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Estimating and Removing the Sampling Biases of the AIRS Obs4MIPs V2 Data

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Key Points:

- The sampling biases of the AIRS Obs4MIPs V2.0 data are estimated based on ERA5 reanalysis and cross-checked based on MERRA-2 reanalysis
- The sampling-bias-corrected AIRS Obs4MIPs V2.1 data are produced by removing the sampling bias estimates based on ERA5
- The new AIRS Obs4MIPs V2.1 data have been published on ESGF and should be used in the future for climate model evaluation

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Abstract The Atmospheric Infrared Sounder (AIRS) Observations for Model Intercomparison Projects (Obs4MIPs) Version 2.0 (V2.0) monthly mean tropospheric air temperature, specific humidity, and relative humidity profile data were designed for climate model evaluation in the context of the Coupled Model Intercomparison Project (CMIP). Due to the limitations of the Aqua satellite orbit and the AIRS retrieval algorithm, the sampling biases of the AIRS Obs4MIPs V2.0 data can be large for certain cases and must be considered when the AIRS Obs4MIPs V2.0 data are used for climate model evaluation. In this study, we estimate the sampling biases of the AIRS Obs4MIPs V2.0 data based on the fifth generation of the European Centre for Medium-Range Weather Forecasts (ECMWF) (ERA5) reanalysis and cross-check them using the Modern-Era Retrospective Analysis for Research and Application, Version 2 (MERRA-2) reanalysis. We then remove the estimated sampling biases from the AIRS Obs4MIPs V2.0 data and produce the sampling-bias-corrected AIRS Obs4MIPs V2.1 data that have been published at the Earth System Grid Federation (ESGF) data centers and should be used in the future for climate model evaluation.

Plain Language Summary We have estimated and cross-checked the sampling biases of the Atmospheric Infrared Sounder (AIRS) Observations for Model Intercomparison Projects (Obs4MIPs) V2.0 data and produced the sampling-bias-corrected AIRS Obs4MIPs V2.1 data that should be used in the future for climate model evaluation.

1. Introduction

The Atmospheric Infrared Sounder (AIRS) (Chahine et al., 2006) Observations for Model Intercomparison Projects (Obs4MIPs) (Waliser et al., 2020) Version 2.0 (V2.0) data (Tian et al., 2019) were designed for climate model evaluation in the context of the Coupled Model Intercomparison Project (CMIP) (Meehl et al., 2005) and have been publicly available at the Earth System Grid Federation (ESGF) data centers (Cinquini et al., 2014) since 2018. The AIRS Obs4MIPs V2.0 data set includes the monthly mean tropospheric air temperature (ta), specific humidity (hus), and relative humidity (hur). For each physical variable (ta, hus, and hur), there are corresponding standard error (Stderr) and number of observations (Nobs) for a rough estimate of the AIRS data retrieval error and sampling uncertainty. These variables are provided for each calendar month from September 2002 to September 2016, on a global $1° \times 1°$ latitude-longitude spatial grid, and on the eight CMIP mandatory vertical pressure levels from 1,000 to 300 hPa (Tian et al., 2019).

A sampling difference exists between the climate model outputs and the AIRS Obs4MIPs V2.0 data because the former is sampled on regular spatial and temporal grids while the latter is not (Tian et al., 2019). The AIRS instrument on the Aqua spacecraft is in a Sun-synchronous low Earth orbit with a limited swath and a limited sampling of the diurnal cycle and synoptic events. Moreover, since the AIRS is an infrared instrument, the AIRS sampling is influenced by clouds, aerosols, coastlines, and other factors that affect its ability to perform successful physical retrievals. Also, for certain months AIRS can have amounts of missing data because of Aqua spacecraft maneuvers. For example, the AIRS instrument was placed in a safe mode for parts of October and November 2003 to avoid possible damages from a solar flare. It also suffered an anomaly in January 2010, that involuntarily placed it in a safe mode for most of that month. Data are also missing after 24 September 2016 because of the power failure of the Advanced Microwave Sounding Unit A2 (AMSU-A2) instrument. All of these sampling differences between the climate model outputs and AIRS data can affect the comparisons between the AIRS Obs4MIPs V2.0 data and climate model outputs (Fetzer et al., 2006; Hearty et al., 2014; Tian et al., 2013, 2019; Yue et al., 2013). Our previous study based on the AIRS Version 5 (V5) data (Hearty et al., 2014) has shown that the AIRS V5 data have sampling biases of cold up to -2 K and dry ~30% over the midlatitude storm tracks and deep convective cloud regions. The AIRS V5 data also have large sampling biases in the boundary layer in the regions with large diurnal variations.

