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Investigation of dynamical processes in the polar stratospheric vortex during the unusually cold winter 2004/2005

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[1] The 2004/2005 Arctic winter was unusually cold with high potential for Polar Stratospheric Clouds formation. We use O_3 and N_2O assimilated fields from Aura/MLS in order to describe the dynamical processes inside the polar vortex during this winter. The evolution of N_2O assimilated field shows that subsidence was the dominant dynamical process between early December and late January. The mixing effect between the polar vortex and midlatitudes has been diagnosed using the effective diffusivity parameter. It shows that from early February to the end of March, mixing was dominant compared to diabatic descent. The vortex-averaged ozone loss profile from O_3 assimilated field shows a maximum of ~1.5 ppmv at 425 K, which is less pronounced compared to other winters of similar meteorological conditions (e.g., 1999/2000). This is due to the importance of the mixing processes between the polar vortex and midlatitudes which bring in ozone-rich air to the vortex. **Citation:** El Amraoui, L., N. Semane, V.-H. Peuch, and M. L. Santee (2008), Investigation of dynamical processes in the polar stratospheric vortex during the unusually cold winter 2004/2005, *Geophys. Res. Lett.*, *35*, L03803, doi:10.1029/2007GL031251.

1. Introduction

[2] The northern hemisphere stratosphere exhibits large interannual variability in relation to the year-to-year meteorological conditions [*World Meteorological Organization*, 2002]. The 2004/2005 Arctic winter was characterized by very low temperature in the lower stratosphere from late November 2004 until mid-March 2005. Large areas of Polar Stratospheric Clouds (PSCs) were present at altitudes between 14 and 26 km [*European Ozone Research Coordinating Unit*, 2005]. The vertical integral of PSCs areas is 25% larger than the previous record values from winter 2000 [*Rex et al.*, 2006]. Such conditions could lead to record ozone loss in the lower polar stratospheric vortex. However, some observations, especially from ozonesondes [*Rex et al.*, 2006], and satellite instruments, for example, Aura/MLS [*Manney et al.*, 2006] showed that ozone loss in terms of mixing ratio during the 2004/2005 Arctic winter was less pronounced compared to other winters of similarly cold meteorological conditions (e.g., 1999/2000).

[3] The aim of this paper is to describe the complex dynamical processes that resulted in the observed relatively low chemical ozone loss in spite of the unusually cold meteorological conditions that took place during the 2004/2005 Arctic winter. *Manney et al.* [2006] highlight the difficulty in diagnosing ozone loss during this winter due to mixing in the vortex edge region and the inhomogeneous ozone distribution within the vortex [*Grooß and Müller*, 2007]. They stated the need for extensive modeling and data analysis to explain the dynamical effects and for a precise determination of chemical ozone loss. Three-dimensional modeling fields have the advantage to better present the time-evolution of the dynamical processes especially in the polar vortex. However, in spite of the recent developments brought to the models, some of them can still show some disagreements [*Richard et al.*, 2001]. In particular, chemical ozone loss calculations by the models can present important differences compared to observations [e.g., *Goutail et al.*, 2005]. Difficulties are especially due to the quantification of both vertical descent and horizontal transport influencing the degree of vortex isolation [*Chipperfield and Jones*, 1999].

[4] Chemical data assimilation, which allows constraints to be put on the models using observations, can be used to overcome the deficiencies of the models [e.g., *El Amraoui et al.*, 2004]. Typically, assimilation systems produce observation minus forecast statistics that are used for monitoring biases between the observations and the models [*Geer et al.*, 2006]. In the polar regions, chemical data assimilation can be used to correct the model heterogeneous ozone depletion and reproduce a near-complete ozone destruction in the vortex [e.g., *El Amraoui et al.*, 2008].

