A Less Cloudy Future: The Role of Subtropical Subsidence in Climate Sensitivity

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An observable constraint on climate sensitivity, based on variations in mid-tropospheric relative humidity (RH) and their impact on clouds, is proposed. We show that the tropics and subtropics are linked by teleconnections that induce seasonal RH variations that relate strongly to albedo (via clouds), and that this covariability is mimicked in a warming climate. A present-day analog for future trends is thus identified whereby the intensity of subtropical dry zones in models associated with the boreal monsoon is strongly linked to projected cloud trends, reflected solar radiation, and model sensitivity. Many models, particularly those with low climate sensitivity, fail to adequately resolve these teleconnections and hence are identifiably biased. Improving model fidelity in matching observed variations provides a viable path forward for better predicting future climate.

Estimates of how much Earth's global surface temperature would increase if the concentration of atmospheric carbon dioxide were double its pre-industrial concentration vary across climate models by a factor of about 2 (1). This metric, termed equilibrium climate sensitivity (ECS), serves as a canonical measure of climate model sensitivity to external changes. Differences across models cause considerable uncertainty in projected future climate. Despite substantial model improvements, the simulated range of ECS has changed little over the past several decades (2). This study therefore addresses the questions of what physical processes govern the spread of ECS among models, and whether model development efforts can be better directed at the goal of reducing this uncertainty.

Changes in clouds exert a primary influence on Earth's energy budget and ECS. Clouds apparently act as a modest net positive feedback (3, 4), thereby amplifying changes due to anthropogenic influences, and most models capture this behavior (5–7). Constraining simulated clouds is a challenge, however, as clouds are complex and difficult to observe. The historical record is plagued by errors associated with the drift and failure of satellites, inconsistencies in the detection of clouds, and instrument biases (8). Moreover, clouds can vary not just in their bulk characteristics but also in their microphysical properties, for which global observations are lacking generally, and considerable uncertainty persists regarding the feedbacks of various cloud types that may occur in a changing climate (9). Hence, owing to the wide range of scales involved, cloud processes in models are often not represented explicitly but instead are parameterized and tuned. Although there is some anticipation that new satellite programs may begin to address observational issues, and model resolution is improving, it is likely to be several decades before observations provide an adequate constraint on models.

We propose an approach for circumventing many of these issues that emphasizes constraints on the environment in which clouds occur, rather than on the clouds themselves. Doing so provides a robust and physically based framework for reducing uncertainty about future climate through the use of readily available observations. Variations in clouds and relative humidity (RH) are inherently linked in nature, and the approach here is motivated by the fact that models generally use RH to parameterize clouds (e.g., fig. S1). Tropospheric RH is proposed as a particularly useful diagnostic because it also is strongly linked to the dynamics of the overturning circulation, for which observable constraints are weak (9). Although it is known that biases exist in the simulated mean state of RH and that a modest relationship exists between its biases and model sensitivity (10), the reasons for the simulated variability of RH remain poorly understood, and constraints linking present-day variations to future climate have not yet been thoroughly explored. Whereas some model fields, such as clouds and the planetary energy budget, are generally tuned (11) to observations, the vertical structure of the troposphere is not. However, observations of RH through the full depth of the troposphere are readily available, including those from microwave observations from operational NOAA satellites and the AIRS (Atmospheric Infrared Sounder) instrument aboard NASA's Aqua satellite since July 2002. Along with balloon-borne measurements, they provide a solid baseline of both the mean state and variability across a range of time scales.

As shown here, the annual cycle provides a useful framework for exploring cloud-RH relationships, given its large variability relative to noise and observational uncertainty. Satellite retrievals from NASA's AIRS and CERES (Clouds and the Earth's Radiant Energy System) instruments are used to examine covariability between the seasonal extremes in RH and albedo, and hence clouds (Fig. 1). In the tropics and subtropics, the annual cycle of the Hadley circulation is intimately linked with that of the monsoon circulations, which lift moist air from the near-surface boundary layer in regions of tropical deep convection (e.g., north equatorial Africa, southeast Asia) into the upper troposphere, resulting in strong precipitation and drying of the ascending air. There it is advected meridionally to subside in the subtropics, where a deep zone of remarkably low RH exists across much of the depth of the free troposphere.

