Laboratoire Atmosphères, Milieux, Observations Spatiales

Université – Versailles-St Quentin

Dr. Rémi Thiéblemont
Laboratoire Atmosphères, Milieux, Observations Spatiales, LATMOS
Institut Pierre Simon Laplace, IPSL
4 Place Jussieu,
75252 Paris Cedex 05, France

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Report on the doctoral thesis "Coupling processes of various timescales in the middle atmosphere" submitted by Mgr. Aleš Kuchař.

It is firmly established that the middle atmosphere (~10-100 km) has a primary influence on the Earth's biosphere and climate system. On one hand, the presence of the stratospheric ozone layer protects the surface from harmful ultraviolet radiations, and on the other hand, it is well established that perturbations of the middle atmosphere at various timescales have a sizeable influence on the tropospheric circulation and regional climate. Therefore, it is crucial to identify accurately the factors and mechanisms that affect the middle atmosphere variability.

The doctoral thesis presented by Mr. Aleš Kuchař aims to better understand how solar irradiance variations at decadal timescales and orographic gravity waves at seasonal to sub-seasonal timescales affect the middle atmosphere variability by: (i) improving the detection and attribution of the signals and (ii) identifying the underlying mechanisms. The manuscript is well written, mostly clear and provides many innovative ideas, methods and outcomes, that are of major importance for the analysis and understanding of the physical processes driving the middle atmosphere. While some already known results are confirmed, very interesting new findings are presented. The thesis is a combination of two peer-reviewed publications that have been published in leading journals in the discipline of atmospheric physics (*Atmospheric Chemistry and Physics* & *Journal of Geophysical Research – Atmospheres* with for both an impact factor greater than 3) and one paper in preparation.

In a brief introduction, the candidate exposes the current understanding of solar influence on climate and the two main mechanisms that are suggested; i.e. the "top-down" and "bottom-up". The "top-down" initiates through changes in the UV affecting the middle atmosphere, which in turn can modulate the tropospheric circulation through stratosphere-troposphere couplings. The "bottom-up" involves changes in the Total Solar Irradiance that directly affect the surface energy input. Nonetheless, as emphasized by A. Kuchař, the attribution of robust and realistic solar signals in observational datasets of the atmosphere is still required to support the two proposed mechanisms and, hence, improve the understanding of solar-induced climate natural variability. This constitutes the main motivation of Chapters 1 and 2.

Chapter 1 presents an updated analysis of the solar signal in three independent reanalysis datasets (MERRA, ERA-Interim and JRA-55) that fully cover the stratosphere (up to at least 1 hPa) over the period 1979-2013. The novelty of this study is the use two nonlinear techniques, the multi-layer perceptron (MLP) and the epsilon support vector regression (ε-SVR), to complement multiple-linear regression (MLR) analysis that is classically used to detect and attribute solar signals in previous studies. These statistical methods, their relevance with regard to solar signal attribution and their caveats are clearly described and then applied to temperature, geopotential height, zonal wind and ozone annually averaged data. Differences in the solar response between the three datasets are emphasized and carefully discussed.

In my opinion, the complementary use of the two nonlinear approaches and the discussion of the signals in terms of relative impact brings novel and highly relevant insights with regard to the detection and attribution of atmospheric signals (not only solar!). For instance, the lower stratosphere equatorial temperature response appears weak, while classical metrics (e.g. regression coefficients and their statistical significance) show a highly significant signal. On the other hand, this non-linear analysis also helps confirming the robustness of signals found in previous studies that were based on linear techniques. The candidate then performs an analysis of monthly averaged state variables and wave-mean flow diagnostics (EP-flux and residual circulation) for winter of both hemispheres, which brings new insights on the mechanism proposed by Kodera and Kuroda (2002). Especially in January/February, the candidate quotes an anomalous mid-to-high latitude EP-flux convergence anomaly in the upper stratospheric levels that contributes to the polar vortex disruption and changes in the residual circulation (i.e; acceleration of the Brewer-Dobson circulation).

A detailed attribution study of the lower-stratospheric tropical temperature signal, as mentioned above, is provided in Chapter 2. As well explained in the introductory part of this chapter, the positive lower tropical stratosphere temperature response classically attributed to the solar cycle, could in fact result from an aliasing with volcanic and ENSO signals. The aim of this chapter is to quantify the influence of these aliasing effects, but also to provide recommendations to minimize them. The solar signal is extracted using a classical MLR model. The MLR is applied to results of ensemble of sensitivity transient simulations of the SOCOL chemistry climate model over the period 1960-2009, where volcanic forcing and SST/SIC boundary conditions are adequately modified to isolate their aliasing effect on solar signal attribution. The simulation results are compared with reanalysis (MERRA) and satellite (AMSU/SSU) temperature data.

