The effect of convection on the summertime extratropical lower stratosphere

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Abstract. Satellite and in situ water vapor and ozone observations near the base of the overworld (θ ≈ 380-K potential temperature) are examined in summertime northern mid-latitudes, with a focus on how their horizontal variations are influenced by deep convection. We show that summertime convection has a significant effect on the water vapor budget here, but only a small effect on the ozone budget. Using a simple model, we estimate that convection increases model extratropical water vapor at 380 K by 40%, but decreases model extratropical ozone by only a few percent, relative to what would occur without convection. In situ data show that this convective injection occurs up to at least ~390 K. This raises the possibility that the convectively moistened air might travel isentropically to the tropics and ascend into the stratospheric overworld without passing through the cold point. We argue that trends in convective moistening should be examined as possible contributors to observed trends in lower stratospheric water vapor, at least during summer months.
Introduction

The mechanisms that determine the chemical composition of the upper troposphere/lower stratosphere (UT/LS) are of considerable interest to the scientific community. One process in particular, vertical transport via deep convection, has been the subject of much recent debate. In the tropics, convection to the altitude of the tropopause and above does occur [e.g., Alcala and Dessler, 2002; Gettelman et al., 2002] and appears to play a role in determining the abundance of trace species there [e.g., Dessler, 2002]. In the extratropics, the canonical view has been that the lowermost stratosphere, bounded at the bottom by the extratropical tropopause and the top by the 380-K potential temperature ($\theta$) surface, is primarily influenced by horizontal, isentropic transport from the tropical upper troposphere and by slow downwelling from the stratosphere above, but not to a great extent by extratropical deep convection [e.g, Holton et al., 1995].

There is, however, plenty of anecdotal evidence that extratropical convection does penetrate well into the lowermost stratosphere [e.g., Roach, 1967; Poulida et al., 1996; Fischer et al., 2003], and even into the overworld ($\theta > 380 \text{ K}$) [Fromm and Servranckx, 2003; Fromm et al., 2000; Wang, 2003; Jost et al., 2004] (see, e.g., Hoskins [1991] or Holton et al. [1995] for definitions and a discussion of the overworld and lowermost stratosphere). A key question is whether these penetrations are simple curiosities, or important in the constituent budget of the lowermost stratosphere or overworld.

To illustrate the problem, we plot in Figure 1 the vertical distribution of water vapor ($\text{H}_2\text{O}$) volume mixing ratio (VMR) measured by instruments on NASA’s WB-57 aircraft during the Cirrus Regional Study of Tropical Anvils and Cirrus Layers — Florida Area
Cirrus Experiment (CRYSTAL-FACE). Only those measurements with coincident measurements of O$_3$ VMR > 400 ppbv are shown here. The data were obtained on flights out of Key West Naval Air Station, Florida, U.S.A. (24°N, 82°W) during July 2002, at latitudes between 14°N and 27°N.

Figure 1 shows that for $\theta > \sim 400$ K, H$_2$O VMRs are 4.5-6.0 ppmv. These are quite typical values for the overworld, and are explained by dehydration to around 3.85 ppmv at the tropical tropopause [e.g., Dessler and Kim, 1999] combined with production of H$_2$O from CH$_4$ and H$_2$ oxidation [e.g., Wofsy et al., 1972; Ehhalt and Tönnißen, 1979]. At and below $\sim 390$ K, H$_2$O VMRs well above these stratospheric values are evident. Since these high values could not have descended from the overworld, some of this air must have come from the troposphere, either by local moist convection or quasi-horizontal eddy transport from the tropical upper troposphere. On the other hand, the O$_3$ values associated with these measurements (> 400 ppbv) are several times greater than typical tropospheric values and are therefore inconsistent with a tropospheric source, suggesting instead an overworld origin for the air. This presents a dilemma. We will show that this dilemma can be resolved by properly accounting for both convective mixing and large-scale transport.

