Description of Data Used in:

Tropospheric Warming Over The Past Two Decades

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Introduction

This document contains a description of the model and observational tropospheric temperature data analyzed in the 2017 Santer *et al.* “Scientific Reports” paper entitled “Tropospheric Warming Over the Past Two Decades”. All data analyzed in the paper are publicly available on the PCMDI website (http://www-pcmdi.llnl.gov).

File naming conventions

There are six `ASCII` files containing satellite-based estimates of monthly-mean changes in the temperature of the mid- to upper troposphere (TMT). The files names are as follows:

1. `newamp1_ALLOBS_tf2-GLB2_RSS_v33jan17_r1979_2016_s1979_2016_nofilt.d`
2. `newamp1_ALLOBS_tf2-GLB2_RSS_v40jan17_r1979_2016_s1979_2016_nofilt.d`
3. `newamp1_ALLOBS_tf2-GLB2_STR_v30jan17_r1979_2016_s1979_2016_nofilt.d`
4. `newamp1_ALLOBS_tf2-GLB2_STR_v40jan17_r1979_2016_s1979_2016_nofilt.d`
5. `newamp1_ALLOBS_tf2-GLB2_UAH_v56jan17_r1979_2016_s1979_2016_nofilt.d`
6. `newamp1_ALLOBS_tf2-GLB2_UAH_v60jan17_r1979_2016_s1979_2016_nofilt.d`

The string "`tf2`" denotes the variable of interest (TMT, corrected for lower stratospheric cooling); "`GLB2`" identifies the 82.5°N-82.5°S domain over which spatial averages are calculated (see below); the strings "`RSS`", "`STR`", and "`UAH`" identify the research group that produced the data (Remote Sensing Systems, The Center for Satellite Applications and Research, and the University of Alabama at Huntsville, respectively), the strings "`v33`", "`v40`" (*etc.*) identify the dataset version number (see below), "`jan17`" is the download date of the raw datasets, "`r1979_2016`" is the reference period used for calculating climatological monthly means, "`s1979_2016`" is the period used for calculating simple time series statistics, and "`nofilt`" signifies that the temperature data were not low- or high-pass filtered prior to output.

Each of the observational data files has the same structure. After 15 lines of header information, there are three columns of data: an integer month counter (column 1), time in years (column 2), and temperature anomalies in degrees C (column 3).

There are 36 `ASCII` files containing model estimates of monthly-mean changes in near-global averages of synthetic TMT. There is one `ASCII` file for each of the 36 model pre-industrial control runs listed in Supplementary Table S2. As in the case of the observational results, model TMT data are corrected for the influence of lower stratospheric cooling. The 36 individual model data files are bundled in a single .tar file ("`tmt_corrected_36models_picontrol_GLB2.tar`").

Here are several examples of model file names:

1. `piControl_36m_tf2-GLB2_ccsm4_r1i1p1_r0000_0000_s0000_0000_nofilt.d`
2. `piControl_36m_tf2-GLB2_giss_e2_h_p1_r1i1p1_r0000_0000_s0000_0000_nofilt.d`
3. `piControl_36m_tf2-GLB2_giss_e2_h_p3_r1i1p3_r0000_0000_s0000_0000_nofilt.d`

As in the case of the observational data, the string "`tf2`" denotes the variable of interest (corrected TMT), and "`GLB2`" identifies the 82.5°N-82.5°S domain over which spatial averages are calculated. The model name (*e.g.*, "`ccsm4`", "`giss_e2_h_p1`", "`giss_e2_h_p3`") is encoded in the file name. Note that "`p1`" and "`p3`" denote different physics versions of the `GISS-E2-H` model. These different physics versions are also encoded in the "ensemble member identifier" ("`r1i1p1`", "`r1i1p3`", *etc.*; see Supplementary Table S2). The string "`r0000_0000`" indicates that anomalies are defined with respect to climatological monthly means computed over the entire length of the control run. The string "`s0000_0000`" indicates that time series statistics are calculated over the entire length of the control run.

Each model file has 32 header lines, followed by six columns of data: an integer month counter (column 1), time in years (column 2), temperature anomalies in degrees C (column 3), the actual number of model grid-points in the selected domain (column 4), the fractional data coverage in the selected domain (column 5), and a simple quality control metric (column 6).

Satellite temperature data

Since late 1978, microwave sounders on NOAA polar-orbiting satellites have measured the microwave emissions of oxygen molecules. Because oxygen molecules are present at all altitudes, the microwave radiance that reaches the satellite is an integral of emissions from thick layers of the atmosphere[*]. The observed microwave radiance, or "brightness temperature", is related to the average temperature of a broad layer of the atmosphere by a weighting function, which describes the relative contribution of each level of the atmosphere to the total radiance. The weighting function is calculated using an atmospheric radiative transfer model. The function depends both on the microwave frequency band that is observed and the angle of observation relative to Earth's surface, allowing the sounder to measure different layers in the atmosphere via the use of different frequency bands and/or different viewing angles[1,2,3].

