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The effects of convection on the summertime mid-latitude overworld

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Abstract

Halogen Occultation Experiment measurements of H_2O are used to investigate the influence of mid-latitude convection on the summertime overworld between 30° N and 40° N. We find that most of the convective influence over this latitude range occurs over the Asian monsoon and over North America. Over North America, the effects of convection extend to ~410 K (17.5 km). Over Asia, the effects of convection extend to ~460 K (19 km), about 50 K (1.5 km) higher than over North America.

1 Introduction

Much effort has been expended over the last decade in assessing the impact of deep convection on the extratropical lower stratosphere. Recently, the role of the northern hemisphere (NH) summertime monsoon circulations over North America and Asia has garnered particular interest (e.g., Dessler and Sherwood, 2004; Gettelman et al., 2004; Bannister et al., 2004; Fu et al., 2006). It is now clear that summertime convection associated with these monsoons has an important impact on the chemical composition of the lowermost stratosphere (that part of the stratosphere with potential temperature θ<380 K) in the NH (e.g., Poulida et al., 1996; Fischer et al., 2003; Hegglin et al., 2004; Hess, 2005).

Dessler and Sherwood (2004, hereafter DS04) showed that summertime convection plays an important role in the Northern Hemisphere (NH) extratropical H_2O budget at 380 K, the boundary between the lowermost stratosphere and the so-called overworld (the stratosphere with θ>380 K). In their two-dimensional model of the 380-K surface, DS04 cast the convective tendency for H_2O as a relaxation toward a target concentration $[H_2O]_c$ with a time constant τ_c:

$$\frac{\partial\,[H_2O]}{\partial t} = \frac{1}{\tau_c}\left([H_2O]_c - [H_2O]\right) \tag{1}$$

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τ_c is the latitude- and longitude-dependent timescale with which air is convectively transported from the lower troposphere to the detrainment height, and is expected to be the same for all constituents. $[H_2O]$ is the ambient stratospheric mixing ratio, and $[H_2O]_c$ is the target H_2O value that convection is pushing that atmosphere toward. DS04 argued that $[H_2O]_c$ is the local saturation mixing ratio. 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; Liu and Zipser, 2005). Evaporation of ice deposited into the UT/LS will tend to drive the region toward saturation, with excess ice sedimenting out. The difference $[H_2O]_c$ minus $[H_2O]$ was referred to by DS04 as the "convective contrast"; it can be thought of as the effect on the H_2O abundance per unit of convection. Put into their model, this simple parameterization was able to accurately reproduce the 380-K H_2O distribution, while a model without it could not.

The mass flux to the 380-K surface is small. However, because the 380-K surface is so warm in the mid-latitudes, the convective contrast is large so DS04 concluded that even a small amount of convection can transport significant amounts of H_2O to the 380-K surface. DS04 also showed that convection has a minor impact on O_3 because the convective contrast for O_3 is small at all latitudes.

An unanswered question in DS04 was how high the impact of convection on the H_2O budget extends. In this paper, we investigate that question.

2 Data

To address this issue, we will use measurements of H_2O made by the Halogen Occultation Experiment (HALOE), which was carried aboard the Upper Atmosphere Research Satellite (e.g., Dessler et al., 1998). HALOE version 19 data are used here, and these H_2O data have systematic errors in the lower stratosphere of 20% (Harries et al., 1996; SPARC, 2000). Constituents are retrieved on a high-resolution grid of 48 levels per pressure decade, with 23 levels between 150 hPa (355 K) and 50 hPa (500 K). The θ of each measurement is determined using daily temperature and pressure fields from

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the National Center for Environmental Prediction (NCEP) that are provided with the HALOE data. H_2O values at particular θ values are obtained by linear interpolation. With uncertainties in the NCEP temperatures of ∼1 K, the uncertainty in the calculated θ is ∼2 K, negligible for this analysis.

The HALOE science team has suggested (E. E. Remsberg, personal communication, 2004) that HALOE H_2O measurements be adjusted to account for an altitude-dependent low bias (SPARC, 2000, Sect. 2.3.1). We follow their guidance in making this adjustment: we have multiplied the HALOE H_2O vmr by factors of 1.20, 1.20, 1.10, and 1.05 for pressure levels of 215, 121, 100 to 68, and 56 hPa, respectively; factors for levels between these are determined by log-linear interpolation. This adjustment has no impact on the conclusions of this paper.

