Identification of human-induced changes in atmospheric moisture content


1Program for Climate Model Diagnosis and Intercomparison, Lawrence Livermore National Laboratory, Livermore, CA 94550; 2Remote Sensing Systems, Santa Rosa, CA 95401; 3National Center for Atmospheric Research, Boulder, CO 80307; 4 Scripps Institution of Oceanography, La Jolla, CA 92037; 5Institut für Unternehmensforschung, Universität Hamburg, 20146 Hamburg, Germany; 6Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich NR4 7JL, United Kingdom; 7National Institute for Environmental Studies, Tsukuba 305-8506, Japan; 8Hadley Centre for Climate Prediction and Research, United Kingdom Meteorological Office, Exeter EX1 3PB, United Kingdom; and 9Lawrence Berkeley National Laboratory, Berkeley, CA 94720

Edited by Inez Y. Fung, University of California, Berkeley, CA, and approved July 27, 2007 (received for review March 27, 2007)

Data from the satellite-based Special Sensor Microwave Imager (SSM/I) show that the total atmospheric moisture content over oceans has increased by 0.41 kg/m² per decade since 1988. Results from current climate models indicate that water vapor increases of this magnitude cannot be explained by climate noise alone. In a formal detection and attribution analysis using the pooled results from 22 different climate models, the simulated “fingerprint” pattern of anthropogenically caused changes in water vapor is identifiable with high statistical confidence in the SSM/I data. Experiments in which forcing factors are varied individually suggest that this fingerprint “match” is primarily due to human-caused increases in greenhouse gases and not to solar forcing or recovery from the eruption of Mount Pinatubo. Our findings provide preliminary evidence of an emerging anthropogenic signal in the moisture content of earth’s atmosphere.

Fingerprint studies, which seek to identify the causes of recent climate change, involve rigorous statistical comparisons of modeled and observed climate change patterns (1). Such work has been influential in shaping the “discernible human influence” conclusions of national and international scientific assessments (2–4). Most fingerprint studies have focused on temperature changes at the earth’s surface (5, 6), in the free atmosphere (7, 8), or in the oceans (9), or have considered variables whose behavior is directly related to changes in atmospheric temperature (10).

Despite a growing body of empirical evidence documenting increases in moisture-related variables (11, 12), and climate model evidence of a number of recent hydrological responses to global warming (13, 14), there have been no formal fingerprint studies involving changes in the total amount of atmospheric water vapor, W. Other aspects of moisture changes have received attention in recent fingerprint work, with identification of an anthropogenic signal in observed records of continental river runoff (15), zonal mean rainfall (16), and surface specific humidity (17).

Warming induced by human-caused changes in well-mixed greenhouse gases (GHGs) should increase W (11, 12). Under the assumption that relative humidity remains approximately constant, for which there is considerable empirical support (13, 18, 19), the increase in W is estimated to be ~6.0–7.5% per degree Celsius warming of the lower troposphere (13, 18). The observed increase in W over the global ocean, as inferred since late 1987 from microwave radiometry measurements made with the satellite-borne Special Sensor Microwave Imager (SSM/I), is broadly consistent with theory (12, 18, 20).

Observational and Model Data

The SSM/I atmospheric moisture retrievals are based on measurements of microwave emissions from the 22-GHz water vapor absorption line. The distinctive shape of this line provides robust retrievals that are less problematic than other types of satellite measurement. For example, the signal-to-noise ratio (S/N) for detecting moistening in the lower troposphere by a measurement of water vapor is several times larger than for measurements of air temperature obtained directly from the Microwave Sounding Unit (18). Because SSM/I moisture retrievals are unavailable over the highly emissive land surface (18), our focus is on the total column water vapor over oceans, W0, for a near-global domain.

Here, we attempt to identify in the relatively short SSM/I record the spatial pattern of human-caused changes in W0. Before performing formal pattern comparisons, we analyze trends in (W0), the spatial average of W0 (the brackets denote a spatial mean). We examine whether model estimates of internal climate “noise,” obtained from control integrations with no forcing changes, can explain the observed (W0) increase over 1988–2005. We also consider whether the observed high-frequency variability of (W0) is reliably captured in 20th century (20CEN) simulations with historical changes in external forcings.

We use control and 20CEN results from 22 climate models. Model results are from the World Climate Research Program’s Coupled Model Intercomparison Project (CMIP-3) archive of simulations. The external forcings imposed in the 20CEN experiments differed between modeling groups. The most comprehensive experiments included changes in both natural external forcings (solar irradiance and volcanic dust loadings in the atmosphere) and a wide variety of anthropogenic influences (such as well-mixed GHGs, ozone, sulfate and black carbon aerosols, and land surface properties). Details of the models, 20CEN experiments, and control integrations are given in supporting information (SI). Text.


