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Communication

Response of Total Column Ozone at High Latitudes to Sudden Stratospheric Warmings

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Abstract: The total column ozone (TCO) at northern high latitudes is increased over a course of 1–2 months after a major sudden stratospheric warming as a consequence of enhanced ozone eddy transport and diffusive ozone fluxes. We analyzed ground-based measurements of TCO from Oslo, Andøya and Ny Ålesund from 2000 to 2020. During this time interval, 15 major sudden stratospheric warmings (SSWs) occurred. The observed TCO variations are in a good agreement with those of ECMWF Reanalysis v5 (ERA5), showing that TCO from ERA5 is reliable, even during dynamically active periods. ERA5 has the advantage that it has no data gaps during the polar night. We found that TCO was increased by up to 190 DU after the SSW of February 2010, over one month. The composite analysis of the 15 SSWs provided the result that TCO is increased on average by about 50 DU over one month after the central date of the SSW.

Keywords: total column ozone; brewer spectrophotometer; meteorological reanalysis; sudden stratospheric warming; composite analysis; stratosphere–troposphere exchange

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1. Introduction

The Arctic ozone distribution is strongly influenced by transport processes related to major sudden stratospheric warmings (SSWs) [1]. Upward propagating Rossby waves interact with the stratospheric polar vortex during winter. A major SSW is associated with the breaking of Rossby waves leading to a rapid increase in the polar stratospheric temperature and a reversal of the vortex from eastward to westward flow for at least 5 days [2–5].

Simulations with the Whole Atmosphere Community Climate Model (WACCM) showed that polar ozone increases (0.5–0.6 ppmv) in the stratosphere above 50 hPa after a major sudden stratospheric warming, and meanwhile, there is a small decrease in ozone below 50 hPa [1]. The ozone increase is mainly due to ozone eddy transport associated with the deposition of planetary wave drag by the SSW [1]. After 1–2 months, the ozone level of the usual climate is reached again due to diffusive ozone fluxes. Similar results were derived from reanalysis data (Japanese 55 year Reanalysis JRA-55), showing a positive ozone anomaly of up to 0.4 ppmv between 50 and 10 hPa [6].

Using reanalysis data of MERRA-2 (Modern-Era Retrospective Analysis for Research and Applications, version 2), the authors of [7] found an average increase in TCO by about 50 DU after the central dates of major SSWs. The ozone anomaly gradually decreases over a course of about 60 days. Using reanalysis data of ECMWF (ERA Interim), the authors of [8] found a larger TCO increase of up to 90 DU for several months. We will see later that these values were possibly overestimated by ERA Interim. A model study of the ozone budget showed that polar vortex ozone was enhanced by 26–28 DU after the SSW in the Arctic winter of 2002–2003 [9]. The model's result was confirmed by measurements of the satellite experiment MIPAS/ENVISAT. The simulation showed that the largest change in polar vortex ozone was due to horizontal advection by planetary waves in January 2003.

The extratropical total cross-tropopause ozone flux is enhanced during winters with SSWs [10]. Low ozone pockets occurred after SSWs and led to regional decreases of stratospheric ozone at mid-latitudes [10]. In addition, the deformation or displacement of the polar vortex into the European longitude sector generated regional ozone decreases, as are often observed above Switzerland after an SSW [11]. However, horizontal advection of ozone-rich air from low-latitudes to high-latitudes is mainly responsible for the increase in ozone in the polar stratosphere after an SSW [10].

The high-latitude ozone variations induced by six SSWs from 2004 to 2020 were analyzed by using MERRA-2 data, ozonesondes and FTIRs (Fourier-transform infrared spectrometers) [12]. The zonally averaged stratospheric ozone showed a strong increase in 9–29% in TCO after each SSW, which lasted up to 2 months. A key role is played by the vertical advection of mid-stratospheric ozone during the SSWs. Magnified vertical advection occurred in the elongated vortex shape in 2009 and 2018.

