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Brief communication
"Stratospheric winds, transport barriers and the 2011 Arctic ozone hole"

M. J. Olascoaga[1], **M. G. Brown**[1], **F. J. Beron-Vera**[1], **and H. Koçak**[2]

[1]Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida, USA
[2]Departments of Computer Science and Mathematics, University of Miami, Miami, Florida, USA

Correspondence to: M. J. Olascoaga (jolascoaga@rsmas.miami.edu)

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Abstract. The Arctic stratosphere throughout the late winter and early spring of 2011 was characterized by an unusually severe ozone loss, resulting in what has been described as an ozone hole. The 2011 ozone loss was made possible by unusually cold temperatures throughout the Arctic stratosphere. Here we consider the issue of what constitutes suitable environmental conditions for the formation and maintenance of a polar ozone hole. Our discussion focuses on the importance of the stratospheric wind field and, in particular, the importance of a high latitude zonal jet, which serves as a meridional transport barrier both prior to ozone hole formation and during the ozone hole maintenance phase. It is argued that stratospheric conditions in the boreal winter/spring of 2011 were highly unusual inasmuch as in that year Antarctic-like Lagrangian dynamics led to the formation of a boreal ozone hole.

1 Introduction

The highly unusual Arctic ozone loss in early 2011 has been well documented by Manney et al. (2011), who described that event as an ozone hole, mainly because its associated chemistry was similar to that of annually recurring austral events. Polar ozone chemistry is now fairly well understood (Solomon et al., 1986; Molina and Molina, 1987; Lefevre et al., 1994; Webster et al., 1993; Solomon, 1999). Acknowledging this, Garcia (2011) pointed out that the 2011 Arctic ozone hole was made possible by unusually cold temperatures throughout the Arctic stratosphere for a sustained time period. A necessary condition for initiation of the sequence of chemical reactions that lead to ozone depletion is the formation of polar stratospheric clouds, which occurs when temperatures are maintained below 185 to 195 K, depending on altitude and chemical composition. Owing to the absence of radiative heating over the poles in the winter, such low temperatures can be achieved in these regions provided the polar stratospheric air is prevented from warming via horizontal mixing with midlatitude air (compression due to the accompanying descent of air at high latitudes also plays a role). In other words, formation of a polar ozone hole in late winter requires confinement of polar stratospheric air throughout much of the winter (Schoeberl and Hartmann, 1991; Shepherd, 2007). Maintenance of an already-formed ozone hole also requires confinement of the ozone-depleted polar air to prevent that air from mixing with ozone-rich midlatitude air. In the following, we show that the required confinement during both the stratospheric cooling phase and the ozone hole maintenance phase is linked to the presence of a stratospheric zonal jet which acts as a meridional transport barrier. We show that a zonal jet of this type is linked to the 2011 Arctic ozone loss, and that the associated Lagrangian dynamics are similar to those associated with annually recurring Antarctic ozone holes.

2 Methods

The connection between zonal jets in planetary atmospheres and meridional transport barriers has been described in a series of papers (Joseph and Legras, 2002; Rypina et al., 2007a; Beron-Vera et al., 2008, 2010a, 2012; de la Cámara et al., 2012). Underlying the results presented in those papers is the assumption that the wind field can be approximately described as an incompressible two-dimensional flow. In the Earth's stratosphere this is a good approximation for time scales up to $\sim$1 month (Haynes, 2005). For fast-evolving processes, such as sudden warmings, in which case tracer distributions arise primarily from vertical motion, the incompressible two-dimensional model is still a good diagnostic of horizontal mixing (e.g., McIntyre, 1982).