[5] In this paper we assimilate O_3 and N_2O from the Aura/MLS instrument in order to describe the dynamical processes in the polar vortex during the 2004/2005 Arctic winter. Chemical ozone loss inside the vortex is also deduced using the vortex average technique [*Harris et al.*, 2002]. The assimilation system used is MOCAGE-PALM [*Massart et al.*, 2005; *El Amraoui et al.*, 2008]. MOCAGE is a three-dimensional chemistry transport model of the troposphere and stratosphere [*Peuch et al.*, 1999]. Its horizontal resolution is 2° both in latitude and longitude with 47 hybrid (σ, P) levels from the surface up to 5 hPa. The chemical scheme used in this study within MOCAGE is the ozone linear parametrization of *Cariolle and Teyssèdre* [2007]. The assimilation module is PALM [*Lagarde et al.*, 2001]. It uses the 3D-FGAT assimilation technique [*Geer et al.*, 2006].

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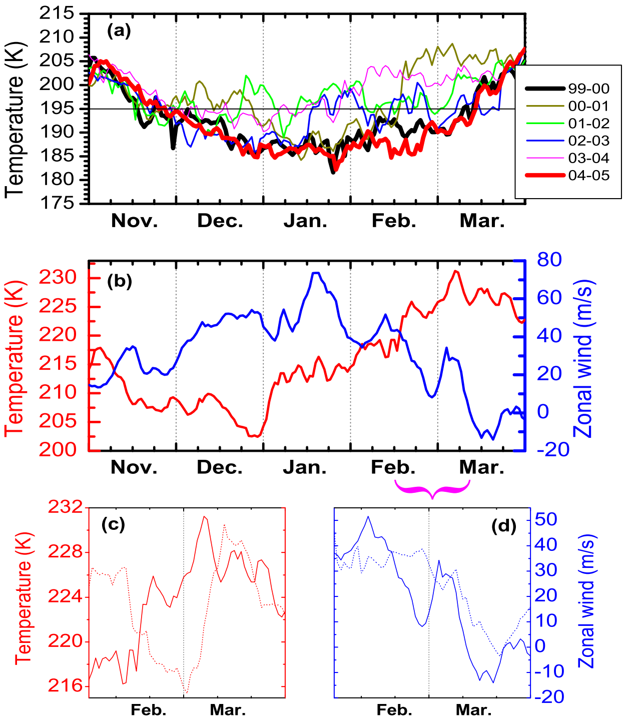

Figure 1. (a) The 475 K minimum temperatures north of 40°N from the ECMWF analyses during the six Arctic winters: from 1999/2000 to 2004/2005. The 2004/2005 Arctic winter is almost similar to 1999/2000 but was unusually cold compared to the other winters. (b) The time evolution of the zonal-mean of the temperature (K) (red) and the zonal wind ($m \cdot s^{-1}$) (blue) at 10 hPa and 60°N. (c) and (d) Comparison for both winters 1999/2000 (dotted line) and 2004/2005 (solid line) of the time evolution of the temperature and the zonal wind, respectively. Both figures present only the February–March period when the mixing effect was important during 2004/2005 Arctic winter.

[6] N_2O assimilated field is used to investigate the large-scale behavior of dynamical effects (diabatic descent inside the vortex and mixing between midlatitudes and the polar vortex) since it is a good tracer in the lower stratosphere. O_3 assimilated field serves to evaluate the ozone evolution inside the vortex.

2. Aura/MLS Measurements

[7] The Aura satellite was launched on July 15, 2004 and placed into a near-polar Earth orbit at ~705 km with an inclination of 98° and an ascending node at 13:45 hours. The MLS instrument aboard Aura uses the microwave limb sounding technique to measure chemical constituents and dynamical tracers principally in the stratosphere and mesosphere as well as upper tropospheric constituents. In this study we use the first publicly available MLS data set, version 1.5, of O_3 and N_2O. O_3 is retrieved between 215 and 0.46 hPa with a vertical resolution of ~3 km. Its precision is around 20–50 ppbv and 0.1–0.2 ppmv in the vertical ranges 215–22 hPa and ~22–0.46 hPa, respectively [*Waters et al.*, 2006]. The N_2O is retrieved between 100 and 0.1 hPa. Its precision does not exceed 30 ppbv in the stratosphere with a vertical resolution around 2–3 km.