The present study investigates how well the TCO variations after SSWs are seen by ground-based instruments at high latitudes and how well the TCO variations in ERA5 are confirmed by the independent observations of the instruments. In addition, we characterized the mean TCO increase after SSWs. The instruments and datasets are described in Section 2. The results are presented in Section 3 and discussed in Section 4.

2. Instruments and Datasets

2.1. Combined Ground-Based Measurements

Combined ground-based TCO time series (GBcomb) were derived by [13] for three northern high-latitude stations for the time interval 2000–2020 (daily values at noon). The TCO time series are available from Oslo (59.95° N, 10.72° E), Andøya (69.28° N, 16.01° E) and Ny Ålesund (78.92° N, 11.88° E). TCO data from Brewer spectrophotometers, ground-based UV filter radiometers (GUVs) and a SAOZ (Système d'Analyse par Observation Zénithale) instrument were combined in order to reduce data gaps. TCO was derived by four different measurement techniques: Brewer DS (direct sun method), Brewer GI (global irradiance method), SAOZ and GUV. The advantage is that TCO is also available when the sky is cloudy and there are high solar zenith angles, but data gaps during the polar night are still present in the time series. The deviations among the ground-based TCO, satellite and ERA5 data are 1–3% [13].

2.2. ERA5

We used hourly TCO data of ERA5 on single levels as provided by the Copernicus data store in cooperation with ECMWF [14]. We restricted the data analysis to the values at noon (12:00 UTC), since the noon values are close to the daytime TCO measurements of the ground stations and the visual/ultraviolet satellite instruments. ERA5 assimilates various total ozone satellite products, as described by [15].

3. Results

The present study was restricted to major SSWs. However, minor SSWs are of interest for ozone changes as well (e.g., [16]) and could be targets of a separate study. From 2000 to 2020, 15 major SSWs occurred according to the literature [6,11,12,17–19]. The central date of a major SSW is defined as when the eastward wind changes to westward wind at 10 hPa, northward of 60° N. Table 1 shows the central dates of the 15 major SSWs.

Table 1. Central dates of major SSWs in the Northern Hemisphere from 2000 to 2020.

20 March 2000	11 February 2001	2 January 2002
18 January 2003	7 January 2004	21 January 2006
24 February 2007	19 February 2008	24 January 2009
9 February 2010	7 January 2013	5 March 2016
11 February 2018	1 January 2019	5 January 2020

In the following, we discuss the deviations in TCO with respect to the climatological TCO values of the time interval 2000–2020. Thus, the seasonal variations of TCO were removed in the plots of the anomalies of ΔTCO. Figure 1 shows a strong increase in ΔTCO to 190 DU after the SSW of 9 February 2010. In spite of data gaps due to the polar night when no UV radiation could be measured, we can see the effects of the SSW at Ny Ålesund, Andøya and Oslo, mainly during the first 50 days after the central date (epoch time 0).