We will focus in this paper on the region around the 380-K $\theta$ surface. This surface is near the tropopause in the tropics, but well within the stratosphere in the extratropics. In the extratropics, the 380-K surface serves as the boundary between the overworld ($\theta > 380$) and the lowermost stratosphere (stratospheric air with $\theta < 380$). This is a significant demarcation. Air injected into the lowermost stratosphere will remain in the stratosphere for at most a few months, while air injected into the extratropical overworld has the
possibility of experiencing relatively rapid isentropic transport to lower latitudes [Minschwaner et al., 1996], where it can be lofted throughout the stratosphere, resulting in a much longer residence time. And since 380 K is just above the typical location of the tropical cold point (~375 K), air following this path can in principle enter the overworld without passing through the tropical cold point. Finally, if the influence of convection does extend to 380 K, it strongly suggests that convection will influence all altitudes below this.

Satellite data can provide a much broader view of the H$_2$O and O$_3$ distributions. Figure 2 shows the distribution of H$_2$O and O$_3$ for July on the 380-K surface from two instruments on the Upper Atmosphere Research Satellite (UARS) [e.g., Dessler et al., 1998]: the Halogen Occultation Experiment (HALOE) [Russell et al., 1993], and the Microwave Limb Sounder (MLS) [Barath et al., 1993]. The HALOE data are version 19 and cover the period from 1993-1999. In response to a recognized low bias in the HALOE H$_2$O measurements [SPARC, 2000, section 2.3.1], we have multiplied the V19 VMRs by factors of 1.20, 1.10, and 1.05 for pressure levels of 121 hPa, 100 to 68 hPa, and 56 hPa, respectively [E. E. Remsberg, personal communication, 2004]. The MLS data have been processed using a new H$_2$O algorithm, known as version 7.02 [Read et al., 2003] and cover 16 days in July 1992. As suggested by Read et al., we have increased MLS H$_2$O at 147 hPa by 30% and at 100 hPa by 20%.

There is broad agreement between the HALOE and MLS H$_2$O data in panels (a) and (b) of Fig. 2. Both show maxima over the Asian monsoon (70°E, 35°N) and over North America (270°E, 30°N), although the shapes of the maxima are different. It seems reasonable that these maxima are likely the result of intense continental convection over
these two regions, as suggested by Randel et al. [2001]. Despite the adjustments described in the last paragraph, an offset between the instruments remains, with the MLS measuring several ppmv higher than the HALOE at this altitude. Some of the differences, such as the shapes of the maxima, are probably due to the different time periods covered and the length of the two data sets. Other differences, such as the offset, likely represent real differences in the measurements, and must be considered a measure of the uncertainty of our knowledge of H$_2$O at 380 K. See Read et al. [2003] for a more detailed intercomparison between the data sets.

Figure 2c shows the O$_3$ distribution measured by the HALOE. Coincident with the H$_2$O maximum over the Asian monsoon is an O$_3$ minimum. One might view this as consistent: the convective detrainment that contains high H$_2$O VMRs also contains low O$_3$ VMRs, so this association between high H$_2$O and low O$_3$ makes sense. This interpretation, however, runs into problems over North America. Here, both data sets again show an H$_2$O maximum. However, there is no associated low O$_3$ region. This is a different view of the same conundrum posed by the in situ data in Fig. 1: air with high H$_2$O VMRs, consistent with convection, but also high O$_3$ VMRs, inconsistent with convection. Another puzzle is that the values of H$_2$O VMR found in the H$_2$O maximum over North America are comparable to those found over the Asian monsoon maximum. This should be surprising, since the Asian monsoon is a region of far more vigorous convection than North America [e.g., Dunkerton, 1995].

In this paper, we will quantitatively explain how convection affects H$_2$O and O$_3$. In particular, we will show that convection can affect different tracers differently — so that
the O$_3$ field is not affected in the same way as the H$_2$O field. In this way, we will explain the different O$_3$-H$_2$O relations over Asia and North America.

**Convective contrast**

To begin to explain the satellite and *in situ* data, we cast the convective tendency for trace gas X at a point in space as a relaxation toward a target concentration \([X]_c\) with a time constant \(\tau_c\):

\[
\frac{\partial[X]}{\partial t} = -\frac{1}{\tau_c}([X] - [X]_c)
\]  

(1)

The time constant \(\tau_c\) is the reciprocal of the rate at which air is convectively exchanged between the detrainment level and the source region, and we expect it to be the same for all constituents. The target concentration \([X]_c\) is the convective equilibrium abundance that would be approached if all other processes ceased; for O$_3$ and most other trace gases, it is closely related to the abundance of constituent X in the planetary boundary layer (PBL).