The purpose of this paper is to estimate, cross-check, and remove the sampling biases of the AIRS Obs4MIPs V2.0 data and produce the sampling-bias-corrected AIRS Obs4MIPs V2.1 data. Section 2 introduces the methodology and data for our sampling bias estimates. Section 3 describes our sampling bias estimates and their cross-check. Section 4 discusses the sampling-bias-corrected AIRS Obs4MIPs V2.1 data followed by a summary in section 5.

2. Methodology and Data for Sampling Bias Estimates

We have applied the methodology described in Hearty et al. (2014) to estimate and cross-check the sampling biases of the AIRS Obs4MIPs V2.0 data based on the state-of-the-art reanalyses. This method has been employed for the AIRS V5 data using the Modern-Era Retrospective Analysis for Research and Application (MERRA) reanalysis and has been found to be consistent with other methods for estimating the AIRS data sampling biases (Yue et al., 2013). The basic idea of this method is that the differences between the monthly mean reanalysis data sampled like the AIRS Obs4MIPs V2.0 data product and the monthly mean reanalysis data sampled over all their time steps are an estimate of the sampling biases of the AIRS Obs4MIPs V2.0 data.

The main reanalysis data we have used for estimating the sampling biases of the AIRS Obs4MIPs V2.0 data is from the fifth generation of the European Centre for Medium-Range Weather Forecasts (ECMWF) (ERA5) global reanalysis (Hersbach et al., 2020). The ERA5 is produced by ECMWF using the Integrated Forecasting System (IFS) Cy41r2 which became operational in 2016. The ERA5 reanalysis is currently available from 1979 to the present. The ERA5 HRES (High Resolution) (stream = oper/wave) subdaily analysis (type = an) data were produced and archived as spectral coefficients with a triangular truncation of T639 or a native resolution of 0.28125° (31 km), a temporal resolution of hourly (00:00, 01:00, 02:00,..., 23:00), and at 37 pressure levels from 1,000 to 1 hPa. The data were interpolated to a regular longitude/latitude grid of 0.25° when they were downloaded as NetCDF files through the Copernicus Climate Change Service (C3S) Climate Data Store (C3S, 2017). We have used both the hourly and monthly average products of instantaneous air temperature, specific humidity, and relative humidity profiles from ERA5 for this study.

To cross-check the sampling biases of the AIRS Obs4MIPs V2.0 data based on the ERA5 reanalysis and test the sensitivity of our sampling bias estimates to different reanalysis data sets, we have also estimated the sampling biases of the AIRS Obs4MIPs V2.0 data based on the MERRA, Version 2 (MERRA-2) reanalysis (Gelaro et al., 2017). MERRA-2 is the latest atmospheric reanalysis of the modern satellite era produced by NASA's Global Modeling and Assimilation Office (GMAO). The MERRA-2 data used in this study are the inst3_3d_asm_Np: 3d, 3-Hourly, Instantaneous, Pressure-Level, Assimilation, Assimilated Meteorological Fields V5.12.4 product (GMAO, 2015).