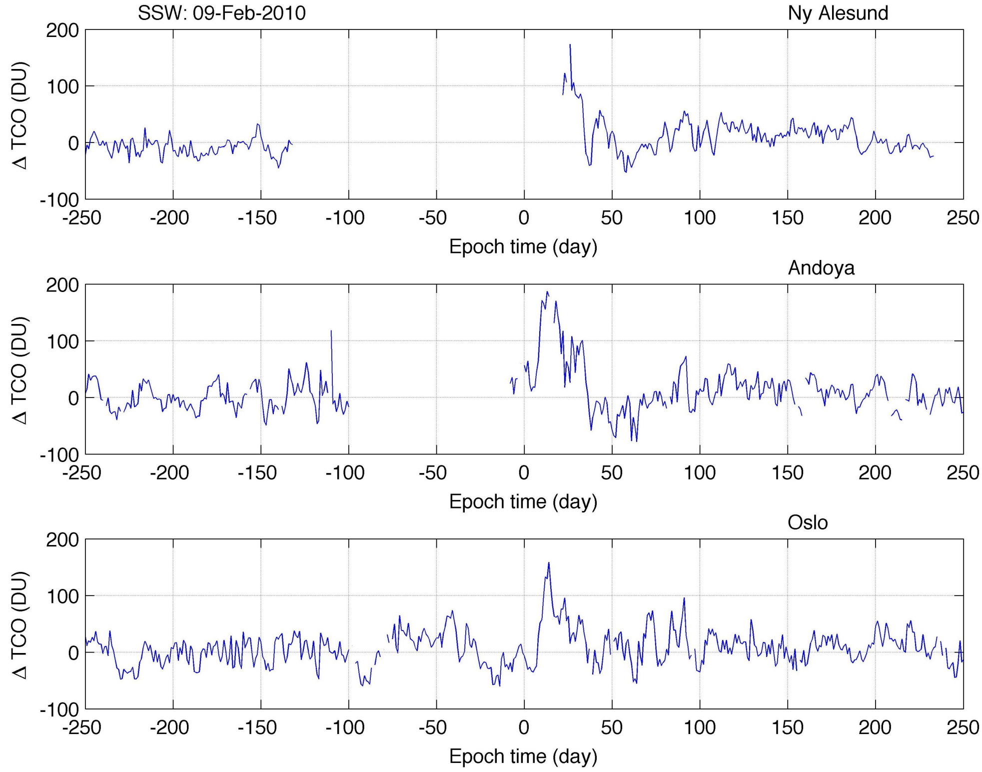

Figure 1. Anomalies in TCO with respect to the climatology observed at Ny Ålesund, Andøya and Oslo (GBcomb dataset). Epoch time 0 corresponds to the central date of 9 February 2010 for the major SSW. Data gaps are due to observations not being obtained in the polar night.

For intercomparison with Figure 1, we show in Figure 2 for the same event the ΔTCO estimate of ERA5. The onset, magnitude and the duration of the ΔTCO increase quite similarly in both figures. We found the following mean biases, standard deviations and correlation coefficients between the ground-based TCO and ERA5 (GBcomb-ERA5) for 2000–2020: Oslo: 0.28 ± 15.79 DU, r = 0.95; Andøya: -2.60 ± 16.56 DU, r = 0.96; Ny Ålesund: 0.71 ± 14.08 DU, r = 0.97. Thus, there is excellent agreement between ERA5 and GBcomb, so ERA5 is highly appropriate for analysis of temporal TCO variations.

Figure 3 shows the composite of the TCO anomalies for 15 SSWs at Ny Ålesund, based on GBcomb data. Due to the polar night, the TCO anomalies could not be observed before and at the beginning of the SSW. The ΔTCO increase reached about 40 DU and was present up to 50 days after the central date (epoch time 0). Values at the end of the polar night are less reliable because of a small number of measurements, as shown in the lower panel of Figure 3.

Figure 4 depicts the composite of the TCO anomalies at Andøya. The data gap is smaller than in the previous figure, since Andøya's latitude is smaller than that of Ny Ålesund. Before epoch time 0, negative values for TCO anomalies were found. However, the small number of samples at that time of the year makes those values relatively uncertain. The anomalies reached about 50 DU in the first 40 days after the central date of the SSW.

Figure 5 shows the composite for Oslo. Here, data gaps because of polar night do not exist. Thirty to one-hundred days before the SSW, ΔTCO was about −20 DU. After the SSW, the anomalies reached 40 DU, and in contrast to the other two locations, there seemed to be a decrease in ΔTCO lasting up to 150 days after the central date. However, it is difficult to verify this long-term influence of the SSW.

