Arctic Ozone Loss in March 2020 and its Seasonal Prediction in CFSv2: A Comparative Study With the 1997 and 2011 Cases

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Abstract Using reanalysis data, observations, and seasonal forecasts, the March Arctic ozone loss events in 1997, 2011, and 2020 and their predictability are compared. All of the three ozone loss events were accompanied by an extremely strong and cold polar vortex, with the shape and centroid of the ozone loss controlled by the polar vortex. The high autocorrelation of the March Arctic ozone at a lead/lag time of 1–2 months from observations might suggest that a reasonable prediction can be obtained if one initializes 1–2 months in advance. Based on the chemical scheme assessment in CFSv2 and several empirical models using the forecasted metric(s) of the stratospheric polar vortex as predictor(s), the predictability of the 2011 ozone loss event is shown to be longer (1–2 months) than the other two (~1 month), possibly due to a moderate La Niña and quasi-biennial oscillation westerly winds favorable for the formation of a strong polar vortex. However, the overall predictive skills of ozone from empirical models (using a forecasted substitute index to forecast the Arctic ozone) during 1982–2020 are lower than the chemical module assessment in the forecast system, though empirical models have some skill. Contrary to the ozone predictions, the lower tropospheric temperature pattern in March 2011 is less reasonable than in 1997 and 2020. Similar conclusions are also true in other years (2005 versus 2016). Those findings might indicate a weak relationship between the Arctic ozone and the surface climate in the Northern Hemisphere.

Plain Language Summary Extremely low ozone concentrations (or an “ozone hole”) develop in the Antarctic every austral spring in present-day atmospheric burdens of ozone-depleting substances. However, similar ozone losses are not observed in the Arctic, though in 1997, 2011, and 2020, ozone loss locally approached that in the Antarctic. This study focuses on the meteorological conditions and predictability for those Arctic ozone loss events. All of the three historical ozone loss events were related to a stratospheric circulation system encircling North Pole (i.e., the stratospheric polar vortex). The shape and centroid of the ozone losses were also controlled by the polar vortex: the ozone loss in March 2020 was displaced toward the North American sector, the March 2011 ozone loss was centered over the North Pole, while the 1997 ozone loss was displaced toward the Eurasian sector. Using the chemical scheme in a seasonal forecasting model and/or empirical models, the lead times for forecasting the three ozone loss events are different due to the tropical forcing. The moderate cold state in the tropical Pacific (i.e., La Niña) and westerly winds in the equatorial stratosphere (i.e., westerly QBO) propel the predictability of the 2011 ozone loss event to around 1–2 months, while the 1997 and 2020 March ozone losses can only be forecasted ~1 month in advance. Nevertheless, a good prediction of the stratospheric ozone shows little impact on the surface predictability in the Northern Hemisphere.

1. Introduction

The stratospheric ozone layer protects life on Earth from solar ultraviolet radiation (Bernhard et al., 2013; WMO, 2014). During the austral spring, a (nearly) complete depletion of lower stratospheric ozone results in the formation of an ozone hole over the Antarctic nearly every year (Manney et al., 2011; Randel & Wu, 1999; Rieder et al., 2014; Solomon, 1999). Stratospheric ozone depletion in the Southern Hemisphere (SH) accelerated in the latter decades of the 20th century and is projected to completely recover only in the latter half of the 21st century (WMO, 2014, 2018). It has been robustly established that Antarctic
stratospheric ozone depletion affects the SH tropospheric and surface climate in a large body of literature (e.g., Polvani et al., 2011; Waugh et al., 2009). Specifically, on the decadal timescale, large changes associated with Antarctic ozone depletion have been observed in the SH troposphere, although some inconsistencies between different studies also exist for the impact of the Antarctic ozone loss on the SH troposphere (Quan et al., 2014; Staten et al., 2012; Waugh et al., 2009). The diverse ozone change magnitudes prescribed in those modeling studies are responsible at least in part for their discrepancies (WMO, 2018).

The largest surface temperature response to ozone depletion was observed over the high-latitude Southern Ocean rather than Antarctica (McLandress et al., 2011), although internal variability likely played a key role in observed temperature trends (Smith & Polvani, 2017; Turner et al., 2016). Dennison et al. (2015, 2016) found that ozone depletion leads to an increased frequency of extreme anomalies and increased persistence of the stratospheric Southern Annular Mode (SAM), stronger and more persistent stratosphere-troposphere coupling, as well as an increase in blocking frequency in the South Atlantic region. SH extratropical rainfall is tied to the position of the midlatitude jet, and recent changes in both extratropical and subtropical astral summer rainfall may be related to the ozone depletion (WMO, 2018). The ozone depletion can force a poleward shift of the subtropical dry zone (Hendon et al., 2014), an increase in synoptic eddy activity (Solman & Orlanski, 2016), and a change in the position of the South Pacific convergence zone (Brönnimann et al., 2017); via those routes, an increase in SH extratropical rainfall is observed (Bai et al., 2016). Projections by chemistry-climate models suggest that a future ozone recovery will lead to the opposite effect. For example, Lim et al. (2016) find that ozone recovery would drive a more negative SAM and less rainfall in higher latitudes.