With the incompressible two-dimensional flow assumption, the equations describing the motion of fluid parcels have Hamiltonian form, where the streamfunction ψ plays the role of the Hamiltonian function. If a local Cartesian coordinate system is adopted with x and y increasing to the east and north, respectively, and the flow is assumed to consist of a background steady zonal flow that is perturbed, then $\psi(x,y,t) = \psi_0(y)+\psi_1(x,y,t)$. The stability (i.e. robustness under perturbation) of fluid parcel trajectories in a system of this type is addressed by a set of results that is referred to as KAM (Kolmogorov–Arnold–Moser) theory (cf., e.g., Arnold et al., 2006). KAM theory predicts that for a fairly general class of perturbations, certain structures that are present in the background flow persist in the perturbed flow and serve as transport barriers in the perturbed flow (cf., also Haller and Beron-Vera, 2012). Owing to a phenomenon referred to as *strong KAM stability* (Rypina et al., 2007b), structures of this type that are particularly robust are found near the core of a zonal jet that circles the globe, where shear vanishes. In the perturbed flow, these structures appear as wobbly, but impermeable barriers to a meridional exchange of fluid. We shall refer to structures of that type as *KAM-like Lagrangian Coherent Structures* (or *KAM-like LCSs*) to distinguish them from the locally most attracting or repelling material curves in a flow, which are commonly referred to as LCSs (Haller and Yuan, 2000; Haller, 2011).

In this paper estimation of KAM-like LCSs will be based on the calculation of continuous fields of finite-time Lyapunov exponents (FTLEs) in both backward and forward time relative to some reference time. FTLEs are a measure of the rate at which neighboring fluid parcel trajectories diverge from one another. A KAM-like LCS can be identified as the locus of points where trenches (elongated regions of low values) in forward-time FTLE fields overlay trenches in backward-time FTLE fields, and where these overlying structures form a closed loop (Beron-Vera et al., 2010a).

Figures 1–4, described in more detail below, include numerical estimates of FTLE trenches computed in the polar stratosphere. The data employed to construct those figures were obtained from the ERA-Interim reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), available from the ECMWF data server at http://www.ecmwf.int. The specific data employed consist of 6-hourly winds and an ozone mixing ratio interpolated on the 475 K isentropic surface at 1.5° resolution over the years 1997, 2010, and 2011. As reported in Dee et al. (2011), ERA-Interim significantly improves the representation of stratospheric winds (e.g., as determined by the age-of-air diagnostic) relative to previous ECMWF reanalyses. In turn, stratospheric ozone transport and depletion is more accurately described than is the case using earlier ERA reanalysis products. But it must be kept in mind that observations of stratospheric ozone at high latitudes during winter and spring are sparse. As a result, the reanalyses tend to produce ozone