3. Meteorological Conditions

[8] The meteorological conditions during the 2004/2005 Arctic winter were quite extreme and colder than other previous winters with high potential for PSCs formation and prime conditions for ozone loss [*Rex et al.*, 2006]. Figure 1a shows the minimum temperatures north of 40°N as calculated from ECMWF analyses for the six winters from 1999/2000 to 2004/2005. The minimum temperature during the 2004/2005 winter is almost the same compared to the 1999/2000 winter but was unusually cold compared to the other winters. The minimum temperature during 2004/2005 Arctic winter remained below 195 K from December to mid-March and even below 188 K during all January 2005. The time evolution of the zonal-mean of the temperature and the zonal wind at 10 hPa and 60°N are presented in Figure 1b. The temperature (zonal-wind) decreased (increased) progressively from the beginning of November to the end of December. This demonstrates that the vortex was stable during this period. During January, the temperature increases. This was accompanied by a deceleration of the zonal wind. This shows that in January, the vortex was perturbed but still enough stable since the subsidence was the important dynamical process (see section 4.1). In Figure 1c and Figure 1d, we present the time evolution of the temperature and the zonal wind on the February–March period when the mixing effect between the vortex edge and midlatitudes was important (see section 4.2). Both figures present a comparison between the 2004/2005 (solid line) and 1999/2000 (dotted line) winters. In early and late February 2005, two minors warming took place. Temperature increases during these events are associated with decreases of the zonal wind intensity. However, during February 2000, the temperature decreases and the zonal wind remains constant. This demonstrates that during February, the vortex was more strong in 1999/2000 than in 2004/2005 Arctic winter. In the second week of March, the zonal mean zonal wind dropped below 0 and became easterly, consequently, the vortex becomes less intense. The temperature increase in March is directly controlled by the planetary waves propagating upward from the troposphere to the stratosphere.

4. Results

4.1. Diabatic Descent

[9] The edge of the vortex is determined using the method suggested by *Nash et al.* [1996]: it is defined as the location of maximum gradient of the potential vorticity (PV) field as a function of equivalent latitude. The time evolution of the vortex averaged N_2O assimilated field is presented in Figure 2 (top). For all selected potential temperature levels, N_2O decreased substantially in the vortex from the beginning of December to late January. This indicates that diabatic descent was the dominant dynamical process during this period. This result agrees well with that of *Manney et al.* [2006]. Figure 2 (bottom) shows the time-evolution of the vortex mean potential temperature for selected N_2O levels. All selected N_2O isopleths show that air masses subsided from the beginning