In the Northern Hemisphere (NH), on the other hand, large chemical ozone loss over the Arctic only occurs when the stratospheric polar vortex persists into spring and lower stratospheric temperatures are unusually low (Arnone et al., 2012). Arctic ozone loss therefore has large interannual variability due to strong planetary wave disturbances and even sudden warmings which ordinarily prevent long-lived low temperatures in the NH (Manney et al., 2011). Hitherto, three NH extreme “ozone loss” events have been observed since 1979 (i.e., March in 1997, 2011, and 2020 in Figure 1). The March 1997 ozone loss event (Newman et al., 1997; Zhang et al., 2013) and especially the March 2011 ozone loss event (Arnone et al., 2012; Chipperfield et al., 2015; Hurwitz et al., 2011; Liu et al., 2011; Manney et al., 2011; Sinnhuber et al., 2011; Solomon et al., 2014; Varotsos et al., 2012) have attracted wide attention. For example, Arnone et al. (2012) analyzed the Arctic dynamics and chemistry during the 2010/2011 ozone loss using the limb sounding infrared measurements. Two major processes are responsible for the low ozone in early spring over the Arctic: heterogeneous chemical loss (Hommel et al., 2014; Solomon, 1999) and a quiescent stratosphere in winter (Olascoaga et al., 2012; Shaw & Perlwitz, 2014; Strahan et al., 2013). When the stratosphere is quiescent and the stratospheric westerly jet is strong, the poleward mass transport from the ozone-rich tropics to the ozone-poor polar regions is blocked with the anomalously strong jet serving as a barrier for the ozone transport (Strahan et al., 2013). Heterogeneous reactions on polar stratospheric cloud (PSC) droplets convert chlorine reservoir species to chlorine radicals that destroy ozone catalytically (Solomon, 1999), so ozone depletion in the Arctic late winter is also dependent on the volume of the polar stratosphere below the temperature threshold for PSC formation (Garfinkel et al., 2015; Harris et al., 2010; Rex et al., 2006). The Arctic stratospheric temperatures in the 2010/2011 winter were one of the coldest in the satellite era since 1979 (Manney et al., 2011; Sinnhuber et al., 2011). The ozone loss rate over the Arctic in the 2011 spring was quantitatively comparable to what is on average observed at present over Antarctica (e.g., Manney et al., 2011; Sinnhuber et al., 2011; Varotsos et al., 2012).

However, we still do not know clearly whether there is any link between Arctic ozone loss and surface climate in the NH. Springs with low Arctic ozone concentration in March are associated with a strong and cold stratospheric polar vortex, which is often accompanied with the positive polarity of NAM/North Atlantic Oscillation (NAO) in early boreal spring (Previdi & Polvani, 2014; Solomon et al., 2014; Thompson & Solomon, 2002). Karpechko et al. (2014) found a connection between the 2011 Arctic ozone loss and the tropospheric climate only when the sea surface temperature anomalies are also included in their model study. Cheung et al. (2014) investigated the impact of the extreme Arctic ozone depletion of 2011 on the tropospheric predictability based on the UK Met Office forecast system, and they found that the stratospheric response to reduced ozone is not significant if the tropospheric wave forcing is not included. Further
evidence from Smith and Polvani (2014) also suggests that simulations with prescribed ozone observations do not show any tropospheric response in their modeling study. The tropospheric response to the Arctic ozone loss might be due to a coincidence of the strong polar vortex and the Arctic ozone loss forced by the strong polar vortex (e.g., Harari et al., 2019). On the other hand, some other modeling and observational studies find a robust stratosphere-troposphere coupling in extremely low versus high ozone years (Calvo et al., 2015; Ivy et al., 2017; Stone et al., 2019). The mixture of a strong stratospheric polar vortex in late winter and spring (sometimes a late onset date of final warming) and an Arctic ozone loss obscure the real forcing of the positive NAO response and the shift of the tropospheric polar jet. Even without Arctic ozone loss, stratospheric dynamical variability has also been shown to influence surface conditions in early studies (Ayarzagüena & Serrano, 2009; Black & McDaniel, 2007; Hardiman et al., 2011). A connection between Arctic ozone variability and extratropical surface is probably mediated by the dynamical variability that typically drives the anomalous ozone concentrations rather than the opposite (Harari et al., 2019).

Manney et al. (2020) recently reported on the chemical processes during the extreme ozone loss in March 2020; however, the predictability of the extreme ozone loss in March 2020 (and in March 1997 and 2011) and of the subsequent surface impact has still not been explored. This paper focuses on the general
meteorological conditions for the three historical ozone loss events in the NH. Seasonal predictions of the three ozone loss events are compared using operational model outputs by an operational forecast system. We will show that the predictability of the ozone loss is largely dependent on the representation of the polar vortex in the forecast system for the three Arctic ozone loss cases and that a more skillful forecast of stratospheric ozone has limited effect on surface predictability for these three cases.

The organization of the paper is as follows. Following section 1, section 2 describes the data, model forecasts, and methods. The background circulation conditions for the three Arctic ozone loss events are shown in section 3. The predictions of the Arctic ozone losses using the chemical module assessment in the forecast system and empirical methods are compared in section 4. Section 5 explores the possible impact of the stratospheric ozone on near-surface predictability. Finally, conclusions and a discussion are presented in section 6.

