



Planetary-Wave modulation of mesospheric and lower thermosphere nitric oxide structure and transport during major Sudden Stratospheric Warmings

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Abstract. Nitric oxide (NO) produced by energetic particle precipitation (EPP) in the polar mesosphere and lower thermosphere (MLT) can descend into the winter stratosphere, where it contributes to catalytic ozone loss and provides a pathway through which solar forcing influences middle-atmosphere composition and dynamics. Previous studies have shown that NO transport during individual sudden stratospheric warmings (SSWs) exhibits pronounced longitudinal structure associated with planetary waves (PWs), but it remains unclear whether this organization is unique to individual events or represents a recurring characteristic of Arctic SSWs. Here, we address this question using ACE-FTS NO observations, SABER temperature and geopotential height measurements, MERRA-2 meteorological fields, and specified-dynamics WACCM-X(SD) simulations for 11 major Arctic SSWs during 2006–2024. Composite analyses show that both observations and simulations exhibit coherent NO structures near 90 km that are organized by PW phase, with enhanced NO preferentially located in PW troughs and reduced NO in PW ridges, demonstrating that PW organization of mesospheric NO is a recurring feature within the analyzed event sample. This PW phase dependence extends throughout much of the 70–100 km region. Profile-derived effective NO transport rates show consistently stronger downward transport in PW troughs than in ridges for split events. In contrast, displaced-vortex SSWs exhibit smaller and more variable ridge–trough descent differences. WACCM-X(SD) qualitatively reproduces the observed behavior but underestimates the observed ridge–trough contrast for split events. These results provide a physically meaningful framework for interpreting mesospheric NO transport during major Arctic SSWs and for evaluating whole-atmosphere chemistry–climate models beyond traditional zonal-mean diagnostics.

1 Introduction

Nitric oxide (NO) produced by energetic particle precipitation (EPP) in the polar winter mesosphere and lower thermosphere (MLT) represents an important source of odd nitrogen ($\text{NO}_x = \text{NO} + \text{NO}_2$) to the middle atmosphere. During polar winter, the photochemical lifetime of NO is sufficiently long for NO-rich air to be transported downward from the MLT into the stratosphere (Bender et al., 2019; Brasseur and Solomon, 2005; Fisher et al., 1993) by the global wave-driven circulation



(Andrews et al., 1987). Once EPP-NO_x reaches the stratosphere, it can participate in catalytic ozone destruction and thereby influence net radiative heating rates, temperature, and large-scale circulation (Randall et al., 2005, 2007, 2009; Baumgaertner et al., 2011; Sinnhuber et al., 2012; Shi et al., 2024, 2025). This process, commonly referred to as the EPP indirect effect, provides a mechanism by which solar and geomagnetic forcing can affect middle-atmospheric composition and climate (Meraner and Schmidt, 2018; Calisto, 2011; Mironova et al., 2015). Recent studies further suggest that EPP-related changes in polar middle-atmospheric dynamics can couple to regional surface climate. For example, geomagnetic activity has been linked to polar vortex variability and increased wintertime electricity consumption in Finland during easterly Quasi-Biennial Oscillation (QBO) conditions (Juntunen and Asikainen, 2023). Seppälä et al. (2025) further suggested that EPP-induced mesospheric ozone loss may influence tropospheric circulation through changes in atmospheric dynamics.

Major sudden stratospheric warmings (SSWs) are among the most dramatic dynamical disturbances in the winter middle atmosphere. They are driven by the upward propagation and breaking of planetary waves (PWs), which produce rapid warming of the polar stratosphere, reverse the climatological westerly winds, and weaken the polar vortex (Scherhag, 1952; Matsuno, 1971; Butler et al., 2017; Baldwin et al., 2021). Major SSWs can strongly affect the mesosphere and lower thermosphere through changes in residual circulation, vertical coupling, tides, gravity waves (GWs), and vortex morphology (Baldwin et al., 2021; Matthias et al., 2013; Pedatella and Harvey, 2022). SSWs modify the descent and redistribution of EPP-produced NO (Siskind et al., 2010; Limpasuvan et al., 2016).

Many previous studies of NO descent during SSWs have relied primarily on zonal-mean diagnostics (e.g., Funke et al., 2017; Jackman et al., 2014; Pérot et al., 2014; Pérot and Orsolini, 2021; Randall et al., 2007, 2009; Orsolini et al., 2017; Hendrickx et al., 2018; Siskind et al., 2007). Zonal averages are valuable for describing the net descent of NO-rich air, but they obscure pronounced longitudinal structure associated with large PWs that are present when the polar vortex is disturbed. Several single-event and case-study analyses have shown that NO enhancements can be highly zonally asymmetric (Salmi et al., 2011; Siskind et al., 2021; Harvey et al., 2021b) and are related to vortex position, PW phase, and coherent transport structures (Newnham et al., 2018; Harvey et al., 2019). These results suggest that a three-dimensional framework is necessary for interpreting MLT NO evolution during dynamically disturbed winters.

A comprehensive study that examines whether PW organization of NO is a recurring feature across multiple Arctic SSWs has not yet been conducted. Moreover, it has yet to be established the extent to which NO structure and transport differ between split and displaced vortex SSWs. Vortex split and displacement event types represent distinct vortex morphologies and PW geometries (Charlton and Polvani, 2007; Butler et al., 2017; Butler and Domeisen, 2021). Split events are commonly associated with strong wave-2 structure and substantial vortex deformation, whereas displaced events are dominated by wave-1 growth and displacement of the vortex from the pole (Charlton and Polvani, 2007; Bancala et al., 2012; Matthias et al., 2016; Lee et al., 2025; Butler and Domeisen, 2021). These different configurations likely alter the location of NO-rich air relative to polar darkness, the degree of confinement, and transport of NO to the stratosphere.

The goal of this study is to examine how PW phase and vortex morphology modulate mesospheric NO structure and transport during major SSWs. The main contribution is a multiple-event composite analysis that separates split and displaced vortex SSWs and diagnoses NO structure using both satellite observations and the specified dynamics (SD) version of the Whole



Atmosphere Community Climate Model with thermosphere and ionosphere eXtension (WACCM-X(SD)). This approach extends previous single-event and zonal-mean studies by organizing NO in a PW phase framework, in which NO distributions are interpreted relative to PW ridges and troughs rather than in geographic coordinates or zonal averages. By comparing the Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS) and Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) observations with WACCM-X simulations, we assess whether the observed PW-NO relationship is reproduced by the model for both split and displaced vortex morphologies. We then derive the effective NO transport rates in PW ridge and trough sectors using observed and simulated NO profiles and contrast the strength of NO transport between two sectors. We also compare the effective NO transport rates to the large-scale zonal mean circulation. By combining PW-phase composites, event-type separation, model-observation comparisons, and a model-based sensitivity test, this study provides a three-dimensional framework for interpreting NO redistribution during dynamically disturbed winters and for evaluating model representation of EPP-related NO transport.

The paper is organized as follows. Section 2 describes the data and methods. Section 3 presents the dynamical context, NO structure and transport during both split and displaced events. Section 4 is the discussion. Section 5 summarizes the main conclusions.

2 Data and Methods

2.1 MERRA-2

The Modern-Era Retrospective Analysis for Research and Applications, version 2 (Gelaro et al., 2017, MERRA-2), is a global atmospheric reanalysis produced by the NASA Global Modeling and Assimilation Office using the Goddard Earth Observing System, version 5 (GEOS-5). MERRA-2 covers the period from 1980 to the present and assimilates a wide range of observations to provide three-dimensional meteorological fields with a horizontal resolution of $0.5^\circ \times 0.625^\circ$ and 72 model levels extending from the surface to 0.01 hPa. In this study, MERRA-2 zonal wind and temperature are used to define SSW onset dates and to characterize the large-scale dynamical evolution of each event.

2.2 WACCM-X(SD)

WACCM-X is a whole-atmosphere chemistry–climate model extending from the surface to approximately 500–700 km altitude (Liu et al., 2018). The physical parameterizations are described by Marsh et al. (2013), Gettelman et al. (2019), and Neale et al. (2013), and the thermosphere–ionosphere extension is described by Liu et al. (2010a). The model includes the major chemical and photochemical processes relevant to MLT composition, including thermospheric NO production by auroral processes and subsequent NO transport.

We use the SD configuration of WACCM-X, hereafter WACCM-X(SD). In this configuration, temperature and horizontal winds below approximately 50 km are relaxed toward MERRA-2. This nudging constrains the troposphere and stratosphere, enabling the model to reproduce the timing and large-scale PW forcing associated with the observed SSW events listed in



Table 1. Above the nudging region, the model evolves freely; therefore, the phase and amplitude of PWs in the upper mesosphere and lower thermosphere are not directly constrained by observations and are evaluated by comparison with independent satellite measurements.

The simulations analyzed here span 2005–2024 and include all 11 major SSW events considered in this study. Model output is available every 3 h on a $1.9^\circ \times 2.5^\circ$ latitude–longitude grid. The model vertical resolution follows the standard WACCM configuration below 0.96 hPa and increases to approximately one-quarter scale height above that level. For comparisons with ACE-FTS, WACCM-X(SD) NO is sampled at the corresponding ACE-FTS latitude, longitude, altitude, and time where possible.

2.3 SABER

The Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument is a 10-channel limb-scanning broadband radiometer aboard NASA's Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite, launched in December 2001 (Russell et al., 1999). SABER alternates between northward- and southward-viewing yaw cycles approximately every 60 days, providing latitude coverage from about 83°N to 52°S and from 52°N to 83°S , respectively. SABER geopotential height (GPH) is derived from retrieved temperature and pressure profiles under the assumption of hydrostatic balance. The vertical resolution is approximately 2 km. Typical single-measurement random temperature errors are less than 0.5 K below 55 km, 1–2 K in the mesosphere, and about 7 K at higher altitudes. Systematic errors are less than 1.5 K below 75 km, about 4 K near 85 km, and about 5 K near 100 km (Remsberg et al., 2008; García-Comas et al., 2008). In this study, SABER Level 2A version 2.0 temperature and GPH are used to evaluate PW structures simulated by WACCM-X(SD), especially in the stratosphere and MLT.

2.4 ACE-FTS

The Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS) is a solar occultation instrument aboard the Canadian SCISAT satellite, launched in 2003 (Bernath et al., 2005). ACE-FTS measures infrared absorption spectra over a broad spectral range and retrieves vertical profiles of temperature, pressure, density, and numerous atmospheric trace gases from the upper troposphere to the lower thermosphere (10–150 km). We use ACE-FTS version 5.3 NO volume mixing ratio (VMR) retrievals. These retrievals have a typical vertical resolution of 3–4 km in the mesosphere. Reported NO retrieval uncertainties are approximately 80% near 60 km, with generally improved sensitivity at higher NO abundances (Boone et al., 2013; Sheese et al., 2016). During boreal winter, ACE-FTS samples high northern latitudes with approximately 15 occultation profiles per day distributed around a near-constant latitude circle. Although the daily sampling is sparse, the longitudinal distribution of profiles is well-suited for identifying PW-scale zonal asymmetries.



