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[1] The hypothesis of large scale control of midlatitude water vapor is evaluated through reconstructions of the water vapor field using a Lagrangian advection-condensation model without microphysics or diffusion. The reconstruction is validated against satellite observations in the 183.31 ± 1 GHz band from the AMSU-B radiometer following a model-to-satellite approach. Because microwave radiation can penetrate clouds, the validation can be performed for cloudy as well as clear sky scenes, with the exception of very cold or precipitating clouds, which are screened out. The results show very good agreement between the simulated top of the atmosphere radiation and the observations, in clear as well as cloudy regions, with a general bias of less than 2K. The results suggest that cloud microphysics and small scale mixing play at most a secondary role in determining midlatitude free tropospheric humidity except perhaps indirectly through their effect on large scale circulation. **Citation:** Brogniez, H., and R. T. Pierrehumbert (2006), Using microwave observations to assess large-scale control of free tropospheric water vapor in the mid-latitudes, *Geophys. Res. Lett.*, *33*, L14801, doi:10.1029/2006GL026240.

1. Introduction

[2] Radiative effects due to changes in atmospheric water vapor substantially amplify the response of climate to virtually any imposed radiative forcing, not least that due to the anthropogenic increase of CO_2 and other long-lived greenhouse gases [e.g., *Cess et al.*, 1990; *Pierrehumbert*, 1995; *Hall and Manabe*, 1999; *Held and Soden*, 2000]. Water vapor feedback thus enters into virtually all climate change processes on Earth, from the very distant past to the near and distant future. There is general agreement on the magnitude of water vapor feedback amongst most of the commonly used general circulation models (GCM), used to study Earth's changing climate. It is not clear why the agreement should be so good, nor is it *a priori* clear to what extent the simulated behavior mimics what will happen in the real atmosphere as climate warms. Water vapor feedback is a delicate matter, since the outgoing infrared radiation is sensitive to changes in the rather small amount of water contained in the mid-to upper troposphere [e.g., *Spencer and Braswell*, 1997]. Moreover, the approximately logarithmic dependence of outgoing infrared radiation on water vapor mixing ratio means that even the very dry air can have a radiative impact if it is made still drier [*Pierrehumbert*, 1995]. The implications of this sensitivity have been particularly well studied for the subtropical dry zones.

[3] In the tropics the free tropospheric water vapor distribution can be strongly influenced by microphysics in cloudy, convective regions [*Emanuel and Pierrehumbert*, 1996; *Held and Soden*, 2000]. The effect of moisture on the radiation budget of the Tropics is also sensitive to the large-scale horizontal mixing coupling the tropical convective regions to the subtropical free troposphere [e.g., *Udelhofen and Hartmann*, 1995; *Sherwood*, 1996; *Salathé and Hartmann*, 1997, 2000; *Pierrehumbert and Roca*, 1998, *Soden*, 1998]. The latter school of work has led to the concept of Large Scale Control (LSC), which suggests that the subtropical (and less confidently the tropical convective) moisture is governed by large scale processes that can in principle be resolved by GCMs. Models generally yield a water vapor feedback which is consistent with the free tropospheric relative humidity (FTRH) remaining approximately fixed in a warming climate [e.g., *Held and Soden*, 2000], and the compatibility of this behavior with infrared satellite observations has been demonstrated by *Soden et al.* [2005]. *Minschwaner and Dessler* [2004] presented a simplified tropical LSC model, compatible with observations, which also indicated that humidity should increase with layer-averaged temperature, though perhaps not so rapidly as Clausius-Clapeyron would suggest. There is a general need for a theoretical framework for discussing the link between water vapor and temperature, and LSC has the potential to provide such a link [*Pierrehumbert et al.*, 2006]. It is thus important to see whether LSC remains valid beyond the commonly studied subtropical dry zones.