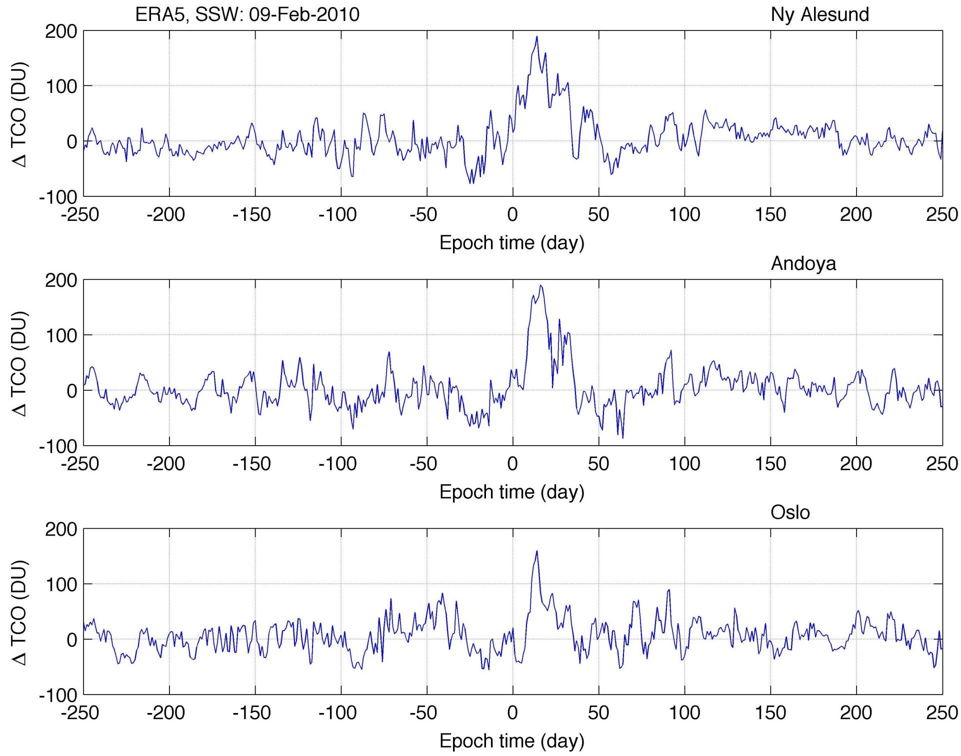

Figure 2. ERA5 estimate of the anomalies in TCO with respect to the climatology at Ny Ålesund, Andøya and Oslo. Epoch time 0 corresponds to the central date of 9 February 2010 of the major SSW.

