climate system and the pattern and magnitude of global climate change. The problem of stratospheric ozone depletion has already demonstrated how human activity can affect a critical component of the global climate system, how a systematic international research effort is required to understand and solve a global environmental problem, how this research needs to be communicated to society, and how ongoing scientific assessment is essential to evaluate the effectiveness of solutions to the problem. All this makes clear that the stratosphere is an integral part of the climate-change problem and will continue to be a crucial component of research on climate change science, impacts, and mitigation.

The two-way coupling we have referred to involves dynamical links between the stratospheric circulation and the tropospheric circulation. The troposphere affects the stratosphere principally through upward propagating atmospheric waves that originate in the troposphere. Until recently it was widely thought that the story ended there, *i.e.* that the stratosphere had little influence on the troposphere. One consequence of this line of thought is that the current generation of global general circulation models (GCMs) typically represent the stratosphere relatively poorly. But several recent lines of research suggest that the stratosphere can in fact significantly influence the tropospheric circulation. The seminal modelling studies of Boville (1984) and Boville and Cheng (1988) demonstrated that degrading stratospheric representation can degrade the simulation of tropospheric stationary waves and transient eddies. Further observational work has developed the view that stratospheric influence involves eddy mean-flow interactions that act on intra-seasonal time scales (Kuroda and Kodera, 1999; Baldwin and Dunkerton, 2001). The cumulative effect of the intra-seasonal time scale coupling leads to a sensitivity of the tropospheric circulation response to stratospheric processes in both the greenhouse-warming and the ozone-depletion problems (Shindell *et al*., 1999; Thompson and Solomon, 2002; Gillett and Thompson, 2003). From the cited studies, and many others, we conclude that improvements to stratospheric representation in models might lead to improvements in seasonal and climate time scale prediction, and ultimately to improvements in the scientific understanding of climate. Characterising and quantifying this kind of stratospheric influence on the troposphere, and ultimately on the global climate system, is a key part of the WCRP SPARC programme.



The goal of this Dynamics and Variability Project for SPARC (which we will refer to by the abbreviation "DynVar") is to approach the question of the dynamical influence of the stratosphere on the troposphere in a systematic way. The principal tools for this effort will be atmospheric general circulation models (AGCMs) with good stratospheric representation. A novel aspect of DynVar is that we will include ocean models coupled to these AGCMs to investigate in a more realistic setting the two-way troposphere-stratosphere coupling. In addition, DynVar will include a significant component devoted to the use of simplified models and more theoretical approaches to build our understanding of stratosphere-troposphere coupling. Here, we outline a modelling and analysis project intended to take place over a period of five years or longer. Previous successful SPARC projects have built collaborative groups around pragmatic and focused plans. With this history in mind, we will propose activities (GCM simulations and diagnostic analyses) that will mesh well with ongoing international projects and with current activities at the modelling centres that are participating in DynVar.

## Project Goals

Our long-term goal is to determine the dependence of the mean climate, climate variability, and climate sensitivity on the stratospheric general circulation as represented in AGCMs. We present a representative list of thematic and more specific research questions of interest to us:

*1. How does the stratosphere (more specifically, the stratospheric general circulation as represented in climate models) affect the tropospheric general circulation?*

- To what extent, and in what way, does a poor representation of the stratosphere degrade the simulation of tropospheric circulation in GCMs?
- What are the consequences of the "fixes" tropospheric modellers need to make (*e.g.* roof/Rayleigh drag) to obtain a reasonable tropospheric climate in their atmospheric GCMs (AGCMs)? To what extent are the model stratospheres sensitive to their treatment of unresolved (*e.g.* gravity) waves and other dissipative processes, and how does this affect the tropospheric simulation?
- How would stratospheric influences on the troposphere affect the simulation of the coupled ocean-atmosphere system?

*2. How does the stratosphere influence climate variability on all time scales?*

- How well do models capture the intra-seasonal vertical coupling between stratosphere and troposphere in the extra-tropics? Does this coupling influence lower tropospheric variability and the variability of the ocean/sea-ice system?
- Does the stratosphere influence the tropospheric tropical and extra-tropical response to ENSO?
- What are the implications of stratosphere-troposphere coupling for long-range predictions of weather and for forecasts of circulation anomalies on seasonal time scales?
- How does the quasi-biennial oscillation (QBO) affect tropospheric climate?
- How do 11-year solar cycle variations affect tropospheric climate? (In collaboration with SPARC SOLARIS.)