The instantaneous ERA5 or MERRA-2 data were first used to simulate the AIRS Version 6 (V6) Level 2 (L2) observations (AIRS, 2013) using the AIRS V6 L2 time, geolocation and quality control information. Each AIRS V6 L2 profile was matched to the nearest ERA5 or MERRA-2 reanalysis profile in time and space. The offsets in time and space (Δtime, Δlon, Δlat) were always ≤(30 min, 0.125°, 0.125°) or ≤(90 min, 0.3125°, 0.25°) between the AIRS V6 L2 data and the ERA5 or MERRA-2 data. Only the matched ERA5 or MERRA-2 data that passed the AIRS V6 L2 quality control criteria used for the AIRS Obs4MIPs V2.0 data were kept, gridded to the 1° × 1° horizontal grid and the same eight CMIP pressure levels, and averaged to the monthly mean to match the AIRS Obs4MIPs V2.0 data product. The differences between this monthly mean ERA5 or MERRA-2 reanalysis data sampled like the AIRS Obs4MIPs V2.0 data product and the monthly mean ERA5 or MERRA-2 reanalysis data sampled over all their time steps are an estimate of the sampling biases of the AIRS Obs4MIPs V2.0 data.

We have calculated the sampling biases of the AIRS Obs4MIPs V2.0 data for each month from September 2002 through September 2016. We have also calculated the multiyear monthly mean climatologies of the