2. CFSv2 Seasonal Forecasts, Data, and Methods

2.1. NCEP Climate Forecast System Version 2 (CFSv2) and its Seasonal Predictions

As a successor to NCEP CFSv1, the NCEP CFSv2 began to operate on 30 March 2011 (Saha et al., 2014). The CFSv2 forecast model is a fully coupled model system with an atmospheric spectral model interacting with ocean, land, and sea ice. The forecast system runs at a T126 (~100 km) horizontal resolution for the atmosphere. This model uses a sigma-pressure hybrid vertical coordinate with 64 levels. The seasonal reforecasts before 2011 by CFSv2 were performed every 5 days. The seasonal forecasts after 2011 were performed every day. The forecasts/reforecasts initialized on the specific days have four members using the initial conditions at 0000, 0600, 1200, and 1800 UTC. The real-time seasonal forecasts were initialized four times (0000, 0600, 1200, and 1800 UTC) per day. The seasonal forecast/reforecast products produced 9-month integrations (https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/climate-forecast-system-version2-cfsv2). CFSv2 is also one of the models participating in the subseasonal to seasonal (S2S) program initialized in 2013 by the World Climate Research Program and World Weather Research Program. Recent studies have shown that this forecast system is among the best at predicting sudden stratospheric warming (SSW) events in both hemispheres (Domeisen et al., 2020a, 2020b; Rao et al., 2019; Rao, Garfinkel, & White, 2020; Rao, Garfinkel, White, & Schwartz, 2020) and downward coupling of stratospheric variability to the surface (Schwartz & Garfinkel, 2020). A full ozone photochemistry scheme is not used in many S2S or seasonal forecast models due to its computational expense, but CFSv2 includes a prognostic ozone parameterization scheme (Compo et al., 2016). Specifically, the time tendency of ozone is specified using the partial CHEM2D Ozone Photochemistry Parameterization (CHEM2D-OPP) method (McCormack et al., 2006).

Considering that Arctic ozone loss events in March are persistent, we focus on the seasonal forecast of the three ozone loss events, rather than the day-by-day forecasts in detail. The CFSv2 initializations at the very beginning of each winter month (November–March; we focus more on initializations in January–March) are downloaded and assessed in this study (Table S1). Similar to the winds, height, and air temperature, the total column ozone estimated by the CHEM2D-OPP method is also a standard output from this forecast system (note that we use the model climatology for calculation of the forecasted anomalies).

2.2. Reanalysis and Observations

The ERA5 reanalysis (Hersbach et al., 2020) is used as the baseline for assessment of the CFSv2 forecasts. The daily and monthly data at a 1.5° × 1.5° horizontal resolution is downloaded from the Copernicus Climate Change Service Climate Data Store after registration (https://cds.climate.copernicus.eu). Variables used in this study include the zonal and meridional winds, air temperature, geopotential (divided by the gravitational acceleration to extract the height), and Ertel potential vorticity (PV) at 37 pressure levels (1,000–1 hPa). The total column ozone (TCO3) is not provided by ERA5, but it can be computed by vertically integrating the ozone mixing ratio (RO3) divided by the gravitational acceleration: 

\[
TCO3 = \frac{1}{g} \int_{P_s}^{P_0} \rho RO3 \, dp,
\]

where \(P_s\) is the surface pressure and \(g\) is the gravitational acceleration constant (\(g = 9.8 \, m/s^2\)). The units of the TCO3 is converted from kg/m² to Dobson unit (DU) with a rough estimate of 1 DU = 2.1415 × 10⁻⁵ kg/m² (http://www.temis.nl/general/dobsonunit.html; Zhang et al., 2019). ERA5 assimilates 19 different ozone observation sources during different periods since 1979 (Figure 7 in Hersbach et al., 2020), so it is reasonable to use TCO3 from this modern reanalysis as a reference state.
The monthly Niño3.4 index is used to identify the phase of the El Niño southern oscillation (ENSO). The sea surface temperature (SST) data are collected by the Japanese Meteorological Agency (COBE SST) and sourced from PSL, NOAA (https://psl.noaa.gov/data/gridded/data.cobe.html). In addition, the quasi-biennial oscillation (QBO) time series shared by Berlin Free University (https://www.geo.fu-berlin.de/en/met/ag/strat-produkte/qbo/index.html) is also used to test the potential predictability source (in addition to SST data), although the series is similar to ERA5.

### 2.3. Methods

To compare the midwinter conditions preceding the three Arctic ozone losses, the SSW and stratospheric final warming (SFW) events during 1979–2020 are also considered. The SSW events are selected using a strict WMO benchmark: a major SSW is defined if the zonal mean zonal winds at 60°N and 10 hPa reverse from westerlies to easterlies (Butler et al., 2015; Charlton & Polvani, 2007). The initializations of SSW and SFW are searched using the same procedure except that a SFW cannot recover to westerlies until the following autumn. Following those steps, it is revealed that no SSWs happened in the preceding midwinter for the three Arctic ozone loss events. Furthermore, the SFW did not happen until April for all three ozone loss events (e.g., 30 April 1997, 5 April 2011, and 29 April 2020).

To assess the predictability of ozone and circulation anomaly distributions, the pattern correlation coefficient (PCC) of anomalies between forecasts and the reanalysis for a variable $V$ is utilized, PCC

$$
\text{PCC} = \frac{\sum_{i=1}^{n} w(i) [V_{FC}(i) - \bar{V}_{FC}] [V_{RE}(i) - \bar{V}_{RE}]}{\sqrt{\sum_{i=1}^{n} w(i) [V_{FC}(i) - \bar{V}_{FC}]^2} \sqrt{\sum_{i=1}^{n} w(i) [V_{RE}(i) - \bar{V}_{RE}]^2}}.
$$

In the PCC formula, $i$ is the spatial grid index, $n$ is the total number of spatial grid points in the extratropics (30–90°N), and $w$ is the weighting (cosine of the latitude). The subscript “FC” denotes the model forecast, and “RE” denotes the ERA5 reanalysis. The overbars in the PCC formula denote spatial averages.