*3. How does the stratosphere influence climate change?*

- Do models predict in a consistent manner how stratospheric climate change will affect the tropospheric circulation and the coupled ocean-atmosphere system?
- How is the circulation response to climate forcing related to the stratosphere-controlled aspects of climate variability raised in the previous set of questions? For example, do stratosphere-troposphere interactions help explain dynamically the downward influence of Southern-Hemisphere ozone depletion on the tropospheric circulation? And are stratospheric dynamical processes required to explain tropospheric circulation trends over the 20th century?

To address these and related questions, we propose to focus this group's efforts on the analysis of AGCMs with a good representation of the stratosphere. A high-quality stratospheric component includes enhanced vertical resolution and a higher model lid than found in standard climate model simulations, and appropriately configured radiative transfer modules and subgrid scale parameterizations, *etc*. We call these models "high-top", as opposed to standard "low-top" (Boville and Cheng, 1988) climate models with a relatively poor representation of the stratosphere. We describe a set of requirements for the high-top models later in the section entitled "AGCM Requirements" below.

Within the set of stratosphere-resolving AGCMs, we also propose to focus on high-top AGCMs with prescribed radiatively active gases, as opposed to stratosphere-resolving coupled chemistry models (CCMs). The interactive chemistry modules in CCMs increase the computational cost of the models, which constrains the length, resolution, and number of ensemble realizations of the simulations that some groups might commit to. But we will of course not exclude those groups who wish to only run their models with interactive chemistry, provided their models satisfy the minimum requirements as outlined in the section entitled "AGCM Requirements" below.

As well as addressing our research questions, DynVar is meant to help inform and guide the introduction of stratospheric components into comprehensive Earth System Models as these are developed. The high-top/low-top comparison should help us determine to what extent a resolved stratosphere is important for climate-change simulations for future international climate assessments such as the IPCC assessments.

We plan to set up DynVar as an intercomparison activity, with a balanced effort on simulation design and analysis tasks. Fortunately, several members of our group have extensive experience in this kind of effort through the SPARC GRIPS, SPARC CCMVal, and CLIVAR "Climate of the 20th Century" (C20C) projects, as well as through the WMO ozone assessments and the IPCC climate assessments. We will take advantage of existing CCM simulations and AGCM simulations from the ongoing CCMVal and C20C projects (see the section entitled "Connections to Other Projects").

Beyond performing and analysing simulations with comprehensive GCMs, DynVar will also have an important component that focuses on developing a dynamical understanding of stratospheric influence. This component will use simplified AGCMs and theoretical approaches to provide a dynamical perspective on the results of the comprehensive models. It is hoped that this component will strengthen the interactions between the modelling and theoretical approaches.

## Project Organization

Paul Kushner is the SPARC DynVar project coordinator, and the co-authors of this newsletter form the project's organizing group. DynVar is divided into four general themes, or "Analysis Areas", under which specific research studies ("subprojects") will be placed. Each analysis area has a coordinator who will act as a contact point for participants, help organize model output release requests, organize workshop sessions, take the lead on summary reports, *etc*. The four analysis areas, which will be described more fully in the next section, are

A. "DynVar Top" (Coordinators: F. Sassi and M. Giorgetta)
B. "DynVar Intraseasonal" (Coordinator: J. Perlwitz)
C. "DynVar Climate Change" (Coordinator: E. Manzini)
D. "DynVar Ideal" (Coordinator: L. Polvani)

**Table 1** lists researchers who, in addition to the organizing group, have expressed interest in participating in DynVar. The project's membership is open; if you are interested in participating, please contact

| | |
|---|---|
| Thomas Birner | U. of Toronto |
| Andrew Charlton | Reading U. |
| Bo Christiansen | DMI |
| Judah Cohen | AER |
| Eugene Cordero | San Jose State U. |
| Veronika Eyring (SPARC CCMVal liason) | DLR Oberpfaffenhofen |
| John Fyfe | CCCma/U. of Victoria |
| Nathan Gillett | CRU/U. of East Anglia |
| Lesley Gray (SPARC SOLARIS liason) | Reading U. |
| Nili Harnik | Tel Aviv U. |
| Daniel Kirk-Davidoff | U. of Maryland |
| Kuni Kodera (SPARC SOLARIS liason) | Nagoya U. |
| Craig Long | NOAA/CPC |
| Steven Pawson | NASA/GSFC |
| Thomas Reichler | U. of Utah |
| David Rind | NASA/GISS |
| Adam Scaife (CLIVAR C20C liason) | UKMO |
| Kiyotaka Shibata | MRI Japan |
| Michael Sigmond | CCCma/U. of Victoria |
| Seok-woo Son | Columbia U. |
| David Thompson | Colorado State U. |
| Darryn Waugh | Johns Hopkins U. |
| Shigeo Yoden | Kyoto U. |

*Table 1: Additional Participants*

SPARC DynVar *via* the project website: **www.sparcdynvar.org** (click on the email link to contact DynVar).