The analysis of the sensitivity experiments demonstrates that, over the period 1980-2009, the tropical temperature signal in the lower stratosphere is reduced by ~50% when major volcanic eruptions are removed, and more than 90% when both major volcanic eruptions and variable SST/SIC are removed. These results emphasize how important the aliasing effects are when restricting studies to the period 1979-onwards, which can lead to strong misinterpretation of the signals. In a second phase, the candidate demonstrates mathematically the causes of aliasing signals, and provides recommendations to limit their effects with regard to solar signal attribution. He further demonstrates the need of properly accounting for auto-correlated residual when performing MLR analysis. All these findings are of primary importance for the analysis and understanding of atmospheric and climate variability.

The third Chapter focuses on the middle atmosphere variability induced by orographic gravity waves (oGW). As this chapter is not closely related to Chapters 1 & 2, the detailed introduction on the theoretical background of the wave-mean flow interaction theory and review of recent results is highly relevant. Orographic gravity wave breaking appears to contribute significantly to the total wave drag (more than 50%) in the lower subtropical stratosphere (70 hPa, 40°N) and regionally located in three orographic hotspots: Himalaya, East Asia and West American. The main objective of this study is to characterize and quantify the influence of these orographic gravity wave hotspots on stratospheric sub-seasonal variability.

The study is mainly based on a specified dynamics CMAM30 model simulation, nudged toward MERRA2 reanalysis. Firstly, the candidate proceeds to a comparison of the CMAM30 model results against satellite observations (SABER and HIRLDS) which reveals very large differences, particularly regarding the absolute gravity momentum fluxes in the mid-latitude stratosphere in boreal winter. These discrepancies, likely due to the parameterization of orographic gravity waves, are acknowledged and carefully discussed. Largest oGWD events are then identified by applying a peak-detection algorithm to the oGWD time series at the three hotspots over the period 1980-2010. The detected events (more than 30 per hotspot) are used to perform a composite analysis of the atmospheric averaged state.

The analysis of zonal mean temperature, zonal wind and ozone anomalies wrt the three hotspots reveal common responses in the upper stratosphere/lower mesosphere, but differences appear at high-latitude in the lower stratosphere. The anomalies are also characterized on isobaric levels, which helps to better understand the regional effect of gravity wave breaking at these hotspots. Basically, the enhanced oGWD at these three hotspots is associated with increasing (decreasing) temperature and ozone on the North (South) edge of these hotspots, and these anomalies are particularly pronounced for the Himalayan hotspot. Throughout the chapter, the statistical significance of the signals is however not assessed, making their robustness unclear. Using 2-D and 3-D wave propagation and wave-mean flow interaction diagnostics, the candidate then demonstrates that these anomalies, in the case of Himalayan composites, can be attributed to residual mass transport triggered by enhanced resolved wave breaking, similar to dynamical signature associated with SSW events. The discussion on dynamical aspects, quite difficult to follow in some places, refers to the relevant literature. Finally, by identifying similarities between the oGWD composites dynamical anomalies (in particular in the case of the Himalaya hotspot) and dynamical anomalies associated with SSWs published in previous studies, the candidate hypothetizes that an orographic hotspot located on the edge of the surf zone may play an important role on polar vortex variability and ozone transport. As acknowledged and carefully discussed by Mr. Aleš Kuchař, the causality remains to be established. This study provides interesting new findings with regard to the influence of gravity waves on the lower stratosphere dynamical processes, and could contribute to a better understanding of the polar vortex variability.

To summarize, the work presented by Mr. Aleš Kuchař in his doctoral thesis provides outstanding progress in our understanding of the middle atmosphere - and more broadly climate - variability, particularly with respect to the solar influence. The thoroughness and relevance of statistical and atmospheric dynamics analysis carried out by the candidate to deliver excellent scientific results should be especially emphasized. The impressive diversity of methods, datasets (meteorological reanalysis, satellite observations, numerical models) and diagnostics employed in this work and mastered by the candidate should also be stressed. The presentation of the outcomes is mostly good and well structured, although some paragraphs and descriptions of results are sometimes difficult to follow, particularly for readers who are not experts in this research field. Existing literature is very appropriately quoted and results are adequately discussed. Finally, the open-science approach adopted by Mr. Aleš Kuchař is highly appreciable.

Mr Aleš Kuchař has presented a doctoral thesis of high scientific quality, soundness and relevance, which demonstrates his ability to perform autonomous and creative research. The outcomes of Mr Aleš Kuchař's thesis lead to significant advances in our research field. His co-authorship to several leading publications in our field and his active involvement in International and European projects (Mr. Aleš Kuchař is currently involved in the WCRP SPARC-SOLARIS/HEPPA program and participates to the design of an H2020 proposal) further stress his scientific excellence, independence and recognition by his peers. I wish the candidate all the best for his career in the years ahead.

Sincerely,

Dr. Rémi Thiéblemont