Final scientific report

Project: 200020_163206 **(**SIMA)
Time: 01.01.2016 – 30.11.2018

1. Summary of the research work and its results.

1.1 Research work conducted in relation to the objectives, milestones and hypotheses mentioned in the research plan.

SIMA is an extension of SNSF project SILA (149182), with the aim to estimate SSI variability, and the response of the atmosphere to that, using observations and chemistry climate models (CCMs). The work aimed to: (i) build on the Bayesian approach developed by Ball et al., 2014, to incorporate other variables beyond the approach that was previously based on ozone alone; (ii) assess and prepare observations and evaluate their uncertainties; (iii) establish the link between SSI and atmospheric variables in 2D and 3D models; and (iv) use the results to estimate SSI variability using atmospheric changes. The results would be of benefit to the climate and atmospheric community who require accurate solar irradiance forcing data to correctly simulate an historically accurate, solar forcing for the climate system.

1.1.1 Extract, evaluate, and publish new estimates of the solar-ozone response from SI2N ozone datasets (WP1).

We determined that it was not possible to extract a meaningful solar cycle ozone response from available composites of stratospheric ozone observations (WP1), as they were constructed using different data and methodologies meant that the spread of solar cycle responses in ozone was larger than the signal estimated from each individual composite (see Fig. 1a). To address this, we developed a new methodology (BASIC, Ball et al., 2017) with which to correct ozone composites. An example of the corrected ozone in the upper equatorial stratosphere is shown in Figure 2. The BASIC method, and the resulting composite, is now considered the most robust to outliers by a recent SPARC report on ozone trends (LOTUS, 2019).
From this work, we successfully extracted and estimated a new solar cycle ozone response (WP1; Fig. 1b) published recently in Geophysical Research Letters (Ball et al., 2019). We evaluated the robustness of the estimates using multiple runs of the CCM SOCOL (WP5), and with models in specified dynamics mode with our collaborators at NCAR (USA; WP5/WP6). We found that the peak equatorial response is at a lower altitude (~35 km) than previous estimates (~43 km) and, further, that there are peaks at mid-latitudes (~43 km); this is the first publication to robustly verify and explain these spatial features: a result of seasonal variability that could only be demonstrated with the application of the 3D CCM SOCOL that contains full dynamics (milestone A; WPs 2 & 4), rather than 2D models alone.

1.1.2 Extension to temperature (WP2) and development of Bayesian inference framework with new SSI priors (WP3).

We successfully expanded the Bayesian inference framework of Ball et al., (2014), to allow for an arbitrary number of variables (e.g. ozone and temperature; WP2/3), and with which to infer solar irradiance variability; additional priors were included for temperature. This expansion allowed for the reconstruction of solar irradiance from ozone and temperature to be performed (WPs 2 & 3); see Figure 3.

1.1.3 Analyze and compare 2D model and 3D nudged-CCM responses to SSI together with observational estimates (WPs 4 & 5).

An analysis of the 3D nudged CCM responses in comparison to SSI was published in Ball et al., (2016), whereby it was shown that the large SORCE solar cycle estimates were not realistic. Further, 3D CCM sensitivity runs were performed and compared with the solar cycle ozone responses estimated from the improved BASIC ozone composites (Fig. 1c). The results indicate that observations and specified-dynamics models were in good agreement with each other and, indeed, SOCOL together with the NCAR/USA 3D CCM WACCM (in collaboration with Dan Marsh), although free-running models may not be.

1.1.4 Construct synthetic SSI (WP6).

From the ozone (WP1) and temperature profiles (WP2), constrained by the priors on these (WP3), we were able to reconstruct solar irradiance variability from 1975 to 2015 (WPs 5 and 6) and results are presented in Figure 3. These results indicate that (i) solar irradiance can be constrained well enough to exclude the large solar cycle estimates from earlier versions of the SORCE data, but (ii) it is not well enough constrained to differentiate between the two main SSI reconstruction models SATIRE-S and NRLSSI (Figure 3). We are preparing a review paper for Reviews of Geophysics that will discuss the differences between these reconstruction models in light of knowledge from ozone variability.

