Technical Note: Evaluation of simultaneous measurements of mesospheric OH, HO_2, and O_3 under photochemical equilibrium assumption: Statistical approach

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Abstract

The Technical Note presents a statistical approach to evaluating simultaneous measurements of several atmospheric components under the assumption of photochemical equilibrium. We consider simultaneous measurements of OH, HO_2, and O_3 at the altitudes of the mesosphere as a specific example and their daytime photochemical equilibrium as an evaluating relationship. A simplified algebraic equation relating local concentrations of these components in the 50-100 km altitude range has been derived. The parameters of the equation are temperature, neutral density, local zenith angle, and the rates of 8 reactions. We have performed a one-year simulation of the mesosphere and lower thermosphere using a 3D chemical-transport model. The simulation shows that the discrepancy between the calculated evolution of the components and the equilibrium value given by the equation does not exceed 3-4% in the full range of altitudes independent of season or latitude. We have developed the technique of statistic Bayesian evaluation of simultaneous measurements of OH, HO_2 and O_3 based on the equilibrium equation taking into account the measurement error. The first results of application of the technique to MLS/Aura data are presented in this Technical Note. It has been found that the satellite data of HO_2 distribution regularly demonstrates essentially lower altitudes of mesospheric maximum of this component. This has also been confirmed by model HO_2 distributions and comparison with offline retrieval of HO_2 from the daily zonal means MLS radiance.

1. Introduction

A prominent feature of the atmospheric photochemical systems is the presence of a large number of chemical components with short lifetime and concentrations close to stable photochemical equilibrium at every instant. The condition of balance between their sources and sinks is described by a system of algebraic equations. This system can be used to determine characteristics of hard to measure atmospheric species through other measurable components, evaluate results of remote or *in situ* measurements, estimate reaction rates usually known with significant uncertainty, and to understand processes and chemical reactions that influence variability of the most important atmospheric components, e.g. ozone, in the geographical region of interest.

This approach has found wide application:

(1) in 3D chemical transport models that include a large set of physical and chemical processes with a broad spectrum of spatio-temporal scales. In particular, the chemical family concept is widely used for simulating gas phase photochemistry of the lower and middle atmosphere (e.g., Douglass et al., 1989; Kaye and Rood, 1989; Rasch et al., 1995), when transport is taken into account only for the concentration of a chemical family, while relative concentrations of the constituent fast components are calculated from the instantaneous stable equilibrium condition. Complemented with the Henry law (e.g., Djouad et al., 2003; Tulet et al., 2006) in multiphase models, this approach markedly saves calculation time and increases the overall stability of the numerical scheme. Moreover, the use of the photochemical equilibrium condition to simulate fast components dynamics reduces the phase space dimension of box models significantly (e.g., Kulikov and Feigin, 2014), allowing a comprehensive analysis of nontrivial nonlinear dynamic properties of various atmospheric photochemical systems (e.g., Feigin and Konovalov, 1996; Feigin et al., 1998; Konovalov et al., 1999; Konovalov and Feigin, 2000; Kulikov et al., 2012).

(2) in investigations of the chemistry of the surface layer and free troposphere in different regions (over megalopolises, in rural areas, in the mountains, over the seas) based on measurements of nitrogen species, peroxy radicals, ozone, aerosols, and other components aimed at understanding processes impacting the surface ozone formation and air quality. The equilibrium condition is most frequently used for nitrogen species. For example, Chameides (1975) proposed a model for determining the vertical distribution of odd nitrogen, in which the HNO_3 profile could be

63 deployed to retrieve profiles of five other components (NO, NO_2, NO_3, N_2O_5, and HNO_2) from their
64 photochemical equilibrium condition. In the paper by Stedman et al. (1975) the equation for NO_2
65 equilibrium that accounted only for the main source and sink of this component was applied to
66 determine the photodissociation constant $J(NO_2)$. A more accurate equation for the NO_2 equilibrium
67 was used by Crawford et al. (1996) and Kondo et al. (1996) to determine the NO_2/NO partitioning
68 and NO_x, allowing, in particular, investigating the spatial distribution of NO_x/NO_y over the Pacific.
69 Night-time equilibrium in the NO_2-NO_3-N_2O_5 system is used to determine surface layer N_2O_5
70 concentration, equilibrium constant of this system, equilibrium partitioning between NO_3 and N_2O_5,
71 and loss coefficients of NO_3, N_2O_5 and NO_x (Martinez et al., 2000; Brown et al., 2003; Crowley et
72 al., 2010; McLaren et al., 2010; Benton et al., 2010; Sobanski et al., 2016).
73 Platt et al. (1979) used the CH_2O photochemical equilibrium condition to analyse results of
74 simultaneous measurement of CH_2O, O_3 and NO_2 and to identify mechanisms of CH_2O formation
75 over rural areas and in maritime air. In the papers by Ko et al. (2003), Cantrell et al. (2003),
76 Penkett et al. (1997), Penkett et al. (1998) algebraic expressions derived from equilibrium
77 conditions for H_2O_2, peroxy radicals and nitrogen species were used to determine equilibrium
78 values of peroxide concentration, total peroxy radical level, and NO/NO_2 ratio, and to diagnose the
79 ozone production and loss levels in clean or polluted troposphere.
80 (3) in stratospheric chemistry studies, including determination of a critical parameter in
81 catalytic cycles of ozone destruction in the polar stratosphere. In particular, the equilibrium
82 condition for ClO and Cl_2O_2 along with the measurement data of daytime and night-time
83 concentrations of these components in the polar stratosphere are used to evaluate the temperature
84 dependence of the ClO concentration, reaction constants determining the
85 $ClO + ClO + M \leftrightarrow Cl_2O_2 + M$ equilibrium, and the photolysis rate of Cl_2O_2 (Ghosh et al., 1997;
86 Avallone et al., 2001, Solomon et al., 2002; Stimpfle et al., 2004; von Hobe et al., 2005; Berthet et
87 al., 2005; Butz et al., 2007; von Hobe et al., 2007; Kremser et al., 2011; Sumińska-Ebersoldt et al.,
88 2012; Wetzel et al., 2012).
89 Pyle et al. (1983) proposed a method for derivation of the OH concentration from satellite
90 infrared measurements of NO_2 and HNO_3 using a simple algebraic relation following from the
91 equilibrium condition for HNO_3. Algorithms for retrieving distributions of OH and HO2 from the
92 satellite measurement data of O_3, NO_2, H_2O, HNO_3 by LIMS/Nimbus 7 and UARS with the help of
93 algebraic models following from the photochemical equilibrium of O_x, HO_x and HNO_3 components

were proposed by Pyle and Zavody (1985), Pickett and Peterson (1996). It is also worthy of note that similar models are widely used for calculating concentrations of components with a short lifetime (e.g. $O(^1D)$ and OH) and subsequent evaluating vertical distributions of eddy diffusivity from measurements of trace gas concentration profiles (see, e.g., Massie and Hunten, 1981).

Kondo et al. (1988) made use of the photochemical equilibrium between NO and NO_2 for understanding diurnal variations of NO concentration measured during aircraft flights. In the paper by Webster et al. (1990) simultaneous *in situ* balloon-borne measurements of NO, NO_2, HNO_3, O_3 and N_2O and the photochemical equilibrium condition for various nitrogen components were used to determine OH, N_2O_5 and NO_y concentrations. A similar approach was employed by Kawa et al. (1990), who obtained NO_2, N_2O_5, $ClNO_3$, HNO_3 and OH concentrations from aircraft measurements of NO, ClO and O_3 concentrations. Hauchecorne et al. (2010) found that NO_3 concentration measured by GOMOS/ENVISAT positively correlates with temperature at altitudes up to 45 km in the region where NO_3 is in chemical equilibrium with O_3. Funke et al. (2005) used NO and NO_2 stable-state photochemistry to verify correctness of the new approach of retrieving distributions of those component from MIPAS/ENVISAT measurement data. Marchand et al. (2007) proposed a method to retrieve the temperature distribution in the stratosphere between 30 km and 40 km from O_3 and NO_3 measurements by GOMOS with the help of a simple equation derived from the night-time NO_3 chemical equilibrium.

(4) in investigations of the chemistry of O_x–HO_x components and atmospheric glows in the mesosphere and MLT area. In particular, Kulikov et al. (2006, 2009) proposed algorithms for the simultaneous retrieval of O, H, HO_2 and H_2O from joint OH and O_3 satellite measurement, in which the assumption of photochemical equilibrium of O_3, OH, and HO_2 was utilized. For several decades the assumption of the photochemical equilibrium of ozone (PEO) was widely used to determine distributions of atomic oxygen and atomic hydrogen at altitudes of the MLT via satellite and rocket measurement of ozone concentration and airglow emissions (e.g., Evans and Llewellyn, 1973; Good, 1976; Pendleton et al., 1983; McDade et al., 1985; McDade and Llewellyn, 1988; Evans et al., 1988; Thomas, 1990; Llewellyn et al., 1993; Llewellyn and McDade, 1996; Mlynczak et al., 2007, 2013a, 2013b, 2014; Smith et al., 2010; Siskind et al., 2008, 2015). Russell and Lowe (2003) applied PEO to infer the seasonal and global climatology of atomic oxygen using WINDII/UARS. PEO was deployed to investigate hydroxyl emission mechanisms, morphology, and variability in the upper mesosphere – lower thermosphere region (Marsh et al., 2006; Xu et al., 2010, 2012;

Kowalewski et al., 2014). Mlynczak and Solomon (1991, 1993) and Mlynczak et al. (2013b) used the equilibrium assumption to derive exothermic chemical heat. The PEO assumption employed for studying the mesospheric OH* layer response to gravity waves (Swenson and Gardner, 1998). In ultimately theoretical works, e.g. Grygalashvyly et al. (2014), Grygalashvyly (2015), PEO was used to derive the dependence of excited hydroxyl layer concentration and altitude on atomic oxygen and temperature. In the paper by Sonnemann et al. (2015) it was used to analyze annual variations of OH* layer. Moreover, PEO is frequently applied implicitly, when authors are equating the night-time loss of ozone in the reaction with atomic hydrogen and production of ozone by a 3-body reaction of molecular and atomic oxygen (e.g., Nikoukar et al., 2007).