The following metrics are used to track the relationship between the stratospheric polar vortex and the Arctic total ozone: (1) the polar cap height area weighted over 60–90°N at 50 hPa; (2) polar cap total column ozone area weighted over 60–90°N (Strahan et al., 2013, used the 63–90°N means); (3) zonal mean zonal winds at 60°N and 10 hPa in December–February (DJF); (4) days of strong polar vortex during DJF with the zonal mean zonal winds at 60°N and 10 hPa greater than 35 or 40 m/s; (5) the volume of the PSCs ($V_{PSC}$) in late winter (February–March [FM]), estimated as $V_{PSC} = (0.8 \times A_{PSC} @ 50 \text{ hPa} + 0.2 \times A_{PSC} @ 30 \text{ hPa}) \times 5.06 \text{ km}$, where $A_{PSC}@50 \text{ hPa}$ is the area at 50 hPa colder than 195.59 K and $A_{PSC}@30 \text{ hPa}$ is the area at 30 hPa colder than 193.61 K (Garfinkel et al., 2015; Rex et al., 2004; Rieder & Polvani, 2013). The fourth and fifth indices are calculated using the ERA5 daily means, and the others are based on the monthly means. Note that monthly mean forecast data are also used to calculate the first and second indices for CFSv2.

### 3. Background for the Three Historical Arctic Ozone Loss Events

Figure 1 shows the time series of several metrics, including the Arctic total column ozone versus polar cap height at 50 hPa in March (Figure 1a), days of strong polar vortex in DJF (Figure 1b), the winter mean polar jet intensity versus late winter $V_{PSC}$ (Figure 1c), and two dominant tropical forcings (ENSO and QBO; Figure 1d). It is evident that polar cap height and ozone in March 1997, 2011, and 2020 rank as the top three low values from 1979 to 2020 (Figure 1a). The high correlation (i.e., 0.80) between polar cap height and the Arctic total ozone indicates that they are strongly coupled with each other. The formation of low Arctic ozone concentrations is also preceded by a quiescent winter with a strong stratospheric polar vortex (Figures 1b and 1c), indicating a weak residual circulation (not shown) and therefore a reduced resupply of ozone. A strong and cold polar vortex allows for the formation of more PSCs (Figure 1c) and chlorine activation (Arnone et al., 2012; Manney et al., 2011), whereby the depletion of ozone is larger than normal. In addition, no midwinter SSW appeared before the three ozone loss events, and the final warming did not occur until April (e.g., 30 April 1997, 5 April 2011, and 29 April 2020). Our results do not suggest any directly significant linear relationship between ENSO and the Arctic total ozone, but the QBO indeed contributes marginally to interannual variability of March ozone (Figure 1d). Hurwitz et al. (2011) also emphasize the possible impact of warm SST anomalies in North Pacific on the strong polar vortex in March 2011, which were not observed in the 1996/1997 winter but were observed in the 2019/2020 winter (not shown).
Figure 2 compares the meteorological conditions for the three Arctic ozone loss events. The climatological ozone is around 420 DU in March (Figure 2a), but the lowest column ozone is below 280 DU for the three loss events (Figures 2b–2d; central minima: 275, 254, and 245 DU). The minimum ozone value over the Arctic in March 2020 is even lower than in 2011 and 1997, and the position of the low center is also different among the events: toward North America in March 2020, symmetric about the pole in March 2011, but toward Eurasia in March 1997. Such a displacement of the low-ozone center is consistent with the shape of the stratospheric polar vortex at 10 hPa (similar at 50 hPa) denoted by the high PV value (Figures 2e–2h) and low height anomalies at 50 hPa (Figure S1). On average, the polar vortex begins to weaken or collapse in March (Figures 2e and S1). However, in March 1997, 2011, and 2020, the polar
vortex was still strong, manifested by the large PV values in the Arctic at 10 hPa (>600 PVU). The PV maximum was located in Arctic Canada in March 2020, near the North Pole in March 2011, and shifted toward Arctic Russia in March 1997 (Figures 2f–2h). Therefore, the Arctic ozone loss is coupled with an extremely strong stratospheric polar vortex.

Climatologically, zonal mean temperatures over the Arctic at 50 hPa in March are 210–215 K, well above the threshold for PSC formation (Figure 2i). In March 2020, 2011, and 1997, the coldest temperature anomalies in the Arctic stratosphere reached ~−18 K in the zonal mean, cold enough to allow widespread ozone loss via heterogeneous chemical reactions (Figures 2j–2l).

The residual (or Brewer-Dobson) circulation dynamically transports mass from the ozone-rich tropics to the ozone-poor extratropics (Figure 2m). The strong polar vortex with strong westerly jet (Figures 2i–2l) is often accompanied with weak upward propagation of waves and therefore the weak wave-forced residual mass circulation and mixing, as is evident by the positive ozone mixing ratio anomalies in tropics and negative anomalies in extratropics especially for the 2011 and 2020 cases (Figures 2n–2p). To summarize, dynamical processes associated with a strong polar vortex partially contributed to the formation of the Arctic ozone losses in 1997, 2011, and 2020, and chemical losses likely played a role due to the persistent temperatures low enough to form PSCs.