Seasonal increases in RH in the deep convective zones are thus dynamically coupled with

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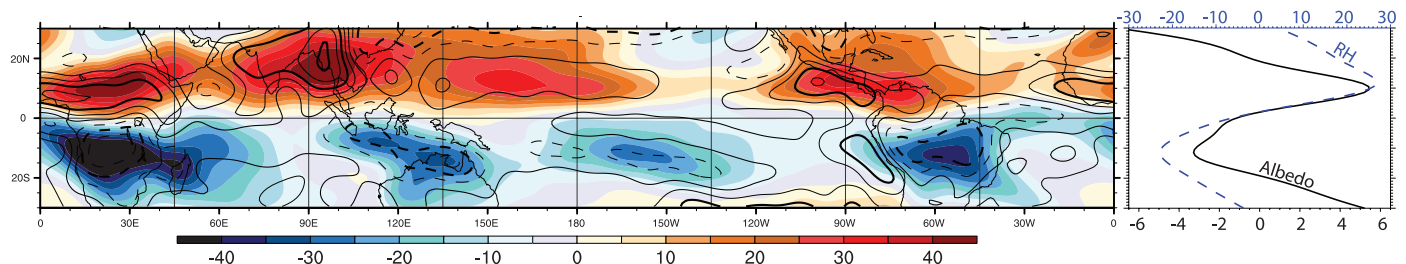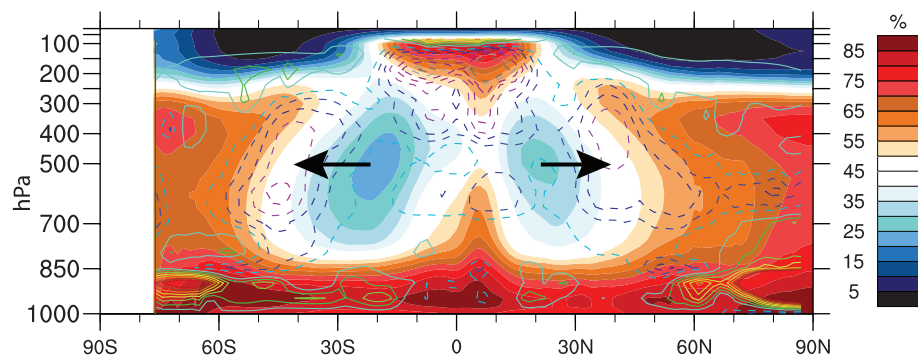
Fig. 1. Seasonal differences in observed RH at 500 hPa (color scale) and albedo (lines, 2% intervals, dashed for negative values) as estimated from the difference between June-to-August and December-to-February climatologies from 2002 to 2007, using NASA AIRS estimates of RH and CERES estimates of top-of-atmosphere radiative fluxes. Zonal mean differences are at right.

subtropical RH minima (12), and a marked spatial coherence between RH variations and albedo therefore exists, particularly from a zonal mean perspective. It is notable that RH at a single level (500 hPa) is strongly related with albedo, which is largely determined by clouds throughout the vertical extent of the troposphere. The coherence underscores the utility of RH in diagnosing clouds both locally and throughout the depth of the vertical column through its association with monsoon teleconnections.

In the annual average, the zonal mean structure of the dry zones exhibits a broad vertical extent and exceptional aridity (Fig. 2), but how well do models capture this observed feature? This question is explored using the CMIP3 model archive, a compilation of present-day simulations and future projections used in the most recent Intergovernmental Panel on Climate Change (IPCC) AR4 climate assessment (1). Comparison of the RH structure with the zonal height structure of projected future cloud loss (dashed lines in Fig. 2) further suggests direct relevance to cloud feedback. A canonical character of future projections under warming is the poleward expansion of the dry zones (arrows in Fig. 2) (13–16), although the lateral extent of projected RH and cloud reductions varies widely across models. It is evident that the regions of strongest future cloud loss also coincide with the poleward fringe of these dry zones (17). The strong spatial coherence between dry zone expansion and cloud loss suggests a direct role for these zones in influencing both the cloud feedback under warming and climate sensitivity. These strong relationships therefore motivate questions regarding model fidelity in resolving the dry zones and whether it exhibits a relationship to climate sensitivity.

Indeed, the present-day RH climatology (Fig. 2) may be ideal for evaluating interactions among RH, clouds, and dynamics in models, as the season coincides with a substantial northward shift of the Hadley cell and a broadening and intensification of the southern subtropical dry zone, similar to that projected under climate change (14).

The vertical structure of the relationship in boreal summer between simulated present-day RH and ECS (Fig. 3) reveals robust and highly statistically significant negative correlations in the dry zones bounding a region of significant positive correlation in regions of monsoonal deep convection. Because the boreal summer encompasses the strong Asian monsoon, the spatial contrast between moist and dry zones is greater, whereas during the austral summer, deep convection is located closer to the equator and subsidence is relatively symmetric about the equator.