It is understood that some participants will wish to use the DynVar Project simulations to support their work in other international projects (*e.g*. SPARC CCMVal, SPARC SOLARIS, CLIVAR C20C, or one of the IPCC AR4 assessment subprojects); in this case it will not be necessary for participants to define a new subproject specific to DynVar, but merely to make a clear link to the other project. It is also understood that DynVar participants who wish to study similar topics independently will not be expected to collaborate with each other, but will be expected to communicate with each other through the Analysis Area coordinators.

Keys to success of DynVar include ensuring that the effort be open, transparent and not too burdensome for participating modelling groups; that the simulations be carefully planned and the right model output saved; and that the analyses be straightforward and reproducible so that they can be repeated as new simulations become available. Fortunately, our efforts will be made simpler by following the lead of two other successful WCRP projects: SPARC CCMVal and CLIVAR C20C.

## DynVar Analysis Areas

We will now describe in more detail the Analysis Areas, which are mainly meant to break DynVar into manageable pieces. We will work with DynVar participants to identify the appropriate Analysis Area for their specific subprojects, but we recognize that typical subprojects will have elements that belong to more than one area.

### *Analysis Area A: "DynVar Top" (Coordinators: F. Sassi and M. Giorgetta)*

Analysis Area A addresses the influence of the stratosphere on the tropospheric circulation, on the ocean circulation *via* air-sea interactions, and on the cryosphere (in particular the sea ice field). Subprojects in this theme will compare high-top and low-top climate models run with a variety of degrees of interaction with the ocean, from prescribed sea-surface temperature (SST) models to models with a dynamical ocean component.

Analysis Area A subprojects that have been proposed to date include: an analysis of the influence of enhanced stratospheric representation on the mean circulation, ENSO teleconnections, and low-frequency variability in the troposphere; a study of stratospheric influences on the stationary wave field; a study on the role of planetary wave reflection in determining tropospheric wave structure; and a study on the importance of momentum-conservation constraints in gravity wave drag parameterizations on the coupled stratosphere-troposphere system.



### *Analysis Area B: "DynVar Intraseasonal" (Coordinator: J. Perlwitz)*

Analysis Area B addresses issues of stratosphere-troposphere coupling on intra-seasonal time scales (time scales of 10–100 days). This theme will focus on high-top simulations of stratospheric sudden warmings, annular mode propagation signals, stratosphere-troposphere interactions forced from the surface, and so on. The emphasis will be on dynamical analysis of the stratosphere-troposphere interactions present in these models and on the implications for the practical problem of seasonal prediction.

Analysis Area B subprojects that have been proposed to date include diagnosis of stratospheric sudden warmings and their tropospheric signatures, analysis of the transient response to snow forcing, and a study of the coupling between the North Atlantic Oscillation and the lower stratospheric circulation.

### *Analysis Area C: "DynVar Climate Change" (Coordinator: E. Manzini)*

Analysis Area C addresses the role of the stratosphere in controlling the tropospheric circulation response to climate change, and the implications of this for oceanic and cryospheric climate change responses. Our experience to date has shown that the stratosphere will have a relatively small direct influence on global climate sensitivity (measured formally in terms of the equilibrated response to doubled $CO_2$); instead, the stratospheric influences here will involve links between radiative forcing and the stratosphere-troposphere circulation.

Analysis Area C subprojects that have been proposed to date include studies of the stratospheric influence on Southern Hemisphere annular mode responses to climate forcing and on sea-ice responses to climate change.

### *Analysis Area D: "DynVar Ideal" (Coordinator: L. Polvani)*

Analysis Area D is the component of SPARC DynVar mentioned above that uses simplified models and more theoretical approaches to improve the dynamical understanding of stratospheric influences. Analysis Areas A–C focus on specific physical phenomena such as the mean stratosphere-troposphere climate, intra-seasonal variability, and climate change responses in the comprehensive AGCM simulations that are the main focus of SPARC DynVar. Analysis Area D, on the other hand, will focus on using complimentary methodologies to elucidate the results of the comprehensive AGCMs. We will encourage Analysis Area D participants to develop research subprojects that aim to explain and characterise the robustness of the comprehensive model results from Analysis Areas A–C.