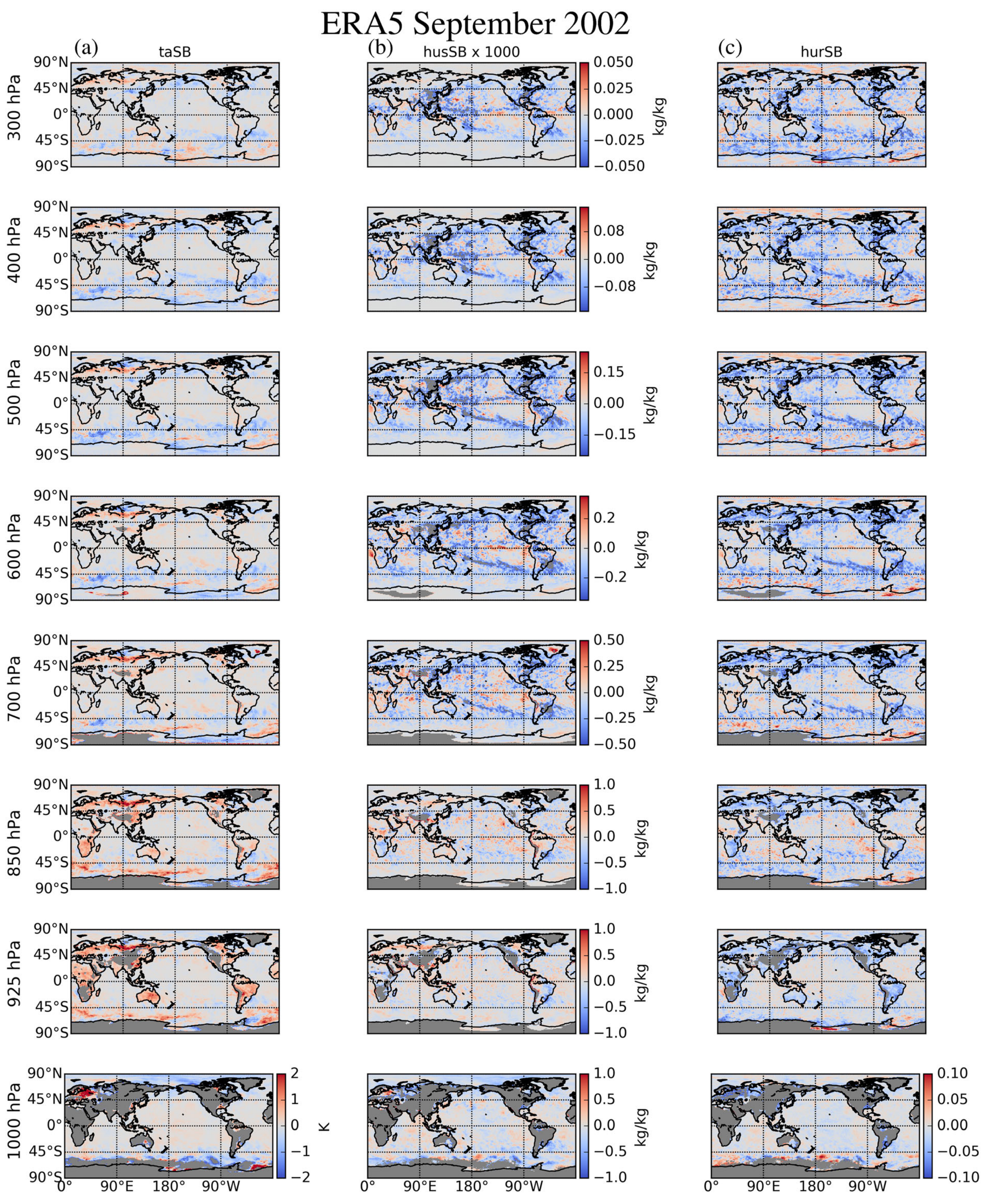

Figure 1. The monthly mean air temperature sampling bias (taSB, a), specific humidity sampling bias (husSB, b), and relative humidity sampling bias (hurSB, c) of the AIRS Obs4MIPs V2.0 data based on the ERA5 reanalysis for September 2002.

sampling bias estimates by averaging over the monthly sampling bias estimates for each month of the year and a yearly sampling bias climatology by averaging over each month in the multiyear monthly mean sampling bias climatology.

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3. Results and Cross-Check of Sampling Bias Estimates

Figure 1 shows the monthly mean air temperature sampling bias (taSB, a), specific humidity sampling bias (husSB, b), and relative humidity sampling bias (hurSB, c) of the AIRS Obs4MIPs V2.0 data based on the ERA5 reanalysis for September 2002. The sampling biases of the AIRS Obs4MIPs V2.0 data (based on the AIRS V6 data) are generally smaller than the sampling biases of the AIRS V5 data that we previously estimated using MERRA due probably to the larger yields in the AIRS V6 data in comparison to the AIRS V5 data. However, the sampling biases of the AIRS Obs4MIPs V2.0 data and the AIRS V5 data do have a similar character. For example, the air temperature sampling biases tend to be negative (cold up to −2 K) in the free troposphere above 600 hPa over the midlatitude storm tracks or over the tropical convective cloudy regions, such as the Intertropical Convergence Zone (ITCZ), the South Pacific convergence zone (SPCZ), the western Pacific warm pool, the equatorial south America, and the south Atlantic convergence zone (SACZ) (Tian & Dong, 2020; Tian, 2015). The specific and relative humidity sampling biases tend to be negative throughout the troposphere over the midlatitude storm tracks or over the tropical convective cloudy regions (e.g., dry up to −0.15 kg kg^{-1} at 500 hPa or −20% of the mean at all levels for hus or dry up to −20% for hur). However, the humidity sampling biases tend to be positive (wet) over the ocean off the west coast of South America and Southern Africa. The air temperature sampling biases tend to be larger closer to the surface and over land where there are larger diurnal variations in air temperature. The sampling biases at 1,000 hPa are mainly the temporal sampling biases while the sampling biases over the free troposphere (above 850 hPa) are mainly the instrumental sampling biases, especially the sampling biases due to clouds (Hearty et al., 2014). It is also noted that the missing sampling bias estimates are due to the missing AIRS Obs4MIPs V2.0 data (Tian et al., 2019). Similar features of the sampling bias estimates are also found for other different months and years with a clear seasonal variation. The yearly climatological mean sampling biases of the AIRS Obs4MIPs V2.0 data are similar to those for September 2002 except for the yearly climatological mean sampling biases are much smoother.

