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Modeling of
boundary layer
interaction between
NO₂ and bromine

E. Tas et al.

Measurement-based modeling of bromine chemistry at the Dead Sea boundary layer – Part 2: The influence of NO₂ on bromine chemistry at mid-latitude areas

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Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Abstract

Understanding the interaction between anthropogenic air pollution and Reactive Halogen Species (RHS) activity has had only limited support of direct field measurements, due to the fact that past field measurements of RHS have been mainly performed in Polar Regions. The present paper investigates the interaction between NO_2 and Reactive Bromine Species (RBS) activity by model simulations based on extensive field measurements performed in the Dead Sea area, as described in a companion paper (Tas et al., 2006). The Dead Sea is an excellent natural laboratory for this investigation since elevated concentrations of BrO (up to more than 150 pptv) are frequently observed, while the average levels of NO_2 are around several ppb. The results of the present study show that under the chemical mechanisms that occur at the Dead Sea, higher levels of NO_2 lead to higher daily average concentrations of BrO_x , as a result of an increase in the rate of the heterogeneous decomposition of BrONO_2 that in turn causes an increase in the rate of the “Bromine Explosion” mechanism. The present study has shown that the influence of NO_2 on BrO_x production clearly reflects an enhancement of RBS activity caused by anthropogenic activity. However, above a certain threshold level of NO_2 (daily average mixing ratios of 0.2 ppbv during RBS activity), the daily average concentrations of BrO_x decrease for a further increase in the NO_2 concentrations.

1 Introduction

The destruction of ozone in the tropospheric boundary layer of Polar Regions by Reactive Halogen Species (RHS) has been well documented during the last two decades (Barrie et al., 1988; Wessel et al., 1998; Murayama et al., 1992; Hausmann and Platt, 1994; Tuckerman et al., 1997; Kreher et al., 1997). It has been shown that Reactive Bromine Species (RBS) activity, with BrO levels up to ~ 30 ppt play a major factor in boundary layer ozone depletion events (ODE's) (Platt and Hoenninger, 2003). Recently

ACPD

8, 7725–7753, 2008

Modeling of boundary layer interaction between NO_2 and bromine

E. Tas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Modeling of boundary layer interaction between NO₂ and bromine

E. Tas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

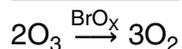
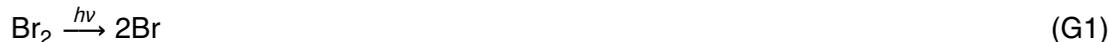
Printer-friendly Version

Interactive Discussion

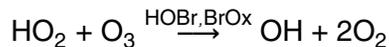
it has been recognized that RBS may also lead to ozone destruction in the boundary layer also at mid-latitude areas. This was evident for the first time at the Dead Sea where very high BrO levels, above 150 ppt, were detected together with daytime depletion of O₃ from levels of above 120 ppb to below the detection limit of the instrument (<1 ppb) (Hebestreit et al., 1999; Matveev et al., 2001). Later, evidence for additional RBS activity has been found at other mid-latitude locations. At the Great Salt Lake, Utah (Stutz et al., 2002), north of the Canary Islands (Leser et al., 2003) and at Salar de Uyuni, Bolivia (Hoenninger et al., 2004).

A companion paper (Tas et al., 2006), presented a chemical mechanism that could account for the RBS activity observed at the Dead Sea. The efficient destruction of ozone through the gas phase was described by the following two well known cycles:

Cycle 1 (BrO-cycle)



Cycle 2 (HOBr-cycle)



**Modeling of
boundary layer
interaction between
NO₂ and bromine**

E. Tas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

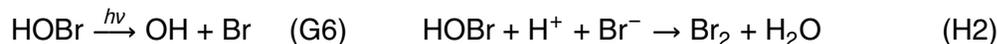
Interactive Discussion

In these chemical cycles, ozone is catalytically destroyed by Br and BrO (BrO_x), while at the Dead Sea, Cycle 1 is more efficient due to the high BrO levels prevalent in this area (Tas et al., 2006). The above is the chemical basis that enables the destruction of ozone within a time scale of a few hours, by RHS, at concentrations three orders of magnitude smaller than ozone. However, it has been suggested (e.g., Lehrer et al., 2004) that the above mechanisms could not explain the observed O₃ destruction rate in the troposphere, if the loss reactions of BrO_x with hydrocarbons were also taken into account.

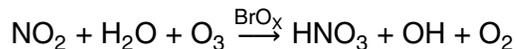
In order to account for the observed BrO_x production and ozone destruction rates at the Dead Sea, more efficient recycling of bromine reservoirs via heterogeneous processes had to be included in the chemical mechanism. This is consistent with other studies (Tang and McConnell, 1996; Sander et al., 1997; De Haan et al., 1999; Michalowski et al., 2000; Pszenny et al., 2004).

It has been shown that the inclusion of the heterogeneous decomposition of BrONO₂ on sulfate aerosols into the mechanism (Hanson and Ravishankara, 1995; Hanson et al., 1996; Sander et al., 1999) can significantly increase BrO_x formation through the production of HOBr. The inclusion of this heterogeneous process together with the “Bromine Explosion” mechanism (Mozurkewich et al., 1995; Vogt et al., 1996; Tang and McConnell, 1996; Platt and Moortgat., 1999) can account for the observed RBS activity at the Dead Sea. These two processes can be described by the following Cycle 3b (Tas et al., 2006):

Cycle 3



net: Cycle 3a



Cycle 3b



Cycle 3b is important because it leads to a nearly exponential growth of Br production via reaction H2, which represents the “Bromine Explosion” mechanism. The importance of the heterogeneous decomposition of BrONO₂, under the Dead Sea conditions, is that it leads to the enhancement of reaction H2 (the rate limiting step in Cycle 3b) by producing HOBr approximately 4 times faster in comparison with reaction (G5).

Based on kinetic considerations the rate of Cycle 3b is enhanced by the concentrations of NO₂ and sulfate aerosols (Tas et al., 2006). This influence of NO₂ and sulfate

Modeling of boundary layer interaction between NO₂ and bromine

E. Tas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



aerosols on the rate of Cycle 3b is of special importance since it represents the influence of anthropogenic activity on the rate of BrO_x production. In practice, the influence of NO_2 levels on the rate of Cycle 3b is more significant since in general, its concentrations change more sharply with the distance from emission sources, than these of SO_2 .