Analysis Area D subprojects that have been proposed to date include studies of stratospheric control on the time scales of tropospheric variability, of surface-forced stratosphere-troposphere interactions, and of principal modes of variability of the potential vorticity distribution in the stratosphere and troposphere.



Having identified general research themes, we now describe the primary model data sets that, contingent on broad participation from the modelling community, will form the core resource for this activity. We first describe a set of minimum requirements that models should satisfy to represent the stratosphere-troposphere circulation accurately and in a statistically robust way. We then outline our current proposal for a sequence of simulations designed to address our research questions and themes.

## AGCM Requirements

***Model resolution and configuration:*** It is important that the high-top models involved in this effort be of sufficient resolution to capture the important dynamics of the large-scale stratosphere-troposphere circulation, particularly in the extra-tropics. At a minimum, these models should be able to resolve baroclinic eddies in the troposphere, Rossby-wave breaking in the stratospheric surf zone, and the vertical structure of extra-tropical planetary-scale waves propagating from the troposphere to the stratosphere, and stratospheric sudden warming events. *Thus the "high-top" models in the DynVar Project should be AGCMs that solve the primitive equations or the non-hydrostatic equations on the sphere, with a horizontal resolution that corresponds to at least T42 (3 to 4 degree resolution), and a vertical resolution of at least 35 levels, with the model lid and the model sponge layer located above the stratopause, which is located at approximately 1 hPa.* Given the relatively low horizontal resolutions considered, the high-top models should also include parameterizations of the gravity wave influence on the large scale atmospheric circulation.

In setting these requirements, we have attempted to weigh the need to realistically represent some of the most important stratosphere-troposphere interactions against the need to encourage broad participation from modelling groups in DynVar. We recognize that if only these minimum requirements are met, some aspects of stratospheric dynamics and stratospheric influence on the troposphere, for example those that need a realistic simulation of the response to solar forcing or of the vertical structure of planetary-scale tropical waves, might not be well represented.

Some DynVar participants plan to develop methods to systematically transition from low- to high-top AGCMs as a means of introducing stratospheric processes in a controlled manner. This is a potentially valuable approach but will not be required for interested groups to participate in the low-top/high-top comparison. For the low-top models, the main requirement will be that the models have at least T42 horizontal resolution.

Finally, we note that some DynVar participants are planning to investigate the role of the QBO in tropospheric climate but for the time being QBO representation has not entered into our minimum requirements.

***Length of simulations (statistical sampling):*** In some important regions of the stratosphere, particularly in the Northern Hemisphere polar stratosphere, the signal-to-noise ratio of the stratospheric response to climate change is expected to be small (*e.g.* Butchart *et al.* 2000, Fomichev *et al.* 2007). The signals of stratospheric influence on the tropospheric response to climate might consequently be expected to be even more subtle. Thus, we will need to aim for multiple realizations of multi-decadal simulations to ensure meaningful statistical sampling. This requirement will need to be balanced against those of spatial resolution. Factoring in the need for multi-decadal simulations and multiple realizations, the simulations listed below will require at a minimum 50 years of simulation time and often 100 or more years of simulation time.

***Boundary and radiative forcings:*** We will try to implement the boundary and radiative forcings used in the models in as consistent a manner as possible. In this effort we will follow the lead of the CCMVal and C20C projects, which have striven for consistency without placing undue burdens on participating modelling centres.

## Proposed Simulations

We propose a sequence of simulations that will help elucidate the effects of stratospheric representation in the absence of coupling to the ocean (AGCM + prescribed SSTs, Simulation Set A), in the presence of thermal coupling to the ocean (AGCM + slab mixed-layer ocean, Simulation Set B), and in the presence of full dynamical coupling to the ocean circulation (AGCM coupled to ocean general circulation model, Simulation Set C).

### *Set A: "C20C Simulations" -- AGCM simulation with historical SSTs and forcings*

The ongoing CLIVAR C20C project (**http://www.iges.org/c20c/**) is studying climate variations over the past 130 years using AGCMs forced with prescribed SSTs and observed radiative forcing. Some modelling groups are already running high-top versions of the C20C simulations. We propose that the SPARC DynVar Project should play a prominent role in examining stratospheric influences for the C20C project, and will encourage participating stratospheric modelling groups to run their own C20C simulations. We also propose that the C20C setup should represent the "workhorse" simulation that represents the initial primary focus of the group.