H$_2$O, however, can condense and sediment out on time scales much less than \(\tau_c\). As a result, the target concentration \([\text{H}_2\text{O}]_c\) is not related to the abundance in the PBL, but instead is related to the local thermodynamic properties of the UT/LS. The idea is that strong updrafts associated with deep convection can carry significant amounts of ice to the UT/LS [e.g., Alcala and Dessler, 2002]. Evaporation of ice deposited into the UT/LS will tend to drive the region toward saturation, with excess ice sedimenting out. In other words, convection drives the local atmosphere towards saturation, so \([\text{H}_2\text{O}]_c\) is equal to the local saturation VMR, \([\text{H}_2\text{O}]^*\). We plot zonally averaged \([\text{H}_2\text{O}]^*\) as a function of
latitude in Figure 3a. Note that the saturation VMR increases rapidly with latitude, from a few ppmv between 10°N and 10°S, to hundreds of ppmv poleward of 40°N.

We will refer to \([X] - [X]_c\) as the “convective contrast” for species X. As the convective contrast increases, Equation (1) suggests that the effect of convection on the abundance of constituent X also increases. At most latitudes at 380 K, \([H_2O]_c \gg [H_2O]\), so Fig. 3a is to a good approximation equal to the convective contrast for H₂O. The increasing convective contrast with latitude means that a single convective event, everything else being equal, will transport more H₂O to the 380-K surface as the location of the convective event moves poleward.

The convective contrast for O₃, \([O_3] - [O_3]_c\), also increases with latitude as the background 380-K O₃ VMR increases, but much more slowly. To see the implications of this, we plot in Figure 3b the absolute value of the ratio of the fractional changes in H₂O to the fractional change in O₃ per unit convection:

\[
\left| \frac{-\frac{1}{\tau_c} ([H_2O] - [H_2O]_c)}{[H_2O]} \right| / \left| \frac{-\frac{1}{\tau_c} ([O_3] - [O_3]_c)}{[O_3]} \right| \equiv (2)
\]

(note that the convective time constant \(\tau_c\) appears in both the numerator and denominator and therefore cancels out). Near the equator, this ratio is near one, meaning that there is a similar fractional change in H₂O and O₃ per unit convection. As one heads poleward, however, this ratio rapidly rises, indicating that the fractional change in H₂O per convective event becomes much larger relative to the fractional change in O₃. This is a direct result of the rapid increase in convective contrast of H₂O shown in Fig. 3a. In other words, convection occurring at high latitudes is expected to perturb the H₂O abundance to a much greater degree than the O₃ abundance.
**Single-level isentropic model**

To investigate the issues discussed above more quantitatively, we have developed a single-level isentropic model, which simulates H$_2$O and O$_3$ on the 380-K $\theta$ surface. The model is driven by UKMO horizontal winds [Swinbank and O’Neill, 1994], interpolated to the 380-K level. The horizontal advection is carried out by a semi-Lagrangian advection scheme [Stainforth and Cote, 1991] with a time step of 15 minutes.

Vertical transport must be parameterized in this model. Once per day, we apply a tendency to account for the Brewer-Dobson circulation, which is a large-scale, slow upwelling at low latitudes and downwelling at high latitudes. The tendency term due to this circulation is parameterized as a relaxation:

$$\frac{\partial [X]}{\partial t}_{\text{BD}} = -\frac{1}{\tau_{\text{BD}}} ([X] - [X]_{\text{BD}})$$

(3)

where $X$ is H$_2$O or O$_3$. $[O_3]_{\text{BD}}$, is assumed to be 75 ppbv for regions of upward motion, and 425 ppbv for regions with regions of downward motion. $[H_2O]_{\text{BD}}$ is 10 ppmv and 4 ppmv for upward and downward motion, respectively. The values of these parameters are set within a range constrained by our knowledge of the TTL, but within that range are adjusted to produce optimal agreement between the model and the satellite measurements. We will discuss the sensitivity of the model to these parameters and its effect on our overall results later in the paper.