The present research investigates the influence of NO_2 on the diurnal profile and total daily production of BrO_x and ozone destruction, caused primarily by the heterogeneous decomposition of BrONO_2 . The sensitivity of BrO_x production to NO_2 levels via the heterogeneous decomposition of BrONO_2 has been investigated by Sander, et al. (1999), who showed that the increase in NO_2 did not necessarily lead to an increase in the production of BrO_x via the heterogeneous decomposition of BrONO_2 . In the present research this issue is investigated based on simulations performed by Tas et al. (2006) in order to explain the RBS activity at the Dead Sea area.

The effects of anthropogenic activity on RBS activity has had only limited support from direct field measurements, due mainly to the fact that past field measurements of RBS have been performed only in Polar Regions. The Dead Sea basin therefore provides a unique natural laboratory for investigating the interaction between RBS and photochemical pollutants, since very intensive RBS activity (BrO levels up to more than 150 pptv) is frequently observed in this area (Tas et al., 2003; Tas et al., 2005). In general, photochemical air pollution in this area can be characterized by average levels of NO_2 and SO_2 around several ppb. The research summarized in this paper contributes to the overall understanding of the influence of anthropogenic activity on RBS activity and ozone destruction at mid-latitude areas.

Modeling of boundary layer interaction between NO_2 and bromine

E. Tas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

2 Experimental

2.1 Model simulations

All of the simulations presented in Sects. 3.1 and 3.2 are based on the methods and parameters that were used in the “FULL” and the “NOB” simulations described previously in Tas et al. (2006). These simulations will be briefly described in the following. The “FULL” simulation is based on the parameters that were measured at the Dead Sea (Sect. 2.2) and lead to a relatively good agreement with measurements. The difference between the two simulations is that the “FULL” simulation includes the bromine chemistry while in the “NOB” simulation the bromine mechanism is absent. The two simulations were performed by a one dimensional chemical transport model (UAHCTM_1D) (Biazar, 1995), which includes an explicit chemical gas phase mechanism and takes into account the vertical motion of the different species based on diffusion and advection calculations as well as on deposition velocity values. In the model the basic photochemical processes are described by 166 gas-phase reactions based on the Trainer mechanism (Trainer et al., 1987), and updated according to Atkinson et al. (2003). Thirty-one reactions, including five photochemical reactions were added to describe the bromine gas phase mechanism. Two heterogeneous processes, the heterogeneous decomposition of BrONO₂ (H1) and the “Bromine Explosion” mechanism (H2) were also added. For the “FULL” simulation the assumptions were that reaction H1 occurred only on sulfate aerosols while reaction H2 occurred only inside sea salt aerosols.

All of the results and discussion presented in Sect. 3.1 are directly based on the “FULL” simulation, while the results and discussion presented in Sect. 3.2 are based on a set of simulations based on the “FULL” simulation and on the “NOB” simulation, while changing only the NO₂ fluxes as described in more detail in Sect. 3.2. Note that in the paper, the magnitude $\frac{\Delta X}{\Delta t}$ represents the rate of reaction number X , according to explanations given in Tas et al. (2006). This magnitude stands for the first derivative with time (t) of an inert species (X) that was added to the actual products of each

Modeling of boundary layer interaction between NO₂ and bromine

E. Tas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



reaction in the model. As described previously (Tas et al., 2006), it provides a direct measure of the contribution of each reaction to the formation of its products.

2.2 Field measurements

The ‘FULL’ and ‘NOB’ simulations were based on a comprehensive set of atmospheric trace gas measurements and relevant meteorological parameters collected at the Dead Sea as described in Tas et al. (2006). The methods used for these simulations will be briefly described in the following. Continuous measurements of O_3 , NO, NO_x , SO_2 , particulate sulfates and nitrates, wind speed and direction, temperature, relative humidity, pressure and solar radiation, were conducted at the evaporation ponds using the techniques described by Matveev et al. (2001) during 2–12 August 2001. The differential optical absorption spectroscopy (DOAS) technique was employed to quantify BrO (detection limit ≤ 7 pptv) and NO_2 (detection limit ≤ 0.5 ppbv) (Matveev et al., 2001). NO_y species ($NO_y = NO_x + HNO_3 + 2N_2O_5 + NO_3 + \text{organic nitrates} + \text{particulate nitrate} + \dots$) were detected by the use of an appropriate converter located before the inlet of the NO_x monitor. This, together with NO_2 data from the DOAS, was used to calculate the NO_z ($NO_z = NO_y - NO_x$) concentrations. During another campaign at the Ein Bokek site canister samples were collected and analyzed for hydrocarbons using GCMS.

3 Results and discussion

3.1 The influence of NO_2 on the diurnal profiles of BrO_x , BrO and Br

The role of NO is not discussed in this section, because the NO levels measured during the field campaigns were usually very low, and frequently dropped to below detection limit (0.1 ppbv) during RBS activity. Additionally, the simulations showed that at these levels, the influence of NO on RBS activity was insignificant. In contrast, NO_2 plays a significant role in the RBS chemistry at the Dead Sea due to its relative high concentrations and its important contribution to the recycling of BrO_x .

Modeling of boundary layer interaction between NO_2 and bromine

E. Tas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Modeling of
boundary layer
interaction between
NO₂ and bromine**

E. Tas et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

The relationship between NO₂ and BrO during daytime is shown in Fig. 1a. An anti correlation trend between the two can be observed, shown more distinctly in the insert (Fig. 1b). The anticorrelation between the two is in agreement with measurements (Fig. 9 in Tas et al., 2006). The insert represents the time period between 07:30 and 18:00 LT in order to exclude the NO₂ peak occurring around 07:00 LT due to advection from the Dead Sea Works and the diminished BrO formation after 18:00 LT. The strong non-linear jagged shape of both NO₂ and BrO is very obvious. Both the anticorrelation between BrO and NO₂ and their jagged shape can be explained by the periodic two stage cyclic process previously described in detail in Tas et al. (2006), and summarized as follows: At the first stage an increase in ozone concentrations leads to an increase in the rate of BrO production via reaction (G2). This in turn leads to greater production of BrO_x, mainly through Cycle 3b, which then leads to the depletion of O₃ during the second stage of this periodic process. As O₃ levels drop below ~1 to 2 ppbv, Br levels decrease further, due to increased tendency to form terminator species, in competition with its reaction with O₃ (reaction G2) (see Fig. 2). As a result of the decrease in Br concentrations, ozone concentrations increase due to advection, initiating the periodic two stage cyclic process again.