The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Freely available online through the PNAS open access option.

Abbreviations: CMIP, Coupled Model Intercomparison Project; EOF, empirical orthogonal function; GHG, greenhouse gas; S/N, signal-to-noise ratio; SSM/I, Special Sensor Microwave Imager; SST, sea surface temperature.

†To whom correspondence should be addressed. E-mail: santer1@lbnl.gov.

*The domain for spatial averaging was 50°N–50°S. This domain was chosen to minimize the effect of model- vs. SSM/I water vapor differences associated with inaccurate simulation of the latitudinal extent of ice margins. All data points over land were masked out before calculation of spatial averages. Averages were area-weighted, properly accounting for both complete and fractional grid-cells within the region.

This article contains supporting information online at www.pnas.org/cgi/content/full/0702872104/DC1.

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Observational and Modeled Water Vapor Time Series

The model 20CEN runs yield overall increases in $\langle W_o \rangle$ in response to the imposed external forcings (Fig. 1). We discuss runs that include anthropogenic forcing only (ANTHRO) and runs with combined forcing by both human influences and natural external factors (ALL). The inclusion of volcanic effects in the ALL runs leads to slightly smaller $\langle W_o \rangle$ increases over the 20th century and causes pronounced decreases in $\langle W_o \rangle$ for several years after major eruptions (21). Such decreases are consistent with volcanically induced cooling of sea surface temperatures (SSTs) and with the strong coupling of interannual fluctuations in tropical SSTs and water vapor (18, 22–24).

In the SSM/I data, $\langle W_o \rangle$ increases over the period 1988–2006 by 0.41 kg/m² per decade, with a 95% confidence interval of ±0.21 km² per decade (20). This trend is significantly different from zero (12). As in the ALL models, $\langle W_o \rangle$ decreases for several years after the eruption of Mount Pinatubo in June 1991 (Fig. 1). The observed post-Pinatubo decrease is partly masked by the effect of a small El Niño event in 1992 and is therefore smaller than in the ALL model average.

Comparison of Observed and Unforced Water Vapor Trends

The “masking” described above illustrates a fundamental problem: observed climate changes represent a complex mixture of internally generated noise and responses to external forcing, and unambiguous separation of the two is difficult. Even if such separation were feasible, the short (19-year) SSM/I record provides only one sample of multidecadal noise. In contrast, climate models can provide multiple estimates of “pure” internally generated variability. The 22 model control runs analyzed here comprise a total of 8,848 years of data, and they yield 459 independent samples of the unforced variability of $\langle W_o \rangle$ on time scales of 19 years. This is the information we use to determine whether the SSM/I $\langle W_o \rangle$ trend over 1988–2006 could be due to noise alone.

To address this question, we calculate $\langle W_o \rangle$ from each model control run, fit linear trends to 19-year nonoverlapping segments of
adequate length, however, to evaluate model performance in
length and the large uncertainties inherent in partitioning that
This is difficult to assess given the short observational record
model noise estimates, particularly on multidecadal time scales.

Model Performance in Simulating Variability

For Nin˜ o 3.4 region (25) or the strength of the coupling between SST
A
and SST
B
Scatterplots show the relationships between the temporal standard deviation of unfiltered
period:

A
B
\frac{\text{mean trend of } 0.34 \text{ kg/m}^2 \text{ per decade in the model 20CEN}}{	ext{the mean trend of } 0.34 \text{ kg/m}^2 \text{ per decade in the model 20CEN experiments} \text{ is not significantly different from}}

A
B
\text{the observed trend over 1988–2006. When model experiments include}

A
B
\text{the observed results. The error bars on the observed}

A
B
\text{expressed relative to climatological monthly means over this period. Standard deviations and correlations were estimated from linearly detrended data. The}

A
B
\text{noise estimates are reliable, internal variability is highly unlikely to}

A
B
\text{form a multimodel distribution of unforced trends (Fig. 2)}

A
B
\text{On both monthly and interannual time scales, the average}

A
B
\text{temporal standard deviations of } (W_o) \text{ are from SSM/I for}

A
B
\text{temporal standard deviations of } (W_o) \text{ are at the locations of the SSM/I values (SSM/I and ERSST in C) and facilitate visual comparison of the modeled}

A
B
\text{error bars on the observed (W_o) trend in B are the 2\sigma trend confidence intervals, adjusted for temporal autocorrelation effects (see SI Text).}
relative to the noise and to enhance detectability of the fingerprint in observations (1). Optimization is often performed by using information on both the spatial and temporal behavior of signal and noise (6, 9, 15–17, 26). Here, given the short length of the SSM/I record, there is little low-frequency structure to estimate, and we apply spatial optimization only. We also consider whether the model fingerprints are identifiable without any optimization.