1.2 Main research results and their relevance to planned research outputs.

- We have developed new ozone datasets which can be used to estimate the ozone response to spectral solar irradiance (SSI) variability. This ozone dataset (BASIC) is now being used in other research studies, and is considered by a SPARC community to be the most robust to effect of outliers on multiple linear regression and trend analysis (LOTUS, 2019). Using BASIC we confirmed that a recovery in ozone in the upper stratosphere was clear and significant, following implementation of the Montreal Protocol. This result was published by Ball et al. (2017, 2018).
- Using BASIC we found that ozone in the lower stratosphere had continued to decline since 1998 and that this decline was large enough to offset the recovery in the upper stratosphere. The findings (Ball et al., 2018) were reported in major international media outlets (see examples in Outputs), and have already led to a number of publications focusing on understanding the mechanisms behind our result; the paper has already accumulated 34 citations (google scholar; 6 January 2019). The result became a headline of the WMO 2018 ozone assessment report executive summary.
- We have successfully extracted and estimated ozone response to SSI variability, and demonstrated using 3D models in specified dynamics and free running modes that these are robust and accurate estimates. This has led to a publication (Ball et al., 2019).
- We successfully performed 2D and 3D model runs to estimate responses of multiple stratospheric chemical constituents and variables. The results of the 3D model runs were included in the recent publication (Ball et al., 2019), while the 2D approach successfully combined temperature and ozone observations to reconstruct solar cycle irradiance variability as demonstrated in Figure 3.
- We reconstructed SSI variability from 1975 to 2015 (see Fig. 3). Our results suggest that solar cycle SSI inference from observations is good enough at least to exclude large changes estimated by earlier versions of the SORCE satellite; this result was one of the main motivators of the SIMA project and such an outcome is deemed a success. For some spectral intervals (e.g., 242-260 nm, see Fig.3) our SSI reconstruction is in good agreement with the state-of-the-art models.
- Another publication funded by SIMA, using a different approach, also showed that the large solar cycle ozone response suggested by the SORCE satellite is unlikely to be correct (Ball et al., 2016); subsequent publications from other research groups support this result, meaning that SSI variability simulated with the solar irradiance models SATIRE and NRLSSI is more likely.

1.3 Major deviations from the research plan.

A major piece of research at the outset of SIMA was to analyze seven of the main ozone composites available (Tummon et al., 2015). We found (a) only four of the ozone products had sufficient data coverage from which to extract a solar cycle signal, and (b) without knowing which was the most robust dataset the remaining four composites encompassed a range that prohibited any success for the project in providing useful constraints on solar cycle variability. The outcome led us to development of new methodology to account for differences in composites, which was not envisaged in the research plan, but was (a) required to account for these differences and (b) successful in allowing us to extract a robust solar cycle signal.

1.4 Contributions of the SNF-coworkers

Dr. William Ball (PMOD/WRC) was employed to as the named postdoc. He led the effort to understand the problems in the ozone composites, and led the team that developed the BASIC methodologies. Dr. Ball made the discovery of the negative lower stratospheric ozone trends. Dr. Ball designed the framework for the SOCOL CCM sensitivity runs which were performed by Dr. Eugene Rozanov (PMOD/WRC). Dr. Ball prepared and executed all the runs with the 2D atmospheric model to construct both temperature and ozone profiles with which to infer solar irradiance forcing from atmospheric data. Dr. Ball is the lead author of all papers directly resulting from this project. Dr. Eugene Rozanov (PMOD/WRC) supported the analysis of results and participated in the preparation of the papers. Prof. W. Schmutz participated in the preparation of the some of the papers supported by this project.