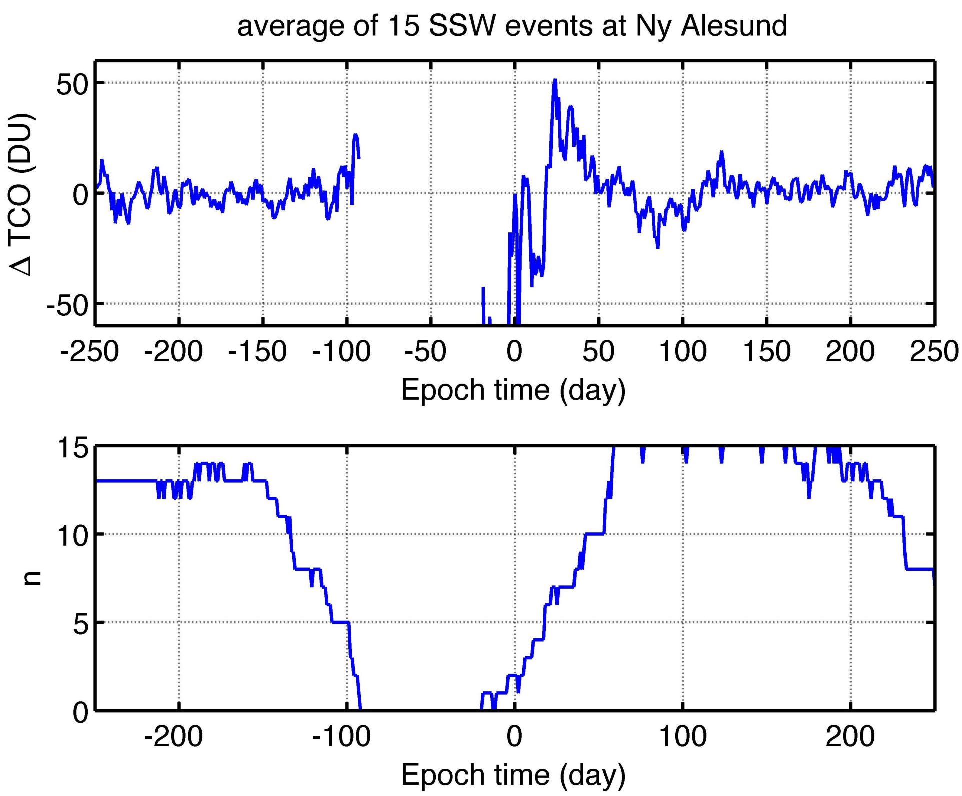

Figure 3. Composite of 15 major SSWs at Ny Ålesund (GBcomb data). The lower panel shows the number of measurements which were averaged in the composite shown in the upper panel.

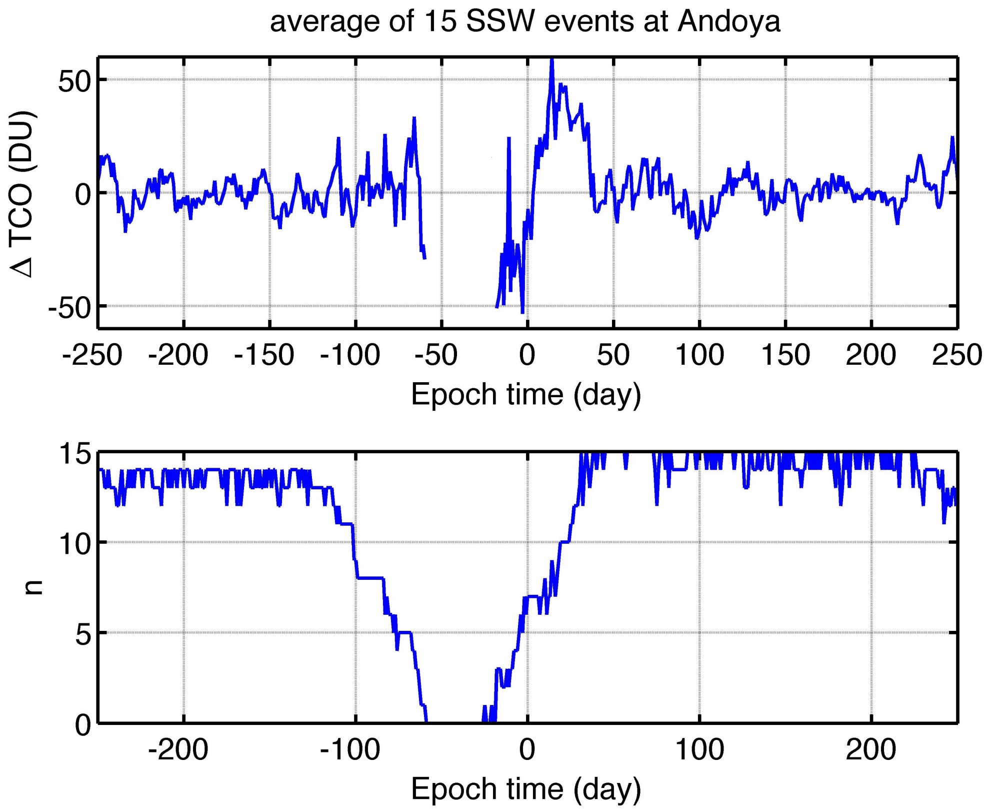

Figure 4. Composite of 15 major SSWs at Andøya (GBcomb data). The lower panel shows the number of measurements which were averaged in the composite shown in the upper panel.