In the present Technical note we demonstrate how the photochemical equilibrium condition of several atmospheric components may be employed to statistically validate data of their simultaneous measurements, particularly in the case when measurement error is large.

We consider the simultaneous photochemical daytime equilibrium of OH, HO_2, and O_3 at the altitudes of the mesosphere. We have derived a simplified algebraic equation

$$F(OH, HO_2, O_3) = 1,$$

describing the relationship between local concentrations of the components at the altitudes of 50–100 km. The only parameters of the equation are temperature, neutral density, local zenith angle, and constants of 8 reactions. One-year simulation of the mesosphere and lower thermosphere based on a 3D chemical-transport model shows that the discrepancy between the calculated evolution of the components and the equilibrium value given by the equation does not exceed 3–4 % in the full range of altitudes independent of season or latitude.

We have developed a technique of statistical Bayesian evaluation of simultaneous measurement of OH, HO_2 and O_3 based on the mentioned equilibrium equation taking into account the measurement error. The first results of its application to MLS/Aura data (Wang et al., 2015a,b; Schwartz et al., 2015) are presented. It is found that the satellite data of HO_2 distribution regularly demonstrates essentially lower altitudes of this component's mesospheric maximum. These results confirm the ones obtained via the offline retrieval of HO_2 from the MLS primary data (Millán et al., 2015).

The Technical Note is structured as follows. A 3D chemical transport model is briefly described in Sect. 2. In Sect. 3 a simplified algebraic relationship between the equilibrium concentrations of OH, HO_2 and O_3 is derived and verified by 3D simulations. Section 4 presents the

156 method of statistical evaluation of simultaneous data of OH, HO_2 and O_3. The results of applying
157 the method to MLS/Aura data are presented in Sect. 5. The last Section contains discussion of the
158 results followed by concluding remarks.
159
160 **2. Model and calculations**
161
162 For our calculations we used the global 3D chemical transport model (CTM) of the middle
163 atmosphere developed by the Leibniz Institute of Atmospheric Physics (IAP) (e.g., Berger, 1994;
164 Ebel et al., 1995; Sonnemann et al., 1998; Kremp et al., 1999; Berger and von Zahn, 1999;
165 Hartogh et al., 2004, 2011; Sonnemann et al., 2006, 2007). It was designed particularly for
166 investigation of the spatio-temporal structure of phenomena in the MLT region and specifically in
167 the extended mesopause region. The grid-point model extends from the ground up to the middle
168 thermosphere (0–150 km; 118 pressure-height levels). The horizontal resolution amounts to 5.625°
169 latitudinally and 5.625° longitudinally. The chemical module described in numerous papers (e.g.,
170 Sonnemann et al., 1998; Körner and Sonnemann, 2001; Grygalashvyly et al., 2009, 2011, 2012)
171 consists of 19 constituents, 49 chemical reactions, and 14 photo-dissociation reactions (see Table
172 1). The reaction rates used in the model are taken from Burkholder et al. (2015). The temperature-
173 dependent reaction rates are calculated on-line, thus, they are sensitive to small temperature
174 fluctuations. We make use of the pre-calculated dissociation rates (Kremp et al., 1999).
175 The evolution of the components of HO_x (H, OH, HO_2, H_2O_2) and NO_x (N, NO, NO_2, NO_3)
176 families is calculated using the chemical family concept proposed by Shimazaki (Shimazaki, 1985).
177 This is done because of the presence of short-lived components among these families, with
178 lifetimes much shorter than those of the families themselves, which imposes significant restrictions
179 on the value of the CTM's integration step. For example, the daytime lifetimes of OH and HO_2
180 above 70 km are about 1 s or less, while the lifetime of the HO_x family is about 10^4 s or more.
181 Therefore, when calculating these components individually it is necessary to set the CTM's
182 integration step to be much less than 1 s. In our work, the Shimazaki technique is applied for
183 calculating the evolution of each component of the HO_x and NO_x families. We emphasize that this
184 technique does not explicitly use the steady-state approximation for the components, instead it
185 utilizes the approach based on an implicit Euler scheme (see Shimazaki, 1985). This allows

increasing the integration step of CTM significantly without loss of accuracy of calculating the short-lived components. In our work the integration time is chosen to be 9 s.

The model includes 3D advective and vertical diffusive transport (turbulent and molecular). Three-dimensional fields of temperature and winds are taken from the Canadian Middle Atmosphere Model (CMAM) for the year 2000 (de Grandpre et al., 2000; Scinocca et al., 2008). We use the Walcek-scheme (Walcek and Aleksic, 1998; Walcek, 2000) for advective transport and the implicit Thomas algorithm as described in Morton and Mayers (1994) for diffusive transport. The vertical eddy diffusion coefficient is based on the results by Lübken (1997).

We calculate the annual variation of spatio-temporal distributions of OH, HO_2, and O_3 and constructed distributions of the $F(OH,HO_2,O_3)$ function introduced in Sect. 1. To remove transitional regions that correspond to sunset and sunrise, we take into account only periods of local time with the solar zenith angle $\chi < 85°$. The obtained results are presented in the model coordinates, so the pressure-height levels are used for the vertical axes. In addition, the approximate altitudes are shown in the figures of Sec. 1, calculated for a given month utilizing averaged temperature profiles of the model and hydrostatic equilibrium.

3. Daytime photochemical equilibrium of OH, HO_2, and O_3 at the altitudes of the mesosphere

The daytime balance of OH concentration at mesospheric altitudes is determined by the following primary reactions (Brasseur and Solomon, 2005):

$HO_2 + O \rightarrow OH + O_2$ (R18 in Table 1)

$H + O_3 \rightarrow OH + O_2$ (R21)

$H + HO_2 \rightarrow 2OH$ (R14)

$OH + O \rightarrow H + O_2$ (R17)

$OH + O_3 \rightarrow HO_2 + O_2$ (R22)

The daytime balance of HO_2 concentration:

$H + O_2 + M \rightarrow HO_2 + M$, M is molecule of air (R20)

$OH + O_3 \rightarrow HO_2 + O_2$ (R22)

$HO_2 + O \rightarrow O_2 + OH$ (R18)

The daytime balance of O_3 concentration:

$O + O_2 + M \rightarrow O_3 + M$ (R12)

217 $O_3 + h\nu \rightarrow O_2 + O$ (R52)

218 $O_3 + h\nu \rightarrow O_2 + O(^1D)$ (R53)

219 $O_3 + H \rightarrow OH + O_2$ (R21)

220 Expressions for local concentrations of OH, HO_2, and O_3 in the photochemical equilibrium
221 are written in the form

222 $$OH = \frac{k_{18} \cdot HO_2 \cdot O + 2k_{14} \cdot HO_2 \cdot H + k_{21} \cdot O_3 \cdot H}{k_{17} \cdot O + k_{22} \cdot O_3}, \quad (1)$$

223 $$HO_2 = \frac{k_{20} \cdot M \cdot O_2 \cdot H + k_{22} \cdot O_3 \cdot OH}{k_{18} \cdot O}, \quad (2)$$

224 $$O_3 = \frac{k_{12} \cdot M \cdot O_2 \cdot O}{k_{52} + k_{53} + k_{21} \cdot H}, \quad (3)$$

225 where k_i are the corresponding reaction constants from Burkholder et al. (2015).

226 We eliminate O and H from Eqs. (1)-(3) and derive an expression depending only on OH, HO_2, O_3.

227 Almost everywhere in the mesosphere and lower thermosphere (with the exception of 85-95
228 km, see Kulikov et al., 2017) the photodissociation is the main ozone sink, i.e. $k_{52} + k_{53} >> k_{21} \cdot H$.
229 Therefore, in the zero order approximation Eq. (3) can be simplified and the concentration of
230 atomic oxygen can be defined in terms of ozone concentration:

231 $$O = \frac{k_{52} + k_{53}}{k_{12} \cdot M \cdot O_2} O_3 \quad (4)$$

232 Making use of Eq. (4) we can derive from Eq. (2) an expression for the concentration of H in terms
233 of concentrations of OH, HO_2 and O_3:

234 $$H = \frac{k_{18} \cdot (k_{52} + k_{53}) / (k_{12} \cdot M \cdot O_2) \cdot HO_2 - k_{22} \cdot OH}{k_{20} \cdot M \cdot O_2} O_3 \quad (5)$$

235 By substituting this equation and Eq. (4) into Eq. (1) we obtain an expression relating OH, HO_2, and
236 O_3:

237 $$F(OH, HO_2, O_3) = \left(\frac{k_{20} \cdot M \cdot O_2}{k_{20} \cdot M \cdot O_2 + k_{21} \cdot O_3 + 2 \cdot k_{14} \cdot HO_2} + \frac{k_{12} \cdot M \cdot O_2 \cdot k_{22}}{(k_{52} + k_{53}) \cdot k_{17}}\right) \cdot \frac{k_{17} \cdot OH}{k_{18} \cdot HO_2} = 1 \quad (6)$$

238 Figure 1 shows height–latitude cross-sections of $< F(OH, HO_2, O_3) >$ for each month (in this
239 Section angle brackets denote monthly averaged zonal mean values). The gray area corresponds
240 to $\chi > 85°$. One can see that eq. (15) is most accurate within the 50–76 km range and above