2.5 Analysis methods

2.5.1 SSW event selection and classification

Major SSWs are defined by the reversal of the zonal-mean zonal wind from westerly to easterly at 60° N and 10 hPa. The 11 major Arctic SSWs analyzed here occur between 2006 and 2024, yielding the five split and six displacement events listed in Table 1. SSW onset dates and coincident elevated stratopause (ES) occurrence are also noted in this study (Limpasuvan et al., 2016; Harvey et al., 2025).

Table 1. Major SSW events included in this study.

Number	Year	SSW onset day	Vortex type	Elevated stratopause
1	2006	21 Jan	Displacement	with ES
2	2007	24 Feb	Displacement	no ES
3	2008	22 Feb	Displacement	no ES
4	2009	24 Jan	Split	with ES
5	2010	09 Feb	Split	no ES
6	2013	06 Jan	Split	with ES
7	2018	12 Feb	Split	no ES
8	2019	02 Jan	Split	with ES
9	2021	05 Jan	Displacement	no ES
10	2023	16 Feb	Displacement	no ES
11	2024	16 Jan	Displacement	no ES

2.5.2 PW ridge/trough sampling

To investigate the relationship between mesospheric NO and PW phase, NO is sampled relative to dynamically defined PW ridge and trough sectors rather than fixed geographic longitudes. PW phase is diagnosed using eddy geopotential height (GPH), defined as

$$G'(\lambda, \phi, z, t) = G(\lambda, \phi, z, t) - \overline{G}(\phi, z, t) \quad (1)$$

where G is GPH, $\overline{G}$ is its zonal mean, and λ , ϕ , z , and t denote longitude, latitude, altitude, and time, respectively. Positive G' values correspond to the PW ridge sector, whereas negative G' values correspond to the PW trough sector.

For the observational analysis, G' is derived from SABER GPH interpolated to the ACE-FTS measurement latitudes on each day. ACE-FTS NO profiles are then classified relative to the observed SABER PW phase. For the model analysis, G' is calculated from WACCM-X(SD) GPH interpolated to the ACE-FTS measurement latitudes on each day, and the corresponding WACCM-X(SD) NO field is likewise classified using the simulated PW phase. This approach evaluates whether the model



reproduces both the observed PW dynamics and the observed NO patterns, providing a simultaneous assessment of model
135 dynamics and chemistry. Throughout Sections 3.2–3.3, WACCM-X(SD) eddy GPH and NO are sampled at the ACE-FTS
latitudes, longitudes, and times. Analysis in fixed latitude bins is used only for the sensitivity test in Section 3.4.

For analyses of the vertical NO structure and descent, PW ridge and trough locations are identified independently at each
altitude and time. NO is then sampled at these altitude-dependent locations to construct separate ridge and trough profiles. By
allowing the PW phase to vary with altitude, this approach explicitly accounts for vertical PW phase tilts.

140 2.5.3 PW phase alignment for composite fields

To examine the vertical PW structure and its relationship to mesospheric NO, we analyze the eddy-GPH and NO fields in a
PW-reference longitude coordinate. Because the geographic longitude of the PW pattern differs among events, compositing
the fields in geographic coordinates would obscure PW structures. To retain PW structures, geographic longitude is replaced
with a PW-phase reference coordinate that extends from -180° to $+180^\circ$. For each event and dataset, 0° reference longitude is
145 defined as the longitude of the primary PW trough (the absolute minimum in G'), at 10 hPa on Day 0. Day 0 is the SSW onset
day given in Table 1. Because the observed and simulated PW structures are evaluated independently, the reference longitude
is identified separately from the SABER and WACCM-X(SD) eddy GPH fields for each event.

For each dataset, the longitude shift that places its primary trough at 10 hPa to be at 0° is applied uniformly to eddy-GPH
and NO fields at all altitudes and analysis times. This approach preserves the temporal evolution of NO relative to the PW
150 structure established at SSW onset while removing event-to-event differences in the geographic longitude of the PW pattern.
The resulting phase-aligned fields are subsequently composited separately for split- and displaced-vortex SSWs.

2.5.4 Profile-derived effective NO transport rate

To quantify the apparent vertical displacement of NO and assess its dependence on PW phase, we estimate profile-derived
effective transport rates from changes in the altitude of fixed NO volume mixing ratio (VMR) levels before and after SSW
155 onset. Similar isopleth-tracking approaches have been used to estimate effective tracer ascent and descent rates in the middle
atmosphere (Ryan et al., 2018; Schranz et al., 2019; Harvey et al., 2021a; Shi et al., 2023).

For each event and PW sector, a baseline NO profile is constructed by averaging the ridge- or trough-sampled profiles from
Day -30 to Day -20. A post-onset profile is constructed by averaging the corresponding profiles from Day +10 to Day +20. The
same procedure is applied to ACE-FTS and to WACCM-X(SD) sampled at the corresponding ACE-FTS locations and times.
160 The profile-derived effective NO transport rate, w_{eff} is computed from the vertical displacement of fixed NO VMR levels
between the pre- and post-onset mean profiles, divided by the time separating the midpoints of the two averaging windows:

$$w_{eff}(NO) = \frac{z_{post}(NO) - z_{pre}(NO)}{t_{post} - t_{pre}} \quad (2)$$

Negative w_{eff} values denote effective descent of NO isopleth, whereas positive w_{eff} values denote effective ascent. The
rates are first calculated separately for each event, dataset, and PW sector; the events are subsequently grouped into split- and
165 displaced-vortex categories.



Because w_{eff} is derived from tracer displacement, it reflects the combined effects of vertical and horizontal advection, resolved and unresolved mixing, chemical production and loss, and changes in observational sampling. Thus, w_{eff} characterizes the effective ascent and descent rates but does not isolate the physical vertical motion of air. Potential uncertainties arise from ACE-FTS retrieval uncertainty, sparse sampling, event-to-event variability, vertical interpolation, and the selection of the averaging windows. To characterize the tracer-derived descent rates in the context of the large-scale circulation, we additionally examine WACCM-X(SD) zonal-mean residual vertical velocity $\bar{w}^*$, interpolated to the corresponding time-varying ACE-FTS sampling latitudes.

3 Results

3.1 Dynamical context and model evaluation

Before examining the evolution of mesospheric NO, we first establish the dynamical context of the 11 major Arctic SSWs and evaluate how well WACCM-X(SD) reproduces the large-scale circulation associated with these events. Figure 1 shows that all events satisfy the major SSW criterion, with the zonal-mean zonal wind at 60°N and 10 hPa reversing from westerly to easterly near Day 0 (top left panel). The temperature response shows rapid warming around onset (bottom left panel). Although all events meet the major SSW definition, their subsequent evolution differs systematically. Split events (middle column) show a more abrupt vortex disruption and a more persistent post-onset wind reversal, whereas displaced events (right column) show wind reversal over a deeper layer and more rapid recovery in the lower stratosphere. These contrasting dynamical evolutions provide the basis for treating split and displaced events separately throughout the remainder of this study.

Figure 2 compares polar temperature anomalies and GPH fields at 10 hPa from SABER and WACCM-X(SD) in geographic coordinates for the split and displaced composites. At 10 hPa, WACCM-X(SD), which is nudged to MERRA-2 at this altitude, closely reproduces the observed large-scale dynamical structure. Both datasets capture the expected warm polar temperature anomaly and distinct vortex configuration associated with the two event types, with a dominant wave-2 structure during split events and a wave-1 displacement during displaced events. Temperature differences are small ($<2\text{K}$ and GPH differences are $<500\text{ m}$), consistent with the good agreement between the observations and the model at this altitude. Figure 2 gives the lower-stratospheric dynamical context for the split and displaced composites and the high level of agreement between the model and the observations defends using this altitude to define the event-specific PW reference longitudes given in Sect. 2.5.3. Note, no longitudinal phase shifting is applied in Figure 2.

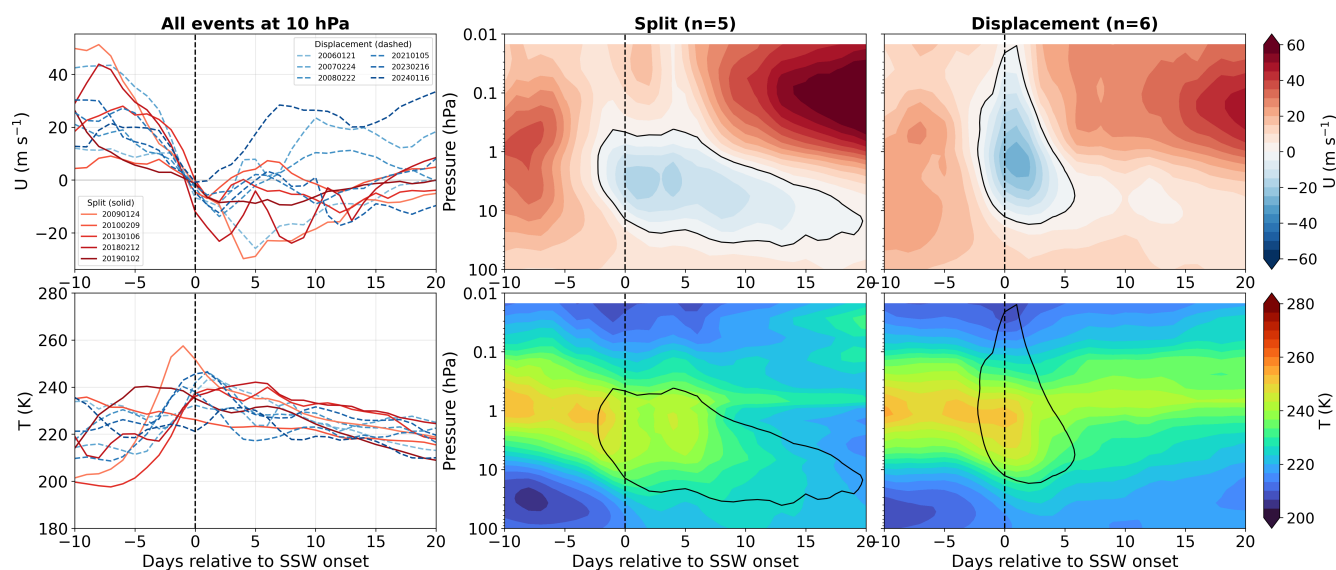


Figure 1. Dynamical evolution of the 11 major SSW events analyzed in this study. The left panels show the zonal-mean zonal wind at 60°N and temperature over $60\text{--}90^\circ\text{N}$ at 10 hPa relative to SSW onset from MERRA-2. The middle and right panels show composite pressure-time sections of zonal-mean zonal wind and polar temperature for split and displaced events, respectively. The vertical black dashed line marks the SSW onset day. The black contour denotes the zero zonal-wind line.