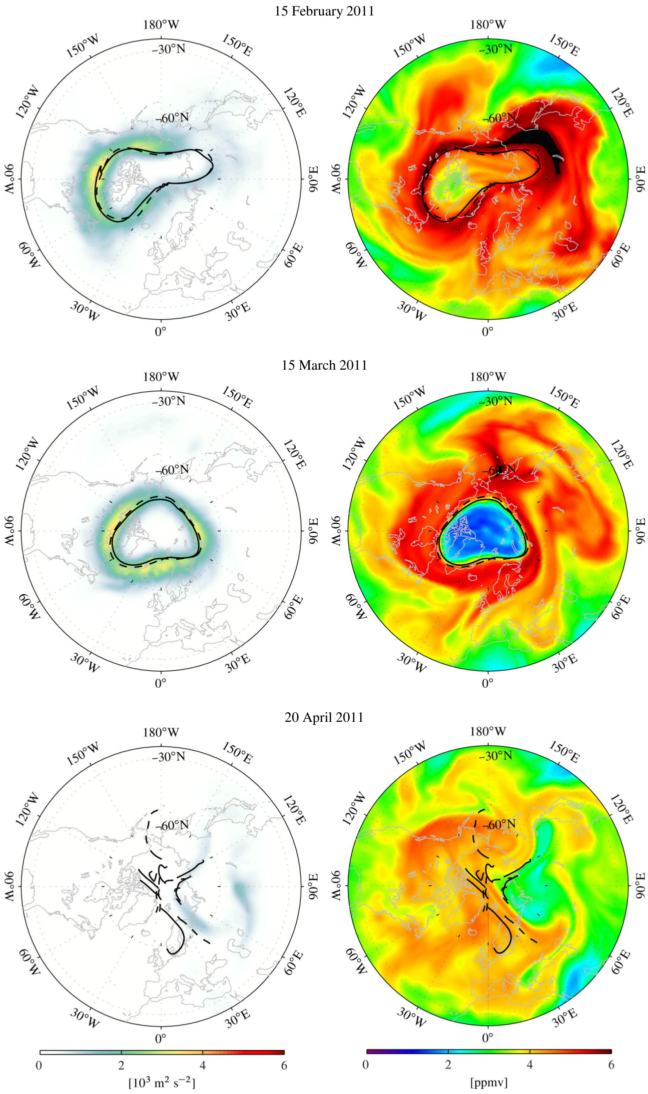


Fig. 1. Stratospheric wind kinetic energy per unit mass (left column) and ozone mixing ratio (right column) on the 475 K isentropic surface (at approximately 20 km altitude) over the boreal polar region on three days in 2011. The days selected are representative of typical behavior in mid-winter, near the winter–spring transition and in mid-spring. Superimposed on each plot are the positions of FTLE (finite-time Lyapunov exponent) trenches, computed in both forward time (solid curves) and backward time (dashed curves) relative to the date indicated on the plots; when solid and dashed curves coincide, a transport barrier is present at the location of the overlapping curves.

minima that are less pronounced than would be produced if the data density were higher (Dee et al., 2011).

The KAM-like LCSs that we seek to identify correspond to FTLE trenches, computed in forward and backward time, that are coincident. We do not address here the technical issue of how close to one another the two closed FTLE trenches have to be in order to be considered coincident. It is evident that in all cases shown here the two FTLE trenches are either very nearly coincident (indicating the presence of a KAM-like LCS), or obviously not coincident (indicating the absence of a KAM-like LCS). The FTLE calculations were carried out assuming full spherical geometry as detailed in Beron-Vera et al. (2010b). The trajectory calculations involved were carried out using an implementation of the Dormand–Prince 4(5) method along with cubic interpolation in space and time. The integration time was chosen to be 7 d, backward or forward, an appropriate choice for stratospheric calculations (Beron-Vera et al., 2010a, 2012).

3 Results

We turn our attention now to polar ozone holes. There are three important phases in the life cycle of a polar ozone hole. Figure 1 shows all three phases for the 2011 Arctic ozone hole. The first phase is the cooling phase, mentioned above, that occurs during the winter prior to the formation of the ozone hole. Cooling is greatly enhanced throughout the winter months if a meridional transport barrier is present. The resulting isolation of polar air allows temperatures to drop sufficiently low that polar stratospheric clouds form. Toward the end of the cooling phase, sunlight triggers the chemical reactions that lead to ozone depletion inside the trapped cold polar air. Within the trapped region, sunlight appears first at its perimeter; as a result, ozone depletion begins near the perimeter of the trapped region. For the 2011 Arctic ozone hole, the cooling phase lasted throughout most of February. The meridional transport barrier that leads to confinement of polar air during the cooling phase is of the KAM-like LCS type. The presence of those structures can be inferred in Figs. 1, 2 and 3 by the overlapping of the solid and dashed curves, which correspond to FTLE trenches, computed in forward and backward time relative to the dates shown on the plots.