3 Depth of penetration of convection into the overworld

For context, we plot in Fig. 1 the average H_2O at 380 K measured by the HALOE between 15 June and 15 August of 1994 through 2005; similar plots appeared in DS04 and Randel et al. (2001). The data show maxima in H_2O between 30° N and 40° N over North America and Asia. DS04 quantitatively connected these 380-K maxima to deep convection, arguing that convection moistens the lower stratosphere in regions where the relative humidity is low. In these regions, the convective contrast is large and even a relatively small convective mass flux can lead to significant moistening.

We focus here on 30° N–40° N during the NH summer – the latitude band and time period where the convective anomalies identified in Fig. 1 occur. To determine the impact of convection here, we calculate the zonal variations in HALOE H_2O measurements. Figure 2 shows how this is done. The top panel shows the HALOE data at 410 K obtained between 15 June and 15 August of 1994 through 2005 and between 30° N and 40° N. These HALOE data are then separated into 30 longitude bins and the average of each bin is calculated, and this is plotted as the solid line in the top panel of Fig. 2. The anomaly, plotted in the bottom panel of Fig. 2, is calculated by subtracting

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the lowest-value bin from all of the bins. In this case, the lowest-value bin is centered at 162° longitude and has a value of 4.57 ppmv. The anomaly clearly shows that H_2O is higher at 60° and 270° longitude.

We repeat this process between 370 and 470 K and plot the resulting anomalies in Fig. 3 as a function of θ and longitude. Consistent with the 410-K data in Fig. 2, Fig. 3 shows that there are two longitudes where large H_2O anomalies exist: around 50° longitude, over the Asian monsoon, and around 270° longitude, over North America. This is also consistent with Fig. 1, and is anyway not surprising since these regions are well known to be the site of vigorous deep convection. Over North America (270° longitude), the anomaly decreases monotonically with height, from ~0.65 ppmv at 380 K (15.5 km) to ~0.1 ppmv at 410 K (17.5 km). This should not be taken to mean that convective detrainment does not occur at higher altitudes: in situ data taken over North America (Hanisco et al., 2006[1]) show evidence of convective detrainment as high as 430 K. However, we speculate that such high-altitude detrainment occur infrequently enough that its effects cannot be discerned by this analysis.

Over Asia (50° longitude), the anomaly also decreases monotonically with height, from ~0.60 ppmv at 380 K (15.5 km) to ~0.1 ppmv at 460 K (19 km). Thus, the anomaly over North American and Asia are of similar magnitude at 380 K, but the convective anomaly over the Asian monsoon extends about 50 K (1.5 km) higher than the North American convection anomaly. This is not unexpected because, by most metrics, convection over the Asian monsoon is far stronger than over North America (e.g., Dunkerton, 1995).

We can immediately rule out a photochemical explanation for the pattern in Fig. 3 because the lifetimes of H_2O, CH_4, and H_2 at these altitudes are decades (e.g., Dessler, 2000). A more plausible explanation is meridional advection of high H_2O from either lower or higher latitudes. We can rule this out, also. Figure 1 shows that this is impossi-

[1]Hanisco, T. F., Moyer, E. J., Weinstock, E. M., et al.: Observations of deep convective influence on stratospheric water vapor and its isotopic composition, Geophys. Res. Lett., submitted, 2006.

ble at 380 K: H_2O is lower both poleward and equatorward of the mid-latitude maxima, so meridional advection cannot explain the maxima. To show this is also true at other θ, we plot in Fig. 4 a latitude-height cross-section through the Asian monsoon. The crosses indicate the latitude of maximum H_2O on selected θ levels. This plot shows that between 380 and 450 K, H_2O between 30° N–40° N is higher than air both poleward and equatorward. Thus, meridional transport cannot be responsible for the high H_2O found there.

Finally, we can rule out downward transport because H_2O tends to decrease with increasing θ in this season and over the θ range of interest here. We also note that it is unlikely that problems in the HALOE data are responsible. The pattern in Fig. 3 would require longitude-dependent biases, and there is no evidence to support the existence of such biases. We conclude that only upward transport can explain the H_2O anomalies, and that the only possible explanation for this upward transport is convection.