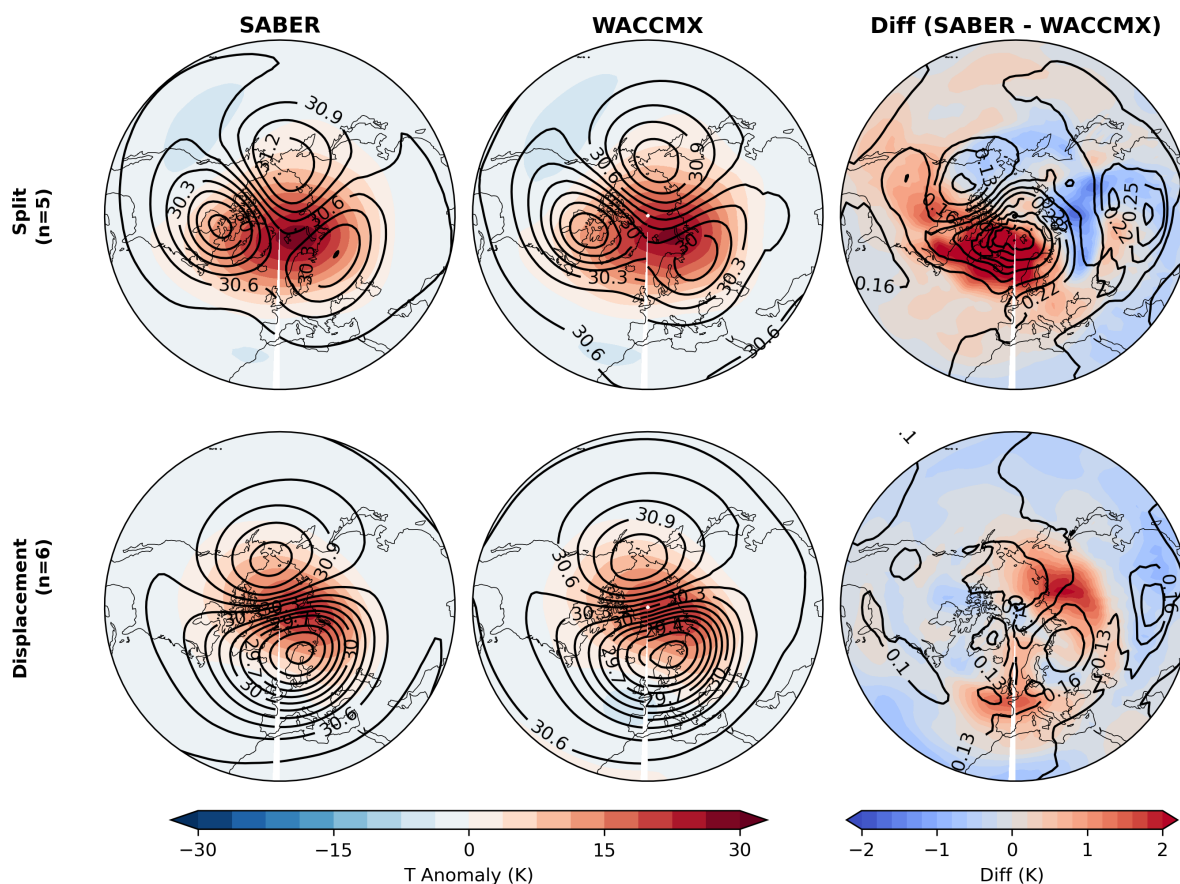


Figure 2. Composite polar temperature anomalies (color) and geopotential height (km, contours) at 10 hPa from SABER (left) and WACCM-X(SD) (middle) for split-vortex (top) and displaced-vortex (bottom) events, averaged from Day -5 to Day +5 relative to each SSW onset date. Shading indicates temperature anomalies, and contours indicate geopotential height. The difference panels on the right show SABER minus WACCM-X(SD), shading indicates temperature differences, while contours show GPH differences, with solid (dashed) contours denoting positive (negative) values.

Figure 3 presents the split and displaced composite altitude vs. reference longitude structure of eddy GPH. By definition, the primary trough at 10 hPa is centered at 0°. In both split and displaced composites, the eddy GPH anomalies tilt westward with height between 30 and 100 km, consistent with vertically coupled PW structures across the stratosphere and mesosphere (Charney and Drazin, 1961). The displaced-event composites exhibit a comparatively smooth and vertically coherent shift of the trough–ridge pattern with height. For both split and displaced composites, largest differences between SABER and WACCM-X(SD) occur near the mesopause. In the split SABER composite, the PW phase reverses over a relatively shallow layer between 90 and 100 km, with the eddy GPH anomalies changing sign with altitude. WACCM-X(SD) does not reproduce this rapid phase reversal, instead showing a more vertically continuous PW structure through this region. This difference in vertical PW phase structure results in substantial model–observation differences from 90–100 km.

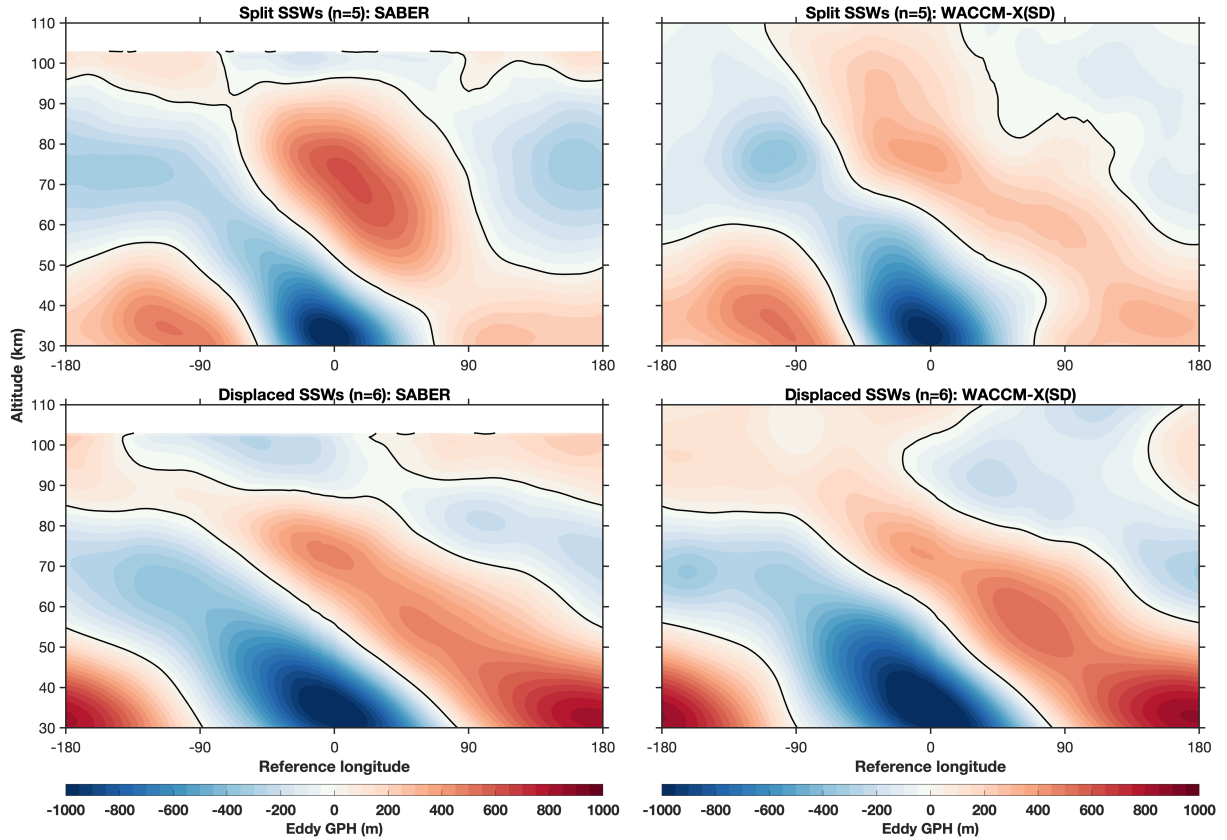


Figure 3. Phase-aligned composite altitude vs. reference longitude sections of eddy GPH for split and displaced SSW from SABER (left) and WACCM-X(SD) (right), averaged from Day -5 to Day +5 relative to SSW onset. For each event and dataset independently, the fields are shifted using the event-specific reference longitude defined in Sect. 2.5.3. Red and blue shading denote ridge and trough sectors, respectively; black contours denote $G' = 0$.

The large model–observation differences near 90 km can be further understood by examining their spatial structure. Figure 4 shows the split and displaced composite temperature anomalies and GPH fields near 90 km in the Northern Hemisphere, revealing how these differences are distributed in longitude and latitude. At this altitude the model is free-running and the circulation is increasingly influenced by tides, GWs, and vertically propagating PWs. Thus, reproducing the observed dynamical structure at this altitude represents a more stringent test of the model than in the lower stratosphere. Significant differences are evident in the amplitude and spatial distribution of the temperature anomalies and especially the GPH fields. For example, for both the split and displaced composites, SABER shows a circumpolar low while WACCM-X(SD) shows strong planetary wave patterns in GPH. For the split composite, SABER shows a -8 K temperature anomaly over Alaska, likely a signature of mesospheric cooling, that is underestimated by a factor of 2 in the model. These discrepancies indicate that the model does not fully reproduce the observed dynamical structure at this altitude. The level of disagreement at this altitude underscores the importance of continued, careful model evaluation in the MLT.