241 86 km, where $|< F > -1| \le 1\%$. The difference reaches 3–4 % in the region between 76 km and
242 86 km. The altitude of this region has an annual variation with a maximum deviation in the winter
243 hemisphere. Below 50 km the value of $< F >$ increases up to 1.2 at 40 km, thus below the
244 stratopause Eq. (6) no longer describes the simultaneous photochemical equilibrium of OH, HO_2
245 and O_3. Note that these components remain short-lived below 50 km (with the lifetimes of about
246 10^2-10^3 s (Brasseur and Solomon, 2005)) depending on height and duration of daylight. However,
247 for quantitative description of their daytime equilibrium it is necessary to include additional
248 reactions involving, in particular, the components of the NO_x family.
249 Note also that Eq. (1) and Eq. (6) take into account only the main daytime source of OH
250 (P_{OH}) specified by reactions R18, R14, and R21:
251 $$P_{OH}=k_{18} \cdot HO_2 \cdot O + 2k_{14} \cdot HO_2 \cdot H + k_{21} \cdot O_3 \cdot H$$
252 These reactions run “inside” the HOx (H, OH, HO_2, H_2O_2) family and do not perturb its total
253 concentration. The height–latitude cross-sections of $< P_{OH} >$ for each month are presented in
254 Fig. 2.
255 The next important daytime source of OH is specified by reactions R59 and R7 involving H_2O, the
256 main source for the HO_x family:
257 $$P_{OH}^{H_2O}=(k_{59} + 2 \cdot k_7 \cdot O(^1D)) \cdot H_2O$$
258 Figure 3 shows height–latitude cross-sections of $< P_{OH}^{H_2O} / P_{OH} >$ for each month. Comparing Fig. 1
259 and Fig. 3, we conclude that the previously indicated 3–4 % deviation of $< F >$ from 1 in the region
260 between 76 km and 86 km is largely due to the neglect of these reactions.
261 Another source of OH is sporadically activated during charged particle precipitation events
262 and exists for a relatively short time (several days). Solar proton events (SPE) perturb the ionic
263 composition in the mesosphere and the upper stratosphere considerably and trigger a whole
264 cascade of reactions involving ions, neutral components and their clusters (e.g., $O_2^+ \cdot H_2O$). This
265 leads to an additional (to reactions R59 and R7) conversion of H_2O molecules into OH and H
266 (Solomon et al., 1981). The maximum of the OH production rate (P_{OH}^{SPE}) induced by SPE is
267 located in the polar latitudes in the region of 60–80 km and, as a rule, does not exceed $2 \cdot 10^3$ cm^{-3}
268 s^{-1} (Jackman et al., 2011, 2014). It can be seen from Fig. 2 that at these latitudes and altitudes the
269 P_{OH}^{SPE} / P_{OH} ratio does not exceed 1-2%, even for the maximum values of P_{OH}^{SPE}. This means that

the impact of P_{OH}^{SPE} on Eq. (6) is of the same order of smallness as in the case of reactions R59 and R7, hence, it may be neglected. A similar conclusion can be made for other reactions from Table 1, not accounted for by Eq. (6), including the ones involving NO_x in both quiet and perturbed conditions in the mesosphere.

4. Method of statistical evaluation of simultaneous measurement of OH, HO_2 and O_3

The proposed method is based on the statistical Bayesian procedure described in the works by Kulikov et al. (2009) and Nechaev et al. (2016). It was originally developed for retrieving trace gas concentrations in the mesosphere from ground-based and satellite measurements of other mesospheric components. With respect to the considered evaluation problem this procedure consists of three steps: (1) constructing conditional probability density function (PDF) of OH, HO_2 and O_3 concentration values at each altitude z in the selected interval assuming that there is certain measurement data of these components and the algebraic relationship (6) is valid; (2) calculating the first moments of this distribution, i.e. expected value and dispersion of each component using the Metropolis-Hastings algorithm (Chib and Greenberg, 1995) for multidimensional integration; (3) comparing the obtained results with the initial measurement data.

For constructing posterior PDF it is convenient to introduce vector $\vec{u}\left\{HO_2^{ret}, O_3^{ret}, OH^{ret}\right\}$, whose components are the retrieved values of chemical species concentrations at a certain altitude z, and vector $\vec{x}\left\{HO_2^{m}, O_3^{m}, OH^{m}\right\}$ composed of experimentally measured values of the components of vector $\vec{u}$, $x_j = u_j + \xi_j$, $j = 1..3$, where ξ_j is a random error of measuring the j-th component of vector $\vec{u}$ at the altitude z. It is assumed that

(1) random variables ξ_j are distributed normally with densities

$$w_j(\xi_j) = \frac{1}{\sigma_j\sqrt{2\pi}} exp\left(-\frac{\xi_j^2}{2\sigma_j^2}\right); \quad (7)$$

(2) ξ_j are mutually independent:

$$\vec{\xi}\left\{\xi_1, \xi_2, \xi_3\right\} \sim W_{\xi}(\vec{\xi}) = \prod_j w_j(\xi_j), \quad (8)$$

where $W_{\xi}(\vec{\xi})$ is the total PDF of all ξ_j;

297 (3) dispersions σ_j in Eq. (7), that are expected error values, are assumed to be known a priori (in
298 our case they are provided by the MLS retrieval algorithm along with measured data).
299 Then the probability to observe vector $\vec{x}$ is given by the conditional PDF

300 $$P_x(\vec{x}\,|\,\vec{u}) = \int \delta(\vec{x}-\vec{u}) W_\xi(\vec{\xi}')\, d^3\vec{\xi}' = W_\xi(\vec{x}-\vec{u}), \quad (9)$$

301 where $\delta(\ldots)$ is delta function.

302 The prior relationship of HO_2^{ret}, O_3^{ret} and OH^{ret} concentrations (Eq. (6)) can be written as
303 $u_3 = G(u_1, u_2)$. Integrating the left-hand side of Eq. (17) with conditional PDF of the variable u_3:

304 $$P_{u_3}(u_3\,|\,u_1,u_2) = \delta\left(u_3 - G(u_1,u_2)\right),$$

305 yields a likelihood function of the model

306 $$P_x(\vec{x}\,|\,u_1,u_2) = w_3\left(x_3 - G(u_1,u_2)\right)\cdot w_1(x_1-u_1)\, w_2(x_2-u_2). \quad (10)$$

307 According to Bayes' theorem, the posterior function, i.e. the probability density of latent variables u_1
308 and u_2, under the condition that $\vec{x}$ is observed, is defined by the expression

309 $$\begin{aligned} P(u_1,u_2\,|\,\vec{x}) &\propto P_x(\vec{x}\,|\,u_1,u_2)\cdot P_{apr}(u_1,u_2) \\ &\propto exp\left(-\frac{(x_1-u_1)^2}{2\sigma_1^2}\right)\cdot exp\left(-\frac{(x_2-u_2)^2}{2\sigma_2^2}\right)\cdot exp\left(-\frac{(x_3-G(u_1,u_2))^2}{2\sigma_3^2}\right)\cdot P_{apr}(u_1,u_2) \end{aligned} \quad (11)$$

310 in which $P_{apr}(u_1,u_2)$ defines prior PDF of u_1 and u_2.

311 The retrieved value of the latent variable $u_{1,2,3}$ is hereinafter understood as the mean value
312 of the function in Eq. (11):

313 $$\begin{aligned} \langle u_{1,2}\rangle &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} u_{1,2}\cdot P(u_1,u_2\,|\,\vec{x})\, du_1 du_2 \\ \langle u_3\rangle &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} G(u_1,u_2)\cdot P(u_1,u_2\,|\,\vec{x})\, du_1 du_2. \end{aligned} \quad (12)$$

314 Its dispersion defines the uncertainty of the retrieval:

315 $$\sigma_{u_j} = \sqrt{\langle u_j^2\rangle - \langle u_j\rangle^2}, \quad j = 1..3, \quad (13)$$

316 where the angle brackets denote averaging in the sense of Eq. (12).
317

318 **5. MLS/Aura data evaluation and results**

We used the latest version (v4.2) of the MLS "standard" product (Livesey et al., 2017) for trace gas concentrations and temperature T within the 1 – 0.046 mbar pressure interval where all data are suitable for scientific applications (Wang et al., 2015a,b; Schwartz et al., 2015). We took the daytime data when the solar zenith angle $\chi < 80°$ for January, May, and September 2005. All data were appropriately screened. "Pressure", "estimated precision", "status flag", "quality", "convergence" and "clouds" fields were taken into account. HO_2 data were seen as the day-minus-night difference as prescribed by the MLS data guidelines (Livesey et al., 2017). Following Pickett et al. (2008), each daytime profile of this component measured on a given day at a latitude Lat, a profile resulting from averaging the nighttime profiles of HO_2, measured on the same day in the latitude range of Lat±5°, was subtracted. This operation eliminates systematic biases affecting HO_2 retrievals, but limits the studied latitude range to the one where MLS observes both daytime and nighttime data.

The integrals in Eq. (12)–(13) were calculated at every pressure level p for each set of simultaneously measured vertical profiles $OH^{MLS}(p)$, $HO_2^{MLS}(p)$, $O_3^{MLS}(p)$, $T^{MLS}(p)$, $\sigma_{OH^{MLS}}(p)$, $\sigma_{HO_2^{MLS}}(p)$, $\sigma_{O_3^{MLS}}(p)$. The vertical profiles $<OH^{ret}>(p)$, $<HO_2^{ret}>(p)$, $<O_3^{ret}>(p)$, $\sigma_{OH^{ret}}(p)$, $\sigma_{HO_2^{ret}}(p)$, $\sigma_{O_3^{ret}}(p)$ were found at each point of the globe along the satellite track. Numerical integration was performed by a Monte Carlo method. For each pressure level, a sample of about $5 \cdot 10^5$ pairs of random variable values $\{u_1, u_2\} = \{HO_2^{ret}, O_3^{ret}\}$ distributed with normalized probability density given by Eq. (11) with $P_{apr}(u_1, u_2) \equiv 1$ was generated with the help of the Metropolis-Hastings algorithm (Chib and Greenberg, 1995). In this case, the statistical moments in Eq. (12)–(13) were determined by summation over the sample.