Figures

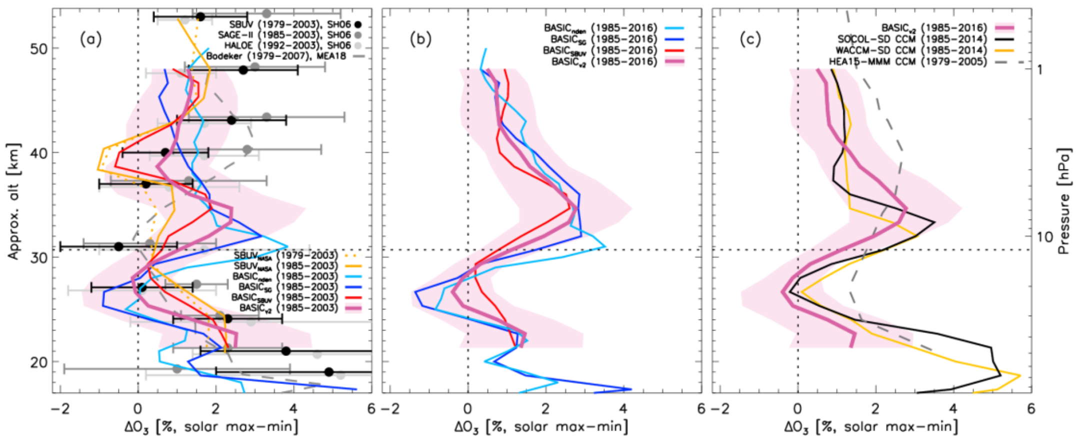

Figure 1: Equatorial (25S-25N) solar cycle ozone responses: (a) for periods considered by Soukharev & Hood [2006], as well as the Bodeker ozone composite profile from Maycock et al., [2018] (MEA18, dashed grey; 30S-30N); (b) BASIC composites for 1985--2016; (c) BASIC$_{v2}$ as in (b) with the mean of three-CCMs from Hood et al. [2015] (HEA15) and SOCOL-SD and WACCM-SD CCMs. The period for each dataset is given in the legends. Uncertainties are for BASIC$_{v2}$ (shading) and SH06 (bars) only; mean profiles for all others. Multiple linear regression used the Mg-II solar proxy for an equivalent of 100 solar flux units of the 10.7 cm radio flux.

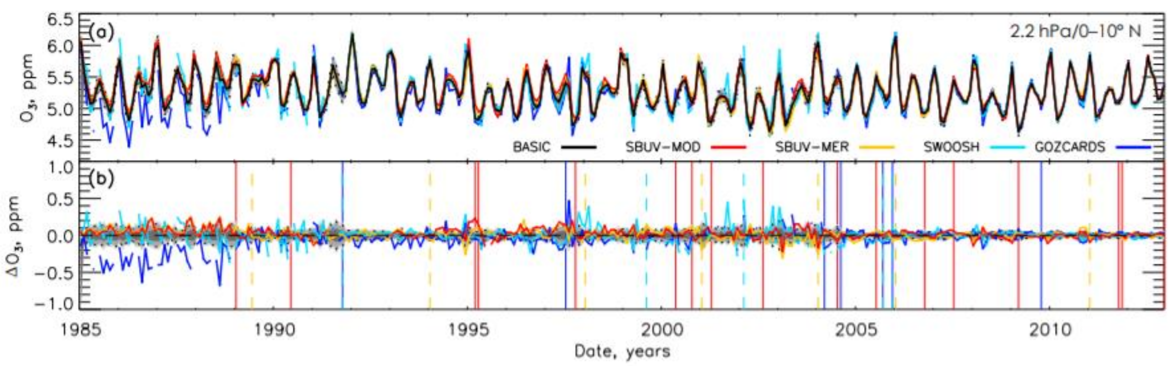

Figure 2. Near-equator (0ºN-10ºN) ozone timeseries (1985-2012) at 2.2 hPa: (a) original timeseries of BASIC, SWOOSH, GOZCARDS, SBUV-MOD, and SBUV-MER ozone composites; and (b) ozone timeseries relative to BASIC. Vertical lines colour coded to correspond to the various ozone composites, in the lower panel, represent when different satellite data end or begin within each composite. Figure from Ball et a., 2017. The period for each dataset is given in the legends. Uncertainties are for BASIC$_{v2}$ (shading) and SH06 (bars) only; mean profiles for all others. Multiple linear regression used the Mg-II solar proxy for an equivalent of 100 solar flux units of the 10.7 cm radio flux.