The structure (Fig. 3) suggests that the depth and intensity of the Hadley circulation and its embedded monsoon circulations links the dry and moist regions; indeed, a strong relationship with the circulation consistent with this interpretation is evident (fig. S2), with a zonal structure that suggests direct monsoonal connections (fig. S3). The correlations with RH are not only statistically significant but of sufficient magnitude to explain a considerable fraction of the variance in ECS across models, with highly significant negative (< −0.8) and positive (>0.5) correlations in the subsident dry and ascending moist domains, respectively. Similar relationships between present-day RH and sensitivity are evident in the newer, though currently incomplete, CMIP5 model archive (fig. S4). A strong spatial coherence between regions where RH and ECS are correlated is also evident in the atmospheric energy budget, with albedo trends (normalized by 21st-century warming) at latitudes
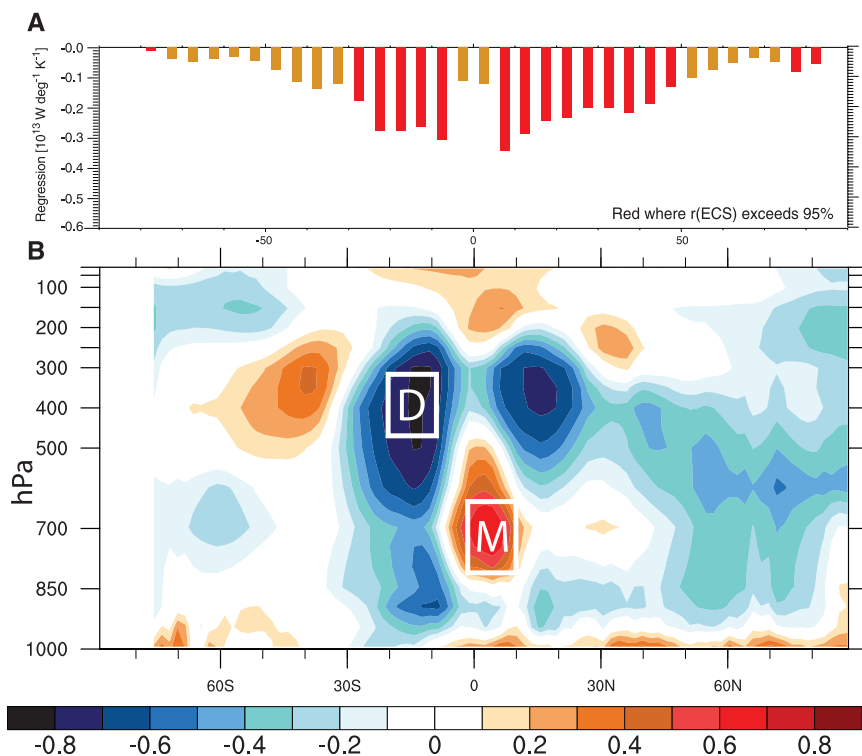

Fig. 2. The zonal height structure over ocean of observed climatological annual mean RH from AIRS (2002–2007) (color scale), with model mean projected changes in cloud amount from the CMIP3 model archive (contour lines, 0.5% intervals, dashed for cloud loss). The cloud loss in a warming climate at about 40°N/S coincides with broadening of the dry zones, as indicated by the arrows.