A typical example of retrieved profiles HO_2^{ret}, O_3^{ret} and OH^{ret} (black curves) in comparison with the measured HO_2^{MLS}, O_3^{MLS} and OH^{MLS} (red curves) is given in Fig. 4. First of all, note that statistics of the retrieved data is in satisfactory agreement with the initial measurement of OH and O_3 concentrations, but not of HO_2. The error of satellite measurement, $\sigma_{HO_2^{MLS}}$, greatly exceeds the uncertainty of retrieval, $\sigma_{HO_2^{ret}}$, so at some altitudes the values of $<HO_2^{MLS}>$ (red dashed curves) do not fall within the corresponding intervals $<HO_2^{ret}> \pm \sigma_{HO_2^{ret}}$. Second, the results of a single

measurement of all three components and their retrieved values have considerable uncertainties relative to their means within the whole interval of altitudes. Therefore, the observed and retrieved data should be compared using the commonly accepted approach (e.g., Pickett et al., 2008) of averaging large ensembles of profiles within certain latitude and time ranges, or zones. It is supposed that the noise of satellite measurement instruments is delta-correlated, so that random values corresponding to each single measured or retrieved profile are statistically independent. In this case the dispersion of a measured or retrieved zonal mean profile is determined by summation

$$\sigma^2{}_{\Sigma} = \frac{1}{N^2}\sum_{k=1}^{N}\sigma^2{}_k ,$$

where N is the number of measured or retrieved profiles within the zone and $\sigma^2{}_k$ is the dispersion of the k-th measured or retrieved profile.

The range of latitudes covered by the satellite trajectory was divided into 17 bins 10^0 each. About 3000 single profiles of each chemical component fall into one bin during a month of MLS/Aura observations. Therefore, the resulting uncertainties due to measurement noise of OH, HO_2 and O_3 concentration profiles (both measured and retrieved) averaged over such ensembles are significantly (about one and a half order of magnitude) lower than the uncertainties of individual profiles. Examples of such profiles for January, May and September 2005 are presented in Fig. 5. One can see that the indicated uncertainties are now small enough to make clear conclusions about the extent to which the observed and retrieved profiles agree by comparing their averaged values only, i.e. $<OH^{MLS}>$, $<HO_2{}^{MLS}>$, $<O_3{}^{MLS}>$ and $<OH^{ret}>$, $<HO_2{}^{ret}>$, $<O_3{}^{ret}>$.

Figures 4–6 show monthly averaged zonal mean pressure–latitude cross-sections of $<HO_2{}^{ret}>$, $<HO_2{}^{MLS}>$, $\Delta HO_2 = (<HO_2{}^{ret}> - <HO_2{}^{MLS}>)/<HO_2{}^{MLS}>$ and similar characteristics for OH and O_3 concentration profiles for three months of the year 2005. First, clearly, the distributions of $<OH^{ret}>$ and $<O_3{}^{ret}>$ are in good qualitative and quantitative agreement with the initial MLS/Aura measurement data at lower altitudes, below ~ 0.07 mbar and 0.1 mbar, correspondingly. At higher altitudes, the distributions of $<OH^{ret}>$ reproduce all the main structural features of $<OH^{MLS}>$, but the retrieved OH concentration has lower values than the observed one with a relative difference ΔOH reaching ~15% at the top. The distribution of $<O_3{}^{ret}>$ above 0.1 mbar, in turn, differs considerably from $<O_3{}^{MLS}>$, both in quantity and quality, and ΔO_3 locally

reaches 50-60% and more. Second, for all months there are significant qualitative and quantitative differences between $<HO_2^{ret}>$ and $<HO_2^{MLS}>$, the most noticeable one being location of the mesospheric maximum of this component's concentration. According to the observations it is close to 0.1 mbar, while the retrieved data demonstrate the altitudes of about ~0.046 mbar or higher. Our analysis of the applied method of statistical evaluation demonstrates that the higher position of this maximum in the distributions of $<HO_2^{ret}>$ is influenced by the OH^{MLS} data in which the mesospheric maximum (see Figs. 6-8) is also located notably higher than 0.1 mbar.

6. Discussion and conclusion

On the basis of the data presented in Section 5 we can conclude that, upon the whole, simultaneous OH, HO_2 and O_3 satellite measurements poorly satisfy the photochemical equilibrium condition. The HO_2 component biases from this condition most prominently. We can conjecture that a possible explanation for the bias is the significant systematic error in HO_2 measurements, in particular, in the height of the mesospheric maximum. This assumption is supported by the calculation of the HO_2 distributions with the use of our 3D chemical transport model (see Fig. 9). It can be seen that the mesospheric maximum of HO_2 in these months, as well as of the $<HO_2^{ret}>$ distributions, lies above 0.046 mbar.

Moreover, new data on the HO_2 distributions were recently obtained from the MLS measurements. Millán et al. (2015) performed the offline retrieval of daily zonal means of HO_2 profiles using averaged MLS radiances measured in 10° latitude bins. Averaged spectra have a better signal to noise ratio, which removes many of the limitations of the MLS standard product for HO_2. In particular, the upper boundary of the altitude region in which daytime data is suitable for scientific use has reached 0.0032 mbar, and the "day-minus-night" correction is not needed at altitudes above 1 mbar. Comparison with various experimental and model data has shown that the offline retrieval reproduces the basic properties of the HO_2 distribution in the mesosphere relatively well (at least qualitatively) (Millán et al. 2015).

The offline retrieval product, the alternative dataset of daytime HO_2, has recently become publicly available at https://mls.jpl.nasa.gov. Figure 10 shows the monthly averaged zonal means of offline retrieval data ($<HO_2^{MLS}{}_{offline}>$) and relative differences with retrieved and MLS standard

product data $(<HO_2^{MLS}> - <HO_2^{MLS}_{offline}>)/ <HO_2^{MLS}_{offline}>$ and $(<HO_2^{ret}> - <HO_2^{MLS}_{offline}>)/ <HO_2^{MLS}_{offline}>$, correspondingly. Figure 10 represents the same time periods as Figs. 6-8. It is worth noting that the distributions $<HO_2^{MLS}_{offline}>$ depicted in Fig. 10 represent significantly different amounts of data. The data sets for May and September include 31 and 27 days of measurements, respectively, whereas the January dataset encompasses only 4 days. The latter makes the graphs in the first row in Fig. 10 noisier than the others. One can see that the results of the offline HO_2 retrieval show the same features as the results of our evaluation technique in comparison to the standard MLS retrieval, i.e. the height of mesospheric HO_2 maximum is notably higher. We can conclude that the distributions of $<HO_2^{ret}>$ better match $<HO_2^{MLS}_{offline}>$ than $<HO_2^{MLS}>$, although some quantitative discrepancy between $<HO_2^{ret}>$ and $<HO_2^{MLS}_{offline}>$ also exists. Note that this may be due to systematic errors in the HO_2^{MLS} distributions, which cannot be excluded within the framework of the introduced technique. For a detailed qualitative and quantitative comparison of $<HO_2^{ret}>$ and $<HO_2^{MLS}_{offline}>$ one should modify the method, so that a statistical evaluation of the OH^{MLS} and O_3^{MLS} standard products, and the data of the offline HO_2 retrieval could be conducted within the framework of a single procedure with no account for the HO_2^{MLS} distributions. This modification is under way and will be presented elsewhere.

The proposed method for statistical evaluation of mesospheric species measurements can be readily generalized to other atmospheric photochemical systems that contain short-lived components (see Introduction). It may also be modified for assessing hard to measure chemical components, characteristics of atmospheric processes (like wind speed or turbulent diffusion rate), or poorly known reaction rates.

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Table 1. List of reactions with corresponding reaction rates from Burkholder et al. (2015).

1	$O(^1D)+O_2 \rightarrow O+O_2$	22	$OH+O_3 \rightarrow O_2+HO_2$	43	$NO_2+O_3 \rightarrow NO_3+O_2$
2	$O(^1D)+N_2 \rightarrow O+N_2$	23	$HO_2+O_3 \rightarrow OH+2O_2$	44	$N+OH \rightarrow NO+H$
3	$O(^1D)+O_3 \rightarrow O_2+2O$	24	$H+OH+N_2 \rightarrow H_2O+N_2$	45	$NO+HO_2 \rightarrow NO_2+OH$
4	$O(^1D)+O_3 \rightarrow 2O_2$	25	$OH+H_2 \rightarrow H_2O+H$	46	$H+NO_2 \rightarrow OH+NO$
5	$O(^1D)+N_2O \rightarrow 2NO$	26	$OH+OH \rightarrow H_2O+O$	47	$NO_3+NO \rightarrow 2NO_2$
6	$O(^1D)+N_2O \rightarrow N_2+O_2$	27	$OH+OH+M \rightarrow H_2O_2+M$	48	$N+NO \rightarrow N_2+O$
7	$O(^1D)+H_2O \rightarrow 2OH$	28	$OH+HO_2 \rightarrow H_2O+O_2$	49	$N+NO2 \rightarrow N2O+O$
8	$O(^1D)+H_2 \rightarrow H+OH$	29	$H_2O_2+OH \rightarrow H_2O+HO_2$	50	$O_2+h\nu \rightarrow 2O$
9	$O(^1D)+CH_4 \rightarrow CH_3+OH$	30	$HO_2+HO_2 \rightarrow H_2O_2+O_2$	51	$O_2+h\nu \rightarrow O+O(^1D)$
10	$O(^1D)+CH_4 \rightarrow H_2+CH_2O$	31	$HO_2+HO_2+M \rightarrow H_2O_2+O_2+M$	52	$O_3+h\nu \rightarrow O_2+O$
11	$O+O+M \rightarrow O_2+M$	32	$CH_3+O \rightarrow CH_2O+H$	53	$O_3+h\nu \rightarrow O_2+O(^1D)$
12	$O+O_2+M \rightarrow O_3+M$	33	$OH+CO \rightarrow H+CO_2$	54	$N_2+h\nu \rightarrow 2N$
13	$O+O_3 \rightarrow O_2+O_2$	34	$CH_4+OH \rightarrow CH_3+H_2O$	55	$NO+h\nu \rightarrow N+O$
14	$H+HO_2 \rightarrow 2OH$	35	$CH_3+O_2+M \rightarrow CH_3O_2+M$	56	$NO_2+h\nu \rightarrow NO+O$
15	$H+HO_2 \rightarrow H_2O+O$	36	$O_3+N \rightarrow NO+O_2$	57	$N_2O+h\nu \rightarrow N_2+O(^1D)$
15	$H+HO_2 \rightarrow H_2+O_2$	37	$NO_3+O \rightarrow NO_2+O_2$	58	$N_2O+h\nu \rightarrow N+NO$
17	$OH+O \rightarrow H+O_2$	38	$O+NO+M \rightarrow NO_2+M$	59	$H_2O+h\nu \rightarrow H+OH$
18	$HO_2+O \rightarrow OH+O_2$	39	$NO_2+O \rightarrow NO+O_2$	60	$CH_4+h\nu \rightarrow CH_2+H_2$
19	$H_2O_2+O \rightarrow OH+HO_2$	40	$NO_2+O+M \rightarrow NO_3+M$	61	$H_2O_2+h\nu \rightarrow 2OH$
20	$H+O_2+M \rightarrow HO_2+M$	41	$N+O_2 \rightarrow NO+O$	62	$NO_3+h\nu \rightarrow NO_2+O$
21	$H+O_3 \rightarrow OH+O_2$	42	$NO+O_3 \rightarrow NO_2+O_2$	63	$CO_2+h\nu \rightarrow CO+O$