We used satellite estimates of atmospheric temperature change produced by three different research groups:

1. Remote Sensing Systems in Santa Rosa, California (RSS)[1,4].
2. The Center for Satellite Applications and Research, NOAA/National Environmental Satellite, Data, and Information Service, College Park, Maryland (STAR)[2,5,6].

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[*] Satellite estimates of the temperature of tropospheric layers also receive a small contribution from the temperature at Earth's surface.

3. The University of Alabama at Huntsville (UAH)[7].

All three groups provide satellite estimates of the temperature of the mid- to upper troposphere (TMT).[†] Trends in TMT are the focus of the Santer *et al.* "Scientific Reports" paper. RSS, UAH, and STAR also produce satellite measurements of the temperature of the lower stratosphere (TLS). TLS is required for correcting TMT for the influence it receives from stratospheric cooling (see below). The approximate altitude ranges and pressure level boundaries for TMT and TLS are given in Table 2 of ref. 8.

Each group provides the most recent version and the previous version of their datasets. The versions available are: 3.3 and 4.0 (RSS), 3.0 and 4.0 (STAR), and 5.6 and 6.0 (UAH). Satellite datasets are in the form of monthly means on 2.5° × 2.5° latitude/longitude grids. At the time this analysis was performed, temperature data were available for the 456-month period from January 1979 to December 2016.

There are differences in the spatial coverage of the satellite temperature data produced by the three groups. While UAH TLS and TMT datasets have global coverage, areas poleward of 87.5° (82.5°) are excluded from STAR (RSS). To avoid any impact of spatial coverage differences on trend comparisons, we calculated all

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[†] The University of Washington (UW) also produces a TMT dataset, but this is available for the tropics only[3]. Since the interest in the Santer *et al.* "Scientific Reports" paper is in global-scale changes in TMT, we did not analyze UW TMT data for the present study.

near-global averages of actual and synthetic satellite temperatures over the area of common coverage in the RSS, UAH, and STAR datasets (82.5°N to 82.5°S).

Details of model output

We used model output from phase 5 of the Coupled Model Intercomparison Project (CMIP5)[9]. A full list of modeling groups participating in CMIP5 is given at http://cmip-pcmdi.llnl.gov/cmip5/docs/CMIP5_modeling_groups.pdf. The simulations analyzed here were contributed by 18 different research groups (see Supplementary Table S1). Our focus was on pre-industrial control runs with no changes in external influences on climate, which provide estimates of the natural internal variability of the climate system (see Supplementary Table S2).

Calculation of synthetic satellite temperatures

To compare satellite-derived atmospheric temperature trends with model estimates of trends arising from natural internal variability, we calculate synthetic TMT and TLS from CMIP5 control runs. This calculation relies on a local weighting function method developed at RSS. At each model grid-point, simulated temperature profiles were convolved with local weighting functions. Local weights depend on the grid-point surface pressure, the surface type (land or ocean), and the selected layer-average temperature (TMT or TLS). This method provides more accurate estimates of synthetic satellite temperatures, particularly over high elevation regions[10].

Treatment of GISS-E2-H and GISS-E2-R models

In the `GISS-E2-H` and `GISS-E2-R` models, the same atmospheric GCM is coupled to different ocean models. In turn, each of these two coupled models provides control run simulation output for model versions with different treatment of aerosol and ozone[11,12]. For `GISS-E2-H`, synthetic MSU temperatures were available from three separate control runs (`p1`, `p2`, and `p3`). For `GISS-E2-R`, synthetic MSU temperatures were available from only two control runs (`p1` and `p2`; see Supplementary Table S2).

In calculating the "weighted" p-values shown in the Santer *et al.* "Scientific Reports" paper,[‡] it was necessary to decide whether atmospheric temperatures from these individual model versions should be treated as different realizations of internal variability performed with a similar physical model, or as results from different models of the climate system. Since there are important differences between these model versions, we decided to treat the five different model versions (three for `GISS-E2-H` and two for `GISS-E2-R`) as five separate models.

[‡] In Fig. 1C and Supplementary Figure S1C.

Correcting TMT for stratospheric cooling

Trends in TMT estimated from microwave sounders receive a substantial contribution from the cooling of the lower stratosphere[13,14,15,16]. In ref. 13, a regression-based approach was developed for removing the bulk of this stratospheric cooling component of TMT. Here, we refer to this "corrected" version[§] of TMT as TMT_{cr}. The Santer *et al.* "Scientific Reports" paper discusses corrected TMT only, and does not use the subscript *cr* to identify corrected TMT.