Figure 2 shows the monthly mean air temperature sampling bias (taSB, a), specific humidity sampling bias (husSB, b), and relative humidity sampling bias (hurSB, c) of the AIRS Obs4MIPs V2.0 data based on the MERRA-2 reanalysis for September 2002. There are some differences between the sampling biases of the AIRS Obs4MIPs V2.0 data based on the ERA5 and MERRA-2 reanalyses particularly at the 1,000-hPa level near the surface. For example, it seems that the ERA5-based result indicates cold temperature sampling biases at 1,000 hPa while the MERRA-2-based result shows warm temperature sampling biases at 1,000 hPa. Also, at this level the humidity sampling biases tend to be larger based on ERA5 in comparison to those based on MERRA-2. These differences are not surprising given the fact that the ERA5 and MERRA-2 reanalyses have different models, different physics, and different spatial and temporal resolutions. These differences could also indicate differences in the diurnal cycle between these two reanalyses. In addition, there are more missing sampling bias estimates based on MERRA-2 than those based on ERA5 at 1,000, 925, 800, 700, and a little 600 hPa at elevated land regions due to the fact that the MERRA-2 does not extrapolate the data to sea level. However, the sampling biases of the AIRS Obs4MIPs V2.0 data based on these two reanalyses are largely consistent with each other in most regions of the world and in most levels of the troposphere. This suggests that our estimates of the sampling biases of the AIRS Obs4MIPs V2.0 data based on the ERA5 reanalysis are robust. Similar tendencies can also be found for the yearly climatological mean sampling biases of the AIRS Obs4MIPs V2.0 data based on the ERA5 and MERRA-2 reanalyses. Because the ERA5 reanalysis uses a more modern model with higher spatial and temporal resolutions relative to the MERRA-2 reanalysis and the MERRA-2 reanalysis has numerous missing elevated land data, we have decided to use the sampling bias estimates based on ERA5 as our final estimates of the sampling biases of the AIRS Obs4MIPs V2.0 data.

4. Sampling-Bias-Corrected AIRS Obs4MIPs V2.1 Data

After estimating the sampling biases of the AIRS Obs4MIPs V2.0 data, we then remove the sampling biases of the AIRS Obs4MIPs V2.0 data estimated based on ERA5 from the AIRS Obs4MIPs V2.0 data to produce the sampling-bias-corrected AIRS Obs4MIPs V2.1 data set. The new AIRS Obs4MIPs V2.1 data set has accounted for the sampling difference between the AIRS and climate model data and should be used in the future to compare with the climate model outputs for climate model evaluation in the context of the