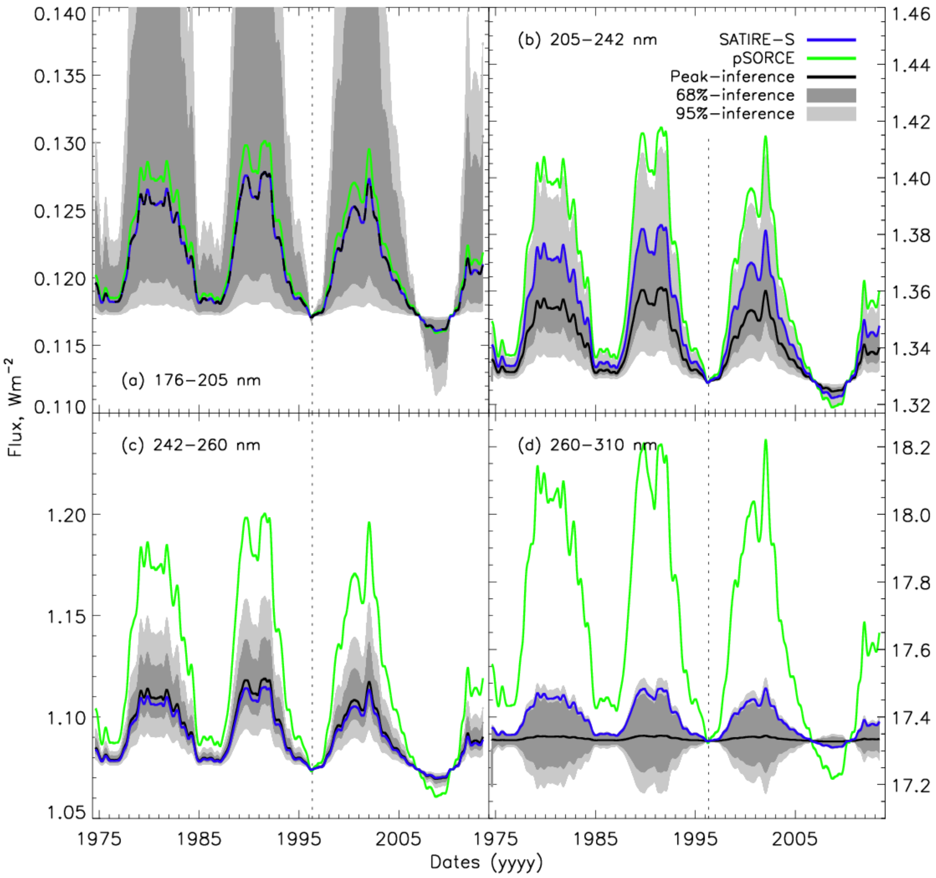

Figure 3. Examples of SSI reconstructions estimated using ozone observations in four wavelength bands: (a) 176-205 nm, (b) 205-242 nm, (c) 242-260 nm, and (d) 260-310 nm. The black line is the most probable estimate, while dark and light shading represents the 68 and 95% credible intervals. The SATIRE SSI model (blue) and extrapolated SORCE observations (green; Ball et al., 2016) are overplotted for comparison.

References:

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Soukharev & Hood (2006), Solar cycle variation of stratospheric ozone: Multiple regression analysis of long-term satellite data sets and comparisons with models, JGR-Atmos., 111(D10), D20314, 10.1029/2006JD007107.

Tummon, F., et al. (2015), Intercomparison of vertically resolved merged satellite ozone data sets: interannual variability and long-term trends, Atmos. Chem. Phys., 15, 3021-3043, 10.5194/acp-15-3021-2015.

2. Research outputs

Here we mention the planned or submitted research output. Research output that has already been published (e.g. publications accepted, published or in press) are available from the "output data" container. Direct and highly relevant to the project results were presented in 17 papers published in high impact journals and more than 20 international workshops and conferences.

SIMA results were used in two major reports:

- SPARC LOTUS report; Long-term Ozone Trends and Uncertainties in the Stratosphere, due early 2019.
- WMO Ozone Assessment Report 2018, due early 2019.

SIMA results were covered in international media:
Ball et al., (2018) publication led to extensive media coverage in February 2018. We list arguably 23 of the most significant of more than 100 media mentions in the “output data” container.

Papers in preparation

Ball et al., Current state of solar irradiance for climate research (to be submitted to Reviews of Geophysics, 2019)
Relevance to the project: In the paper, we will review recent progress in SSI observations, reconstructions and future projections.

Rozanov et al., How the QBO and solar signal interact in the tropical stratosphere (in preparation for ACP)
Relevance to the project: Follow-up to Ball et al., 2019, to explain the important dynamical interaction in the tropics.

Rozanov et al., Spectral solar irradiance reconstructions using stratospheric observations (in preparation for ACP)
Relevance to the project: In the paper, we will present SSI reconstructions obtained in the SIMA project framework.