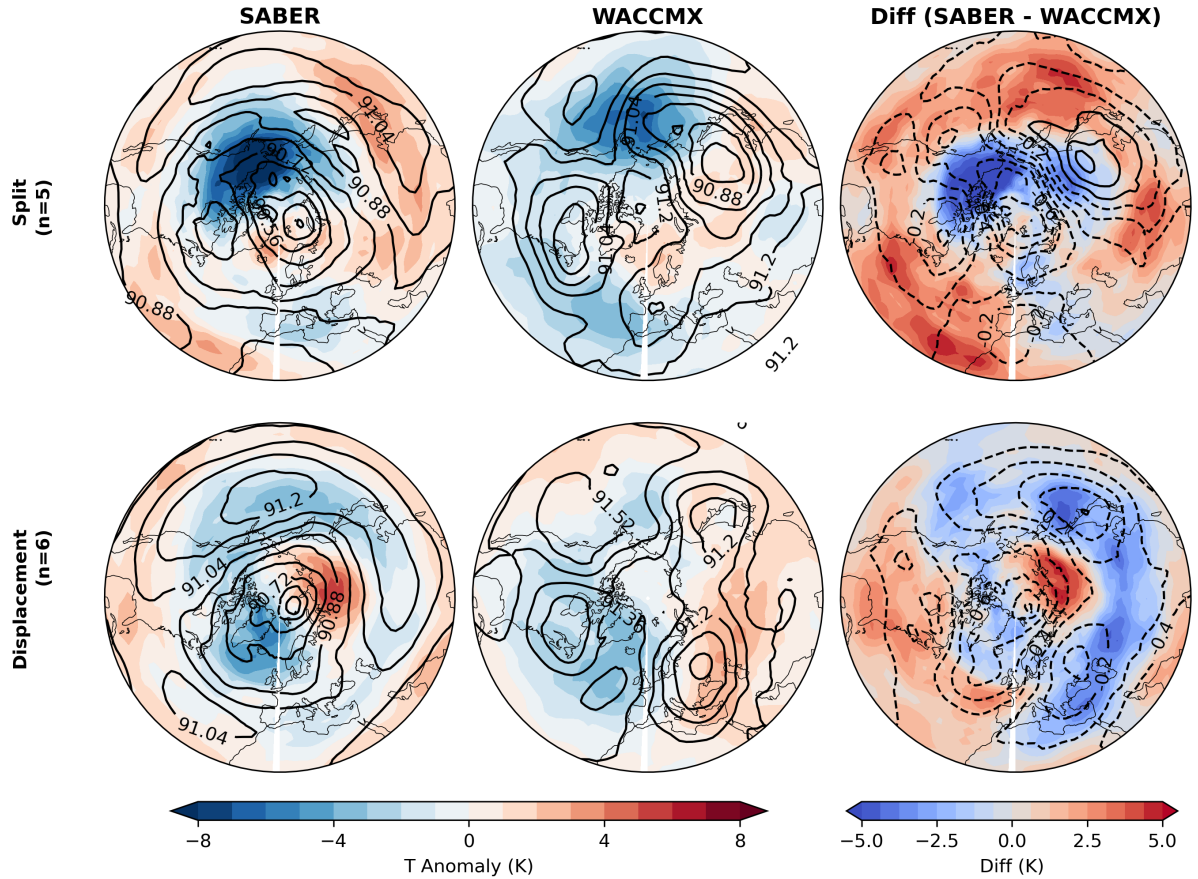


Figure 4. Same as Figure 2, but near the mesopause at 0.001 hPa.

3.2 NO spatial structure modulated by PWs

Having established the dynamical state of the composite SSWs and the corresponding PW structure, we now examine the temporal evolution of mesospheric PWs and NO near 90 km to determine whether NO exhibits a consistent relationship with
 215 PW phase across multiple SSW events. Event-by-event longitude–time Hovmöller diagrams show that NO near 90 km is not zonally uniform during major SSWs but instead exhibits pronounced longitudinal organization associated with the planetary-wave field (Figure 5, see Figure A1 for shifted plots). In both the observations and WACCM-X(SD), enhanced NO is generally located in PW troughs, where eddy GPH is negative, whereas lower NO occurs preferentially in PW ridges, where eddy GPH is positive. Although the amplitude, timing, and spatial coherence of the NO enhancements vary among individual events, the
 220 overall relationship between PW phase and NO is remarkably consistent.

Because the geographic longitude of the PW pattern differs from event to event, composites constructed in fixed geographic coordinates obscure coherent NO structures. Therefore, to preserve the recurring PW-NO relationship we apply a longitude shift to each event as described in Sect. 2.5.3. Therefore, the x-axes in Figure 6 are reference longitude rather than geographic



longitude. The eddy-GPH pattern on Day 0 in Figure 6 is consistent with the 90 km altitude level in Figure 3. In particular, the displacement of the mesospheric trough away from the 0° lower-stratospheric reference reflects the vertical PW phase tilt identified in the altitude–longitude composites. These phase-aligned composites reveal a clear and persistent preference for enhanced NO to reside within PW troughs for both split and displaced events. These composites demonstrate that the PW organization of mesospheric NO identified by Harvey et al. (2021b) for the 2009 SSW is not unique to a single event but is a recurring feature of major Arctic SSWs.

WACCM-X(SD) reliably reproduces the relationship between PW phase and NO, with enhanced NO occurring preferentially within PW troughs for both split and displaced events. Although the simulated NO structures are generally smoother and exhibit a weaker ridge–trough contrasts than observed by ACE-FTS, the model captures the same overall PW organization of NO. The qualitative agreement indicates that WACCM-X(SD) reproduces the preferred NO location relative to its own simulated PW structure, despite the PW structure deviating from observations (as seen in Figures 4 and 5). The weaker NO gradients in WACCM-X(SD) may reflect a combination of model resolution, uncertainties in NO production and loss, and imperfect representation of tides, PWs, GWs, and small-scale transport processes.

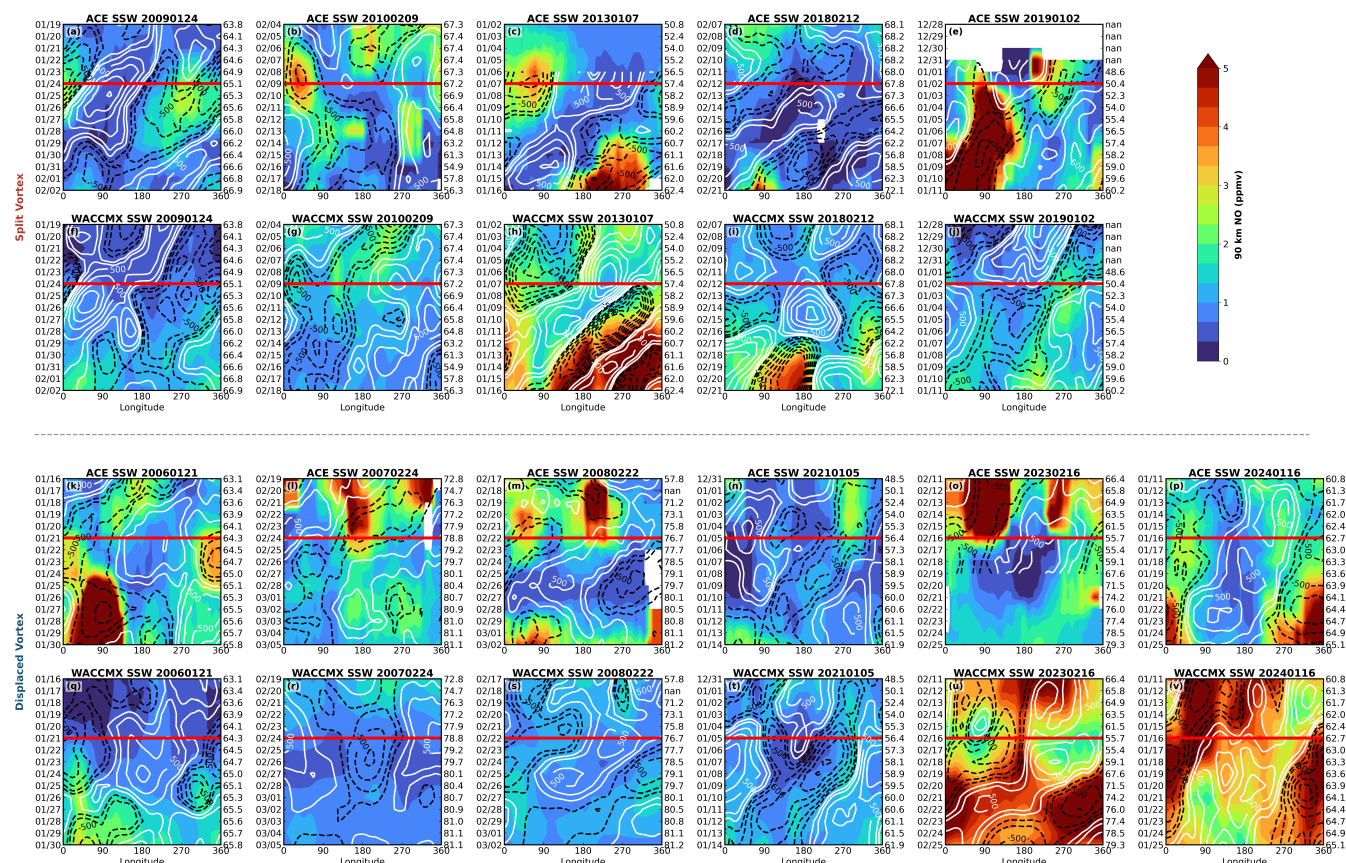


Figure 5. Event-by-event longitude-time Hovmöller diagrams of NO VMR (color) and eddy GPH (contour) near 90 km for split (top two rows) and displaced SSWs (bottom two rows). ACE-FTS NO is shown with SABER-derived eddy GPH. WACCM-X(SD) NO is sampled at ACE-FTS locations and shown with WACCM-X(SD)-derived eddy GPH. The ACE-FTS sampling latitude is listed on the right-hand side of each panel. Time is referenced to the SSW onset day, marked by the red horizontal lines.