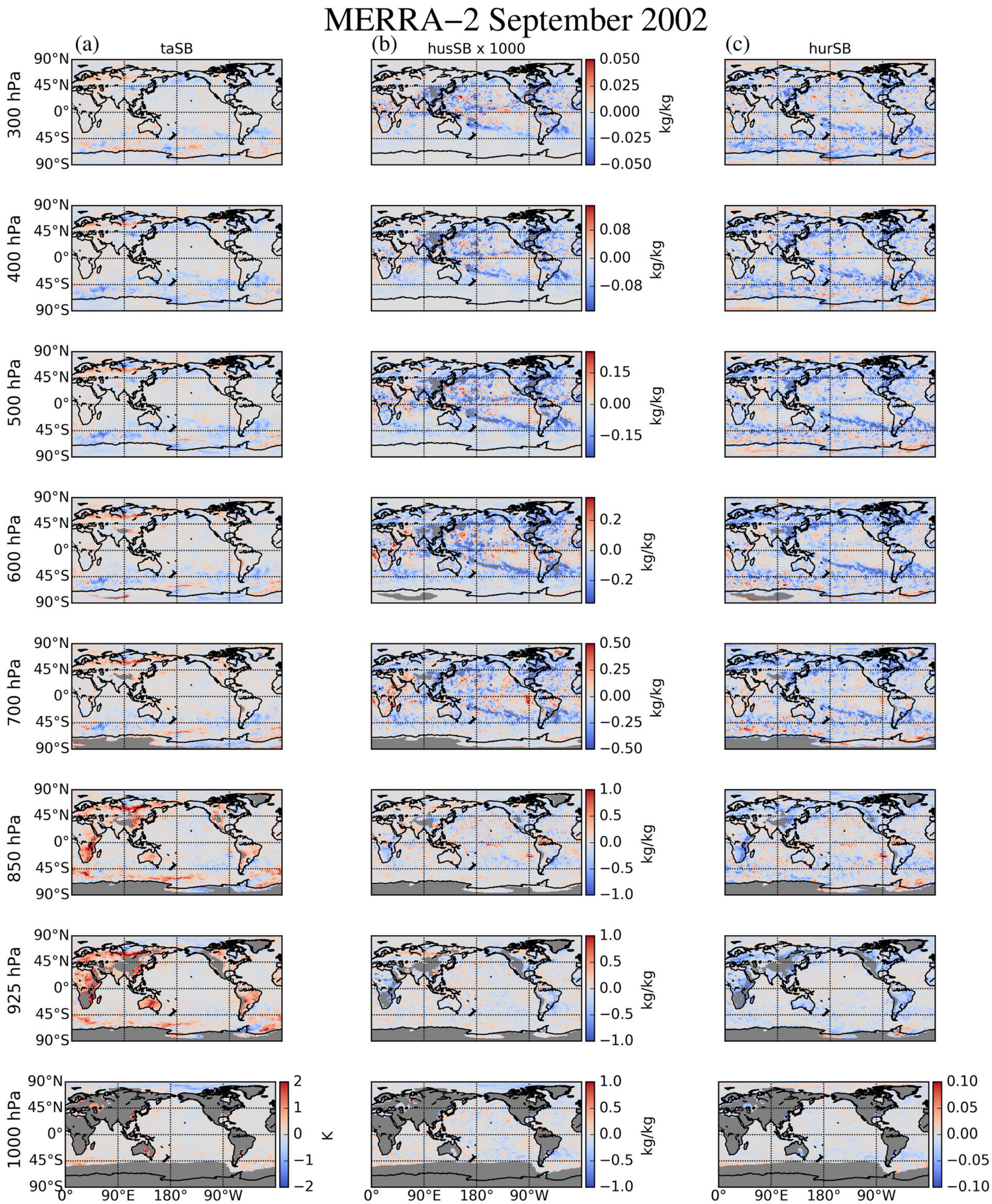

Figure 2. The monthly mean air temperature sampling bias (taSB, a), specific humidity sampling bias (husSB, b), and relative humidity sampling bias (hurSB, c) of the AIRS Obs4MIPs V2.0 data based on the MERRA-2 reanalysis for September 2002.

CMIP. Figure 3 shows the monthly mean relative humidity (hur) from the AIRS Obs4MIPs V2.0 data (a) and the sampling-bias-corrected AIRS Obs4MIPs V2.1 data (b) as well as the monthly mean relative humidity sampling bias of the AIRS Obs4MIPs V2.0 data (SB, c) for September 2002 at the 500-hPa pressure level.

