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Evidence for Control of Atlantic Subtropical Humidity by Large Scale Advection

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Abstract. The interplay between large scale dynamics and tropospheric moisture is investigated. A simple conceptual model of the sources and sinks of humidity is used to reconstruct, using a backward Lagrangian trajectory technique, the water vapor distribution in the tropical and subtropical free troposphere. Satellite data in the water vapor channel from both Meteosat-3 and Meteosat-4 satellites are then used to validate the model following a model-to-satellite approach over the whole Atlantic ocean. There is excellent agreement between simulations and observations in the drier regions, but the simulated brightness temperature exhibits a warm bias within and near moist, convective regions. This bias is most probably due to the neglect of cloud effects in reconstructing the simulated brightness temperature, rather than to a dry bias in the simulation. A second advective simulation, performed with monthly mean rather than full transient winds, led to a substantially drier subtropics. This calculation demonstrates the importance of synoptic scale transient eddies in determining the humidity of the subtropical dry zones. It is speculated on this basis that discontinuous changes in synoptic eddy activity could provide a mechanism for rapid global climate changes.

Introduction

The radiative feedback due to changes in atmospheric water content has long been recognized as a key determinant of the sensitivity of climate to changes in CO2 and solar radiation [Manabe and Wetherald, 1967]. Atmospheric water vapor has also been implicated in rapid Holocene climate transitions [Broecker, 1997]. Changes in the mid to upper tropospheric humidity of the extensive dry subsiding regions of the subtropics are of signal importance in determining the nature of the water vapor feedback [Sun and Lindzen, 1993; Pierrehumbert, 1995]. It has been suggested that this humidity is governed by complex and poorly understood cloud-scale microphysics [Sun and Lindzen, 1993; Spencer and Braswell, 1997], the representation of which is problematic in current climate models. On the other hand, evidence has been accumulating that subtropical water vapor may be controlled primarily by large scale transport of moisture from the regions of the atmosphere directly moistened by convection [Emanuel and Pierrehumbert, 1996; Sherwood 1996, Salathé and Hartmann, 1997; Pierrehumbert, 1998; Soden, 1998] a process that models can handle with a greater degree of confidence. Satellite based studies using the 6.3 micron band on board geostationary satellites indeed suggest a strong relationship between the upper tropospheric moisture distribution and the large scale dynamics [Picon and Desbois, 1990, Schmetz et al., 1995], at least on monthly mean time scales.

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In this Letter, we present a case study employing a novel data set and moisture reconstruction technique, which provides a very rigorous test of the advective control hypothesis in the Atlantic region. The results show that even the very intricate patterns of moisture appearing in an individual satellite image can be accurately reproduced on the basis of advection by winds of a scale large enough to be resolved by typical general circulation models. We also show that synoptic scale transient eddies are crucial to the mixing process which injects water vapor into the subtropics.

Data and Methodology

From 21 Feb. 1993 to May 1995, Meteosat-3 was operational over South America at 75°W together with Meteosat-4 at its nominal position 0°W, in a configuration that afforded synoptic coverage of the entire Atlantic in the 6.3μm water vapor channel [de Waard et al., 1992]. In clear sky regions the 6.3 μm channel is mainly influenced by mid to upper tropospheric humidity. In order to test the hypothesis that the observed subtropical moisture is governed by large scale advection, we constructed simulations of the three-dimensional moisture field using a variant of the fully-Lagrangian back-trajectory technique employed in [Pierrehumbert, 1998]. To estimate the water vapor at a given point in space and time, we compute backwards trajectories from the point until the trajectory encounters the lower boundary layer (defined here as the 900mb level), at which point the air parcel is presumed to be saturated with moisture. As elaborated in [Pierrehumbert, 1998], the estimate of water vapor concentration at the target point is then given by the minimum saturation mixing ratio encountered along the trajectory. This accounts for the sink of moisture due to precipitation when the air parcel becomes sufficiently cold, and assumes that there are no sources of water vapor interior to the atmosphere. The precise degree of saturation of the boundary layer has little effect on the water vapor estimates at altitudes of interest for the radiative feedback. For example, with a typical tropical temperature profile, air that is 50% saturated at the ground becomes saturated when lifted to about 700mb, at which point it loses memory of its initial relative humidity. Very arid air in desert boundary layers