The increase in Br and BrO levels during the first stage leads to a decrease in the concentrations of NO₂. This is mainly due to a higher rate of consumption of NO₂ to form HNO₃ via Cycle 3b, and to a lesser extent due to an enhancement in the formation of BrONO₂ and BrNO₂ (Tas et al., 2006). Thus, during this stage of the periodic process, NO₂ tends to decrease while BrO tends to increase. During the second stage of the process a decrease in BrO and Br concentrations occurs and thus leads to a decrease in NO₂ consumption rate, due to a slower rate of formation of HNO₃, BrONO₂ and BrNO₂. Thus, during this stage of the periodic process, NO₂ increases while BrO tends to decrease. Thus, the two stages process leads to a jagged shape in the diurnal profiles of BrO and NO₂ with an anti-correlation between the two.

The relationship between the termination reactions of RBS activity, represented by the terminator product HBr, and the mixing ratios of O₃, NO₂, Br and BrO is shown

Modeling of boundary layer interaction between NO₂ and bromine

E. Tas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

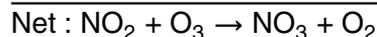
Interactive Discussion

in Fig. 2. It can be seen that, with an analogy to the above explanations, when O₃ levels dip below ~2 ppbv, there is an increase in the mixing ratios of HBr (Fig. 2a and c), which is the main Br termination product. Figure 2c also shows that during intense RBS activity (between 08:00–18:30 LT), NO₂ correlates with HBr mixing ratios. The NO₂ peak around 07:00 LT, is a result of advection for that day, and is an exception. The correlation between NO₂ and HBr is the result of the tendency of these two species to increase as ozone mixing ratios drop below ~2 ppbv during the second stage of the periodic process, and to decrease during the first stage of the periodic process.

At noontime O₃ tends to reach nearly zero concentrations as some of the main bromine terminator species (i.e., HO₂ and CH₂O) reach maximal concentrations. As a result, the depletion of BrO around noontime was repeatedly detected at the Dead Sea area (See Tas et al., 2006, Fig. 5). The relatively high rate of reaction of Br with its terminators during noon time causes the sharp increase in HBr between 10:30 a.m. and 12:30 p.m., simultaneous with Br and BrO depletion and NO₂ increase, as a part of the periodic process (Fig. 2b and c). This contradicts the predictions by von Glasow et al. (2002) that at the Dead Sea, in contrast to other sites, depletion of BrO will not occur during noontime due to the high BrO levels. Their assumption might still be correct for other areas of the Dead Sea, in which the depletion in O₃ is not as intense as it is at the evaporation ponds.

Cycle 4, in addition to Cycle 3, is another important chemical pathway for the recycling of BrO_x via interaction with NO₂:

Cycle 4



Modeling of boundary layer interaction between NO₂ and bromine

E. Tas et al.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


Model simulations show that under the conditions prevalent at the Dead Sea the rates of cycles 4 and 3a are about the same. Cycles 4 and 3a are less important, in terms of O₃ destruction, compared to Cycle 3b, which leads to an exponential net production of Br. However, these cycles (4 and 3a) are important due to their contribution to recycling of BrO_x, while preserving the bromine in the form of BrO, so that it can continue to react through Cycle 3b.

The direct reaction of NO₂ with Br via reaction G9 leads to a null chemical pathway, since the produced BrNO₂ is rapidly photolyzed to give the original reactants as shown in Cycle 5:

Cycle 5



In contrast to cycles 3a and 4, Cycle 5 preserves the bromine in the form of Br, and thus tends to decrease the formation rate of BrO_x via Cycle 3b. During the second stage of the periodic process, the rate of reaction G9 increases in parallel with a simultaneous decrease in the rate of ozone destruction (reaction G2) (Fig. 3a and inset 3a'), reflecting the increase of cycle 5 at the expense of cycles 3 and 4. The rate of reaction G9 increases because less ozone is available to react with Br, and also because of the increase in the ratio [Br]/[BrO]. Because, at this stage, NO₂ has a greater tendency to react with Br than with BrO, the rate of reaction G7 also decreases, in parallel with the increase in reaction G9 and the decrease in reaction G2 (Fig. 3b). Figure 3 shows that the depletion in the rates of reactions G2 and G7 and the increase in reaction G9, are most significant when O₃ mixing ratios drop below the threshold level of about 1 to 2 ppbv.

The influence of O₃ levels on the relative rates of reactions G7 and G9 has an important influence on the way that NO₂ interacts with BrO_x. A decrease in O₃ leads to an

**Modeling of
boundary layer
interaction between
NO₂ and bromine**E. Tas et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

increase in the ratio $[\text{Br}]/[\text{BrO}]$, a consequent increase in the rate of reaction G9 relative to the rate of reaction G7, and therefore to a lower rate of reactions through cycles 3 and 4 relative to the rate of reactions through Cycle 5. This leads to a decrease in the growth of BrOx mixing ratios and therefore a decrease in the destruction rate of O₃, and a lower rate of increase in the mixing ratios of NO₂ (Fig. 2). In contrast, an increase in O₃ levels leads to a higher rate of NO₂ reaction via cycles 3 and 4 relative to the rate of reactions through Cycle 5. This results in an increase in the mixing ratios of BrOx, and therefore an increase in the destruction rate of O₃ and a simultaneous decrease in the mixing ratios of NO₂ (Fig. 2).

3.2 The influence of NO₂ on the daily average levels of BrO_x

As discussed in the previous section, the tendency of NO₂ to react, during daytime, through Cycle 3b, as well as cycles 3a and 4, rather than Cycle 5, greatly enhance the formation of BrOx and ozone destruction. In this section the investigation is limited only to the influence of NO₂ concentrations on the daily (06:00–20:00 LT) average concentrations of BrO, Br, BrO_x and O₃ during RBS activity. Its influence on the diurnal profile of these species is ignored.