The second phase of ozone hole evolution is the ozone hole confinement phase, during which ozone-depleted air is trapped over the polar region. Like the cooling phase, a critical element of the ozone hole confinement phase is the presence of a meridional transport barrier (at the perimeter of the ozone hole) of the KAM-like LCS type which is associated with a zonal jet. This structure prevents the exchange of ozone-depleted air within the ozone hole with ozone-rich midlatitude air. For the 2011 Arctic ozone hole, the confinement phase lasted from early March to early April. The confinement phase of ozone hole evolution ends with the break-up of the barrier that traps ozone depleted air. This break-up is caused by a weakening of the zonal jet that is associated with the KAM-like LCS transport barrier. When the barrier breaks, ozone-depleted polar air is exchanged with ozone-rich midlatitude air and the ozone hole loses its identity over a period of about a week (breaking of the confining transport barrier is effectively instantaneous, but about a week is required for the ozone-depleted polar air to mix with the ozone-rich midlatitude air). The breakup of the Arctic vortex occurred in early April 2011.

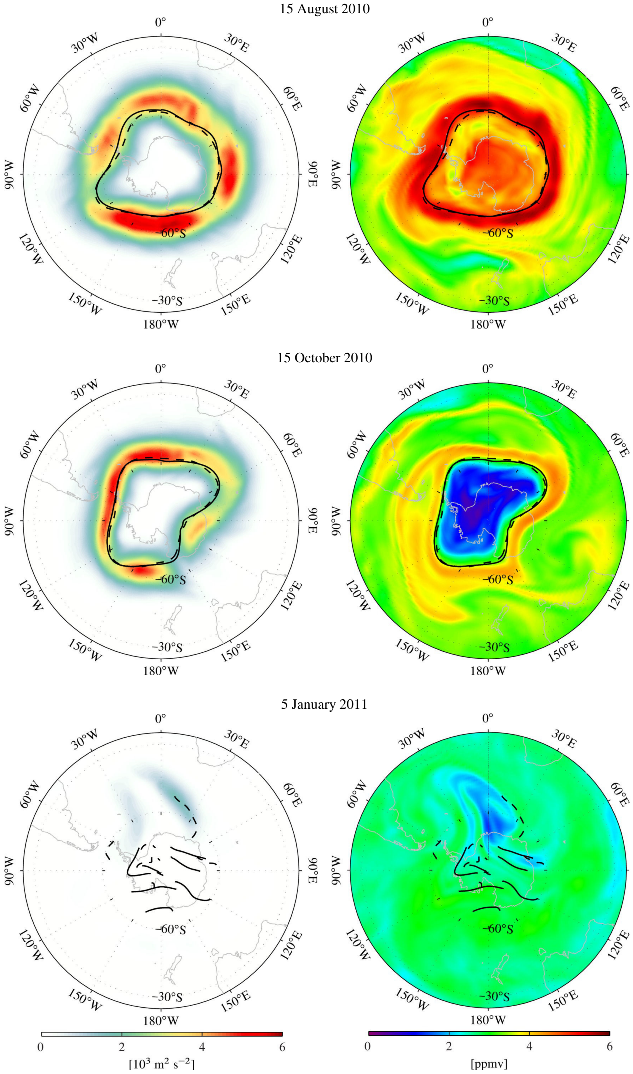


Fig. 2. Same as Fig. 1, but over the austral polar region on two days in 2010 and one day in 2011.

The third phase of ozone hole evolution is the post breakup phase, which is characterized by (1) the absence of the meridional transport barrier of the KAM-like LCS type that is associated with the zonal jet; (2) the absence of a well-defined zonal jet; and (3) the absence of a well-defined ozone hole. These features can be seen in the 20 April plots in Fig. 1.

Figure 2 shows the three phases of the life cycle of the 2010 Antarctic ozone hole. Note the qualitative similarity between Figs. 1 and 2; the three phases in the life cycle of a polar ozone hole that were described above are clearly seen in Fig. 2. The principal difference between Figs. 1 and 2 is that the austral polar jet in Fig. 2 is stronger, and longer-lived, than the boreal polar jet shown in Fig. 1. As a result, confinement is longer-lived in the Antarctic, leading to enhanced cooling, earlier (relative to seasonal changes) development of the ozone hole, and later break-up of the ozone hole. The essential qualitative features seen in Figs. 1 and 2 are identical, but there is a very important difference between the Arctic and Antarctic – the 2011 Arctic ozone hole was highly unusual, while the Antarctic ozone hole formation and destruction cycle has occurred each austral winter/spring since the late 1970s (Farman et al., 1985), although the 2002 break-up occurred unusually early (Shepherd et al., 2005).