While convection reaching the overworld, even as high as 460 K, might seem surprising, previous studies provide anecdotal evidence to support this conclusion. Fromm et al. (2000) reported several occurrences of forest fire smoke in the overworld, while Fromm and Servranckx (2003) described observations of forest fire smoke as high as 460 K. Wang et al. (2003) has modeled summertime continental convection and has simulated convection reaching θ>400 K, well into the overworld. Several studies have used biomass burning products as signatures of recent convection. Livesey et al. (2004) observed a biomass burning product, methyl cyanide, at 100–68 hPa (16–19 km or 400–450 K) in the summertime NH mid-latitudes. In situ data analyzed by Jost et al. (2004) showed biomass burning products at altitudes between 380 and 400 K. We should note that it is possible that the final θ of biomass products is higher because of radiative lofting of a smoke-filled plume after detrainment, which would not affect plumes containing no smoke.

While Fig. 3 tells where convection is important, we believe that one cannot quantitatively assess the impact of convection from the figure. Model runs with the DS04 model suggest that the effects of convection over North America and Asia are transported zonally throughout the latitude band, so the entire latitude band is contaminated by convection. If the DS04 model is correct on this point, then the impact of convection on this latitude band is larger than the perturbations observed in the convective regions of Fig. 3. We are presently pursuing other approaches to determine quantitatively by how much convection increases the NH summertime extratropical overworld.

Several papers (e.g., Dessler and Sherwood, 2004; Gettelman et al., 2004; Bannister et al., 2004; Fu et al., 2006) have discussed how this monsoonal circulation provides a pathway for air to enter the overworld without passing through the tropical tropopause cold-point, which is usually found below 380 K. Our work is consistent with this idea. We see significant transport of H_2O by mid-latitude convection to θ levels above 380 K. This transport does indeed bypass the tropical cold-point. If this air is subsequently transported equatorward and lofted up into the stratosphere, it could possibly perturb the abundance of water throughout the stratosphere.

4 Conclusions

We have used HALOE H_2O measurements to investigate the influence of extratropical convection on the summertime overworld between 30° N and 40° N. We find that most of this convection occurs over the Asian monsoon and over North America. Over North America, the effects of convection extend to ~410 K (17.5 km). Over Asia, the effects of convection extend to ~460 K (19 km), about 50 K (1.5 km) higher than over North America.

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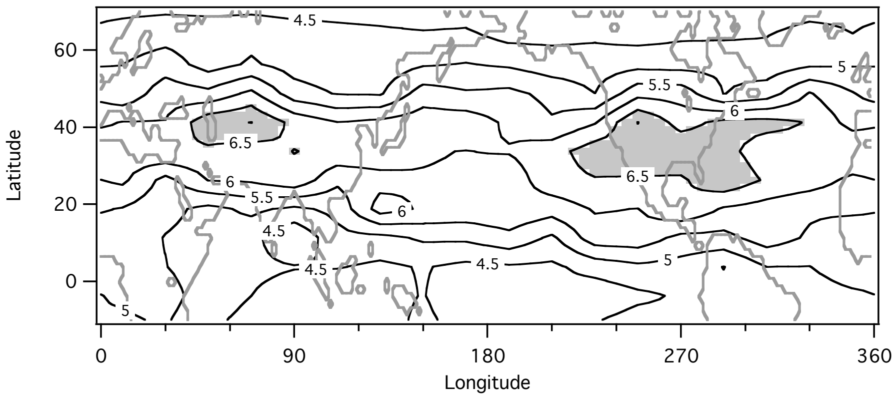

Fig. 1. Distribution of H_2O at 380-K θ measured by the HALOE between 15 June and 15 August of 1994–2005. Units are ppmv, and regions >6.5 ppmv are shaded.