Fig. 3. (**A**) Median change in simulated top-of-atmosphere net shortwave flux as a function of latitude under 21st-century warming in CMIP3 SRES A1B projections. Red bars denote latitudes at which the change in net shortwave flux correlates with ECS at the 5% confidence limit. (**B**) Zonal mean vertical structure of the correlation between present-day (1980–1999) simulated RH over ocean from May to August in CMIP3 models and ECS. Boxed regions highlight peak positive and negative correlations in the moist (M) and dry (D) zones, respectively, where the statistical significance of the relationships exceeds the 1% confidence limit.
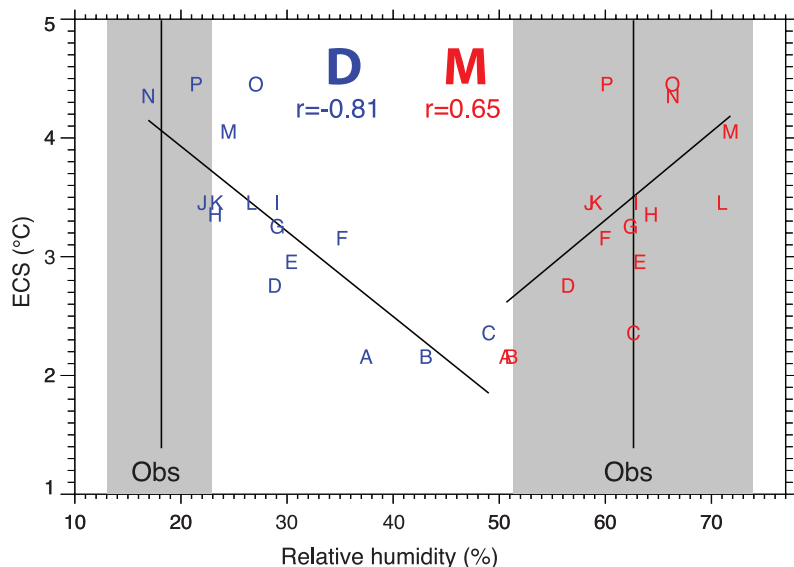
Fig. 4. Scatterplot of present-day simulated zonal mean RH over ocean from May to August in the dry (D) and moist (M) zones (Fig. 3) versus equilibrium climate sensitivity. Mean observed values (vertical black lines) and their range (gray) are based on values from AIRS retrievals and the MERRA and ERA Interim reanalyses. Letters denote individual model runs from coupled 20th-century runs (table S1). The correlations with ECS for each region are shown and indicated by the least-squares regression line. Observations and model values are based on climatologies from 1980 to 1999, except for AIRS, which is based on 2002–2007 data.

from 5° to 30°S and 5° to 50°N also exhibiting strong correlations with ECS (Fig. 3, upper panel).

Observed RH fields from satellite and re-analysis data sets can be used to evaluate the model distributions (Fig. 4) in the regions of peak positive and negative correlations in the moist ascending and dry descending domains (regions labeled M and D in Fig. 3, respectively). The strength of these relationships is robust to details in the choice of domain (fig. S5). The range of uncertainty in observations in Fig. 4 is gauged from the full range of climatologies from existing estimates of the mean state combined with the uncertainty arising from their temporal variability. The observations show that models are generally systematically too moist in the sub-sident domain, with only three models falling within the observed range. Although the correlation with climate sensitivity in the deep convective regime (M) is also strong, the range of uncertainty in observations is greater than for the dry zone; only a few models, generally of lower sensitivity, are identifiably biased. Because the meridional extent of subsident regimes greatly exceeds that of deep convective regimes (e.g., Fig. 2), their relative influence on the area-integrated energy budget is also disproportionately greater. The ability of observations to constrain the value of RH in the subsident domain is also greater, as there are fewer complicating factors involving clouds and precipitation.

These results suggest a systematic deficiency in the drying effect of either subsident cir-culations or spurious mixing of moister air into the region in low-sensitivity models (figs. S2 and S3) that directly relate to their projected changes in cloud amount and albedo. Although the lower-sensitivity models are clearly at odds with observations, extrapolating the consequences of these model biases to climate sensitivity is nontrivial, as the net feedback in terms of energy depends on the interaction of RH trends with the cloud field, whose vertical distribution in models is known to be biased (18). Thus, even if the RH response is well represented in models, its projection onto biased cloud fields may result in an incorrect estimation of the net cloud feedback. The results thus underscore the need to correctly represent the seasonally varying vertical structures of both RH and clouds in order to correctly project future climate.

Given the challenges involved in resolving the forced component of climate change in observed trends, process-based constraints on feedbacks such as the one proposed here are likely to be a key to reducing the uncertainty in future projections. The physically based perspective relates RH to ECS while explaining substantial variance across models, using fields in which observational uncertainty is small relative to model spread. In addition to providing a focus for improving models, the results strongly suggest that the more sensitive models perform better, and indeed the less sensitive models are not adequate in replicating vital aspects of today's climate. The correct simulation of the vertical structure of RH and clouds should be a prereq-

uisite for developing confidence in projections for the future.

Major questions persist. These include the relative contributions of various cloud types to the overall cloud feedback (19) and the sources of biases in the vertical RH and cloud distributions, and these are the focus of ongoing research. In a broader context, improved representation of regions of strong subsidence, particularly at low latitudes, is of fundamental importance. Such an improvement is essential not only for correctly simulating climate sensitivity, but also for characterizing changes in climate extremes and related impacts. Their scrutiny is therefore likely to be beneficial in understanding the broad range of uncertainties that currently exist in our future climate.

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