The Brewer-Dobson circulation time constant $\tau_{\text{BD}}$ is a function of latitude and longitude and is equal to $C_1/|\partial \theta / \partial t|$, where $|\partial \theta / \partial t|$ is the absolute value of the local 380-K daily heating rate (heating rates are calculated according to Rosenfield et al. [1994]).
constant $C_1$ is chosen to give a time constant of $\sim$60 days in the tropics. This leads to Brewer-Dobson relaxation time scales of 20-30 days at high latitudes.

Also once per day, we apply a tendency to account for convection in regions where deep convection is occurring. We parameterize the convective tendency according to Equation (1), with $[O_3]_c$ of 75 ppbv and $[H_2O]_c$ equal to the local saturation VMR. For estimates of $\tau_c$, we use observations of outgoing longwave radiance from satellites to indicate the location of deep convection.

Figure 4 plots the fraction of pixels with 11-$\mu$m brightness temperatures less than 210 K, $f_{\text{conv}}$, during July 1992. The data are from the Advanced Very High Resolution Radiometers (AVHRR) onboard the NOAA-11 and 12 satellites. The data are from the morning and afternoon overpasses of these satellites, as stored in the International Satellite Cloud Climatology Project’s (ISCCP) B3 product. This product contains a small fraction of the original AVHRR data, but at its native 1-km (at nadir) resolution.

One can clearly see the overall distribution of deep convection: frequent in the tropics, with the occurrence dropping off rapidly with latitude. If we assume that $1/\tau_c$ is proportional to $f_{\text{conv}}$, then it becomes clear that convective moistening should be strongly peaked in the mid-latitudes: it is the product of two functions, one that increases rapidly with latitude (convective contrast) and the other that decreases rapidly with latitude (convective mass transport).

The convective relaxation time constant $\tau_c$ is the same for H$_2$O and O$_3$ and is equal to $C_2/f_{\text{conv}}$. The constant $C_2$ is chosen to give a time constant of 6.5 days at the location of the maximum $f_{\text{conv}}$. This scaling gives an overall convective turnover time for the 380-K surface in the tropics of several weeks, consistent with the results of Dessler [2002].
Choosing a constant convective threshold higher than 210 K produces a distribution similar in shape, but with higher frequencies at all locations. By changing the constant $C_2$ accordingly so that the maximum time scale remains at 6.5 days, similar results are obtained, suggesting our analysis is insensitive to the brightness temperature used to quantify convective transport, given $\tau_c$. We also investigated whether a latitude- and longitude-dependent temperature threshold would be better, since the 380-K surface becomes warmer outside the tropics so a constant threshold may undercount mid-latitude convection. For example, we tried a threshold based on the local temperature of the 380-K surface, where we counted a pixel as indicating deep convection if the temperature of the pixel was colder than that. Unfortunately, in mid-latitudes the temperature tends towards isothermal well below the 380-K surface, eliminating the possibility of any straightforward relationship between cloud-top temperature and height above the tropopause. In the end, we found no single method that was entirely satisfactory, so with a nod toward simplicity we adopt a constant threshold of 210 K.

UKMO temperature and pressure are used to calculate saturation relative humidity (RH). To account for a known warm bias in the UKMO fields [Randel et al., 2000], we adjust the temperatures downward: temperatures below 200 K are reduced by 3 K, temperatures between 200 and 220 K are reduced by an offset that linearly decreases from 3 K at 200 K to 0 at 220 K, temperatures above 220 K are unadjusted.

We used this model to simulate the month of July for each of the years 1992-99. To establish the initial condition for each July, we first ran the model with initially zonally symmetric O$_3$ and H$_2$O distributions using perpetual July 1 winds. When this reached steady state, the resulting O$_3$ and H$_2$O fields were then used as the initial condition for a
July run using daily winds. Convective relaxation rates were calculated separately for each July using the frequency of occurrence over that month of satellite pixels meeting the 210K threshold, and did not vary during the month. The July 1992 simulations will be compared with MLS data, while the average of the July 1993-99 simulations will be compared with the HALOE data.