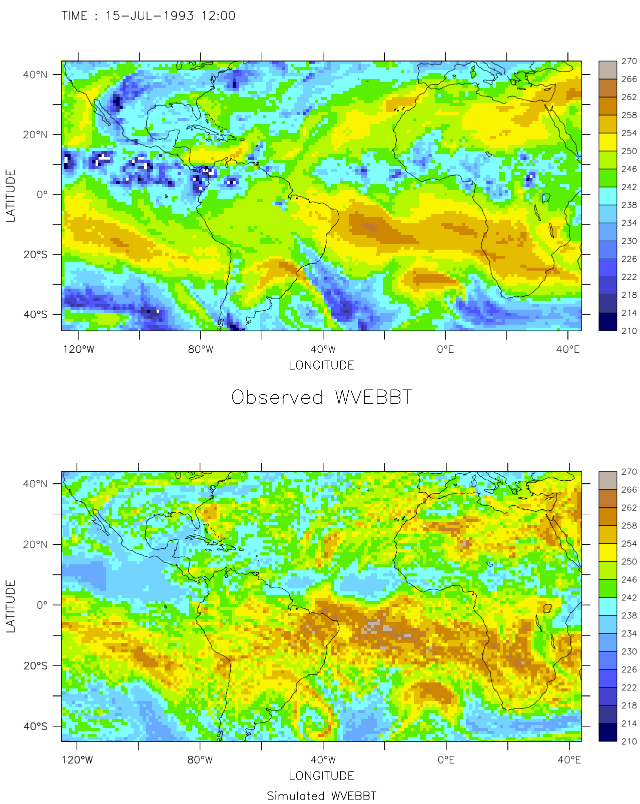

Figure 1. Upper panel: 6.3 μm brightness temperature observed on 12Z July 15, 1993 by Meteosat-3 and Meteosat-4. Lower panel: 6.3 μm brightness temperature for the same date reconstructed from the advective simulation of moisture. Low brightness temperatures correspond to high mid-tropospheric humidity. Modifications of the original calibration along the lines of [van de Berg et al, 1995] is included.

could in principle lead to significant errors, but in practice it was found that higher level trajectories never track back to these areas, which are generally in regions of strong subsidence. The trajectory calculation was driven by vertical and horizontal winds obtained from the six-hourly NCEP analyses having 2.5° spatial resolution [Kalnay et al., 1996]. The simulation differs from [Pierrehumbert, 1998] in that the vertical velocities we use are diagnosed from the horizontal winds through the continuity equation, rather than a simplified approximation obtained from radiative cooling rates, and differs from [Salathé and Hartmann, 1997] and [Pierrehumbert, 1998] in that we represent the moisture source by tracking air parcels back to their origins in the moist boundary layer, rather than terminating the back-trajectory as soon as it encounters a convective region. We adopt the latter procedure for reasons of simplicity. If one tracks the air all the way back to the boundary layer, then there is no need for auxiliary information (e.g. cloud fields or, archived convective-adjustment information) to determine the "convective region". All the information needed is already contained in the three dimensional wind field, which is readily available from archived analysis/assimilation products.
Our procedure estimates what the water vapor concentration would be under the simplest possible picture: that the only source resides in the boundary layer, that microphysical effects such as evaporation of falling ice crystals play no role in the source, and that turbulent or molecular diffusion amongst neighboring air parcels is inconsequential. The method is also, by construction, entirely free of spurious numerical diffusion that may plague moisture transport in Eulerian general circulation models. Following the pioneering work of [Schmetz and Van de Berg, 1994; Morcrette, 1991; Soden and Bretherton, 1994] on model-to-satellite comparisons, agreement between the simulated and observed moisture fields was evaluated by using the simulated three dimensional field to reconstruct the corresponding 6.3 μm brightness temperature. The procedure is as described in [Roca

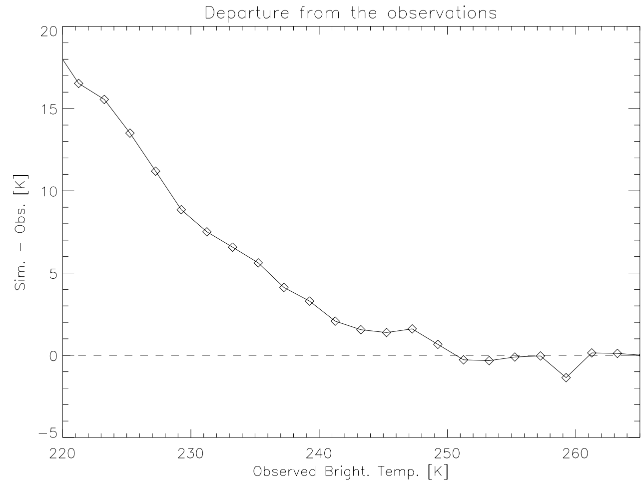

Figure 2. Difference Simulated minus Observed $T_{6.3}$ binned with respect to the Observed $T_{6.3}$, in Kelvin.