4. Prediction of Arctic Ozone Loss

4.1. Prediction of 1997, 2011, and 2020 Arctic Ozone Loss by CFSv2

The predictions of the March total ozone and the geopotential height (PV at pressure levels is unavailable for CFSv2) anomalies from initializations at the beginning of February and March are shown in Figure 3. While the early initializations correctly forecast the sign of the ozone anomalies, the anomaly amplitudes are largely underestimated (Figures 3a, 3c, and 3e). The early initializations better capture the 2011 ozone loss (central low: ~−80 DU) than the 1997 and 2020 ozone losses (central low: ~−40 DU), indicating a different degree of predictability of ozone loss for the three events. The March initializations have a similar predictive skill for the three ozone loss events, with a pattern correlation around 0.9 (Figures 3b, 3d, and 3f). The distribution of the column ozone is largely controlled by the polar vortex both in the reanalysis (contours) and in forecasts (shadings; Figures 3g–3l). The low centers of the total column ozone and height anomalies are closely situated. The predictability of the total column ozone is highly consistent with that of the stratospheric height: the strong polar vortex in March 2011 is well forecasted in the early February initializations (Figure 3i), which exceeds the average predictive limit of strong stratospheric polar vortex (Domeisen et al., 2020a).

The predictions of ozone based on the CHEM2D-OPP calculation in CFSv2 for initializations at the beginning of November, December, January, February, and March are shown in Figure 4. For initializations at the beginning of March, nearly all of the Arctic ozone anomalies can be reproduced by CFSv2 (Figures 4a–4c). For initializations in early February 2011, most of the negative Arctic ozone anomalies in March 2011 are forecasted (Figure 4b). For initializations around 1 January or earlier, little predictive skill is present in the forecasting system. The pattern correlation of the extratropical total ozone is also much larger for initializations in March than other winter months (Figures 4d–4f). These results suggest that March Arctic ozone loss events can be accurately predicted around 1 March or earlier.

While to a large degree anomalies in ozone are persistent from one month to the next, with a 1-month (2-month) autocorrelation value of 0.87 (0.44) (Figure S2), dynamical processes with the atmosphere can also contribute to anomalies in ozone. Specifically, the predictability of the Arctic stratospheric polar vortex is dependent on tropospheric conditions. Rao et al. (2019) and Rao, Garfinkel, and White (2020) reported that favorable external forcings such as Madden-Julian Oscillation (MJO; also see Garfinkel & Schwartz, 2017), ENSO, and QBO can increase the predictive limit for some SSWs. It is noticeable that the mild cold ENSO state and the QBO westerly winds (Figure 1d) in the 2010/2011 winter together favor a strong polar vortex response in forecasts. The ENSO and QBO were nearly neutral in the 1996/1997 and 2019/2020 (developed to QBO easterlies in spring) winters, and the polar vortex anomalies are accurately forecasted only for March initializations (Figures 3h, 3j, and 3l).
4.2. Predictability of the Arctic Total Ozone in March in Other Years

In order to provide context for the 3 years with pronounced ozone loss, we now consider other years. Specifically, we first consider CFSv2 forecasts from two additional years—2005 and 2016—which were characterized by an unusually strong vortex in midwinter, but the strong vortex anomaly did not persist into spring (Manney et al., 2006; Manney & Lawrence, 2016). We now consider these two events as a foil for the ozone loss events in 1997, 2011, and 2020, in order to assess whether ozone predictability in March arises from the initialized ozone, or from the dynamical evolution of the model (Figure 5). Different from the persistent strong polar vortex from winter to early spring in the 3 years with an extreme ozone loss, the polar vortex gradually weakened from winter to early spring in 2005 and 2016, and an early final warming was even observed in 2016 (4 April 2005 and 6 March 2016). In March 2005, the stratospheric polar vortex was

![Figure 3](image1.png)

**Figure 3.** (a) CFSv2 predictions of the total ozone anomalies (first row, units: DU) and height anomalies at 50 hPa (second row, units: km) in shadings. The contours show the observed anomalies from the ERA5 reanalysis, with an ozone interval of 20 DU and height interval of 0.2 km (zero skipped). The first two columns (a, b, g, h) show predictions for 1997 March ozone loss, the middle two columns (c, d, i, j) show predictions for 2011 March ozone loss, and the last two columns (e, f, k, l) show prediction for 2020 March ozone loss. Only predictions initialized at the beginning of February (a, c, e, g, i, k) and March (b, d, f, h, j, l) are shown. The pattern correlation of ozone/height anomalies between ERA5 and forecasts is also printed on the top right for each plot.

![Figure 4](image2.png)

**Figure 4.** (a–c) CFSv2 predictions of the total ozone anomalies (units: DU) in March over the polar cap (60°–90°N) for the three historical ozone loss events in 1997, 2011, and 2020. The abscissa shows the initialization time at the beginning of each month, and four members are available. The filled histogram shows the forecast, and the unfilled histogram shows the ERA5 reanalysis. (d–f) As in (a–c) but for pattern correlations between the forecasts and the reanalysis.

![Figure 5](image3.png)

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Figure 5. As in Figure 3, but for the seasonal forecast of the March total column ozone (top row) and height (bottom row) anomalies in 2005 (left two columns) and 2016 (right two columns).