Figure 3 shows features of the boreal stratosphere in the winter and spring of 2010. In terms of boreal ozone chemistry 2010 is a typical year (Hurwitz et al., 2011). None of the qualitative features that we have pointed out in Figs. 1 and 2 are present in Fig. 3. There is no persistent boreal polar jet throughout the winter, and, as a result, there is no meridional transport barrier and winter cooling is limited; this prevents the formation of polar stratospheric clouds and, in turn, formation of an ozone hole. Furthermore, there is no boreal polar jet in the spring (had an ozone hole formed in the winter, the meridional transport barrier associated with the springtime boreal polar jet would be needed to isolate the ozone-depleted air).

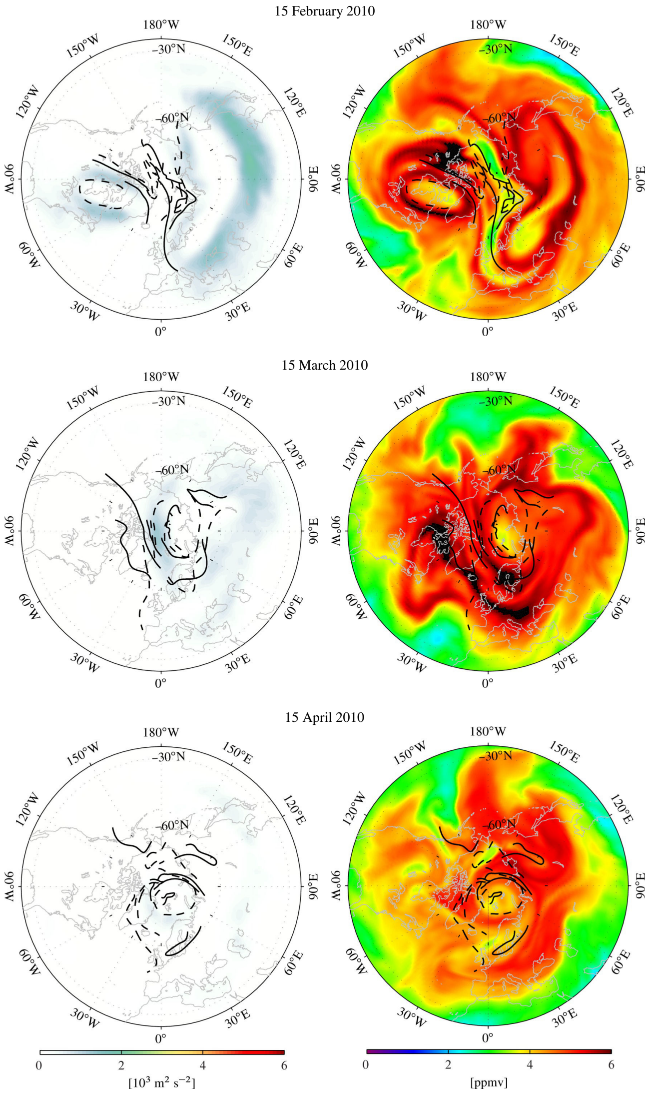
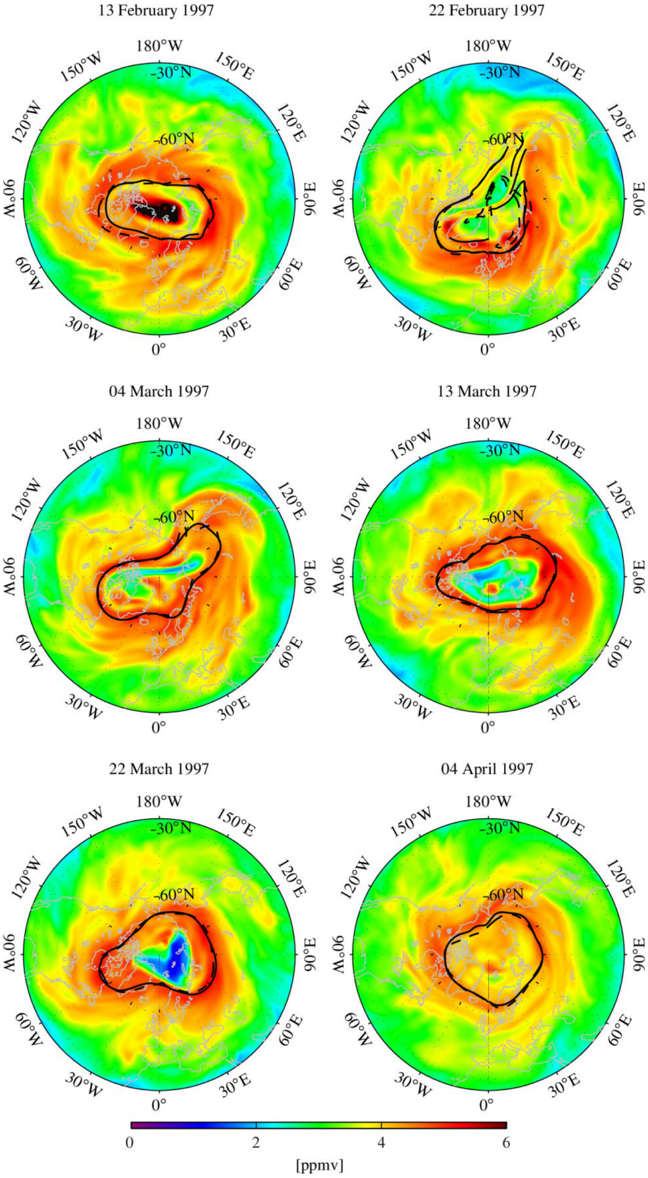