The influence of different levels of NO₂ on BrOx concentrations was examined for 11 simulations with various levels of NO₂ fluxes. These simulations were based on the parameters of the “FULL” simulation (Sect. 2) as a base case scenario, and changing only the NO₂ flux levels. For each of these simulations, the value of the NO₂ flux was multiplied by a single factor at each update time (every 15 min). Each of the 11 scenarios was run using a different multiplication factor, n , which was varied from 0.1 to 100, where n is the value by which the NO₂ fluxes of the “FULL” simulation were multiplied. Each of the 11 simulations was run again under the same conditions, except that the bromine mechanism was excluded. Thus, for example, a simulation that was run with $n=1$, represents the “FULL” simulation if the bromine mechanism was included and the “NOB” simulation (Sect. 2) if the bromine mechanism was not included. $n=40$ denotes NO₂ fluxes 40 times larger than those given by the “FULL” or “NOB” base case

simulations. Table 1 shows the daily average mixing ratios of some species and NO₂ fluxes during RBS activity (06:00–20:00 LT) obtained for the different simulations.

Figure 4 shows the results for the eleven simulations relating to the variations in BrO_x, Br and BrO levels with increasing NO₂ levels obtained for the 11 simulations that are based on the “FULL” simulations. Roughly, for Br and BrO_x, the results of these simulations show two distinct zones of influence with respect to the NO₂ levels, separated at approximately $n=40$. In the lower zone, the Br and BrO_x concentrations increase sharply until $n=10$ and less strongly until $n=40$, reaching peak values of 0.2 and 0.25 ppb, respectively. From this point onwards there is a slow decrease in concentrations for both Br and BrO_x. In contrast, the BrO shows a continuous decrease in levels from a value of around 0.04 ppb at $n=0.1$, to half that value at $n=100$. Thus, the increase in BrO_x at the lower zone is due to the strong increase in Br that more than compensates for the decrease in BrO (see Table 1 and Fig. 4).

In the lower zone, the increase in NO₂ leads to an increase in the rate of reactions through Cycle 3b and hence to an increase in the concentrations of Br and BrO_x. The reason for the decrease in the production rate of Br and BrO_x in the lower zone, for $n>10$, and for the decrease in their concentrations at the higher zone, is related to the increase in the tendency of NO₂ to react through Cycle 5 relative to its tendency to react through cycles 3 and 4 for higher NO₂ fluxes. As was explained in Sect. 3.1, the tendency of NO₂ to react through cycles 3 and 4, relative to the rate of reactions through Cycle 5, is determined mainly by the [Br]/[BrO] ratio, which is highly sensitive to variations in O₃ levels. For $n<10$ the ozone concentrations are still high and thus the ratio [Br]/[BrO] (Fig. 5b) is relatively low, and the rate of reactions through Cycles 3 and 4 is high relative to the rate of reactions through cycle 5. Thus, in this range a sharp increase in the concentrations of Br and BrO_x occurs as a result of the increase in NO₂ fluxes (Fig. 4 and Table 1). However, Fig. 6 (see below) shows that this ratio constantly increases for higher n values, and hence an increase in the formation of BrNO₂ occurs at the expense of BrO_x production via Cycle 3b.

The question raised at this stage is the reason for the increase in the ratio [Br]/[BrO]

Modeling of boundary layer interaction between NO₂ and bromine

E. Tas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Modeling of
boundary layer
interaction between
NO₂ and bromine**

E. Tas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

and the consequent decrease in Br and BrO_x concentrations, for increasing *n* values at the higher range. Figure 5 shows that an increase in the ratio [Br]/[BrO] cannot be solely the result of the increase in ozone levels, since above *n*=20 this ratio increases in parallel with the ozone concentrations (Fig. 5a). The increase in the ratio [Br]/[BrO] is the result of the production of Br at the expense of BrO, due to the higher rate of reactions through Cycle3b as the NO₂ levels are higher. The increase in the ratio [Br]/[BrO] leads to an increase in the rate of reactions through Cycle 5 relative to the rate of Cycles 3 and 4, and thus to an enhancement of the production of BrNO₂ at the expense of BrONO₂. Thus, the increase in the concentrations of NO₂ cannot lead to an unlimited increase in the concentrations of Br and BrO_x, since the increase in the formation of Br leads to production of BrNO₂ at the expense of BrO_x production, above a certain level of NO₂.

Figure 5 further demonstrates the complex influence of NO₂ on BrO_x levels. Figure 5c shows the variation in mixing ratios of BrONO₂ and BrNO₂ with increasing NO₂ flux. The increase in the ratio [BrNO₂]/[BrONO₂] for higher *n* values (Fig. 5b), is the result of the increase in the ratio [Br]/[BrO], and reflects an increase in the formation of the reservoir BrNO₂ through Cycle 5, at the expense of the enhancement of BrO_x production and BrO recycling through cycles 3 and 4, respectively. At a certain stage the rate of reactions through Cycle 5 become predominant relative to the rate of reactions through Cycle 3b. This leads to a decrease in the growth of Br and BrO_x concentrations above *n*=10 and to a decrease in their concentrations above *n*=40.

The constant increase in BrONO₂ reflects the constant increase in the rate of reactions through Cycle 3b for higher *n* values, which leads to the increase in the concentrations of the total bromine (Br_t) species (Fig. 5d). However, although Br_t increases at higher *n* values, the increase in the formation of BrNO₂ via Cycle 5 dominates the BrO_x production above *n*~4, and leads to a decrease in the ratio [BrO_x]/[Br_t].

The influence of the increase in NO₂ concentrations on ozone destruction via BrO_x production is demonstrated in Fig. 6. This figure shows the average ozone mixing ratios with and without the effect of bromine chemistry. Under the full bromine chemistry

**Modeling of
boundary layer
interaction between
NO₂ and bromine**

E. Tas et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

conditions the average ozone levels show a continuous drop for increases in n values, reaching minimum levels (~ 1 ppb) at $n=20$. It should be remarked that the reduction in O₃ levels in this lower NO₂ zone occurs under NO_x limited conditions in terms of the efficiency of photochemical ozone production. Above $n=20$, ozone levels continuously increase due to the decrease in BrO_x levels. Between $n=20$ and 40 there is an increase in O₃ levels although the BrO_x levels increase. This increase is due to the greater contribution of NO₂ to form O₃ via photochemical processes, in comparison with its contribution to O₃ destruction as a result of BrO_x formation. In contrast, when no bromine chemistry is active, the ozone concentrations increase with increasing NO₂, since the system is NO_x limited. However from levels above $n=40$ a sharp decrease in ozone levels is observed, due to titration between O₃ and NO. From this point forward the ozone concentrations remain almost constant.