Figure 5 shows the model results, with the data from Fig. 2 overplotted as contours. Overall, the simulations of both constituents are good, with the location of maxima and minima well represented. Importantly, the model simulates high H$_2$O VMRs over both Asia and North America, but low O$_3$ VMRs only over Asia. The most serious difference is in the location of the H$_2$O maximum associated with the Asian monsoon in the comparison with HALOE data in panel (a). The HALOE data show the H$_2$O maximum located west and poleward of where the model predicts it. It’s unclear whether this represents a deficiency in the model or the HALOE data since the MLS data, panel (b), show the H$_2$O maximum close to where the model predicts it. One clue is that in the Asia-west Pacific region the two model calculations are closer to each other, despite the different time periods, than the two observations, suggesting that the latter difference might be instrument-related rather than a result of interannual variability. Clearly, future measurements will be required to sort this out.

To show the sensitivity of the model to the parameters we have chosen, we plot in Fig. 6 zonal average H$_2$O and O$_3$ abundances from the model calculated after varying the free parameters in the model. At low latitudes, model-predicted H$_2$O field is insensitive to the choice of parameters, instead being primarily determined by temperature through the imposed limit of 100% RH. In mid latitudes, the H$_2$O VMR is sensitive to the choice
of the convective turnover time $\tau_c$. This shows that convection is important to the $\text{H}_2\text{O}$ budget at this altitude unless $\tau_c$ is much longer than our best-guess value. At high latitudes, both $\text{H}_2\text{O}$ and $\text{O}_3$ VMRs are most sensitive to the abundance of $\text{H}_2\text{O}$ and $\text{O}_3$ in air descending as part of the Brewer-Dobson circulation, with high-latitude $\text{H}_2\text{O}$ also showing some sensitivity also to $\tau_c$. In all model runs, however, the mid-latitude $\text{H}_2\text{O}$ peak and the insensitivity of the $\text{O}_3$ fields to convection are robust features. The model is insensitive to the other parameters.

Figure 7 shows zonal averages of modeled and measured $\text{H}_2\text{O}$ and $\text{O}_3$ at 380 K as a function of latitude. Fig. 7a shows that the model agrees well with $\text{H}_2\text{O}$ measured by the MLS. The model and MLS, however, are both 1-2 ppmv higher than the HALOE data. The CRYSTAL-FACE in situ data in Fig. 1, obtained around Florida, show that $\text{H}_2\text{O}$ at 380 K there ranges between 7 and 13 ppmv, a range that compares well with the model’s simulation of ~10 ppmv in that region.

The mid-latitude maximum in $\text{H}_2\text{O}$ VMR is seen in both satellite data sets and its location and magnitude are well reproduced by the model. Also shown on this plot is a model simulation of the HALOE period (1993-99) where convection has been turned off. This model run shows no mid-latitude maximum, suggesting, perhaps unsurprisingly, that convection is responsible.

Figure 7b shows a similar comparison for $\text{O}_3$. The standard model and the HALOE data show good quantitative agreement. The model without convective relaxation shows slightly higher $\text{O}_3$ VMRs at all latitudes, in agreement with our expectations.

To emphasize the effects of convection, Figure 8 plots the differences between the models with and without convection, as a function of latitude. For $\text{O}_3$, the difference is at
a maximum at around 10°N, where convective mass flux to the UT/LS is a maximum (see Fig. 4). Convection does play a role in regulating the abundance of O$_3$ here, in agreement with a previous analysis [Dessler, 2002]. For H$_2$O, however, the impact of convection maximizes between 30°N and 50°N, but is important throughout the extratropics. While convection in mid-latitudes is much less frequent than in the tropics, the relative humidity on the 380-K surface is much lower in mid-latitudes and therefore the convective contrast is high — so the convective tendency reaches a maximum in this region.

Thus, our isentropic model simulations confirm that the effects of convection are different for different constituents. Convection at 10°N, for example, has an important effect on O$_3$ but a relatively small one on H$_2$O; convection at 50°N, conversely, has an important effect on H$_2$O but a negligible one on O$_3$. Because the convective contrast for O$_3$ is relatively constant, horizontal variations in the effects of convection on O$_3$ tend to be driven by horizontal variations in $\tau_c$. For H$_2$O, on the other hand, horizontal variations in the effects of convection are driven by variations in both $\tau_c$ and convective contrast.

