Chapter 1: Introduction

Ozone is a key species in the atmosphere, as it protects life on Earth by filtering out damaging ultraviolet (UV) radiation from the sun. The evaluation of the effect of ODSs on the long-term evolution of stratospheric ozone levels dates back to the late 1970s when the threat linked to increased levels of chlorine in the stratosphere due to industrial products started to emerge. Since then, ozone research has played a pioneering role in alerting on the impact of human activities on the global environment, promoting a direct link between science and policy action. In the early 1980s, atmospheric models predicted the maximum impact of ODSs on ozone in the upper stratosphere, around 40 km (*WMO, 1985*). The discovery of the Antarctic ozone hole changed this understanding of the ozone equilibrium in the stratosphere (*Farman et al., 1985; Solomon et al., 1986*). It became clear that chemical processes involved in polar ozone depletion could also affect ozone in the lower stratosphere at the global scale. Following the signing of the Montreal Protocol in 1987, a strategy was devised to accurately monitor the evolution of stratospheric ozone. Since 1989, the WMO/United Nations Environment Programme (UNEP) Ozone Assessments report on the state of the ozone layer and on the attribution of long-term changes in both the total column and the vertical distribution of ozone to ODSs, as well as on other direct and indirect processes that affect ozone levels, for example changing atmospheric temperature due to the accumulation of greenhouse gases (GHGs), or volcanic eruptions that inject aerosols into the stratosphere. In order to support these assessments, several international evaluation exercises have been organised. After the International Ozone Trend Panel (1988) that addressed the evaluation of trends from total column ozone measurements, the first SPARC/WMO report (*SPARC, 1998*) tackled the issue of trends in the vertical distribution of ozone. It provided a detailed description of both satellite and ground-based ozone profile measurement techniques, assessed their quality, and provided the first estimates of decreasing trends in stratospheric ozone since 1980 based on a combination of various data sources. This study showed statistically significant negative trends in ozone levels in the whole stratosphere, with two clear maxima in the upper stratosphere at around 40 km altitude and in the lowermost stratosphere at about 15 km (*SPARC, 1998*).

The accumulation of halogen compounds peaked in the stratosphere between the mid-1990s and the beginning of the 21st century, with a turnaround time that depends on altitude and latitude (*WMO, 2014*). As the decrease of ODS levels is becoming more apparent, it is now crucial to evaluate the success of the Montreal Protocol with regards to the recovery of the ozone layer. In addition, after 2000, the launch of several new satellite platforms dedicated to atmospheric composition measurements (*e.g.*, Earth observing system (EOS) Aura and EnviSat (Environmental Satellite)) provided new global ozone records. This resulted in the necessity of merging the various data records to determine the long-term evolution of ozone vertical distribution. The SPARC[1], IO3C[2], IGACO-O3[3], and NDACC[4] (SI2N) activity that started in 2011, aimed to evaluate the ozone profile trends from ground-based and satellite observations, including the new merged satellite data records. The activity was intended to contribute to the WMO/UNEP 2014 Assessment on the state of the ozone layer, but concluded only after the release of the report. From the combination of available ozone trend profiles, the Assessment reported a significant increase of ozone values by 2.5–5 % per decade around 35–45 km altitude at mid-latitudes and in the tropics during the period 2000–2013. These findings were in agreement with global climate model simulations that attributed the upper stratospheric ozone increase to both declining ODS levels and stratospheric cooling by increasing GHGs (*WMO, 2014*).

The SI2N team used another approach to determine the significance of ozone profile trends compared to that used for the WMO/UNEP 2014 Assessment. SI2N analyses re-evaluated long-term ozone profile trends from all available ozone records over the period 1979–2012 and results were published in *Harris et al.* (2015). For the period before the ODS peak, the reported trends were in good agreement with those reported in the 2014 Assessment. For the potential "recovery" period (*e.g.*, 1998–2012), positive trends of ~2 % per decade in mid-latitudes and ~3 % per decade in the tropics were found in the upper stratosphere from the combination of ozone profile trends, in somewhat broader agreement with *WMO* (2014). However, the significance of these combined increasing trends was investigated using several methods. The first one, similar to that used in *WMO* (2014), estimated the uncertainty of average trends from the weighted mean of the individual trends' standard deviations. The second used the joint distribution of the individual variances around the arithmetic mean of the estimators (*e.g., SPARC, 2013*). The addition of uncertainty related to satellite drift, estimated from ground-based ozone profile measurement records (*Hubert et al., 2016*), increased the total uncertainty of the trend and resulted in insignificant positive trends throughout the stratosphere, in contrast to results of the *WMO* (2014). The study concluded that it was too early to confirm the significant increase of ozone in the upper stratosphere, considering the length of the "recovery" period since 1998 and uncertainties in combined ozone trends.

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[1] SPARC: Stratosphere-troposphere Processes And their Role in Climate; [2] IO3C: International Ozone Commission; [3] IGACO-O3: Integrated Global Atmospheric Chemistry Observations (Ozone); [4] NDACC: Network for the Detection of Atmospheric Composition Change.

The new SPARC, WMO and IO3C activity entitled "Long-term Ozone Trends and their Uncertainties in the Stratosphere (LOTUS)" was initiated in 2016 to revisit the causes of differences in the conclusions regarding the significance of post-turnaround ozone trends between the SI2N study and the 2014 WMO/UNEP Assessment. Since the end of the SI2N activity, historic ground-based and satellite time series have been revised and new merged satellite data sets have been produced. The main objectives of LOTUS are thus to assess the new long-term ozone profile records, provide a better understanding of all relevant uncertainties in the records, and revise the methods used to derive trends and their associated uncertainties.

This Report summarises the main results obtained during the first year of the LOTUS activity, which was targeted at providing timely inputs to the 2018 WMO/UNEP Ozone Assessment. This deadline defined the scope of this Report and focused the LOTUS activities primarily on changes in ozone levels in the middle and the upper stratosphere outside the polar regions as observed by merged satellite records. These studies were complemented by an analysis of ground-based data and recent model data provided by the CCMI (*Morgenstern et al.,* 2017). The short timeline of this work necessitated leaving several pressing topics for the second phase of LOTUS, most notably: the significance of recent trends in the lower stratosphere, the attribution of trends to ODSs and GHGs using model data, and estimates of trends in the polar regions.

The structure of this Report is as follows: *Chapter 2* describes improvements in the historic data records and the newly released data sets for both ground-based and satellite measurements. Challenges for trend studies are addressed in *Chapter 3* and include the evaluation of sampling biases and drifts between the various time series. Methodologies designed to assess the stability of the various satellite records are also described. *Chapter 4* describes the regression methodology used in LOTUS and related sensitivity tests, while *Chapter 5* provides updated ozone profile trends from the various records. A substantial part of this chapter is devoted to an assessment of the methods used to combine trends from the individual records and estimate the significance of the combined trends. The main conclusions of the LOTUS study are drawn in the *Executive Summary* and remaining open issues are listed.