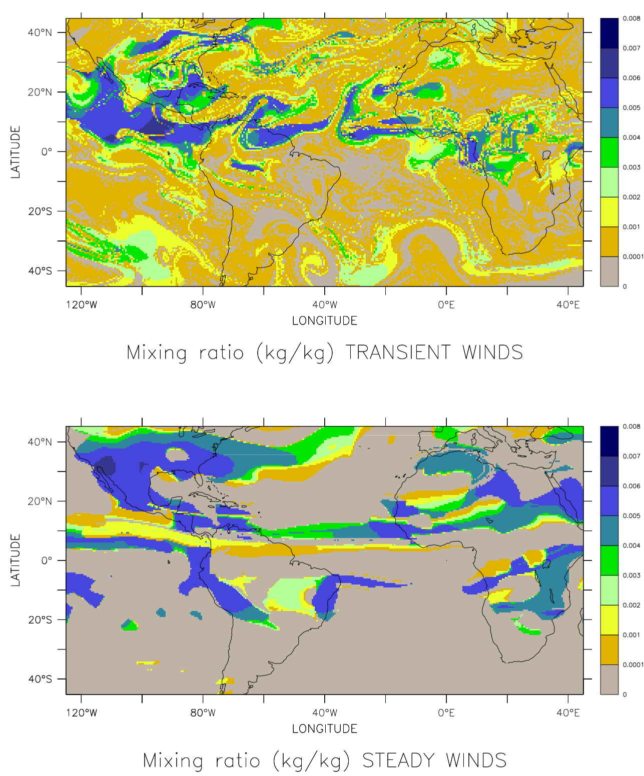

Figure 3. 500mb moisture mixing ratio on July 15, 1993 simulated by the advective model with time-dependant flow (upper panel) and steady monthly-mean flow (lower panel). Grey areas have mixing ratio less than 10^{-4}.

et al., 1997] except for the substitution of a narrow-band radiation scheme. The calculation was done using clear-sky radiation physics. Because the subsiding regions which are our principal object of study, are generally free of high and mid-level clouds, the neglect of the influence of clouds does not compromise our conclusions. In this Letter, we present results for 12GMT on July 15, 1993.

Results and Discussion

Figure 1 compares the observed and simulated brightness temperatures. Regions of high brightness temperature are the dry regions of primary concern in this Letter. The simulation reproduces the disposition of the subtropical dry regions very well. The large gradients in the $T_{6.3}$ field from the Tropics to the Subtropics are well characterized in the simulation. Fine structures, like the dry area located around 10°W, 25°S, or the colder tongue over South Africa are reproduced as well. In both the simulation and the data, one can see the signature of moist tongues with brightness temperatures of 238-242K that have been injected into the Atlantic northern subtropics. The southern subtropics, in contrast, is more isolated from the convective region. The main differences are seen in the moist, convective regions, where the simulated brightness temperature generally exceeds the observations. Quantitative evaluation of the agreement between the observed and simulated $T_{6.3}$ field is provided in Figure 2, where the brightness temperature difference between the model and the satellite data is shown as a function of the observed $T_{6.3}$. A strong warm bias is seen for the $T_{6.3}$ ranging from 220K to 240K. Interpreted strictly in terms of moisture, this would suggest that the advective simulation underestimates the humidity of the moist, convective regions. Our reconstruction of $T_{6.3}$ from the advective simulation is based on clear-sky radiation physics, and the satellite data have not been cloud-cleared; this, of course, will cause the model to overestimate $T_{6.3}$ in places where the real atmosphere has significant high cloud cover. Thus, the difficulty of assessing cloud effects complicates the verification of the advective model within the convective region. However, moisture errors in this region might not have a severe effect on climate, given that the sensitivity of the radiation budget to moisture is lower for very moist air than it is for very dry air [Spencer and Braswell, 1997].