That convection has little effect on O$_3$ in the mid-latitudes at 380 K might seem surprising. After all, the HALOE O$_3$ plot in Fig. 2 shows that there is a broad low-O$_3$ region associated with the Asian monsoon anticyclone, a region of vigorous convection. One might have reasonably assumed that these low VMRs were the result of convection. It turns out, however, that an O$_3$ minimum appears there in our model whether convection is turned on or not. Rather than convection, the source of the low O$_3$ VMRs in this region is quasi-horizontal isentropic transport from the deep tropics, a region of low O$_3$ VMRs.
That is not to say that convection has no effect here. O₃ VMRs in the Asian monsoon in our model with convection turned on are ~60% of the VMRs when convection is turned off. One factor that contributes to the effectiveness of convection over this region, despite the very low convective contrast found there, is that once air gets into the monsoon region, it becomes “trapped” in the anticyclone (e.g., see the trajectory calculations plotted in Fig. 5 of Dethof et al. [1999]). As the air repeatedly circulates around the anticyclone, even a slow convective tendency can significantly lower the O₃ abundance. That is not the case over North America, where the weaker convection does not produce a closed circulation.

Because of this, three-dimensional chemistry-transport models can be expected to do a reasonable job of simulating O₃ on the 380-K surface, despite the well-documented limitations of their convective parameterizations [e.g., Emanuel and Raymond, 1993]. However, based on our work here, we conclude that successfully simulating the O₃ fields at 380 K does not provide any confidence that the model’s H₂O fields or convective processes are reasonable.

We can also now explain the questions posed in the beginning of this paper. We noted in both the satellite and in situ data that air over North America presented a conundrum: high H₂O (> 10 ppmv), consistent with upward transport, but high O₃ (> 400 ppbv), not consistent with upward transport. Our work in this paper presents an explanation. Air at 380 K over North America is, by and large, stratospheric. Mid-latitude convection transports little mass to these levels of the atmosphere. But because of the large convective contrast for H₂O here, transport of even a small amount of mass can significantly moisten the stratosphere. Such convection, however, leaves the O₃
largely unchanged. Such a conclusion is qualitatively consistent with a tracer analysis of Ray et al. [2004], which showed that air at these altitudes over North America retained a predominantly stratospheric character, despite clearly being perturbed by convection.

The CRYSTAL in situ data in Fig. 1 show that the influence of convection (as represented by measurements with H$_2$O VMRs > 7 ppmv) drops off rapidly above 380 K, and is entirely gone by 400 K. The fact that the mid-latitude convection penetrates to such high altitudes is significant. 390-K $\theta$ is about 10-15 K above the tropical cold-point tropopause. Thus, if this convectively-influence air is transported isentropically to the upwelling equatorial region, it can be lofted into the main bulk of the overworld stratosphere without ever crossing the tropical cold-point.

Initial investigations using our model suggest that such transport is likely not important. Model runs where extratropical convection is turned off show little change in tropical H$_2$O VMRs. The reason is that the tropics are maintained near saturation by slow upwelling and convective transport. There is little room for increasing the H$_2$O there in our model unless supersaturation is allowed. In addition, most of the moistening from extratropical convection occurs on the warm, poleward flank of the extratropical convective regions. Being located well in the mid-latitudes, significant amounts of this air appear not to make it into the tropics. This conclusion must be considered tentative, however, and more work done to verify it.

**Relation to tropical dehydration**

We have argued in previous publications that convection in the tropics reaching the tropopause, i.e., into the TTL, may dehydrate the air there by detraining H$_2$O mixing ratios lower than those prevailing in the environment [Sherwood and Dessler, 2000;
That model successfully simulated the abundance of water [Sherwood and Dessler, 2001] and water’s isotopologues [Dessler and Sherwood, 2003] in the TTL and stratosphere, and produced reasonable seasonal cycles of H$_2$O and a CO$_2$-like passive tracer in the tropical stratosphere [Sherwood and Dessler, 2003].