The correction method appiled in ref. 13 has been validated with both observed and model atmospheric temperature data[14,17,18]. Correction was performed locally, at each observational and model grid-point. Corrected grid-point data were then spatially averaged over 82.5°N-82.5°S.

For calculating tropical averages of TMT_{cr}, ref. 15 used:

$$\text{TMT}_{cr} = a_{24}\text{TMT} + (1 - a_{24})\text{TLS} \tag{1}$$

where $a_{24} = 1.1$. Subsequent analyses of tropical data in ref. 16 obtained very similar estimates[¶] of a_{24}. For the near-global domain considered here, lower stratospheric

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[§] In other publications[3,15], TMT_{cr} is designated as TTT (the temperature of the tropical troposphere) or as T_{24} (since it is generated using brightness temperatures estimated with the emissions measurements obtained from channels 2 and 4 of microwave sounders).

[¶] See Table 1 in 16.

cooling makes a larger contribution to TMT trends[‖], so a_{24} is larger[13,16]. In refs. 13 and 16, $a_{24} \approx 1.15$ was applied directly to near-global averages of TMT and TLS. Since we are performing corrections on local (grid-point) data, we used $a_{24} = 1.1$ between 30°N and 30°S, and $a_{24} = 1.2$ poleward of 30°. This is approximately equivalent to use of the $a_{24} = 1.15$ for globally-averaged data.

In calculating corrected TMT from UAH TLS and TMT data, we did not 'mix' different versions of the UAH datasets: *i.e.*, version 5.6 of UAH TMT_{cr} was computed with version 5.6 of UAH TLS and TMT data, and version 6.0 of UAH TMT_{cr} was computed with version 6.0 of UAH TLS and TMT data. The same holds for the STAR corrected TMT data: version 3.0 (4.0) of STAR TMT_{cr} was calculated with version 3.0 (4.0) of STAR TLS and TMT data.

For RSS, version 3.3 of TMT_{cr} was calculated with version 3.3 of RSS TLS and TMT data. Version 4.0 of RSS TMT_{cr} relied on version 4.0 of RSS TMT and version 3.3 of RSS TLS (since version 4.0 of RSS TLS is not yet available). The residual errors that were corrected in the transition from version 3.3 to version 4.0 of the RSS TMT data are unlikely to have pronounced impact on TLS, so the inconsistency in the TMT and TLS versions used to generate version 4.0 of the RSS TMT_{cr} data is not important[1].

[‖] This is due to two effects: the tropopause is lower at mid- to high latitudes than in the tropics, and stratospheric cooling over the satellite era is larger at high latitudes than in the tropics[10].

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Supplementary Table 1: CMIP5 models used in this study.

	Model	**Country**	**Modeling center**
1	ACCESS1.0	Australia	Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology
2	ACCESS1.3	Australia	Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology
3	BCC-CSM1.1	China	Beijing Climate Center, China Meteorological Administration
4	BCC-CSM1.1(m)	China	Beijing Climate Center, China Meteorological Administration
5	CanESM2	Canada	Canadian Centre for Climate Modelling and Analysis
6	CCSM4	USA	National Center for Atmospheric Research
7	CESM1-BGC	USA	National Science Foundation, U.S. Dept. of Energy, National Center for Atmospheric Research
8	CESM1-CAM5	USA	National Science Foundation, U.S. Dept. of Energy, National Center for Atmospheric Research
9	CMCC-CESM	Italy	Centro Euro-Mediterraneo per I Cambiamenti Climatici
10	CMCC-CM	Italy	Centro Euro-Mediterraneo per I Cambiamenti Climatici
11	CMCC-CMS	Italy	Centro Euro-Mediterraneo per I Cambiamenti Climatici
12	CSIRO-Mk3.6.0	Australia	Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence
13	FGOALS-g2	China	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences; and CESS, Tsinghua University
14	FIO-ESM	China	The First Institute of Oceanography, SOA
15	GFDL-CM3	USA	NOAA Geophysical Fluid Dynamics Laboratory
16	GFDL-ESM2G	USA	NOAA Geophysical Fluid Dynamics Laboratory

Supplementary Table 1: CMIP5 models used in this study (continued).