[4] The goal of the present work is to improve the understanding of water vapor dynamics in the relatively neglected midlatitude regions. In particular the work of *Pierrehumbert and Roca* [1998] (hereinafter referred to as PR98) is extended. At the same time, we take advantage of the increasing availability of satellite measurements in the 183.31 ± 1 GHz microwave spectral band to extend the analysis into the cloudy regions of the midlatitudes. Compared to the more widely used IR observations near 6.3 μm, the key advantage of microwaves is their penetration of clouds, which are opaque to radiation in the IR thus limiting water vapor studies to regions free of high and mid-level cloudiness [e.g., *Udelhofen and Hartmann*, 1995]. Microwave observations are not immune to cloud contamination, but are strongly affected by a much more restricted class of clouds. This will allow us to determine directly if microphysical processes keep midlatitude ascending, condensing regions substantially undersaturated; models based on LSC invariably keep such regions close to saturation. The ability of microwave water vapor data to yield information in

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tropical convective systems is also of great interest, but this is beyond the scope of the present paper.

2. Data and Methods

[5] The Advanced Microwave Sounding Unit-B (AMSU-B) has provided observations of the atmospheric humidity onboard the NOAA polar orbiting satellites since 1998, through 3 channels centered around the 183.31 GHz water vapor absorption line (183.31 ± 1, ±3, ±7). The resolution of AMSU-B is 16 km at nadir [*Saunders et al.*, 1995]. The weighting function of the first channel is similar to the 6.3 μm channel: it provides a measure of the water vapor in the 700–200 hPa layer (i.e., the FTRH), with a maximum near 400 hPa, the actual width of the layer depending upon the humidity content [see *Spencer and Braswell*, 1997]. The link between FTRH and the 183.31 ± 1 GHz brightness temperature (BT) is compromised only for cold and/or precipitating clouds composed of ice particles or liquid water droplets that scatter the up-welling radiation. To remove such clouds, we applied a cloud screening based on complementary measurements in the two other AMSU-B channels at 89 GHz and 150 GHz following *Hong et al.* [2005] (for the convective clouds) and *Greenwald and Christopher* [2002] (for the precipitating clouds). In addition to this decontamination a limb correction was also applied, bringing all the viewing angles to an equivalent nadir position.

[6] To evaluate the atmospheric processes that control mid-latitude humidity, we reconstruct the water vapor field using the Lagrangian advection-condensation model described by *Pierrehumbert* [1998] and by PR98: at a given point of space and time, the water vapor mixing ratio of an air mass corresponds to the minimum mixing ratio encountered along its trajectory, since the time it was last resaturated by contact with the boundary layer (defined here as the 850 hPa level). The tropospheric water vapor distribution is thus a function of the atmospheric circulation and the temperature distribution, both of which affect the position where the air parcel last experienced saturation. This model deliberately excludes microphysical processes, which have the potential to maintain convecting regions in a markedly subsaturated state [*Tompkins and Emanuel*, 2000]. The Lagrangian method has no numerical diffusion, and therefore also allows us to completely suppress mixing of moisture amongst air parcels, such as might be caused by small scale turbulent diffusion. Likewise, the model ignores the redistribution of moisture due to evaporation of precipitation as it falls through subsaturated air; in essence, the precipitation efficiency is taken to be 100%. There is little *a priori* justification in ignoring such processes, but by evaluating how well one can do with such a minimal model, one gets an appraisal of the importance of the neglected processes.

[7] The model-to-satellite approach used by PR98 is applied with slight modifications. First, all three components of the wind are taken from the 6-hourly NCEP data (2.5°) [*Kalnay et al.*, 1996]. The reconstruction is performed on a 0.5° grid for 7 pressure levels, ranging between 200 hPa and 850 hPa, the reconstructed profiles being filled out toward the top of the atmosphere and the surface using observations from the ERA-40 re-analyses data from

