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CLOUD PHYSICS AND WATER VAPOR IN THE EVANESCENT CONVECTION ALTITUDE REGIME

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1. INTRODUCTION

Efforts to explain the aridity of the stratosphere have led to closer scrutiny of the behavior of convective and cirrus clouds in the neighborhood of the tropical tropopause. Several puzzles have emerged:

1. The stratosphere is somewhat drier than one would predict on the basis of climatological temperature profiles—especially given the apparent prevalence of homogeneous nucleation as a "last resort" mechanism for initiating ice formation near the tropopause. The dryness must be enhanced in transient temperature fluctuations, but the nature of these fluctuations is debatable.
2. Isotopic fractionation of water vapor in the lower stratosphere is less severe than would be predicted by equilibrium fractionation to the observed H_2O mixing ratio. Recent authors have shown that either lofting of ice in convective systems, or nonequilibrium mixing effects, can in principle lead to the observed discrepancy (e.g., Keith, 2000).
3. Horizontal variations in time-average vertical velocity near the tropopause that cannot be easily explained have been inferred from data (Sherwood, 2000).

Such puzzles have led many investigators to suggest that intense convective cells reach beyond the tropical tropopause, attain unusually low water vapor mixing ratios, then mix into and dehydrate the air rising into the stratosphere. In principle, this could resolve each of the aforementioned puzzles, including the third one since the insertion of cold air can drive thermally direct baroclinic circulations across the tropopause. However, as yet no calculations have been done to determine whether a single, reasonable spectrum of convective motions can simultaneously explain all of the observations quantitatively. In particular, the observation of seasonal cycles propagating upward from at or below the tropopause level with little attenuation calls into question the feasibility of large amounts of cross-tropopause convective transport.

2. MODEL CALCULATIONS

We present calculations using the model of Sherwood and Dessler (2001) (SD01) to address these issues. This model included two regions, in one of which overshooting convection occurred. Other effects include a prescribed diabatic circulation and isentropic mixing rate. Overshooting is calculated via a bouyancy-sorting algorithm with explicit mass transports, constrained by environmental CAPE and simple closure assumptions. The model-predicted water vapor and ozone profiles in the neighborhood of the tropical tropopause were encouragingly realistic, given suitable tuning of the amount of ice retained in updrafts.

Here we have added prediction of the stable isotope HDO to the model, have added a passive, CO_2-like tracer, and have run the model in a transient mode so that the seasonal cycle can be simulated. The main goals are to determine whether the convective characteristics assumed or deduced by SD01 would, first, produce reasonable predictions of isotopic abundances in the stratosphere and through the tropopause region, and second, be consistent with observed seasonal cycle amplitudes and lags.

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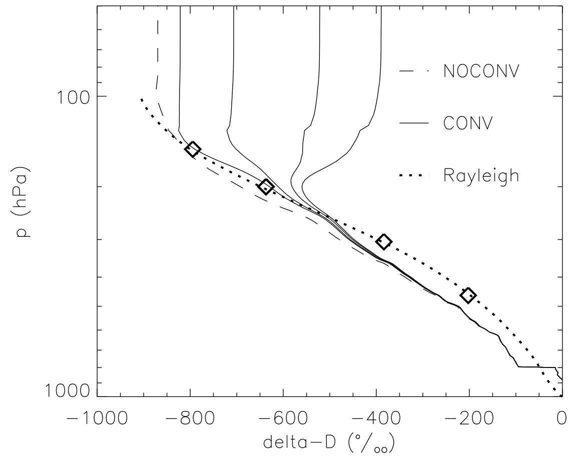

FIG. 1: δ-deuterium vs. height in the model vapor for several simulations; each result is an average of δD in the two regions. The curve labeled Rayleigh is the equilibrium curve calculated using the ambient Region-1 temperature with instantaneous removal of condensate. The four solid curves are obtained by setting δD_{ice} to that of the Rayleigh vapor curve at (from left to right) 150, 200, 300, and 500 hPa (each indicated by a thick diamond). These simulations do not include chemical fractionation in the stratosphere.

Isotopes were added to the model using simple, equilibrium theory. Lofted ice in cumulus updrafts is assigned an isotopic value that must be prescribed.

The behavior of the model with convective overshooting (CONV) was contrasted with a variety of models in which overshooting convection was omitted in favor of convective homogenization up to some tropopause height p_{mix}, above which no further convective effects persisted. This no-overshooting version of reality was simulated both by omitting overshooting from the SD01 model (NOCONV), with p_{mix} fixed separately in regions 1 and 2 of the model; and alternatively by constructing a simple Lagrangian random-walk model of nonconvective transport across the tropopause.