We employ two sets of moisture fingerprints, estimated separately from the ALL and ANTHRO 20CEN runs (see SI Text). The fingerprints are the leading empirical orthogonal functions (EOFs) of the atmospheric moisture changes over 1900–1999 in the ALL and ANTHRO multimodel averages. Use of $W_o$ data for the entire 20th century (rather than simply for the period of overlap with SSM/I) provides a less noisy estimate of the true $W_o$ response to slowly varying external forcings. It also provides a response that is more similar across models (see SI Fig. 6).

The ALL and ANTHRO fingerprint patterns are very similar, and primarily reflect the large mean changes in $W_o$ over the 20th century (Fig. 4A and B). In both fingerprints, $W_o$ increases over the entire domain and varies smoothly along bands of latitude, with the largest increases close to the equator and the smallest increases toward the extratropics. The single realization of observed $W_o$ changes over the short SSM/I period is noisier than the model fingerprints, but it also shows coherent increases in $W_o$ over most of the world’s oceans, with the largest increases occurring in the western equatorial Pacific (Fig. 4E).

The leading noise modes have similar structure in the ALL and ANTHRO model control runs (Fig. 4C and D) and primarily...
Table 1. Detection times for model-predicted atmospheric moisture fingerprints in observational data

<table>
<thead>
<tr>
<th>Noise</th>
<th>Raw</th>
<th>Optimized</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F_{ALL}</td>
<td>F_{ANTHRO}</td>
</tr>
<tr>
<td>Mean retained</td>
<td>C_{ALL}(t)</td>
<td>2002</td>
</tr>
<tr>
<td></td>
<td>C_{ANTHRO}(t)</td>
<td>2002</td>
</tr>
<tr>
<td>Mean removed</td>
<td>C_{ALL}(t)</td>
<td>ND</td>
</tr>
<tr>
<td></td>
<td>C_{ANTHRO}(t)</td>
<td>ND</td>
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</table>

Detection times were calculated as described in SI Text. Results are given for both raw and optimized fingerprints and for analyses with the spatial mean included and removed. Detection times are shown for all four possible combinations of the fingerprints F_{ALL} and F_{ANTHRO} (and their optimized counterparts) and the noise data sets C_{ALL}(t) and C_{ANTHRO}(t). All optimized results are for a truncation dimension m = 15. Results are relatively insensitive to the choice of ALL or ANTHRO data for fingerprint or noise estimation. ND indicates that the fingerprint was not detectable before the end of the SSM/I record in 2006.

The centered (spatial means removed) pattern correlations between the observed W_o changes in Fig. 4e and the ALL and ANTHRO model fingerprints in Fig. 4a and b are 0.50 and 0.52, respectively. The corresponding values for the correlation between the observed W_o changes and the leading ALL and ANTHRO model noise modes in Fig. 4c and d are 0.19 and 0.28. The noise modes were estimated by calculating EOFs from two pooled data sets (see SI Text) consisting of concatenated control run W_o data from the ALL and ANTHRO models (26). Because the signs of the EOFs are arbitrary, only absolute values of the pattern correlation are given.

Fig. 5. Precipitable water changes in model single-forcing runs. Shown are column-integrated changes in monthly mean W_o in experiments performed with the Parallel Climate Model (PCM) (28) (A) and the MIROC3.2(medres) model (29) (B). For each model, there are a total of six experiments. In the first five, climate forcings were varied individually according to estimates of their historical changes over the 20th century. The five forcings considered were changes in well mixed GHGs, anthropogenic aerosol effects, tropospheric and stratospheric ozone, solar irradiance, and volcanic aerosols. These forcings were varied simultaneously in the sixth experiment (ALL). In PCM, the anthropogenic aerosol forcing involves only the direct (scattering) effects of sulfate aerosols. The MIROC anthropogenic aerosol experiment considers forcing by both the direct and indirect effects of sulfate and carbonaceous aerosols (29) (see SI Table 2). All changes in W_o were defined relative to climatological monthly means over 1900–1909. Results are ensemble averages and were decadal-filtered (K = 145 months) to damp high-frequency noise (see SI Text). The ensemble size was 10 for the MIROC ALL integration and 4 for the PCM ALL experiment and for each PCM and MIROC single-forcing run (except the PCM volcanic forcing case, for which only two realizations were available).

Mean removed fingerprint even without optimization (see SI Fig. 9).'