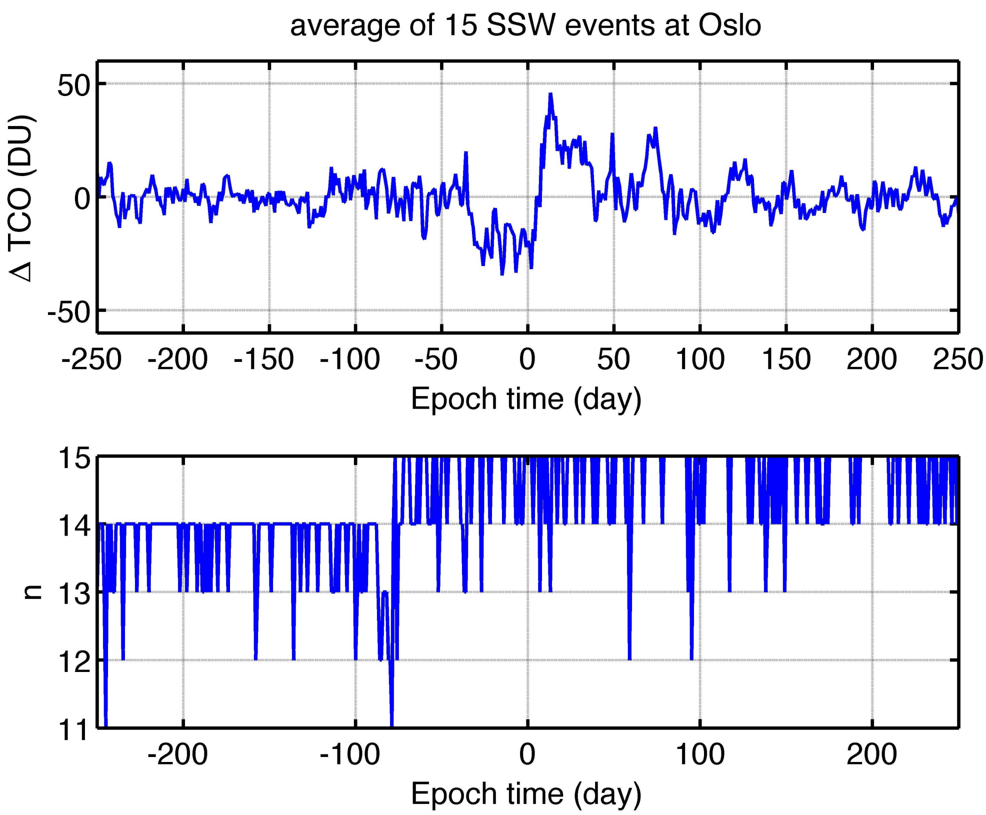

Figure 5. Composite of 15 major SSWs at Oslo (GBcomb data). The lower panel shows the number of measurements which were averaged in the composite shown in the upper panel.

Figure 6 shows the ERA5 composite of the 15 SSWs at Ny Ålesund, Andøya and Oslo. The advantage is that no data gaps are present here. However, it is likely that ERA5 TCO data during polar night are not so reliable, since the TCO measurements of visual and ultraviolet satellite instruments are not available during the polar night and cannot be assimilated into ERA5. The main results of Figures 3–5 can be confirmed with Figure 6. The TCO increase was up to 50 DU in the first 50 days after the central date. Again, at Oslo, there are indications that the influence of the SSW lasts longer—up to 150 days after the central date. At all three locations, we can see a negative TCO anomaly of about −25 DU from day −30 to 0 before the SSW.