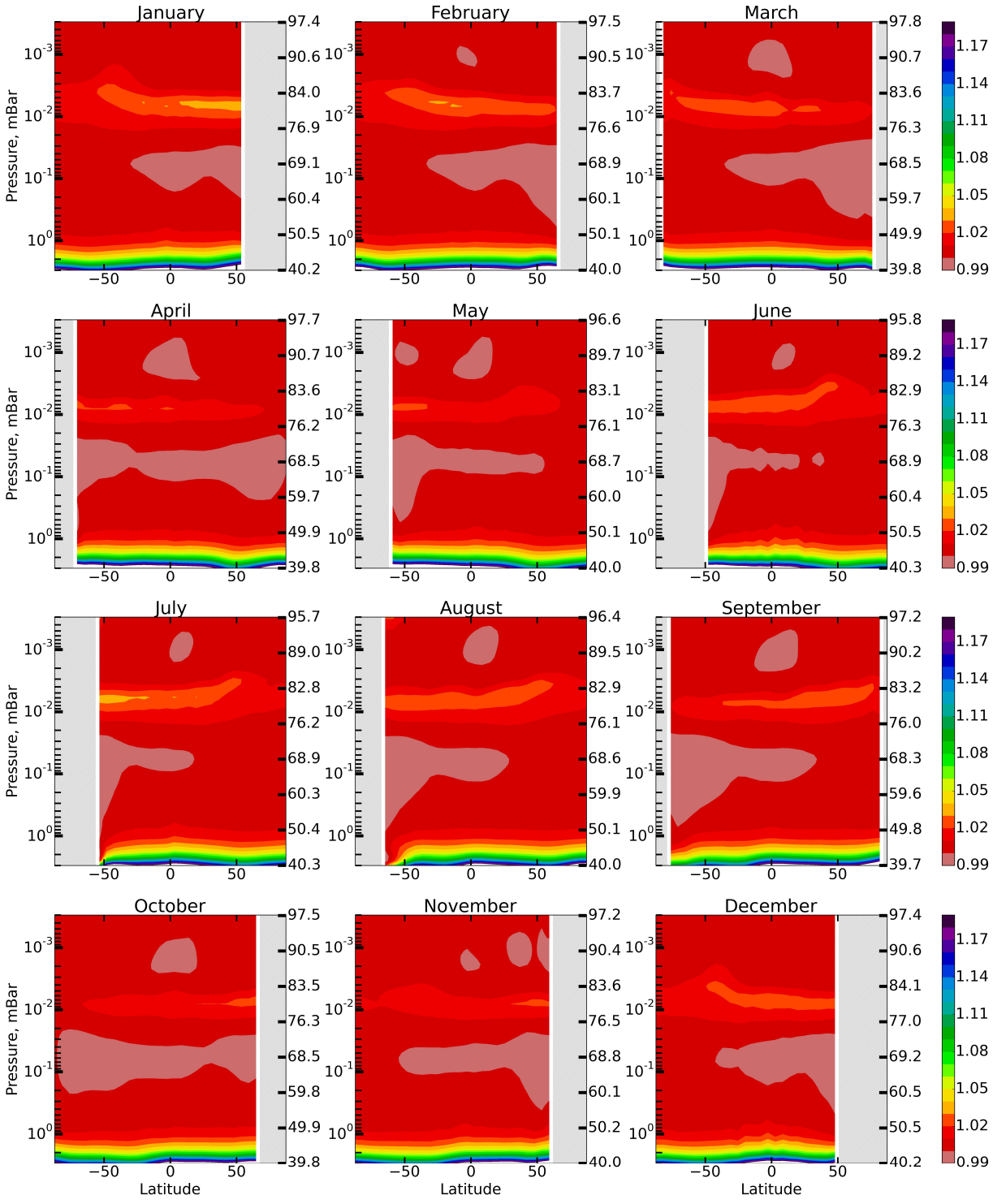

Figure 1. Daytime monthly averaged zonal mean F distributions.

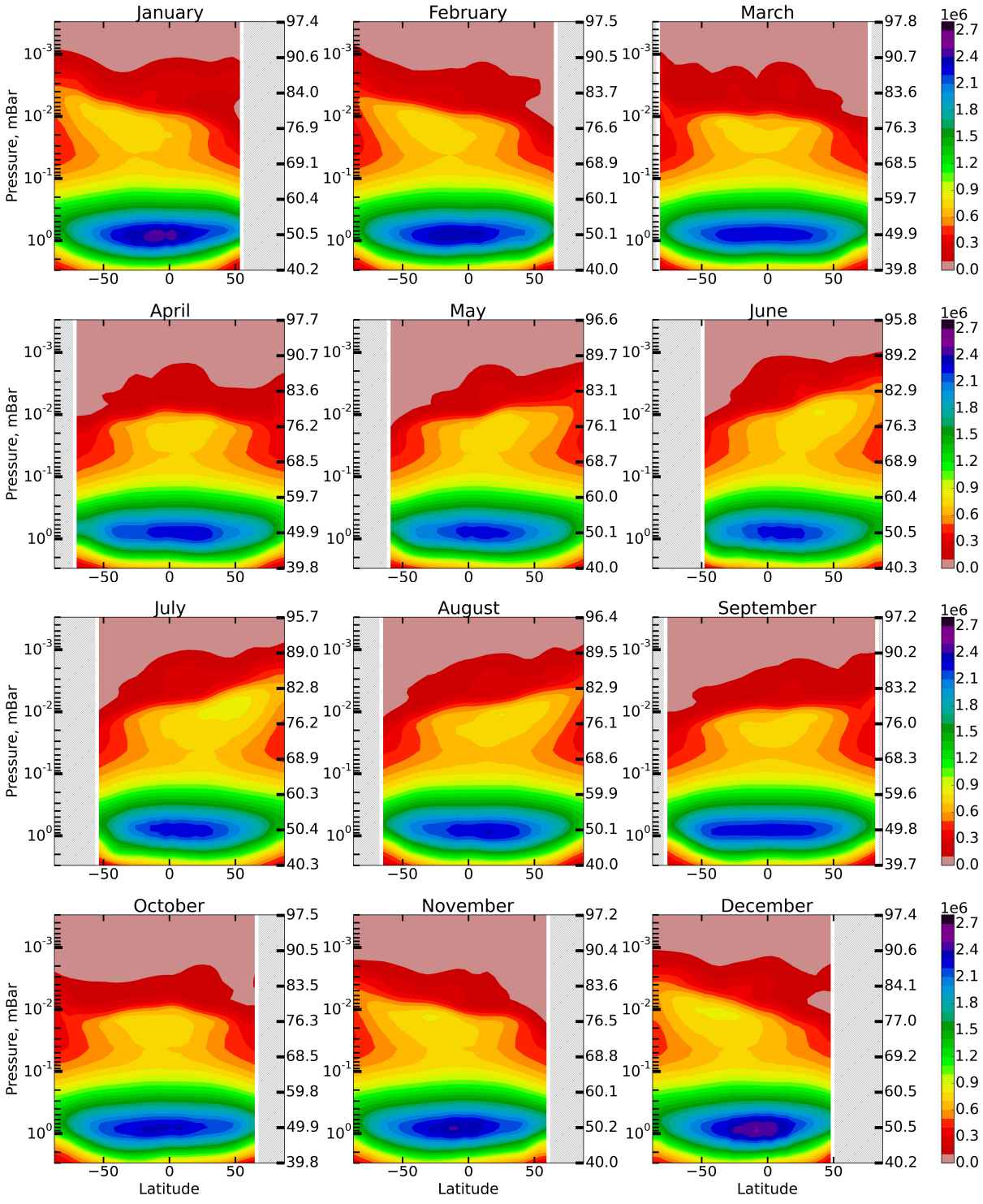

Figure 2. Daytime monthly averaged zonal mean P_{OH} distributions (in $cm^{-3}s^{-1}$).