3. RESULTS

3.1 *Isotopes*

This talk will focus on the simulation of water vapor isotopes. HDO has a slightly higher saturation vapor pressure than H_2O, so that the two isotopes condense unequally during saturated ascent in cumulus clouds. According to equilibrium theory, by the time vapor levels have been reduced to those observed in the stratosphere, the δD measure of fractionation should attain a value near -900‰, but observations place it closer to -670‰. Recent reanalysis of ATMOS data (Kuang et al., 2002) indicate

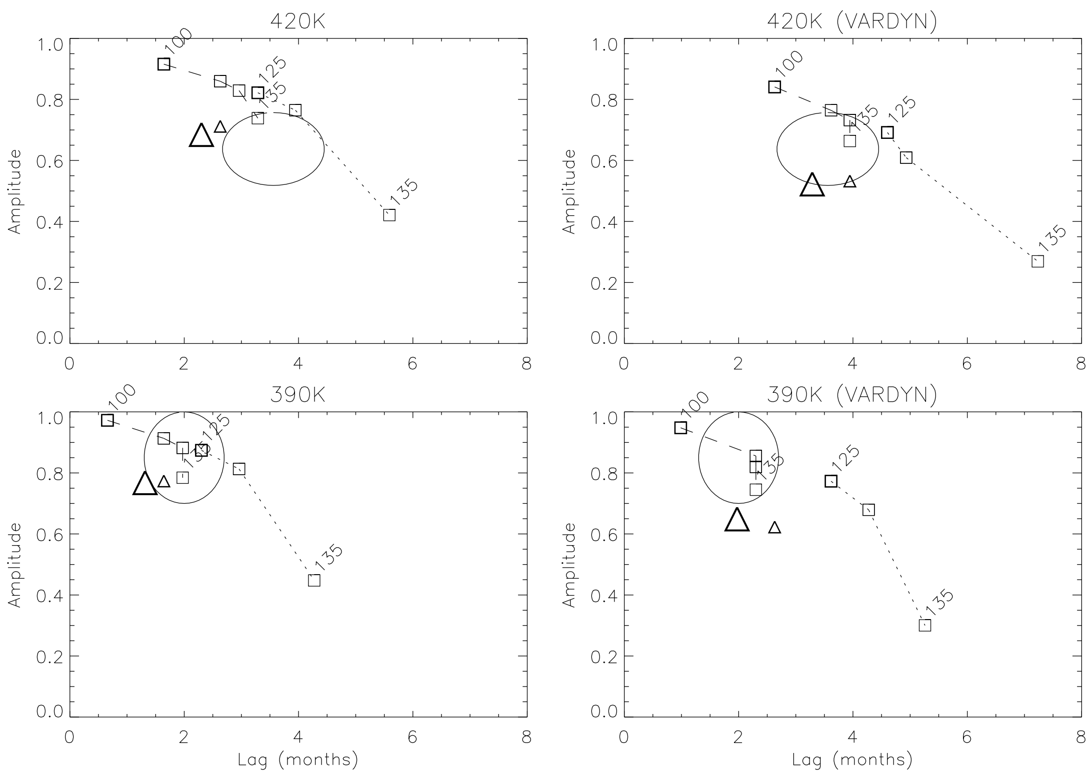

FIG. 2: Lag vs. amplitude for the CONV (triangle) and NOCONV (square symbol) model runs, at 420 K (top) and 390 K (bottom). Amplitudes are fractions of the lower tropospheric variation. Right panels show results with seasonally varying dynamics. Small triangle denotes CONV with lower convective mixing. Four NOCONV runs with $p_{\mathrm{mix}(1)} = 100$ hPa and $p_{\mathrm{mix}(2)} = 100, 125, 130, 135$ hPa are connected by a dashed line; three runs with $p_{\mathrm{mix}(1)} = 125$ hPa and $p_{\mathrm{mix}(2)} = 125, 130, 135$ hPa are connected by a dotted line. Further increases in $p_{\mathrm{mix}(2)}$ have little effect; further increases in $p_{\mathrm{mix}(1)}$ with $p_{\mathrm{mix}(2)} > p_{\mathrm{mix}(2)}$ produce very weak seasonal cycles. Error ellipses for observations are shown. Error at 390 K is our own crude estimate; error at 420 K includes the errors estimated by Andrews et al. (1999) in addition to the error of the reference surface at 390 K.

that this value remains nearly constant down to about 13 km, despite the fact that the water vapor mixing ratio varies by nearly an order of magnitude between those levels.

Our results with default model settings reproduce this recent observation, provided that we assign a δD of about -600‰(??) to the ice that is lofted near the tropopause (see Fig. 1). The near-invariance of δD above 14 km in the model results from the extreme dryness of overshoot cloud mixtures that detrain at levels significantly higher than this. Each isotope is diluted in equal proportion, so that no further fractionation occurs.

3.2 *Seasonal cycle*

The observed seasonal cycle of CO_2 shows no clear damping by the 390 K potential temperature level, and only modest damping up to the 450 K level (Andrews et al., 1999). However, there is a phase lag at 390 K relative to the CO_2 cycle at the surface, of about 2 months (Boering et al., 1994). Fig. 2 compares the simulated seasonal cycles with estimated lags and amplitudes from observations.

This comparison shows that the CONV simulation comes quite close to the correct amplitude and lag at each latitude, including correct simulation of the $\sim$2-month lag at 390 K. Results for H_2O are similar. Runs without convection can reproduce these only if convection is assumed to mix tropospheric properties to at least 125 hPa or so; this conclusion was confirmed using the Lagrangian random walk model (not shown).

4. CONCLUSIONS

Based on this work, we conclude that the basic physics of SD01—overshooting convective elements mixing with the environment and settling at their new level of neutral buoyancy—is indeed capable of producing the putative diabatic, hydrological, and isotopic roles of convection required to explain the relevant observations, while also reproducing the seasonal cycles of H_2O and CO_2.

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