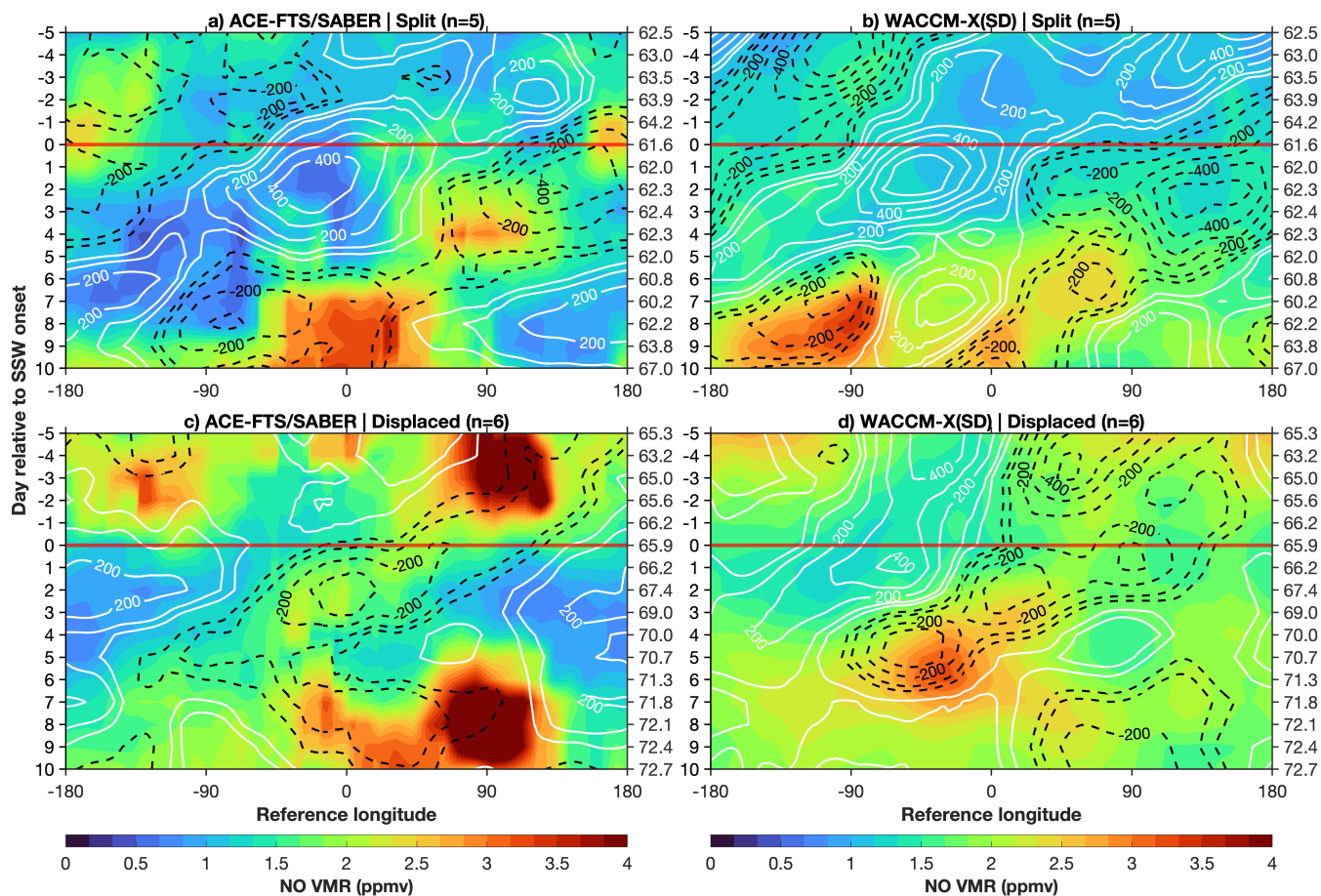


Figure 6. Phase-aligned composite reference longitude-time Hovmöller diagrams of NO VMR (color) and eddy GPH (contours) near 90 km for split (top panels) and displaced (bottom panels) SSWs in the observations (left column) and simulations (right column). Eddy GPH and NO fields have been shifted relative to the longitude of the primary PW trough at 10 hPa on Day 0 (see text for details).

3.3 PW modulation of effective NO transport rates

The analyses presented above focused on the longitudinal organization of NO near 90 km. We now examine whether this PW organization of NO extends throughout the entire mesosphere and whether it is associated with systematic differences in NO transport between PW phase and SSW type.

To place the subsequent PW-phase analysis in a broader vertical context, Figure 7 first shows the composite evolution of NO VMR from 30 days before to 30 days after SSW onset for split and displaced events in ACE-FTS and WACCM-X(SD). These composites are constructed using all available ACE-FTS data, with WACCM-X(SD) sampled at the corresponding time-varying ACE-FTS latitudes. The ACE-FTS sampling latitude varies throughout the 60-day analysis period, generally ranging from approximately 50–68°N before SSW onset and shifting poleward around and after SSW onset, often reaching 80–83°N. In all composites, NO increases with altitude, and the NO contours shift downward after onset, consistent with the descent



of NO-rich air from the upper mesosphere. For split events, ACE-FTS and WACCM-X(SD) are in good agreement, and both show a coherent post-onset descent signal, with notably strong descent between days +20 and +30. Because three of the five the split events also include an ES, this strong descent is likely driven, to some extent, by GWs that are also responsible for
250 ESs (e.g., Randall et al., 2009; Limpasuvan et al., 2016).

For displaced events, the ACE-FTS composite shows pronounced post-SSW descent, with the NO contour lines descending by approximately 2.5–5 km during the first two weeks following SSW onset. WACCM-X(SD) captures the overall downward evolution of NO but substantially underestimates its magnitude, with the corresponding contours descending by approximately 1 km or less over the same period. This approximately fivefold underestimate in mesospheric descent is consistent with Randall
255 et al. (2015), who found that modeled NO descent was substantially weaker than observed during the displaced 2004 SSW event with ES. These composite values mask substantial variability among individual events. In addition, before SSW onset the displaced-event composites also show higher NO abundances across much of the 60–100 km region than the split-event composites (white contours are at lower altitudes). These differences in the pre-onset NO distribution affect both the magnitude and interpretation of profile-derived effective NO transport rates calculated below.

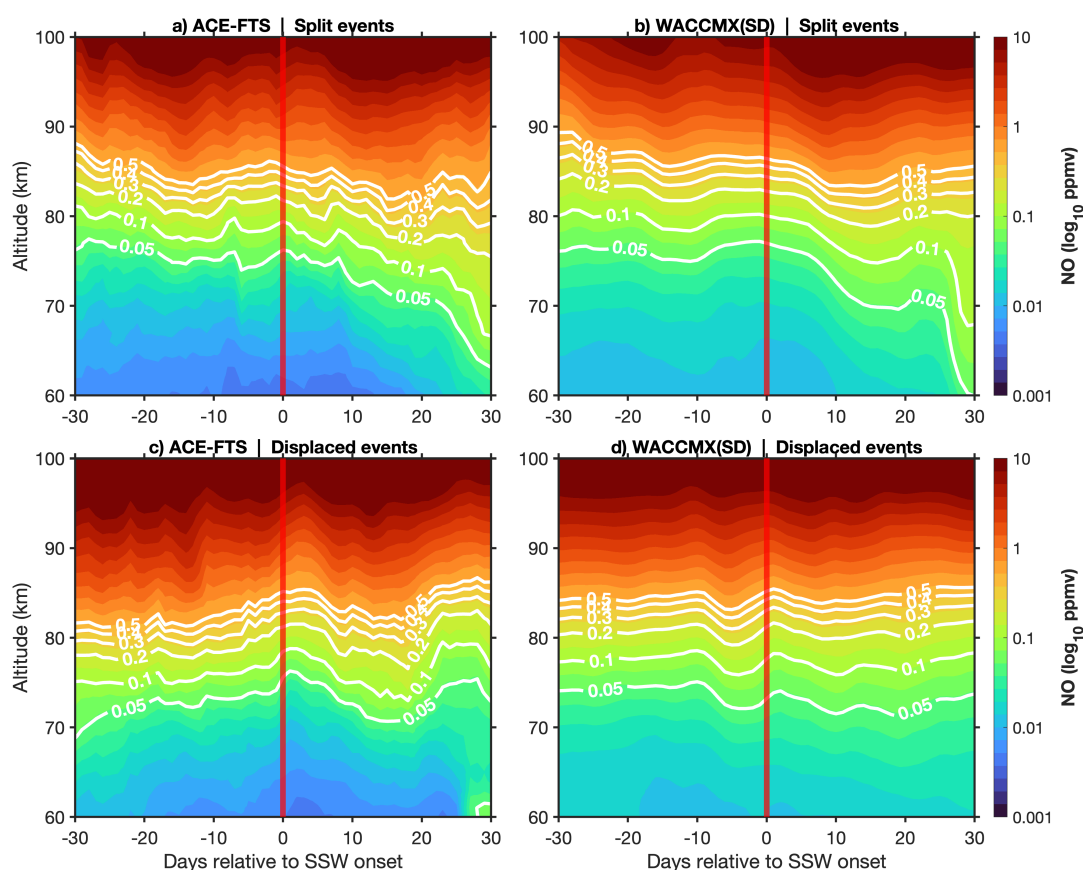


Figure 7. Composite altitude-time evolution of NO VMR during split and displaced SSW events from ACE-FTS (left panel) and WACCM-X(SD) (right panel). Colors indicate NO volume mixing ratio on a logarithmic scale, and white contours mark selected NO isopleths.



260 Next, we provide a quantitative comparison of composite NO profiles in PW ridge and trough sectors to evaluate how well WACCM-X(SD) reproduces observations. Composite NO profiles (Figure 8) show that NO concentrations increase with altitude for both split and displaced events and in both PW sectors. WACCM-X(SD) reproduces the overall vertical structure of the NO profiles, including the increase of NO with altitude. However, relative to ACE-FTS observations, the model systematically underestimates (by 50-100%) NO abundances in the trough sector and overestimates (by 25-50%) NO in the ridge sector, particularly between 75 and 90 km. Consistent with NO fields in Figure 6, these biases in the ridge and trough sectors produce weaker ridge-trough contrasts than observed by ACE-FTS.

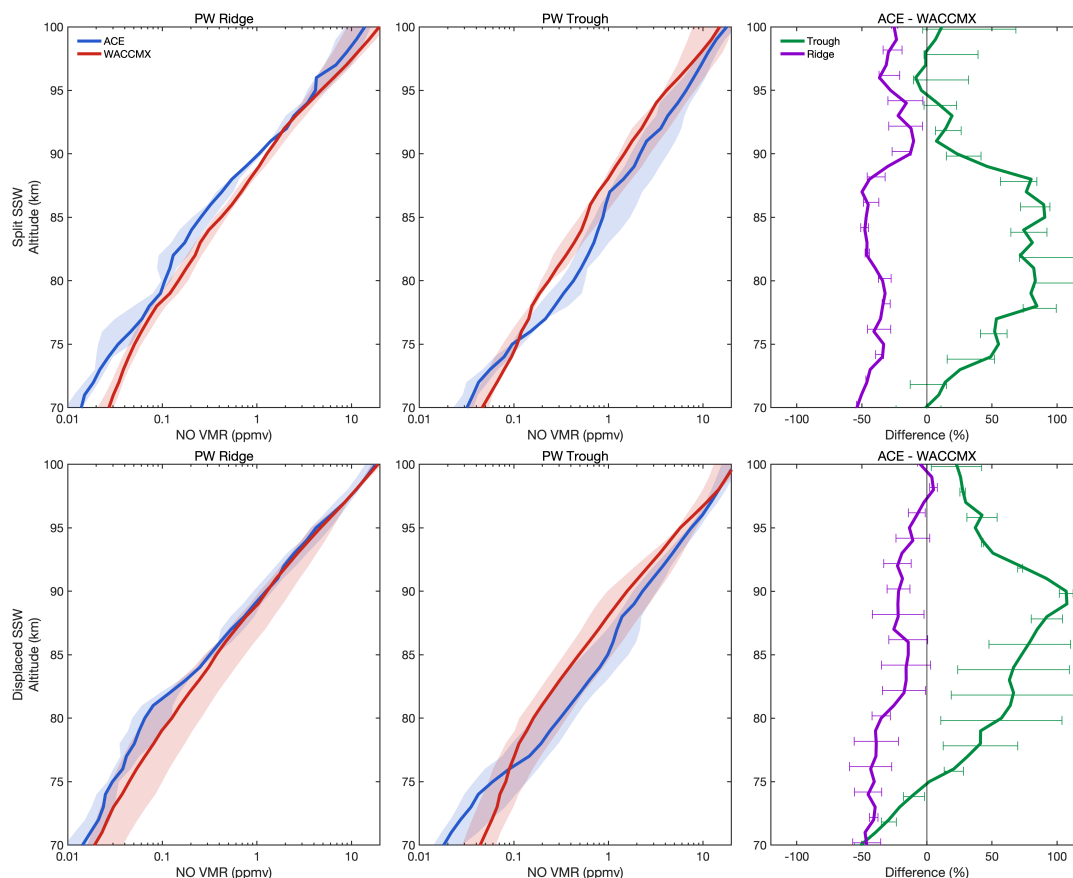


Figure 8. Composite NO profiles at the altitude-dependent PW ridge (left column) and trough (middle column) sectors after onset from Day 0 to Day +20 for split (top panels) and displaced (bottom panels) SSWs. Blue lines indicate ACE-FTS and red lines indicate WACCM-X(SD). Shading shows the interquartile range in log (NO) space. Difference panels (right column) show ACE-FTS minus WACCM-X(SD) relative differences; horizontal bars indicate the interquartile range.