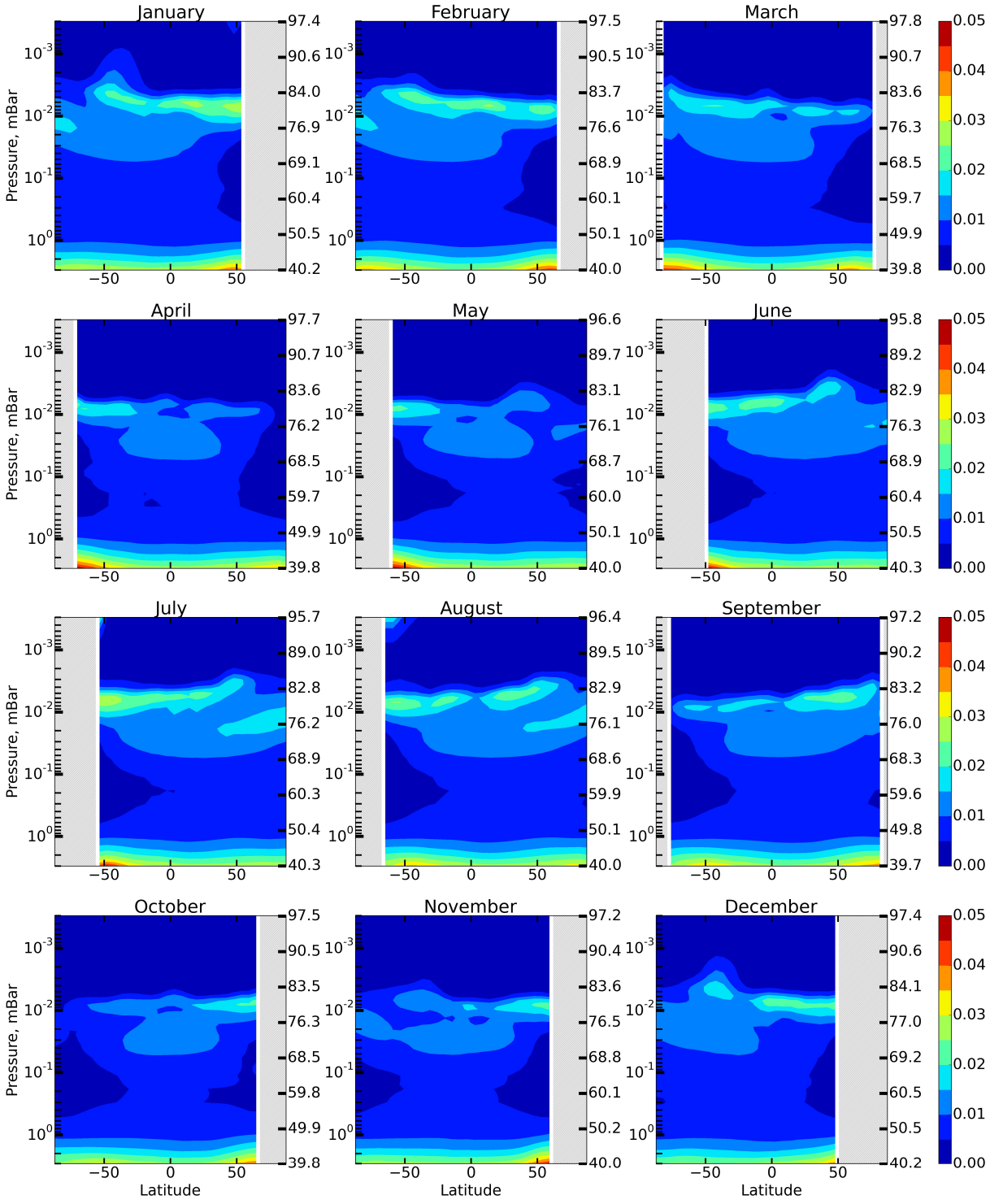

Figure 3. Daytime monthly averaged zonal mean $P_{OH}^{H_2O} / P_{OH}$ distributions.

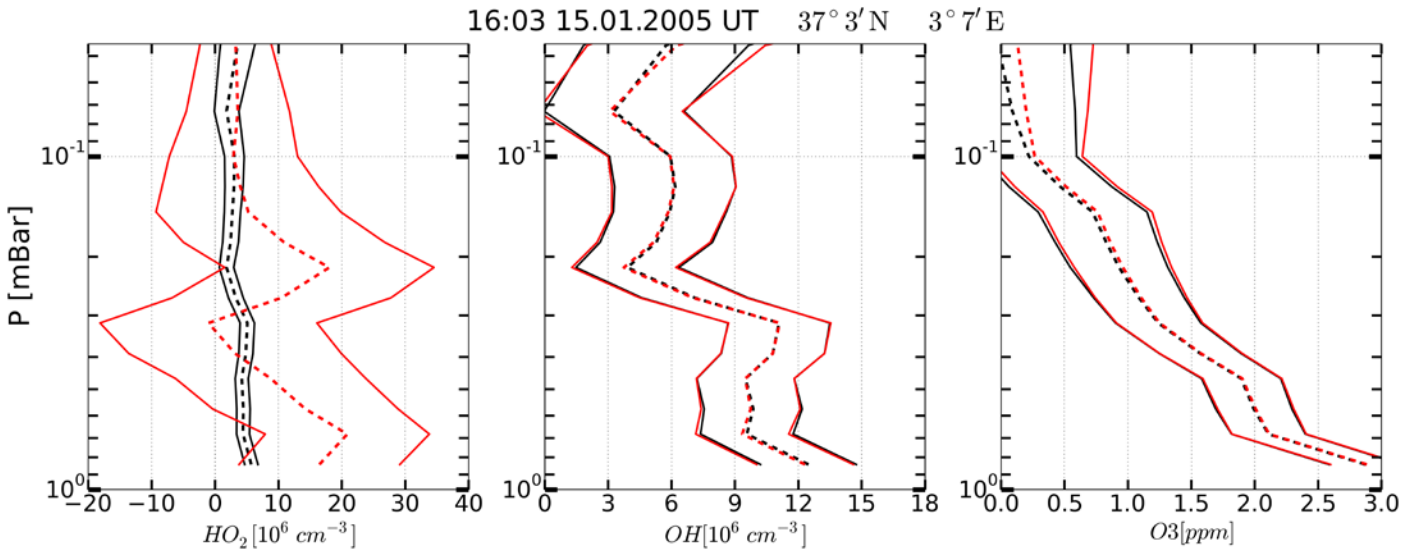

Figure 4. Example of OH, HO_2 and O_3 vertical profiles measured (red curves) on 15 January 2005 at 16.03 UT, $37^0 3'$N, $3^0 7'$E and corresponding retrieved profiles (black curves). Solid curves: boundaries of the 65% confident intervals, dashed curves: medians.

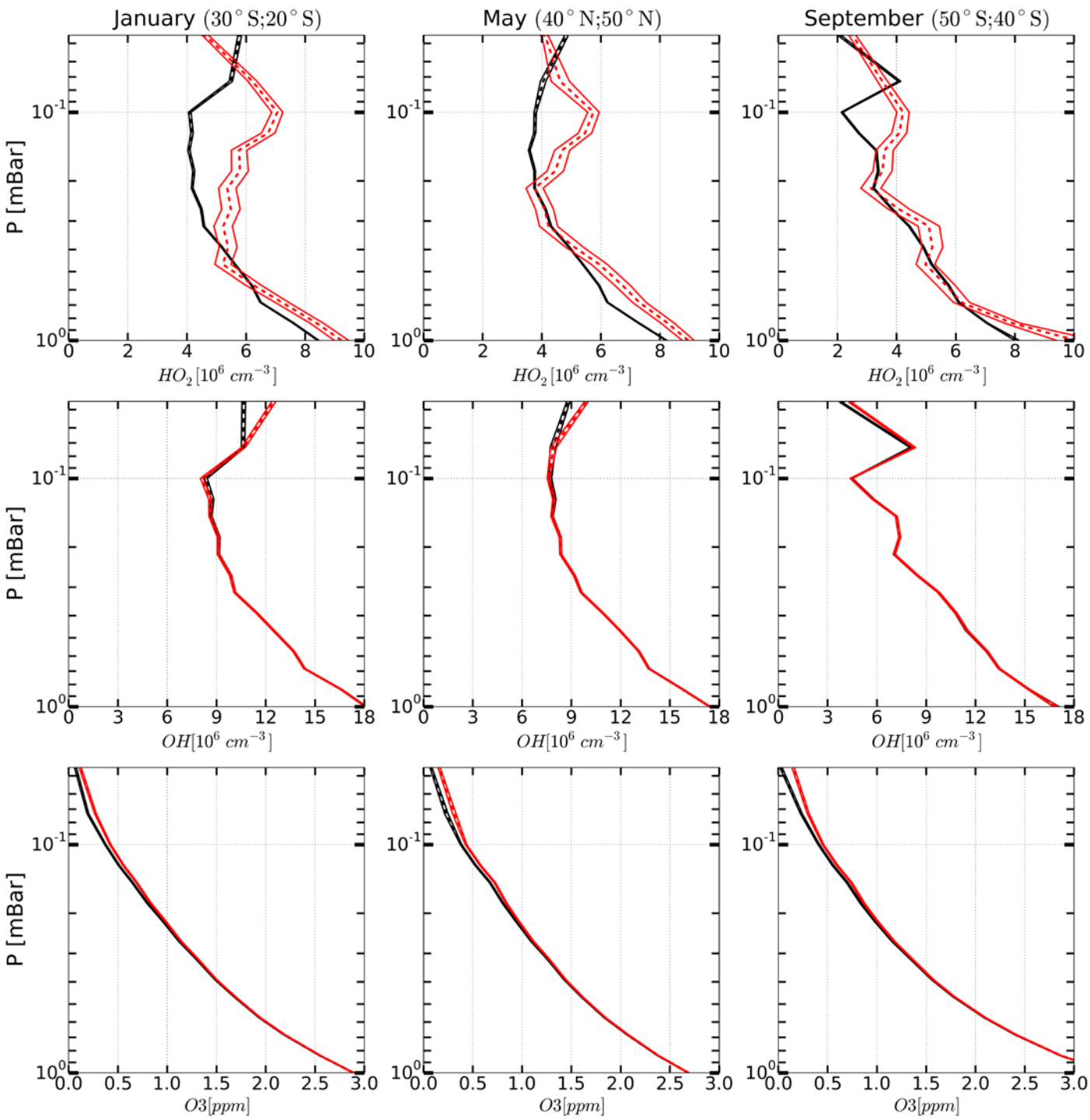

Figure 5. Examples of monthly averaged zonal mean vertical profiles of OH, HO_2 and O_3 measured (red curves) in January, May and March 2005 and corresponding retrieved profiles (black curves). Solid curves: boundaries of the 65% confident intervals, dashed curves: medians.