Figure 6. Year-by-year (1982–2020) predictions of the total ozone anomalies (units: DU) in March over the polar cap (60–90°N) by CFSv2 with the initialization times at the beginning of (a) January, (b) February, and (c) March. The black (blue) curve shows the ERA5 reanalysis (forecasts). The correlation between the reanalysis and forecasts is also printed on the top right of each plot.
displaced toward the North Atlantic, and the low ozone center was also displaced from the North Pole. In March 2016, more Arctic total ozone was observed due to stronger wave activities associated with an early final warming.

Similar to the prediction of the ozone losses in forecasts initialized around the beginning of March in 1997, 2011, and 2020, the ozone loss in March 2005 and ozone surplus in March 2016 were well forecasted in Figures 5b and 5d for early March initializations (PCC = 0.80 and 0.76), consistent with the comparable predictive skill of height in the same initializations (Figures 5f and 5h; PCC = 0.63 and 0.91). The forecasts initialized around the beginning of February predict extratropical ozone to different degrees of success for the 2005 and 2016 cases (Figures 5a and 5c; PCC = 0.59 and 0.16). The PCC for March 2016 ozone is relatively low for initializations in early February, but the model is still capable of simulating a weakened vortex and elevated ozone for March, even though the model was initialized with a stronger than average vortex. In general, the Arctic ozone loss in March 2005 and surplus in March 2016 are captured by the early March initializations, consistent with the prediction of circulation, and skill is not due solely to memory from the initialization.

These results are extended to all years in Figure 6, which shows the year-by-year predictive skill of the Arctic ozone in March by CFSv2 for forecasts initialized at beginning of January, February, and March. The correlation between the forecasts at different lead times versus ERA5 is also calculated and compared with the autocorrelation of the ozone in Figure S2. The predicted Arctic ozone anomaly magnitude is underestimated in most years from 1982 to 2020 in earlier initializations (Figures 6a and 6b). Initializations around the beginning of February predict extratropical ozone to different degrees of success for the 2005 and 2016 cases (Figures 5a and 5c; PCC = 0.59 and 0.16). The PCC for March 2016 ozone is relatively low for initializations in early February, but the model is still capable of simulating a weakened vortex and elevated ozone for March, even though the model was initialized with a stronger than average vortex. In general, the Arctic ozone loss in March 2005 and surplus in March 2016 are captured by the early March initializations, consistent with the prediction of circulation, and skill is not due solely to memory from the initialization.

Figure 7. (a) Scatterplot of the polar cap height at 50 hPa in FM (units: km) versus the polar cap total ozone in March (units: DU). The year is marked with a two-digit integer. The horizontal and vertical dashed lines are the mean of the March polar cap height at 50 hPa and total ozone, respectively. The thick line is the linear regression between the height and total ozone. (b) As in (a) but for scatterplot of the volume of polar stratospheric clouds in FM ($V_{PSC}$; units: $10^6$ km$^3$) versus the total ozone area averaged over the polar cap region in March. (c–e) Empirical predictions of the polar cap total ozone in March (units: DU) using the forecasted polar cap heights. Empirical predictions of the polar cap total ozone in March using the forecasted $V_{PSC}$ also are skillful, but the $V_{PSC}$ is highly underestimated (even zero) by the monthly data in most years (see Figure S4).
Figures 6b and 6c are somewhat larger than the ozone autocorrelation at those time leads/lags (Figures S2b and S2c; correlation: 0.44 and 0.87), although the forecasts depend to large extent on the initial value.

4.3. Empirical Prediction of the 1997, 2011, and 2020 Arctic Ozone Losses

For a forecast system without a chemical module or ozone output, the prediction of ozone can be derived from a variable highly correlated with ozone (e.g., the polar vortex strength or $V_{PSC}$). Based on this, Seviour et al. (2014) designed a statistical plus dynamical forecast procedure but for seasonal prediction of the Antarctic ozone, as the GloSea5 forecast system does not include a diagnostic chemical module. An empirical prediction of the Arctic total ozone using the forecasted polar cap height (see Figure S3) is shown in Figure 7. Based on the ERA5 reanalysis, the simple linear regression between height and ozone is established (Figure 7a), which can then be used to predict (in an empirical manner) Arctic total ozone. Figures 7c–7e assess the skill of such an empirical ozone predictive model. Note that initializations earlier than February have outputs for February and March forecasts, but the early March initializations do not have outputs for February forecasts (i.e., forecasts cannot be earlier than the initial time). Therefore, the reanalysis in February and forecasts in March for the early March initializations are combined to calculate the FM mean of heights/$V_{PSC}$ as the predictor(s) in empirical models.

The empirical prediction model underestimates the extremity of the low ozone in initializations earlier than March, but the empirical model can well reproduce the observed anomalies in the initializations at the beginning of March. The earlier initializations (November–January) contain little skill at forecasting the ozone loss in March, except that initializations in February 2011 still have high skill possibly due to the cold ENSO and westerly QBO conditions. We also assess sensitivity to basing the empirical model on the regression between $V_{PSC}$ in late winter (FM) and the Arctic total ozone (Figure 7b), and no improvement is found.
V_{PSC} is underestimated using monthly mean model output, and daily forecasted data in the stratosphere are unavailable. Overall, the statistical model might have some skill in forecasting seasonal mean polar ozone (e.g., Seviour et al., 2014), but its predictive skill is low for the March ozone loss events in earlier initializations.