The analysis presented in this section shows that an increase in the growth of BrO_x, as a result of an increase in NO₂ levels, occurs for a wide range of NO₂ concentrations, representing a wide range of anthropogenic pollution levels (see Table 1). Thus, also in other areas in which the heterogeneous decomposition of BrONO₂ and the “Bromine Explosion” mechanism occur efficiently enough, an increase in NO₂ concentrations should result in an increase in BrO_x concentrations and a consequent depletion in ozone concentrations.

In other cases for which these two processes do not occur efficiently enough, the increase in the concentrations of NO_x can lead to continues decrease in the concentrations of BrO_x. For example, several studies (e.g., Beine et al., 1997; Sander et al., 1999; Ridley and Orlando., 2003) have showed that an increase in the concentrations of NO_x impedes the destruction of ozone due to its tendency to form reservoirs by interaction with BrOx. Thus, simultaneous depletions in ozone and NO_x, during ODE’s were explained by the higher impact of RBS activity on reduction in ozone levels due to a decreased tendency to form bromine containing nitrogen reservoirs, as the NO_x levels are lower. It should be remarked that these simultaneous depletions in NO_x (representing mainly depletion in NO₂) and ozone concentrations might also be the result

**Modeling of
boundary layer
interaction between
NO₂ and bromine**

E. Tas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

of the heterogeneous decomposition of BrONO₂ that may lead to both NO₂ depletion (e.g., Tas et al., 2006; Morin et al., 2007) and ozone destruction via BrO_x formation. The significant influence of heterogeneous recycling of BrONO₂ on the way that an increase in the NO_x concentrations influences RBS activity was also demonstrated by von Glasow et al. (2003). Their study showed that when the total surface area of particles available for the recycling of BrONO₂ and HBr is high enough, the transformation of RBS into bromine-containing nitrogen reservoirs is significantly reduced.

It has been shown in this section that even in cases where the two heterogeneous processes, the “Bromine Explosion” mechanism and the heterogeneous decomposition of BrONO₂ take place in the chemical mechanism, increasing NO₂ cannot continue to increase the concentrations of BrO_x indefinitely. Above a certain threshold value of NO₂, the concentrations of BrO_x are predicted to decrease. According to the present research, under conditions typical of the Dead Sea, this threshold value averages 0.2 ppbv during 06:00–20:00 LT time period (see Table 1). This value is equivalent to an average NO₂ concentration of about 2.1 ppbv, for the same conditions without the bromine mechanism. This threshold value is influenced by many factors. Basically, a decrease in BrO_x, for an increase in NO₂ levels, is predicted to occur only if O₃ levels are low enough in order to enable a low enough [Br]/[BrO] ratio. The [Br]/[BrO] ratio and hence also the threshold value are sensitive to other parameters, including the total surface area available for heterogeneous decomposition of BrONO₂, the rate of bromine release into the gas phase, etc. Thus, the threshold level of NO₂ should be different at other locations.

An earlier study (Sander et al., 1999) suggested that an increase in NO₂ levels did not result in a higher contribution to BrO_x production by the heterogeneous decomposition of BrONO₂. The reason given for that (Sander et al., 1999) was that the higher levels of NO₂ led to a significant increase in the reaction rates of NO₃ and N₂O₅ with Br⁻ via the heterogeneous reactions (H3) and (H4):





In contrast, under the conditions at the Dead Sea, which were also used by the “FULL” simulation, the daytime levels of NO_3 and N_2O_5 remained in the sub-ppt level. For example, for the “FULL” conditions the NO_3 levels were at least two orders of magnitude smaller than NO_2 , while N_2O_5 levels were four orders of magnitude smaller than NO_2 levels. Thus, it appears that under the conditions represented by the present study, reactions (H3) and (H4), which involve NO_3 and N_2O_5 , can be neglected in comparison with reaction H1.

4 Summary

The influence of NO_2 on both the diurnal profiles and daily average production of Br and BrO was investigated in this study, based on measurements performed at the evaporation ponds at the Dead Sea. It has been shown that the ratio $[\text{Br}]/[\text{BrO}]$ has a significant influence on the way that NO_2 influences both the diurnal profiles and average daily production of Br and BrO. Higher levels of $[\text{Br}]/[\text{BrO}]$ lead to a decrease in the concentrations of BrO_x during the day and on a daily average basis. This is because higher levels of $[\text{Br}]/[\text{BrO}]$ lead to higher rates of reactions of NO_2 through Cycle 5 relative to the rate of reactions through cycles 3 and 4. During the daytime, higher levels of ozone were the major factor causing an increase in the production of BrO_x by decreasing the ratio $[\text{Br}]/[\text{BrO}]$. However, for higher NO_2 levels and on a daily average basis, the NO_2 concentrations were the major factor to influence the BrO_x concentrations by changing the $[\text{Br}]/[\text{BrO}]$ ratio, while ozone had only a secondary effect on this ratio.

The present study shows that the influence of NO_2 on the daily average BrO_x production, can be divided into two main zones of NO_2 levels, separated by a certain threshold value of NO_2 concentrations. According to the present research, under the Dead Sea conditions this threshold value equals about 0.2 ppbv on a daily (06:00–

**Modeling of
boundary layer
interaction between
 NO_2 and bromine**

E. Tas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



20:00 LT) average. This value is equivalent to a daily average concentration of NO_2 of about 2.1 ppbv, for the same conditions excluding the bromine mechanism. In other geographical locations the value of this threshold level is expected to be different because it depends on many parameters, including the total surface area available for heterogeneous decomposition of BrONO_2 , among other factors.

In the lower zone, below the threshold level of NO_2 , an increase in NO_2 leads to a higher production of BrO_x , which results in more intensive destruction of O_3 , as a result of an increase in the rate of reactions through cycles 3 and 4 relative to the rate of reactions through Cycle 5. For higher NO_2 levels the rate of Cycle 5 relative to cycles 3 and 4 becomes higher until, above a certain threshold level of NO_2 , an additional increase in NO_2 levels leads to a decrease in BrO_x levels and O_3 destruction. It is demonstrated by the present study that, on a daily average basis, above a certain threshold level of NO_2 , an increase in the concentrations of NO_2 leads to a decrease in the BrO_x concentrations, in a self-terminating process.