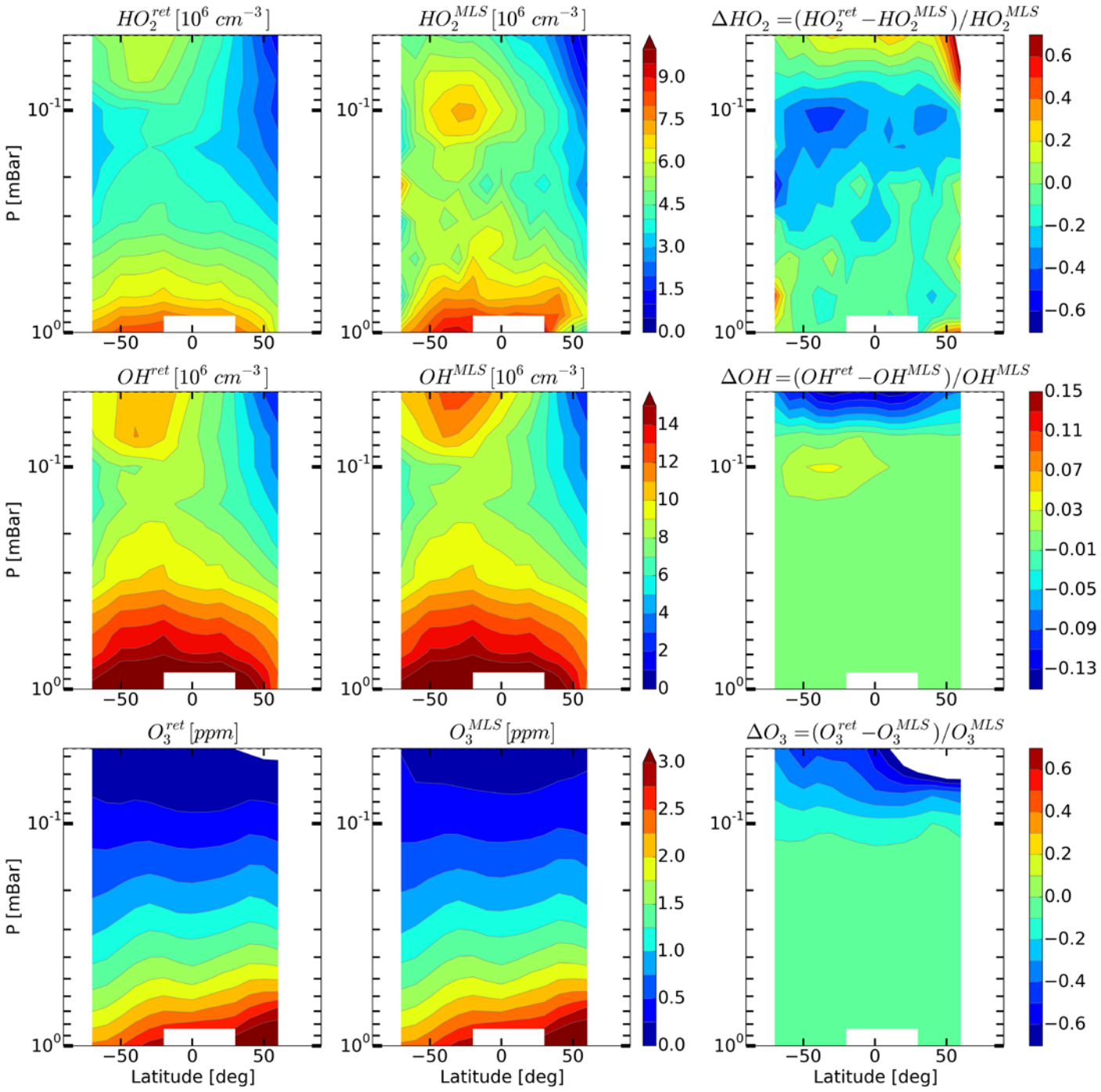

Figure 6. Daytime monthly averaged zonal mean retrieved (left column) and measured (middle column) distributions of HO_2, OH, and O_3 and their relative difference (right column) in January 2005.

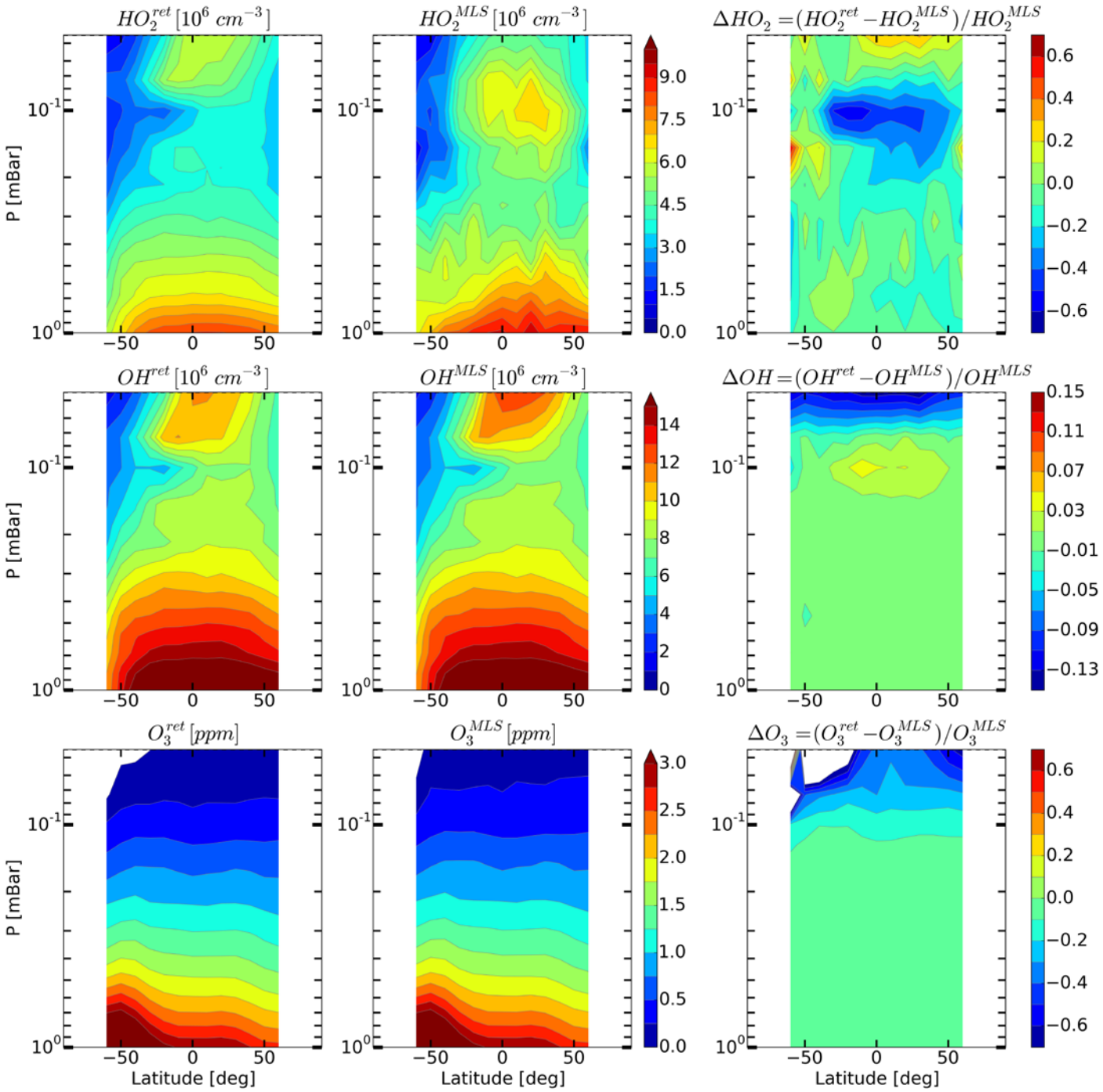

Figure 7. Daytime monthly averaged zonal mean retrieved (left column) and measured (middle column) distributions of HO_2, OH, and O_3 and their relative difference (right column) for May 2005.