We next consider an empirical model for years other than the three ozone loss events. Specifically, the prediction of the Arctic ozone during 1982–2020 using the simple linear regression model and height forecasts by CFSv2 initialized at the beginning of January, February, and March are shown in Figure 8. The empirical model shows limited skill in the early January initialization (Figure 8a; correlation: 0.22 < r_{\alpha} = 0.1), implying that it is difficult to predict the Arctic ozone in forecasts at such a lead time, consistent with the

(Figure S4): V_{PSC} is underestimated using monthly mean model output, and daily forecasted data in the stratosphere are unavailable. Overall, the statistical model might have some skill in forecasting seasonal mean polar ozone (e.g., Seviour et al., 2014), but its predictive skill is low for the March ozone loss events in earlier initializations.

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CHEM2D-OPP prediction (Figure 6a). The three extreme ozone losses in 1997, 2011, and 2020 are also not forecasted. The interannual variability of the Arctic ozone in this initialization is much smaller than observations. The empirical prediction of the Arctic ozone in the early February initialization is incorrect for most years from 1982 to 2020, although the correlation between forecasts and observations is significant (Figure 8b; \( r = 0.35 > r_{0.1} \)), mainly due to the success in 2011. In contrast, if height from the early March initialization is used, then the empirical prediction is highly correlated with observed ozone (Figure 8c; correlation: 0.66), and the ozone losses in 1997, 2011, and 2020 are well forecasted.

We also formed an empirical model based on polynomial fitting (Figures S5 and S6 show the second-order fitting), and the explained variance changes little as compared to a simple linear regression (\( R = 0.8 \) for a linear regression and \( R = 0.83 \) for a polynomial fit). In addition, the multiple regression using the polar cap height and \( V_{PSC} \) as predictors (Figure S7;\( R = 0.8 \)) also does not work better than the simple linear regression. For succinctness, only the linear regression model is shown in the paper. In summary, the empirical model shows some skill of forecasting Arctic ozone, but not as good as the CHEM2D-OPP module (cf. Figures 6 and 8).

5. Seasonal Prediction of Surface in Spring Following Extreme Arctic Ozone Losses

As discussed in section 1, there is still a debate about the possible impact of Arctic stratospheric ozone variability on the surface. We now consider a related question: does a prediction of extreme ozone loss lead to surface predictability in spring? Figure 9 shows the prediction of the March–April mean temperature anomalies at 850 hPa (t850) for forecasts initialized around the beginning of February and March for the three ozone loss events. The most prominent and common feature of the spring temperature for the three ozone loss events

Figure 10. As in Figure 9, but for CFSv2 predictions of the March–April air temperature at 850 hPa (t850, units: °C; shadings) anomalies following the midwinter strong stratospheric polar vortex in 2005 (top row) and 2016 (bottom row) from early February (left column) and early March (right column) initializations.
are the warm anomalies over most parts of the Eurasian continent and/or cold anomalies over Greenland and Arctic Canada (contours in Figure 9). This dipole pattern of temperature anomalies (e.g., warm Eurasia and cold North America) is reminiscent of the positive phase of the Arctic oscillation (AO) (e.g., Figure 1 in Thompson & Wallace, 1998) associated with the downward impact of the strong stratospheric polar vortex, although Stone et al. (2019) recently argued that extreme Arctic stratospheric ozone loss in March might also contribute to the lower tropospheric temperature response based on reanalysis data.

However, a skillful prediction of the Arctic ozone loss in March 2011 does not correspond to a good prediction of the lower tropospheric response (contours in Figure 9). While the predictive skill of the Arctic ozone loss in March 2011 is higher than the other two cases (section 4), the prediction of \( t_{850} \) following the 2011 ozone loss is less skillful than for the other two cases. Specifically, the prediction of the March–April mean \( t_{850} \) for the 1997 and 2020 cases is more reasonable than for 2011 for both early February (Figures 9a, 9c, and 9e) and early March (Figures 9b, 9d, and 9f) initializations. Such a paradox suggests that stratospheric ozone variation (even during ozone loss) does not necessarily lead to improved prediction of the surface.

Figure 10 shows the prediction of the March–April temperature anomalies in the lower troposphere in 2005 and 2016 as a further comparison with the three ozone loss events. The predictive skill (PCC is around 0.5–0.6) of early March initialization for those 2 years shows little difference from the three ozone loss years (cf. Figures 9b, 9d, 9f, 10b, and 10d). Although the March ozone prediction in the early February prediction is more skillful for the 2005 case than the 2016 case (Figures 5a and 5c; PCC = 0.59 and 0.16), there is no evidence for a corresponding better prediction of the lower troposphere (Figures 10a and 10c; PCC = −0.1 and 0.23). The predicted \( t_{850} \) more resembles the negative phase of AO (shading in Figures 10b and 10c) associated with the weakening of the stratospheric polar vortex in March (Figures 5e–5h), although the observed \( t_{850} \) anomaly pattern might also be modulated by other forcings. A comparison between the 2005 and 2016 cases seems to suggest once again that Arctic ozone contributes little to the predictability of the surface at least in the CFSv2 forecasting system.

### 6. Conclusions and Discussion

Since 1979, three extreme March ozone loss events have been observed with a monthly minimum of Arctic total ozone lower than 280 DU (the area-averaged ozone poleward of 60°N lower than 360 DU in Figure 1): 1997, 2011, and 2020. Unlike the Antarctic ozone hole that has formed every spring since the 1980s, an Arctic ozone loss event has happened only every one or two decades. The (maximum) predictive limit of the Arctic ozone loss and its impact on the surface predictability is unexplored in the literature. Based on the ERA5 reanalysis, observations, and seasonal forecasts by CFSv2, the meteorological backgrounds of the historical Arctic ozone loss events and their predictability by the CHEM2D-OPP scheme in CFSv2 are assessed. Empirical prediction of Arctic ozone using metrics of the stratospheric polar vortex is also visited in this study. The main conclusions are as follows.