One of the most significant contributions of the present study refers to the relation between anthropogenic activity and RBS activity. It was shown that an increase in the concentrations of NO_2 leads to an enhancement of ozone destruction via an increase in the concentrations of BrO_x for a relatively wide range of NO_2 levels, reflecting different levels of anthropogenic activity. Similar influence of anthropogenic activity on RBS activity is expected to occur in other areas that are under the influence of anthropogenic activity, in which the heterogeneous decomposition of BrONO_2 and the release of bromine into the gas phase activated by HOBr are involved in the chemical mechanism. It should be remarked that in other areas in which these two processes, are not significant enough, the increase in NO_x levels may cause a decrease in ozone destruction rates due to the formation of bromine-containing nitrogen reservoirs.

The present study shows that, on a daily average basis and for all levels of NO_2 that were investigated, the levels of the total bromine species in the gas phase increase for higher NO_2 levels, as the result of an absolute increase in the rate of Cycle 3b. In the higher zone, the formation of BrNO_2 is favored at the expense of BrO_x . Once the

Modeling of boundary layer interaction between NO_2 and bromine

E. Tas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

ozone concentrations increase again, this reservoir may undergo fast photolysis during daytime, thereby increasing the concentrations of BrO_x.

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Modeling of boundary layer interaction between NO₂ and bromine

E. Tas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Modeling of
boundary layer
interaction between
NO₂ and bromine**

E. Tas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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**Modeling of
boundary layer
interaction between
NO₂ and bromine**

E. Tas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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**Modeling of
boundary layer
interaction between
NO₂ and bromine**

E. Tas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Table 1. Average (06:00–20:00 LT time period) concentrations of various species obtained for NO₂ different levels.

Multiplication factor (<i>n</i>) for NO ₂ fluxes*	BrO (ppbv)	Br (ppbv)	NO ₂ (ppbv)	O ₃ (ppbv)	NO ₂ ** (NOB) (ppbv)	O ₃ ** (NOB) (ppbv)
0.1	0.0444	0.0523	0.0424	4.81	0.795	70.3
0.125	0.0444	0.0526	0.0425	4.80	0.797	70.4
0.167	0.0444	0.0531	0.0426	4.77	0.798	70.5
0.25	0.0444	0.0541	0.0430	4.71	0.801	70/6
0.5	0.0445	0.0575	0.0436	4.44	0.809	71.0
1	0.0445	0.0651	0.0439	4.20	0.825	72.0
2	0.0445	0.0824	0.0450	3.60	0.857	73.7
4	0.0438	0.121	0.0518	2.80	0.922	76.9
6	0.0412	0.153	0.0631	2.02	0.984	79.8
8	0.0406	0.184	0.0767	1.33	1.05	82.5
10	0.0395	0.193	0.0964	1.08	1.11	85.0
20	0.0381	0.199	0.211	1.02	1.47	95.4
40	0.0328	0.223	0.194	1.52	2.05	109
60	0.0294	0.211	0.921	2.25	76.9	229
80	0.0250	0.196	1.39	2.98	98.3	213
100	0.0238	0.182	1.89	3.69	115	198

* The “*n*” factors represent the values by which the NO₂ fluxes included in the “FULL” simulation were multiplied (see Sect. 3.2). The average NO₂ flux used for “FULL” simulation is $3.61 \cdot 10^{13}$ molec/m² during RBS activity (06:00–20:00 LT).

** Mixing ratios obtained during “NOB” simulation.

Modeling of boundary layer interaction between NO₂ and bromine

E. Tas et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Modeling of
boundary layer
interaction between
 NO_2 and bromine

E. Tas et al.

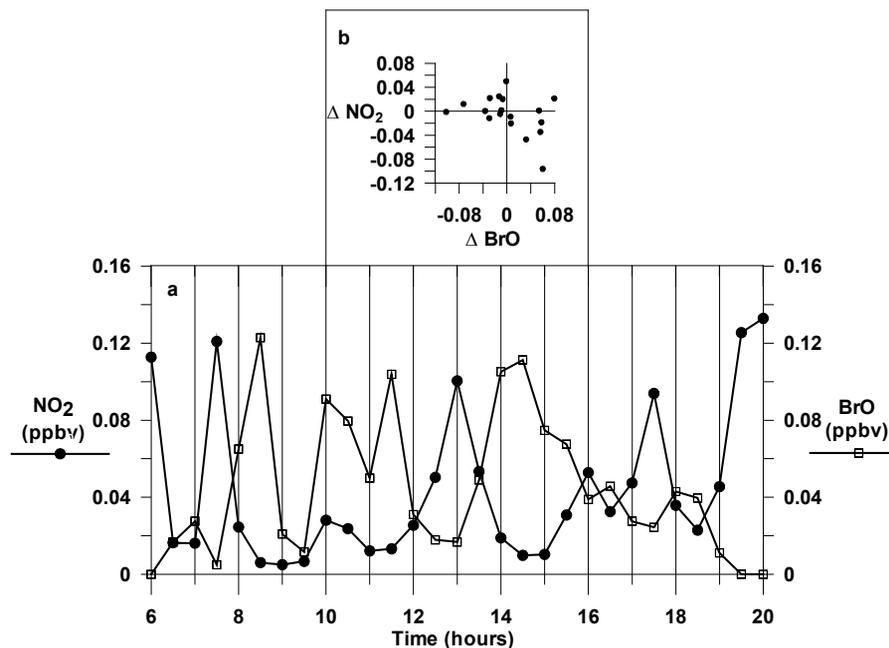


Fig. 1. Simulated mixing ratios of BrO and NO_2 . **(a)** BrO and NO_2 diurnal profiles obtained for “FULL” simulation. **(b)** The difference in NO_2 mixing ratios between each two following time points was calculated and presented vs. the concurrent difference in BrO mixing ratios. The graph shows the data between 07:30–18:00 LT.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Modeling of boundary layer interaction between NO_2 and bromine