Fig. 3. Same as Fig. 1, but over the boreal polar region on three days in 2010.

Hurwitz et al. (2011) have shown that in the satellite era, the years 1997 and 2011 are distinguished from other years by unusually low Arctic winter/spring ozone levels. With this in mind, it is natural to investigate the Lagrangian dynamics associated with the 1997 Arctic ozone loss, and compare those dynamics to the 2011 dynamics. Figure 4 shows ozone concentration distributions in the lower stratosphere on six different dates in 1997; superimposed are the positions of forward- and backward-time FTLE trenches. Plots of this type reveal that a transport barrier of the KAM-like LCS type was present between approximately 13 February and 19 February. This is illustrated by the 13 February plot in the figure; on that date ozone depletion has been initiated in the region interior to the transport barrier, near the perimeter of the barrier. As noted above, this behavior is typical of the early stage of ozone hole formation. The KAM-like LCS transport barrier breaks on approximately 21 February and does not clearly reform again until approximately 4 March. The 22 February plot in Fig. 4 illustrates behavior during the non-trapping period. During this period moderately low ozone levels are observed over portions of the polar region, but, owing to the absence of a KAM-like LCS, there is significant exchange of polar air with ozone-rich midlatitude air. On approximately 4 March the KAM-like LCS reforms and that barrier is then maintained until approximately 10 April. The plots in Fig. 4 corresponding to 4 March, 13 March, 22 March and 4 April show the evolution of the ozone distribution during this second trapping phase. The critical observation relating to this period is that when the KAM-like LCS reforms, it encloses both ozone-depleted and ozone-rich air. These air masses then mix with each other; the fact that these air masses are isolated from ozone-rich midlatitude air is of little consequence because there is already ozone-rich air inside the transport barrier. In the period between approximately 4 March and 4 April, the ozone-rich and ozone-depleted air masses *inside* the transport barrier mix with each other, leading to a near-complete erosion of an identifiable ozone-depleted air mass. Subsequent breaking of the KAM-like LCS transport barrier in mid April is of little consequence for the ozone distribution in the polar region because the ozone-depleted air mass had lost its identity prior to the