For brightness temperatures warmer than 240K, which encompass the subtropical dry zones with which we are primarily concerned, the bias overall lies within 2K and vanishes to almost nothing over 250K-257K.

The quality of the results obtained in the advective simulation is sensitive to the data set used for the vertical velocity field. An earlier attempt at the comparison above, calculated using the NCEP analysis archived vertical winds (rather than winds reconstructed using the continuity equation) yielded overall worse agreement in the disposition of the convective regions, especially near the Gulf of Mexico. Recovering vertical winds from finite-difference evaluated divergence has some smoothing effect, which evidently eliminates some noise in the archived vertical velocity. One could perhaps do even better by adopting the diagnostic technique of [Sardeshmukh, 1993].

Having verified the advective simulation against the satellite data we may now, with some confidence, use the model to examine aspects of the water vapor field that have not yet been directly observed. First, we examine the spatial scales of the moist intrusions that are embedded within the subsidence regions. Owing to inherent vertical smoothing, the satellite images over-estimate the scale if the positions of moist filaments vary appreciably with altitude. Figure 3 (upper panel) shows the simulated 500mb mixing ratio for the case study date. Confirming the arguments given in [Pierrehumbert, 1998], chaotic mixing in the subtropics generates fine-grained moist features, with scales of 50 km. or less, in which most of the subtropical moisture resides. Next we probe the role of transient motions in determining the moisture field. The lower panel of Figure 3 shows the simulated moisture field computed with the winds held steady at their monthly-mean values for July, 1993. Without transients, there is essentially no mixing of moist air into the subtropics; in fact, the mixing ratio of the subtropical grey areas in this panel are generally on the order of 10^{-4} and lower, which are characteristic of the saturation mixing ratio of the tropical tropopause. This is nearly an order of magnitude drier than most of the dry areas typically encountered in the transient case. On comparison of the upper and lower panels of Figure 3, we note also that the Northern subtropics receives its moisture by mixing equatorward from the Northern Hemisphere extratropical storm track, as well as by mixing northward from the tropical convection zone. Similar behavior has been noted in a March case for the Central Pacific [Sherwood, 1996]. One doesn't ever expect the transient eddies to disappear completely, and it should come as no surprise that transients are crucial to the mixing. This comparison is offered by way of a sensitivity analysis, demonstrating that one must get the essential character of the transients right in order to get the moisture right.

Arid though it is, the small amount of water vapor in the subtropics has a strong effect on the planet's infrared cooling to space. A radiative transfer calculation employing a typical subtropical temperature profile shows that changing the mixing ratio in the 850mb-100mb layer from 10^{-5} to 10^{-4} decreases the outgoing infrared radiation by $25.8 W/m^2$, if the CO2 concentration is 330ppmv. By way of comparison, doubling CO2 for the same profile has a radiative effect of only $4.13\ W/m^2$ for a 850-100mb water vapor mixing ratio of 10^{-5}, and $3.96\ W/m^2$ when the mixing ratio is 10^{-4}. Nonetheless, regarding the ability of climate models to faithfully represent water vapor feedback, our results shift the focus of concern away from the subtropics. In order for a general circulation model to properly handle the subtropics, it is only necessary that it generate a realistic level of large scale tropical transient activity, and that its moisture transport scheme avoid excessive numerical diffusion. Microphysical influences are potentially of greatest importance in the convective regions themselves, which occupy a far smaller portion of the globe than do the subtropics, and in which radiative sensitivity to water vapor is not so steep [Spencer and Braswell, 1997]. As long as convection is able to keep the convective region reasonably close to saturation, the detailed moisture dynamics of this region will not have a severe influence on the subtropics.

With regard to the climate of the last glacial maximum, our results indicate that cooling of the midlatitude and poleward movement of the storm tracks should be immediately reflected in the subtropical humidity, implying a strong coupling between midlatitude and tropics. This lends plausibility to the emerging picture of a cold tropics during glacial times [see summary in Webb *et. al*, 1997)]. We further speculate that the sensitivity of subtropical humidity to transients could provide a mechanism for effecting the water vapor changes that have been suggested [Broecker, 1997] as a mediator of rapid global climate transitions. If a gradual shift in conditions were to shut off one of the instabilities that contribute to tropical transient eddy activity, the reduction in mixing would lead to a precipitous decline in subtropical humidity, with attendant global cooling.

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