E. Tas et al.

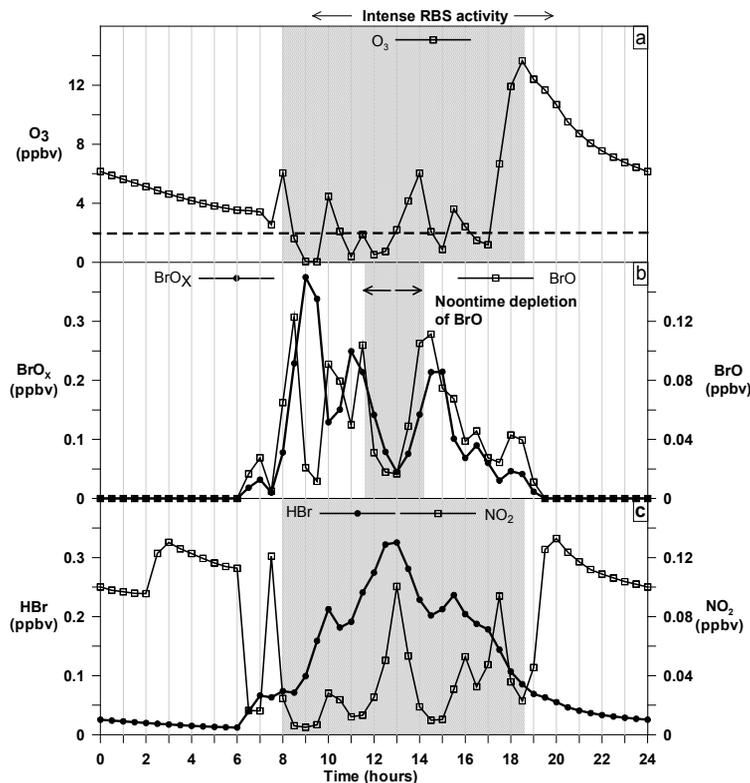


Fig. 2. The influence of O_3 depletion below $\sim 1\text{--}2$ ppbv on BrO , BrO_x and NO_2 diurnal profiles*. **(a)** When O_3 levels are reduced below $\sim 1\text{--}2$ ppbv, mixing ratios of HBr increase, indicating an increase in the rate that Br undergoes termination reactions (c). **(b)** This in turn causes the decrease in Br and BrO mixing ratios, and hence leads to lower BrO_x levels. **(c)** The decrease in Br and BrO mixing ratios as O_3 dip below $\sim 1\text{--}2$ ppbv leads to an increase in NO_2 mixing ratios, due to lower consumption rate by Br and BrO . This is the reason for the positive correlation between NO_2 and HBr . The increase in the mixing ratios of NO_2 and HBr is most significant during the noontime, as the mixing ratios of Br and BrO are depleted.

* All presented diurnal profiles were obtained during “FULL” simulation. The shaded area in **(a)** and **(c)** refers to intensive RBS activity, while the shaded area in **(b)** refers to noontime (see Sect. 3.1).

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

Modeling of boundary layer interaction between NO₂ and bromine

E. Tas et al.

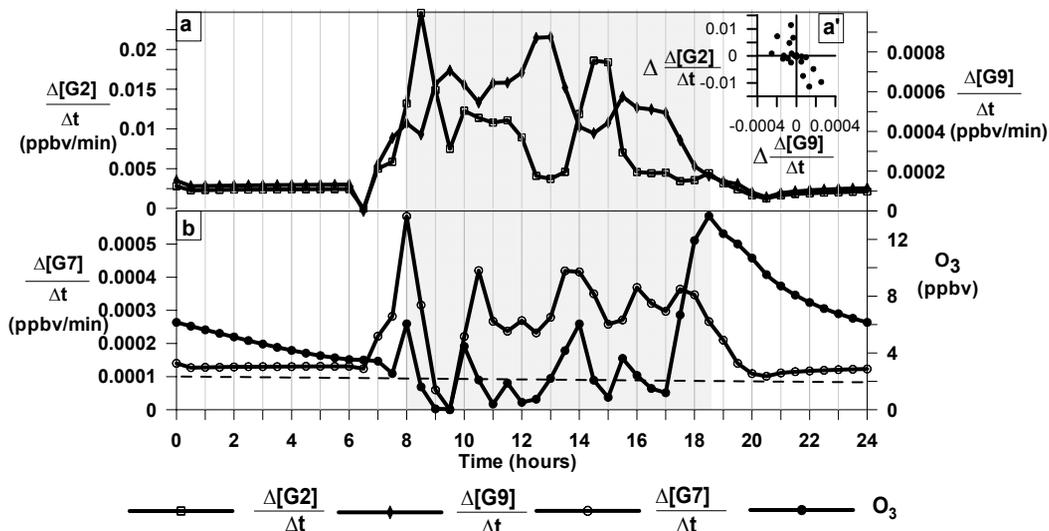


Fig. 3. The influence of ozone levels on the relative tendencies of NO₂ to react through cycles 3, 4 and 5*. **(a)** During the second stage of the periodic process as intensive RBS take place (indicated by the shaded areas in plots a and b) a decrease in the rate of reaction G2 and an increase in the rate of reaction G9 occur, as a result of the decrease in ozone mixing ratios, below the level of ~ 1 to 2 ppbv, and a consequent increase in the ratio [Br]/[BrO]. The insert 3.a' presents the difference in reaction rate G2 between each two following time points versus the compatible differences in the values of the rate of reaction G9. This graph relates only to values that were obtained during RBS activity (06:00–20:00 LT). **(b)** The phenomena described above occur most significantly as a decrease in ozone mixing ratios below the threshold level of ~ 1 to 2 ppbv occurs. Due to the increase in the ratio [Br]/[BrO] during the second stage, the rate of reaction G7 also decreases parallel to the decrease in the rate of reaction G2 and the increase in the rate of reaction G9.

* All presented diurnal profiles were obtained during “FULL” simulation.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

Modeling of boundary layer interaction between NO_2 and bromine

E. Tas et al.

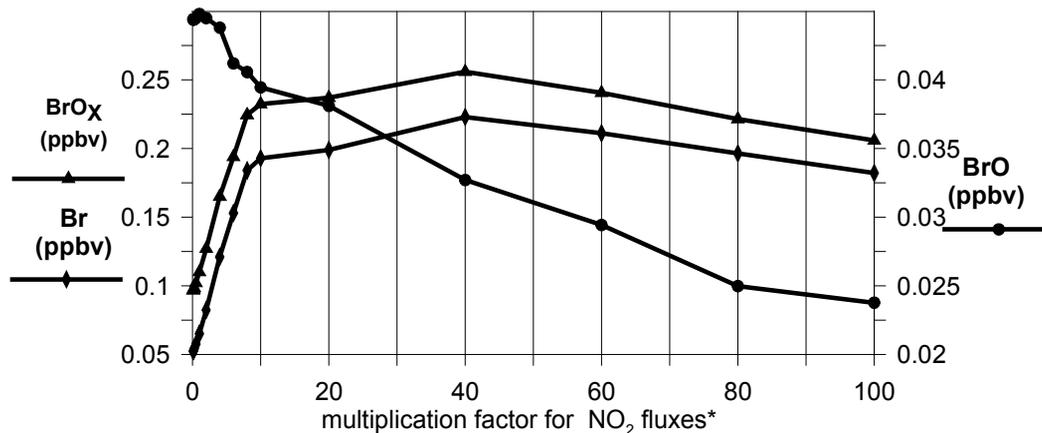


Fig. 4. Br, BrO and BrO_x mixing ratios as a function of NO_2 flux magnitude. The mixing ratios of Br, BrO and BrO_x obtained for the 11 simulations based on the “FULL” simulation are presented versus the multiplication factor for NO_2 fluxes, n^* . Two zones can be observed for changes in Br and BrO_x concentrations, separated in the graph at $n=40$. In the lower zone Br and BrO_x increase sharply until $n=10$. In contrast, BrO concentrations decrease sharply from $n<1$.