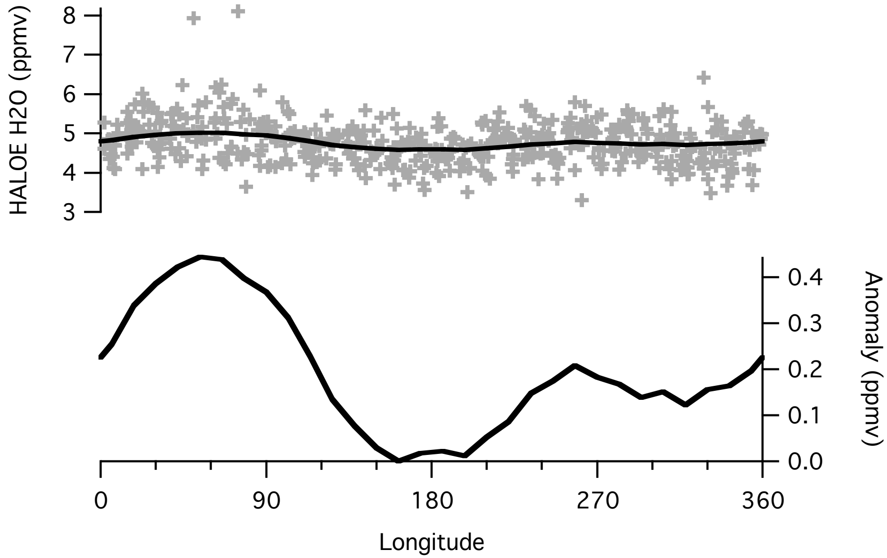

Fig. 2. (top) HALOE measurements of H_2O obtained between 30° N and 40° N and between 15 June and 15 August of 1994–2005 and at 410-K θ. Individual measurements are the gray crosses; the line is an average through the data. (bottom) The anomaly line, calculated by subtracting the minimum of the average line from the average line. See text for details.

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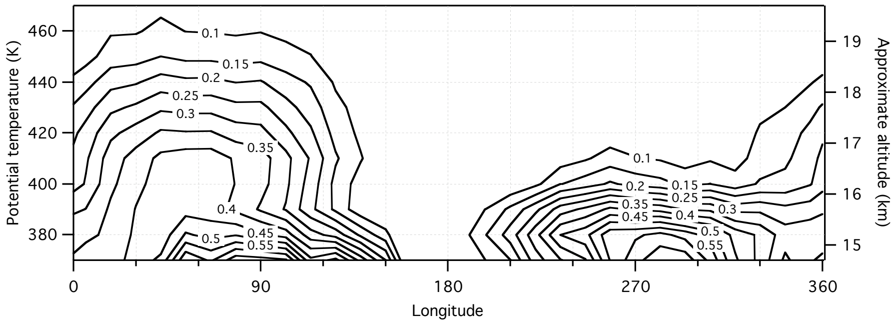

Fig. 3. H_2O anomaly as a function of θ and longitude. See text for details of how the anomaly is calculated. HALOE measurements were obtained between 30° N and 40° N and between 15 June and 15 August of 1994–2005.

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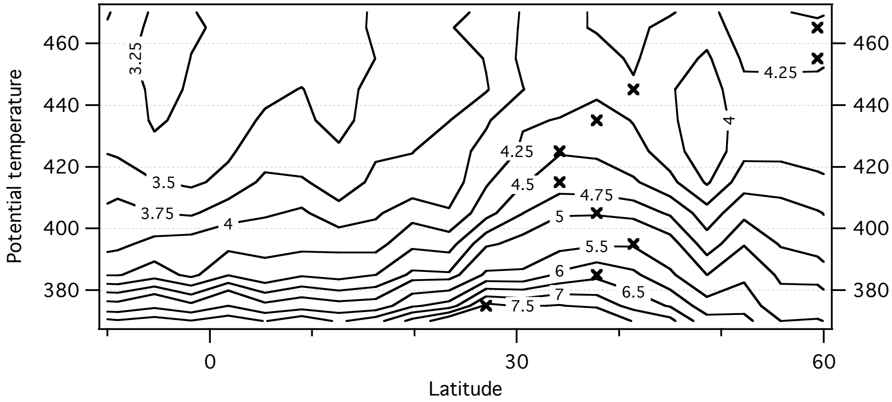

Fig. 4. Meridional cross-section of H2O over the Asian monsoon (30°–90° of longitude). Black crosses indicate the latitude where H_2O on that theta surface is a maximum. Contour interval is 0.25 ppmv below 5 ppmv and 0.5 ppmv above 5 ppmv. HALOE measurements were obtained between 30° N and 40° N and between 15 June and 15 August of 1994–2005.

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