The parameterization we present in Equation (1), a relaxation to saturation, predicts a zero tendency from convection in regions where the atmosphere is saturated, and negative tendency in regions where the atmosphere is supersaturated. Such saturated or supersaturated conditions often do occur in the tropics [e.g., Jensen et al., 1999]. Under such conditions, details of ice microphysical processes that are relatively unimportant in regions of rapid evaporation might become important and lead to deviations from the simple behavior predicted by Equation (1). Our work in this paper sheds no light on the issue of convective moisture tendencies in the tropics; clearly, more work on it is necessary to resolve the issues involved.

**Conclusions**

By differencing the model runs with and without convection, we estimate that deep convection (primarily intense continental thunderstorms over Asia and North America) increases northern hemisphere extratropical H$_2$O (averaged over the region poleward of 30°N) on the 380-K potential temperature surface by about 40% during summer, while decreasing O$_3$ by about 6%. While these numbers must be treated as rough estimates, we believe that the success of the model in reproducing zonal variations of both tracers leaves no doubt that local deep convection is an important component of the H$_2$O budget of the extratropical lower stratosphere during this time, but much less important for O$_3$. It also seems certain that the H$_2$O abundance of the entire altitude range of the
summertime lowermost stratosphere, and even the bottom of the overworld, is influenced by deep convection.

That convection can moisten even the overworld is potentially significant, in that the moisture can be transported isentropically to the tropics [Minschwaner et al., 1996] and then be lofted into the stratosphere without having to pass through the tropical cold-point tropopause, which is located ~375 K. Our runs do not suggest that this contributes significantly to water vapor in the upwelling regions. However, our model is not ideally suited to test this idea and this issue deserves further study.

Our analysis suggests that convection plays a minor role in regulating extratropical O$_3$ at 380 K. Rather, the O$_3$ distribution is primarily determined by horizontal advection and the slow Brewer-Dobson circulation. This is true even of the O$_3$ minimum over the Asian monsoon, which arises not from convective transport but primarily from large-scale dynamics. This accounts for the lack of a corresponding O$_3$ minimum over North America, where the flow is predominantly zonal and there is little northward transport of low O$_3$ air into the region.

We have argued that convection affects H$_2$O and O$_3$ differently owing to differences in what we term the “convective contrast”: the difference between the abundance of a constituent in a convective outflow and in the ambient environment. In mid latitudes, where the relative humidity of the lower stratosphere is low (and therefore the saturation VMR >> [H$_2$O]), even infrequent convection can transport significant H$_2$O. Such convection, however, has only a small effect on the abundance of O$_3$. This provides an explanation for the puzzling observations of air with stratospheric O$_3$ (> 400 ppbv) and tropospheric H$_2$O (> 10 ppmv).
The convective contrast is high for H$_2$O in the extratropics due to low relative humidities. To understand why this occurs, first notice from Fig. 7 that the H$_2$O VMR is, within a factor of about two, constant on the 380-K surface. Air transported isentropically out of the tropics as well as that descending to the 380-K surface from higher altitudes have both been dehydrated to VMRs consistent with the temperatures at the tropical tropopause [e.g., Dessler, 1998]. At the same time, the 380-K isentrope descends in altitude as one precedes poleward, warming substantially as it does so. This leads to saturation VMRs in the extratropics greatly in excess of the local H$_2$O VMRs. Thus, it is ultimately the temperature difference between the tropics and extratropics at 380 K that determines the difference between the ambient H$_2$O VMR and the saturation VMR and therefore allows significant moistening by such small inputs of tropospheric air. If the 380-K isentrope had a constant temperature, then it would be nearly saturated everywhere and there would be no increase in convective contrast — and likely no H$_2$O maxima associated with the monsoon circulations.

In summary, this work suggests that, in the summer at least, deep convection plays an important part of the overall budget of H$_2$O at ~380 K and below in the mid-latitudes. As a result, trends in convective moistening might be playing a role in H$_2$O trends in the mid-latitude lowermost stratosphere. Such trends could arise from either trends in the amount of convective mass flux or trends in the convective contrast ([H$_2$O]$_c$-[H$_2$O]). Trends in convective contrast can arise due to changes in the latitude of convection, microphysical changes affecting the delivery of ice to the highest levels reached, or changes in the temperature difference between the tropics and extratropics. This latter might change as our climate changes, for example, due to changes in wave-driven
stratospheric overturning. These possibilities should be considered in assessing trends in the instrumental record of lower stratospheric water vapor below ~390-K potential temperature.