* See additional information on the multiplication factor, n , in Sect. 3.2.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

Modeling of boundary layer interaction between NO_2 and bromine

E. Tas et al.

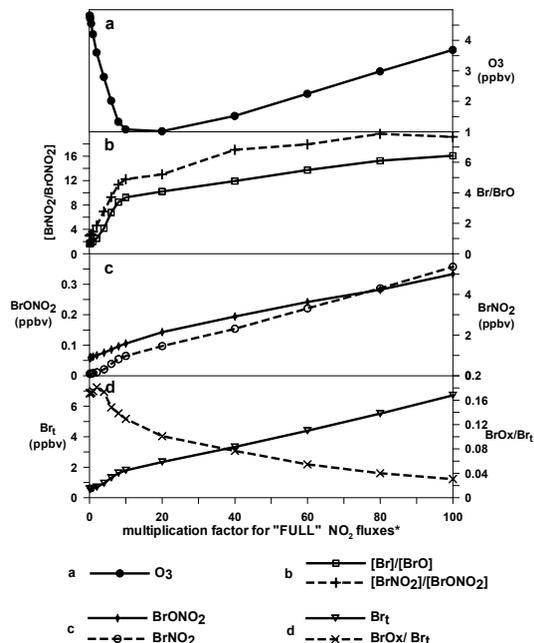


Fig. 5. Production of BrO_x and total bromine species as a function of NO_2 fluxes. **(a)** O_3 mixing ratios obtained for the 11 simulations that included the “FULL” bromine mechanism. O_3 concentrations decrease for an increase in n values until around $n=20$. The increase in the concentrations of O_3 for $n \gtrsim 20$ indicates that the ratio $[\text{Br}]/[\text{BrO}]$ is not influenced only by the O_3 concentrations. **(b)** The ratio $[\text{Br}]/[\text{BrO}]$ constantly increase for an increase in n levels, mainly as a result of the higher rate of reactions through cycle 3b that lead to production of Br at the expense of BrO. The increase in the ratio $[\text{Br}]/[\text{BrO}]$ leads to an increase in the ratio $[\text{BrNO}_2]/[\text{BrONO}_2]$, for higher n values. This reflects an increase in the rate of reactions through Cycle 5 relative to the rate of reactions through cycles 3 and 4. This, in turn, leads to a faster production of BrNO_2 via Cycle 5 at the expense of BrO_x production and recycling via cycles 3b and 3a and 4, respectively. At a certain stage the ratio $[\text{Br}]/[\text{BrO}]$ is high enough, to cause a decrease in the concentrations of Br and BrO_x for an increase in n values. **(c)** Both the concentrations of BrNO_2 and BrONO_2 constantly increase for an increase in n values. **(d)** The continuous increase in the concentrations of BrONO_2 leads to a continuous increase in BrI , for an increase in n values, due to an increase in the rate of Cycle 3b. The increase in the ratio $[\text{BrNO}_2]/[\text{BrONO}_2]$ leads to an increase in the ratio $[\text{BrI}]/[\text{BrO}_x]$ above $n \gtrsim 4$, due to an increase in the rate of Cycle 5 relative to the rates of cycles 3 and 4.

* See additional information on the multiplication factor, n , in Sect. 3.2.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

Modeling of boundary layer interaction between NO₂ and bromine

E. Tas et al.

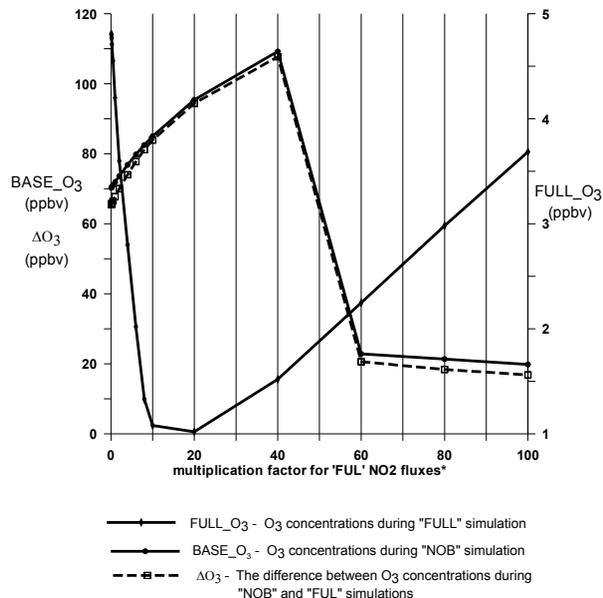


Fig. 6. Destruction of ozone by RBS activity as a function of NO₂ flux magnitude. Presented are the O₃ mixing ratios obtained for the 11 simulations that includes the “FULL” bromine mechanism (FULL_O₃), the O₃ mixing ratios that were obtained during the 11 simulations that didn't include the bromine mechanism (BASE_O₃), and the difference between these two categories (ΔO₃). The “FULL_O₃” concentrations decrease for n values smaller than 20 due to an increase in BrO_x concentrations as a result of the increase in the rate of Cycle 3b. For these n values the “FULL_O₃” decrease although the “BASE_O₃” production is NO_x limited in terms of photochemical ozone production. Between $n=20$ and $n=40$ an increase in “FULL_O₃” concentrations occurs although BrO_x concentrations increase too. This should be the result of the more intense effect of NO₂ to increase O₃ due to the limited NO_x conditions in terms of photochemical ozone production, compared to its effect to reduce O₃ as a result of increase in BrO_x production.

* See additional information on the multiplication factor, n , in Sect. 3.2.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[⏪](#)
[⏩](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)