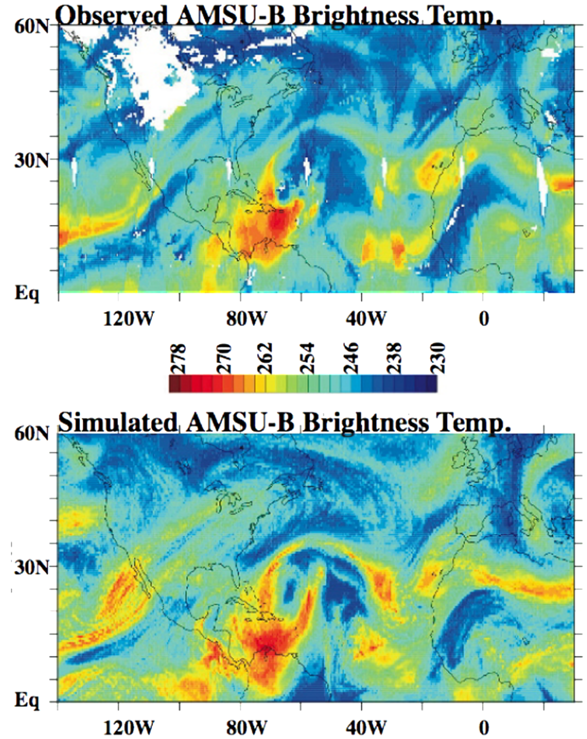

Figure 1. (top) 183.3 ± 1GHz BT (in Kelvins) as observed on December 1st 2001 by AMSU-B. (bottom) 183.3 ± 1GHz BT reconstructed using the Lagrangian model and the RTTOV8 radiative code. White areas denote missing data, either from gaps in the orbital coverage (near 25°N), either from the cloud screening algorithm or from snow cover.

ECMWF [*Uppala et al.*, 2005]. Sensitivity analyses on the BTs have shown a little influence of the humidity values used to fill out the reconstructed profiles, as expected from the shape of the weighting function. We found that increasing or decreasing the specific humidity by 50% has a mean impact on the BTs of 0.21 ± 0.09K and −0.23 ± 0.15K, respectively, over the whole area. Second, whereas a narrow band radiation model was used by PR98, we use the RTTOV-8 radiative code [*Matricardi et al.*, 2004] to reconstruct the observed clear-sky 183.31±1 GHz field. The computations are performed on a 0.5° grid for the first 15 days of December 2001, and we focus on the region [100°W–0°E/15°N–60°N] in order to cover a large part of the mid-latitude areas. Although it extends toward part of the subtropics, the choice of this area gives access to the whole range of observed BTs in this channel.

3. Results and Discussion

[8] Comparisons between the observed and the reconstructed BT maps of Figure 1 for December 1st 2001 show good agreement between the two. Because of the relative sparsity of the cold/precipitating clouds, masked in the observations, compared to cloudy regions in general, this analysis extends water vapor coverage much deeper into cloudy regions than would be the case for IR. Note that the solidly masked area located over Canada is due to the anomalous microwave signature of snow, caught by the

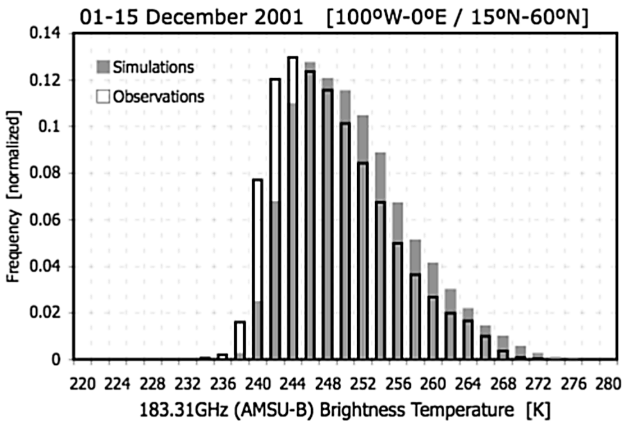

Figure 2. Histogram of normalized frequencies of the 183.31 ± 1GHz BT over the region [100°W–0°E/15°N–60°N] for the first 15 days of December 2001, as observed (white) and simulated (gray).

screening algorithm for rainy clouds [see *Greenwald and Christopher*, 2002].

[9] The main features and the filamentary structures that characterize the observed BT field are both fully captured by the back-trajectory reconstructions based on 4xdaily wind observations. For instance, the large dry zone over the Caribbean is very well represented in the simulations, as well as the dry arch it expels toward North Atlantic. Moreover, regions of strong gradients of BT (e.g., West Africa) are also reproduced in the simulations. Finally, the minima and maxima are correctly located, although of slightly different amplitudes than observed.