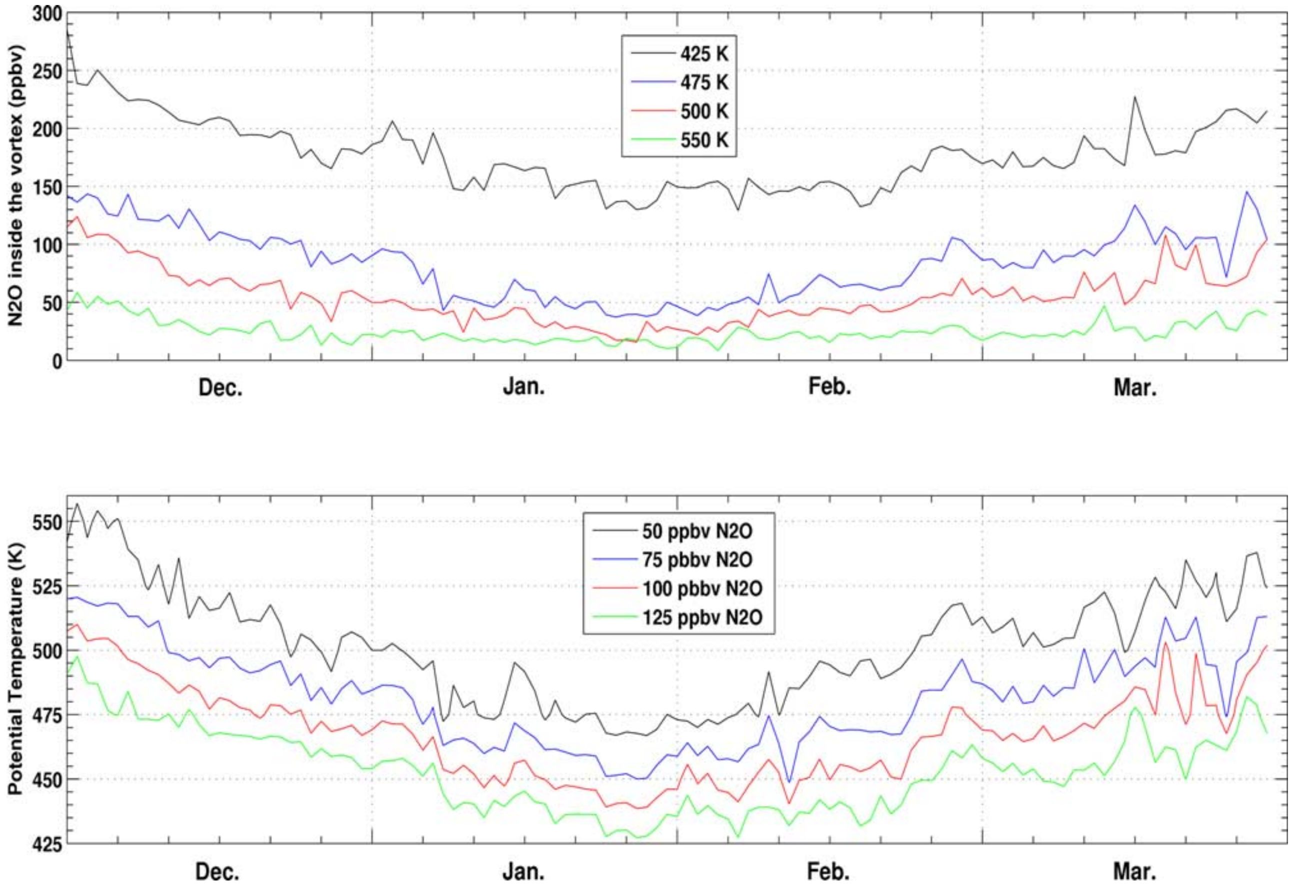

Figure 2. (top) Time evolution of the averaged value of N_2O assimilated field inside the vortex for selected potential temperature levels. (bottom) Vortex mean potential temperatures for selected N_2O levels. Diabatic descent is especially important from the beginning of December to the end of January. The diabatic descent rate is estimated to ~1.2 K/day between the beginning of December and late January when subsidence was the dominant dynamical process.

of December to late January. During this period, when subsidence was the dominant dynamical process, the diabatic descent rate is estimated to ~1.2 K/day.

4.2. Diagnostic of the Mixing Processes Between the Polar Vortex and Midlatitudes

[10] Although the winter was cold, transport processes from midlatitudes or vortex edge into the vortex interior were more important than during previous cold Arctic winters [*Manney et al.*, 2006]. This was in connection with the temperature increases and the zonal wind deceleration between January and March 2005 (see section 3). The aim of this section is to diagnose the mixing processes occurring between midlatitudes and the polar vortex during this winter.

[11] Many authors have used the tracer-tracer correlations technique of long-lived species in order to diagnose the impact and the strength of the isentropic mixing across the vortex edge [e.g., *Richard et al.*, 2001]. However, if the compact relation between two long-lived tracers is nonlinear, any individual mixing event between two air masses separated in tracer-tracer space will produce points that fall off the compact relation [*Müller et al.*, 2001]. On the other hand, when the relationship between the tracers is not linear the change can be due to both descent and mixing [*Rex et al.*, 1999]. Indeed, mixing and chemical ozone loss could be misinterpreted since both processes could lead to a similar pattern in tracer-tracer relations. Thus, a careful selection of profiles used for the establishment of the correlation is essential to the applicability of this method.

[12] Another parameter used to evaluate the intensity of the vortex edge barrier and its permeability is the effective diffusivity proposed by *Nakamura* [1996]. It is a measure of the geometric structure of a tracer field and hence the mixing strength. It was widely used to test the permeability of the vortex edge and to quantify the transport and mixing of chemical constituents between the polar vortex and midlatitudes [e.g., *Hauchecorne et al.*, 2002].