	Model	**Country**	**Modeling center**
17	GFDL-ESM2M	USA	NOAA Geophysical Fluid Dynamics Laboratory
18	GISS-E2-H (p1)	USA	NASA Goddard Institute for Space Studies
19	GISS-E2-H (p2)	USA	NASA Goddard Institute for Space Studies
20	GISS-E2-H (p3)	USA	NASA Goddard Institute for Space Studies
21	GISS-E2-R (p1)	USA	NASA Goddard Institute for Space Studies
22	GISS-E2-R (p2)	USA	NASA Goddard Institute for Space Studies
23	HadGEM2-CC	UK	Met. Office Hadley Centre
24	HadGEM2-ES	UK	Met. Office Hadley Centre
25	INM-CM4	Russia	Institute for Numerical Mathematics
26	IPSL-CM5A-LR	France	Institut Pierre-Simon Laplace
27	IPSL-CM5A-MR	France	Institut Pierre-Simon Laplace
28	IPSL-CM5B-LR	France	Institut Pierre-Simon Laplace
29	MIROC5	Japan	Atmosphere and Ocean Research Institute (the University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology
30	MIROC-ESM-CHEM	Japan	As for MIROC5
31	MIROC-ESM	Japan	As for MIROC5
32	MPI-ESM-LR	Germany	Max Planck Institute for Meteorology

Supplementary Table 1: CMIP5 models used in this study (continued).

	Model	**Country**	**Modeling center**
33	MPI-ESM-MR	Germany	Max Planck Institute for Meteorology
34	MRI-CGCM3	Japan	Meteorological Research Institute
35	NorESM1-M	Norway	Norwegian Climate Centre
36	NorESM1-ME	Norway	Norwegian Climate Centre

Supplementary Table 2: Start dates, end dates, and lengths (N_m, in months) of the 36 CMIP5 pre-industrial control runs used in this study. EM is the "ensemble member" identifier.*

	Model	EM	Start	End	N_m
1	ACCESS1.0	r1i1p1	300-01	799-12	6000
2	ACCESS1.3	r1i1p1	250-01	749-12	6000
3	BCC-CSM1.1	r1i1p1	1-01	500-12	6000
4	BCC-CSM1.1(m)	r1i1p1	1-01	400-12	4800
5	CanESM2	r1i1p1	2015-01	3010-12	11952
6	CCSM4	r1i1p1	800-01	1300-12	6012
7	CESM-BGC	r1i1p1	101-01	600-12	6000
8	CESM-CAM5	r1i1p1	1-01	319-12	3828
9	CMCC-CESM	r1i1p1	4324-01	4600-12	3324
10	CMCC-CM	r1i1p1	1550-01	1879-12	3960
11	CMCC-CMS	r1i1p1	3684-01	4183-12	6000
12	CSIRO-Mk3.6.0	r1i1p1	1651-01	2150-12	6000
13	FGOALS-g2	r1i1p1	201-01	900-12	8400
14	FIO-ESM	r1i1p1	401-01	1200-12	9600
15	GFDL-CM3	r1i1p1	1-01	500-12	6000
16	GFDL-ESM2G	r1i1p1	1-01	500-12	6000
17	GFDL-ESM2M	r1i1p1	1-01	500-12	6000
18	GISS-E2-H (p1)	r1i1p1	2410-01	2949-12	6480
19	GISS-E2-H (p2)	r1i1p2	2490-01	3020-12	6372
20	GISS-E2-H (p3)	r1i1p3	2490-01	3020-12	6372
21	GISS-E2-R (p1)	r1i1p1	3981-01	4530-12	6600
22	GISS-E2-R (p2)	r1i1p2	3590-01	4120-12	6372
23	HadGEM2-CC	r1i1p1	1859-12	2099-12	2881
24	HadGEM2-ES	r1i1p1	1859-12	2435-11	6912
25	INM-CM4	r1i1p1	1850-01	2349-12	6000
26	IPSL-CM5A-LR	r1i1p1	1800-01	2799-12	12000

Supplementary Table 2 (continued): Information on the 36 CMIP5 pre-industrial control runs used in this study.

Model	EM	Start	End	N_m
27 IPSL-CM5A-MR[§]	r1i1p1	1800-01	2068-12	3228
28 IPSL-CM5B-LR	r1i1p1	1830-01	2129-12	3600
29 MIROC5	r1i1p1	2000-01	2669-12	8040
30 MIROC-ESM-CHEM	r1i1p1	1846-01	2100-12	3060
31 MIROC-ESM	r1i1p1	1800-01	2330-12	6372
32 MPI-ESM-LR	r1i1p1	1850-01	2849-12	12000
33 MPI-ESM-MR	r1i1p1	1850-01	2849-12	12000
34 MRI-CGCM3	r1i1p1	1851-01	2350-12	6000
35 NorESM1-M	r1i1p1	700-01	1200-12	6012
36 NorESM1-ME	r1i1p1	901-01	1152-12	3024

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[*] See http://cmip-pcmdi.llnl.gov/cmip5/documents.html for further details.

[§] The `IPSL-CM5A-MR` control run has a large discontinuity in year 2069. We therefore truncated the `IPSL-CM5A-MR` control run after December 2068.