[10] Before going on to a discussion of the statistics of the model-observation comparison, we make here a few remarks on the interpretation of the microwave BT. Indeed, the BT depends on both the temperature profile and on the vertical distribution of water vapor. In the tropics, temperature is fairly uniform, so BT fluctuations are unambiguously tied to FTRH fluctuations. In the midlatitudes, however, there are substantial lateral temperature variations, so a region of higher BT could, in principle, represent a warmer but moister region or a colder but drier region. Insofar as the NCEP temperature field is accurate, our model-to-satellite analysis will spot any moisture biases between the Lagrangian reconstruction and observations, since the synthetic BT is computed using the correct local temperature profile for the pixel which is being compared. We have chosen to perform the comparison in terms of BT, in order to involve fewer questionable assumptions than the inversion into a layer-averaged FTRH. It is useful to have some feel for what the BT values mean in terms of humidity. Using temperature profiles for warm and cold extremes in the midlatitudes, the BT was computed using RTTOV-8 for 25% and 100% relative humidity profiles, yielding to the following ordering of BT: cold and moist (236K), warm and moist (239K), cold and dry (248K), warm and dry (251K). Thus, even in the midlatitudes, one can unambiguously associate regions of low BT with moist regions and regions of high BT with dry regions. Values of BT greater than 251K occur primarily in subtropical dry zones.

[11] Figure 2 summarizes the distribution of BT as observed and simulated for the full period. The range of values extends from 232K to 272K for both observed and simulated cases. The simulations yield a larger frequency at high values, and fewer points of lower values. On Figure 3 is represented a quantitative comparison of the two fields. A bias is observed at both extremes. A warm bias greater than 4K is present for BT lower than 241K, whereas a cold bias reaching up to −3K is seen above 265K. Given the fact that we performed clear sky computations, the warm bias is most likely caused by imperfections in the cloud screening algorithm. As discussed by *Greenwald and Christopher* [2002] such a depression in the observed BT (≤240K) can be caused by the presence of cold clouds in the pixel of observation. Other techniques have been developed that would certainly allow for a better screening [e.g., *Berg et al.*, 1999]. It is unlikely that the BT discrepancy represents a true moisture difference between theory and observations, because the bias would indicate that the real atmosphere is substantially moister than the LSC theory, which already yields nearly saturated air in ascending regions. However, the seriousness of the cold bias is mitigated by the sparsity of such cold values: Figure 2 shows indeed that values below 240K are indeed rarely observed, the percentage of observation being less than 0.6% for the considered period.

[12] The cold bias observed above 265K is more physically interesting. These regions are very dry, but the comparison suggests that the real air may be even drier than that produced by the Lagrangian simulation. It might be thought that the moist bias in the simulations arises from the neglect of microphysically-induced drying in the condensing regions. However, such an effect would lead to a pronounced moist bias for air of intermediate dryness as well, and not just for the driest air. The most likely explanation is that the moist bias in the driest regions arises because the NCEP data set underestimates the intensity of the subsidence in the atmosphere's most strongly subsiding regions, or perhaps the model underestimates how the back-trajectories should approach the tropopause. Note that most of the high extremes of BT occur in the subtropics (Figure 1), suggesting that any problems with the analysis apply mostly to the vigor of the large scale subtropical circulation, rather than to midlatitude baroclinic eddies. In any event, the frequency of these extremely dry regions is small.