[13] We use N_2O assimilated field as a tracer for the calculation of the effective diffusivity parameter. Figure 3 presents the time evolution of the logarithm of normalized effective diffusivity (hereinafter noted NED) as a function of equivalent latitude at 500 K potential temperature level. In the beginning of the winter, lowest values of NED were observed inside the vortex showing the strongest isolation of the vortex. At this level, the vortex isolation started in early December and persisted until the beginning of January.

[14] The surf zone characterized by strong values of NED and within which there is rapid isentropic mixing, is bounded by the vortex edge on its pole-ward side and by the sub-tropical barrier on its equator-ward side. The area of

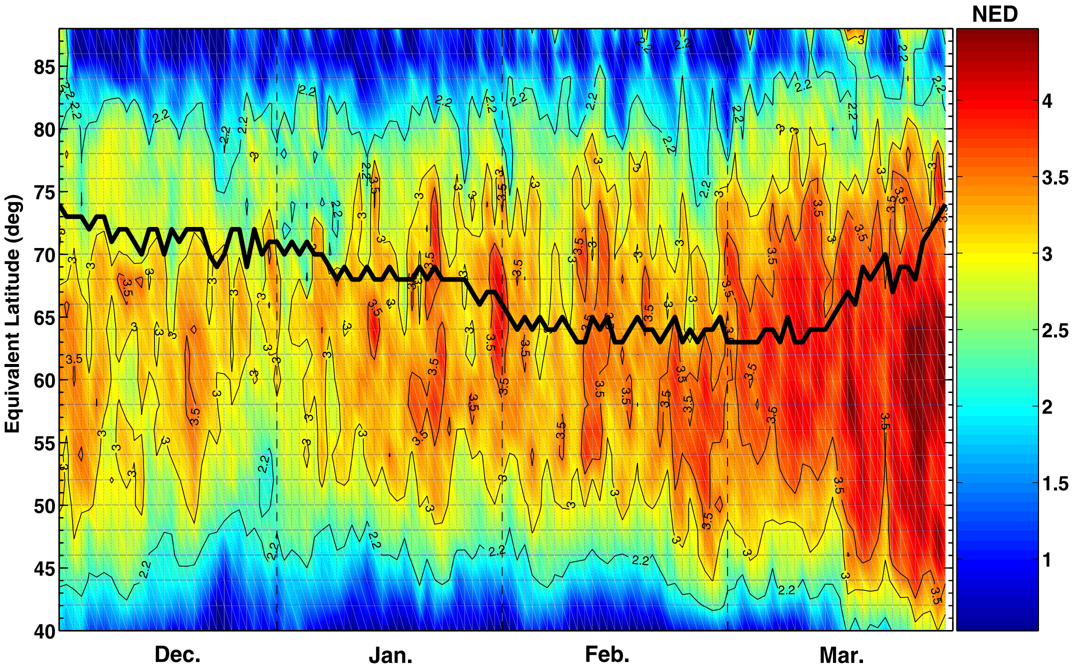

Figure 3. Time-versus-equivalent latitude logarithm of normalized effective diffusivity (NED) on the 500 K isentropic level using N_2O assimilated field as a tracer for the 2004/2005 Arctic winter (high values of NED correspond to strong mixing and vice versa). The black line corresponds to the vortex edge of the maximum gradient of PV field after [*Nash et al.*, 1996]. The exchange between the vortex interior and midlatitudes is clearly important from the beginning of February, when the first minor warming appeared, to the second week of March, when the vortex becomes less intense (see Figure 1).

the surf zone decreases progressively with time until the beginning of January. This shows that the vortex was stable during December. Between the beginning of January and the beginning of February, moderate values of NED have been noted inside the vortex: weak mixing from midlatitudes began to take place. However, the evolution of N_2O inside the vortex (see Figure 2) suggests that for this period the diabatic descent was more important than the isentropic mixing. This suggests that in spite of the isentropic mixing effect, the vortex was still enough stable during January. From the beginning of February until the end of March, the surf zone is broader. Moreover, high values of NED inside the vortex are recorded (>3.5). These high values of NED straddle the vortex edge, consequently, the vortex was less isolated and significant mixing between high and midlatitudes became more intense with time.