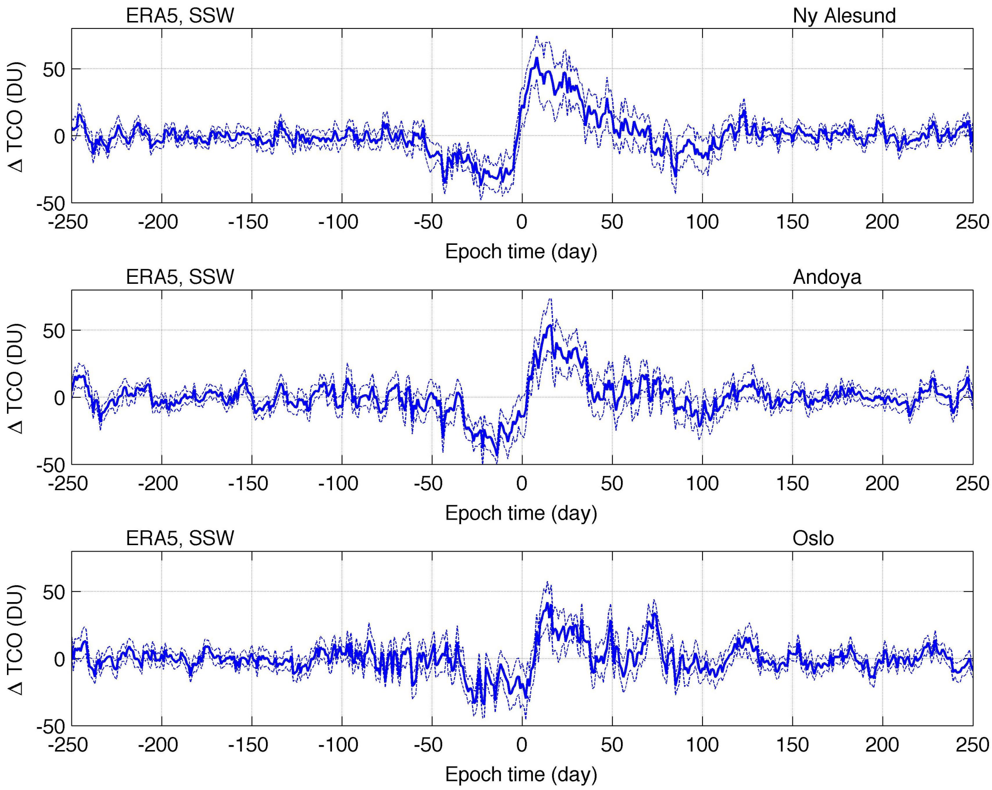

Figure 6. ERA5: Composite of 15 major SSWs at Ny Ålesund, Andøya and Oslo. The dashed lines show the mean error of the composite.

4. Discussion and Conclusions

We found similar main results for SSW influences on TCO in the ground-based measurements (GBcomb data) and ERA5. The high correlation (r = 0.95 to 0.97) between GBcomb and ERA5 further suggests that ERA5 is highly appropriate for the analysis of temporal variations in TCO. The main results for the positive TCO anomalies after the SSW (magnitude up to 50 DU, duration up to 50 days) are in good agreement with previous findings of [1,6,7,12]. As indicated in the previous studies, ozone-rich air is transported poleward during a major SSW. In addition, it can be speculated that the temperature increase during the SSW resulted in the reducing and ensuing disappearance of polar stratospheric clouds (PSC), so that a slowdown in the chemical destruction of ozone in the lower polar stratosphere occurred.

The negative anomalies of TCO before the SSW have not been mentioned before in the literature. The negative anomalies might be due to a strong polar vortex with ozone and poor air in the weeks before the SSW. In contrast to our results, the previous composite analysis of [8] gave larger values for the TCO increase and its duration. The study of [8] was solely based on ERA Interim reanalysis data [20], the predecessor of ERA5. In the case of Oslo, our composite also showed a long duration of the SSW influence of up to 150 days after the SSW. This is possibly a subjective impression, since the other two stations did not show such a long lasting effect for TCO.

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Data Availability Statement: The combined ground-based measurements of TCO (version v1.0) are available at https://doi.org/10.5281/zenodo.6760259 (accessed on 13 February 2023) [21].

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Conflicts of Interest: The authors declare no conflict of interest.

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