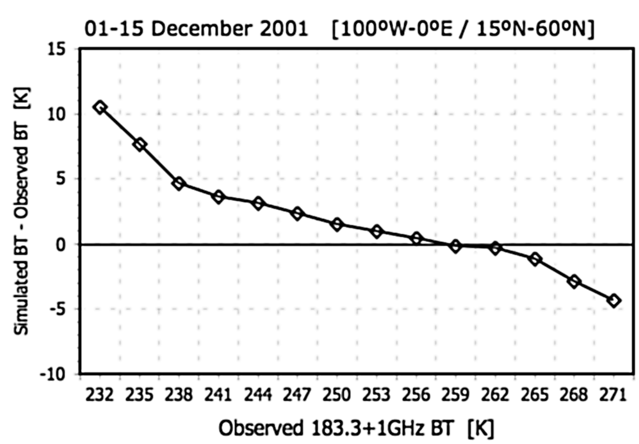

Figure 3. Differences in Kelvins between simulated and observed 183.31 ± 1GHz BT averaged over data falling within each 3K interval of observed BT.

[13] Between 241K and 265K (roughly between 80 and 10% of relative humidity in the 700–200 hPa layer), the bias lies within 2K around the observed values, highlighting a very good agreement of the simulated data to the observed one, which would translate in small relative uncertainties on the FTRH, of the order of 10 to 20% of the estimated relative humidity.

[14] Our primary interest in water vapor stems from its effect on outgoing longwave radiation (OLR, from the NOAA-CDC database). To estimate the effect on OLR of the aspect of the humidity measured by 183.31 ± 1 GHz BT, we performed a multiple regression of observed OLR against BT and T_{500} in the midlatitudes, writing the regression in the form $OLR' = a \cdot BT' + b \cdot T'_{500}$, where primes denote deviations from the mean. The regression yields a = 2.717, b = 1.961, and fits the data with a correlation coefficient of 0.77. The 90% confidence intervals on (a, b), estimated by the bootstrap method, are respectively [2.708; 2.726] and [1.955; 1.968]. There is some correlation between BT and T_{500}, but the two are not tightly correlated. Note that because we use observed all-sky OLR in this analysis, the moisture effect includes any tendency of high clouds to preferentially form in moist regions. From this analysis, we conclude that midlatitude OLR fluctuations are not at all dominated by temperature. Based on the value of a, we can estimate that the moisture variations in the midlatitudes, measured by a 20K range in BT, lead to variations in OLR in excess of 50 W/m^2. This confirms that midlatitude dry air plays an important role in cooling the climate, providing windows through which infrared can escape to space just as subtropical dry zones do at lower latitudes.

[15] The reconstruction of the water vapor fields based on large-scale circulation agrees well with observations, based on validation by using the computed water vapor field to create synthetic 183.31 ± 1 GHz BT fields with clear-sky radiative physics. This combination not only succeeds in clear, dry areas but also produces a correct distribution of the tropospheric water vapor in moist regions where clouds are most likely to appear. Earlier work showing large scale control of subtropical dry zones has thus been extended to the entire midlatitudes. This is a nontrivial extension, since midlatitudes are under the influence of a synoptic eddy dominated circulation regime very different from the large scale quasi-steady flow that prevails in the Tropics. Based on the OLR-BT correlation, we can estimate that the moisture yielded by LSC theory overestimates the true OLR by 5.5 W/m^2 or less, excluding the rare moist and dry extremes. This work extends the portion of the globe over which large scale processes resolved in general circulation models can be expected to correctly predict water vapor feedback on climate change. Together with other recent observational work [*Soden et al.*, 2005], it supports a high degree of confidence in the correctness of water vapor feedback simulated in GCMs of the climate changed caused by an increase in anthropogenic greenhouse gases. It remains to extend the inquiry to tropical cloudy regions, which will be the subject of a separate paper.

[16] Similar Lagrangian BT reconstructions based on GCM wind and temperature fields may be useful in diagnosing water vapor dynamics in GCMs. They could distinguish the effect of errors in model temperature vs wind fields, and errors due to excessive numerical diffusion of water vapor. Recent work based on such reconstructions shows that the use of Lagrangian calculation may actually produce a better water vapor field than the overly diffuse internal field, especially when considering low resolution GCMs [*Pierrehumbert et al.*, 2006]. However, although LSC gives models a good chance to accurately simulate water vapor, this does not guarantee that the models actually generate Lagrangian circulation statistics that sufficiently closely mimic those in the real atmosphere. While it seems likely that they do so, it will be important to verify this in future work.

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