4.3. Chemical Ozone Loss

[15] The chemical ozone loss in the polar stratospheric vortex is estimated using the vortex average technique from O_3 assimilated field. During winter, diabatic cooling in the vortex results in subsidence, thus the potential temperature of air parcels is not conserved [*Rex et al.*, 2002]. Diabatic descent must then be accounted for in the calculation of chemical ozone loss. The time evolution of N_2O inside the vortex is used to remove the contribution of subsidence using the same method as *Rex et al.* [2002]. The chemical contribution to the global ozone reduction is then deduced.

[16] The vortex-averaged ozone loss profile between the second week of January and the second week of March as a function of potential temperature is presented in Figure 4. The largest chemical ozone loss is observed between 400 and 450 K. It peaks at 425 K at ~1.5 ppmv, which is consistent with the findings from other independent observations [e.g., *Rex et al.*, 2006]. *Manney et al.* [2006] applied the vortex-averaged technique to both Aura/MLS and

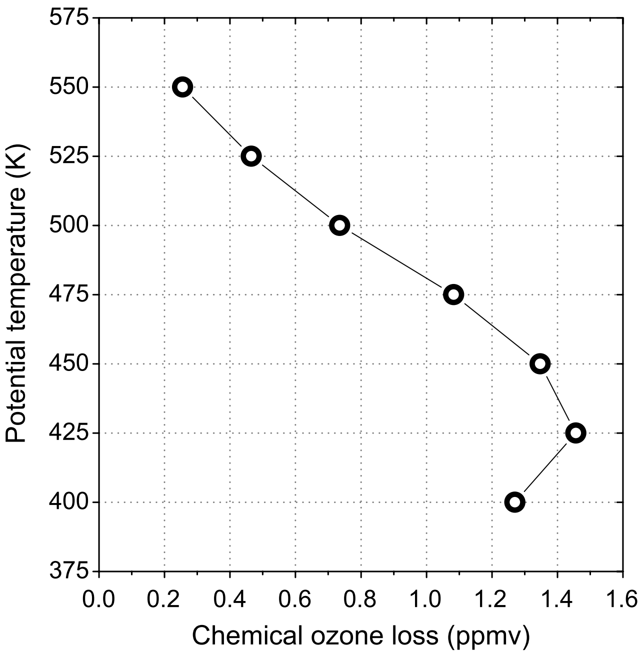

Figure 4. Estimated ozone loss mixing ratio between 10 January and 10 March 2005 versus potential temperature after removing the effects of diabatic descent. The maximum ozone loss of ~1.5 ppmv is observed at 425 K.

POAM measurements using trajectory calculations and a radiation code to estimate the descent rates. They found a maximum vortex-averaged chemical loss of ~1.3 ppmv near 450 K. The maximum of the ozone loss profile for the 2004/2005 winter was smaller than the record value reached in the 1999/2000 winter which was 2.7 ppmv at 453 K potential temperature level [*Rex et al.*, 2002]. This is due to the importance of the mixing processes, which took place especially between early February and mid-March compared to other cold winters and which we have documented in this paper.

5. Conclusions

[17] In this paper, we investigated the dynamical processes in the polar vortex during the 2004/2005 Arctic winter using the assimilated fields of O_3 and N_2O measurements from Aura/MLS. The time evolution of the assimilated field of N_2O, a dynamical tracer, inside the vortex shows that diabatic descent was dominant from the beginning of December to early February. The use of effective diffusivity shows that mixing effects between the polar vortex and midlatitudes were important from the beginning of February to the last week of March.

[18] The deduced ozone loss profile, after removing the subsidence effect, shows a maximum of ~1.5 ppmv at the 425 K potential temperature level. This is consistent with other findings from independent observations [e.g., *Rex et al.*, 2006].

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