We propose to compare low-top and high-top versions of the focus period of the C20C simulations that begins in the late 1940's. These simulations will be used to answer many of our research questions related to Analysis Areas A and B. For example, they will help determine the direct influence of representation of the stratosphere on the simulated climate and climate variability. They will also afford us the opportunity to examine the causes of biases in the stratospheric simulation throughout the suite of participating models, which may well affect the character of the stratosphere-troposphere coupling. Trends that are present in the C20C simulations will begin to address the climate change questions of Analysis Area C. It is hoped that at least three realizations of each simulation will be carried out. This will require roughly 150 simulation years for each of the high- and low-top models.

It should be stated that many groups are not prepared to run with the comprehensive list of forcings specified by the C20C. (The forcing prescriptions for the C20C project are available online at **http://www.iges.org/c20c/c20c_forcing/home.html** and include prescriptions for sea-surface temperatures, sea ice, stratospheric volcanic aerosols, carbon dioxide, and ozone.) This will not be a barrier to participation, as long as whatever forcings are used are implemented consistently and are well documented.

***Set B: Coupled AGCM/slab mixed-layer ocean model simulations***

We have raised a variety of issues related to the influence of the stratosphere on the coupled atmosphere-ocean-cryosphere system. We propose to separately investigate this question using configurations in which an AGCM is coupled to a mixed-layer ocean model (Simulation Set B) and in which an AGCM is coupled to a dynamical ocean model (Simulation Set C). At this point, some groups are focusing their efforts on the mixed layer ocean model approach and others on the dynamical ocean model approach. It is hoped that SPARC DynVar will stimulate groups to pursue both approaches.

For Simulation Set B, participating groups will be asked to run low-top and high-top versions of their coupled models out to equilibrium, which typically takes 50–100 years. Simulations with radiative forcing components representing present day or preindustrial atmospheric composition will be used to address issues related to Analysis Areas A and B. To investigate Analysis Area C, the response to climate change, we propose to use similar simulations in which $CO_2$ is doubled.

***Set C: Coupled AGCM/dynamical ocean model simulations***

Finally, we propose to examine the influence of coupling to a dynamical ocean model, building on the Set A and Set B simulations. Several groups are now putting together stratosphere-resolving coupled ocean atmosphere models, and it is hoped that this project will allow these models to be analysed in a coordinated way.

Similarly to the simulations described above, we will encourage modelling groups to contribute model output from high- and low-top versions of their coupled ocean atmosphere models as these are developed. As they come online, we will take advantage of available control simulations with time-independent forcing to address various issues in Analysis Areas A and B, and climate-change simulations to address Analysis Area C. Proposals being discussed at this point for climate change simulations include using the forcing scenarios from the IPCC AR4, or using the simpler 1%/year $CO_2$ increase forcing from the Coupled Model Intercomparison Project 2 (CMIP2, see **http://www-pcmdi.llnl.gov/projects/cmip/index.php**).

## Connections to Other Projects

*Connections to the SPARC CCMVal Project (Liason: V. Eyring):* A key focus for CCMVal is the evaluation of processes that determine the basic dynamical state of the stratosphere in the underlying GCMs on which the CCMs are based and the response of the stratospheric Brewer Dobson circulation (BDC) to climate change. There is a natural overlap here with DynVar because planetary-scale wave and gravity wave forcing drive much of the BDC overturning. CCMVal is already well established; ongoing diagnostic efforts with existing multi-CCM simulations will certainly help clearly define and begin to answer many of the questions we have raised. In turn, DynVar will support CCMVal with studies to understand statistical uncertainties and to identify robust diagnostics. Thus, the two projects have several points of contact and we can expect mutual benefits for both projects.

*Connections to the SPARC SOLARIS Project (Liasons: L. Gray and K. Kodera):* The aims of SOLARIS are very specific to understanding the influence of solar variability on both the stratosphere and the troposphere, compared to the aims of DynVar which are much broader. Nevertheless, several of the possible mechanisms for solar influence on the troposphere are identical to those studied in DynVar, so there will be significant potential collaborations, both in terms of simulations and diagnostics.