13 February 1997

22 February 1997

04 March 1997

13 March 1997

22 March 1997

04 April 1997

Fig. 4. Ozone concentration on the 475 K isentropic surface on six different dates during the boreal winter/spring of 1997; superimposed are the positions of forward- and backward-time FTLE trenches as in Figs. 1–3.

breaking of the transport barrier. In summary, the evolution shown in Fig. 4 reveals that the 1997 boreal winter/spring event had qualitatively different Lagrangian dynamics than those highlighted in Figs. 1 and 2, corresponding to the 2011 boreal event and typical austral events, respectively.

This leads to the question of whether there was an ozone hole during the boreal winter/spring of 1997. The answer depends on how one chooses to define an ozone hole. Ozone concentrations at certain times and locations in the boreal winter/spring of 1997 are as low as those observed in the boreal winter/spring of 2011; thus, if one chooses to invoke an ozone concentration threshold-based definition, either both or neither events qualify as ozone holes. But, given that the term ozone hole is widely used to describe austral winter/spring events, and that the 2011 boreal event had qualitative Lagrangian characteristics identical to those of austral events while the 1997 boreal event did not, it seems natural to describe the 2011 boreal event as an ozone hole and to use some other term to describe the 1997 boreal event. Regardless of how this semantic issue is settled, the results presented above reveal that the 2011 boreal event was unprecedented in the sense that it was the first documented boreal event whose evolution had qualitative Lagrangian features identical to those observed during each austral winter/spring.

4 Discussion

We have emphasized the connection between zonal polar jets and the meridional transport barriers that are essential to the formation and maintenance of polar ozone holes. We have argued that the associated transport barriers are of the KAM-like LCS type. An alternate argument is that there is a potential vorticity (PV) barrier near the latitude of the mean position of the polar jet that inhibits meridional transport (Juckes and McIntyre, 1987; McIntyre, 1989; Dritschel and McIntyre, 2008; Manney et al., 2011). The two arguments are not mutually exclusive. Indeed, it is possible that the explanations are complementary in that the PV-barrier might act to strengthen the KAM-like-LCS-type barrier. But it should be pointed out that *westward* zonal jets in both Jupiter's weather layer (Beron-Vera et al., 2008) and the Earth's subtropical stratosphere (Beron-Vera et al., 2012) have been shown to serve as meridional transport barriers. These transport barriers are predicted by the arguments that we have presented, but not by the PV-barrier argument (because meridional PV gradients are very small near the cores of westward zonal jets). This observation suggests that the KAM-like LCSs on which we have focused are the critical structures that lead to meridional confinement.

It is interesting to ask whether Arctic strong ozone loss will form in future boreal winters (Baldwin et al., 2007; Shaw and Shepherd, 2008). It is possible that increasing greenhouse gas concentrations could alter the atmosphere in such a way as to enhance the probability of future Arctic ozone holes. We will not speculate on whether this is likely to occur. But we emphasize that the ability to predict future ozone holes rests on one's ability to predict stratospheric winds. Both the winter stratospheric cooling that leads to formation of polar ozone holes and the maintenance of ozone holes during the spring are intimately linked to the presence of a stratospheric polar jet capable of sustaining a KAM-like LCS. So the relevant question relating climate change and possible future Arctic ozone holes is might increasing concentrations of greenhouse gases enhance the probability of a strong and persistent boreal jet?

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