To quantify NO transport, profile-derived effective NO transport rate, w_{eff} , is estimated from the displacement of NO profiles between the pre-onset (Day -30 to Day -20) and post-onset (Day 10 to Day 20) time windows, as described in Section



2.5.4. Because this diagnostic tracks the displacement of NO profiles, it should be interpreted as an estimated tracer transport rate rather than as a direct estimate of vertical wind.

For split events (Figure 9), w_{eff} is predominantly negative throughout the 70-90 km region in both ACE-FTS and WACCM-X(SD) PW ridges and troughs, indicating apparent downward transport of NO-rich air relative to the pre-onset time. Considerable event-to-event variability is evident in both the observations and the model. Nevertheless, all individual events exhibit stronger effective descent in the PW trough than in the PW ridge, with trough-sector NO descent that is 2-5 times stronger than in the ridge sector. This results in composite w_{eff} profiles that show an approximately 4-fold increase in NO descent in the trough than in the ridge in both ACE-FTS and WACCM-X(SD), although WACCM-X(SD) generally underestimates the magnitude of the observed ridge–trough difference, especially in the upper mesosphere above 80 km.

For displaced events (Figure 10), w_{eff} for individual events often spans both positive and negative values in both ACE-FTS and WACCM-X(SD) PW ridges and troughs, resulting in composite profiles that remain close to zero through much of the 75-90 km region. While some individual events exhibit stronger effective descent (or weaker effective ascent) in the PW trough than in the ridge, the opposite behavior also occurs, and w_{eff} frequently changes sign with altitude within a given event. As a result, these event-to-event and altitude-dependent variations largely cancel in the composite, producing ridge and trough profiles that remain close to zero through much of the 75–90 km region and show no vertically consistent ridge–trough contrast. The PW-phase dependence of effective NO transport rates therefore appears highly variable for displaced events, with complex vertical structure that cannot be characterized reliably from the present sample. A substantially larger event set is required to determine whether systematic PW-phase relationships emerge for displaced SSWs.

The smaller negative or positive w_{eff} values during the displaced events are also influenced by the pre-onset NO distribution. As shown in Figure 7, the displaced-event composite contains enhanced NO in the mesosphere before SSW onset compared with the split-event composite. Consequently, the displacement between pre- and post-onset profiles is reduced, producing smaller effective w_{eff} values even in the presence of large-scale descent. Thus, the contrast between split and displaced events reflects differences in NO preconditioning and the subsequent dynamical evolution.

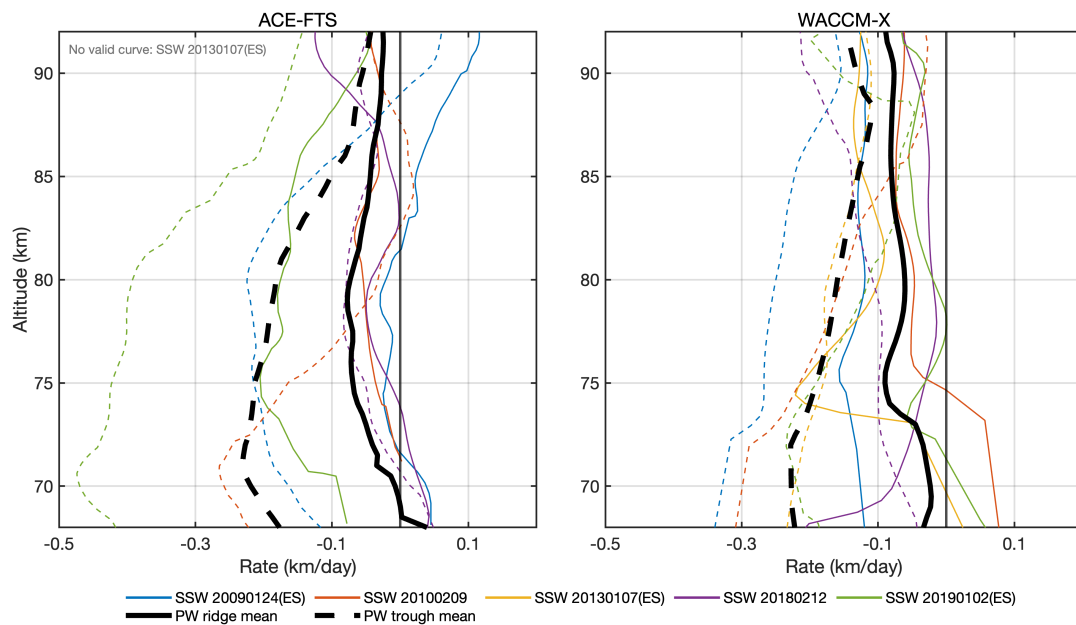


Figure 9. Split event composite (thick black) and individual event (color) profile-derived effective NO transport rate, w_{eff} from ACE-FTS (left) and WACCM-X(SD) (right). Solid and dashed lines show rates derived from NO profiles in PW ridge and trough sectors, respectively.

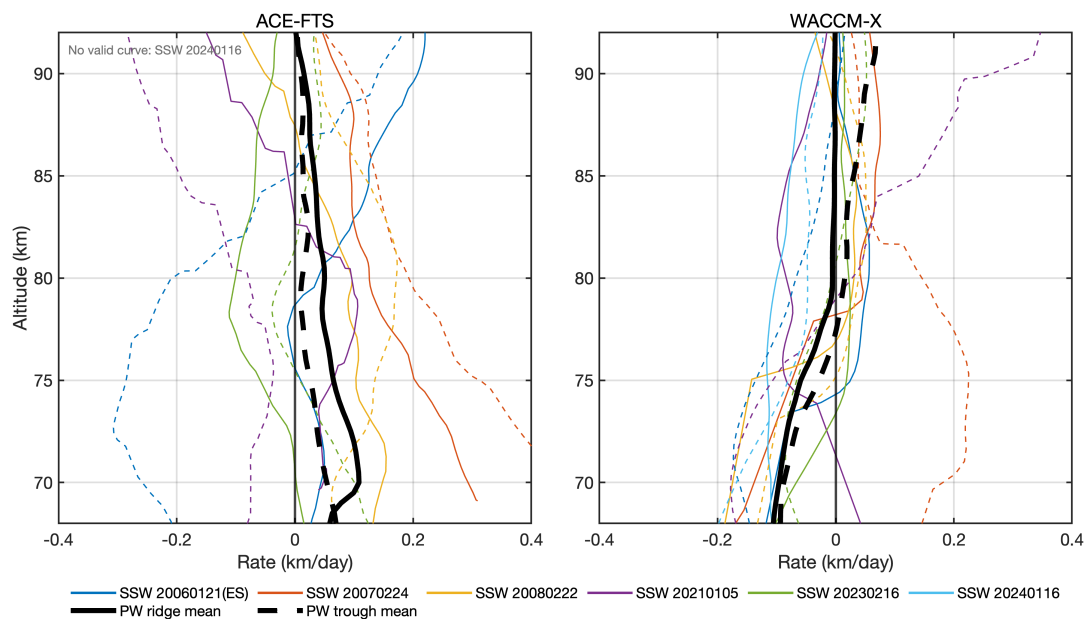


Figure 10. Same as Fig. 9, but for displaced SSWs.

Figure 11 places the event-to-event profile-derived effective NO transport rates in the context of the zonal-mean residual circulation sampled at the ACE-FTS latitudes. For each day during each event $\bar{w}^*$ is interpolated to the corresponding ACE-



FTS sampling latitudes; it is then averaged from 70-90 km and from Day -25 to Day +15. The averaging interval corresponds
295 to the period between the midpoints of the two profile windows used to derive w_{eff} . The sampled $\bar{w}^*$ is negative during
every event, indicating zonal mean residual-circulation descent. The profile-derived w_{eff} and residual vertical velocity $\bar{w}^*$
are fundamentally different diagnostics and are therefore not expected to agree quantitatively. Whereas $\bar{w}^*$ represents the
zonal-mean residual circulation, w_{eff} is inferred from changes in NO profiles and can be influenced by vertical and horizontal
advection, mixing, and chemical production and loss. Differences between w_{eff} and $\bar{w}^*$ therefore do not indicate disagreement
300 between two estimates of the same vertical motion. Instead, they show that changes in NO profiles cannot be interpreted in
terms of zonal-mean vertical motion alone. Determining the relative contributions of vertical transport, horizontal transport,
mixing, and chemistry would require a three-dimensional NO tendency-budget analysis.

This analysis also provides a quantitative summary of the event-to-event behavior shown in Figures 9 and 10 and compares
the strength of the tracer estimated effective transport rates in the PW ridge and trough during split and displaced SSW types.
305 For split SSWs, w_{eff} values from both ACE-FTS and WACCM-X(SD) are all negative and consistently indicate stronger NO
descent in the PW trough than in the ridge. Overall, the event-by-event behavior matches the composite analysis, demonstrating
that the stronger descent in the trough identified in Figure 9 is true for all events. For displaced SSWs, w_{eff} spans both negative
and positive values despite consistently negative $\bar{w}^*$. In contrast to the split events, the relationship between PW phase and w_{eff}
varies from event to event. The single displaced ES event in 2006 shows stronger effective descent in the PW trough than in the
310 ridge in both ACE-FTS and WACCMX(SD). Outside of this event, however, no consistent ridge–trough relationship emerges.
This mixed event-to-event behavior is consistent with the weak and inconclusive ridge–trough contrasts in the displaced-event
composites (Figure 10).

Although the event sample size is limited to five split and six displaced SSWs, Figure 11 shows a consistent ridge–trough
relationship among the split events, whereas displaced SSWs exhibit more event-to-event variability. Results are similar when
315 CO is used as the tracer (not shown). Given the small sample sizes and that ES occurrence is unevenly distributed between
the two categories, this analysis does not determine whether these differences are associated with vortex morphology, ES
occurrence, or both.