*Connections to the CLIVAR C20C Project (Liason: A. Scaife):* C20C has involved the use of both ocean-forced AGCMs and observed data, to study climate variations and changes over the last 130 years, in particular the period since the late 1940's. The analysis subprojects comprising this effort provide an observationally based testing ground for GCMs and Earth Systems Models as they evolve. The standard Set A C20C historical-forcing simulations are carried out fairly routinely at some centres and can provide data that addresses several of our research questions. Several modelling groups, some of whom are already participating in C20C, are planning to improve stratospheric representation or have done so already. Overall the goals and plans of the C20C project mesh well in several respects with those of DynVar.

## Conclusion

Many aspects of the SPARC DynVar Project are still in the planning stage. We are at this point identifying interested participants and their subprojects, and identifying modelling groups that are prepared to contribute model output to DynVar. We will next proceed to work with the modelling groups on issues of simulation design and will establish a method of data distribution. Discussion and details of DynVar will take place *via* email and the website being built at **www.sparcdynvar.org**. We will provide updates on the project's progress at the CCMVal meeting in June 2007, at the SPARC SSG meeting in September 2007, and through brief SPARC Newsletter contributions. We plan to report scientific progress on DynVar at the Chapman Conference on stratosphere-troposphere coupling in September 2007 and at the SPARC General Assembly in 2008, and plan to organize focus workshops in the coming year.

In their 1988 study, Boville and Cheng remarked that the "vertical truncation in current GCMs appears to be based primarily on related justifications which are of purely practical origin." The situation remains much the same today, as does the onus on stratospheric scientists to demonstrate to the broader climate community that improved stratospheric representation will improve Earth System Models and will modify the simulated response to climate change. Our sense is that improving stratospheric representation is a tractable task and one that might provide valuable benefits to Earth System Models at a reasonable and predictable cost.

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# A SPARC Tropopause Initiative

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### Introduction/Goal

**SPARC has, since its inception, tried to stimulate research into the dynamics, transport and chemistry in the Upper Troposphere/Lower Stratosphere (UTLS) region. One success has been the organization of several multidisciplinary workshops on this topic, starting with the influential Cambridge workshop in 1993 that resulted in the seminal review by Holton *et al.* (1995). Given the present SPARC emphases of dynamical coupling, detection and attribution, and chemistry-climate modelling, it is appropriate now to examine what SPARC activities promoting the science of the UTLS might be most useful. The intention of this paper is to stimulate discussion about what directions might be most useful, and encourage interested scientists to join that discussion.**

This article is not intended as a comprehensive review of tropopause science or literature (and, for example, many key papers have no doubt been left out of the reference list). Our goal is to identify key science questions and gaps in understanding. We have taken account of previously published reviews on this topic, plus recent developments, including the output of recent workshops (most sponsored in part by SPARC). We have also received useful input from several scientific colleagues, many of whom have been involved in planning these workshops.

The UTLS region, or equivalently, the tropopause region, has been identified as being of key importance for chemistry and climate. The Tropical Tropopause Layer (TTL), sets the chemical boundary conditions for the stratosphere. The radiative balance of the TTL, including clouds, is important for the global energy balance. The extra-tropical tropopause layer (ExTL) or extra-tropical UTLS, regulates the ozone budget of the extra-tropical UTLS with potential important impacts on chemistry down to the surface. Dynamical coupling between the troposphere and stratosphere may be modulated in an important fashion by the tropopause region, and this will affect stratospheric dynamics and polar ozone chemistry, as well as surface climate, particularly at high latitudes where dynamical forcing is strong. Whilst most of the above statements are widely accepted, few of them can be made with absolute certainty and fewer still can be made quantitatively precise. Furthermore, it is unclear what horizontal and vertical resolutions, or what representations of small-scale processes are required for these effects to be captured correctly in global climate or chemistry-climate models. Thus, there is a lot of work remaining to be done.

This is an exciting time for tropopause research. We have unprecedented satellite coverage of the UTLS with an international constellation of satellites. The community also has extensive resources for sampling the tropopause *in-situ* from both aircraft and balloon platforms, and there have been many recent campaigns, particularly in the tropics, the results from which are still being analysed and interpreted. New global modelling tools with coupled chemistry are now available to simulate the region.

Our analysis can be summarized in a few key points:

- Recently there have been significant advancements made in understanding the TTL structure, in analysing stratosphere-troposphere coupling at high latitudes and representations of extra-tropical stratosphere-troposphere exchange (STE). However, the dominant processes on various time scales are uncertain, so