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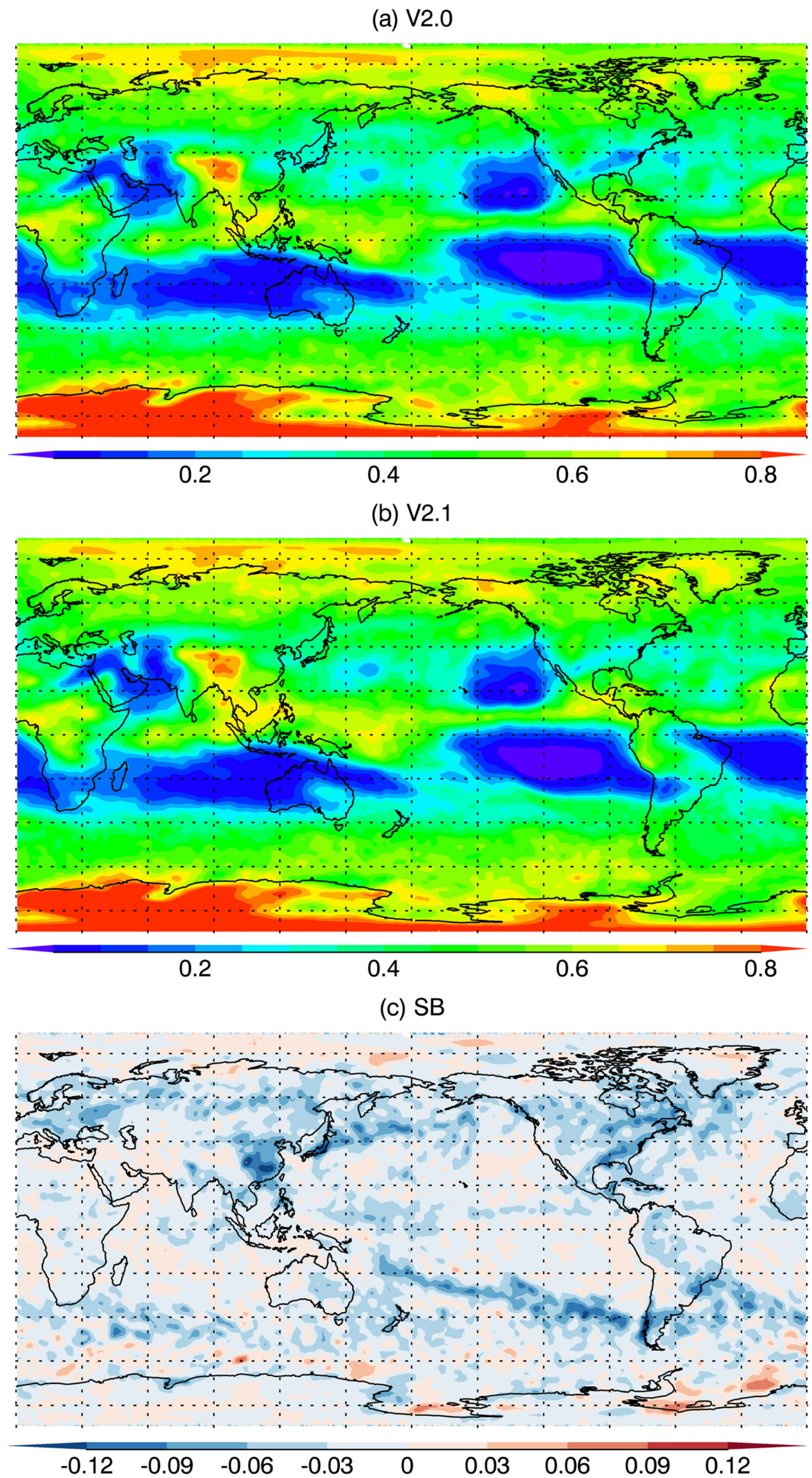

Figure 3. The monthly mean relative humidity (hur) from the AIRS Obs4MIPs V2.0 data (a) and the sampling-bias-corrected AIRS Obs4MIPs V2.1 data (b) as well as the monthly mean relative humidity sampling bias of the AIRS Obs4MIPs V2.0 data (SB, c) for September 2002 at the 500-hPa pressure level.

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Table 1
The Sampling-Bias-Corrected AIRS Obs4MIPs V2.1 Data Set File Names and Contents

File names	File contents
ta_mon_AIRS-2-1_BE_gn_200209–201609.nc	The sampling-bias-corrected monthly mean air temperature (ta) in Kelvin
taStderr_mon_AIRS_Obs4MIPs_V2.1_200209–201609.nc	The standard error (Stderr) of air temperature in Kelvin
taNobs_mon_AIRS_Obs4MIPs_V2.1_200209–201609.nc	The number of observations (Nobs) of air temperature
TechNote_ta_AIRS_V2.1.pdf	The technical note of air temperature
hus_mon_AIRS-2-1_BE_gn_200209–201609.nc	The sampling-bias-corrected monthly mean specific humidity (hus) in kg/kg
husStderr_mon_AIRS_Obs4MIPs_V2.1_200209–201609nc	The standard error (Stderr) of specific humidity in kg/kg
husNobs_mon_AIRS_Obs4MIPs_V2.1_200209–201609.nc	The number of observations (Nobs) of specific humidity
TechNote_hus_AIRS_V2.1.pdf	The technical notes of specific humidity
hur_mon_AIRS-2-1_BE_gn_200209–201609.nc	The sampling-bias-corrected monthly mean relative humidity (hur) (unitless)
hurStderr_mon_AIRS_Obs4MIPs_V2.1_200209–201,609.nc	The standard error (Stderr) of relative humidity (unitless)
hurNobs_mon_AIRS_Obs4MIPs_V2.1_200209–201,609.nc	The number of observations (Nobs) of relative humidity
TechNote_hur_AIRS_V2.1.pdf	The technical notes of relative humidity