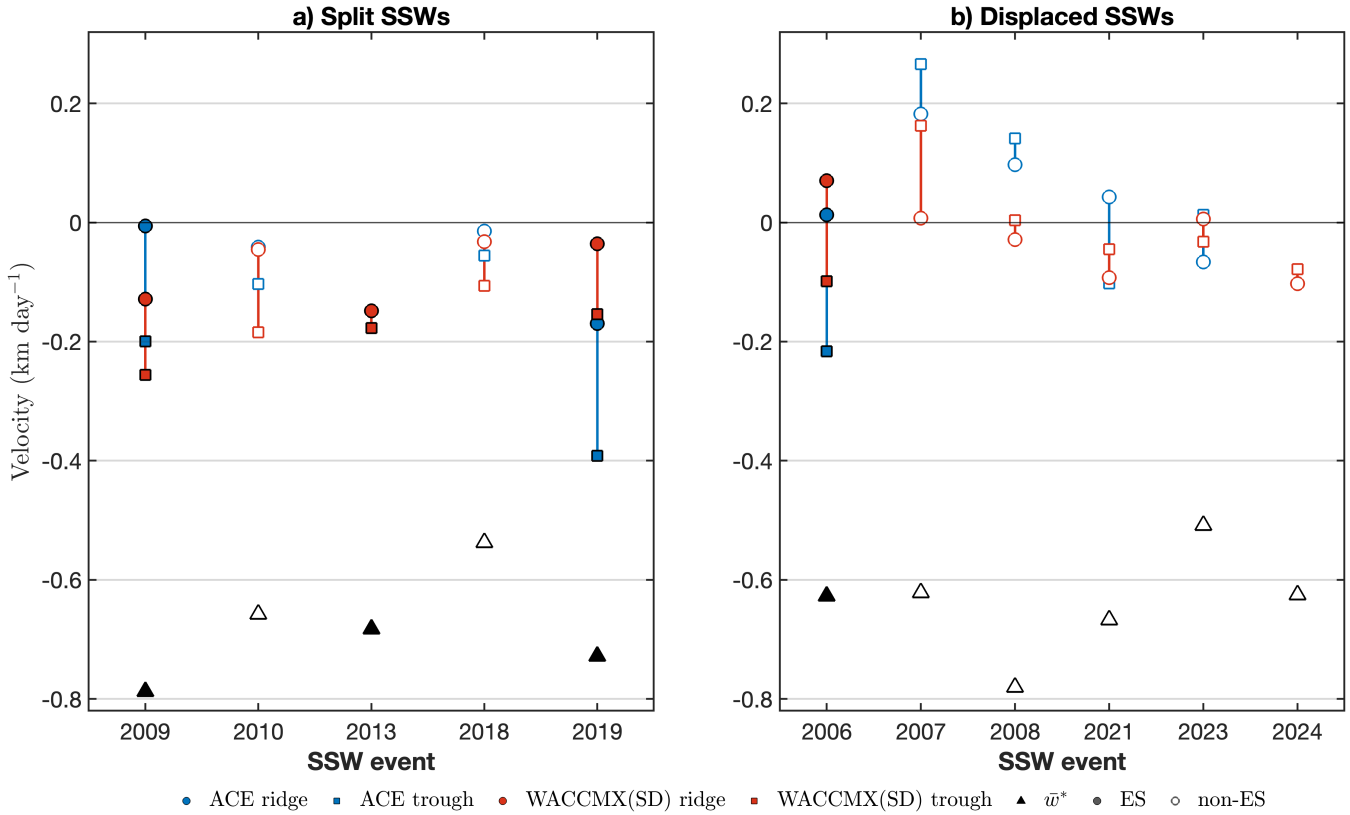


Figure 11. Profile-derived effective NO transport rates w_{eff} (circles and squares) in PW ridge and trough sectors, together with the WACCM-X(SD) zonal-mean residual vertical velocity $\bar{w}^*$ (triangles) for split (left) and displaced (right) SSWs. Circles and squares denote w_{eff} in PW ridges and troughs, respectively. Blue and red colors denote ACE-FTS and WACCM-X(SD), respectively. Filled symbols indicate ES events, and open symbols indicate non-ES events. Thin blue and red vertical lines connect ridge and trough values from the same event and data source. The sampled $\bar{w}^*$ is shown to provide large-scale circulation context and is not an equivalent estimate or validation of w_{eff} .

3.4 Model-based test of the PW ridge–trough contrast

The analysis in Figures 9 and 10 use ACE-FTS and WACCM-X(SD) sampled at the sparse, time-varying ACE-FTS locations. To determine whether the modeled ridge–trough contrast depends on this sampling, we repeat the analysis using WACCM-X(SD) over all longitudes at three fixed latitudes (65°, 70°, and 75°N). Figure 12 shows the event-by-event trough-minus-ridge differences, Δw_{eff} , as the median over 70–90 km using all available model days within the pre- and post-SSW analysis windows defined in Sect.2.5.4 (Day -30 to Day -20 and Day +10 to Day +20). Negative values indicate stronger effective NO descent in the PW trough than in the ridge.

For split events, Δw_{eff} is negative around all three latitude circles. Although the magnitude varies among events and latitudes, the sign of the ridge–trough contrast is always negative. Thus, the modeled tendency toward stronger effective NO descent in the PW trough than in the ridges is not an artifact of ACE-FTS sampling. Displaced events exhibit a less consistent



and more event-dependent response. The 2006, 2023, and 2024 events show negative Δw_{eff} at all three latitudes whereas the 2007, 2008, and 2021 events are near zero or change sign within their variability ranges. No systematic directional dependence
330 on latitude is evident across the displaced-event sample.

Overall, Figure 12 demonstrates that the negative modeled ridge–trough contrast is repeatable across the five split events under an alternative sampling configuration, whereas the displaced-event response depends on the event. The pronounced negative contrasts during the 2023 non-ES event demonstrates that an ES is not required for stronger descent in the trough. This sensitivity test establishes that the model result is robust to an alternative sampling strategy, but does not independently
335 isolate the effects of latitude, longitudinal coverage, or temporal sampling.

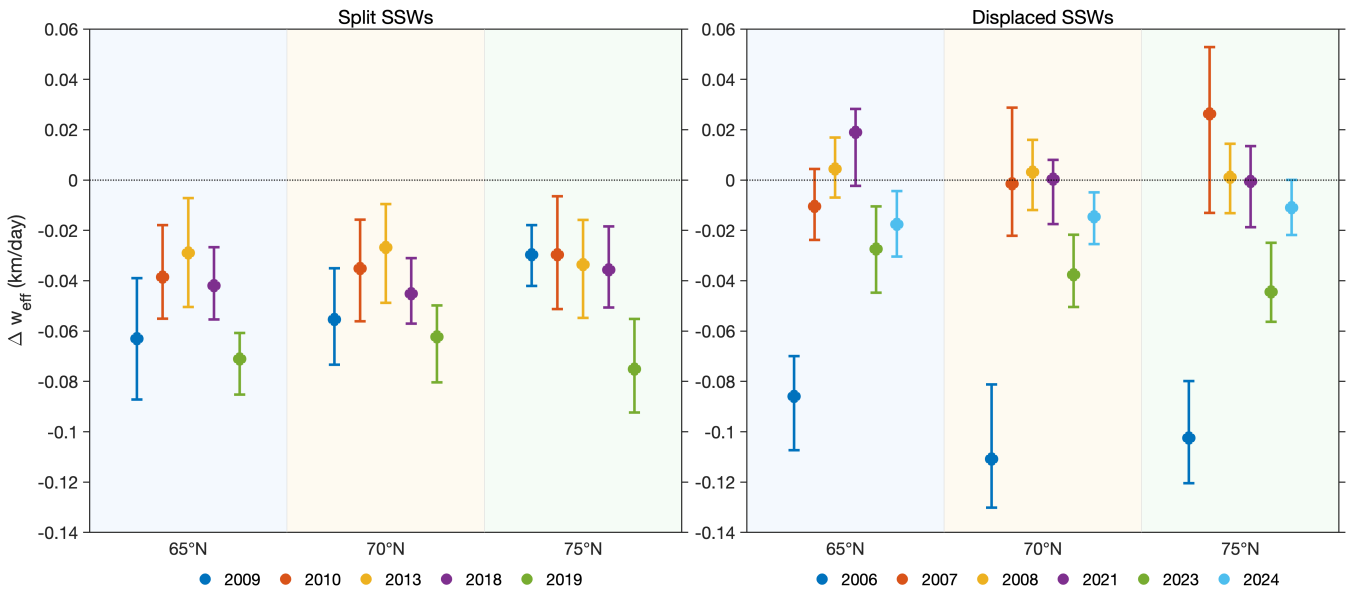


Figure 12. WACCM-X(SD) $\Delta w_{eff} = \Delta w_{eff,trough} - \Delta w_{eff,ridge}$ for all split (left) and displaced (right) SSWs at three fixed model latitudes. Δw_{eff} is the median over 70–90 km at 65°, 70°, and 75°N. Vertical error bars indicate the 2.5th–97.5th percentile range across 500 within-event paired bootstrap replicates. Colors identify individual SSW events. Negative values indicate stronger effective NO descent in the PW trough than in the PW ridge.

4 Discussion

This study demonstrates that the spatial organization of mesospheric NO by PWs is a recurring feature within the analyzed major Arctic SSWs, extending previous studies of individual events (Salmi et al., 2011; Siskind et al., 2021; Harvey et al., 2021b). Collectively, the results indicate that PW phase provides a meaningful framework for interpreting mesospheric NO
340 structure and transport across the analyzed major Arctic SSWs. The ridge–trough transport contrast is more repeatable among the five split events, whereas the displaced events exhibit greater event-to-event variability. By organizing NO relative to PW ridges and troughs, this framework preserves the three-dimensional transport pathways that are largely obscured by traditional



zonal-mean diagnostics (Funke et al., 2017; Jackman et al., 2014; Pérot et al., 2014; Orsolini et al., 2017; Randall et al., 2007; Hendrickx et al., 2018).

345 The preferential occurrence of enhanced NO within PW troughs likely reflects dynamical coupling between the upper-mesospheric PW field and the disturbed polar vortex below. During major SSWs, PWs deform and displace the vortex, modifying both horizontal and vertical transport pathways. PW troughs are preferentially associated with enhanced NO and larger downward shifts of NO-rich air, whereas ridge sectors generally contain lower NO abundances. Because the observed NO distribution reflects both horizontal redistribution and vertical motion, it cannot be interpreted solely in terms of zonal-mean
350 descent (Newnham et al., 2018; Harvey et al., 2019, 2021b). The recurring ridge–trough contrast shown in this work demonstrates that mesospheric NO transport during disturbed winters has an important longitudinal component that is obscured by traditional zonal-mean diagnostics.