1. Some similarities of meteorological conditions and ozone distribution are found for the three ozone loss events. (1) No midwinter SSWs happened before the March ozone loss events, which is consistent with the extremely strong polar vortex throughout the winter, as well as more days in DJF with a strong westerly jet and with extremely low temperatures that allow for PSCs to form (denoted by large \( V_{\text{pdc}} \)). (2) The final warming occurred in April for the three ozone loss events, after the ozone loss already had developed. (3) The ozone low center is mainly controlled by the simultaneous polar vortex shape: displaced toward Canada and Greenland during March 2020, symmetrically distributed about the North Pole during March 2011, and displaced toward Arctic Russia during March 1997. (4) A dipole stratospheric ozone mixing ratio anomaly pattern was found for ozone loss events, that is, the positive ozone anomaly in the tropical stratosphere is contrasted with the negative ozone anomaly in the extratropical stratosphere.

2. Differences between extreme Arctic ozone loss events are also evident. (1) The backgrounds are different for the three ozone losses, with the March 2011 ozone loss happening following a moderate cold ENSO state and a weak QBO westerly in winter. However, the ENSO and QBO were nearly neutral in the 1996/1997 and 2019/2020 winters. (2) The 2011 ozone loss event may have been more predictable than the other two due to favorable conditions for a strong stratospheric polar vortex.

3. The high autocorrelation of the March Arctic ozone with its “initial value” at a lead time of 1–2 months might suggest that a reasonable prediction can be initialized 1–2 months in advance. Therefore, the
predicted ozone losses in March 1997, 2011, and 2020 by the early March initializations in CFSv2 are in part due to such an autocorrelation. However, the predictive skill of the early February initializations varies with the case and is particularly high for 2011, which might be due to the phase of ENSO and QBO.

4. Empirical forecasts of the Arctic total ozone loss are compared for the three historical ozone loss events using different regression methods. The simple linear regression model using the polar cap height in the early February and early March initializations shows a reasonable prediction. The simple linear regression model with other metrics (e.g., $V_{PSC}$) shows a relatively lower skill. A trial of higher-order polynomial fitting and multiple regression for the Arctic total ozone suggests that their improvement relative to the simple regression method is small, and the explained variance is nearly unchanged. Although the predicted ozone losses in March 1997, 2011, and 2020 in the empirical model are comparable to the CHEM2D-OPP method in the February and March initializations, the overall skills from 1982 to 2020 are different (with the latter better).

5. A better prediction of the Arctic ozone in March does not necessarily produce extended predictability of the lower troposphere. Even as Arctic ozone loss is more skillfully forecasted in March 2011 than in 1997 and 2020, the 1850 anomaly pattern shows a larger bias in March 2011 than in 1997 and 2020 for the February and March initializations. An extended analysis of the 2005 and 2016 cases (without an ozone loss but with weakening of the stratospheric polar vortex in March) also suggests that a better prediction of the stratospheric ozone in March 2005 (compared with 2016) does not correspond to a higher predictability of the lower troposphere. It might be inferred that the Arctic stratospheric ozone variability does not directly affect the troposphere (and its predictability), at least in the CFSv2 forecast system.

The CFSv2 is among the best models at predicting the stratospheric evolution (Domeisen et al., 2020a, 2020b; Garfinkel et al., 2020; Rao et al., 2019; Rao, Garfinkel, & White, 2020; Rao, Garfinkel, White, & Schwartz, 2020; Schwartz & Garfinkel, 2020), and hence, we expect that our conclusions will be representative of other state-of-the-art models with a chemistry module. Our results are based on the seasonal forecasts, and we do not rule out the possibility of a short-term (subseasonal) effect of the extremely low springtime ozone in the Arctic on NH regional surface climate (WMO, 2018). Ivy et al. (2017) find that extreme Arctic stratospheric ozone anomalies in March are associated with the regional climate of the NH in March–April. However, the strong stratospheric polar vortex necessary for the ozone loss in the Arctic complicates the attribution of the surface response. The ozone loss might be a coupled signal with the stratospheric circulation, which intrinsically affects the surface (Harari et al., 2019). Our comparative study of the predictability of the Arctic ozone and the lower troposphere based on the forecasts by CFSv2 indicates a weak relationship.

We also find that the ozone predicted from an empirical model using model output is also skillful (but not as good as ozone actually predicted by the CHEM2D-OPP method). This implies that one can use models in the S2S archive (which do not archive ozone) to study predictability of ozone loss events. Namely, the intensity of the stratospheric polar vortex in March and $V_{PSC}$ calculated based on temperatures is a good substitute index for Arctic ozone prediction. We leave for future work a more detailed study of empirical prediction of ozone based on forecasted polar vortex metrics in S2S models in a companion paper.

**Data Availability Statement**

The authors thank the ECMWF and CPC for providing the ERA5 reanalysis (https://cds.climate.copernicus.eu) and CFSv2 forecasts (https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/climate-forecast-system-version2-cfsv2) data, respectively. The SST data are compiled by the JMA and redistributed by PSL, NOAA (https://psl.noaa.gov/data/gridded/data.cobe.html). The QBO observations are collected and updated by Berlin Free University (https://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/index.html).

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