Single-Forcing Experiments

Although the W_o fingerprints are highly similar in the ALL and ANTHRO experiments (Fig. 4a and b), and both fingerprints are identifiable in the SSM/I data, these results alone do not allow us to make reliable inferences about the relative contributions of anthropogenic and natural external forcing to the observed W_o increase over 1988–2006. There are at least two reasons for this. First, the partitioning of the CMIP-3 20CEN results into ALL and ANTHRO groups does not cleanly isolate the effects of natural

One further sensitivity test involved repeating our entire fingerprint analysis with patterns of percentage changes in W_o. Anomalies in each individual data set (observations, 20CEN runs, and control integrations) were defined relative to the overall climatological annual mean of the data set and then converted to percentage changes. This procedure reduces the possible impact of model moisture biases on the estimated signals and noise. Fingerprint patterns are more uniform, because per degree Celsius increase, the percentage change in W_o is much closer to being a constant than is the actual change in W_o, which increases rapidly with increasing temperature. When spatial means are included, the use of percentage changes yields positive and consistent detection of an anthropogenic fingerprint, with detection times similar to those shown in Table 1 for actual changes in W_o. Because the “percentage change” fingerprint is spatially more uniform than the fingerprints shown in Fig. 4a and b, it is less meaningful to explore the detectability of a mean-removed fingerprint.
external forcings; there are also important differences in some of the anthropogenic forcings that were applied in the two groups (see SI Table 2). Second, it is likely that the large-scale spatial structure of the water vapor feedback will be similar for any spatially coherent surface warming signal. This implies that there may be degeneracy (24, 26) between the \( W_o \) response patterns caused by solar irradiance changes, GHG increases, and the slow recovery from the cooling induced by massive volcanic eruptions. The latter is of particular concern here because the “rebound” of \( W_o \) from the 1991 Pinatubo eruption occurs near the beginning of the SSM/I record.

As noted above, purely statistical approaches do not permit unambiguous separation of the short SSM/I \( W_o \) record into volcanic, solar, anthropogenic, and unforced components (27). Here, we use results from single-forcing experiments performed with the Parallel Climate Model (PCM) (28) and the MIROC3.2(medres) model (29) to quantify the contributions of various factors to the simulated changes in atmospheric moisture (Fig. 5). Our focus is on the period of overlap between the SSM/I data and the PCM and MIROC experiments (1988–1999 and 1988–2000, respectively). In both models, the \( W_o \) trends in the “volcano only” experiment are slightly negative, and in absolute terms they are approximately a factor of 5 smaller than the moisture change caused by GHG increases (SI Fig. 10). Solar-induced changes in \( W_o \) are four to eight times smaller than the GHG component of \( W_o \) increase. In PCM and MIROC, therefore, forcing by natural external factors alone cannot explain the large post-1988 increase in \( W_o \).

Conclusions

In summary, model fingerprints of the response of atmospheric moisture to external forcings are identifiable in observations with high statistical confidence, despite the short length of the SSM/I record. Single-forcing experiments performed with two different models (28, 29) suggest that the large increase in \( W_o \) is primarily due to human-caused increases in GHGs (Fig. 5) and not to solar forcing or the recovery from the Pinatubo eruption. Our analysis of model control run data illustrates that internally generated variability is also a highly unlikely explanation for the observed \( W_o \) changes.

The credibility of these conclusions depends on the reliability of model-based noise estimates. On monthly and interannual time scales, where SSM/I data are of sufficient length to make such reliability assessments, the models used here do not systematically underestimate the amplitude of variability in \( W_o \) or the strength of the correlation between SSTs and \( W_o \). In fact, the simulated variability of \( W_o \) is, on average, slightly larger than observed, both with and without interannual filtering.

These findings, together with related work on continental-scale river runoff (15), zonal mean rainfall (16), and surface specific humidity (17), suggest that there is an emerging anthropogenic signal in the moisture content of earth’s atmosphere and in the cycling of moisture between atmosphere, land, and ocean. Detection and attribution studies have now moved beyond “temperature-only” analyses and show physical consistency between observed and simulated temperature, moisture, and circulation changes. This internal consistency underscores the reality of human effects on climate.

We thank the modeling groups for providing their simulation output for analysis, the Program for Climate Model Diagnosis and Intercomparison for collecting and archiving these data, the World Climate Research Program’s Working Group on Coupled Modeling for organizing the model data analysis activity, and Susan Solomon (NOAA Aeronomy Laboratory, Boulder, CO) and three anonymous reviewers for constructive comments. The CMIP-3 multimodel data set is supported by the Office of Science, U.S. Department of Energy. NOAA ERSST data were provided by Dick Reynolds at the National Climatic Data Center (Asheville, NC).