The comparison between ACE-FTS and WACCM-X(SD) shows broad qualitative agreement, providing confidence that the observed PW organization reflects physically meaningful transport. Although WACCM-X(SD) smooths the observed ridge-trough contrast by underestimating NO in trough sectors and overestimating NO in ridge sectors, it nevertheless reproduces the
355 observed tendency for high NO to organize by PW phase. This is true for CO as well (not shown). The reduced ridge–trough contrast in NO likely reflects a combination of finite model resolution in the MLT (Marsh et al., 2013; Liu et al., 2010b), uncertainties in energetic particle production of NO and photochemical loss (Funke et al., 2017; Minschwaner and Siskind, 1993; Bender et al., 2019), numerical diffusion, and the representation of tides, PWs, and GWs above the specified-dynamics nudging
360 region (Pedatella et al., 2014; Meraner et al., 2016). Sparse ACE-FTS sampling (Bernath et al., 2005; Dupuy et al., 2009) may also contribute to some of the observation-model differences. Nevertheless, the ability of WACCM-X(SD) to reproduce the observed PW–NO relationship is encouraging, particularly given the known challenges of representing observed mesospheric dynamical fields near the mesopause. These results highlight both the value of whole-atmosphere models for investigating mesospheric transport and the importance of continued evaluation against observations in the MLT.

365 The repeatable ridge–trough contrast during split SSWs may reflect differences in both vortex morphology and post-SSW mesospheric dynamics. ES occurrence is a likely contributor: three of the five split events, but only one of the six displaced events, are classified as ES events, and previous studies have linked ES recovery to enhanced mesospheric descent associated with changes in GW forcing and the residual circulation (Randall et al., 2009; Limpasuvan et al., 2016). However, ES occurrence cannot explain the ridge–trough contrast alone. The fixed-latitude experiment shows stronger trough descent during both
370 the 2006 ES and 2023 non-ES displaced events. Other factors, including pre-onset NO abundance, seasonal timing, geomagnetic forcing, GW activity, and event-specific vortex evolution, may therefore contribute to the observed variability. The small and unevenly distributed event sample does not allow these influences to be separated.

The differences between the profile-derived effective NO transport rate and $\bar{w}^*$ further illustrate the importance of three-dimensional transport. Although $\bar{w}^*$ indicates zonal-mean residual-circulation descent during all events, the effective NO
375 transport rates vary substantially with event and PW phase. This difference is expected because changes in NO profiles reflect not only vertical motion but also horizontal advection, mixing, chemical production and loss, and longitudinal variations in NO gradients (Meraner et al., 2016; Salmi et al., 2011; Harvey et al., 2021b). Thus, the two quantities are not expected to agree



quantitatively, and separating the processes controlling NO evolution would require a three-dimensional NO tendency-budget analysis.

380 More broadly, because the descent of NO contributes to catalytic ozone loss in the winter stratosphere (Randall et al., 2009, 2007; Orsolini et al., 2017), the recurring PW organization of NO identified here raises the possibility that EPP-induced ozone depletion may likewise exhibit coherent regional structure. The PW-phase framework developed here provides a physically meaningful foundation for future investigations of whether regional patterns of NO descent in the mesosphere drive regional patterns of odd nitrogen enhancement and ozone loss in the stratosphere.

385 5 Conclusions

This work investigated PW modulation of mesospheric NO transport during 11 major SSWs using ACE-FTS NO observations, SABER temperature and geopotential height data, MERRA-2 meteorological fields, and WACCM-X(SD) simulations. Building upon previous single-event studies, we demonstrate that PW organization of mesospheric NO is a recurring feature of major Arctic SSWs rather than a characteristic of individual events. By organizing the observed and modeled eddy GPH
390 and NO fields in PW-relative longitude coordinates, this study provides a physically meaningful approach for interpreting mesospheric NO transport during dynamically disturbed winter conditions.

Phase-aligned eddy-GPH composites reveal pronounced vertical phase tilts from the lower stratosphere into the mesosphere for both split and displaced SSWs. This result demonstrates that the mesospheric trough is displaced from the primary 10 hPa trough and must therefore be identified locally at the altitude and time of the NO analysis. Within this local PW structure,
395 NO near 90 km shows a recurring preference for higher NO to be located in troughs and lower NO to be found in ridges. WACCM-X(SD) reproduces the broad vertical PW morphology and preferred NO location within its simulated PW troughs, but underestimates the observed ridge–trough NO contrast.

Separating the events into split and displaced vortex morphologies provides additional insight into the dynamical evolution of NO transport. Split SSWs consistently exhibit stronger downward transport of NO in PW troughs than in ridges, whereas
400 displaced SSWs show a more variable ridge–trough relationship. Although the zonal-mean residual vertical velocity is downward during all analyzed events, the profile-derived effective NO transport rates vary with event type and PW phase. Note, however that these two quantities are not directly comparable. In WACCM-X(SD), the negative ridge–trough contrast for split events persists at 65°, 70°, and 75°N under full-longitude sampling, providing a more robust measure of PW-phase modulation. Because the present 11-event sample partially confounds vortex morphology, ES occurrence, and pre-onset NO structure,
405 larger observational and model event samples are needed to quantify their respective contributions and determine the statistical significance of these transport differences.

Overall, this study demonstrates that PW phase provides a physically meaningful framework for understanding the 3D redistribution of EPP-NO_x during major Arctic SSWs. Because descending NO contributes to catalytic ozone loss in the winter stratosphere (Randall et al., 2007, 2009; Orsolini et al., 2017), the recurring PW organization identified here raises
410 the possibility that EPP-induced ozone depletion may likewise exhibit coherent regional structure. Future work will examine



whether the PW organization of mesospheric NO propagates downward into corresponding regional patterns of odd nitrogen enhancement and ozone depletion in the stratosphere.

Code availability. As a component of the Community Earth System Model, WACCM-X source codes are publicly available at <https://www.cesm.ucar.edu/> (NCAR, 2026).

- 415 *Data availability.* ACE-FTS version 3.5 NO data are available from the ACE mission data archive at <https://database.scisat.ca/>. SABER version 2.0 data are available from the SABER data portal at <http://saber.gats-inc.com/>. MERRA-2 reanalysis data are available from the NASA GES DISC: <https://doi.org/10.5067/QBZ6MG944HW0>. Major SSW event dates follow the NOAA CSL SSW Compendium: <https://cs1.noaa.gov/groups/csl8/sswcompendium/majorevents.html> (last access: March 2025). The 3-hourly WACCM-X(SD) simulation output is archived on NCAR's campaign storage.

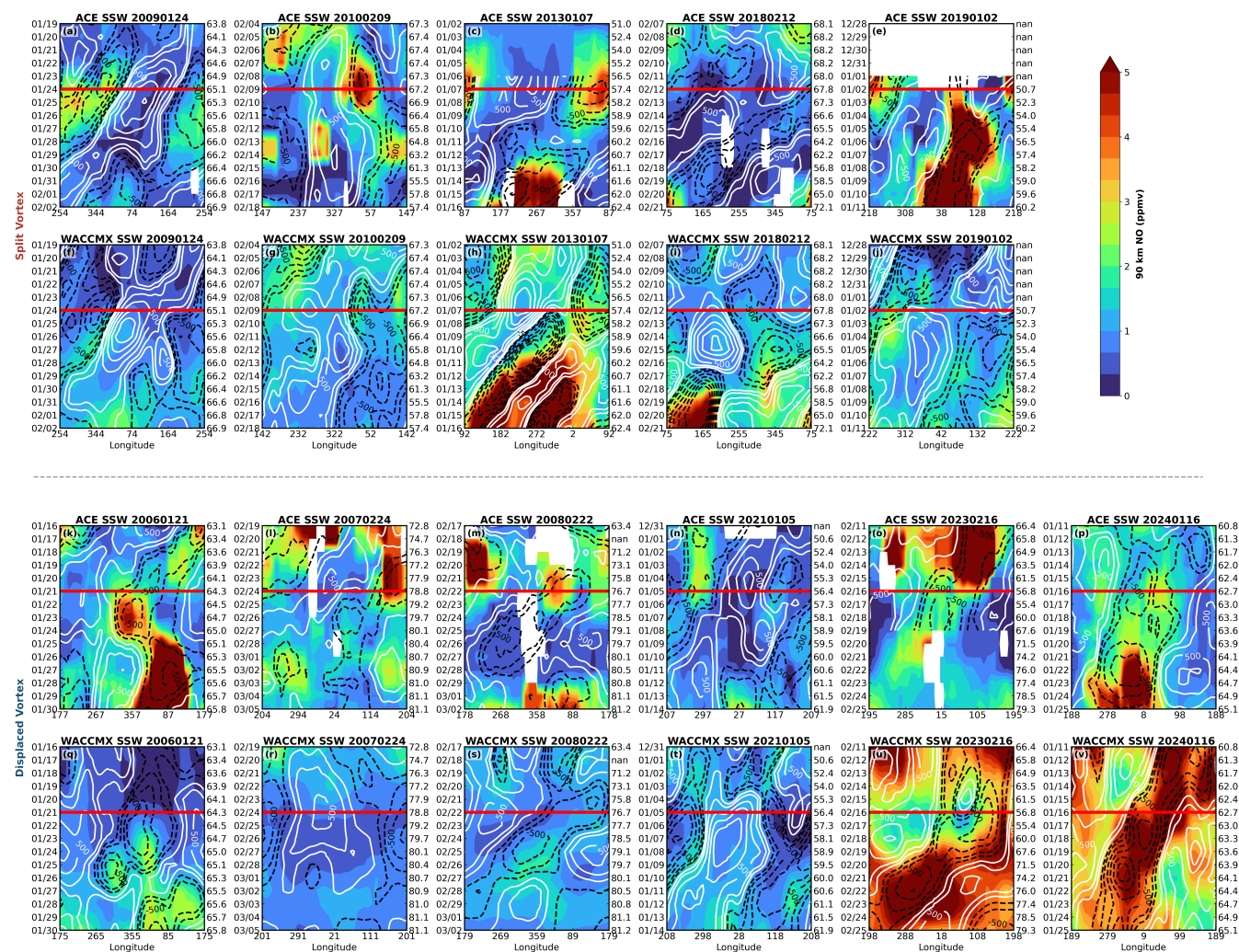


Figure A1. Event-by-event longitude-time NO and eddy GPH structures used to construct the phase-aligned composites.

420 **Author contributions.** G. Shi designed the study, performed the WACCM-X(SD) simulations, carried out the analysis, and wrote the manuscript. V. L. Harvey supervised the study and contributed to the interpretation of the results. H. Liu and N. Pedatella provided technical guidance on WACCM-X(SD), model configuration, chemistry, and NO parameterization. All authors reviewed the manuscript and contributed to interpretation and editing.

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