Clearly, the monthly mean relative humidities from the AIRS Obs4MIPs V2.0 data (a) and the sampling-bias-corrected AIRS Obs4MIPs V2.1 data (b) are very similar to each other. However, the monthly mean relative humidity sampling bias (SB, c) is as large as ±15% compared to the monthly mean relative humidity and can clearly impact the monthly mean relative humidity distribution. For example, over the southeastern United States, Figure 3b shows no dark blue color area and smaller blue area after the bias correction in comparison to Figure 3a before the bias correction. Similar features are also seen in the SACZ and SPCZ regions over the ocean in Southern Hemisphere. In addition, the monthly mean relative humidity sampling bias (SB, c) will impact the interpretation of the climate model bias that is the difference of the climate model outputs and the AIRS data (Tian et al., 2013). The sampling-bias-corrected AIRS Obs4MIPs V2.1 data are publicly available on the ESGF website (https://esgf-node.llnl.gov/projects/obs4mips) to replace the AIRS Obs4MIPs V2.0 data with the same data structure as described in Tian et al. (2019). Three technical notes (Tian & Hearty, 2020a, 2020b, 2020c) that describe the key information needed to use this data set for CMIP climate model evaluation have also been provided. The file names and their contents of this sampling-bias-corrected AIRS Obs4MIPs V2.1 data set are listed in Table 1.

5. Summary

The AIRS Obs4MIPs V2.0 data set designed for CMIP model evaluation includes the monthly mean tropospheric air temperature, specific humidity, and relative humidity profiles from September 2002 to September 2016 (Tian et al., 2019). Due to the limitations of the Aqua satellite orbit and the AIRS retrieval algorithm, the sampling biases of the AIRS Obs4MIPs V2.0 data can be as large as the measurement uncertainties for certain cases and must be considered when the AIRS Obs4MIPs V2.0 data are used for climate model evaluations (Tian et al., 2019). In this study, we have estimated the sampling biases of the AIRS Obs4MIPs V2.0 data based on the ERA5 reanalysis and cross-checked them using the MERRA-2 reanalysis. We have removed the sampling biases of the AIRS Obs4MIPs V2.0 data estimated based on the ERA5 reanalysis from the AIRS Obs4MIPs V2.0 data and produced the sampling-bias-corrected AIRS Obs4MIPs V2.1 data that have been published at the Earth System Grid Federation (ESGF) data centers (Tian & Hearty, 2020a, 2020b, 2020c) and should be used in the future for climate model evaluation.

Data Availability Statement

Data sets for this research are available in these references: Tian et al. (2019), Tian and Hearty (2020a, 2020b, 2020c), AIRS (2013), C3S (2017), Hersbach et al. (2020), GMAO (2015), and Gelaro et al. (2017). The AIRS Obs4MIPs V2.0 and V2.1 data sets are publicly available at the Earth System Grid Federation (ESGF) website (https://esgf-node.llnl.gov/projects/obs4mips). The AIRS V6 L2 data are publicly available from the NASA Goddard Earth Sciences Data and Information Services Center (GES DISC) (https://disc.gsfc.nasa.gov). The ERA5 and MERRA-2 data are publicly available from the Copernicus Climate Change Service Climate Data Store (CDS) (https://cds.climate.copernicus.eu/cdsapp) and the NASA Global Modeling and Assimilation Office (GMAO) website (https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/), respectively.

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