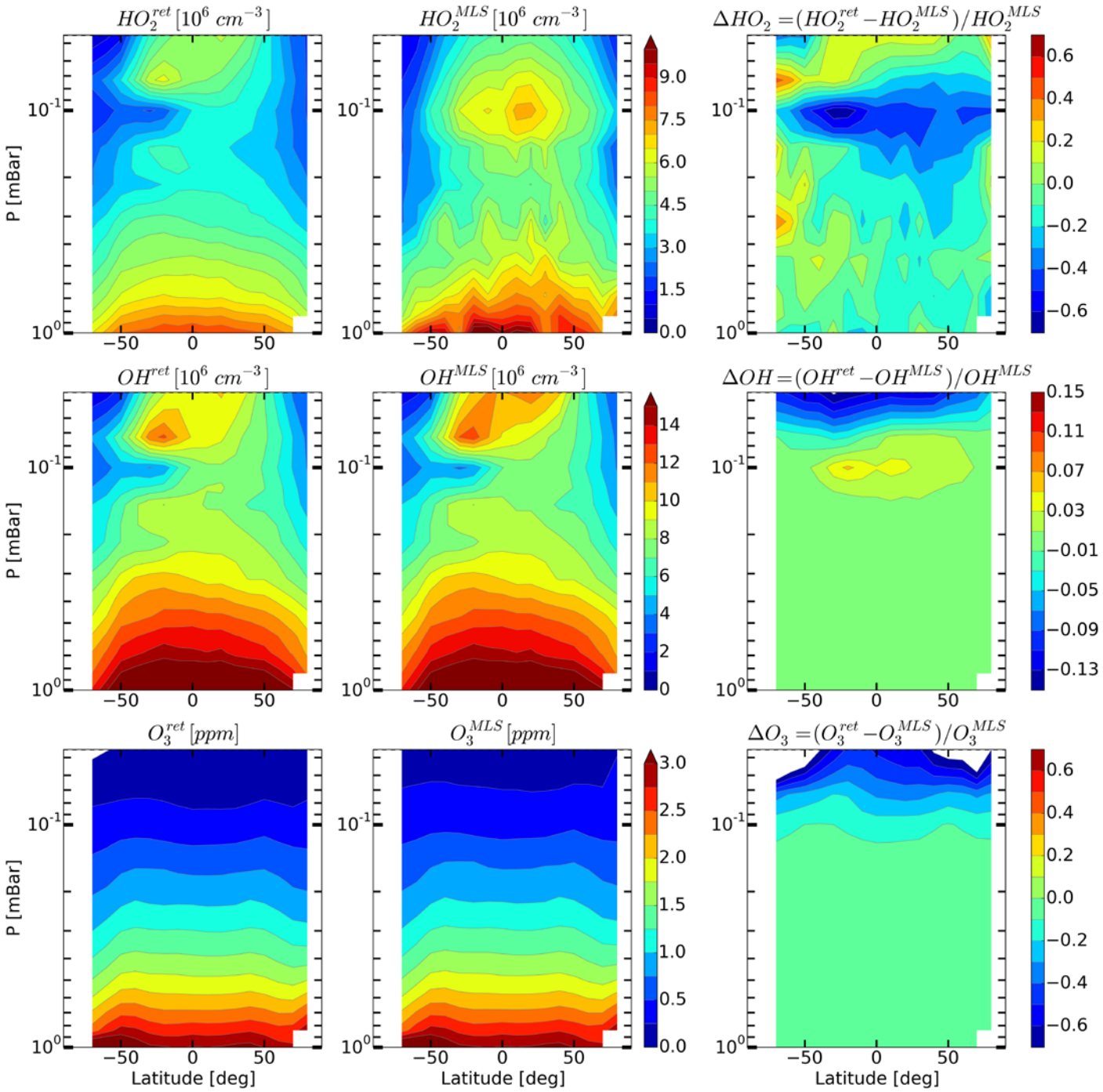

Figure 8. Daytime monthly averaged zonal mean retrieved (left column) and measured (middle column) distributions of HO_2, OH, and O_3 and their relative difference (right column) for September 2005.

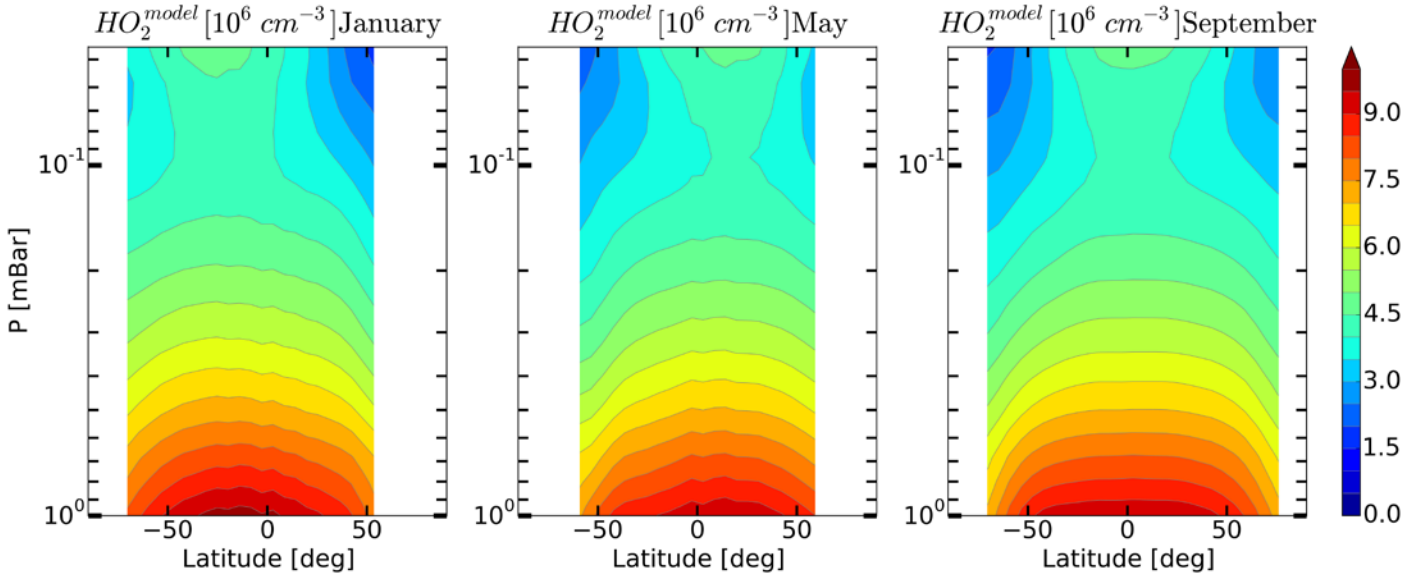

Figure 9. Daytime monthly averaged zonal mean model distributions of HO_2 for January, May, and September.

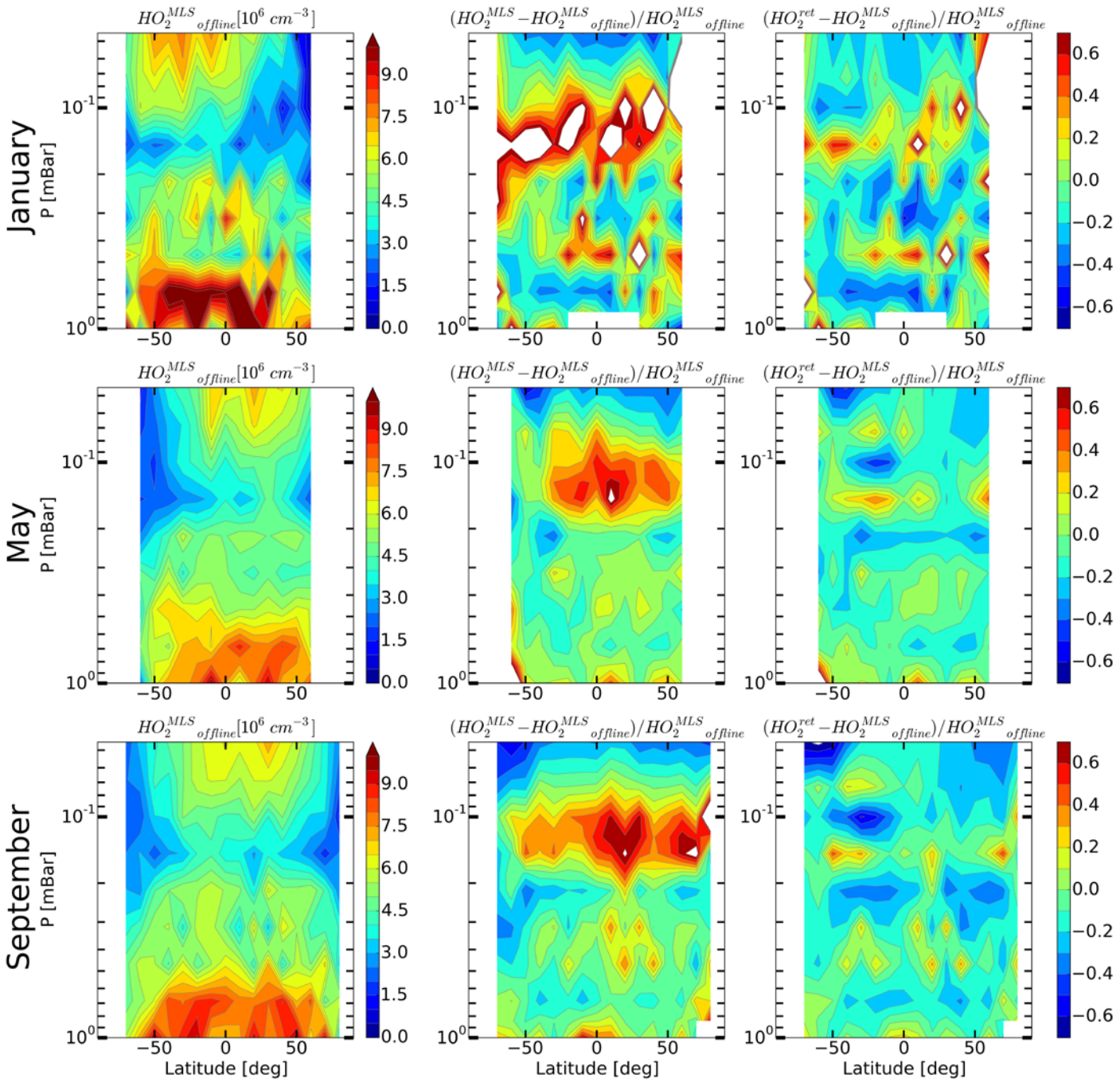

Figure 10. Daytime mean monthly averaged distributions of HO_2 retrieved by Millán et al. (2015) and relative differences $(<HO_2^{MLS}> - <HO_2^{MLS}{}_{offline}>)/<HO_2^{MLS}{}_{offline}>$ and $(<HO_2^{ret}> - <HO_2^{MLS}{}_{offline}>)/<HO_2^{MLS}{}_{offline}>$.