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References


Figure 1. Water vapor VMR (ppmv) vs. potential temperature (K) measured during the CRYSTAL-FACE mission in July 2002. Only points with corresponding O$_3$ VMRs greater than 400 ppbv are shown. The water vapor instrument is described by Weinstock et al. [1994]; the O$_3$ instrument is described by Proffitt and McLaughlin [1983]; temperature and pressure measurements were made by the NOAA Pressure/Temperature instrument suite.
Figure 2. (a) and (b): average H$_2$O VMR (ppmv), (c): average O$_3$ VMR (ppbv) at 380-K $\theta$. Data in (a) and (c) were measured by the HALOE between June 15 and Aug. 15 of 1993 through 1999; data in panel (b) were measured by the MLS during 16 days in July 1992. The $\theta$ of each measurement is determined using daily temperature and pressure fields from the United Kingdom Meteorological Office (UKMO) [Swinbank and O’Neill, 1994], and linear interpolation is used to determine the VMR at 380 K. The MLS and HALOE H$_2$O data have been adjusted, as described in the data section. For the MLS data, only measurements at 147 hPa and higher altitudes have been used.
Figure 3. (a) Plot of zonally averaged H$_2$O saturation VMR at 380 K as a function of latitude. Based on UKMO temperature fields for July 1992. Because the saturation VMR $\gg$ the ambient H$_2$O VMR at most latitudes, this plot is to a good approximation also the convective contrast (b) Ratio of fractional change in [H$_2$O] to [O$_3$] per unit of convection (Equation (2)). Calculated using the zonally averaged HALOE H$_2$O and O$_3$ fields from Fig. 2 and the H$_2$O saturation VMR from (a) as $[\text{H}_2\text{O}]_c$. $[\text{O}_3]_c$ is assumed to be zero, which assumes a maximum convective effect on O$_3$. 

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Figure 4. Fraction of 11-µm radiance observations with brightness temperature < 210 K during July 1992. The outer contour is 1%, with contours progressively increasing by 1%. Data from the morning and afternoon overpasses of the NOAA-11 and -12 satellites, as stored in the International Satellite Cloud Climatology Project’s (ISCCP) B3 product.
Figure 5. (a) and (b): average H$_2$O VMR (ppmv), (c): average O$_3$ VMR (ppbv) at 380-K $\theta$, as simulated by the single-level isentropic model. Data in (a) and (c) are simulations of July 1993-1999; data in panel (b) is a simulation of July 1992. The contours in each panel are the measurements from the corresponding time period, which was plotted in the corresponding panel of Fig. 2.
Figure 6. Zonal average of (a) H$_2$O and (b) O$_3$ from July 1992 runs of the single-level isentropic model. The heavy dotted line is the model run shown in other figures in the paper. The lighter gray lines are runs of the model were we have varied one of the following parameters by a factor of two: [O$_3$]$_{BD}$ (values for ascending and descending air are varied independently), $\tau_{BD}$, and $\tau_c$. [H$_2$O]$_{BD}$ is varied by 2 ppmv. For each of these parameters, we have two runs, one for an increase and one for a decrease.
Figure 7. Zonal average of (a) H$_2$O (ppmv) and (b) O$_3$ (ppbv) from the HALOE and MLS measurements and the model simulations shown in Figs. 2 and 5. The black solid lines are the model simulations from Fig. 5 (in the top plot, both the 1992 and 1993-99 simulations are shown). The black dotted line is the model run (1993-99) with convection turned off. The gray solid line is the HALOE data and the gray dashed line is the MLS data, both from Fig. 2.
Figure 8. Differences between the zonal-average H$_2$O (solid line, right-hand axis, in ppmv) and O$_3$ (dotted line, left-hand axis, in ppbv) predicted by models with and without convection. Positive values mean that the model with convection predicts higher VMRs for a constituent; negative means the opposite. The time period simulated is July 1993-99.